Final Report

Project Title: Development of a Renewable Hydrogen Production and Fuel Cell Education Program

Project Period: August 30, 2008 to September 1, 2011
Date of Report: November 30, 2011

Recipient: University of North Dakota
Award Number: DE-FG36-08GO18110

Working Partners: National Renewable Energy Laboratory and Distributed Energy Systems

Cost-Sharing Partners: None

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Project Objective:

The objective of this project is to develop a comprehensive program that will:

- Provide exposure to the basics of hydrogen-based technologies to a large number of students. This exposure will provide a level of training that will allow students to converse and work with other scientists and engineers in this field. It will also serve to spark a level of interest in a subset of students who will then continue with more advanced coursework and/or research.

- Provide a “mid-level” training to a moderate level of students. More detailed and directed education will provide students with the ability to work to support industry and government development of hydrogen technologies. This level of training would be sufficient to work in the industry, but not be a leader in research and development.
- Provide detailed training to a smaller subset of students with a strong interest and propensity to make significant contributions to the technology development. These individuals will have extensive hands-on experience through internships that will allow them to play a major role in industry, government, and academia.

For the purposes of this grant, the terms hydrogen-based technologies, hydrogen energy and hydrogen education are used broadly to include the production, transport, storage, and utilization of hydrogen. This includes both electrolysis and fuel cell applications.

Background:

The University of North Dakota (UND) has developed a strong research program in sustainable and renewable energy. SUNRISE (SUtainable eNergy Research, Infrastructure, and Supporting Education), UND’s sustainable energy initiative includes a focus on hydrogen. UND developed a PhD program in Energy Engineering in 1992 to take advantage of the strong interest in energy within the School of Engineering and Mines (SEM) and UND’s Energy & Environmental Research Center (EERC). Through this program, UND has been able to attract high quality students whose primary interests are in sustainable and renewable energy. Departments within SEM have developed energy related courses that are taught at both the undergraduate and graduate level, and SEM has developed a hydrogen laboratory focused on PEM electrolysis and fuel cell research, education, and applications.

UND proposes to take advantage of existing infrastructure and programs to provide a comprehensive renewable hydrogen production and fuel cell education program. This program is comprehensive from the standpoint of the level and number of students that will be involved in the program. It is designed to provide multi-discipline formal training to both undergraduate and graduate level engineers and scientists. This will be accomplished by developing case studies that will be implemented into classes through all four years of the undergraduate curriculum. These case studies will be broadly disseminated though the National Center for Case Studies in Science Teaching web site making them available to any school in the United States. Two new classes will be generated that will be offered as technical electives at the undergraduate and graduate level. In addition to our on-campus students, the undergraduate class will also be offered though our Distance Education Degree Program (DEDP) to provide access to hundreds of off-campus students across the country and other nations. UND’s DEDP program is the nation’s only ABET EAC accredited undergraduate engineering program.

Several new hydrogen-related student experiments will be added to our undergraduate laboratory sequence to provide hands-on experience for our students. Additional hands-on experience will be available to selected students through our on-going research at UND, and through summer intern programs to be established with the National Renewable Energy Laboratory (NREL) and Distributed Energy Systems (designer and manufacturer of PEM hydrogen production systems). UND will develop a hydrogen seminar, brining in experts in the field from the National Renewable Energy Laboratory (NREL) and Distributed Energy Systems to present to UND students. Internships and research opportunities are also available for students at UNDEERC.

This program is designed to provide an introduction of hydrogen energy to a large number of students, both on and off the UND campus through the case studies and student laboratories. It will provide more detailed training on the topic to a smaller, but still significant group of students through two new courses that will be added to our curriculum and offered through our distance program. In-depth training will be provided to a select group of undergraduate and graduate students through in-house research and internships with the EERC, NREL, and Distributed Energy Systems. We feel this approach will provide high quality students with the exposure of hydrogen energy required to support research, development, and demonstration activities in the government, industry and academia sectors.

Results

Task 1: Development of Case Studies:

A variety of case studies were developed for the undergraduate curriculum, designed to fit into specific courses with the intent of reinforcing fundamental concepts using hydrogen production and/or utilization examples. While these were found to provide a good introduction to hydrogen, there was some difficulty incorporating these into core courses. While most faculty like new problems for application in their courses, they have limited time within the semester schedule to add significant content. They found it difficult to implement a case study that required a whole class period. A better approach was found to be utilizing the problem based learning concept implemented in the Michigan Tech program, where shorter directed-problems were developed.

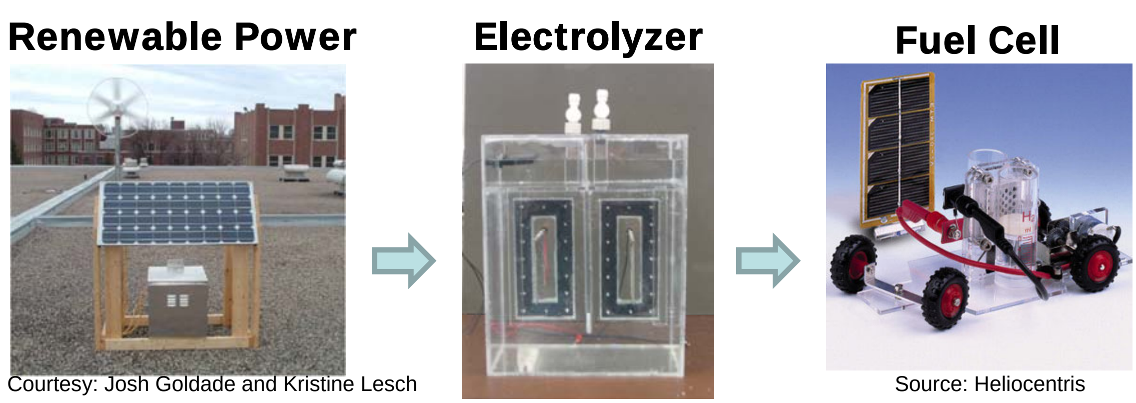
Case studies were found to be successful in survey courses where faculty are looking to expose students to examples of how technology can meet the needs of today’s society. These courses are good places to introduce “non-technical” aspects of engineering to students, such as political and social constraints in making engineering decisions.

Task 2: New Course Development

A new course entitled Hydrogen Production and Storage was developed and taught both to our on-campus and distance students. Topic areas include an overview on “why hydrogen” followed by sections on hydrogen production from fossil fuel and biomass, hydrogen from water, hydrogen distribution and storage and safety. The course primarily used open source materials, and provided students with an extensive library of material.

The course content in EE 522-Renewable Energy Systems was modified to increase the content related to fuel cells and electrolysis. Wind energy/turbines was discussed for the first half of the semester. The second half of the course focused on fuel cells, electrolysis, and solar cells. The basics of different types of fuel cells was discussed followed by a focus on PEM fuel cells including details of the electrical and chemical characteristics and operation. Information presented in the course included the relevant fundamentals of electrochemical thermodynamic laws (Gibbs free energy, enthalpy, and entropy); losses (activation, ohmic and mass transport) and their causes in PEM fuel cells; and the relationships between Nernst, Tafel, and Butler-Volmer equations. Students experimentally verified the V-I characteristic curve of the fuel cell and the electrolyzer. Specifically, the V-I characteristics of two fuel cells both in series and in parallel experimentally were measured and verified. This course is a technical elective taken by both undergraduate and graduate students. Students in the course received an extensive exposure to the theoretical and experimental details of fuel cells and its hydrogen fuel.

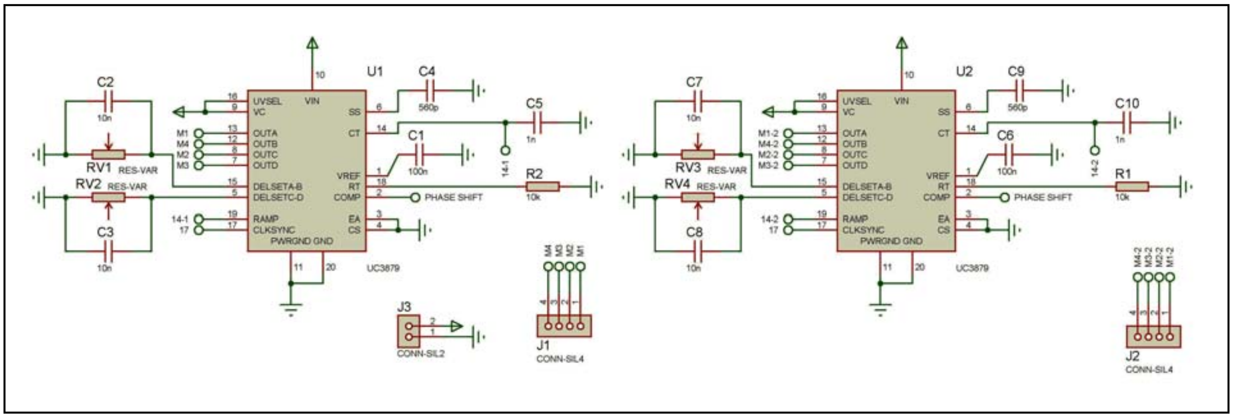
As a result of this program, the school has encouraged the development of hydrogen based projects for the senior capstone design course. The Renewable Hydrogen Electrolyzer project focused on taking energy from a renewable source, and storing that energy in the form of hydrogen to later be used in a fuel cell. To do this an alkaline electrolyzer was designed and built to produce hydrogen through the process of electrolysis. The overall project goal was to integrate the electrolyzer with an existing wind and photovoltaic power supply, and deliver produced hydrogen to a miniature fuel cell car. The figure below depicts the overall system, where the electrolyzer was the system being developed for this project.



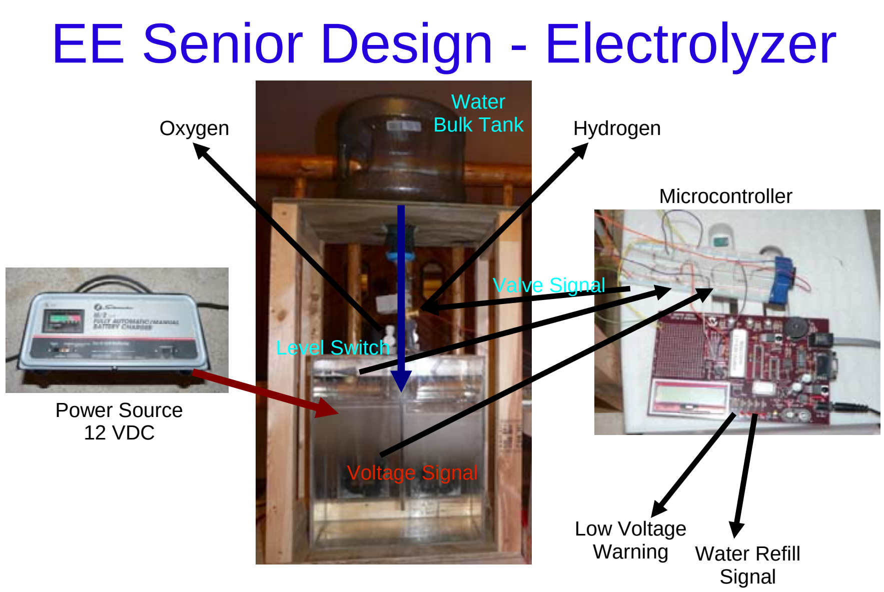
Courtesy: Josh Goldade and Kristine Lesch

Source: Heliocentris

The goal of the Combining Alternative energy Power Sources (CAPS) project was to combine and control the output of unregulated direct current (DC) sources such as fuel cells into a single regulated output to match the load. The purpose of combining sources is to increase the usefulness of alternative energy fuel cell generators which commonly produce unregulated DC output. The solution proposed utilizes a DC to AC (alternating current) converter, a multi-winding transformer, and an AC to DC inverter. In a three stage system the incoming DC is converted via a full H-bridge to AC, where it is then passed over a two input one output transformer. The power combines in the magnetic spectrum on the transformer core, and the output of the transformer is then converted back into a single DC output. A copy of the circuit design is presented below.



A senior design project in Electrical Engineering involved developing a lab scale electrolyzer system that can be used as a teaching tool, or in applications requiring small hydrogen flows. His system is depicted below.

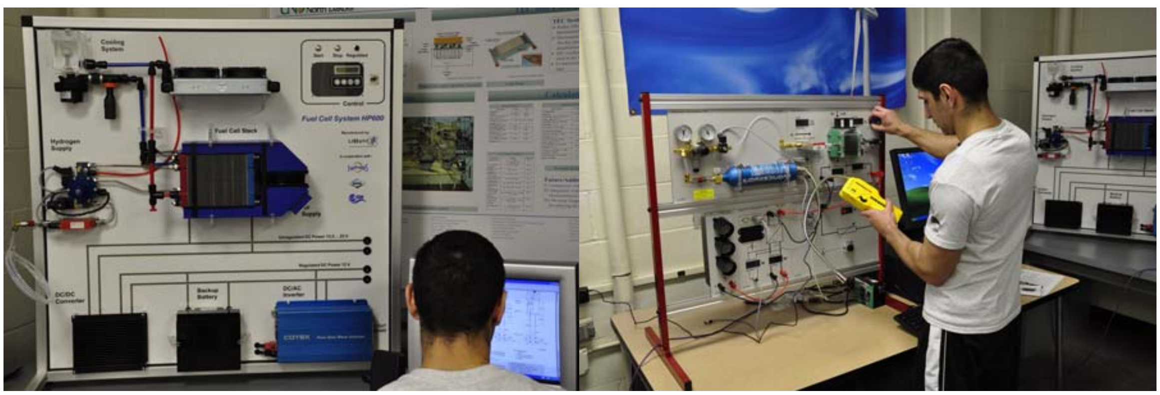


A senior design group from chemical engineering chose to design a process that utilizes a waste gas stream from a biomass to fuel processing plant to produce hydrogen. The waste stream contained small amounts of hydrogen, methane, ethane, propane, with a larger amount of CO and the balance of nitrogen and CO2. Using a steam reforming and high and low shift reactors followed by a Benfield separation plant, the group demonstrated that the process is technically and economically feasible. The group showed that this utilizing this waste stream as a source of hydrogen was technically feasible, and economically feasible (depending upon the assumptions made for the price of hydrogen).

Task 3: Laboratory Experiments in Hydrogen

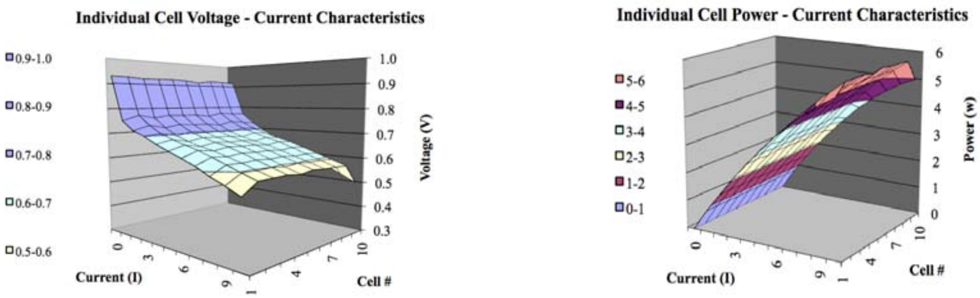
During the first semester of the program, students performed experiments using an existing hydro-geniuses laboratory experimental setup. This equipment contains a solar cell, a single cell PEM electrolyzer, two single cell PEM fuel cells, and a small resistive load. Students generated the I-V characteristic curves of the fuel cell and the electrolyzer and analyzed system efficiencies. The two fuel cells were operated both in series and in parallel.

Two new experimental setups were purchased from Heliocentrics. The HP 600 includes a 600 watt water-cooled PEM fuel cell stack, a DC/DC and DC/AC converter, metal hydride storage kit, electric load, and an integrated control system. The off-grid instructor includes a 40 watt fuel cell with integrated microprocessor, electronic load, metal hydride storage, and the constructor kit. A Masters student helped develop a set of laboratories that were implemented into the undergraduate curriculum during the 2009-2010 academic year. Photos of the equipment are given below.



An advanced fuel cell laboratory for junior- and senior- level, as well as graduate electrical and chemical engineering students has been developed using the 50W and 600W fuel cells. Operating under the assumption that the students have had exposure to fuel cell equipment through the previous lower level labs, this set of experiments works towards two objectives: developing the voltage-current curve and measuring the effect of internal resistance. Emphasis is placed on these characteristics of the fuel cell stack as they are indicative of system performance. Through this process the students gain additional knowledge of basic PEM fuel cell operation and behavior.

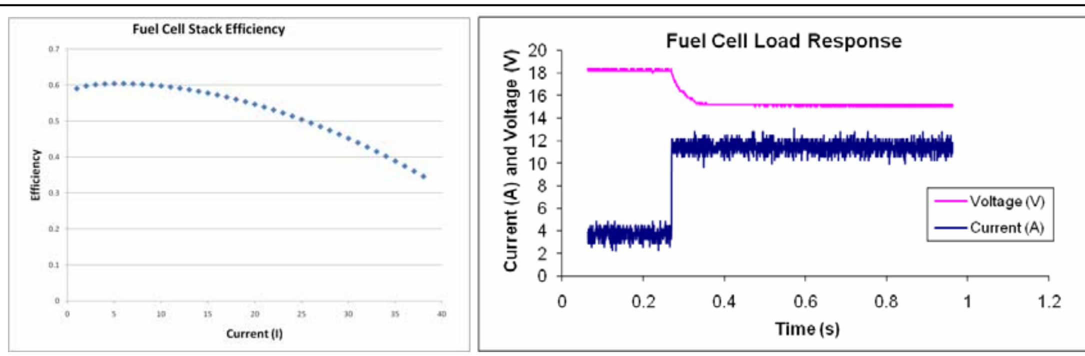
In addition to performing the basic experiments to generate IV and power curves, an experiment was added to record individual cell responses to increases in load current. Ambient temperature (approximately 26 degrees Celsius versus stack temperature of approximately 40 degrees) impacts the performance of the outer cells, and therefore, the overall performance of the stack. However, it is assumed that the effect is minimal. Examining the performance of individual cells can help explain the overall behavior of the stack and is a good introduction for student investigation into the more complex reactions occurring in each cell (see below).



Characteristics IV and power curves developed during the lab

The consideration of voltage drop is also important when evaluating the performance of the fuel cell system. Comparison of the open circuit voltage potential of the stack and the system shows that there is resistance from the system components above and beyond resistance from the fuel cell stack itself. Examination of the trend of the voltage drop of the system versus the voltage drop of the fuel cell stack alone shows that there are other effects to take into account as the load increases. While this experiment does not examine these additional effects, it, again, serves as a good starting point for designing future investigations. Were this a comprehensive analysis of the fuel cell system, the broad end goal may be to determine whether it is, as O'Hayre et al. says, a "good" or "bad" fuel cell stack1. While different fuel cell applications have different specifications, the evaluation of system performance is generally a comparison of its ideal operation to its actual operation. Ideal operation is the most power produced for the fuel provided – or the greatest efficiency. This topic also begs further investigation and serves as a good exploratory discussion to incorporate into laboratory planning.

A second set of experiments was developed to demonstrate the effectiveness of the fuel cell as a power source under varying load conditions. Students begin by generating the typical IV curve and power curve to develop and understanding of efficiency as a function of load. Dynamic load tests show the students the lag time between a change in load and the response of the fuel cell. For electrical engineering labs, this can be



Results from experiments to demonstrate the effects of load change further utilized to develop equivalent circuits and to study the time constants related to a dynamic system.

The obvious value for students of the experiments is that they will gain a better understanding of the way a fuel cell operates – specifically the relationship between voltage, current and power output. However, it is the manner in which the students gain this knowledge that should be the focus for educators. Students have the opportunity to perform the experiments described with minimal guidance. When problems arise, critical thinking is required to troubleshoot and find solutions. After the initial set of data is collected, following manufacturer load current increment recommendations, students propose additional experiments. This step requires imagination, and questions are posed and answered, such as what type of variations could be made on the original experiment in order to gather telling data.

ABET requires institutions of higher education to demonstrate that their students achieve a number of program outcomes. Several of these outcomes and objectives address the need for engineers who can apply knowledge from the classroom to real-world problems. The use of hands-on experiments designed to encourage student exploration is one of the ways UND prepares students to be successful engineers. Hands-on experiential learning allows students to supplement their classroom background with actual results and to improve critical thinking skills by developing and solving research problems of their own design. Details of these student laboratories were presented at the 2010 summer meeting of the American Society of Engineering Education.

New experimental capabilities were also generated to demonstrate how fuel cell membranes can be made and tested.

In addition, students in NATURE, UND's summer program for Native American students were introduced to fuel cell technology through a demonstration on the Fuel Cell test equipment.

Task 4: MS/PhD Teaching Experience

To help improve the depth of knowledge and skills of our MS and PhD candidates, a variety of teaching experience opportunities were provided. PhD and MS students developed the laboratory experiments for implementation in the undergraduate labs. This provided the opportunity to test the equipment and determine which of its capabilities could be best utilized to demonstrate the fundamentals of hydrogen based energy. These students also provided input for case studies and participated in the summer outreach programs for undergraduate students. Two PhD and two MS students received training as a direct result of this program.

Task 5: Summer Internship

One of the goals of this program was to provide internship opportunities for students that received training through a combination of their laboratory experience and the hydrogen related classes. This training was expected to add value to the student, making it easier for them to obtain internships. Students were placed in summer internships at the National Renewable Energy Lab, Oak Ridge National Lab, and the EERC National Center for Hydrogen Technology.

Task 6: Hydrogen Seminary Series

A variety of seminars were presented during this program. Topics included:

- an overview of PEM fuel cell technology
- the utilization of nanocatalysts on silica support as new material for membrane electrode assemblies
- utilization of electrolysis as a technique for grid stabilization
- design of an integrated wind-hydrogen system for distributed energy applications
- characterization of PEM electrolyzer and PEM fuel cell stacks using electrochemical impedance spectroscopy
- incorporating advanced catalysts into the membrane design to improve performance and reduce cost

UND students were provided free attendance to the annual Hydrogen Summit sponsored by the Energy & Environmental Research Center. Students were allowed to choose relevant sessions and/or talks to attend in this two day conference.

PhD Jivan Thakare delivered several training seminars on how to make and test membrane electrode assemblies.

Task 7: Develop Modules for PowerOn!

The student organization, PowerOn develops experiments that are incorporated into a mobile laboratory. This mobile laboratory is taken to middle schools as a part of a program to stimulate interest in STEM areas. As a part of this DOE program several undergraduate chemical engineering students developed suitable laboratories on hydrogen production and utilization. Implementation of the PowerOn program was performed under a separate grant, and is not a part of this program.

To facilitate this effort, a special topics class was established for the spring semester to provide a structured forum for the undergraduate students. Students earned one credit of coursework as they developed new experiments that are currently being used as a part of an outreach program funded through a separate grant. PowerOn made its public début April 2010 at Super Science Saturday in Grand Forks, ND. Since then, PowerOn has sponsored over 15 events and based upon the take home kits given out, over 1000 kids have participated in the event.

Accomplishments

Over 200 students were directly impacted by program.

- Over 150 chemical and electrical engineering undergraduate students were exposed to various aspects of hydrogen through in-class case studies and laboratory experiments.
- Twenty-seven students were involved in senior design projects related to hydrogen.
- Three hydrogen related courses were developed and taught, with enrollment of 73 students.
- Twenty-one undergraduate students were involved with PowerOn to develop modules to demonstrate hydrogen and other renewable energy technologies. Demonstrations were made to over 1000 youth.
- Two PhD and two MS students were trained through the development of instructional material for this program. Nine interns were placed working in hydrogen related fields.
- Two undergraduates were placed at the EERC National Hydrogen Center and one at NREL. Two PhD graduates were placed with Nissan in their fuel cell division in Detroit.
- Results of this work has been presented at the 2010 annual ASEE meeting in addition to the DOE annual program merit review meetings.

Patents: None

Publications / Presentations:

Development of a Renewable Hydrogen Production and Fuel Cell Education Program presented at the 2009, 2010 and 2011 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meetings

Blekhman, D., J. Keith, A. Sleiti, E. Cashman, P. Lehman, R. Engel, M. Mann, and H. Salehfar, 2010, "National Hydrogen and Fuel Cell Education Program Part I: Curriculum," ASEE Annual Conference & Exposition, Louisville, KY.

Blekhman, D., J. Keith, A. Sleiti, E. Cashman, P. Lehman, R. Engel, M. Mann, and H. Salehfar, 2010, "National Hydrogen and Fuel Cell Education Program Part II: Laboratory Practicum," ASEE Annual Conference & Exposition, Louisville, KY.

Goldade, J., T. Haagenson, H. Salehfar, and M. Mann, 2010, “Design of A Laboratory Experiment to Measure Fuel Cell Stack Efficiency and Load Response," ASEE Annual Conference & Exposition, Louisville, KY.

Task Schedule

Task Number	Project Milestones	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Develop and implement three new case studies	05/15/09	5/31/10	5/31/10	100%	Completed
1	Post three case studies on NSF sponsored web site*	08/15/09	3/15/11	8/30/11	100%	Completed*
1	Develop and implement five new case studies	05/15/10	12/31/10	8/30/11	100%	Completed
1	Post new case studies on NSF sponsored web site*	06/30/11		8/30/11	100%	Completed*
2	Develop and teach new undergraduate course	05/15/09		12/31/09	100%	Completed
2	Develop and teach new graduate level course	05/15/10		12/31/09	100%	Completed
3	Develop and teach 3 new undergraduate laboratory experiments	05/15/09		5/30/10	100%	Completed
3	Develop and teach 3 new undergraduate laboratory experiments	05/15/10	5/15/11	5/15/11	100%	Completed
5	Identify and place two interns	05/15/09		4/15/09	100%	Complete
5	Identify and place two interns	05/15/10		3/30/10	100%	Completed
5	Identify and place two interns	05/15/11		4/15/11	100%	Completed
6	Presentation for hydrogen seminar	3/15/09		3/15/09	100%	Complete
6	Presentation for hydrogen seminar	3/15/10		12/31/10	100%	Complete.
6	Presentation for hydrogen seminar	3/15/11		4/15/11	100%	Completed
7	Develop hydrogen related modules for PowerOn	05/15/09	6/30/10	3/31/10	100%	Completed

*The case studies developed were not found to be highly effective. Therefore, only a select few were submitted for publication.

Project Spending and Estimate of Future Spending								
Quarter	**From**	**To**	**Estimated Federal Share of Outlays***	**Actual Federal Share of Outlays**	**Estimated Recipient Share of Outlays***	**Actual Recipient Share of Outlays**	**Cumulative**
3Q08	8/30/08	9/30/08	10,000	6,900	2,000	1,634	8,534
4Q08	9/1/08	12/31/08	35,000	3,502	6,925	814	12,852
1Q09	1/1/09	3/31/09	66,141	67,049	15,401	10,403	90,304
2Q09	4/1/07	6/30/09	31,541	14,853	8,925	4,912,	110,069
3Q09	7/31/07	9/30/09	31,543	7,701	8,623	4,143	121,913
4Q09	10/1/07	12/31/09	23,946	2,215	5801	16,903	141,031
1Q10	1/1/07	3/31/10	23,946	10,819	5801	6,697	158,547
2Q10	4/1/07	6/30/10	23,946	32,160	5801	6,773	197,480
3Q10	7/31/07	9/30/10	30,996	69,127	4,537	8,717	275,922
4Q10	10/1/07	12/31/10	21,300	17,153	3,500	7,902	300,966
1Q11	1/1/07	3/31/11	21,300	17,130	3,500	3,249	321,356
2Q11	4/1/07	6/30/11	25,470	34,582	2,819	9,787	365,725
3Q11	7/31/07	9/1/11	25,470	16,359	0	1,660	383,744
Totals	**8/30/08**	**9/1/11**	**300,150**	**300,150**	**74,966**	**83,594**	**383,744**