TEACHING PRODUCT DESIGN
Through the Investigation of Commercial Beer

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Historically, design courses in the chemical engineering curriculum focus on teaching *process design* rather than *product design.* A traditional program may contain one or two design courses at the senior level—the first generally addresses the design of unit operations such as physical separators, distillation columns, heat exchangers, turbomachinery, and other process components, while a subsequent capstone design course provides an opportunity for students to combine what they have learned in previous courses such as thermodynamics, reaction engineering, and transport phenomena. In the capstone design course, students' efforts are usually geared toward designing a process to manufacture a commodity chemical, such as cumene or styrene. This traditional design education originated and was driven by the needs of the chemical commodity industry that dominated the chemical industry during the twentieth century.

Recently, Cussler[1] indicated the importance of including product design in the capstone design course. His view is consistent with a new industry reality where the traditional oil and chemical companies are introducing major changes to remain competitive. Process optimization, energy integration, and alternative raw matrials are no longer sufficient to provide chemical companies with a leading edge. This new business reality suggests that producing shorter-life products and being the first on the market is the "new" way to succeed in business and stay profitable.

In the U.S., new start-up companies, mostly in the product business, are constantly emerging. Cussler's statistics also show that in the last twenty years, more chemical engineering graduates have gone to work in companies that manufacture products rather than in traditional chemical plants. Westerberg and Subrahmanian[2] also address the importance of introducing product design in the chemical engineering curriculum and give a clear description of the differences between process and product design. They list the main characteristics that define chemical products as

- *Products that are chemicals, such as pharmaceutical drugs, proteins, pesticides, and cleaning fluids*
- *Products that require chemistry in the manufacturing process, such as computer chips*
- *Devices that involve chemistry in their functionality, such as asbestos-removal systems, fuel cells, and portable oxygen generators*
- *Products that are produced in small volumes and that possess a high added value*

Such products have to meet certain customer needs and can only be conceived and designed by a multidisciplinary team that includes engineers. If chemical engineering students are to be ready to participate in product design, the curriculum must be adjusted to introduce product design.

At Rowan University, the first introduction to product design occurs in the Freshman Clinic, a two-semester sequence that introduces all freshman engineering students to engineering. The first semester of the course focuses on multidisciplinary engineering experiments using engineering measurements as a common thread; the theme of the second semester is the reverse engineering of a commercial product or process. Previous reverse engineering projects have involved products such as automatic coffee makers,[3,4] hair dryers,[5] and electric toothbrushes.[6] We also incorporated the design and reverse engineering of a *process* into our Freshman Clinic through a brewing process.[7] The project described in this paper focuses on the investigation of commercial beer as a means of providing a first introduction to chemical product design.

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BACKGROUND

Many properties are important in determining the overall character, flavor, and stability of beer. They include head stability, apparent carbonation, color, specific gravity, pH, alcohol content, sugar content, protein content, and viscosity. In addition, packaging properties such as material, color, fill level, and sound-upon-opening contributed to the overall sensory experience and perception of the product.

Some of these properties can be evaluated by simple observation, while others can be evaluated only by using specialized instrumentation or chemical analyses. We evaluate the packaging material, the fill level, the sound-upon-opening, and head stability, the apparent carbonation, the color, the pH, the alcohol content, the sugar content, and the cost of three commercial beers. We also consider the broader picture by addressing environmental issues and recycling, economics, marketing, and ethics.

Packaging is the final stage of the brewing process and represents the consumer's first impression of the product. Beer packaging, therefore, represents a highly competitive marketing focus that requires marketing creativity and technological advancement to fulfill consumer needs and build sales and profits. In the United States, 11% of beer packaged is on draft, 53% in cans, and 33% in bottles.[8] Since the first trials of putting beer into cans almost seventy years ago (Kreuger Brewing Company, Newark, New Jersey), beer companies have continually striven to develop innovative packaging materials and methods. Recently, two major U.S. brewers (Miller Brewing and Anheuser-Busch) began market testing beer in bottles made of polyethylene terephthalate (PET).[9] Other recent packaging innovations include unique can and bottle shapes, foam-inducing devices, and creative labeling.[10]

Glass beer bottles are manufactured in a variety of shapes, sizes, and colors. Clear or green bottles have become a popular marketing feature, but they provide absolutely no protection against light exposure—and beer can develop a skunky flavor within minutes of exposure to light[8] as desirable iso-α-acid bitter substances undergo light degradation to form 3-methyl-2-butene-1-thiol (MBT). Amber, brown, and black are the only glass colors that provide protection against light.

Plastic beer bottles were recently introduced after engineers overcame many challenges in developing suitable materials for this application. Some of the desired characteristics of plastic bottles are a shelf life of 120 days, low oxygen permeability (<1.0 ppm), minimal loss of carbon dioxide (<15%), heat stability during pasteurization, protection against UV light, recyclability, and cost-effectiveness.[11] Research focuses on developing polymers and treatments that improve these features. For instance, innovations in reducing the oxygen permeability of the package material include incorporating oxygen scavengers into the plastic.[12] Other challenges faced by engineers are the economics of plastic packaging and the recyclibility of the plastic materials. PET bottles are currently 20-50% more expensive to produce than glass bottles, and the economics of plastic bottle production will become competitive with glass only for a production in excess of 100 million bottles per year.[13] The amber color that is added to the PET to provide protection against UV light contaminates the PET, reducing its recyclability.[14]

Aside from the obvious marketing opportunities provided by the beer label, government regulations require that all alcoholic beverage labels must include the following information: brand name, class and type designation, commodity statement, name and address, health warning statement, net contents, and country of origin.[15] In 1995, the United State Supreme Court struck down a 60-year ban on listing the alcohol content on beer labels, claiming that the law violated free speech rights.[16]

The fill level of the liquid inside the bottle is important. If the level is lower than 1.5 inches below the cap, oxidation may produce off flavors and the carbonation may decrease, causing "flat" beer. If the bottle is filled higher than 1 inch below the cap, metallic off flavors may develop from interaction with the metal cap.

The ability for a beer to form foam, the stability of the foam, and the uniformity of bubbles are all very important qualities in beer. Upon pressurization in its container, typical beer is supersaturated with between 2.2 and 2.8 volumes of carbon dioxide per volume of beer.[17] This carbon dioxide is released in bubbles that form by nucleation on sites such as small irregularities on the surface of the glass, particles in the beer, or gas pockets that form upon opening.

The presence of foam in beer directly and positively affects the release of flavor components from the beer. There are substances in the beer that are vital to the flavor, and some of these substances are surface active, preferentially distributing themselves on the surface of the foam.[18] Thus, it is desirable to achieve a nice foam in the beer and for this foam to be stable over the time it takes to drink the beer.

Certain compounds are considered "foam negative" because of their negative effect on foam formation and stability. Some of these compounds occur naturally in the brewing process—for instance, some amino acids and lipids involved in the fermention are foam negative if they remain in the final product. In addition, several external factors can interfere with foam stability in beer. Improper cleaning of the beer glass can leave a foam-negative residue, as can greasy food or lipstick on the rim of a glass.

Size uniformity of bubbles is a desirable characteristic of the foam because it contributes to foam stability. Pressure inside a small bubble is greater than that inside a large bubble, causing a small bubble to "disappear" if it contacts a larger one. This phenomenon, called disproportionation, can be reduced by adding a gas of low solubility, such as nitrogen, to the beer. Guinness is an example of a beer that uses nitrogen to achieve small bubbles of uniform size, as shown in Figure 1. The larger bubbles in most beers appear to flow upward through the liquid to the surface; however, the small bubbles in Guinness appear to flow downward. Researchers performed a flow simulation using FLUENT to explain this phenomenon: small bubbles (<0.05 mm diameter) succumb to a downward drag force in the boundary layer near the glass, whereas larger bubbles have sufficient buoyancy to resist this force. In the middle of the glass, all bubbles flow upward.[19]

The widget is a device used to help create a long-lasting, stable foam in certain styles of beer that do not easily form a foam. The first commercial use of a widget was introduced by Guinness.[20] Guinness patented their widget design and other beer producers have since patented their own proprietary designs. Until 1999, the widget found inside Guinness cans was a hollow plastic pod found in the bottom of the can of beer. After 1999, a new design was introduced. The new widget looks similar to a ping-pong ball and should be cheaper to manufacture than the original design. Both designs, however, are covered by the same patent and function in the same way. There is a small hole in the widget through which beer can flow in or out when exposed to a pressure difference. The can is filled with beer and pressurized with carbon dioxide. A small quantity of liquid nitrogen is added immediately before the can is sealed; it quickly vaporizes and increases pressure inside the container, forcing beer and gases into the widget through the small hole. When the can is opened, the pressure is released; the beer and the gases in the widget are forced out through the small hole at a very high speed, and as this stream rips through the liquid in the can, it causes foam to form inside the can. This produces a nice, stable foam in a beer that otherwise would not have a very good foam. In addition, the N_2/CO_2 foam that forms has smaller bubbles that make it more stable than a traditional CO_2 foam. The widget designs are shown in Figure 2.

Beers are found in a wide range of colors, from very pale straw-colored lagers to amber or copper-colored ales, to dark, almost black stouts. The color is determined by the malt and other solid materials that are used in the brewing process. Heat-induced Maillard reactions between sugars and amino acids occur during the kilning of malt, to produce meladonins and color pigments. Higher kilning temperatures result in darker color malt and final product. The meladonins produced during kilning have an important impact on beer flavor.[21]

The pH is a very important factor influencing the flavor of beer. Beers are acidic, with pH values typically in the range of 4.0 to 4.5. As pH falls below 4.0, the flavor tends to be sharper and more acidic, and the aftertaste is dry. Above 4.6, the taste is cloying, and a chalky aftertaste occurs. The pH also affects the stability of the foam and the clarity of the beer. Beers with pH above 4.5 have poorer foam stability and also tend to form haze (protein particles that cloud the beer).

The specific gravity of the liquid is monitored throughout all the stages of the brewing process. A change in specific gravity during fermentation occurs when sugars are converted to alcohol according to the reaction

$$C_6H_{12}O_6 \rightarrow 2\,CO_2 + 2\,C_2H_5OH$$

The initial specific gravity prior to fermentation is high due to the starches and sugars dissolved in the liquid; the specific gravity decreases as fermentable sugar is converted to alcohol. The difference between the initial specific gravity (before fermentation) and the final specific gravity (of the product) readings may be used to calculate the total alcohol content of the beer.

In the U.S., alcohol content of beer is typically given in weight percent (%w/w), that is, grams of alcohol per 100 grams of water. In other countries, it is much more common to give alcohol content in volume percent (%v/v). A beer that has an alcohol content of 5% v/v has an alcohol content of only 3.95% w/w. These percentages are related by the densities of alcohol and water, and the conversion can be performed by using the equation

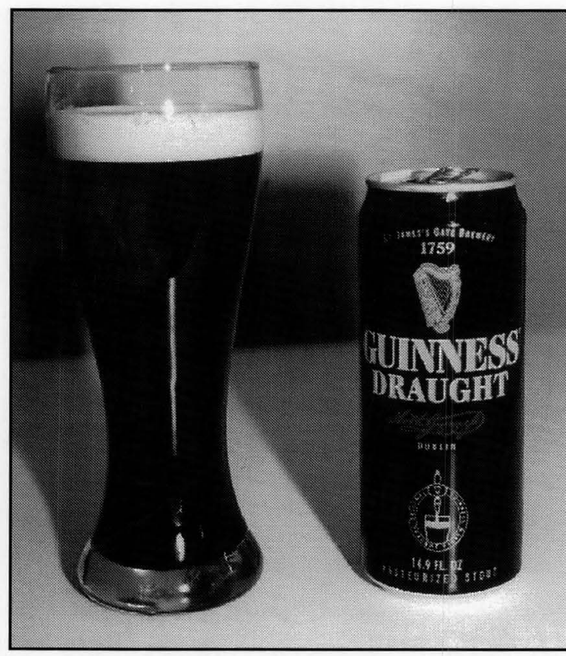

Figure 1. The small, uniform bubbles in Guinness are due to nitrogen.

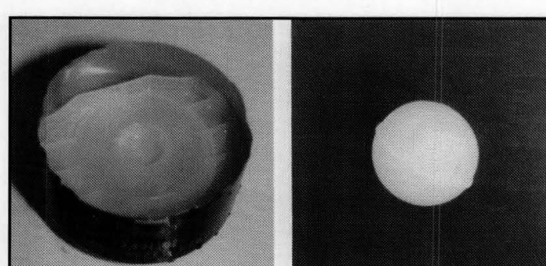

Figure 2. The Guiness widget (1999 on left, 2001 on right).

$$\%v / v = \frac{\%w / w}{\left(\frac{0.789 \text{ g alcohol}}{\text{ml alcohol}}\right)\left(\frac{100 \text{ ml water}}{100 \text{ g water}}\right)} \quad (1)$$

EXPERIMENT AND RESULTS

During a three-hour laboratory period, students can reasonably analyze and compare three beers. In our laboratory, we analyzed several commercial beers, but found the following best suited for student experiments: 1) Budwiser, an American lager that is quite light in color and is available in cans or brown bottles, 2) Bass Ale, a slightly darker English ale that is available in brown bottles, and 3) Guiness Draught, an Irish stout ale that is packaged in an aluminum can with a widget. Guinness was chosen to provide an opportunity to explore the widget, stable foam, and small-bubble flow; Bass Ale and Budweiser were chosen for the availability of published information. This section describes the methods and results of the commercial beer analysis.

The experimental procedure includes several standard tests used in the brewing industry, modified as necessary to be performed in a student laboratory by individuals without specialized training. The results presented in this section are typical experimental results obtained by students in an educational setting rather than in a research laboratory or a consumer testing facility. They should not be interpreted as an endorsement of any brand name or particular product.

Packaging • Prior to opening the package, students should note

- *The material of the packaging (glass or aluminum)*
- *The color of the container if it is glass*
- *The hardness of the container if it is a can. Does it dent easily if squeezed?*
- *Any labeling information, e.g., the type of beer (ale, lager, stout), where it is produced, alcohol content, if it is pasteurized, and patent information*
- *The distance from the cap to the liquid level*

To gain an appreciation for the governmental regulations on labeling and advertising of alcoholic beverages, students researched the laws on labeling information as a homework assignment.

Sound-Upon-Opening • The next step is to open the beer and listen to the sound as pressure is released. Students should describe the sound as a high pitch (indicating a high level of carbonation) or a low pitch (indicating low carbonation).

Head Retention • After opening the beer, the next step is to pour the beer and observe the foam stability or head retention. For the case of Guinness Draught, the beer must be poured immediately after it is opened because the widget creates a generous amount of foam that must be captured in the head; for other beers, it is less important to work so quickly.

To compare the head retention of different beers, the following standard pouring procedure is followed for each product. Approximately 200 ml of the beer is poured into a 500-ml glass beaker. The beaker should be tilted and the beer poured steadily onto the side so that approximately 1 inch of head (foam) develops on top of the 200 ml of liquid beer. The foam formation should be observed; where do the bubbles appear to come from—the top or the bottom? The size and uniformity of the bubbles should be noted.

A good rule-of-thumb for head retention is given by Fix.[22] A one-inch head should last for five minutes without the appearance of voids (spots where the surface of the beer liquid is not covered by foam). Students use this guideline to evaluate the foam retention of the beer.

Color • After pouring the beer for the foam-retention test, there will be enough beer left in the container to proceed to the remaining analyses. There are several methods for measuring color in beer, two of which are used in this experiment. The first method uses a color comparison chart, called a Davison Color Chart (available for about $6.00 at local homebrew shops), to match the beer color to a standard color on the chart. The chart assigns color values from 3 degrees Lovibond (°L) to 19 (°L). The second technique is a spectrophotometric method standardized by The American Society of Brewing Chemists. This method, called the Standard Reference Method (SRM), measures the absorbance of light with a wavelength of 430 mm through a sample of one-half-inch width. The color of the beer as quantified by the SRM procedure is related to absorbance by Beer's Law (named after the scientist, not the beverage)

$$A = C_{SRM}\left(\frac{\text{Degrees SRM}}{\text{in}}\right)(0.5 \text{ in}) \quad (2)$$

where A is the absorbance and C_{SRM} is the color in degrees SRM. In the case of Guinness Draught, which is very dark in color, it was necessary to dilute the beer by a factor of 4 prior to spectrophotometric analysis, subsequently including this in the SRM calculation. This was not necessary with other beers. In addition, the standard cuvettes available in our laboratory had a path length of 1.0 cm, and the appropriate conversion factor of 1 cm/0.3937 in was applied to the path length in Eq. (2).

Degrees Lovibond are equivalent to 10 degrees SRM, and the results of the two methods for color analysis can be compared. Student results of 2.5 °L for Budweiser, 12 °L for Bass, and 24 °L for Guinness compare well with the published values provided in Table 1 (obtained using the Davison Color Chart and taken from Fix[22]).

pH • The pH of the beer can be analyzed using a pH meter or a pH test strip. The results are then compared to published values (taken from Fix[22] and shown in Table 1).

Specific Gravity • Because commercial beers were used in this experiment, it is impossible to measure the specific gravity of the liquid medium prior to fermentation. The final gravity was measured and typical values of initial specific gravity for each style of beer were used to estimate the alcohol content. The specific gravity is measured using a hydrometer, which can be purchased from a homebrew shop for approximately \$6.00. Specific gravity is typically reported at 60°F, and measurements taken at other temperatures can be adjusted using the temperature correction factor

$$CF = 2 \times 10^{-6} T^2 - 0.0001 T + 0.0018 \quad (3)$$

where T is in °F. This equation was obtained using a polynomial fit through manufacturer-supplied, tabulated specific gravity values (True-Brew-USA) in the range of 32°F to 86°F.

The conversion of sugar to alcohol during fermentation is accompanied by a change in specific gravity as expressed by

$$\%w / w = 105\left(SG_{initial} - SG_{final}\right) \quad (4)$$

where the factor 105 is dimensionless and accounts for the change in density of a solution as sugar is converted to alcohol by the reaction described above. The initial specific gravity is estimated using the typical values for various types of beer shown in Table 2,[23] allowing the calculation of the alcohol content. The estimated alcohol content is then compared to the alcohol content obtained by direct measurement (see next section) as well as published values.

Alcohol Analysis • The alcohol content of the beer was analyzed using a YSI 2700 Biochemistry Analyzer. These results are compared to the estimated alcohol content using the specific gravity method, as well as published values in Table 3. An alternate technique for measuring alcohol content is to use one of the commercial enzyme test kits, such as the Ethanol Test Kit from Boehringer-Mannheim. These require only a spectrophotometer for analysis, but were a little difficult for the freshmen to use.

The Widget • The final step in the product analysis is to investigate the widget in the can of Guinness Draught. The Guinness can should be carefully cut apart. Inside the can is the plastic widget, which should be examined. Students should look for the tiny laser-drilled hole from which the liquid beer and gases rush out upon opening to induce nucleation by mechanical shear. For homework, students read the patent and learn more about how the widget works.

Cost • Through comparison of the different commercial beers, students gain understanding of the desirable properties that contribute to the overall quality of the product. An important factor closely linked with these properties is the cost. Students can obtain cost information on commercial beers in local newspaper advertisements and by calling local stores that sell beer. Bottles of Budweiser and Bass Ale are sold in 6-packs of twelve-ounce containers, while Guinness Draught cans are sold in 4-packs of 14-ounce containers. Students obtain pricing information and calculate the unit price per ounce of the products. Typical results (for the Southern New Jersey area, based on a single pack) are: Budweiser, \$0.063/oz; Bass Ale, \$0.111/oz; Guinness Draught, \$0.116/oz.

FURTHER INVESTIGATION

In addition to writing a laboratory report, the homework assignment and additional out-of-class activities include investigation of the issues that contribute to the "broader picture" of product design: patents, environmental and recycling issues, marketing, government regulations and taxation, economics, and ethics.

Students research the Guinness widget patent to learn more about the features, function, and production of this device. The patent provides detailed information on materials of construction, methods of manufacture, gas solubility, dimensions, function, and pasteurization. This information is summarized in Table 4. Students also search for patents on proprietary devices related to the widget.

Students consider environmental issues as they are asked to investigate sustainability of the brewing industry. After learning about the brewing process, students investigate topics such as reducing water use, waste minimization, and recycling of containers.

Government regulations regarding production, marketing and labeling, sale, and consumption of alcoholic beverages is another aspect of product design that must be considered. Students are asked to research the government regulations regarding alcoholic beverage labels, as previously described in the Background section of this paper. The importance of marketing is emphasized by having students present a marketing plan for a new product to potential investors. Ethics is

TABLE 1
Analysis of Commercial Beer
(Properties were compiled from several sources.)

Beer	*Color (Lovibond)*	*pH*[22]	*Alcohol % by volume (by weight)*	*Calories/100 ml*[26]
Budweiser	2.0[23]	~4.40	4.66 (3.60)	40
Bass Pale Ale	10.0[23]	3.97	4.50 (3.60)	45
Guinness	~25.0[23]	-	4.27 (3.42)	43

TABLE 2
Starting Specific Gravity of Various Beer Styles
Typical values of the starting specific gravity are given by Papazian.[23] These are given as ranges for general types of beer rather than for each specific brand of beer.

Style of Beer	*Example*	*Starting SG*
American Lager	Budweiser	1.035 - 1.045
Classic Ale	Bass	1.043 - 1.050
Stout	Guinness	1.036 - 1.055

also emphasized in our Freshman Clinic, and there are many possibilities for investigation related to beer and the brewing industry. One controversial topic for investigation is the marketing of alcoholic beverages to inner-city consumers and economically disadvantaged minorities.[24,25]

CONCLUSIONS

Commercial beer is used as a means of introducing freshmen to the concept of product design. Issues relevant to product design are addressed, including packaging, properties of interest to consumers, patent information, and the importance of marketing the product. Student feedback indicates that this approach is well-received by the students and presents a first opportunity to consider the design of a chemical engineering product. Overall course evaluations averaged 4.6 to 5.0 for the three years the course has run. Student comments indicate that the most important things learned in this course were teamwork, presentation skills, the interdependence of engineering and marketing, and the relevance of broader issues such as intellectual property and ethics.

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TABLE 3
Sample Results of Alcohol Analysis of Three Commercial Beers

Beer	*Alcohol content estimated using SG (%w/w)*	*Alcohol content using YSI analyzer (%w/w)*	*Published alcohol content[26]*
Budweiser Lager	3.8	3.71	3.73
Bass Ale	3.7	3.55	3.60
Guinness Stout	3.5	3.38	3.42

TABLE 4
Examples of Information Contained in the Guinness Patent (US 4832968)

Property or Feature	*Details*
Method of foam production	Shear-induced nucleation as liquid and gases are released through a tiny hole in the plastic pod at a high velocity
Tiny hole	0.061 cm diameter; laser-bored
Material	Polypropylene
Manufacturing technique	Blow molding
Volume of liquid in plastic pod	15 ml
Gas Mixture for pressurization	N_2 (2% vol/vol) and CO_2 (150% vol/vol), supersaturated
Pasteurization	After sealing, 60°C for 15-20 minutes

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