Session 3166

# ACHIEVING COURSE OBJECTIVES:

# THE BENEFITS OF A HANDS-ON DESIGN PROJECT

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## ABSTRACT

While there has been a push in the last few years to integrate more hands-on exercises in undergraduate education, all too often large enrollment engineering courses still rely on design projects that require complex analysis and optimization of a particular situation to achieve course, program, and institutional objectives. Often, these designs are restricted to a paper analysis and fail to give students the ability to feel the physics of what actually happens. For this, and a host of other reasons, a hands-on design project was sought for the Fluid Mechanics course at the United States Military Academy. A variant of the national Hydropower contest was selected. The project required teams of students to design, build and test a water turbine to lift either a small weight as quickly as possible, or a large weight given a constrained amount of water. This paper presents the educational benefits of the water turbine design and specifically assesses the extent to which the project assisted in the achievement of course objectives. Anecdotal evidence and survey data indicate that the project did contribute to the achievement of course objectives and that most students enjoyed the project even though it required more hard work than paper designs.

## INTRODUCTION

There has been a move in the last few years to incorporate more and more hands-on laboratory exercises, demonstrations and projects as part of a larger effort to reform engineering curriculum. The primary impetus for this curricular reform comes from industry. Baunopane[1] noted that industry is often frustrated by graduates who are unable to translate theory into practice. Aglan and Ali stated that "current engineering curricula do not fully address the needs of industry and the actual function of engineers in practice."[2] This, coupled with other discrepancies such as the inability of students to quote or relate to the order of magnitude of basic engineering quantities[3], implores educators to reform engineering curriculum. Van Valkenberg[4,5] and Fromm and Quinn[6] also stated the case for engineering educational reform and suggested that curriculum should include hands-on experiences, open ended problem solving experiences and a host of other topics.

Many universities have embraced engineering education reforms and several educators have documented the benefits of hands-on experiences. Aglan and Ali[7] concluded that the inclusion of hands-on experiences in a Mechanical Dissection course increased motivation and retention of engineering students. Bourgeois[8] confirmed the motivational benefits of hands-on experiences and additionally documented increases in creativity, self-confidence, and problem solving skills. Other studies relay similar results[9,10]. While it is fairly easy to find evidence that students are excited by hands-on activities, finding evidence that students actually learn course material better as a result of these activities is more elusive. This paper serves as a starting point for assessing whether a hands-on design project can help to achieve technical, as well as developmental, course objectives.

## BACKGROUND

The mission of the United States Military Academy (USMA) is "To educate, train, and inspire the Corps of Cadets so that each graduate is a commissioned leader of character committed to the values of Duty, Honor, Country; professional growth throughout a career as an officer in the United States Army; and a lifetime of selfless service to the nation."[11] The Academic Program at USMA is designed to meet the intellectual demands of this mission statement. The overarching goal of the Academic Program is "to enable its graduates to anticipate and to respond effectively to the uncertainties of a changing technological, social, political, and economic world."[12] In order to achieve this goal, USMA has established intermediate goals in ten separate areas. One of those intermediate goals, the Engineering and Technology goal, requires that graduates be able to "apply mathematics, science, technology, and the engineering design process to devise technological problem solutions that are effective and adaptable."[13] The Engineering and Technology goal is instrumental in the design of the Mechanical Engineering Program, and likewise the Fluid Mechanics course, at USMA.

The Fluid Mechanics course is typically taken in a cadet's fifth semester and is one of the first engineering courses taken. This course provides the foundation for further study in aerodynamics, energy systems engineering, automotive engineering, civil engineering, and environmental engineering. Because of its timing and its broad audience, the course must excite cadets and provide a positive first impression of engineering. The formal course objectives are:

1. To give cadets a technically based, working knowledge of fluid mechanics.
   a. Define and determine the fundamental physical properties of fluids.
   b. Apply the laws of conservation of mass, momentum and/or energy to static fluids, general fluid flows, flows in conduits, and open channels.
   c. Predict performance/behavior of a full-scale prototype through the use of modeling and similitude.
2. To inspire cadet curiosity about the fluid mechanics phenomena surrounding their lives.
3. To aid cadets in internalizing a problem solving process that is based in a critical analysis approach.
4. To introduce cadets to various fluid mechanics systems and challenges they may encounter as US Army officers.
5. To foster teamwork and collaborative learning among cadets.
6. To introduce the engineering design process in developing a solution to a complex problem involving fluid mechanics principles.

While the Fluid Mechanics course employs many techniques to achieve these various course objectives, it relies heavily on the course design project to specifically address Course Objective 6. As can be seen above, Course Objective 6 is easily achieved by many projects, whether paper or hand-on. Therefore, it is a project's ability to supplement the remaining course objectives that is often used to select a new course design project.

**PROJECT OVERVIEW**

At the start of the 2001 academic year, a new design project was sought that would require application of the conservation laws, inspire more cadet curiosity about fluid mechanics phenomena, foster teamwork and collaborative learning among students and, in general, bring excitement to the course. The course faculty selected an adaptation of the national Hydropower contest[14]. The USMA Water Turbine Competition has been used for four consecutive semesters (including the current semester). The contest provides students a fun and competitive environment for learning. In two or three person teams, students build a water turbine that will lift a weight eight feet using only the potential energy stored in a 30 liter tank of water suspended approximately 13 feet above ground level. Figure 1 illustrates the test stand.

As with the national competition, there are two possible competition classes. The first class, the Power Class, requires that a 1.25-pound weight be lifted as quickly as possible using one of the five supplied turbine wheels. The second class, the Torque Class, requires as much weight as possible to be lifted and allows the students to fabricate their own turbine wheel. While the Torque Class could devolve into a gear ratio battle, the teams were constrained by the volume of water available to power the turbine. Detailed rules for the contest were very similar to those used in the national competition.[15]

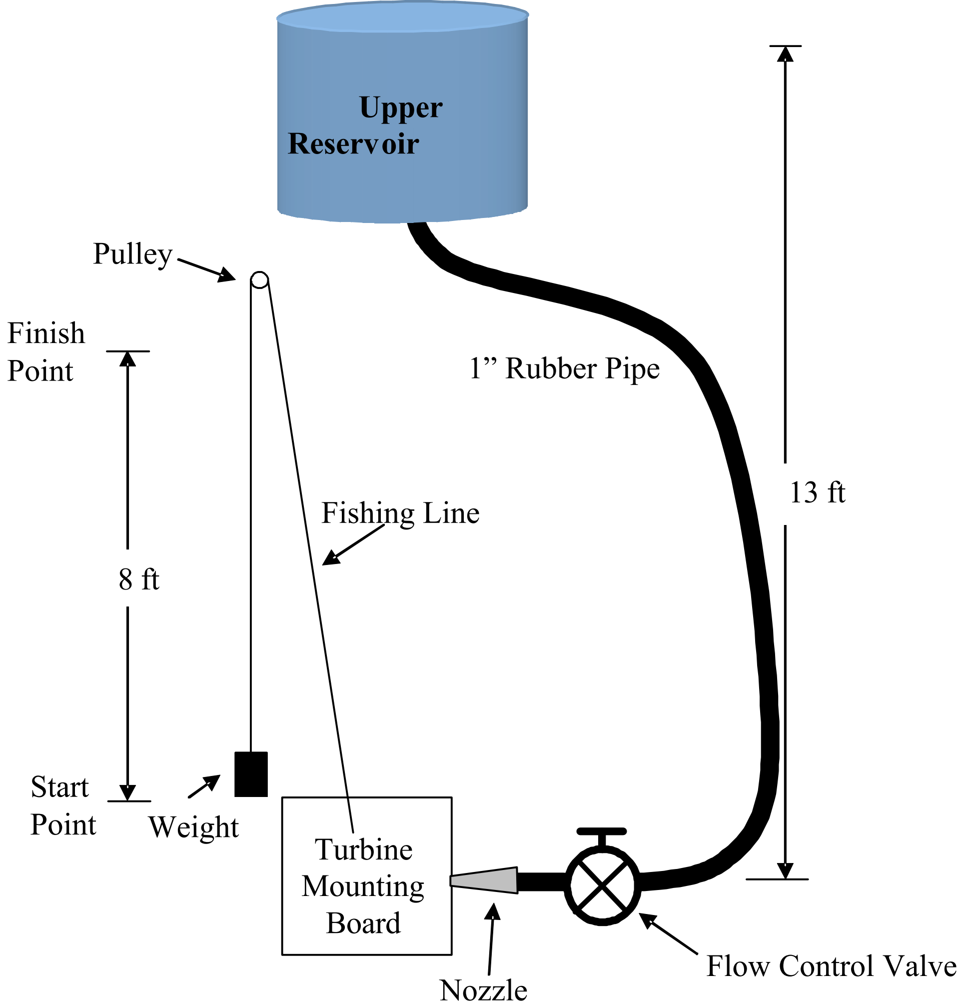


**Figure 1: Sketch of Turbine Test Stand**

## THE WATER TURBINE COMPETITION: THREE SEMESTERS OF EVOLUTION

The design project has continually evolved each semester in structure and in the materials available. Students were surveyed after the conclusion of the third semester regarding the ability of the turbine design competition to achieve course objectives. The survey was administered electronically and anonymously. Surprisingly, all 58 students in the course completed the survey. Survey data was only collected after the third offering of the design project. However, anecdotal evidence from the first two iterations, as well as instructor observations of project and final report quality, also illustrates the extent to which this project supported course objectives.

Project Materials

In the first offering of the design, students were issued a kit that was of marginal use and consisted of the materials shown below.

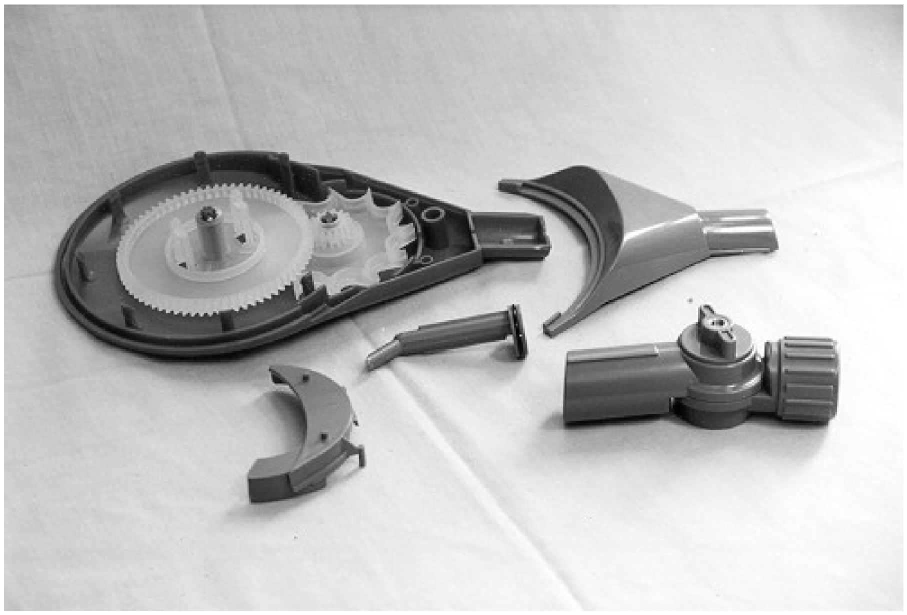

**Figure 2: Original issued turbine kit (Photo from Hydropower website)**

The device as issued was very weak and unable to lift the required weight. The nozzle was too small, the gears suffered from excessive friction, and there were significant losses in the hose fitting. Because so little equipment was provided to the students, a great deal of ingenuity and creativity was seen in the designs. Many groups succeeded because they either bought components that "looked good" or because they happened to have something in their desk drawer that would work. Some groups expressed frustration at the lack of materials, while a few groups were unable to lift the required weight.

In an attempt to level the playing field and reduce the financial burden on some students, a more substantial parts kit was provided in the second iteration of the design. The second iteration kit included the original kit plus garden hoses, several different styles of garden hose nozzles and fittings, and construction materials. Instructors observed only marginal improvements in competition performance and project construction compared to the previous semester. Additionally, second iteration projects displayed less creativity. One positive observation was that students expressed less frustration.

In the third offering of the turbine design project, the Department purchased many of the newest components from the national Hydropower competition and even more basic construction materials. Students had the choice of several plastic turbine wheels, molded nylon gears to customize the gear ratio, several interchangeable nozzles, axles and threaded rods of varying diameters, screws, nails, epoxy, garden hoses and connectors. Some of the components can be seen below.

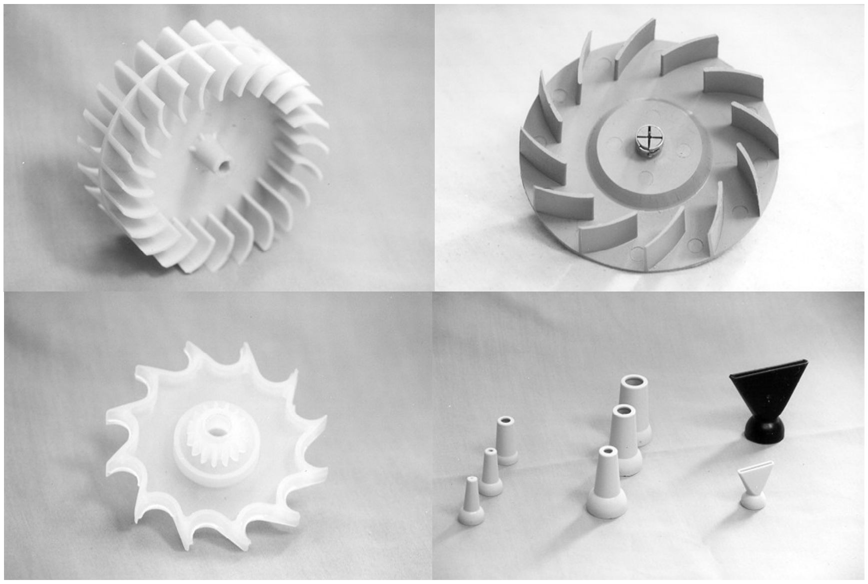

**Figure 3: Photos of Available Parts (Photos from Hydropower Website)**

The approximate cost of each kit is $35. The overall quality of the designs in the third iteration was the best of the three completed competitions. There were very few unsuccessful groups. With many components available, students were forced to question which choice was best. In many cases, students asked instructors for advice on which nozzle or turbine wheel to use. Instructors were always quick to respond, "What does your analysis tell you?" and point them to the analysis that would help them to answer their own question. In previous semesters, students failed to consider even basic analysis of components (for example, nozzle diameter or turbine wheel radius). Ultimately, the materials offered influenced what students learned and how well they were able to apply conservation laws.

Course – Project Integration

One of the challenges of the Water Turbine Competition was integrating the design into the course so that the students had enough knowledge to perform the required analysis while also having enough time to build and test their devices. To successfully perform the analysis, students needed to have a firm grasp of Conservation of Mass, Momentum, and Energy, and classical pipe flow theory. The first iteration of the design was fairly unstructured, gave little direction, and did not require students to submit any theoretical calculations prior to construction of the device. The result was that the students built their turbines with little insight into which parameters were most important and tried to perform calculations after the fact. Project performance was often due to luck, and the quality of the design reports was poor. In the first iteration, the project was introduced at lesson 23, leaving students only a few weeks to analyze, design and build the water turbine. The timing of the project assignment, competition date, and final report due date contributed to poor student performance.

In the third offering, the project was assigned earlier. Specific analysis-based In-Progress Reviews (IPRs) and a formal safety class were programmed into the syllabus. Compared to previous semesters, the competition date was moved earlier in the semester to allow more time for students to complete a high-quality technical report. Instructors observed better projects, higher-quality reports, and improved student learning as results of better course - project integration.

Intermediate Submissions: Guiding Student Learning

In the first iteration of this project, many students were overwhelmed by the complexity of the task. In addition, some were unable to dissect the water turbine system into smaller components for analysis. Course faculty attempted to correct these issues in subsequent iterations of the project. During the second semester that the design was offered, each student was required to do a pipe flow analysis of the flow coming out of the nozzle. Students compared water power available with varying nozzle diameters. The following figure illustrates the impact of nozzle diameter on the amount of power available in the water jet.

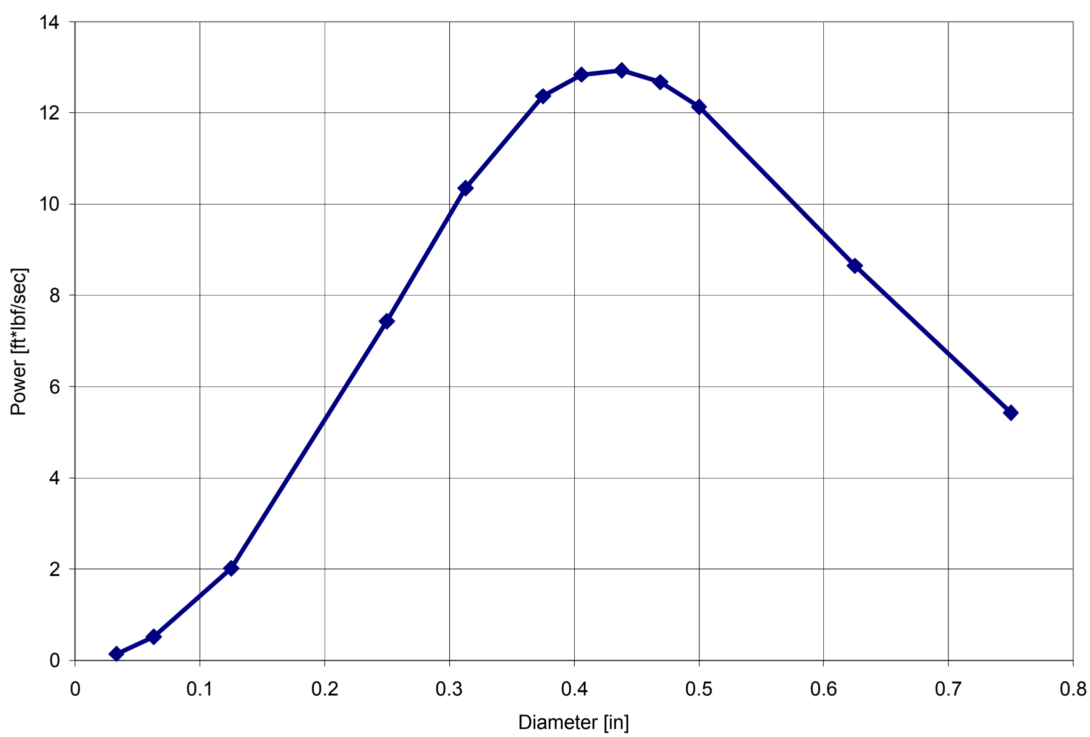


**Figure 4: Nozzle Exit Power Available versus Nozzle Diameter**

By requiring this analysis in a preliminary phase of the project, most groups were able to successfully select the optimum nozzle. While this was helpful and ensured that a maximum amount of power was available in the water jet, it did not guarantee that the turbine would be successful. For instance, if the group used a gear ratio that was too high then the turbine would not produce enough torque to lift even the smallest weight. On the other hand, if the group selected a gear ratio that was to low then the device would lift the weight very slowly. Most groups understood this concept and could explain it, but they struggled with performing the required analysis. The result was that they would, just as before, build something and hope that it worked.

The third offering of the design sought to better prepare students and give them enough guidance to successfully optimize their water turbine. The guidance was in the form of a course-wide homework problem that required the analysis of a rotating turbine wheel. The analysis required applications of conservation of mass, momentum and energy. In addition, the homework required students to independently learn about and use relative velocities—a concept that is not introduced in any lesson in the course. The homework illustrated that the amount of torque applied to a turbine shaft impacts how much power is produced by the turbine and that there is a torque that will yield a maximum power production. From figure 5, it can be seen that the amount of torque applied to the turbine wheel shaft affects the tangential velocity of the turbine wheel and ultimately how much power the turbine produces.

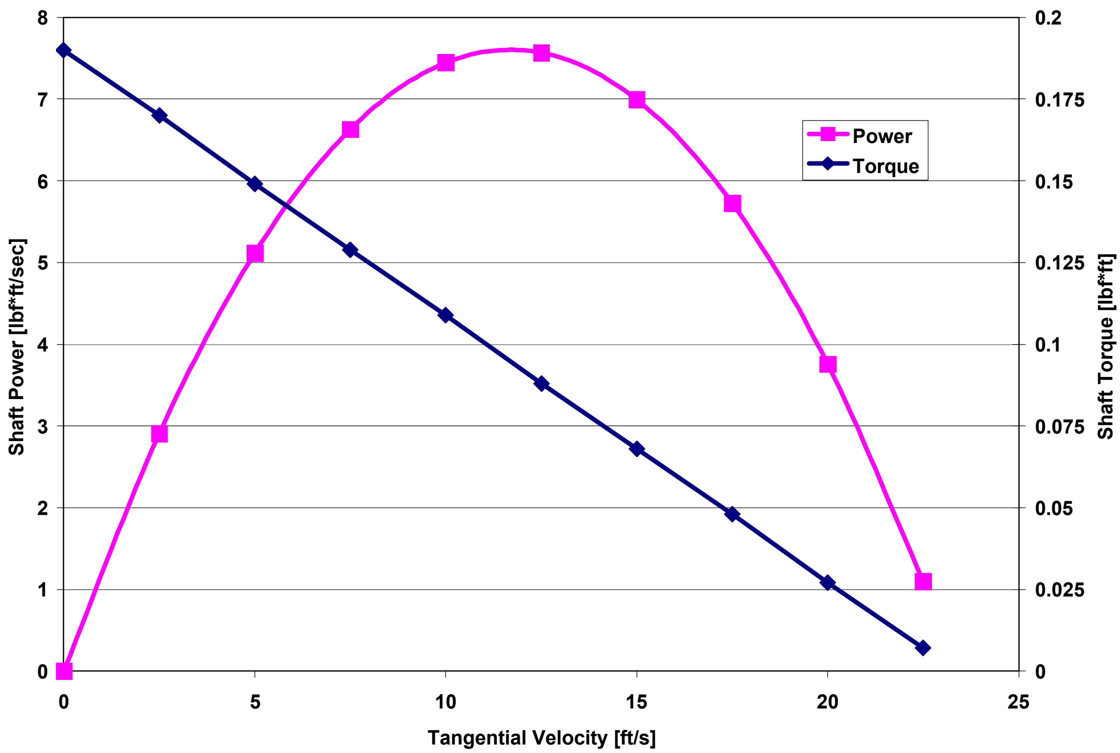


**Figure 5: Shaft Torque and Power versus Turbine Wheel Tangential Velocity**

While the homework assignment was not part of the turbine design project, the intent was for the students to connect the two assignments. With an understanding of the shaft torque and turbine power curves, students were expected to select a gear ratio to maximize turbine output power. Most students, however, did not connect the homework and the design, which can be attributed to the large time difference (almost two months) between the homework assignment and the turbine construction. Additionally, there was no requirement for the analysis to be done prior to turbine construction. Free response survey comments confirm that, again, many groups built their turbines without completely analyzing the device and many failed to see the connection between theory and reality.

Current Semester Revisions

The third offering of the turbine design adequately reinforced all of the Fluid Mechanics course objectives. Nevertheless, there are certain modifications that will be made in the upcoming semester that will make the project even more successful. First, the project will be started sooner. Part of the reason for the late start date is that students were not taught how to perform the required pipe flow analysis techniques until 4 weeks before the competition date. The design could not be started before this because every aspect of the design depends on the velocity and power of the water jet. Rather than changing when pipe flow is covered within the course, course faculty decided to require students to experimentally generate a Nozzle Power Available versus Nozzle Diameter curve (i.e., figure 4) instead of analytically. By making this change, the design will be started about 5 weeks earlier. The current project timeline and course syllabus are illustrated in Table 1.

Because the students will have 8 weeks from the start of the project to competition day, instructors will require students to submit a paper design of all of the major components of the device before they are issued any parts. This will ensure that students understand how the conservation laws apply to the problem and ease frustration about availability of supplies. The students will identify early on what they need. Any special parts not on-hand can be ordered or manufactured by the department's technicians. Additionally, a standard kit will be issued to the cadets that will include a nozzle, a set of gears, a turbine wheel, a tube of epoxy, and other construction materials. With these modifications, we believe the turbine design competition will improve from a very good to an outstanding design project.

Results and Analysis of Student Feedback

One of the main reasons that this project was chosen was that it directly required the application of the conservation laws. Formal survey results from the third iteration confirm many of these results. Figure 6 illustrates that the turbine design was very successful in some respects and not as successful in others. As figure 6 shows, only 21% strongly agreed with the statement that the project contributed to their ability to apply the conservation laws, while 57% agreed with the statement. This could indicate that most students could see how the concepts applied, but did not actually perform the analysis required to design their turbine. This is supported by several of the open-ended question responses. An example comment from a student:

> *"More importance should have been placed on the actual planning of the design. We went into the building process with only a bare understanding of our objective, and this made the construction much more difficult than it should have been."*

| LSN | DATE | LESSON TOPIC | HYDRO POWER PROJECT |
|---|---|---|---|
| FL-1 | 21-Jan | Fluid Properties I | |
| FL-2 | 23-Jan | Fluid Properties II | |
| FL-3 | 27-Jan | Lab 1: Fluid Properties | |
| FL-4 | 29-Jan | Hydrostatic Pressure | |
| FL-5 | 31-Jan | Hydrostatic forces on plane surfaces | |
| FL-6 | 4-Feb | Hydrostatic forces on curved surfaces | |
| FL-7 | 6-Feb | Buoyancy | |
| FL-8 | 10-Feb | QUIZ 1 | |
| FL-9 | 12-Feb | Fluid Kinematics | |
| FL-10 | 14-Feb | Conservation of Mass | |
| FL-11 | 19-Feb | Bernoulli Equation I | |
| FL-12 | 21-Feb | Bernoulli Equation II | **PROJECT ASSIGNMENT** |
| FL-13 | 24-Feb | Lab 2: Flow Measurement | |
| FL-14 | 26-Feb | Conservation of Linear Momentum I | |
| FL-15 | 28-Feb | Conservation of Linear Momentum II | **IPR #1 DUE: EXPERIMENTAL POWER and FLO W RATE ANALYSIS** |
| FL-16 | 4-Mar | Conservation of Energy | |
| FL-17 | 6-Mar | Differential Conservation Laws | |
| FL-18 | 8-Mar | TEST 1 | |
| FL-19 | 11-Mar | Experimental Design | |
| FL-20 | 13-Mar | Dimensional Analysis | **IPR #2 DUE: TURBINE WH EEL and GEAR RATIO ANALYSIS** |
| FL-21 | 24-Mar | Modeling | |
| FL-22 | 26-Mar | Experiment Presentations | **SAFETY CLASS** |
| FL-23 | 28-Mar | Conduct Experiments | |
| FL-24 | 1-Apr | Friction Drag I | **IPR 3: TURBINE SKETCH and PARTS REQUEST** |
| FL-25 | 3-Apr | Friction Drag II | ↑ |
| FL-26 | 7-Apr | Pipe Flow I | |
| FL-27 | 9-Apr | Pipe Flow II | |
| FL-28 | 11-Apr | Lab 3: Pipe Friction | **TURBINE CONSTRUCTION AND TESTING** |
| FL-29 | 15-Apr | Pipe Flow IV | |
| FL-30 | 17-Apr | Pipe Flow V | |
| FL-31 | 21-Apr | Pipe Flow VI | ↓ |
| **HYDROPOWER COMPETITION DAY** | | | |
| FL-32 | 23-Apr | TEST 2 | |
| FL-33 | 25-Apr | Open Channel Flow I | |
| FL-34 | 29-Apr | Open Channel Flow II | |
| FL-35 | 1-May | Compressible Flow I | |
| FL-36 | 5-May | Compressible Flow II | |
| FL-37 | 7-May | Drag I | |
| FL-38 | 9-May | Drag II | **FINAL EDP REPORT DUE** |
| FL-39 | 13-May | QUIZ 2 | |
| FL-40 | 15-May | Course Review | |

**Table 1: Course Syllabus and Project Timeline for Current Semester**

This result was disappointing given that efforts were already taken to show how the theory could be applied to the real device. Instructors and cadets alike believed that most students did not complete the analysis prior to turbine construction because of lesson and assignment scheduling: there was not enough time between when the students had all of the information to perform the analysis and when the turbine had to be built.

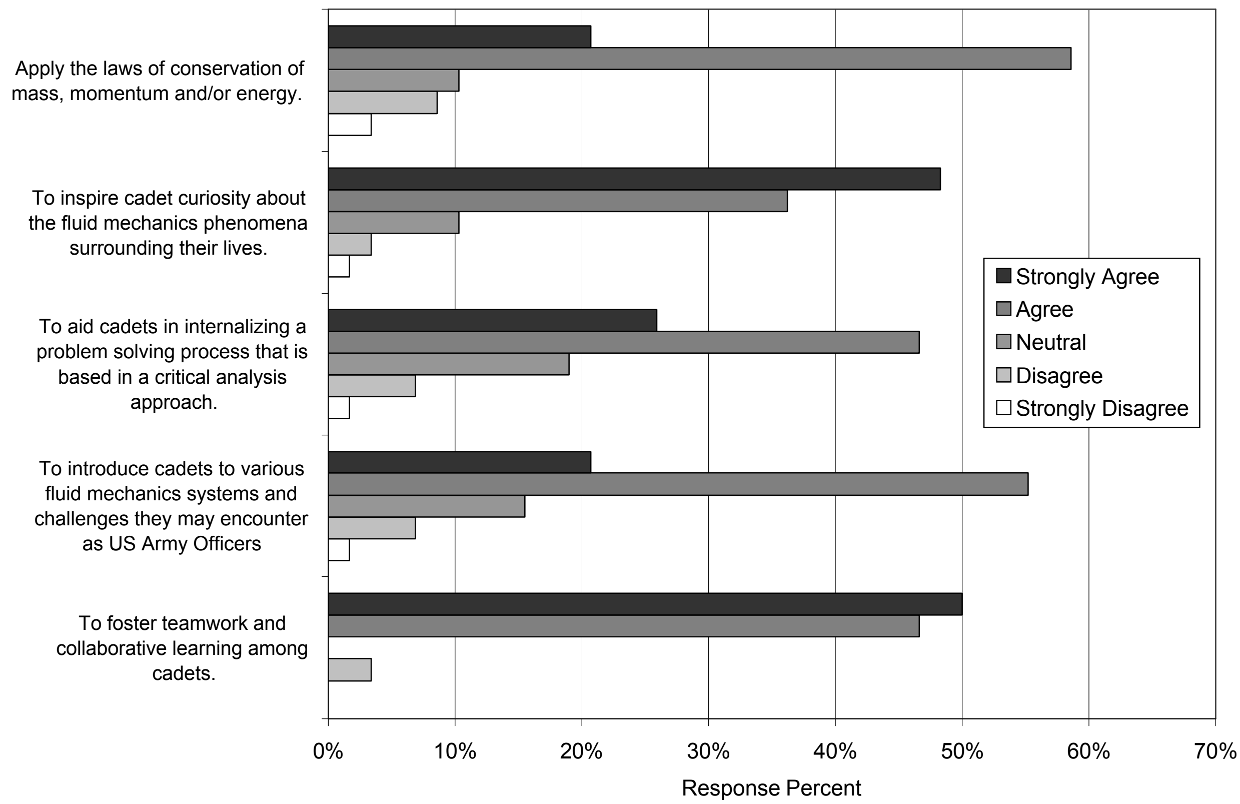


**Figure 6: Did the Turbine Design contribute to the achievement of course objectives?**

On a positive note, a surprisingly large percentage of the students, 48%, strongly agreed that the turbine design competition inspired student curiosity about fluid mechanics phenomena. Additionally, another 36% of the students agreed with this statement. Although it is somewhat unclear why so many students' curiosity was piqued by the project, a possible explanation lies in the fact that the design was a competition. Students were told that top groups would receive recognition and a Hall of Fame and Wall of Shame were maintained to showcase outstanding entries. This undoubtedly motivated some students and had them continually thinking about how they could make a better turbine.

An overwhelming 98% of the students either strongly agreed or agreed that the turbine design competition fostered teamwork and collaborative learning. While this result was encouraging, instructors were disappointed that only 50% of the students strongly agreed with this statement. A possible explanation for this is the limited amount of supplies. For instance, supplies of epoxy, nails, screws, and wood were much lower than desired and one student commented:

> *"We were unable to locate or have enough of anything. The work place was a madhouse. If you left a part lying around, it was gone in a few seconds."*

Additionally, although the competitive structure probably increased student curiosity, it may have discouraged some collaboration between groups. This result was anticipated and was addressed by publishing absolute grading standards. For instance, it was conceivable that all of the groups could have scored 100% on the competition.

Students were also asked to identify which aspect of the design contributed most to its ability to achieve course objectives. Figure 7 clearly indicates that the hand-on nature of the project had the largest impact.

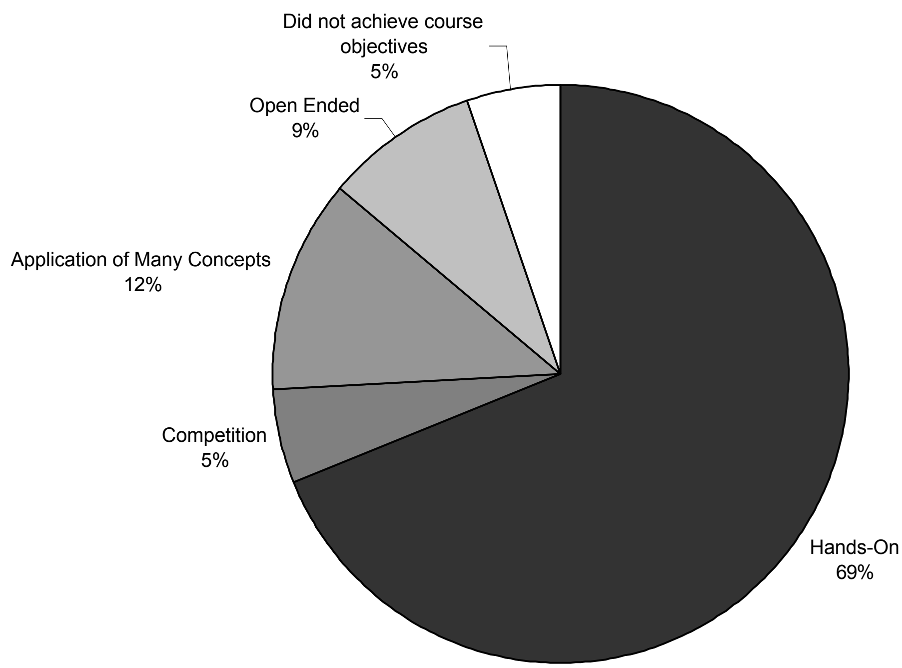


**Figure 7: What single aspect of the Turbine Design was most influential on its ability to achieve course objectives?**

It is likely that the students placed such a high premium on these kinesthetic attributes because most still had no physical reference for the relevant flow parameters as a result of only in-class theory and homework problems. One student wrote:

> *"This project gave me a frame of reference to use when looking at the problems we faced. Otherwise I don't really have a way to connect the number we use to a real world problem."*

This project showed whether a velocity of 25 ft/s was fast or slow, whether 13 ft of elevation head was a little or a lot. Additionally, the turbine illustrated concepts that they had seen previously in other courses such as torque and power.

The hands-on turbine design project was largely responsible for the course objective that dealt with introducing students to various fluid mechanics systems and challenges that they may encounter as US Army officers. As seen in Figure 6, over 75% of the students either agreed or strongly agreed that the turbine design contributed to the achievement of this course objective. One possible explanation for this result is that this project developed the student's problem solving skills and creativity. One cadet explained:

> *"This project highlighted many of the difficulties one may encounter when designing and building even simple engineering projects. I feel better prepared to anticipate problems and think of creative ways to overcome them when it comes time to plan and build more complex designs."*

While this statement does not specifically address the Army, many students know that problem solving skills and creativity are attributes that the Army values.

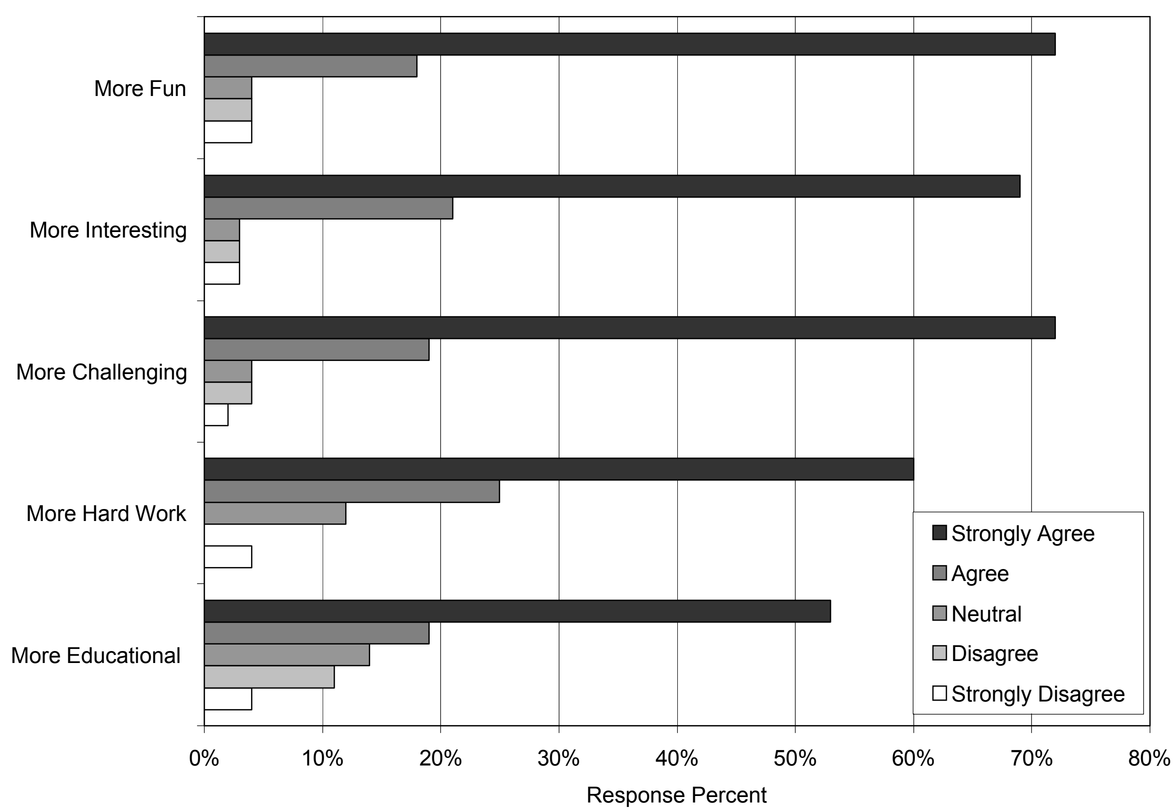


**Figure 8: Compared to a Paper Design, the Turbine Design was:**

Survey results strongly illustrate the benefits of a hands-on project vice a paper design. On the next survey question students were asked to compare the turbine design with traditional paper designs. Figure 8 makes a very compelling case for hands-on design projects.

In every area, students responded that the turbine design was a great project and that they found it more fun, interesting, challenging, hard work and educational than the typical paper design. These results are not particularly surprising, but they do serve to verify that students do not mind working hard if the task is fun and challenging. One of the most compelling testimonies of student interest and enthusiasm, however, did not come from surveys. Many students strongly expressed a desire to compete in the national Hydropower competition with their water turbines.

## CONCLUSIONS

Hands-on design projects, such as the USMA Water Turbine Competition, are excellent educational tools. While few dispute this claim, this paper has shown how the project directly contributed to the achievement of course objectives. The turbine project provided a direct physical application of the conservation laws, offering students a quantitative reference for flow parameters rather than just numbers. Because of its kinesthetic nature, the project inspired more cadet curiosity about fluid mechanics. As a group exercise, it fostered teamwork and collaborative learning among students. Most importantly, however, the turbine project injected some excitement into a course that cadets used to dread. Feedback revealed that students believed the water turbine project was more fun and interesting than paper designs even though it also required more hard work.

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