USE OF ENGINEERING DESIGN COMPETITIONS
for Undergraduate and Capstone Projects

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Providing high-quality undergraduate education is the goal of any engineering school. As part of this, the use of final-year design projects or capstone projects is a useful tool to engage students and enhance the undergraduate experience. At the University of Waterloo Department of Chemical Engineering many engineering students choose to do design projects and capstone projects as part of their involvement with various technical competition teams. Recently, many team entries have included hydrogen fuel cell technology such as "Challenge X—Crossover to Sustainable Mobility," a competition sponsored by GM, the USDOE, and Natural Resources Canada, in which students designed and built a full-size hydrogen fuel cell vehicle. Students have also entered into the H2U Hydrogen Facility Design Competition sponsored by the U.S. National Hydrogen Association as well as others. Although all of these design competitions are multidisciplinary and involve members from all departments and other faculties, chemical engineering students have typically held leadership roles because of the applicability of the competition subject matter. Further, faculty advisors have also come from the Department of Chemical Engineering.

Undergraduate design projects and upper-year capstone projects offer many valuable benefits to students. As well as being an opportunity for applying concepts learned during

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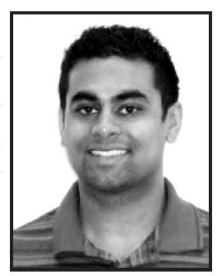

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a student's previous classes, these projects are also used by many schools to help the students develop "soft skills" such as leadership, communication, and project management.[1, 2] Studies of undergraduate research, which shares many similarities with design work, found that students were able to develop professionally by acquiring research and other technical skills. They were also able to gain a greater sense of what science and engineering research work entailed, which changed their attitudes toward such work and helped clarify career plans. A separate survey study by Kardash[3] echoes some of the above points. This study was able to further detail the skills gained by undergraduate researchers, finding that the ability to understand concepts in one's field, observe and collect data, and write a research paper all improved after the research experience. Making design projects available to first-year engineering students is thought to lead to lower attrition rates since students can see the applicability of course material which they may otherwise characterize as "boring."[4]

Technical competitions can also provide the framework for design projects. Competitions, such as the Chem-E-Car competition, involve a significant design and analysis component[5] and can be complemented with presentations and reporting to also encourage development of communication skills. A study by Padgett[6] found that when a design competition is used, student motivation can be very high and it is believed that undergraduate education may improve through a better retention of course concepts. Further, students learn team-building skills[2] and younger students have been observed to develop an interest in undergraduate research after participation.[7, 8]

There are also benefits to participating professors and graduate students. Faculty and graduate students who serve as supervisors for undergraduate researchers gain valuable mentoring experience that can be later translated to other jobs.[9] Some of the challenges with undergraduate research include extra start-up time and effort required. Also, since students come from a variety of different backgrounds their abilities can be varied. Undergraduate schedules tend to be variable as they attempt to balance lab work as well as social lives, schoolwork, and exams. Thus, work output and motivation can be variable.[3] Further, graduate students involved as mentors will have less time to focus on their own thesis work.

This paper will examine the benefits and challenges of using competitions for undergraduate design projects and upper-year capstone projects through the use of a case study of students participating in the Hydrogen Ambassador Competition. Experiences as they relate to undergraduate and graduate students, as well as faculty advisors and the department and faculty as a whole, will be explored from the perspective of the authors—one of whom participated as a graduate student and the other as a faculty advisor—as well as from surveying undergraduate student participants. The aim is to show that the use of competitions can benefit all parties and is worth the extra effort.

CASE STUDY BACKGROUND—HYDROGEN FUEL CELL UNDERWATER DIVER PROPULSION

In 2005 a Hydrogen Ambassador Competition was announced as part of the Hydrogen and Fuel Cells Exhibit at the Hanover Fair, one of the largest trade shows in Germany. The goal of the competition was to develop an idea for the commercial use of fuel cells in an application that could be developed and marketed today. If accepted, the idea and any prototypes could be shown at the 2006 Hanover Fair. The project began with three students—two graduate students from the Department of Chemical Engineering and a 4th-year student from the Department of Electrical Engineering who was going to use the competition submission as a capstone project. These students formed the core of the team and together they developed the idea of entering a fuel cell-powered diver propulsion vehicle. A diver propulsion vehicle is any kind of external propulsion aid for an underwater diver. Over the course of the project a number of other ChE undergraduates were added to the team to complete the project, which also extended to other events beyond the Hanover Fair.

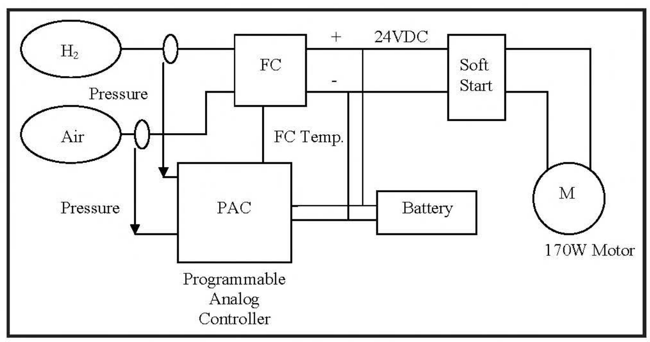

Figure 1. *Overall fuel cell DPV system.*

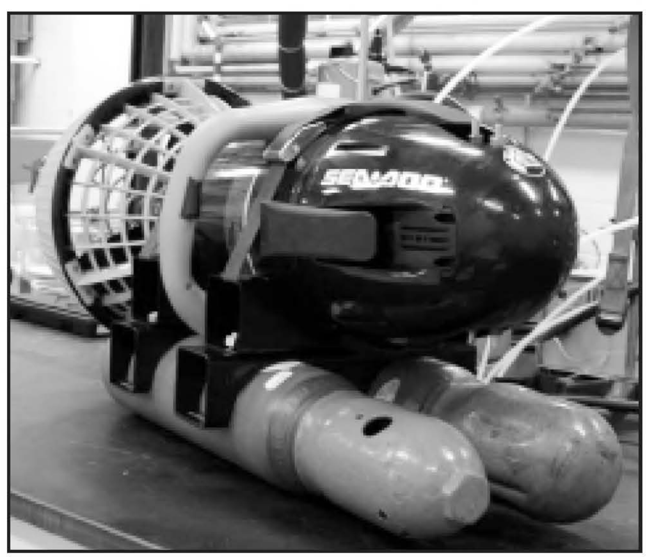

Figure 2. *Completed prototype of the fuel cell-powered diver propulsion vehicle.*

The design of a fuel cell-powered diver propulsion vehicle (DPV) involved many technical challenges for the students participating. The main thrust of the project was to take an existing battery-powered DPV and replace the battery with a fuel cell while keeping the same size and basic functionality of the unit. A fuel cell is an electrochemical device similar to a battery. Unlike a battery, which contains a finite amount of reactants, a fuel cell can be continuously supplied with reactants and therefore theoretically generate electricity for as long as a user may want. The benefit of using a fuel cell in the DPV is that is would have near-instantaneous refilling times as compared to the 8-hour recharge times of the battery, and offer longer range. Some of the impediments are that the weight is higher and the cost is significantly higher at the current stage of fuel cell technology development. Nevertheless, such a product would certainly be accessible for wealthy diving enthusiasts or military interests.

To acquire the necessary materials to develop a prototype, team members contacted manufacturers of stock DPVs and fuel cells. A DPV was obtained from DAKA corporation and a fuel cell stack from Hydrogenics corporation. The fuel cell was sized to meet the requirements of the DPV motor. To fund the rest of the project, and to assist in travel funding, group members submitted proposals to an undergraduate engineering endowment fund (Waterloo Engineering Endowment Fund —WEEF), and sought financial support from the Department of Chemical Engineering, Department of Electrical Engineering, and the Dean of Engineering's office. Materials, fittings, and other equipment were also used from the faculty advisor's research lab, and the faculty advisor also provided funding for smaller components.

Figure 1 is a schematic of the fuel cell system that needed to be designed. It includes features such as compressed-air and hydrogen reactants, pressure sensors, DC/DC converters, an electrical control system, temperature management, and safety features, as well as other auxiliary systems. Component selection and packaging was possibly the most challenging aspect of the project since components needed to not only be suitable for the demands of the fuel cell system but also fit into the same space occupied by the battery in the DPV. This involved extensive design work and the fabrication of several frames and mounts. The design of the control system was also a challenge since functionality of the system and safety considerations were of importance. Finally, the testing work was centered around evaluating the fuel cell stack received from Hydrogenics as well as creating testing apparatuses for the fuel cell system at different levels of development. Although this task was not as challenging technically, it required many practical electrical, mechanical, and workshop skills as well as experience with compressed gasses, specifically hydrogen.

Ultimately, the final prototype shown in Figure 2 was exhibited at the fuel cell exhibit at the Hanover fair. This included a small booth in the same area as other hydrogen ambassador competitors and fuel cell companies as well as a live interview on the main stage. While at the fair, government officials also toured the booth for the DPV and the project was also featured on a number of fuel cell and hydrogen-related news Web sites. The project was also presented as a poster at the Toronto Green Energy Fair at the University of Toronto and was featured in a University of Waterloo Faculty of Engineering *Annual Report*, which is read by alumni.

When surveyed, undergraduate competition participants highlighted the hard and soft skills gained through participation as part of the positive benefits. Technical skills such as programming and building hardware as well as gaining experience with new technology were specifically mentioned as were soft skills such as project management and oral communication skills.

BENEFITS AND CHALLENGES

Undergraduate Experience

The hydrogen fuel cell DPV project for the Hydrogen Ambassador's Competition had many of the characteristics essential to creating a positive undergraduate design experience for both younger undergraduate and final-year capstone project participants. It should be noted here that undergraduates receive no extra credits for participating in the competition and students doing capstone projects within the competition are only marked on their selected design project and not on any extra work that they may also do.

Over 35 participants from several competitions including the Hydrogen Ambassador Competition were surveyed. They were asked to reflect on the perceived benefits and challenges of working on a project centered on a competition as well as to give their opinions on how the project work for a competition differed from project work done for credit. A list of the questions and typical responses is provided in Table 1 (next page).

First, the organizational structure of the team was particularly well suited to meeting the needs of all the undergraduate participants. The graduate students at the core of the team were able to supervise the overall project and day-to-day lab activities, and to divide tasks among all the students. This provided necessary control for safety aspects, as well as the ability to teach necessary technical skills to the undergraduates. Furthermore, the tasks themselves could be divided to

TABLE 1
Survey Questions and Typical Responses

Question	Typical Responses
Were the projects that you did with the team technical in nature? Did you apply concepts learned in courses?	Projects were mostly technical in nature and related to the design and building of components. Tasks also extended to economic analysis and public outreach. In all technical and economic cases, course concepts were applied.
Were team projects organized and did they have clear objectives? Could projects be completed in a school semester?	Due to the structure of the competitions there were clear objectives that each team was required to meet that enhanced the organization of tasks. Since the teams themselves designed the tasks to meet the objectives, they could usually be completed in the required time frame.
List some of the main benefits of participating on a project team for competition.	Respondents benefited from experience with new technologies, job opportunities, development of new skills, and the acquisition of real-world experience.
List some of the main drawbacks of participating on a project team for competition?	All respondents unanimously identified the large time commitment involved as a drawback since it takes away from time needed to spend on classwork.
Is participating on a project for a competition different from other noncompetition projects?	Survey respondents all thought that competitions were different. They generally thought that projects for competitions had more stringent deadlines, real consequences to failure, and that the idea of winning was highly motivational and lacking in other class-based projects.
What skills have you gained from your experiences?	Technical skills: CAD, fuel cell system design, mechanical design, electrical design, system controls, computer programming. Nontechnical skills: time and project management, teamwork, marketing, oral and written skills.
Did you receive any academic credit?	The majority of respondents received no academic credit, 14% participated as part of a capstone project.
Did participation increase your appreciation for engineering?	All respondents agreed that their appreciation for engineering had increased.

meet the needs and interests of the individual students. Undergraduate participants generally wanted more experience with hands-on aspects of the project, and had a great desire to actually work with the fuel cell technology. Undergraduate could therefore be given "mini" projects such as the design and fabrication of tank mounts, hydrogen management components, the sizing and selection of components, or the testing of the system. These projects had a very narrow scope and could be done in the allotted time and around the undergraduates' other commitments. When surveyed, undergraduate competition participants highlighted the hard and soft skills gained through participation as part of the positive benefits. Technical skills such as programming and building hardware as well as gaining experience with new technology were specifically mentioned as were soft skills such as project management and oral communication skills. Finally respondents also described being exposed to a multidisciplinary team as a positive benefit.

Undergraduates using the project as the basis of their capstone project also had a positive experience. As a requirement, capstone projects had to be broader and more complicated than the projects given to younger, undergraduate participants; this was easily accommodated. One such project was performed by a core team member who focused on the design and setup of the DPV control system. This applied skills in detail control system development as well as hardware selection and integration. Other capstone projects included the design and construction of a hydrogen management and water knockout system, and testing of the fuel cell systems. All students were also involved in the overall project design, sponsorship recruiting, and testing. Once the initial events associated with the project were complete, other projects such as further design iterations of the control software were initiated. These projects were also of sufficient size and scope to be used as capstone projects for students even after the completion of the original competition.

There were certain benefits that were unique to the use of a competition for undergraduate design projects apart from the obvious travel to the Hanover Fair—although the potential for travel to an international conference was certainly a very strong motivator for participants in this competition. Through the fund-raising activities students had an opportunity to interact with members of undergraduate funding organizations, departments, and the Faculty of Engineering and thus develop communication and project-management skills, as well an introduction in dealing with media organizations. The experience of being part of a competition with real awards and recognition was also a much more satisfying experience than capstone projects which only lead to academic credit. This was primarily because of the unique experience of teambuilding and camaraderie that comes from competing and winning as a group. The competition aspect also adds more "flair" to the project, and creates a better and more memorable experience. Survey respondents described these real rewards, the desire to win, and tangible consequences for failure as a positive motivating force that was not present in other design projects for credit. Many students desire exposure to new and innovative technologies, and in this case being able to work with a hydrogen fuel cell stack provided this experience. Therefore students generally applied themselves more and hence were able to gain more from the academic experience.

Despite the many benefits of the project there were several challenges when applying this particular contest to undergraduates. Only a certain type of student is capable of carrying out the projects. As indicated by Smith,[10] the participants must be more driven and resourceful and be able to work in a diverse team with more of an organizational structure as compared to smaller group work. Since the scope of the project as a whole was large, the most successful students were those who could work independently *and* on a team, simultaneously. From the perspective of undergraduate participants, the most common challenge was that time spent on the competition project meant less time spent studying as well as challenges when transferring work from one participant to another. The timeline of the competition was also a concern in this case study, as initial proposals for the Hydrogen Ambassador Competition were required before the official start of capstone projects (this was one reason why graduate students initiated entry into the competition). Also, undergraduates were challenged by missing a week of classes to attend the conference during the school term.

Graduate Experience

The graduate experience in the project was also unique. Since the project was initiated with a team that included graduate students, there were ample opportunities to develop leadership and project-management skills. Also, some of the tasks required increased focus and skill that normally only a graduate student with more experience would possess. One of the challenges of participation was that the competition was not an extension of a specific student's research project, but was instead a side project with limited prospects for academic credit or recognition in the realm of research. As such, many of the benefits from the participation depended on the value that the students attributed to them. For the graduate students involved in the DPV project the extra work created by the project was offset by the travel opportunity to Germany and participation in an industry-focused international conference in the fuel cell field. The graduate students also benefited from increased exposure to the department and faculty, which eventually lead to participation in the Engineering *Annual Report*. Most importantly, the graduate students benefited from having a separate experience from their thesis work, which added value to their resumes and increased their marketability in the workplace. In this case participation in a system-integration project provided a broader understanding of fuel cell engineering and the challenges associated with fuel cell engineering.

Faculty Advisor and Departmental Experience

From a faculty perspective it can be difficult to see the benefits to supporting students in a competition of this nature, especially graduate students since there is little value added to specific publishable research. Undergraduate design projects can sometimes assist specific research projects in the lab simply by providing extra labor. With projects based on competitions, however, the goals of the design are often separate from the research interests of the advisor. As such, one challenge is the time commitment needed to help manage the project as there is little recognition in merit reviews and no teaching relief to the advisor. Nevertheless there are many reasons to participate.

If the professional development and education of both undergraduates and graduate students is valued then participation in the Hydrogen Ambassador Competition had many benefits. The most important one was that the educational experience of the student team members was enhanced. A project of this nature excites undergraduates and thus assists in graduate recruitment and placement of graduates in the industry. Of the students involved with the DPV, two were already graduate students with fuel cell-related research; one went on to work in the fuel cell industry, a second went on to graduate studies in fuel cell research, and another continued graduate studies in the green energy field (other members are still continuing their undergraduate education). Another benefit was that the prize of going to the fuel cell exhibit within the Hanover Fair placed the lab in a high-profile industry event that allowed for increased exposure of the lab and its research aims to potential industry partners. A final benefit is that the DPV platform can be used for future capstone projects. This is important because often there is little budget to support capstone projects and thus project with high equipment costs are generally not feasible. Ultimately it becomes a decision based on what values faculty advisors have and what role they feel they play in the education of their students.

At the departmental and faculty level the main benefits for financially supporting the participants of this project is the increased international exposure of the institution. For this project in particular, the exposure was at a trade show where potential student co-operative education employers would be present, and thus able to see the quality of work by students at the university. To this end the participants also distributed information about the Waterloo engineering program and co-opertive education program at a display booth. New students to both the graduate and undergraduate program often comment that their university decision was based on exposure to one of the student team projects at some event.

CONCLUSIONS

This paper has shown that engineering design competitions can be effectively used as an educational tool to give undergraduate students project design opportunities as well as used for capstone projects. The use of competitions meets all the requirements of a good project, and provides a valuable interdisciplinary experience. For the DPV, the projects had focused topics with clear objectives and gave students experience with an exciting technology. The project had a large-enough breadth to accommodate a number of students, adequate possibilities for true partnership among all the participants, and potential for completion within a reasonable time frame. There were also many benefits for graduate-student involvement including the development of leadership skills and a wider exposure to the technology. For the faculty advisor, department, and faculty, support of this design competition provided a strong educational opportunity for a number of students as well as good exposure for the institution.

REFERENCES

1. Kentish, S.E., and D.C. Shallcross, "An International Comparison of Final-Year Design Project Curricula," *Chem. Eng. Educ.*, **40**(4) 275 (2006)
2. Mackenzie, L., and S.J. Masten, "Design Competitions: Does 'Multidisciplinary' Contribute to the Team-Building Experience?" 26th Annual *Frontiers in Education Conference Proceedings*, **1**, 276-279 (1996)
3. Kardash, C., "Evaluation of an Undergraduate Research Experience: Perceptions of Undergraduate Interns and Their Faculty Mentors," *J. of Educ. Psych.*, **92**, 191 (2002)
4. Kartam, N.A., "Integrating Design into Civil Engineering Education," *International J. for Eng. Educ.*, **14**, 130 (1998)
5. Lewis, R.S., A. Moshfeghian, and S.V. Madihally, "Engineering Analysis in the Chem-E- Car Competition," *Chem. Eng. Educ.*, 40, 66 (2006)
6. Padgett, W.T., "Teaching Design Through Design Competition," 27th Annual *Frontiers in Education Conference Proceedings*, **1**, 1477-1480 (1997)
7. Avanzato, R., "Mobile Robotics for Freshman Design, Research, and High School Outreach," 2000 IEEE conference on Systems, Man, and Cybernetics, **1**, 736-738 (2000)
8. Marchman, J., and W. Mason, "Freshman/Senior Design Education," *International J. for Eng. Educ.*, **13**, 143 (1997)
9. Pfund, C., C. Pribbenow, J. Branchaw, S. Lauffer, and J. Handelsman, "The Merits of Training Mentors," *Science*, **311**, 473 (2006)
10. Smith, L., "Social Engineering," Poster presentation at the 17th NACCQ, (2004) ❐