Final Technical Report

Project Title: Hydrogen Education Curriculum Path at Michigan Technological University

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Recipient: Michigan Technological University
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Working Partners: Michigan Technological University
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Project Objective: The objective of this project was four-fold. First, we developed new courses in alternative energy and hydrogen laboratory and update existing courses in fuel cells. Secondly, we developed hydrogen technology degree programs. Thirdly, we developed hydrogen technology related course material for core courses in chemical engineering, mechanical engineering, and electrical engineering. Finally, we developed fuel cell subject material to supplement the Felder & Rousseau and the Geankoplis chemical engineering undergraduate textbooks.

Background: There is a need to educate students on the advantages and disadvantages of a hydrogen economy. This is important since hydrogen has been proposed for use in transportation applications as a replacement fuel for gasoline, with fuel cells replacing the internal combustion engine. This project developed a curriculum focused on hydrogen technology and hydrogen fuel cells. Current efforts are focused on curriculum development in two areas: new course development and development of modules that can be used to supplement the traditional curriculum with information about hydrogen and fuel cell technology. The modules are available on a Michigan Technological University website. During the course of this project, over 480 students were taught about hydrogen and fuel cells.

Status: This is the final technical report for this three year project. Over course of the project, progress has been made on several fronts which will now be described.

Progress on Task 1. First of all, Task 1 of this project relates to the development of new courses and refining existing courses. As such, two course proposals were submitted by Jason Keith at the start of this project. The courses are:

- CM/ENT 3977: Fundamentals of Hydrogen as an Energy Carrier. This is a one credit course designed for undergraduate students. It was taught during fall semesters, beginning in fall 2009. The course catalog description reads: “This course provides an overview of traditional and alternative energy sources, with particular emphasis on hydrogen energy. Discussion of energy production and sources; electric and hydrogen vehicles; production, distribution, and policy of hydrogen and the hydrogen economy.”
- CM/ENT 3978: Hydrogen Measurements Laboratory. This is a one credit course designed for undergraduate students. It was taught in spring 2010 and is planned to be offered in spring of 2012. The course catalog description reads: “This course provides an introduction to basic experiments and measurements that relate to hydrogen and hydrogen powered fuel cells. Includes chemical and electrical safety, fuel cell operation and introduction to fuel cell integration into practical applications.”

Both of these course proposals were approved by the Department of Chemical Engineering (CM). The courses are co-listed under the Michigan Technological University Enterprise Program (ENT) as they will serve as electives for the Minor in Enterprise that is available to undergraduate students. The courses were taught by Jason Keith.

The course schedule for CM/ENT 3977 is listed below:

- Week 1 Lecture: History of Energy Production
- Week 2 Lecture: Energy Sources, Capacity, and Emissions
- Week 3 Lecture: Electric and Hybrid Electric Vehicles
- Week 4 Lecture: Fuel Cells and Fuel Cell Vehicles
- Week 5 Lecture: Hydrogen from Natural Gas Part 1: Steam Reforming
- Week 6: In-Class Quiz
- Week 7 Lecture: Hydrogen from Natural Gas Part 2: Hydrogen Purification
- Week 8 Lecture: Hydrogen from Coal
- Week 9 Lecture: Hydrogen from Biomass
- Week 10 Lecture: Hydrogen from Electrolysis / Wind
- Week 11 Lecture: Hydrogen from Solar Energy
- Week 12: In-Class Quiz
- Week 13: Hydrogen from Nuclear Energy
- Week 14: Hydrogen Public / Government Policy (guest lecture by B. Solomon)

There were ten homework assignments in this course. Each homework problem had an equal weight and the combined score from the homework problems contributed to 50%

of the student's final grade. There were two quizzes in this course, and each quiz counted for 25% of the student's final grade.

This course was taught in fall 2009 by J. Keith with an enrollment of 27 students, and again in fall 2010 with an enrollment of 15 students. The course was updated prior to the fall 2010 offering to include improved homework problems in module format (which included example problems) designed to maximize student learning. This was done in the form of energy modules, which are co-listed with the power and energy course modules in electrical engineering. All of the students taking the course did well and the course evaluations were highly positive. The students are from chemical engineering, mechanical engineering, and materials science and engineering majors. The course is planned to be taught in fall 2011.

For assessment purposes, an energy knowledge survey was prepared and students took the quiz at the beginning and again at the end of the semester. For general energy questions, the students improved their scores on all but one of the energy topics. Results also indicated for course specific questions a tendency to guess from the multiple choice answers and not work out the solution. The quiz will be modified for the next time the course is taught to better assess student learning.

During this project for CM/ENT 3978, grant funds were used by J. Keith to order four new items from Heliocentris Energy Systems. These items are:

- Fuel Cell Professional solar electrolyzer and two-cell fuel cell (1.7 W maximum power output)
- Instructor Training System – Basic Package (50 W maximum power output)
- Resistor Load for Nexa 1.2 kW fuel cell (the 1.2 kW fuel cell was already at Michigan Technological University before the start of this project)
- Dr. Fuel Cell model car

The Fuel Cell Professional kit was installed and tested by J. Keith and an exchange student from Germany. The model car and instructor system were installed and tested by J. Keith and an undergraduate student.

The eight laboratory experiments used in the course (and the setup to be used) include:

- Solar Panel Characteristic Curve (Two-Cell Fuel Cell) – students will learn how changing the load (light source) affects the current and voltage through the solar cell. This cell will be used in follow-on experiments to produce hydrogen.
- Faraday's Law for Electrolysis (Two-Cell Fuel Cell) – students will verify Faraday's law for hydrogen production in the electrolysis unit and for hydrogen consumption in the fuel cell.
- Fuel Cell Characteristic Curve (Two-Cell Fuel Cell) – students will measure the current and voltage output of the fuel cell as a resistive load is varied for two single-cell fuel cells as well as for the two cells connected electrically in series and in parallel

- Current, Voltage, and Power in a Fuel Cell (50 W Fuel Cell) – Students will measure current and voltage output of a larger fuel cell, and scale up the system to power a home.
- Faraday's Law for the Fuel Cell (50 W Fuel Cell) – students will measure the relationship between hydrogen flow rate and electrical current using Faraday's first law
- Efficiency of the Fuel Cell Stack (50 W Fuel Cell) – students will measure the current efficiency and voltage efficiency of the fuel cell stack and determine operating conditions to maximize efficiency
- Determine voltage, current, hydrogen consumption (1.2 kW Fuel Cell) Nexa – Students will power a 1.2 kW fuel cell using a variable load and determine the stack voltage and current as a function of the applied load. Students will perform basic fuel cell calculations including cell voltage, LHV efficiency, hydrogen consumption rate, and applied resistance.
- Hydrogen Fuel Economy (Fuel Cell Car) – Students will use a fuel cell powered car and measure the distance it travels with a certain amount of hydrogen and determine the "fuel economy" of this vehicle.

Also, a quiz was developed to give to the students, so that there is an individual component to the lab course grade. The eight experiments each count for 10% of the total grade, with the remaining 20% of the total grade coming from the quiz.

This course was taught for the first time during spring 2010 with an enrollment of 11 students from chemical, mechanical, and civil engineering majors. The course is scheduled to be taught in spring 2012.

In addition to the new courses, existing fuel cell courses were refined as part of this project. The course CM/ENT 3974 Fuel Cell Fundamentals, was taught by J. Keith in fall 2009 with an enrollment of 41 students. This is nearly twice the amount of students that have ever taken this course (it was taught every fall between 2004 and 2007). The course was taught again in fall 2010 with an enrollment of 23 students. The course was updated prior to the fall 2010 offering to include improved homework problems in module format (which included example problems) designed to maximize student learning. The students are from chemical engineering, mechanical engineering, materials science and engineering, and mechanical engineering technology majors. The course is scheduled to be taught in fall 2011.

All of the students taking the CM3974 course did well and the course evaluations were highly positive. Since he is considering a faculty career, graduate student Daniel Lopez Gaxiola (supported on this project) taught three lectures and presented course modules during the fall 2011 offering. At the end of the term, students were asked to create their own homework problem and present it to the class, or develop a YouTube video on fuel cells. The students did a very good job with these presentations, with one group choosing the video option (the video can be found at the following web URL: http://tinyurl.com/mtufuelcellyoutubeproject.

There is also a course MEEM 4260/5990 Fuel Cell Technology, which was taught by A. Mukherjee in fall 2009 with an enrollment of 23 students. The course was taught again in fall 2010 with an enrollment of 25 students. All but a handful of these students are mechanical engineering graduate students.

In this course a special project was assigned to discuss journal articles in an online forum. This was a very successful project and student feedback was very positive.

Finally, B. Solomon taught SS 3800 Energy Technology and Policy in spring 2010 and will be teaching it again in spring 2011. In this course, the lecture on the hydrogen economy has been updated. Overall course evaluations were positive for this course, which is an elective course for the hydrogen minor.

*Progress on Task 2.*The second task on this project was to develop curriculum programs in hydrogen technology. A draft proposal for an interdisciplinary minor in hydrogen technology that was created by the PI was initially circulated through the Department of Chemical Engineering curriculum committee, Enterprise Program governing board, Dean of Engineering, University Senate curricular policy committee, and the Dean’s Council. At each step in the process the minor was improved to better meet the needs of the university community. The proposal stood for discussion and was approved by the University Senate, Provost, and President in April 2009.

As such, the minor can now be received by students at Michigan Technological University.

The catalog description for the minor reads as follows:

> This interdisciplinary minor focuses on hydrogen technology as an alternative to fossil fuels for stationary and transportation applications. One component is participation in the Alternative Fuels Group Enterprise with project work based upon hydrogen fuel cells and/or other hydrogen technologies, such as hydrogen production or storage. Students will also enroll in hydrogen related elective course modules to receive the appropriate training. Students will also be exposed to the broader, societal impacts of hydrogen technology. Although the minor is open to all students, targeted majors are chemical engineering, electrical engineering, mechanical engineering, materials science and engineering, electrical engineering technology, and mechanical engineering technology.

It is noted that all minors at Michigan Technological University require at least 6 semester credit hours of 3000 level or higher courses which are not required for the Major degree program except as free electives, and that a minimum cumulative grade point average of 2.0 is required for courses in the minors.

The requirements for this 16 semester credit hour minor are for students to obtain credits in the following areas.

- Alternative Fuels Group Enterprise Project work (between 4 to 6 credits)
- Fuel Cells (1 to 3 credits)
    - CM/ENT3974 Fuel Cell Fundamentals (1 credit) OR
    - MEEM4990/5990 Fuel Cell Technology (3 credits)
- Hydrogen Fundamentals (1 to 2 credits)
    - CM/ENT3977 Fundamentals of Hydrogen as an Energy Carrier (1 credit)
    - CM/ENT3978 Hydrogen Measurements Laboratory (1 credit)
- Approved Electives (remainder of credits)
    - Common elective credits for chemical engineering students
        - CM3110 Transport / Unit Operations 1 (3 credits)
        - CM3120 Transport / Unit Operations 2 (3 credits)
        - CM4000 Chemical Engineering Research (1-3 credits)
        - CM4310 Chemical Process Safety / Environment (3 credits)
    - Common elective credits for electrical engineering students
        - EE2110 Electrical Circuits (3 credits)
        - EE3120 Introduction to Energy Systems (3 credits)
        - EE3221 Introduction to Motor Drives (4 credits)
        - EE4000 Electrical Engineering Undergraduate Research (1-4 credits)
    - Common elective credits for electrical engineering technology students
        - EET2120 Circuits II (4 credits)
        - EET3131 Instrumentation (3 credits)
        - EET3390 Power Systems (3 credits)
    - Common elective credits for mechanical engineering students
        - MEEM3210 Fluid Mechanics (3 credits)
        - MEEM3230 Heat Transfer (3 credits)
        - MEEM3999 ME Undergrad Research Project (3 credits)
        - MEEM4220 Internal Combustion Engines 1 (3 credits)
        - MEEM4990/5990 Micro- and Nanofabrication for Energy Applications (3 credits)
    - Common elective credits for mechanical engineering technology students
        - MET3250 Applied Fluid Mechanics (4 credits)
        - MET4300 Applied Heat Transfer (3 credits)
        - MET4390 Internal Combustion Engines (3 credits)
        - MET4900 Alternative Energy Systems (3 credits)
    - Typical elective credits for materials science and engineering students
        - MY3100 Materials Processing I (4 credits)
        - MY3110 Materials Processing II (4 credits)
        - MY4140 Science of Ceramic Materials (3 credits)
        - MY4990 Materials Science and Engineering Undergraduate Research (1-6 credits)
        - MY5410 Materials for Energy Applications (3 credits)

- In addition, the following elective courses are related to societal impacts of hydrogen technology
    - EC4620 Energy Economics (3 credits)
    - ENG5510 Sustainable Futures I (3 credits)
    - ENG5520 Sustainable Futures II (3 credits)
    - ENT3956 Industrial Health and Safety (1 credit)
    - SS3800 Energy Technology and Policy (3 credits)

The structure of the minor has an emphasis on project work through the Michigan Technological University Enterprise program. Project-based, hands-on learning has been a cornerstone of engineering education at Michigan Technological University, and the engineering education literature has proven that students learn by doing, through team-based interactive projects.

In addition, Michigan Technological University approved a "Graduate Certificate in Hybrid and Electric Vehicle Engineering." The courses taught as part of this project (see Task 1) can be taken as part of this certificate. The certificate requires 15 credits, which must be broken down in the following categories:

- Required: EE/MEEM 5295 Advanced Propulsion for Electric Drive Vehicles (3 credits)
- Required: Choose any two of the following (6 credits total)
    - EE/MEEM 4925 Intro. To Propulsion Systems for Electric Drive Vehicles (3 credits)
    - EE 4227 Power Electronics (3 credits)
    - MY/CM 5760 Vehicle Battery Cells and Systems (3 credits)
    - EE 5221 Advanced Electrical Machines (3 credits)
    - MEEM 5450 Vehicle Dynamics (3 credits)
- Electives: Choose 6 additional credits from this list:
    - EE/MEEM 4925 Intro. To Propulsion Systems for Electric Drive Vehicles (3 credits)
    - EE 4227 Power Electronics (3 credits)
    - MY/CM 5760 Vehicle Battery Cells and Systems (3 credits)
    - EE 5221 Advanced Electrical Machines (3 credits)
    - MEEM 5450 Vehicle Dynamics (3 credits)
    - EE/MEEM 4296 Intro. To Propulsion Systems for Electric Drive Vehicles Lab (1 credit)
    - EE/MEEM 5296 Adv. To Propulsion Systems for Electric Drive Vehicles Lab (1 credit)
    - EE/MEEM 4750 Distributed Embedded Control Systems (3 credits)
    - EE/MEEM 5750 Distributed Embedded Control Systems (3 credits)
    - EE 5200 Advanced Methods in Power Systems (3 credits)
    - EE 3120 Electric Energy Systems (3 credits, not for EE or CPE majors)
    - EE 4221 Power System Analysis 1 (3 credits)
    - EE 4222 Power System Analysis 2 (3 credits)
    - EE 5223 Power System Protection (3 credits)

- EE 5230 Power System Operations (3 credits)
- EE 5290 Selected Topics in Power Systems (3 credits)
- MEEM 4200 Principles of Energy Conversion (3 credits)
- MEEM 4220 IC Engines 1 (3 credits)
- MEEM 5200 Advanced Thermodynamics (3 credits)
- MEEM 5250 IC Engines 2 (3 credits)
- MEEM 5670 Experimental Design in Engineering (3 credits)
- MEEM 5680 Optimization (3 credits)
- MEEM 5700 Dynamic Measurement and Signal Analysis (3 credits)
- MEEM 5715 Linear Systems (3 credits)
- MEEM 4620 Fuel Cell Technology (3 credits)
- MEEM 5220 Fuel Cell Technology (3 credits)
- MY 4165 Corrosion and Environmental Effects (3 credits)
- MY 5100 Thermodynamics and Kinetics 1 (3 credits)
- MY 5110 Thermodynamics and Kinetics 2 (3 credits)
- MY 5410 Materials for Energy Applications (3 credits)
- CM/ENT 3974 Fuel Cell Fundamentals (1 credit)
- CM/ENT 3977 Fundamentals of Hydrogen as an Energy Carrier (1 credit)
- CM/ENT 3978 Hydrogen Measurements Laboratory (1 credit)

The Alternative Fuels Group Enterprise is one of over twenty enterprises on the Michigan Tech campus. The Enterprise program is an opportunity for teams of students from various disciplines (such as chemical, electrical, and mechanical engineering, as well as business) and different levels of their academic careers (sophomore, junior, and senior) to work in a business-like setting to solve real-world problems. Each Enterprise is intended to operate like a real company in the private sector and is run by the students with faculty supervision.

The Alternative Fuels Group has been in existence since fall 2002 and has been advised by Jason Keith and coPI Jay Meldrum. It is listed as course numbers ENT1960, ENT2950, ENT2960, ENT3950, ENT3960, ENT4950, and ENT4960. All courses are 1 credit with the exception of ENT4950 and ENT4960 which are for 2 credits. Students that are enrolled in the course attend a weekly business meeting and meet outside of class with their teammates. Each student is part of a sub-team which is assigned a group project. There are usually two or three projects each semester.

For the fall semester of 2008, there were two projects related to hydrogen and fuel cells. These will now be briefly described.

- <u>Analysis of a Hydrogen Powered John Deere e-Gator</u>: The purpose of this semesters' project was to gain a better understanding of the electrical system of a hydrogen-powered John Deere E-Gator that was designed and constructed by students in the Alternative Fuels Group during the fall of 2007 (see figure 1). Design requirements were provided by the enterprise advisors. Major goals of the testing included characterization of electrical flow in the system:

- Hydrogen is fed in parallel to two Ballard Nexa fuel cell units (with a maximum electrical power of 1.2 kW)
- Electricity from the fuel cells is combined using a battery isolator which acts as a diode to allow for load leveling and to prevent backflow into the fuel cells
- Electricity from the battery isolator flows through a deep cycle 12 V battery to boost the voltage to be in the proper range for the e-Gator motor controller to move the vehicle
- The circuit is closed via electrical flow back into the fuel cells.

During the fall semester of 2008 the team finalized the experimental setup and the experiments will begin during the spring semester of 2009.

Figure 1. John Deere e-Gator with two fuel cells.

- Hydrogen Economy at Michigan Technological University: The main objective of this project is to explore the feasibility and obstacles of replacing the gasoline-fueled MTU motor pool vehicles with hydrogen vehicles. Based on the ideas and principles discussed in “The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs” report by the National Research Council and the National

Academy of Engineering, the issues relevant to this type of conversion were discussed and weighted in order to devise a plan of action to make such a conversion possible in the future. Included in this report are assumptions that were made regarding the infrastructure, costs, production and safety and environmental issues that made this initial work possible. The intention of this work is to outline the necessary considerations for a conversion to a hydrogen-fueled motor fleet for Michigan Tech.

The students found that on-site steam reforming of natural gas was the best option for this project. Due to the remote location of Michigan Tech, they did not consider any centralized hydrogen production and transmission through pipelines. They also did not consider carbon sequestration at this time.

For the spring semester of 2009, there were three projects related to hydrogen and fuel cells. These will now be briefly described.

- Analysis of a Hydrogen Powered John Deere e-Gator: This is a continuation of a previous project. During the spring 2009 semester, the students purchased and installed two meters into the dashboard of the vehicle. Each meter provided the voltage drop as well as the current flowing through one fuel cell. The students also used a hand-held multimeter to record the voltage drop across the deep cycle battery.

  The students performed two separate tests. The first was operation from a stationary position. At time t = 0, the accelerator was fully depressed and the vehicle was driven for 30 seconds. It was found that the power output of each fuel cell was nearly identical. The maximum power level for each fuel cell was about 900 W. It was found that nearly 80% of the maximum power level was attained in the first ten seconds. During this test it was also found that the deep cycle battery consumed nearly an equal amount of energy as each fuel cell.

  The second test was run with the vehicle being driven at a relatively uniform speed around a building. The test was run for nearly one minute. The power level for each fuel cell, and for the deep cycle battery, was about 1000 W.

  Both of these tests suggest that the battery contributes significantly to vehicle propulsion. If a test is run for several minutes, the battery charge would decrease until the voltage is not high enough to power the motor, and the vehicle would stop until the battery is recharged by the fuel cells.

- Hydrogen Economy for the Upper Peninsula of Michigan: The main objective of this project is to explore the feasibility and obstacles of developing a hydrogen fueling infrastructure in the Upper Peninsula of Michigan. Several assumptions were made based upon the recent report titled “The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs” report published in 2004 by the National Research Council and the National Academy of Engineering.

Consider the hypothetical scenario in the year 2025, when 10% of all vehicles have fuel cells for propulsion. The students estimated that 250,000 vehicles would require hydrogen fuel. The total fuel demand would be 4.5 million kg of hydrogen (note that a full-scale hydrogen economy in the United States would require 100 billion kg of hydrogen). The students made a recommendation to produce the hydrogen from natural gas via steam reforming in a centralized location with hydrogen transportation as a compressed gas to twelve fueling stations as seen in the map below (figure 2).

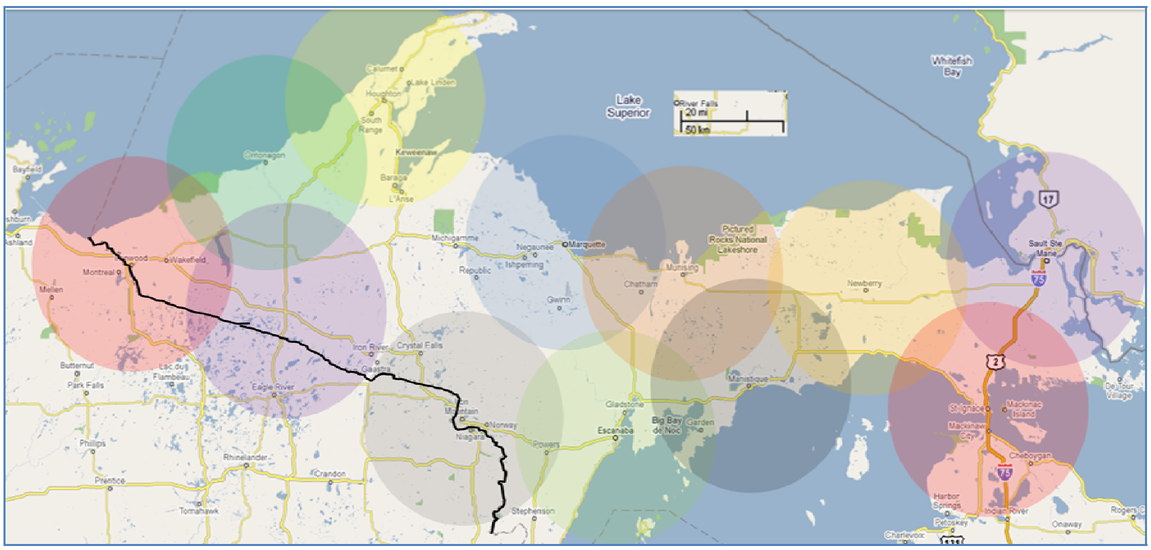

Figure 2. Proposed hydrogen refueling station locations.

It is interesting to note the students had a broader vision beyond the project definition given to them by the instructor. Using central production resulted in excess hydrogen, which they imagined distributing across state lines (to Wisconsin, for example) to increase profit. Alternatively, they could operate the plant at a lower production rate, and have reserves available for expansion to future years. Finally, the students recommended compressed gas distribution over liquefied distribution due to energy losses in the hydrogen. This recommendation was made despite the fact that the economics favored liquefied distribution.

- Design and Economic Analysis of a Fuel Cell / Electric Hybrid Fork Lift: The "Clean Lift" team was charged with a project to replace a propane forklift with one that operated on fuel cell power. This was due to the fact that the propane forklift was used indoors and it was desired to limit carbon monoxide emissions.

  The students could use one of two large fuel cells available at Michigan Technological University (5 kW and 12 kW). The students decided that 5 kW would be appropriate and identified an electric forklift with similar characteristics. Although the lifting and driving characteristics seemed reasonable, the economics on purchasing compressed hydrogen at 99.999% purity were not favorable.

In order to finish the semester, the project scope was adjusted to an economic analysis of a large distribution facility that used a large number of forklifts. If a hydrogen production facility capable of producing 50 kg H_2 per day were used, and if the cost of hydrogen production was $6 / kg, the economics of using hydrogen powered forklifts was favorable when compared with propane. However, the cheapest option remained using battery powered forklifts charged by electricity.

It is noted that the students also estimated greenhouse gas emissions as well as other environmental impact factors including chlorofluorocarbon, heavy metal, and carcinogenic emissions as well as acidification and eutrophication effects.

For the fall semester of 2009, there were four projects related to hydrogen and fuel cells. These will now be briefly described.

- <u>Combined Heat and Power Fuel Cell Design:</u> The Combined Heat and Power (CHP) team was given the task of utilizing both the electrical and thermal power generated by a 5 kW fuel cell provided by the Keweenaw Research Center (KRC) at Michigan Technological University. Several heat transfer systems were designed and compared in order to develop the best possible combined heat and power system. After some discussion with the team advisors, an in-floor heating system was chosen for this project.

  In order to maximize the efficiency of the fuel cell, a specific design was created implementing both the hot water and electrically powered resistors. The electrical energy output from the fuel cell will be dissipated into the floor using resistive heating elements. Under load, the fuel cell will produce heat. The 5 kW fuel cell is water cooled. The coolant water flowing through will be sent through the in-floor heating unit prior to entering the fuel cell radiator. Thus the heat will be dissipated in the floor.

  The students also made certain assumptions were also made regarding the fuel cell in order to obtain initial heat transfer calculations necessary for further investigation. It is hoped that the students will begin experiments after completing their initial design in the spring semester of 2010.

- <u>Carbon Dioxide Sequestration of Hydrogen Generated from Natural Gas for Detroit, MI</u>: The main objective for the carbon dioxide sequestration team is to find a practical yet sustainable way to capture and store carbon dioxide that is produced from a Steam-Methane Reforming hydrogen production facility. The area of interest is the Metro-Detroit area in Michigan. The Metro-Detroit area consists of six counties; Lapeer, Livingston, Macomb, Oakland, St. Clair, and Wayne. The population of Metro-Detroit is 4.4 million. In their report, the students investigated the methods of sequestration, possible locations for sequestration, the materials needed, and costs.

The students selected a geological storage approach. In this method, the carbon dioxide is pumped underground into potential reservoirs. Beneath nearly all of Michigan's Lower Peninsula there are deep saline formations which are potentially the best option to store the carbon dioxide in the area. To store the carbon dioxide in deep saline formations the carbon dioxide must be in a supercritical phase and at least 1,000 feet below the surface. Geologic reservoirs that have not been manmade have held oil, water and natural gases for millions of years had minimal leakage, so storage of carbon dioxide in those depleted reservoirs would also only result in minimal leakage.

Possible locations for the sequestering of carbon dioxide in Metro-Detroit vary in distances from the city of Detroit. The best location was chosen to be south of Lake Sherwood in Oakland County, which is to the North West of Detroit. This location is approximately one half mile by one half mile in size. This location would possibly contain both the hydrogen production facility and the carbon dioxide sequestration site. This site is approximately 37 miles from the center of Detroit. This is a feasible option due to the fact of convenience. Piping, between the capture and sequestering would be kept to a minimum. However the piping used for transporting the hydrogen across the Metro-Detroit area would not be kept to a minimum. This location is surrounded mostly by an agricultural area.

This scenario assumes that the carbon dioxide sequestration site is located at the production facility. This case has the lowest possible transportation cost of the sequestered carbon dioxide. A pipeline was modeled for underground sequestration of the carbon dioxide. For the case involving sequestration directly at the production facility in Detroit, approximately 1000 meters of pipeline will be needed to connect the plant to the deep saline aquifer formation. To maintain a pressure of 150 bar prior to injection, a 200 kW two-stage compressor will be needed.

- Alternative Energy Solutions for an Off-Grid Cabin: At the beginning of the semester, a Michigan Tech alumna came to the team's advisor asking the students to create an environmentally friendly energy solution to eliminate the need for a gasoline generator, which is currently in place at her eco-friendly cabin. The group's purpose was to research possible solutions that could be presented to the owner and eventually narrow them down to the best available options. From these, the team would choose the most feasible energy source and in the future implement the plan at the cabin.

  The group began by splitting into several teams to research specific types of alternative energy methods which might be possible for the cabin. The sources of energy which were researched included: fuel cells, wind/solar, efficient remodeling, geothermal, pellet stoves, and propane combustion.

Batteries are necessary in order to provide a consistent supply of power from alternative energy sources. Their main purpose is to store energy when power is being produced and have it available when power requirements are higher than the power being produced. For the sources being researched, the power produced will be limited and the source cannot fully sustain the cabin on its own. The lack of hydrogen, wind, or sunlight will require additional power to sustain the cabin's energy requirements. The ideal way to meet these requirements is to use a battery array and integrate it into a hybrid system.

The fuel cell must be able to accommodate the average daily load of 2.7 kW power for the daily use of the cabin. A suggested fuel cell system for the cabin is the DEA 3.0 fuel cell system that has 120 cells, 3kW power, 72-114V voltage range, and an unregulated DC output. The fuel cell and hydrogen costs were too high for further consideration, but it was an instructive exercise for the students.

- Development of Course Modules to Bring Wind Energy into MTU Freshman Engineering Curriculum: The goals of the project were to develop a hands-on curriculum for the first year engineering course focused on wind energy. The team was to research the history, mechanics, design and analysis of wind turbines and translate that into something pre-calculus freshmen could easily understand. The undergraduate students could relate to the freshmen courses and apply what the team felt worked well when they took the lower level engineering courses. The AFG group designed the following course materials: lectures, a list of student deliverables, two working prototypes, and testing materials.

  In the spring semester, the project will focus on calculations and modeling focused around hydrogen production for use in fuel cell applications.

For the spring semester of 2010, there were four projects related to hydrogen and fuel cells. These will now be briefly described.

- Combined Heat and Power Fuel Cell Design: In this project, students were to take an exhaust stream from a 5 kW fuel cell and obtain thermal energy from it. The students developed a paper-based design for the system. After careful consideration, the students chose an in-floor heating application because of simplicity of design, cost, and experimentation. As a first step, the system was tested on a smaller scale. A circulation heater was used to heat a reservoir of water to the exit temperature of the liquid fuel cell coolant. Using gravitational potential energy, this warm water (at 35 ^{o}C) was sent through the floor system. The floor system was constructed by routing out a serpentine channel through a sandwich of two 4'x4' oriented strand boards and inserting a tube in the channel. Most of the heat was removed from the floor heating unit and the floor itself also heated up by a noticeable amount. This project may be scaled up to integrate the fuel cell in a future semester.

- Participation in the Hydrogen Education Foundation's Hydrogen Student Design Contest: The goal of this externally developed project was to develop a hydrogen community for the area of Santa Monica, CA. Five undergraduate students identified three resources that could produce up to 1000 kilograms of hydrogen per day. The students decided to produce hydrogen from steam reforming of methane biogas generated from solid waste digestion at a local treatment plant. Then, the students identified customers who could consume up to 250 kg of hydrogen per day. The students also designed and sited a hydrogen fueling station, performed an economic and business analysis, as well as environmental and safety analyses. This project combined technical design with several soft skills that are required of professional engineers.

- Energy Storage in an Alternative Energy Powered Off-Grid Cabin: This project was sponsored by a graduate of the Michigan Technological University Department of Chemical Engineering. The students investigated several alternatives to powering the cabin, including wind turbines, solar panels, and hydrogen fuel cells. Because of the cost of fuel cells, this option was removed from consideration. The students eventually designed a hybrid system with wind turbines combined with an existing gasoline generator coupled with a battery bank to provide sufficient capacity for the cabin. The students and cabin owner also developed a plan to reduce energy consumption at the cabin in order to better fit with the available wind turbines on the market.

- Development of Course Modules to Bring Wind Energy into MTU Freshman Engineering Curriculum: This project was co-advised by J. Keith and two faculty in the Department of Engineering Fundamentals at Michigan Technological University who have a National Science Foundation grant to redesign the first year engineering curriculum. In addition to creating lecture material and course handouts, the students worked to develop two functional wind turbine prototypes, and tested them to measure revolutions per minute in different wind environments. The students also helped develop a mathematical model to predict the instantaneous power for a large scale wind turbine and determine the amount of energy that could be stored in the form of hydrogen gas (created via electrolysis). These projects will be pilot tested in fall 2010 with actual freshmen students.

For the fall semester of 2010, there were three projects related to hydrogen and fuel cells. These will now be briefly described.

- Direct Methanol Fuel Cell Production Facility: This group of students did an initial sizing of direct methanol fuel cells for portable power applications, particularly for laptop computers. Then, the group investigated alternative membrane designs with the goal of minimizing methanol crossover to improve the fuel thermal input to electrical power output efficiency of the fuel cells. Furthermore, the group developed a strategy for the spring 2011 semester to develop a process to manufacture methanol from natural gas, via steam reforming to synthesis gas followed by methanol synthesis. The design will include plant cost and economics for methanol production. An alternative route of methanol production from wind and solar using hydrogen as an intermediate will also be investigated.

- Solid Oxide Fuel Cell Cogeneration: This group of students investigated powering the Michigan Technological University campus using Solid Oxide Fuel Cells with natural gas as the energy source. The group determined the average power consumption at the university and used those figures to estimate the number of Bloom Box fuel cells required. The group is also looking at cogeneration of thermal energy using waste heat from the high temperature fuel cells. In the spring semester the group will look at process economics as well as consider powering a fraction of the fuel cell units using hydrogen obtained from renewable sources such as wind and solar.

- Stationary Solar Cell Analysis: This group of students is studying the performance of solar panels in the climate of Michigan's Upper Peninsula. During the fall semester their work focused on sizing some of the auxiliary components needed for the solar panel installation. During the spring semester the group will perform more analysis of the weather conditions and energy produced and also estimate hydrogen production from the panels for use in fuel cell stationary power applications.

For the spring semester of 2011, there were three projects related to hydrogen and fuel cells. These will now be briefly described.

- Direct Methanol Fuel Cell Production Facility: There were two parallel goals to this project. The first was to size a chemical plant to produce methanol from natural gas to use in direct methanol fuel cells for portable power applications (cell phones, laptop computers, etc.). The second goal was to study the research literature and evaluate the different materials currently being used for membranes in direct methanol fuel cells. The students worked through the procedure to determine fuel requirements for laptop computers and then scaled the chemical plant to meet the requirements.

- Solid Oxide Fuel Cell Cogeneration: The goal of this project was to evaluate the feasibility of using Bloom Box solid oxide fuel cells on the campus of Michigan Technological University. The students determined the electricity demand on campus and evaluated the technical specifications of the fuel cell to determine the number of fuel cell units required. The students also looked at using the waste heat from the fuel cells to produce steam. As a final note, the students also looked at placing wind turbines on the campus and using the wind power to produce hydrogen to power the fuel cells.

- Stationary Solar Cell Analysis: The goal of this project was to help in the design and placement of a solar panel at Michigan Tech's Keweenaw Research Center.

The students helped KRC staff identify materials to mount the panels and did some preliminary analysis of the performance of the cells. The students also performed some correlation analysis between KRC weather station data and energy production. The students also investigated hydrogen production from the solar energy for use in stationary and mobile power applications. There are plans in the future to add additional solar panels at KRC.

Progress on Task 3. The third task of this project is to develop modules for core courses in chemical, mechanical, and electrical engineering courses.

Each module contains basic information and background material needed to complete the module. The modules also contain an example problem statement and solution, and a home problem statement. The home problem solution is password protected.

The goal of the modules is to allow faculty around the world to drop in fuel cell and hydrogen technology related problems into their curriculum.

The chemical engineering modules are available online at: http://www.chem.mtu.edu/~jmkeith/fuel_cell_curriculum/ and will be archived at Jason Keith's new website at Mississippi State University at: http://www.che.msstate.edu/pdfs/h2ed.

The courses and associated module titles are given below.

Introductory Material:
Overview of Hydrogen Energy and Fuel Cells
Fuel Cell Sizing Made Easy (Knovel Engineering Cases)
The Short-Term Hydrogen Economy: Fueling Fuel Cells (Knovel Engineering Cases)

Material and Energy Balances:
Heat of Formation for Fuel Cell Applications
Material Balances in a Solid Oxide Fuel Cell
Energy Balances in a Solid Oxide Fuel Cell
Generation of Electricity Using Recovered Hydrogen
Material Balances in Fuel Cell Systems
Heats of Reaction and Energy Balances in an SOFC

Thermodynamics:
Equation of State for Hydrogen Fuel
Equilibrium Coefficient and Van't Hoff Equation for Fuel Cell Efficiency
Fuel Cell Efficiency
Vapor Pressure / Humidity of Gases
Nernst Equation

Fluid Mechanics:
Pressure Drop in Fuel Cell Bipolar Plate Channel

Finite Difference Method for Flow in a Fuel Cell Bipolar Plate
Compressor Sizing and Fuel Cell Parasitic Losses

Heat and Mass Transfer:
Conduction and Convection Heat Transfer
Microscopic Balances Applied to Fuel Cells
Diffusion Coefficients for Fuel Cell Gases
Conduction, Convection, and Radiation Heat Transfer in a Solid Oxide Fuel Cell

Kinetics and Reaction Engineering:
Tafel Equation and Fuel Cell Kinetic Losses
Hydrogen Adsorption and Catalyst Surface Coverage
Pressure Drop in a Water Gas Shift Reactor
Water Gas Shift Reaction in a Palladium Membrane Reactor
Equilibrium Simulation of a Methane Steam Reformer
Reaction Kinetics in a Solid Oxide Fuel Cell
Reactor Design Applied to a Solid Oxide Fuel Cell

Separations:
Hydrogen Purification
Air Separation for Coal Gasification
Hydrogen Production by Electrolysis with a Fuel Cell
Hydrogen Production by Natural Gas Assisted Steam Electrolysis

Process Safety and Process Design:
Stoichoimetric Analysis of Fuel Combustion
Energy Value of Fuels
Hydrogen Production Cost
Fuel Energy Cost and Energy Density
Hydrogen Flammability
Theoretical Fuel Consumption and Power
Unisim Modeling of a Proton Exchange Membrane Fuel Cell
Unisim Modeling of a Solid Oxide Fuel Cell

Materials Science and Engineering:
Ion and Electrical Conduction in a Solid Oxide Fuel Cell
Non Steady-State Carbon Diffusion in Solid Oxide Fuel Cell Interconnects
Mechanical Failure of Solid Oxide Fuel Cell Electrolyte

The mechanical engineering modules are available online at: http://www.chem.mtu.edu/~jmkeith/fuel_cell_curriculum/index-me.html and and will be archived at Jason Keith's new website at Mississippi State University at: http://www.che.msstate.edu/pdfs/h2ed.

The courses and associated module titles are given below.

Fluid Mechanics
Pressure Losses During Internal Flow in a Fuel Cell
Internal Multiphase Flow in a Fuel Cell

Heat Transfer
Energy Balance with Convection and Radiation Heat Transfer in a Fuel Cell
Natural Convection Cooling of a Fuel Cell
Transient Conduction with Convection Cooling in a Fuel Cell
Phase Change in a Fuel Cell

Principles of Energy Conversion
Energy Value of Fuels (co-listed in chemical engineering)
Hydrogen Production Cost (co-listed in chemical engineering)
Fuel Energy Cost and Energy Density (co-listed in chemical engineering)
Battery / Fuel Cell Vehicle Range (co-listed in chemical engineering)
Solar Energy Analysis (co-listed in chemical engineering)
Wind Energy Analysis (co-listed in chemical engineering)

Fuel Cell Technology
Computation of Fuel Cell Irreversibilities
Computation of Fuel Cell Voltage Gain due to Increased Air Pressure

Internal Combustion Engines
Engine Cycle Analysis for Different Fuels
GT Power Model Analysis for Different Fuels

Combustion and Air Pollution
Flame Temperature Analysis and NOx Emissions for Different Fuels
Manual Calculation of Adiabatic Flame Temperature: Hydrogen vs. Conventional Fuels
Effect of Temperature on Laminar Flame Speed
Effect of Equivalence Ratio on Laminar Flame Speed
Stoichiometric Analysis of Fuel Combustion (co-listed in chemical engineering)
Hydrogen Flammability (co-listed in chemical engineering)
Theoretical Fuel Consumption and Power (co-listed in chemical engineering)

Nonlinear Systems Analysis and Control
Control System Design for Convective Cooling of Fuel Cells

Failure of Materials in Mechanics
Structural Analysis of Thin Film Oxide Electrolyte in SOFCs
Fatigue and Failure of Thin Membrane Electrode Assembly in PEMFC

Metal Forming Processes
Analysis of Hydroforming vs. Stamping of Metallic Bipolar Plates
Stainless Steel Bipolar Plates: Hydroforming vs. Stamping
Die Design for Hydroforming Stainless Steel Bipolar Plates

The electrical engineering modules are available online at: http://www.chem.mtu.edu/~jmkeith/fuel_cell_curriculum/index-ee.html and will be archived at Jason Keith's new website at Mississippi State University at: http://www.che.msstate.edu/pdfs/h2ed.

The courses and associated module titles are given below.

Introduction to Power and Energy
Energy Consumption Analysis
Energy Efficiency Analysis
Energy Emissions Analysis
Battery Energy Analysis
Battery / Fuel Cell Vehicle Range
Solar Energy Analysis
Wind Energy Analysis

Circuits and Instrumentation
Fuel Cell Series Load Analysis
Fuel Cell Parallel Load Analysis
Proton Exchange Membrane Fuel Cell Stack Performance: Single Load
Solid Oxide Fuel Cell Stack Performance: Single Load
Analysis of DC/DC Converter in a PEM Fuel Cell Application

Electrical Engineering Laboratory
Renewable Energy Characteristics

The modules were tested extensively at Michigan Technological University and also at several institutions nationwide with very positive comments from students.

Progress on Task 4. In this task, textbook supplements were developed for two textbooks commonly used in the chemical engineering curriculum. The first text is titled *Elementary Principles of Chemical Processes* and is authored by Richard M. Felder and Ronald W. Rousseau, published by Wiley. The supplements created were original example problems prepared in workbook format to allow students extra practice in solving material and energy balance problems. Students who pass this course usually are able to graduate with chemical engineering degrees. These problems were prepared to introduce students to the fundamental skills needed to be successful in a future hydrogen economy. The book chapter titles and number of modules are:

Chapter 2: Introduction to Engineering Calculations – 10 modules
Chapter 3: Processes and Process Variables – 11 modules
Chapter 4: Fundamentals of Material Balances – 23 modules
Chapter 5: Single-Phase Systems – 12 modules
Chapter 6: Multiphase Systems – 6 modules
Chapter 7: Energy and Energy Balances – 5 modules

Chapter 8: Balances on Nonreactive Processes – 6 modules
Chapter 9: Balances on Reactive Processes – 12 modules
Chapter 11: Balances on Transient Processes – 5 modules

A similar procedure was followed for the textbook Transport Processes and Separation Process Principles by Christie J. Geankoplis, published by Pearson Prentice Hall. This text is used for junior level courses in momentum, heat, and mass transfer. The book chapter titles and number of modules are:

Chapter 1: Introduction to Engineering Principles and Units – 12 modules
Chapter 2: Principles of Momentum Transfer and Overall Balances – 14 modules
Chapter 3: Principles of Momentum Transfer and Applications – 9 modules
Chapter 4: Principles of Steady-State Heat Transfer – 17 modules
Chapter 5: Principles of Unsteady-State Heat Transfer – 7 modules
Chapter 6: Principles of Mass Transfer – 7 modules
Chapter 7: Principles of Unsteady-State and Convective Mass Transfer – 2 modules
Chapter 9: Drying of Process Materials – 4 modules
Chapter 11: Vapor-Liquid Separation Processes – 2 modules
Chapter 12: Liquid-Liquid and Fluid-Solid Separation Processes – 1 module

All of these modules will be archived at Jason Keith's new website at Mississippi State University at: http://www.che.msstate.edu/pdfs/h2ed.

Progress on Task 5. This is the project management and reporting task of this project. All quarterly reports were submitted on time. Presentations were given at the Annual Merit Review and the annual report was also submitted on time.

Patents: Not Applicable. No work on this project is confidential or patentable.

Publications / Presentations: The following section contains a list of peer-reviewed papers and oral presentations given as part of this project.The PIs feel this project has been made highly visible.

Peer-reviewed papers:

J. M. Keith*, D. Lopez Gaxiola, D. Crowl, D. Caspary, J. Naber, J. Allen, A. Mukherjee, D. Meng, J. Lukowski, B. Solomon, J. Meldrum, T. Edgar, "Development and Assessment of Energy Modules in the Chemical Engineering Curriculum," ASEE Conference Proceedings, June 2011.

A. Minerick*, J. M. Keith, F. Morrison, M. F. Tafur, A. Gencoglu, "Connecting Mass and Energy Balances to the Continuum Scale with COMSOL DEMos," ASEE Conference Proceedings, June 2011.

A. Mukherjee*, J. M. Keith, D. Crowl, D. Caspary, J. Allen, D. Meng, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Fuel Cells and Hydrogen Education at

Michigan Technological University," International Fuel Cell Science, Engineering & Technology Conference, June 2010.

J. M. Keith*, D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Interdisciplinary Minor in Hydrogen Technology at Michigan Technological University," ASEE Conference Proceedings, June 2010.

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

D. Blekhman*, J. M. Keith, A. Sleiti, E. Cashman, P. Lehman, R. Engel, M. Mann, H. Salehfar, "National Hydrogen and Fuel Cell Education Program Part I: Curriculum," ASEE Conference Proceedings, June 2010. **2nd place paper award – Energy Conversion and Conservation Division**

J. M. Keith*, D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Hydrogen Curriculum at Michigan Technological University," ASEE Conference Proceedings, June 2009.

Oral presentations:

J. M. Keith* (speaker), D. Lopez Gaxiola, D. Crowl, D. Caspary, A. Mukherjee, D. Meng, J. Naber, J. Allen, J. Lukowski, B. Solomon, J. Meldrum, T. Edgar, "Energy Modules for Hydrogen and Fuel Cells in the Chemical Engineering Curriculum," 2011 AIChE Annual Meeting, Minneapolis, MN.

J. M. Keith* (speaker), D. Lopez Gaxiola, D. Crowl, D. Caspary, A. Mukherjee, D. Meng, J. Naber, J. Allen, J. Lukowski, B. Solomon, J. Meldrum, T. Edgar, "Development and Assessment of Energy Modules in the Chemical Engineering Curriculum," 2011 ASEE Annual Meeting, Vancouver, BC.

A. Minerick* (speaker) and J. M. Keith, "Connecting Mass and Energy Balances to the Continuum Scale with COMSOL DEMos," 2011 ASEE Annual Meeting, Vancouver, BC.

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "An Interdisciplinary Minor in Hydrogen Technology at Michigan Technological University," 2010 AIChE Annual Meeting, Salt Lake City, UT.

J. M. Keith (speaker), T. F. Edgar, G. P. Towler, H. S. Fogler, D. A. Crowl, D. T. Allen, D. Schuster, "Energy Modules for the ChE Curriculum," 2010 AIChE Annual Meeting, Salt Lake City, UT.

D. Lopez Gaxiola (speaker) and J. M. Keith, "Hydrogen and Fuel Cell Workbook for Material and Energy Balances," 2010 AIChE Annual Meeting, Salt Lake City, UT.

J. M. Keith (invited speaker), "Research and Education in Fuel Cell Materials," 2010, Oklahoma State University School of Chemical Engineering Seminar Series, Stillwater, OK.

A. Mukherjee (speaker), J. M. Keith, D. Crowl, D. Caspary, J. Allen, D. Meng, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Fuel Cells and Hydrogen Education at Michigan Technological University," International Fuel Cell Science, Engineering & Technology Conference, June 2010.

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Interdisciplinary Minor in Hydrogen Technology at Michigan Technological University," 2010 ASEE Annual Meeting, Louisville, KY.

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

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

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Hydrogen Curriculum Path at Michigan Technological University," 2010 DOE Hydrogen Program Annual Merit Review, Washington, DC.

J. M. Keith (speaker), D. Chmielewski, H. Scott Fogler, and M. Gross, "Update from the CACHE Fuel Cell Task Force," 2009 AIChE Annual Meeting, Nashville, TN.

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Hydrogen Education Curriculum at Michigan Technological University," 2009 AIChE Annual Meeting, Nashville, TN.

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Hydrogen Curriculum at Michigan Technological University," 2009 ASEE Annual Meeting, Austin, TX.

J. M. Keith (speaker), D. Crowl, D. Caspary, J. Allen, D. Meng, A. Mukherjee, J. Naber, J. Lukowski, J. Meldrum, and B. Solomon, "Hydrogen Curriculum Path at Michigan Technological University," 2009 DOE Vehicle Technologies Program Annual Merit Review, Arlington, VA.