FUEL CELL CAR DESIGN PROJECT FOR FRESHMAN ENGINEERING COURSES

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In *Educating the Engineer of 2020 Adapting Engineering Education to a New Century*, the National Academy of Engineering recommended that iterative process of "designing, predicting performance, building, and testing" be introduced at the earliest stage of the curriculum.[1] Implementation of a design project in a freshman design course is now considered a best practice,[2] but is still not universal.[3] Competitive team design projects have been linked to increased student motivation, better retention of course concepts, and enhancement of soft skills such as teamwork and communication. The value of freshman engineering courses in general,[1] and hands-on design courses in particular, has been attributed to a number of factors including a cooperative environment that encourages early networking, the hands-on nature of the activities, and the emphasis on student success.[1,4] It has also been postulated that learning the "habits of an engineer" through a freshman design course is advantageous because it affects student perspectives and preparedness for the remainder of the curriculum.[3] In addition, since there are no "wrong" answers students develop confidence in stating their ideas. All of these attributes tend to have more of an impact on underrepresented students who are more likely to feel they "don't fit in" and internalize negative feedback. Participation in a team-based freshman design course has been shown to greatly increase retention, particularly among underrepresented groups. Over a five year period, Knight, *et al*. (2003) tracked the retention rate of more than 2,500 students. Forty percent of the students took a freshman engineering project course. After seven semesters, 64% of the students who took the freshman design course were still enrolled compared to 54% of the students who did not take the course. The increase in retention was 15% for men and 27% for women. For Asian students there was only a 3% gain. However, for African-American students the gain was 36%, and for Latino students it was 54%. Similar results have

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been reported at other institutions.[4] Students participating in design competitions are also more likely to develop an interest in undergraduate research, which has also been linked to retention and advancement in engineering, particularly for students from underrepresented groups.[5,6]

However, while the value of a freshman design experience is well recognized, it is not always easy to implement. In chemical engineering, the impracticalities and dangers of working with chemicals can make it difficult to create meaningful design projects that are hands-on and relevant to the curriculum. In addition, freshmen lack sufficient chemistry, biology, and math training to tackle complex chemical or material design problems. At Auburn University, our remedy was to develop a creative design project around a toy fuel cell car. Among the myriad possible subjects for a freshman chemical engineering design course,[2] the toy fuel cell car project was selected for several reasons. First, working on a fuel cell car design project freshman year enables rapid integration into the chemical engineering community. Since 1999, thousands of chemical engineering students have annually participated in regional and national American Institute of Chemical Engineers (AIChE) Chem-E-Car competitions, and a similar competition has been implemented in Australia.[7] The Chem-E-Car competition has been integrated into both sophomore and junior courses at Oklahoma State.[8] In addition, University of Waterloo chemical engineering students have taken leadership roles in interdisciplinary international fuel cell competitions such as "Challenge X—Crossover to Sustainable Mobility," in which students designed and built a full-size fuel cell vehicle, and the H2U Facility Design Competition that is sponsored by the U.S. National Hydrogen Association and other organizations.[9]

Second, incoming freshmen are aware of the need for alternative energy sources; we have seen this expressed in first-week assignments in which freshmen were asked why they chose to study engineering. At the time our fuel cell car project was first implemented, there was growing awareness that incoming students wanted to make a difference, and that introducing how engineers can affect societal and global issues increased retention.[1,10] The project helps students envision how as future engineers they can "make a world of difference," and "shape tomorrow."[10] More recently, the fuel cell car project has become a complement to course lectures focused on the National Academy of Engineering's Grand Challenges[11] and Engineering Messages.[10]

Third, using a relatively inexpensive, readily available toy designed for home use by middle school students makes the project accessible. Students can readily understand the instructions that come with the kit, and can work on their projects without the constraints of having to meet with an instructor or access laboratory space. Since the kits are designed for home use, students can work on the project outside of class time in convenient locations such as the dorm or library.

Fourth, the project provides numerous opportunities for teaching fundamental chemical engineering principles. The kits come with fundamental scientific information that provides a foundation for introducing chemical engineering content such as dimensional analysis, reactions, safety, and the ideal gas law.

Since the design project was first conducted in 2005, there has been a significant increase in the number of toys and K-12 educational kits focused on alternative energy (*e.g.*, fuel cells, solar, wind). However, relatively few college courses are taking advantage of this boom in materials and resources, and very few instructors are repurposing inexpensive components of these kits to be used for engineering and design concepts. It is our hope that our experience with a fuel cell car project will provide a framework for understanding the value of such projects and may provide a foundation for other departments seeking to modify their freshman engineering courses.

DESIGN PROJECT DESCRIPTION

In Auburn's Samuel Ginn College of Engineering, all freshman and transfer students take a two-credit course called "ENGR1110: Introduction to Engineering." The course places significant emphasis on engineering career paths and soft skills such as teamwork and communication that are associated with success in both the engineering curriculum and future employment.[12] The learning objectives for ENGR 1110 serve the dual purpose of ensuring that all students have 1) basic knowledge in calculations, units, and notation; and 2) a design experience that requires teaming, creative problem solving, ethics, and written and oral communication. All of the ENGR 1110 sections place significant emphasis on providing students a positive engineering design experience. The aim is to increase the likelihood students will remain interested in engineering while taking predominantly math, science, and general curriculum courses. Students generally take the section taught by an instructor in the discipline they intend to major in, but this is not required. In the chemical engineering sections, approximately 80% of the students plan to major in chemical engineering. The idea for the fuel cell car project came about in 2004 in response to chemical engineering students complaining that their projects were boring compared to the skateboards, airplanes, and remote control vehicles being made in other majors. At that time, the chemical engineering project was to select a chemical or material and then complete a team report and presentation on the manufacturing or applications of that chemical or material. Author Duke recognized the potential for the Thames and Kosmos toy fuel cell car kits to be used for a more engaging, hands-on project that could be closely tied to the chemical engineering curriculum. The design project, and the number of kits available, has continued to evolve since the project was first implemented in Fall 2005. Designing a fuel cell car has become part of our department culture and a rite of passage for our students. The project has been included in more than 12 semesters of ENGR 1110 classes, with class sizes ranging from 30 to 180 students. It has become a continuous thread throughout the ENGR 1110 course and some subsequent courses. Incorporation of the project throughout the semester provides ample opportunities for student reflection through writing that promotes deeper understanding.[3]

The entire ENGR 1110 section meets together for a weekly 50-minute lecture and in smaller groups of up to 62 students for two weekly 75-minute labs. Certain project activities, and course lectures and laboratories, are used to introduce students to the concepts of learning outcomes and their assessment. Students learn about the existence and purpose of ABET, and several times during the semester a department student outcome is directly cited as the reason for the project or learning activity. For example, one of the initial course lectures is used to introduce ABET and department outcomes relating to design. Different types of design, including process and product design, are described. Emphasis is placed on the open-ended and iterative nature of the design process. Students are taught that design is the "heart of engineering" and the way engineers learn. Students are then randomly assigned to teams of four to six students. They are provided information on a fuel cell car kit such as the Horizon Fuel Cell Car Science Kit[13] or the Thames and Kosmos Fuel Cell X7.[14] Both kits include a PEM fuel cell, clear plastic tanks for oxygen and hydrogen, a plastic vehicle chassis, motor, and wheels. They come with manuals and experiment guides written for middle school students that contain useful information about vehicle operation and the chemistry of fuel cell operation. The students are told that after assembling the car and making an initial evaluation of the car's performance, they will need to redesign the car to compete in a final design competition.

The competition typically includes several components: 1) fastest time down a 10 m long, 1.5 m wide track on a tile floor; 2) most stylish design; and 3) a poster presentation. Additional competitions such as towing capacity or driving over rough terrain are voted on by the class during the semester. The design and competition constraints include that the sole power source on the car is the fuel cell that comes with the kit, that teams can spend no more than \$80 in addition to the kit, and that the design is consistent with the AIChE Chem-E-Car Competition rules.[15] During the semester, the teams provide informal presentations to one another on their progress and periodically submit technical progress memos to the instructor. The initial laboratory sessions focus on effective teaming strategies used in industry. In the first laboratory session, the teams are introduced to fundamental teaming concepts including team roles, ground rules, establishing a charter, and the characteristics of both effective and dysfunctional teams. To allow everyone to experience as many aspects of teamwork as possible, teams are required to rotate key roles such as leader, recorder, gatekeeper, and innovator several times during the semester. The first memo is due after two lab sessions and includes the team roles, team member contact information, ground rules, and a team charter that incorporates a SMART goal (specific, measurable, actionable, realistic with timing). Initial charters are often vague or unrealistic statements such as "we will have the fastest car." However, by the teams listening to each other's charters and revising them with the instructor, teams arrive at concrete charters such as "we will redesign the car two weeks before race day, and perform preliminary testing to demonstrate an average speed that is twice as fast as that of initial design." The ability to concretely determine the goal of a team or project is a valuable skill that the students use in other courses such as the junior and senior laboratory courses and the senior design course.

The next laboratory session and memo typically focus on economics. The team members all contribute to the cost of the car kit and supplies. The team compares vendors of the assigned kit including tax, shipping, and handling fees. They establish a budget for purchasing the basic car, supplies, and materials they anticipate they will need for the redesign. A small fraction of the \$80 each team is allowed to spend in addition to the kit is used for mandatory supplies such as distilled water and batteries that provide faster charging than the included solar cell. The maximum team cost is typically less than \$200 or \$40/student assuming a five-member team. This is significantly less than the cost of many engineering textbooks. Some teams have successfully completed the project for less than \$20/student. Some of the newer kits cost less than \$90 and many teams use scrap materials such as bottle caps, CDs, and old toys in their designs.

As soon as the teams have ordered and received their kits, they learn about the importance of safety. The instructors provide a lecture on chemical safety, laboratory safety, and the importance of health, safety, and environmental considerations in both product and process design. Although the kits are designed to have few hazards, the students spend a laboratory session completing the same job safety analysis (JSA) required for the Chem-E-Car Competition.[16] This provides the students familiarity with Materials Safety Data Sheets (MSDS), considering the need for personal protective equipment, and locating eye washes, safety showers, fire extinguishers, and other safety equipment before performing work. The JSA is then updated by the students and approved by the instructor prior to the students' redesigning the vehicle. Typical safety considerations are the flammability of the small quantity of hydrogen produced, pinch points, the need for ventilation when spray painting, and the need for safety goggles when working with a Dremmel or other cutting tool.

Other laboratory sessions focus on performing basic laboratory tests that teach students about the reversible PEM fuel cells, the reactions taking place, and the minimum voltage for hydrolysis. Students measure the volume of water consumed and hydrogen and oxygen produced and convert these values to moles and mass. They also complete these steps for the reverse reaction. This seemingly simple exercise provides significant opportunities for learning about the factor-label ("rail-road track") method for dimensional analysis, the ideal gas law, reactions, stoichiometry, significant figures, and measurement error. Some students arrive in the freshman class with high test scores and grades achieved through rote memorization of factoids such as *there are 22.4 l/mole*, but lack the underlying understanding that this value is only for an ideal gas at STP. In our opinion, these students gain an appreciation for the important details of phase, temperature, and pressure when they compare their measured and calculated values for the volume and moles of water consumed to the corresponding values of hydrogen and oxygen produced. Students that erroneously apply 22.4 l/mol to the liquid water consumed or assume that all the water initially put in the tank is converted to gas, often calculate incorrect values including that the volume of hydrogen and oxygen produced is orders of magnitude greater than the volume of the tank. We believe that comparing the volumes they calculated to their physical measurements of the tank sizes provides deeper understanding than simply being given problems disconnected from the design project. Similarly, teams get practice with significant figures and statistical analysis when they are asked to measure or calculate the amount of gas produced, the vehicle speed, the vehicle dimensions and mass, the voltage generated, and other quantities that they use to report or evaluate product performance. Such use of real-world engineering examples for teaching mathematical and physical concepts has been reported to improve student success rates.[12]

The teams also perform evaluation trials on the time it takes the as-received car to complete the test track. They then use a selection-grid approach to determine what design elements need to be changed for successful completion of their charter. The selection-grid exercise reinforces the open-ended and iterative nature of the design process while teaching tools for choosing among potential alternatives. Since the cars used to-date have all used small PEM fuel cells, the biggest speed gains have typically been achieved through mechanical modifications such as making sure the car goes in a straight line, increasing wheel diameter, minimizing friction losses, changing motor gear ratio, and/or reducing vehicle mass. Efforts to pressurize the gases, heat the fuel cell with a blow dryer, or add hydrogen peroxide have also been pursued but have typically had little effect compared to reducing mass. Students also attempt to evaluate design effectiveness or sustainability: they develop their own criteria or definitions and attempt to measure parameters and calculate values to quantify efficiency or endurance.

All of the team, economic, safety, and technical data are compiled into a mid-semester team report that enables students to gain their first experience with technical writing and realize the cohesive body of work they have generated by mid-semester. Preparing the report enables students to gain experience with using Microsoft Excel to generate plots with labeled axes and error bars and using Microsoft Word to prepare a formal report. The instructor grades this document as if it was being submitted by seniors and provides detailed critical feedback. Holding the freshmen accountable to the same standards as seniors reinforces the importance of written communication and demonstrates standards they are expected to meet. The instructor also provides reassurance that this report is a smaller fraction of the final grade than the final report. The expectation is that the teams will consider the comments and make corrections or improvements for the final report. Mid-semester is also used to evaluate team effectiveness. Teaming evaluations and surveys are completed and students are reminded that not contributing to the team will have a negative impact on their grades. The surveys are also used to reveal dysfunctional teams. The instructor meets with dysfunctional teams and with individual team members in an effort to improve communication and team dynamics. Depending on the type and origin of dysfunctional behavior, the instructor may refer to the course material on developing effective teams, reinforce that a lack of participation will result in a low grade, or facilitate team communication. If appropriate, the instructor may also refer students to a suitable campus resource for student health or success strategies.

During the second half of the semester, teams work on their designs and fulfilling their team charter. This requires iterative work on the Job Safety Analysis, Gantt chart, selection grids, and budget. This portion of the project allows for significant creativity and personalization. The teams with the most creative and fastest cars have typically replaced all of the car components except for the fuel cell itself. The fastest cars often use lighter-weight materials such as balsa wood, foamed materials, or K'NEX for the chassis, balloons or plastic syringes for the tanks, larger diameter wheels, and a motor with a higher gear ratio. Since some teams' charters set goals related to aesthetic appeal or adherence to a theme instead of speed, a broad range of designs is implemented every year. The cars are often related to an interest of the team members. The designs draw upon the team members' skills and past experience with everything from graphic design to Lego and balsa wood model building. Figure 1 highlights the range of cars that have been designed in recent years. Dragsters and fictional cars are popular. Since the initial kit car velocities are on the order of 0.2 m/s, some teams embrace the lack of speed and design snail or turtle shells for their cars. Many cars, particularly during fall semesters, include football-related components such as Auburn's orange and blue colors, logo, or mascot. Every semester there are themes and cars that have not been seen before such as the Spring 2011 Lucky 7 and Fall 2012 winged Grecian shoe (Figure 1). Since the project has become a departmental tradition, and the students often work on their cars in the chemical engineering building's atrium, the project facilitates freshmen informally interacting with

Figure 1. Examples of completed fuel cell cars. From top left: a patriotic theme dragster, a winged Grecian shoe, the Lucky 7, a snail, and an Auburn football theme car.

upperclassmen, graduate students, and faculty. Sophomores, juniors, and seniors often chat with the teams of freshmen and reminisce about their own fuel cell car experience.

The final Race Day competitions are public events held during the normal laboratory times; the awards are chosen by the students during the semester, but are most often in the form of bonus points. On Race Day, faculty and students gather around the atrium where the competition is held to watch the races. Team spirit is evident throughout the competition. Many teams have T-shirts made or dress in accordance with their car theme. To cover the 10 meter track the original fuel cell car from Thames and Kosmos takes about 30 seconds and the Horizon car took about 70 seconds. Since the Horizon car has a spinning bottom drive wheel, students are allowed to use tape or toothpicks to block the wheel in the straight position. For the redesigned cars, about a third of the teams come up with cars that travel the 10 meters in 15 seconds or less (<0.67 m/s). The fastest car traveled it in 7.4 seconds (1.4 m/s) and several others have completed the course in approximately 8 seconds. The two fastest cars have had three wheels, with the drive on an axle connecting two wheels.

Race Day also includes a poster competition and a style competition. The poster competition consists of each team presenting a 20" $\times$ 30" poster to a panel of judges consisting of a chemical engineering faculty member, an undergraduate AIChE car team member, a faculty member from outside the department, and whenever possible, alumni. In order to keep Race Day within the allotted 75 min laboratory time, each team presents its poster in a specific five-to-seven-minute time block. Having the teams do PowerPoint presentations has also been attempted, but it was more difficult to keep the presentations on time. Criteria for the poster competition are similar to the AIChE Chem-E-Car competition[15] and include a description of the technical features of the car, a description of the engineering process, explanation of design enhancements, inclusion of safety considerations, and overall presentation effectiveness. The style competition is usually judged separately by the department chair, another faculty member, and/or alumni. The use of external judges for the poster and style venues increases the competition excitement, and it also provides interactions for the freshmen with faculty, older students, and practicing engineers.

After the final Race Day, teams typically have two weeks to compile all of the information gathered throughout the semester into a final report. Ideally, the final report expands the information from the mid-semester report and includes improvements in overall organization, style, and writing based on the mid-semester instructor feedback. Completion of the final report provides students their first experience in refining written and graphical communication of information, and assimilating a comprehensive technical report. The report includes the team charter, technical information on fuel cells, the current and potential applications of fuel cells, an analysis of the initial fuel cell car design, their approach for improving the design to meet their charter, an assessment of how well they met the objectives stated in the team charter, and recommendations for improvement.

ASSESSMENT

Formal assessments have included end-of-course assessment surveys (EOCs) by students and faculty, sophomore surveys, senior exit interviews, and university course evaluations. Unfortunately, all of the assessment tools have experienced major changes during the past eight years; this prevents displaying of multi-year assessment data in a consistent format. However, the various assessment methods have all highlighted the value of the project. In anonymous ENGR 1110 surveys from 2007 to 2010, an average of 46% of the students specifically mentioned the fuel cell car project in response to the open-ended question, "What most contributed to your learning in the course?" Comments about the teamwork and hands-on aspect of the project were particularly prevalent. In addition, many students cited the value of writing the project reports even though this is typically the most time consuming and arduous part of the class. The project was also mentioned in regard to the questions about what hindered learning; particular issues were team members not performing their share of the work or problems with damaged fuel cells.

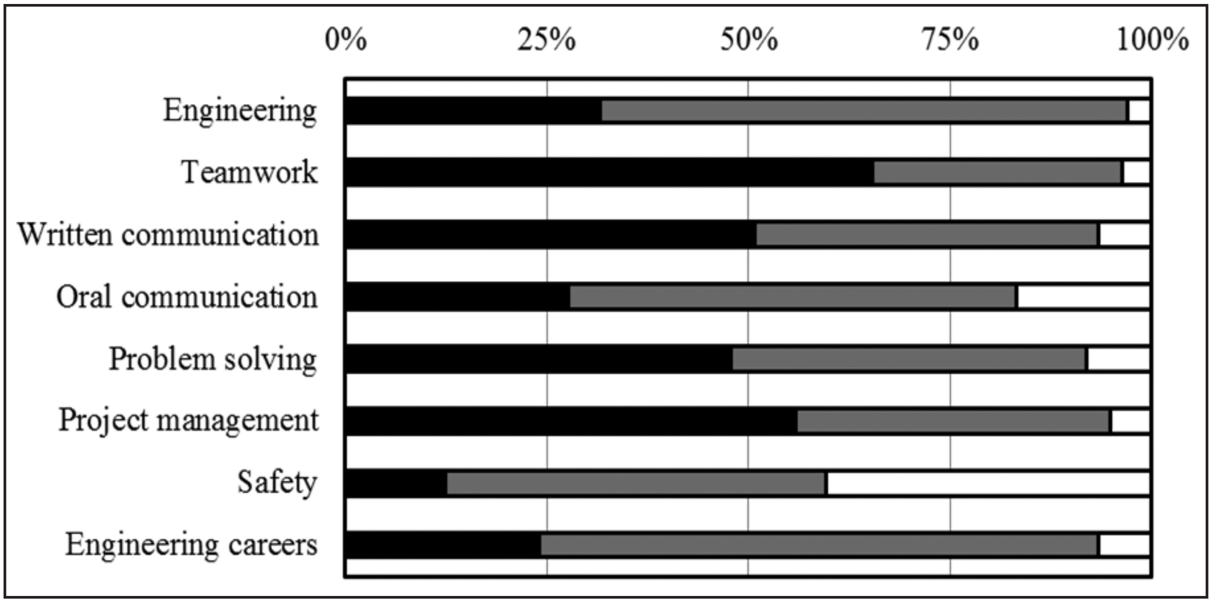

Figure 2. *Student responses to clicker quiz questions "How much did the fuel cell car project improve your knowledge of ...." Black = A great extent, Gray = Some, White = Not at all. Responses are combined from the Fall 2010 and Spring 2011 Semesters, n = 136 students.*

For the Fall 2010 and Spring 2011 semesters, clickers were used to survey students on specific aspects of the project. Responses were remarkably similar both semesters, in spite of several key differences. The Fall class was taught to first-semester freshmen by author Davis and had approximately 100 students (91 students responding). The Spring class was taught by author Duke to second-semester freshmen and transfer students who already had college experience, and had approximately 50 students (46 students responding). The students used their clickers to answer a series of questions. Figure 2 shows that the majority of students said that the project improved their knowledge of teamwork, written communication, and project management to a great extent. The only two categories where more than 10 percent of the students selected "not at all," were for oral communication and safety. The oral communication aspects of the project have been limited to informal presentations at the end of laboratory sessions and the poster presentation. This element could be strengthened, but has been limited due to time constraints. For safety, 40% of the students stated that the project did not help their understanding at all. This is likely due to a combination of the relatively benign nature of the materials and the Job Safety Analysis not being stressed in the final competition. There have not been any safety incidents since the inception of the competitions. To increase the emphasis on safety, the instructors are placing an increased emphasis on the Job Safety Analysis and stressing that safety will be emphasized in future classes. By graduation, all students are expected to earn a Safety and Chemical Engineering Education (SAChE) Certificate.

During the same class periods, students were also asked how much the project had improved their capabilities in key areas. As shown in Figure 3, responses were very similar to the "knowledge of" questions. More than 97% percent of the students felt the project had improved their preparation to succeed in future courses. More than half the students felt the course had greatly improved their ability to work in a team, and roughly one-third of the students responded that the project had significantly improved their preparation for future courses, written communication skills, and problem-solving skills. The students were also asked whether they a) completely agreed, b) somewhat agreed, c) neither agreed nor disagreed, d) somewhat disagreed, or e) completely disagreed with the following statements: 1) The fuel cell car project was fun, and 2) The fuel cell car project was a valuable learning experience. The majority of students agreed either completely or somewhat agreed that the project was fun and valuable (67% and 73%, respectively). On the other hand, 13% of the students completely disagreed with the statement that the project was fun and 7% disagreed with the statement that it was valuable.

A number of students who took ENGR 1110 prior to the project implementation, or took ENGR 1110 in a different department, have expressed regret at not getting to complete the project. Students who did complete the project and worked well with their teammates often form long-lasting study groups. Upperclassmen often interact with the freshmen to inquire about the latest variation in the project requirements and share their past experiences. In addition, many faculty and students gather to watch the races. Recruiters for co-op,

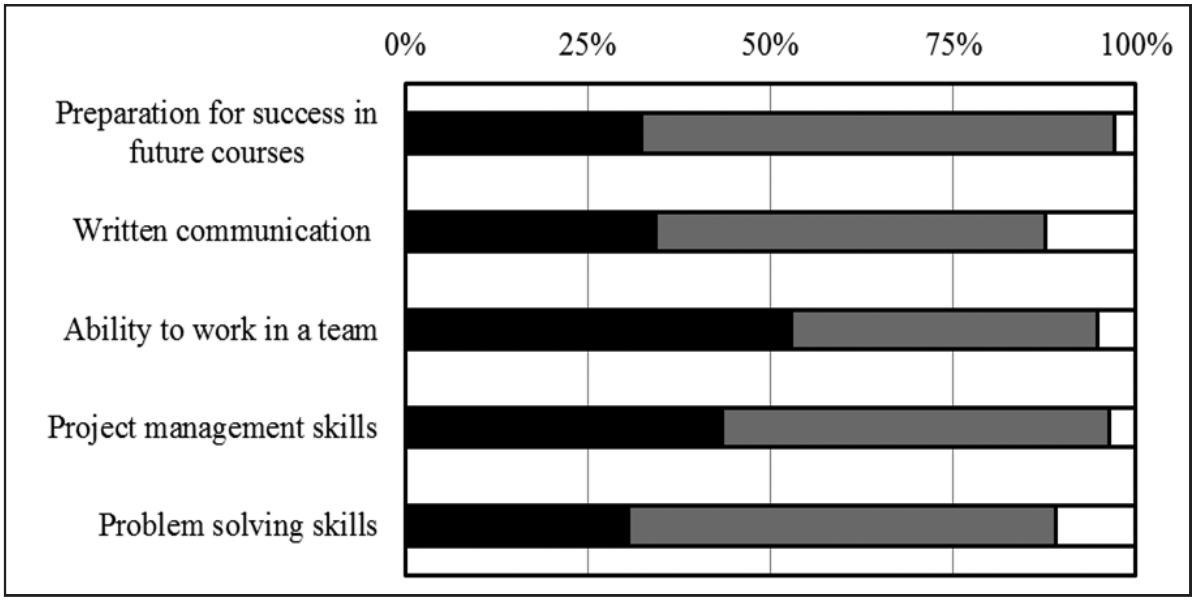

Figure 3. *Student responses to questions on how much the fuel cell car project had improved their capabilities. Black = a great extent, Gray = Some, White = Not at all. Responses are combined from the Fall 2010 and Spring 2011 Semesters, n = 136 students.*

internship, and permanent hires frequently report that the students discuss the fuel cell project while responding to a variety of questions. Alumni who have participated in the Race Day event have noted the value of the project, and complimented the students' teamwork, designs, and communication skills.

Overall, both the formal and informal assessments reveal that the fuel cell car project has succeeded in creating enthusiasm in the class, garnering student interest in the major, and preparing students for later courses. Since the laboratory sessions are predominantly used for teamwork, the instructor gets to act as a facilitator, which creates personal interaction with the students. The informal and formal involvement of other faculty, upperclassmen, and alumni helps students feel like they are a part of the department. The science and engineering project components are hands-on, and they present opportunity to explore timely topics like energy and environment. The use of the car is also inexpensive (less than the cost of a textbook) and relatively safe, while still providing exposure to chemistry and engineering. There is a direct link to the AIChE Chem-E-Car and student chapter: freshmen and sophomores are active on the Chem-E-Car teams and generally get their start from exposure during the ENGR1110 class.

The instructors have appreciated that the project offers levels of adjustability and varying levels of focus. There are an increasing number of alternative energy kits and toys on the market, which provide ample possibilities for the project starting point. In addition, the competitions can be varied to include inclines, towing capacity, run time, or rough terrain. Changing the competition criteria results in different design solutions and reduces the number of students that implement ideas from previous semesters. In addition, different aspects of the project can be emphasized to increase student learning of fundamental science, communication, environmental issues, safety, communication, etc. One recurring negative comment about the project, however, is that it is more work than the students expected from a two-credit-hour class. While some of this chagrin is expected from students transitioning to an engineering program, it highlights that there is a limit to the depth with which each potential design-project-related topic can be covered effectively.

SUMMARY

The toy fuel cell car design project enables freshmen to quickly develop a sense of "fitting in" to the chemical engineering culture, which promotes retention. The project addresses many learning outcomes at the introductory level and it has advantages such as using relatively low-cost, low-hazard, and readily available materials. After 12 semesters of implementation, project enthusiasm remains high, and by making slight changes to the starting kit or range of competitions, students continue to develop new designs. As with other design projects, students gain skills in communication and teaming and are able to seek creative solutions to open-ended problems. In addition, having the project run as a continuous thread throughout the semester provides numerous opportunities for enhancing student learning through written reflection and learning the basic problem-solving skills that are needed for success in the sophomore year and beyond.

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REFERENCES

1. National Academy of Engineering, *Educating the Engineer of 2020 Adapting Engineering Education to a New Century*, Washington, D.C.: National Academies Press (2005)
2. Keith, J.M., D.L. Silverstein, and D.P. Visco, "Ideas to Consider for New Chemical Engineering Educators, Part 1. Courses Offered Earlier in the Curriculum," *Chem. Eng. Ed.*, **43**(3), 207 (2009)
3. Ambrose, S.," Undergraduate Engineering Curriculum The Ultimate Design Challenge," *The Bridge*, Summer 2013, p. 16
4. Knight, D.W., L.E. Carlson, and J.F. Sullivan, "Staying in Engineering: Impact of a Hands-On, Team-Based First-Year Projects Course on Student Retention," *Proceedings* of the 2003 American Society for Engineering Education Annual Conference and Exposition, Washington, D.C. (2003)
5. Russell, S., M. Hancock, and J. McCullough, "Benefits of Undergraduate Research Experience," *Science*, **316**, 548 (2007)
6. Hathaway, R.S., B.A. Nagda, and S.R. Gregerman," The Relationship of Undergraduate Research to Graduate and Professional Education Pursuit: An Empirical Study," *J. College Student Development*, **43**, 614 (2002)
7. Rhodes, M., "Chem-E-Car Downunder," *Chem. Eng. Ed.*, **36**(4), 288 (2002)
8. Lewis, R.S., A. Moshfeghian, and S.V. Madihally, "Engineering Analysis in the Chem-E-Car Competition," *Chem. Eng. Ed.*, **40**(1), 66 (2006)
9. Kundu, S., and M.W. Fowler, "Use of Engineering Design Competitions for Undergraduate and Capstone Projects," *Chem. Eng. Ed.*," **43**(2), 131 (2009)
10. Committee on Implementing Engineering Messages, "Messaging for Engineering: From Research to Action," Washington, D.C.: National Academies Press (2013)
11. National Academy of Engineering. NAE Grand Challenges for Engineering. <http://www.engineeringchallenges.org/>
12. Stephens, R., "Adapting Engineering Education and Experience to Meet the Needs of Industry and Society," *The Bridge*, Summer 2013, 2013, p. 31
13. Horizon Fuel Cell Technologies. Fuel Cell Car Science Kit. <http://www.horizonfuelcellstore.com/us/fccsk.html> (accessed July 27, 2013)
14. Thames and Kosmos. Fuel Cell X7. <http://www.thamesandkosmos.com/products/x7/x7.html> (accessed July 27, 2013)
15. American Institute of Chemical Engineers. Chem-E-Car Competition Rules. <http://www.aiche.org/community/students/chem-e-car/chem-e-car-competition-rules>
16. American Institute of Chemical Engineers. Job Safety Assessment Form Chem-E-Car. <http://www.aiche.org/sites/default/files/docs/pages/2013_National%20JSA.pdf> ❐