AC 2012-3046: AN APPROACH TO USING UNDERGRADUATE STUDENT TEAMS TO DEVELOP UNDERGRADUATE LABORATORY EXPERIENCES

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An Approach to Using Undergraduate Student Teams to Develop Undergraduate Laboratory Experiences

Abstract

The technical information presented in many undergraduate engineering courses is emphasized and solidified by using laboratory experiences. As new, interesting technology is introduced into undergraduate courses or new courses introduced into the curriculum, some professors find themselves wanting to provide new hands-on exercises for their students to support their course objectives. At the same time, they often find they are short on time, money, or resources needed to develop their ideas into meaningful, level-appropriate learning events meant to timely support their students' learning.

In this effort, a senior-level mechanical engineering student group in a mechanical instrumentation and measurements course at the United States Air Force Academy (USAFA) was tasked to develop an engaging, relevant laboratory learning experience for other undergraduate students while they met the learning objectives of their instrumentation course. The intention was to use this student-designed lab in a newly implemented undergraduate renewable energy course. The development process, benefits, as well as difficulties encountered in this approach are discussed and recommendations provided. An example "lab experience" developed by undergraduates, guided by staff, during this process is included. This example could be implemented as is or modified with minimal time and money investment for relevant courses.

Keywords: laboratory experiments, laboratory experiences, laboratory exercises, hands-on learning opportunities, undergraduate student team

Introduction

The technical information presented in many undergraduate engineering courses is emphasized and solidified by using laboratory experiences. In his paper, entitled "Tell me, I'll forget; show me, I'll remember, involve me, I'll understand;" Eastlake states, "Engineering without labs is a different discipline. If we cut out labs we might as well rename our degrees Applied Mathematics."[1] Although there isn't much discussion about removing labs from engineering education, this statement does help emphasize the importance of laboratory experiences in engineering curricula as a key method for promoting student learning. Also, many students of mechanical engineering state that they learn best by hands-on investigation. Many verbalize that a main reason for selecting their major was the opportunity for hands-on work in school and in their careers. Typically labs provide students with these desired hands-on learning opportunities.

Hands-on "lab experiences" vary widely in complexity, value, cost, ease of use, and faculty-student time investment. As new, interesting technology is introduced into undergraduate courses, some professors find themselves wanting to provide new hands-on exercises for their students in support of course objectives. These instructors often find they are short on time, money, or resources needed to develop their ideas into suitable learning events that support desired learning outcomes. In their 2006 report entitled "America's Lab Report"[2], the National

Research Council of the National Academies' authors presented a comprehensive list of seven goals for laboratory experiences. These seven are: enhancing the mastery of subject matter, developing scientific reasoning, understanding the complexity and ambiguity of empirical work, developing practical skills, understanding the nature of science, cultivating interest in science and interest in learning science, and developing teamwork abilities. Although this work was developed in the context of high school science laboratory research, the resulting comprehensive list of laboratory goals is general to science education[3, 4] and can be extended through many levels of engineering education. These goals can be achieved to various degrees by using lab-based learning opportunities that range from classroom demonstrations to dedicated laboratory courses to student-designed, open-ended research efforts. In any case, the time, money and effort investment from the instructor and students compared to the value added toward accomplishment of course objectives needs to be carefully considered.

In this effort at the USAF Academy, an undergraduate, senior-level mechanical engineering student team in a mechanical instrumentation and measurements course was employed to develop an engaging, relevant laboratory learning experience for other undergraduate students. The team members or developers were concurrently fulfilling the learning objectives of their instrumentation course. The intention was to use the student-designed lab in a newly implemented Renewable Energy undergraduate course. The development process, strategies, and assessment as well as issues encountered in this approach are discussed and recommendations are provided. An example "lab experience" developed by undergraduates using this process is attached.

Background

Prior to the spring 2011 semester at the Air Force Academy Department of Engineering Mechanics, the decision to offer a new undergraduate mechanical engineering elective called Renewable Energy was made. The course development occurred quickly so that the first offering could be made during spring 2011. Several of the students who took this offering for credit commented that some laboratory experiences could improve the course for the next offering. One of the course objectives was "Provide cadets with the ability to analyze and compare those systems which rely on renewable resources as a source of energy." See Appendix A for the Renewable Energy course objectives. Based on this course objective, there existed an ideal opportunity to add a renewable energy, hands-on laboratory experience related to parameter measurement, efficiency calculations and comparison into the course. The students performing the lab during the course would be required to collect experimental data during a typical class period and therefore, it was termed a "mini-lab." These students would then be required to submit their data, analysis, and conclusions in the form of an abbreviated lab report, termed "mini-report." The mini-report is an abbreviated lab report because the typical Introduction, Background, Lab Setup/Equipment Descriptions, and Procedure sections are not required as they are included with the lab handout to the students.

Concurrently, course projects for another department course, Experimental Mechanics, offered fall of 2011, were being developed. This course is a graduation requirement for all mechanical engineering majors. The course has several objectives focused on test planning, execution, data analysis, and technical reporting. Literature research and instrumentation planning are included in the test planning phase. See Appendix A for the Experimental Mechanics course objectives.

The course description states "Hands-on laboratory experience constitutes one-half of the course." All course objectives are met or partially met by an open-ended, ill-defined course project involving instrumentation and measurement. One proposed project was a three-person student team tasked with instrumenting a hydrogen fuel cell. The goal of the project would be for students to characterize fuel cell efficiency. A secondary goal of this team was to propose a first draft fuel cell efficiency laboratory experience that students in the Renewable Energy course could perform to increase their understanding and appreciation of fuel cells.

Research Approach/Strategy

An Experimental Mechanics fuel cell project was proposed with the intention that the results be evolved into a useable undergraduate laboratory experiment for the Renewable Energy course. The course objectives for both courses had to be analyzed to determine whether this was a feasible approach. Efficiency measurement of a Polymer Electrolyte Membrane (PEM) fuel cell was chosen for three main reasons: hydrogen fuel cell equipment is commercially produced, the price of a fuel cell was reasonable at approximately $150.00 for readily-available hydrogen PEM fuel cells, and PEM fuel cell safety is relatively easily managed in the laboratory setting. See Appendix B for a listing of equipment, vendors, and pricing. Several measurements are required for calculation of efficiency of a fuel cell and several variables could be rather easily controlled in order to determine their effects on efficiency. Therefore, with these considerations in mind, this proposal was accepted. Other factors considered in the selection of this equipment were relatively easy setup, fairly user-friendly operation, adaptability to small student teams, and the ability to be integrated with current laboratory data acquisition hardware and software. In order to provide the students taking the Experimental Mechanics course with an ill-defined or open-ended problem experience per course objectives, students were tasked, as stated in the project abstract, to research fuel cells and then propose in their team's test plan their developed approach to efficiency measurement. Their approach had to include a definition of the efficiency they chose to investigate. It also had to include the variables to be measured to calculate efficiency as well as their instrumentation and data acquisition strategies to achieve required measurements.

Prior to the semester starting, a fuel cell and an electrolyzer were purchased. The fuel cell chosen was a dissectible, transparent construction that was especially suited for student exploration of fuel cell internal components. It was purposefully manufactured to dimensions larger than necessary to aid in disassembly and reassembly by students. Considerable care was required to prevent damage or contamination of the proton exchange membrane when disassembled. Tools required for disassembly and reassembly were included with the fuel cell, as were normal operating and safety instructions. The electrolyzer was also purchased to provide a source for hydrogen gas for the fuel cell experiments. The electrolyzer purchased could be powered by a typical DC power supply and came complete with hydrogen and oxygen water-displacement gas storage reservoirs. The reservoirs were designed to accommodate volume readings and to store relatively small gas volumes for safety reasons. Also, prior to the semester starting, possible team leaders for this effort were discussed with the prior Renewable Energy course director who provided input based on observed interest, personality, and work ethic of students from the past semester's first offering of the Renewable Energy course. The Experimental Mechanics course allows for student self-selected teams of three; therefore the remaining two team members were left to the students to decide upon after a basic project abstract was provided. Once the team formed, a meeting with the team and faculty advisor was arranged to discuss project background, available equipment, and desired outcome. References including a fuel cell technical background website[8] as well as a current news link discussing fuel cells for future home electrical power generation[9] were provided to the team. A description of the dissectible fuel cell was also provided.[10] The team members expressed interest in the hands-on aspects of working with a fuel cell as well as producing a lab for another course.

Meetings with the team were held to discuss test planning as well as the progress of their instrumentation plan implementation and test execution. Feedback and guidance were provided to the team concerning their proposed parameters and associated measurements. Additional equipment was purchased for planned testing including thermocouple mini connectors to fit the existing lab digital thermometer and temperature data logger. Since the team proposed measuring the temperature of the polymer membrane itself, silicon lacquer was purchased for coating thermocouples to electrically insulate them so as to prevent electrical short circuit damage to the fuel cell membrane. The team also required assistance with environmental chamber testing as they proposed running the fuel cell over a range of ambient temperatures. PASCO Scientific's Data Studio software was selected to provide a simple data display; recording time stamped data and near-real-time power calculations with display.

Feedback on draft test plans was provided by the team advisor as well as the instrumentation course instructor. Comments on their final report submission, including the mini-lab shown in Appendix C, were also made. Assessment tools to determine effectiveness of the developed lab and attitudes concerning their experience were administered to the developing team students after their final report was submitted. One of the developing students agreed to assist in administering the lab to the independent verification or lab trial team. Assessment tools were administered to the verification team pre- and post- completion of the experimental portion of the lab. The students on the verification team were also members of the senior mechanical engineering class. Figure 1 shows the verification team collecting data as the student lab administrator watched. The quantitative and qualitative assessment tools and results are presented.

Figure 1: Lab Trial (Verifier) Student Team Acquiring Data

Assessment and Results

Several assessments were accomplished to determine effectiveness of using the Experimental Measurements course student team to develop a laboratory experience for another undergraduate course. These assessments were to determine if: 1) Experimental Measurements course objectives were met or furthered by students developing the lab, 2) Renewal Energy course objectives were met or supported by the lab the students developed, and 3) lab goals, as discussed in literature, were also advanced.

After the lab development efforts were completed, three volunteer lab verifying students were first given a ten minute quiz on fuel cells prior to doing any part of the lab. See Appendix D, Figure D-1 for the fuel cell quiz. The six technical questions were formulated with the Renewable Energy course objectives in mind. They were constructed to have an increasing level of technical difficulty relating to the topic of fuel cells and efficiency. After the verifying/trial students completed the pre-quiz, the verifiers were guided through the theory and data collection portions of the lab by one of the developing students who volunteered to administer the lab.

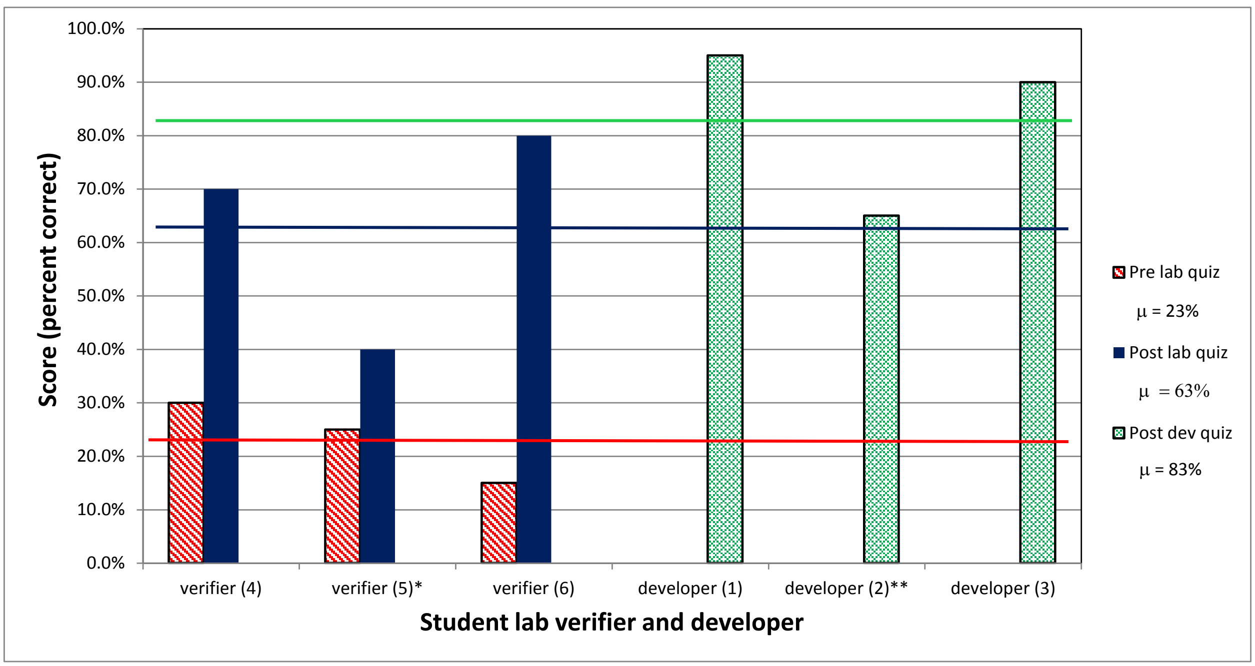

Figure 2: All Students Pre- and Post-Quiz Scores

The three students were again given the identical assessment as a post-quiz once they completed the hands-on data collection portion of the lab. The pre and post written quizzes were graded on a ten point scale and assigned percentage correct scores. The results of both the pre- and post-quizzes are shown in Figure 2. Several observations were made:

1. When comparing the verifier students pre and post quizzes, these data show an increase in the mean quiz score of forty percentage points from 23% mean correct pre-lab to 63% mean correct post-lab score. Note: limitations of this lab verification testing included only having one team of three students taking the lab for verification purposes. The assessments were completed during semester final exams week by volunteer senior mechanical engineering

students; two of which were not yet completed with final exams as of the verification date. One of the three verifying students, #4, had completed the first offering of the Renewable Energy course the semester prior and the other two had not. During several lessons in this course, fuel cell technology had been presented and discussed in a lecture setting but no hands-on lab experiences were available at that time. All three students knew that their performance concerning this experiment was not for a grade but was to improve another undergraduate course. Due to time constraints, the verifying students were not required to reduce, analyze and report their lab data. All verifying students were given the post-quiz after data collection was completed for a typical lab data run of the electrolyzer and fuel cell.

While scoring the quiz assessments given to students, it became apparent that several questions could be improved to be clearer and more direct. Some recommended improvements to the fuel cell assessment quiz found in Appendix D are included in the recommendations section.

The same quiz assessment was also administered to the three students from the lab development team. The quiz was administered after their final report submission for Experimental Mechanics. The final report submission signified the completion of their lab development efforts as the mini-lab was required with their final report.

2. Figure 2 shows that the average score for the developers post-quiz was 83%. When developers 2 and 3 were separately asked why developer 2 (marked with two asterisks) scored lower than the other two, both independently responded that student 2 was not as involved in the data analysis as the other two. Instead of data analysis, student 2 performed most of the writing for the final report. In written comments, developer 2 stated, “I did not complete too much of the test results in the write up (although I did write the abstract).” Also worth noting is that both students 1 and 3 enrolled in and completed the first offering of the Renewable Energy course. Again, during the course, fuel cell technology had been presented and discussed in a lecture setting only.

Figure 3 shows the individual question results for the six question post-quiz as a percent improvement over the pre-quiz scores. For the three verifying students, four questions had an average 33% higher student score and the remaining two questions had an average 50% higher score for the post-lab offering.

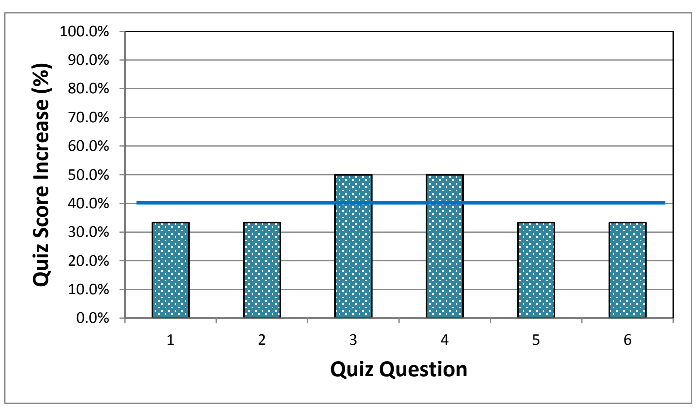

Figure 3: Verifying Students Post-Quiz Score Increase from Pre-Quiz Score

The lab developers achieved a 20% higher average score on the post-quiz when compared to the lab verifiers post-quiz as shown in Figure 4. The developers showed a higher score on all quiz questions except one, question 5, where they matched scores. Question 5 dealt with significant fuel cell losses. Providing additional information involving PEM fuel cell losses during theoretical discussions prior to students performing the lab would likely result in increased scores for this question.

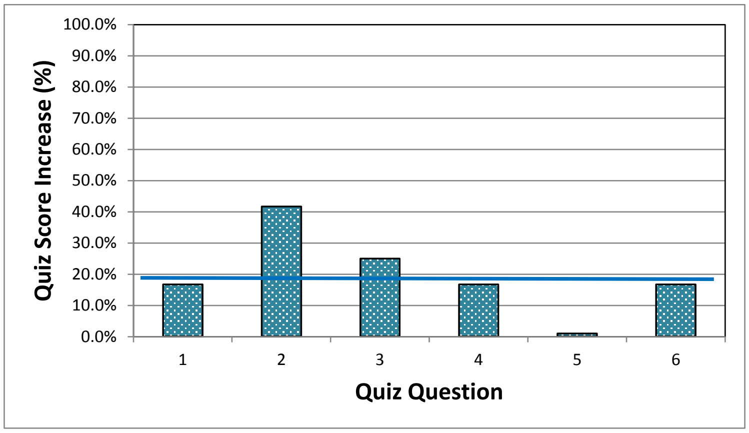

Figure 4: Lab Developer Post-Quiz Higher Scores compared to Verifier Post-Quiz Score

Although the students developing the lab were not given the pre-quiz, their post-quiz scores compared to the verifiers' pre-quiz showed an average 60% higher score, seen in Figure 5. All questions showed a minimum of 30% better score.

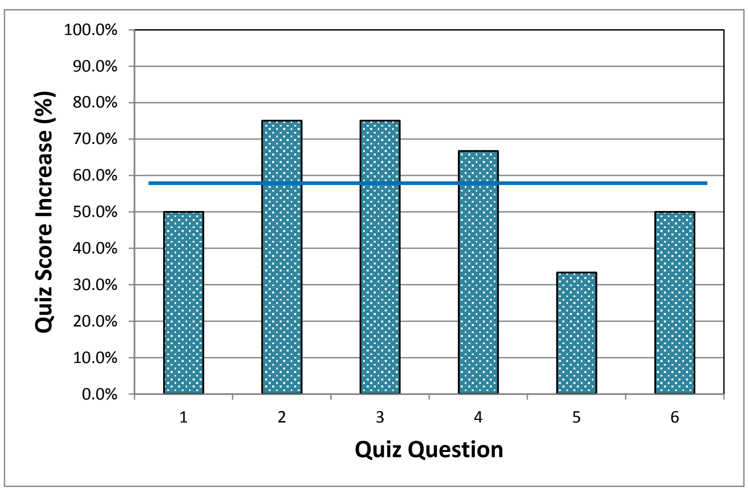

Figure 5: Lab Developer Post-Quiz Higher Score compared to Verifier Pre-Quiz Score

In addition to pre- and post-quizzes, trial students were given Likert surveys to measure student attitudes toward specific course objectives and lab goals being met by their respective experiences. The verifier students were given a nine-item Likert survey with accommodation for additional comments. The survey results are shown graphically in Figure 6. Table 1 shows these results with calculated mode, median and range. This survey included statements concerning course objectives for the Renewable Energy course but not about the Experimental Mechanics course as these three students were not the ones developing this fuel cell lab in the Experimental Mechanics course. This survey also included statements about lab experience goals derived from literature.[2] All survey responders were asked to use the five-level Likert scale shown in Figure 7 to evaluate each survey item. Each responder was asked to provide written comments related to the survey items.

These survey responses showed that the three students agreed or strongly agreed with items 1 and 2 relating to contributing to meeting course objectives for the Renewable Energy course. Items 3, 4, and 9 had at least one student that disagreed. One student disagreed with item 3. Item 3 stated that this project helped develop scientific/engineering reasoning abilities as well as use of theories and assumptions. This disagreeing student arrived late and was distracted during the short theoretical explanation provided prior to lab execution and had no prior knowledge of fuel cells. From his written comments, "We jumped into theory too fast. Equations were written on the board before I ever knew what a fuel cell was." He also wrote other comments, "My brain is fried from finals and a bunch of other stuff going on in my life. Take that into consideration when seeing my comments."

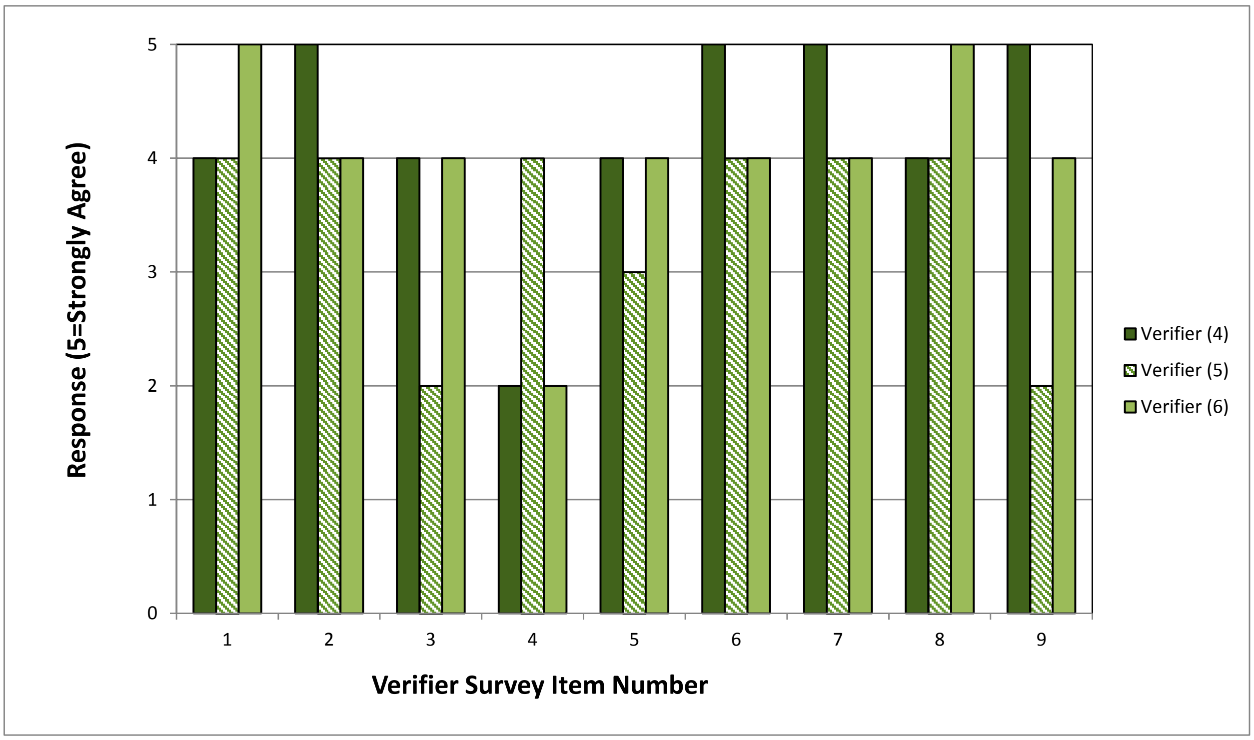

Figure 6: Verifier Likert Survey Item Responses

Five Point Likert Scale				
1	2	3	4	5
Strongly Disagree	Disagree	Don't know	Agree	Strongly Agree

Figure 7: Likert Scale Used For Survey Assessments

Item #	Likert Item	Verifier (4)	Verifier (5)	Verifier (6)	MODE	MEDIAN	RANGE
1	Performing this work provided me a deeper understanding of fuel cells.	4	4	5	4	4	1
2	I am now more equipped in my ability to analyze and compare fuel cells to other sources of electrical energy.	5	4	4	4	4	1
3	This project helped develop my scientific/engineering reasoning abilities as well as use of theories and assumptions.	4	2	4	4	4	2
4	I developed an increased appreciation for computer tools (data acquisition, analysis, etc) by completing this project.	2	4	2	2	2	2
5	My understanding of the complexity and ambiguity of experimental (empirical) work increased.	4	3	4	4	4	1
6	Teamwork was important on this project.	5	4	4	4	4	1
7	I have questions or areas of fuel cell technology that I'd like to research if I had time.	5	4	4	4	4	1
8	The knowledge that my work was for improvement of another course interested me.	4	4	5	4	4	1
9	I feel that fuel cells are relevant to everyday life and this project increased that feeling.	5	2	4		4	3

Table 1: Verifier Likert Scale Assessment Results

Two students disagreed with item 4. This item stated that they developed an increased appreciation for computer tools by completing this lab. Both of these students stated that the computer software for lab data acquisition was already set up for them and they only had to press go to start the software. Although they felt this was a nice feature, they also commented that it provided little to no insight into computer tools. Due to time limitations during testing, these students were not required to analyze and report lab test data; therefore, they were not given the opportunity to employ computer tools for data analysis and presentation. One student disagreed with item 9, which was that they felt fuel cells are relevant to everyday life and this lab increased that feeling. This verifying student performed this lab experiment outside of the context of any course since he had not taken the first offering of the Renewable Energy course and did not watch the fuel cell news video that was provided to the other team at the start of the project.

The developers of the lab were given a fifteen-item Likert survey with accommodation for additional student comments. These students were asked to respond to each item using the same five-point Likert scale shown in Figure 7. The survey results are graphically displayed in Figure 8. Table 2 shows these results with calculated mode, median and range. This survey included statements concerning course objectives for both the Renewable Energy course as well as the Experimental Mechanics course as these students were developing the lab under the course objectives of Experimental Mechanics. This survey included the same statements about lab experience goals as the verifier survey plus additional items involving improving another course and undergraduate teaching.

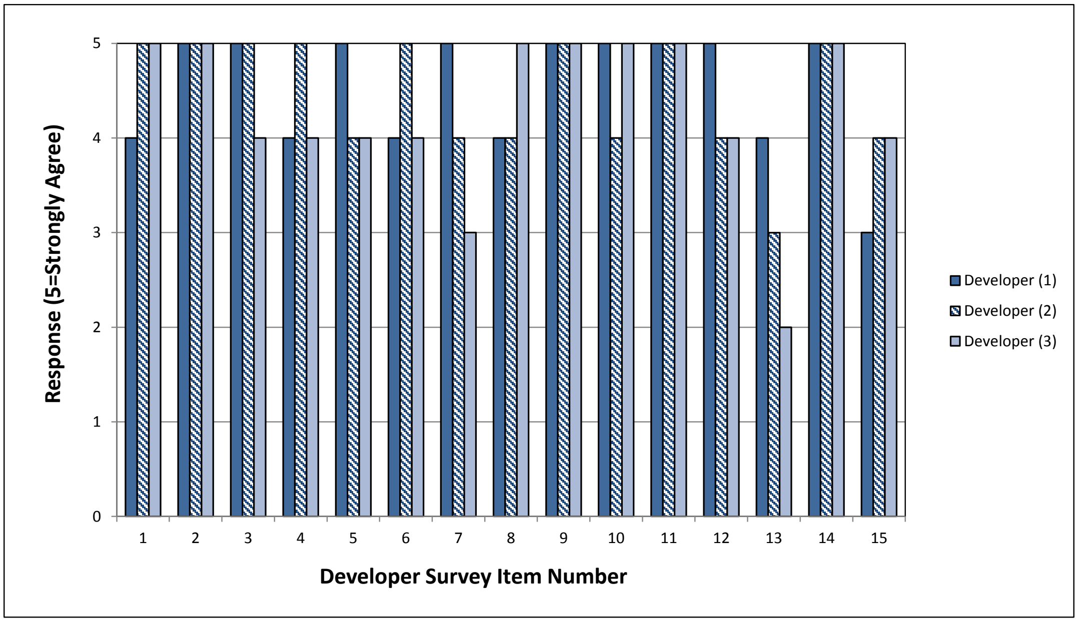

Figure 8: Developer Likert Survey Item Responses

Item #	Likert Item	Developer (1)	Developer (2)	Developer (3)	MODE	MEDIAN	RANGE
1	Performing this work provided me a deeper understanding of fuel cells.	4	5	5	5	5	1
2	I am now more equipped in my ability to analyze and compare fuel cells to other sources of electrical energy.	5	5	5	5	5	0
3	This task assisted me in a deeper understanding of instrumentation for mechanical measurement and helped me develop practical instrumentation selection/testing skills when faced with an open-ended test scenario.	5	5	4	5	5	1
4	I learned how to develop a test plan to implement chosen measurements.	4	5	4	4	4	1
5	I learned how to perform measurements to execute a test plan.	5	4	4	4	4	1
6	I learned how to analyze collected data as part of executing a test plan.	4	5	4	4	4	1
7	I learned how to report results of an executed test plan.	5	4	3		4	2
8	This project helped develop my scientific/engineering reasoning abilities as well as use of theories and assumptions.	4	**4**	5	4	4	1
9	I developed an increased appreciation for computer tools (data acquisition, analysis, etc) by completing this project.	5	5	5	5	5	0
10	My understanding of the complexity and ambiguity of experimental (empirical) work increased.	5	4	5	5	5	1
11	Teamwork was important on this project.	5	5	5	5	5	0
12	I have questions or areas of fuel cell technology that I'd like to research if I had time.	5	4	4	4	4	1
13	I feel that fuel cells are relevant to everyday life and this project increased that feeling.	4	3	2		3	2
14	The knowledge that my work was for improvement of another course interested me.	5	5	5	5	5	0
15	I learned something about undergraduate teaching from my experience in producing a lab.	3	4	4	4	4	1

Table 2: Developer Likert Scale Assessment Results

These survey responses showed that developers agreed with items 1 and 2 which were based on furthering the Renewable Energy course objectives. They all agreed with items 3 through 6 which were based on the Experimental Mechanics course objectives. One student marked "Don't know" for item 7 which stated that they learned how to report results of an executed test plan. This student commented that he "Reported basically the same way we always do." So although he felt he didn't learn anything new when it came to technical reporting, he basically reaffirmed what he already knew relating to this course objective. All three students agreed with items 8 through 12 which were based on the list of goals for laboratory experiences in literature.[2] Item 13, based on the final of the seven goals in literature, showed one student didn't know and one student disagreed with the statement. This item stated that they felt fuel cells are relevant to everyday life and that this project increased that feeling. The student that disagreed stated that "I've never seen one outside a lab." and the student who didn't know stated, "They have the potential to be relevant; not there yet."

Especially interesting are items 9 and 14 for which lab-developing students unanimously strongly agreed. Item 9 stated that they developed an increased appreciation for computer tools by completing this project. Their "strongly agree" was in contrast to the already presented trial students' responses where two of the three disagreed with this statement. The developers of the lab exercised this component by configuring and using the data acquisition and display hardware and software. They also used data processing, analysis, and presentation software to incorporate results into their final report. Item 14 stated that the knowledge that their work was for improvement of another course interested them. Some comments accompanying this item included, "Anytime feedback can be turned directly into progress, especially when benefitting future courses, is very worthwhile." and "This was one of my favorite aspects."

Other written comments related to the Likert items from student developers and trial verifiers were also collected on these survey forms. Some interesting statements made by these students include: When asked if this work helped in their understanding of any other areas or topics, the developers said, "Testing: it never goes right the first time." and "Some chemistry." "I enjoyed it, but it was occasionally very frustrating." For item 15 (I learned something about undergraduate teaching from my experiences in producing a lab) the developers commented "Labs are difficult to develop and must be kept simple for classrooms." and "Our teachers take a lot of time to develop our labs." When asked if they might want to teach engineering undergraduates at some point in their careers, the developers responded, "I really enjoy the material and want to show others why it's interesting too." and "Yes, I enjoy showing people how things work and undergraduate students seem to be some of the most curious students of any age." When asked for Other Comments, two responses were: "I really enjoyed the hands-on aspect. Given something with no idea how to do it meant thinking on our feet more than any other time here." and "More time to just fool around with the FC would have been nice."

These student statements indicated several positive results and attitudes. The students had an increased appreciation for the trials and frustrations of experimentation but also the rewards. They had an increased understanding and appreciation for those who develop labs, especially hands-on experiences, to aid in their undergraduate learning. The students all had a strong desire to help other undergraduates learn. Some had a desire for more time to investigate the scientific topic.

Issues and Observations During Implementation

Safety: the developing team performed all work in a safe manner and highlighted a safety concern pertaining to touching/damaging the fuel cell membrane in their mini-lab. Multiple safety considerations were discussed with the team prior to them starting any experimentation; however, they neglected to include all items but one in their mini-lab. For example, mitigating procedures that were later added to the lab concerned the explosive nature of hydrogen gas.

The team proposed several temperature measurements for their fuel cell project. Although they have had considerable exposure to strain gages and strain measurement, as seniors they had little background in the use of thermocouples and temperature measurement in general. The team realized that certain components were not available in our department and had to be ordered to support the project. This caused a minor schedule delay. Providing the students with links to online reference documents for thermocouples and connectors provided them with insight into the use of thermocouples. Additional time should be budgeted for assistance when students are employing instruments or techniques for which they lack familiarity. Emphasis on vendor references as resources can be a valuable learning point.

Software non-familiarity and level of proficiency by students developing the lab drove their reluctance to use some of these important tools. The three students were slightly familiar with the PASCO DataStudio data acquisition and display software as well as PASCO Scientific hardware from various other lab experiences in their education thus far. Although they had used this software in the past as a pre-configured tool, they were hesitant to attempt to program the software interface for their specific fuel cell project. They were advised during the test planning phase to use the PASCO software for multiple reasons: 1) real time data display, 2) ability to calculate and display parameter such as power output real-time, as well as 3) reducing possible error in recording data, 4) storing data for future analysis, and 5) time stamping of all data recorded. Even after discussing the reasons for suggesting using this software, they still proposed in the draft test plan using a simple voltmeter and ammeter to take manual readings of electrolyzer input as well as fuel cell output. With increased emphasis, a quick demonstration, and an offer of assistance in programming, they changed their test plan to include using the PASCO Scientific software. After implementation in the project, a developer who performed most of the data recording and data analysis for the team commented, “PASCO is awesome – real-time data was great to have and (MS) Excel, as usual, saves time and effort.”

Aside from renewable energy and instrumentation, increased understanding of other technical areas can be gained from projects such as these. Based on a student comment discussed earlier, this project provided the opportunity to learn some chemistry. Not only the details of a redox reaction, chemical equations, and half reactions were investigated but also the use/issues of a catalyst, the ideal gas law, energy of formation, and the process of diffusion, to mention some. Although the students didn’t comment directly, they also were exposed to electrical engineering principles such as Faraday’s laws. They were required to use voltage sources, voltmeters, ammeters, and circuit design to develop a dial-up, selectable resistive load using power resistors. The mechanical engineering student that spent time and effort determining that the ammeter was incorrectly wired in parallel with the load in his fuel cell circuit will likely not make that mistake again anytime soon. All students involved have a better understanding of the complexity of multidisciplinary projects.

Thermodynamics was important in this lab development but could be emphasized more in the final lab as well as the quiz by incorporating a control volume analysis of the fuel cell. A first and second law derivation from first principles of ideal fuel cell efficiency would be another valuable exercise for students if not completed during another portion of the Renewable Energy course. Units analysis of resulting equations could also enhance understanding and confidence in these resulting derived equations. Although scientific theories, laws, and engineering tools (control volumes, first and second laws of thermodynamics; units analysis, etc.) are emphasized over and over in their course work, undergraduates may still have a tendency to not rely on or employ these approaches when faced with an ill-defined problem. These tools cannot be over-emphasized in an undergraduate mechanical engineering curriculum.

The size of a single fuel cell (approximately 2” by 2” by 1.5”) made it manageable for use and storage. The compact nature of the equipment, as shown in Figure 9, led to portability of the entire experimental setup as well, making it well suited for a table top lab setup with added benefit of minimal storage burden between semesters. Multiple fuel cell setups to accommodate small student groups could be managed on minimal laboratory countertop real estate.

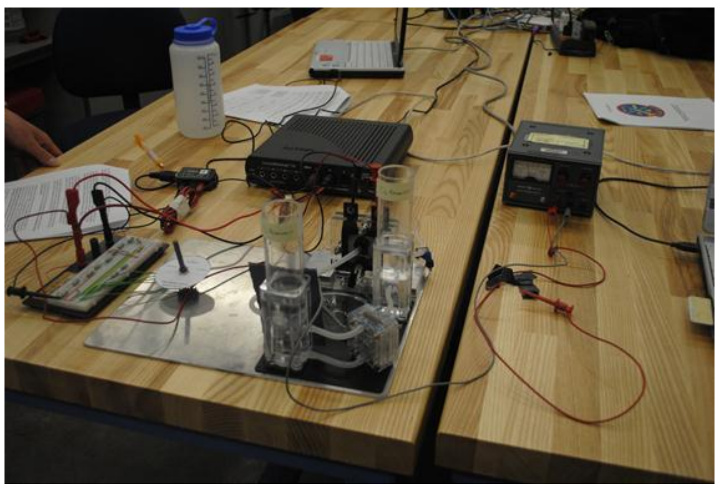

Figure 9: Fuel Cell Experiment Setup

On page 9 of their mini-lab in Appendix C, the developing students included some post-lab questions for students performing the lab to answer as part of their final lab report. The purpose of including these pre-determined questions was to provide a thought-provoking scenario to promote additional critical thought and student learning. However, the effectiveness of questions in promoting inquiry can likely be significantly improved. Students being asked to write their own questions can be a useful method for promoting inquiry in an otherwise resource-constrained classroom lab scenario.[5] Each student should be required to develop three pre-lab and three post-lab questions independently. The pre-lab questions are meant to focus student thinking on the upcoming experiment and potential results. The post-lab questions are meant to encourage student thought about new questions that derive from the experiment. These also require critical thinking to determine if their questions can be answered within the classroom lab environment. The acts of formulating both sets of questions constitute student practice in the art of generating pertinent technical questions, emphasis on inquiry, and development of student scientific process techniques. The process of scientific question generation, as discussed by Lawson, could increase student engagement and understanding.[6]

All three students on the developing team expressed strong positive attitudes when asked to comment on the experience of developing a lab for an undergraduate course. See Appendix E for their written qualitative comments. The student involved in administering the lab to the verifying student team stated, “Teaching in this way was rewarding for me because I discovered how much I had learned over the course of the semester and because of the opportunity to teach students about some amazing technology that will most likely become increasingly important in today’s emerging energy demands.” “Overall, I think the development of a lab by senior undergraduate students is an outstanding idea and should be continued by the Air Force Academy as a way of educating both its upper and lower level students.”

Recommendations

Implementation: the next step in the evaluation of this laboratory experience would be to implement the modified lab in the Renewable Energy course. Several modifications were made to the student-submitted mini-lab. These alterations included: an expanded safety section to highlight several safety considerations from the standpoint of personal safety and from laboratory equipment care perspectives, the requirement for students to independently generate three pre-lab and three post-lab technical questions, and the requirement for students to perform a control volume analysis from first principles on a fuel cell to determine an expression for ideal efficiency using the first and second laws of thermodynamics. Data tables were also added to clarify and emphasize the data to be recorded during the lab execution. Larger sample size and more extensive assessment data should be collected during this implementation. A pre-lecture quiz as well as the pre- and post-lab quizzes with all the enrolled course students would provide a higher fidelity assessment. This would be especially true if the post-quiz was administered after the students completed required data analysis and reporting. The actual grades on lab reports during this implementation would also serve as a quantitative assessment of learning.

Quiz improvements: while scoring the quiz assessments given to students, it became apparent from student responses that several questions could be improved to be clearer and more direct. Some recommended improvements to the fuel cell assessment quiz found in Appendix D, Figure D-1 include: 1) The first question should be reworded so that students know that defining the acronym “PEM” is not sufficient. The question could be two parts to specifically ask them to define the acronym but also ask them to qualitatively describe what a fuel cell does. 2) For the second question, specifically asking for a control volume diagram showing inputs and outputs for a H_2 PEM fuel cell could improve this question. 3) The third question could be two parts: the first part clearly requesting students to name two types of fuel cell efficiency and the second part asking them to either describe with an equation or in words how these efficiencies are computed. 4) Question five could specifically request students to name two significant sources of PEM fuel cell losses and then a short description of each. Based on results for question 5 of the quiz assessment, increased information involving fuel cell losses should be provided during classroom lectures or during the theoretical discussions of fuel cells prior to students taking the quiz and performing this lab.

Enhancements: several future modifications to enhance learning when using this lab could include using the disassembly feature of the dissectible fuel cell to provide an opportunity to investigate the physical components of the cell. The lab could also be expanded to include a photovoltaic (PV) cell to power the electrolyzer. Both the PV cell and electrolyzer efficiencies could be calculated after appropriate measurements. Employing a reversible fuel cell to act as both the electrolyzer and then reconfiguring by students so that the same hardware is then the fuel cell could possibly help enhance understanding of these electro-chemical systems.

Another useful modification could be to include a units analysis exercise to a pre- or post-lab assignment, especially to help understand and verify the final Faraday efficiency equation. For the purposes of conserving time during execution and increasing required team work, multiple experimental station teams could be simultaneously implemented. Each team would be responsible for collecting a portion of the required data. Each team would then be required to share their data with the larger group to support the necessary data analysis and efficiency comparisons.

Student team and topic selection: the final recommendation is to be selective of the students and projects chosen for such an endeavor. As noted by Wankat, "The amount of guidance students need depends upon their maturity."[7] The maturity, motivation, dedication, and tenacity of the team members in successfully completing this type of project should not be overlooked. Speaking with the past Renewable Energy course director for his recommended student team leader for this project was invaluable. Although not a requirement, selected projects that involve new, emerging technologies provide for a level of excitement in undergraduate students. These projects are more prone to produce lab experiences that are motivating to the future students who find them incorporated into their undergraduate learning.

Conclusions

An undergraduate student team in a senior-level instrumentation course was able to develop a lab experience for other undergraduate students in a different course. Although the lab required some modifications prior to implementation in a course, it required relatively little additional effort. The assessment tools should be modified as recommended and administered to a future offering of the Renewable Energy course for further evaluation.

Results of a pre- and post-quiz given to an independent verifying student team showed that performing this lab aided in understanding of fuel cells and fuel cell efficiency. The students scored better, 40% higher on average, on the fuel cell exam questions after participating in the student-developed lab experience. The developers of the lab experience scored better on the post-lab exam than the verifying students by an average of 20% and much better than the verifiers' pre-quiz by 60%. When looking at individual student results for the lab developers, the degree of involvement in data analysis appeared to be an important factor in post-quiz results. For the lab verifiers, the degree of external distraction while working through the lab appeared to play an important part in technical material retention based on post-quiz score and student comments.

Qualitatively, developer students felt that the lab experience contributed to meeting course objectives for both the Renewable Energy course and the Experimental Mechanics course. The verifying students agreed that the lab experience contributed to meeting course objectives for the Renewable Energy course. Both groups were in agreement that their experiences contributed to fulfilling several of the National Research Council of the National Academies' desired outcomes of laboratory experiences.[2]

Acknowledgements

The authors would like to thank both Dr. Mike Maixner and Dr. Dan Jensen, professors in the Department of Engineering Mechanics at USAFA, for their guidance and advice concerning this research, as well as Mr. Lonn Rodine, for his support in experimental equipment purchasing and setup. Special thanks to the three-student team of verifiers, C1Cs Bill Song, John Krzyminski, and Jacob Daniels, who volunteered their time and efforts to aid in this study.

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Appendix A. Course Objectives for Renewable Energy and Experimental Mechanics Courses

Course Objectives:

1. Instill in cadets the need for alternative sources of energy and for more efficient means of implementing existing conventional power production schemes.
2. Provide cadets with the ability to analyze, compare, and contrast enhancements to more conventional energy systems to improve their efficiencies.
3. Provide cadets with the ability to analyze, compare those systems which rely on renewable resources as a source of energy.

Course Objectives: Cadets should be able to:

1. Describe which measurement approaches are typically available to AF mechanical engineers.
2. Identify issues associated with standard mechanical measurement approaches.
3. Choose a measurement approach when faced with an open-ended test problem.
4. Develop a complete test plan to implement a chosen measurement approach by choosing appropriate components and parameters for a given measurement approach.
5. Perform standard static and dynamic mechanical measurements to execute a test plan.
6. Analyze collected test data as part of executing a test plan.
7. Clearly report results of an executed test plan.

Appendix B. Equipment, vendor, part number, and price

Name	Picture	Vendor	Part #	Price
Dissectible Fuel Cell *		PASCO Scientific	SE-8834	$149.00
Electrolyzer 10 *		PASCO Scientific	SE-8836	$209.00

*For more details on all PASCO equipment please see www.pasco.com.

Figure B-1: Equipment, vendors, and part numbers used in this lab

Appendix C. Fuel Cell Mini-Lab, USAFA Department of Engineering Mechanics

Fuel Cell Mini-Lab

Purpose: The purpose of this mini-lab is to evaluate the performance of a hydrogen proton exchange membrane (PEM) fuel cell operating in pure oxygen and compare it to the performance of the same fuel cell operating in ambient air conditions.

SAFETY:

- You will be producing hydrogen as a fuel to be used in this experiment. Hydrogen is explosive therefore do not accumulate more than required to run this experiment. Once the hydrogen reservoir is full, disconnect the electrolyzer to stop additional hydrogen production. **Wear safety glasses** to protect your eyes in the event an explosion does occur.
- Do not operate the electrolyzer or fuel cell in the presence of an ignition source.
- Do not open the fuel cell. The membrane inside the fuel cell can be easily contaminated or damaged.
- Do not connect an electrical power source to the fuel cell as this will destroy the sensitive membrane.
- Use distilled water only as the catalyst will likely be poisoned by contaminates found in tap water.

Objectives:

1. Understand the principles behind fuel cell operation.
2. Evaluate the hydrogen, Faradaic, and overall efficiencies of a fuel cell.
3. Understand the parameters effecting fuel cell operating capability and efficiencies.
4. Develop the ability to analyze and interpret experimental data.

Equipment: The Electrolyser 10 unit, shown in Figure 1, uses distilled water and electrical power to chemically separate the hydrogen and oxygen molecules, dispensing the separated components into their respective gas chambers/storage reservoirs. These reservoirs are shown in Figure 2, connected via surgical tubing. The volume markings on the gas chambers can be used to measure gas volumes in the reservoirs. Gas volume readings in conjunction with time readings will be used to calculate gas volumetric flow rates. The electrolyzer is connected to a power supply in order to produce the necessary reactants. Additional surgical tubing directs the oxygen and hydrogen components into the Proton Exchange Membrane Fuel Cell (PEMFC), shown in Figure 3. The voltage or potential across the fuel cell is measured across the red and black terminals coming out of the top of the fuel cell using a PASCO voltmeter. The current from these same terminals is passed through an electrical circuit containing various resistors to provide an electrical load on the fuel cell. The PASCO ammeter is used to measure the resulting current produced. Both the ammeter and the voltmeter are connected to the ScienceWorkshop 750 in order to interface with a computer for data collection and real-time data display.

2

Figure 1: Electrolyzer

Figure 2: Gas Chamber

Figure 3: PEMFC

The figures below show the rest of the system components as they are to be setup for testing.

Fig. 4 ScienceWorkshop 750 Setup

Fig. 5 Electrolyzer with Lab Voltage Source Setup

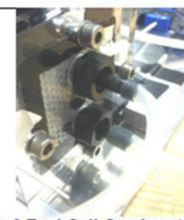

Fig 6 Fuel Cell Gas Input (top) & Output (bottom) Ports

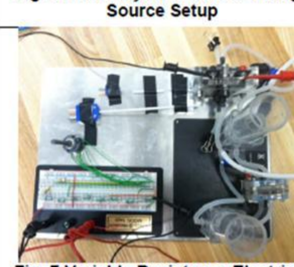

Fig. 7 Variable Resistance Electrical Load Circuit and Rotary Select Switch

Be sure to read through the entire lab procedure before performing any lab procedures. Understand, in advance of starting, what measurements will be taken and recorded during the lab. Understand how you will use these measurements in post-lab data analysis.

3

** **Each member of your three person team needs to develop three technical questions concerning fuel cell operation and/or fuel cell efficiency. Submit these questions to your lab instructor prior to performing the lab.**

Lab Experimental Procedures:

1. Ensure all wires are disconnected from the fuel cell and electrolyzer.

2. Open the hose clamps between the gas chambers and input sides of the fuel cell, as well as the clamps on the output hoses of the fuel cell.

3. Fill the gas chambers with distilled water until just below the white dashes on the upper portion of the chamber shown in Figure 2. Ensure no gas bubbles are trapped in the lower portion of the gas chamber. **Close the clamps on the fuel cell output tubes once water starts to drain through them.**

4. Turn on the power supply in voltage source mode and voltage is set to 4 Volts. Note: higher voltage could damage the electrolyzer. Connect the power supply to the electrolyzer by clipping it to the red (positive) and black (negative) terminals on the side of the unit.

Note: Immediately upon supplying electrical power to the electrolyzer in the presence of water, the device will begin splitting the water chemically into both gaseous hydrogen and oxygen. Hydrogen will be produced twice as quickly as oxygen. Why is this so?

5. Produce approximately 20 cm^3 of hydrogen and oxygen. Remember that you will need to purge some hydrogen during this process as it's reservoir will fill at twice the rate of the oxygen reservoir.

6. Now purge the tubing between each of the gas chambers and the fuel cell. To purge, open the clamps on the fuel cell output tubes one at a time, but only open enough to let the water drip out. Once the gas starts to leave the tube, immediately close the clamp. The purge occurs quickly so be on guard when you open the output valves. The electrolyzer can continue producing gas while the purge is completed.

7. Once the water has been removed from both sides of the fuel cell input tubes, allow both gas chambers to fill again until approximately 30 cm^3 of hydrogen and oxygen have accumulated. Again, additional hydrogen gas can be purged using the same clamps as in step 5 in order to fill both chambers with equal amounts of gas components. Disconnect the power to the electrolyzer when gas chambers are filled to the desired amounts.

8. Ensure the resistor select rotary switch is turned all the way to the left (the lowest resistance value of 0.4 ohms). This switch changes the resistive load seen by the fuel

cell in order to investigate the fuel cell performance under various electrical loads. How do you expect performance to be effected by electrical load?

9. Connect the circuit to the fuel cell by attaching the red and black clamps to the red and black terminals of the fuel cell. **At this point the fuel cell is operating and electrical current is being produced.**

10. Begin a test run by pressing the start command in the Data Studio program. You should see a real time display of current and voltage as well as a calculated real time power output (P=I*V). If the power graph begins to drop, inert gasses are likely building up in the fuel cell and must be purged by briefly opening the clamp on the oxygen output tube of the fuel cell. Remember that the purge occurs quickly. **If too much oxygen is released during purge and water re-enters the fuel cell input tubing, disconnect one of the fuel cell electrical terminals and return to step 5 to produce more oxygen so that the input tube can be purged properly.**

11. Iterate on Step 10 until the calculated fuel cell power graph remains level and then end the test run. A test run is ended by opening the electrical circuit by unclipping either lead from a fuel cell terminal. At any point before starting an experimental run, the electrolyzer can be run in order to replenish the oxygen and hydrogen gas chambers.

12. Start another run in the data studio program and take an initial volume measurement in the gas chamber. To get accurate volume measurements your eyes should be level with the tick marks on the cylinder when taking a reading. To ensure level, you can visually align the marks on the front of the reservoir with the corresponding marks on the back of the cylinder as it is transparent and marked on front and back. **Also be sure to account for the meniscus when taking readings. How is this done?**

13. Measure and record the hydrogen gas reservoir content volume every minute after the initial reading for a total of five minutes. Record your data on the included data table. Stop the data collection and disconnect the fuel cell circuit after the last volume measurement.

14. The contents of the gas chambers may have to be replenished between runs if the volume falls below 15 cm^3. Change the resistive load by turning the resistor rotary switch two clicks to the right. Two clicks from the 0.4 ohm position skips the 0.8 ohm and sets the resistance to 1.3 ohms for the next data run.

15. Re-accomplish Steps 11, 12, and 13 for this resistance value of 1.3 ohms and then again for two more clicks right which skips the 12.1 ohm and sets the last of the three tests to 22 ohms.

16. Unhook the circuit from the fuel cell and tighten the hose clamp around the oxygen input tube to the fuel cell.

17. Remove the oxygen tube from the input side of the fuel cell and remove both black input ports with a small adjustable wrench. This will allow the fuel cell to be operated in air (approximately 20.95% oxygen) instead of with 100% pure oxygen produced by the electrolyzer.

18. Refill the hydrogen gas chamber and connect the circuit to the fuel cell. Re-accomplish steps 11 thru 15 in open air mode.

19. Remove circuit, reattach the oxygen hose, and tighten all hose clamps.

20. Record atmospheric pressure and ambient temperature for future calculations.

Data table for Electrolyzer run

H_2 produced	cm^3	Power Source Elec Potential(Volts)	Elec Current (Amps)
after 1 min			
after 2 min			
after 3 min			

Data table for pure O_2 Fuel Cell data runs

H_2 used	0.4 ohm	1.3 ohms	22 ohms
Initial H_2 Volume			
H_2 vol after 1 min			
H_2 vol after 2 min			
H_2 vol after 3 min			
H_2 vol after 4 min			
H_2 vol after 5 min			

Data table for air (~21% O_2 and 78% N_2) Fuel Cell data runs

H_2 used	0.4 ohm	1.3 ohms	22 ohms
Initial H_2 Volume			
H_2 vol after 1 min			
H_2 vol after 2 min			
H_2 vol after 3 min			
H_2 vol after 4 min			
H_2 vol after 5 min			

Atmospheric Pressure ________________ Ambient Temperature ______________

Theory/Analysis: A PEM Fuel Cell relies on the oxygen and hydrogen components to produce an electrical current. Figure 8 provides a schematic of the inner-workings of the fuel cell.

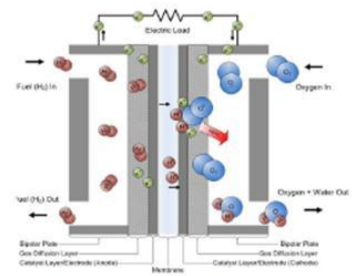

Figure 8: Fuel Cell Schematic

The half reactions at the anode and cathode of this hydrogen fuel cell are respectively:

$$H_2 \leftrightarrow 2H^+ + 2e^- \quad \text{(Eqn 1)}$$

$$O_2 + 4e^- + 4H^+ \leftrightarrow 2H_2O \quad \text{(Eqn 2)}$$

The net reaction is then given by:

$$H_2 + \tfrac{1}{2}O_2 \leftrightarrow H_2O \quad \text{(Eqn 3)}$$

Since they are not conventional heat engines, fuel cells are not limited by the same Carnot efficiency that heat engines operating between a hot and cold thermodynamic reservoir are bounded by as learned about in thermodynamics. Fuel cell efficiencies can be calculated in several different ways. The three efficiencies dealt with here are the hydrogen, overall, and Faradaic efficiencies.

1. The hydrogen efficiency is a measure of the energy produced for a given volume of hydrogen compared to the theoretical amount of energy in that same volume of hydrogen. This can be calculated with the following:

$$E_{FC} = \overline{P_{FC}} \cdot t_{FC} \quad \text{(Eqn 4)}$$

$$E_{H2} = V_{H2,c} \cdot LHV_{H2} \quad \text{(Eqn 5)}$$

$$\eta_{H2} = E_{FC}/E_{H2} \quad \text{(Eqn 6)}$$

**See Table 1 for variable/symbol definitions for efficiency calculations.

2. The overall efficiency is a measure of the energy produced by the fuel cell compared to the energy required to produce the same volume of hydrogen consumed. The energy to produce a volume of hydrogen is 10.8 x 10^6 $^J/_{m^3}$. The efficiency can then be calculated with the following:

$$r_v = V_{H2,c}/t_{E,total} \qquad \text{(Eqn 7)}$$

$$t_E = V_{H2,c}/r_v \qquad \text{(Eqn 8)}$$

$$E_E = \overline{P_E} \cdot t_E \text{ where } \overline{P_E} = I_E \cdot Volt_E \qquad \text{(Eqn 9, 10)}$$

$$\eta_{overall} = E_{FC}/E_E \qquad \text{(Eqn 11)}$$

3. Finally, the Faradaic efficiency is a comparison of the theoretical volume of hydrogen consumed given the current, temperature, time, and pressure. This theoretical volume can then be compared to the actual volume consumed. The analysis is performed using the following equations:

$$V_{H2,theo} = \frac{RITt}{Fpz} \qquad \text{(Eqn 12)}$$

$$\eta_{Faraday} = V_{H2,theo}/V_{H2,c} \qquad \text{(Eqn 13)}$$

Symbol	Description
E	Energy (J)
P	Power (W)
V	Volume (m^3)
η	Efficiency
r_v	Volumetric reaction rate (m^3/s)
t	Time (s)
R	Universal gas constant (8.314 J/mol K)
LHV	Lower heating value
I	Current (A)
Volt	Voltage (V)
T	Temperature (K)
F	Faraday's constant (96,485 C/mol)
p	Ambient pressure (Pa)
z	# of electrons to release one molecule (See eqn 1)

Subscript	Description
FC	fuel cell
H2	hydrogen
E	electrolyzer
c	consumed
g	generated
v	volumetric
theo	theoretical

Table 1: Variables and Subscript Definitions

Results:

1. Consolidate the data in order to create:
   a. Voltage vs. Amperage charts
   b. Power comparison charts between pure oxygen and air sources

2. Calculate and plot the three efficiencies for the resistive load tests in pure oxygen and in air.

3. Using first principles, derive eqn 12 in this lab. Hint: start with Faraday's Law for electrolysis. Assume that H_2 is an ideal gas.

4. Using a schematic of a fuel cell, perform a control volume analysis. Using the 1st and 2nd Laws of Thermodynamics, develop an expression for the ideal efficiency of this PEM fuel cell.

5. Use the standard TFSE mini-lab format as specified on the TFSE web site.

6. Comment on your results; compare them to results from the lecture, your course text, etc.

7. Include answers to the following in your report:
   a. What are some sources of error for this experiment?
   b. What could be done with any waste heat?
   c. Which efficiency is most important? To whom is it important?
   d. What are other potential factors or variables affecting fuel cell efficiency?.
   e. Submit three technical questions concerning additional research you could perform on this fuel cell.

Appendix D. Assessment Instrument

Name:___________________________

1. What is a PEM fuel cell?

2. What are the inputs and outputs of a PEM H_2 fuel cell?

3. How do you calculate fuel cell efficiency?

4. List 2 specific variables that effect H_2 fuel cell efficiency.

5. Where do the significant PEM fuel cell losses come from? (use short descriptions please)

6. How does a change in the amount of fuel cell current produced change the Faraday efficiency?

   Why?

Figure D-1: Fuel Cell Pre- and Post-Quiz

Appendix E. Student Comments on the Experience of Developing an Undergraduate Lab

Developer 1

Through the course of testing many variables effecting fuel cell efficiency, our team also developed a fuel cell mini-lab for the ME 468 Sustainable Energy course started in the spring of 2011. Creating the lab was the most exciting element of working with the fuel cells because the team felt like the work we did during the project would create a lasting impression on the students that would come after us. Additionally, having the development of the mini-lab as part of our final turn-in gave us motivation to put in extra work hours to produce a meaningful product that would require little alteration by any professors that decide to use our lab for their course. Finally, developing the fuel cell lab helped us document our work better than we would have if we did not have this additional assignment. Our team took more pictures, created a platform for all of the components to sit neatly, and formed a step-by-step process for our work that could be easily repeated. I feel each of these tasks were accomplished more fully because we were tasked with creating the lab.

The experience of developing a lab also aided me in better understanding the systems and engineering principles involved in the operation of a fuel cell. The fuel cell lab we created was for students enrolled in an introductory course to learn about many sustainable energy systems. This is not a course for advanced study in hydrogen fuel cells, and therefore the lab emphasizes many of the basic electrochemistry principles and application of thermodynamic analyses. Creating this lab forced us to fully understand and even memorize all of the basics regarding fuel cells and then allowed us to delve into a few more in-depth topics regarding fuel cells.

I also had the opportunity to administer the lab our team created to three other students. One of the primary reasons for having these students work through the lab was to work out the “bugs” and overly confusing aspects that could be altered or removed before actual implementation in the sustainable energy course. This proved to be incredibly useful because of the few flaws that were brought to our attention and the confirmation that the lab was not too easy or unreasonably difficult for engineering students. Additionally, my comprehension of the material was tested because I was given a chance to teach the three students the basic fuel cell principles before I administered them the lab. Teaching in this way was rewarding for me because I discovered how much I had learned over the course of the semester and because of the opportunity to teach students about some amazing technology that will most likely become increasingly important in today’s emerging energy demands.

Overall, I think the development of a lab by senior undergraduate students is an outstanding idea and should be continued by the Air Force Academy as a way of educating both its upper and lower level students. I thoroughly enjoyed working to create a lab, which proved to be very challenging at times but also very rewarding.

Developer 2

After spending time developing the lab, I now see the merit in creating labs for future groups to use. We were able to make the lab interesting and practical for future groups to use by tapping in our past experience. Using knowledge developed by doing numerous labs in other courses, we selected interesting variables and provided clear procedures for cadets to work off of. Since it was for others to use, we had to ensure we were thorough with everything. The best part about creating the lab was knowing cadets would be using it to further their knowledge in future courses.

The lab also helped us further our own understanding. Since we were developing the lab for others to use we knew we could not cut any corners. We had to have complete understanding of the fuel cell's operations along with the theoretical foundations behind the operations of the fuel cell. There were several times our group had to seek further knowledge in order to verify our data was valid. If there was no future use for others to use the lab we could have simply written our calculations off as being correct. Instead, we expanded on what we knew to ensure the credibility of the lab in the future.

Developer 3

It’s a good idea to have students who’ve taken a course develop a lab for that course. Past students of a course understand what future students will know prior to the lab, their time constraints, and their desire to get hands-on.

Past students also have a desire to get hands-on since they’ve taken the course and have a basic knowledge of the material but haven’t seen it demonstrated yet.

As we developed this lab, we realized the difficulty in preparing a lab for an undergraduate course. The experiment must be simple and produce relatively obvious results and trends. (Error analysis is important to verify that a trend actually happened.)

When I took ME 468, I remember one or two days of lecture on fuel cells. If I had conducted a lab like this one, I’d have a much deeper and longer-lasting understanding of fuel cells.