Final Technical Report

Hydrogen Energy in Engineering Education (H_2E^3)

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Executive Summary

In 2008 the Schatz Energy Research Center (SERC) launched the Hydrogen Energy in Engineering Education (H_2E^3) curriculum development project with support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Project partners included the University of California, Berkeley (UCB), represented by their Institute of Transportation Studies (ITS), and industry partner Protonex Technology Corporation.

The objectives of the project as stated in our Statement of Project Objectives (SOPO) were:

1. to deliver effective, hands-on hydrogen energy and fuel cell learning experiences to a large number of undergraduate engineering students at multiple campuses in the California State University (CSU) and University of California (UC); and
2. to provide follow-on internship opportunities for students at hydrogen and fuel cell companies; and
3. to develop commercializable hydrogen teaching tools including a basic fuel cell test station and a fuel cell/electrolyzer experiment kit suitable for use in university engineering laboratory classes.

Over its three-year implementation period, the project achieved these objectives and more. To date the curriculum has been adopted at five CSU and UC campuses, with faculty at several other campuses in these two systems and outside California expressing interest. Approximately 1,100 students participated in the curriculum, with two of them going on to work as paid interns at industry partner Protonex Technology Corporation.

A rigorous monitoring and evaluation component tracked student learning and faculty and student opinions of the curriculum. Assessment outcomes showed that use of the curriculum did advance student comprehension of hydrogen fundamentals at the same time the students were meeting the existing learning objectives of the engineering courses in which the curriculum was used. Students and teachers alike responded positively to the lesson plans and the hydrogen experiment equipment.

The project web site (hydrogencurriculum.org) provides general information about the H_2E^3 project, access to downloadable materials (lecture presentations, labs, and instructional support tools), a list of recommended readings, links to project partners' websites, and links to instructional videos produced by the project team. Originally produced for instructors, the videos are also used by students.

By participating in H_2E^3, university engineering students build skills that make them more competitive as they seek employment in the growing hydrogen and fuel cell industry. Sharing the curriculum with numerous university engineering departments has helped equip these institutions to better teach hydrogen energy fundamentals to their students.

Future plans include expanding use of the curriculum beyond California and seeking business partners to commercialize the lab equipment. SERC is now looking for further funding and new contacts to pursue these goals.

Introduction

A recurring theme in the hydrogen energy field is the unmet need for a new generation of graduating engineers trained specifically in hydrogen and fuel cell energy technologies. The purpose of our project was to help meet this need, specifically in the context of the California State University and University of California systems. Together these universities grant over 7,000 engineering degrees each year.

Adding hydrogen curriculum to existing undergraduate engineering programs is not a trivial task. Engineering departments and the Accreditation Board for Engineering and Technology require students to meet numerous stringent requirements in order to graduate. There is little slack in a typical undergraduate engineering course plan to add new curriculum. In order to add hydrogen education to existing engineering programs, we needed to find creative ways to fold it into courses and help instructors meet their existing course objectives.

We worked closely with engineering faculty to develop lesson plans that can be integrated seamlessly with existing courses, including introductory engineering, introductory and advanced thermodynamics, engineering experimentation, renewable energy, transport phenomena, engineering probability and statistics, and energy and society. We also developed laboratory hardware that the students are able to use to perform hands-on experiments that reinforce key points covered in the lecture material. The partners on this effort brought years of relevant experience in teaching about hydrogen energy and developing fuel cell technology.

The three-year project, branded as "Hydrogen Energy in Engineering Education" (H_2E^3) was led by the Schatz Energy Research Center (SERC), affiliated with the Humboldt State University Sponsored Programs Foundation (HSUSPF). Our principal partner on the project was the University of California, Berkeley (UCB), represented by their Institute of Transportation Studies (ITS). Protonex Technology Corporation participated as an industry partner, providing employment for student interns after they participated in the curriculum.

SERC approached this project with an established history in successful energy curriculum development. We had previously collaborated with Lawrence Hall of Science on the DOE-funded Hydrogen Technology and Energy Curriculum (HyTEC) project and with the Alliance to Save Energy on development of curriculum on energy efficiency that has been used nationwide.

Goals and Objectives

The overarching goal of the project was to improve hydrogen and fuel cell education at the university level. The specific objectives of the project as stated in our Statement of Project Objectives (SOPO) were:

1. to deliver effective, hands-on hydrogen energy and fuel cell learning experiences to a large number of undergraduate engineering students at multiple campuses in the California State University (CSU) and University of California (UC); and
2. to provide follow-on internship opportunities for students at hydrogen and fuel cell companies; and
3. to develop commercializable hydrogen teaching tools including a basic fuel cell test station and a fuel cell/electrolyzer experiment kit suitable for use in university engineering laboratory classes.

Expected outcomes expressed in the SOPO were:

1. increased use of hydrogen energy curricula and laboratory activities in California's public universities;
2. greater understanding of hydrogen energy among graduating engineering students in California's public universities; and
3. an increase in the number of students in California's public universities choosing hydrogen energy as an area of study emphasis and/or employment after graduating.

We established quantitative success metrics in the SOPO, specifically:

- fabrication of 24 fuel cell/electrolyzer kits and two test stations;
- adoption of curriculum modules by at least three UC/CSU campuses in addition to UCB and HSU; and
- placement of at least 12 students in industry-sponsored internships

Accomplishments

The project's most significant accomplishments were in curriculum development, design and production of teaching tools for use with the curriculum, successful adoption of the curriculum at multiple campuses, and the creation of student internships in the hydrogen energy industry.

<u>Curriculum development.</u> Based on our prior experiences with introduction of hydrogen education in university engineering courses, we understood the importance of creating curriculum that could be incorporated in existing classes, helping instructors to meet their learning objectives for their students. We consulted with instructors, identifying several who were interested in pilot testing of the curriculum in their courses. Specific curriculum modules developed are discussed under Products Developed below. The modules were developed and improved iteratively over the duration of the project, incorporating feedback and lessons learned from our monitoring and evaluation process.

<u>Design, fabrication, and deployment of laboratory equipment.</u> In consultation with participating faculty, we created hydrogen experiment kits and fuel cell test stations for use with our curriculum. The designs for this equipment evolved from earlier equipment we had built in the

course of previous projects. During the first two years of the project, we produced two fuel cell test stations, 54 fuel cell/electrolyzer experiment kits (using supplemental funding from DOE), and extensive user documentation (see Figure 1).

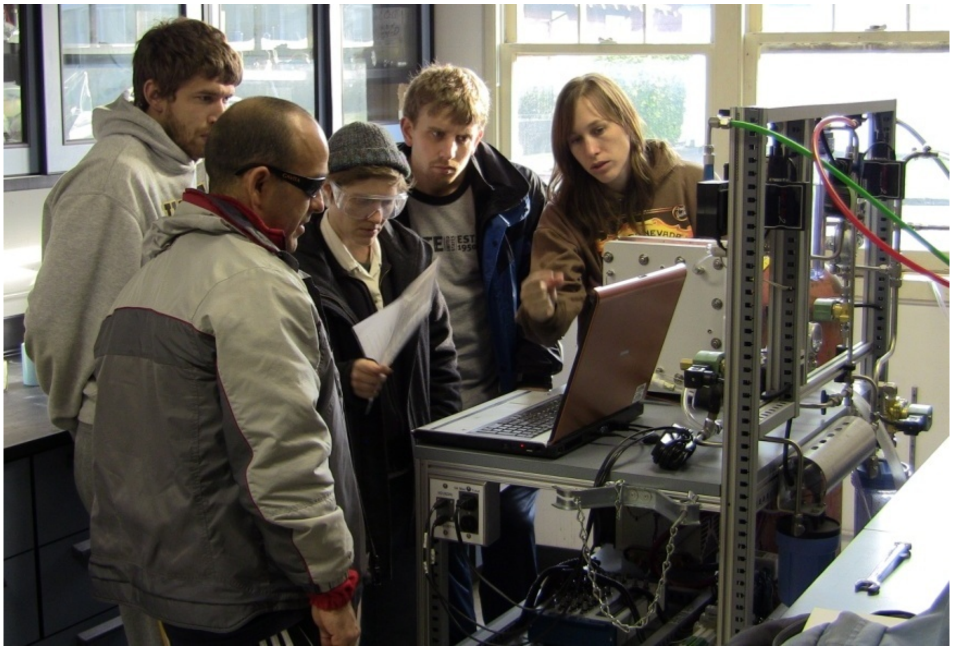

Figure 1. HSU students perform experiment using fuel cell test station

Adoption of curriculum. We found numerous opportunities to incorporate the curriculum in courses, initially at HSU and UCB, as well as at other campuses during the project's final year. Table 1 marks our progress over the second and third years of the project in adoption of the curriculum for use in numerous courses at five UC and CSU campuses.

Internships. We successfully placed two HSU undergraduate engineering students, Brett Selvig and Ryan Dunne, as interns at Protonex Technology Corporation during summer 2011. The students worked for a period of ten weeks on PEM and solid oxide fuel cell technologies. Both students and their supervisor/mentor, Nate Palumbo, were very positive about the interns' experiences at Protonex when we interviewed them after completion of the internships.

Table 1. California campuses and courses where H_2E^3 curriculum has been used to date

Campus	Fall 2009	Spring 2010	Fall 2010	Spring 2011
Humboldt State	✓ Intro to Engineering ✓ Intro to Thermo	✓ Intro to Engineering ✓ Intro to Thermo ✓ Advanced Thermo	✓ Intro to Engineering ✓ Intro to Thermo ✓ Statistical Analysis ✓ Renewable Energy ✓ Energy for non-Engineers	✓ Intro to Engineering ✓ Intro to Thermo ✓ Statistical Analysis ✓ Transport Phenomena
UC Berkeley	✓ Energy and Society	✓ Intro to Engineering	✓Energy and Society	✓ General and Quantitative Chemical Analysis ✓ Hydrogen Safety
Sonoma State				✓ Energy Forum
San Francisco State				✓ Engineering Experimentation
UC Riverside				✓ Green Engineering

Satisfaction of success metrics established in the SOPO. We were completely successful in fabricating the numbers of test stations and kits established in the SOPO (two and 24, respectively); in fact, we were able to make 30 additional kits with supplemental funding from DOE. We also achieved our goal of adoption of the curriculum by at least three UC/CSU campuses in addition to UCB and HSU. We did not meet our objective of placing at least twelve students in industry-sponsored internships. In light of the global economic downturn and resulting attrition in the fuel cell industry during our project period, this objective turned out not to be feasible. However, we are satisfied with the outcomes for the two interns we were able to place.

Accomplishments beyond project scope. On several occasions we found opportunities to advance the project in ways not originally envisioned when we developed our scope of work.

- Project manager Richard Engel took a half-year leave from the project to serve as a Fulbright scholar in El Salvador. There he assisted Don Bosco University with development of its renewable energy curriculum. He took along one of the H_2E^3 fuel cell/electrolyzer experiment kits and was able to demonstrate it for students in workshops on hydrogen energy at both Don Bosco University and the University of El Salvador (see Figure 2). He left the kit with Don Bosco University and trained several faculty in use of the kit. He also translated a fuel cell lecture presentation, the kit user guide, and lab activities into Spanish.

Figure 2. Demonstration of fuel cell/electrolyzer kit at University of El Salvador
(photo courtesy of University of El Salvador)

- Reviewers at the 2011 Annual Merit Review meeting commented that the curriculum should be adapted for use with high schools. We had an opportunity to try this idea in July 2011 when a group of high school students from Lower Lake, California's high school Upward Bound program attended a workshop at Humboldt State University. The students were given a presentation on hydrogen and fuel cells adapted from H_2E^3 curriculum, then performed an experiment using the fuel cell/electrolyzer kits. The students responded with enthusiasm and generally showed a high level of comprehension of the activity (see Figure 3).

Figure 3. High school students perform experiment with fuel cell/electrolyzer kit

- Faculty from one of the participating universities, San Francisco State University, decided they would rather purchase fuel cell/electrolyzer kits than accept kits on loan from the program. They negotiated a purchase of eight kits, made to order by SERC outside the scope of the H_2E^3 project. We have also received inquiries from colleges outside California that have learned of the project via SERC's website and are interested in obtaining experiment kits. We also recently provided a fuel cell test station based on the portable H_2E^3 test station design (but outside the scope of this project) to the Masdar Institute in United Arab Emirates. These interactions support our hypothesis that there is commercialization potential for the products developed as part of H_2E^3.
- In a 2011 project, SERC built a custom fuel cell test station for the Masdar Institute of Science and Technology in Abu Dhabi, United Arab Emirates. Along with the system documentation, we provided the test station lab activities developed for H_2E^3. This test station is destined for use mainly as a research tool for graduate students, but one instructor plans to use the stack heat balance lab in his undergraduate thermodynamics course.

Summary of Activities by Task

The project was organized into ten tasks:

Task 1. Develop curriculum modules
Task 2. Develop portable test station, software, and fuel cell/electrolyzer kits
Task 3. Pilot test the curriculum at UCB and HSU
Task 4. Promote and distribute the curriculum throughout the UC and CSU
Task 5. Conduct internships for UCB and HSU students at industry partners
Task 6. Monitor and analyze hydrogen fueling stations as class projects
Task 7. Implement the curriculum at other UC and CSU campuses
Task 8. Conduct internships for UC and CSU students at industry partners
Task 9. Conduct project monitoring and evaluation
Task 10. Conduct project management and reporting

The following discussion describes activities conducted as part of each of these tasks.

Task 1. Develop curriculum modules. We developed course modules for a variety of undergraduate engineering courses. The modules typically consist of a slide show for lecture presentation and an accompanying laboratory or analysis activity. Most of the modules make use of equipment developed under Task 2. The modules are designed to teach students fundamentals of hydrogen energy technology while simultaneously helping students achieve the existing learning objectives of the course in which a given module is used. Materials developed for these modules are available for download on the project website at hydrogencurriculum.org/downloads

Modules developed principally by SERC include:

- **Fundamentals of fuel cells and electrolysis**. This module was used in introductory engineering classes along with the fuel cell/electrolyzer kits. The module introduces students to the basic concepts of electrolysis and fuel cell electrochemistry. At the same time, it introduces students to science and engineering fundamentals such as the ideal gas law, electric power and energy measurement, and efficiency of energy conversion processes. Students operate both the electrolyzer and fuel cell while measuring electric energy and chemical energy consumed or produced. By comparing these values, they are able to calculate the efficiency of each device.
- **Thermodynamics of electrolysis.** This module was used in introductory thermodynamics along with the fuel cell/electrolyzer kits. The lecture reinforces some of the same material used in the fundamentals of fuel cells and electrolysis module and introduces enthalpy, Gibbs free energy, and the heat transfer equation $Q = m\ C_p\ \Delta T$. This formula is used in the first of two lab activities, in which students operate the kit's electrolyzer with the u-tube containing electrolyte immersed in a water bath. Students measure temperature rise and calculate heat transfer from the u-tube to the water bath, thus accounting for the heat energy lost to the environment in the electrolysis process.

- **Fuel cell stack concepts.** In this second introductory thermodynamics activity, the students operate the kit's fuel cell as in the introductory engineering module, but this time they connect multiple cells in series, thus exploring the use of a fuel cell stack to attain higher voltages and power larger loads.
- **Hydrogen fueling station data analysis.** This module is designed for use in engineering probability and statistics courses. The module makes use of real-world operating data collected at the Humboldt State University Hydrogen Fueling Station. Students use confidence intervals and hypothesis tests as tools to evaluate the change in performance of a commercial electrolyzer after replacement of its electrolysis stack. Students participate in a real or virtual fueling station tour, learning the function of each major component and observing fueling of a vehicle. Students are given data sets with fueling station operating parameters and are asked to calculate station efficacy (kWh consumed per kg H_2 produced) and other performance measures.
- **Introduction to fuel cell stack testing.** This module is designed for use in courses such as renewable energy power systems and advanced thermodynamics. Students learn to operate the H_2E^3 test station and to create polarization (I-V) curves. Under supervision, they work in teams to generate polarization curves for a given fuel cell stack operating at different temperatures and at different air stoichiometry levels. The students analyze the data to draw conclusions about how these parameters affect fuel cell performance.
- **Fuel cell stack heat balance.** This module is designed for use in courses such as transport phenomena or advanced thermodynamics. Students again operate the H_2E^3 test station, making use of its hydrogen and air mass flow meters/controllers, water flow meter, and the multiple thermocouples mounted in the stack's air and water manifolds to perform a heat balance on the stack while it is operating under near-steady-state conditions. Students consider both convective and radiative heat transfer.
- **Hydrogen, energy and society.** This lecture-only module was used in Dr. Daniel Kammen's Energy and Society course at UCB. The lecture covers fundamentals of hydrogen energy and fuel cells including thermodynamic aspects, the state of the art of fuel cell technology, economics of fuel cells, and hydrogen codes and standards. The lecture is accompanied by a demonstration of the H_2E^3 fuel cell test station.
- **Spanish translations of hydrogen modules.** Project manager Richard Engel translated portions of the H_2E^3 curriculum for use at two universities in El Salvador while on a Fulbright teaching assignment there in 2010. Translated materials included the Hydrogen, Energy, and Society lecture presentation/slide show, the instructor guide to use of the fuel cell/electrolyzer kits, and a fuel cell design assignment originally developed in English by SERC and Lawrence Hall of Science as part of the DOE-funded Hydrogen Technology and Energy Curriculum (HyTEC) project.

In addition to these modules, subawardee UCB developed a set of lecture presentation slide shows on specific hydrogen sub-topics. UCB's Tim Lipman recognized that there is often significant overlap in the content of presentations on hydrogen that are made in different engineering courses. The intent in developing these presentations was to create a “mix and match” set of short slide shows that can be combined as appropriate to create complete lectures for presentation in a variety of courses. These modular presentations created by Dr. Lipman’s team include:

- Module 1a: "H_2 101." A non-technical overview of hydrogen energy technologies that dispels common misperceptions; suitable for students from any discipline.
- Module 2a: Fuel Cells Part 1. Discusses type of fuel cells and their operating principles.
- Module 2b: Fuel Cells Part 2. Discusses fuel cell thermodynamics.
- Module 3a: Electrolyzers. Discusses types and operating principles; provides some examples of commercial models.
- Module 4a: Mobile Applications. A look at fuel cell vehicles and fueling infrastructure.
- Module 4b: Stationary Applications. Considers economics and environmental performance of stationary fuel cells; includes case studies of existing systems.
- Module 5a: Hydrogen Safety. An overview of hydrogen’s physical properties and strategies for dealing with hydrogen emergencies.
- Module 6a: Hydrogen Production and Storage. Discussion of the various technologies for generating, distributing, and storing hydrogen.
- Module 7a: Renewable Hydrogen Case Studies. Several real-world examples of systems that generate hydrogen using renewable energy.

Task 2. Develop portable test station, software, and fuel cell/electrolyzer kits. Development of lab equipment and associated software for conducting hydrogen experiments was essential to this project. Some fuel cell education equipment is commercially available, but we saw a need for equipment that is robust, affordable, portable, and appropriately designed to convey the key concepts of our curriculum. We produced a total of 54 fuel cell experiment kits and two test stations with operating software. The equipment is described in greater detail below under “Products Developed.”

Task 3. Pilot test the curriculum at UCB and HSU. We introduced the modules at both UCB and HSU in fall semester 2009. This process began with recruiting interested faculty at both campuses. We provided one test station and fuel cell stack and twelve fuel cell/electrolyzer kits to each campus (see Figure 4). At HSU we worked with the Environmental Resources Engineering department, selecting ENGR 115 (Introduction to Engineering) and ENGR 331 (Introduction to Thermodynamics) as initial courses for use of the curriculum. At UCB we began with a senior and graduate level E100/E200 (Energy and Society) course.

Figure 4. SERC senior research engineer Richard Engel and director Peter Lehman deliver fuel cell test station to UCB faculty members Tim Lipman and Dan Kammen

An unexpected but welcome opportunity to expand the curriculum emerged at UCB in early 2011, when project staff met with faculty and staff from UCB's Berkeley Center for Green Chemistry. BCGC staff queried us about the fuel cell/electrolyzer kits' performance and proposed that, rather than using the kits in a chemistry class to perform pre-designed experiments, they would let the students design their own projects to investigate possible improvements to the kit design. This plan was adopted, and the students presented their projects in a May 2011 poster session (see Figure 5).

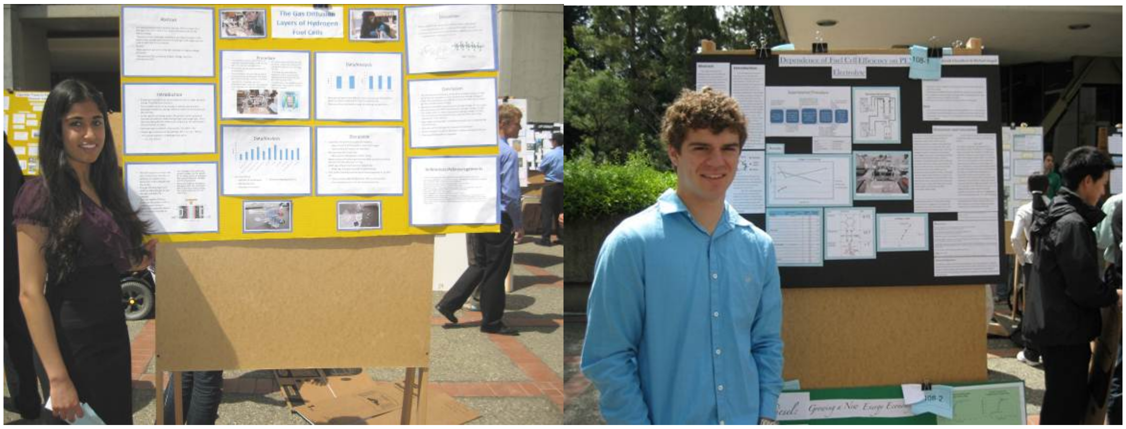

Figure 5. UCB chemistry students present their design experiments using the H_2E^3 fuel cell/electrolyzer kits

Task 4. Promote and distribute the curriculum throughout the UC and CSU. Efforts began in summer 2010 to seek other campuses interested in adopting the curriculum. We developed a marketing plan which included directly contacting colleagues at other universities and development and distribution of promotional materials, including a flyer describing the curriculum and a web page where electronic versions of curriculum materials can be downloaded. Later, in response to feedback from engineering faculty that they needed more technical guidance in use of the laboratory equipment, we developed a series of videos, which have been uploaded to YouTube and linked to the project web page.

- Contacts with colleagues: We spoke with or emailed numerous engineering faculty members in the UC and CSU systems who we already knew to have an interest in hydrogen energy, such as Alexandra von Meier at Sonoma State University and David Blekhman at California State University Los Angeles. Participation by project staff in intercampus professional meetings, such as the 2011 Green Campus Summit in Long Beach, CA led to additional contacts.
- Development of promotional flyer: The two-page flyer was developed at the request of Dr. David Blekhman at CSU Los Angeles, who used it to promote interest in the curriculum among his colleagues. The flyer, titled "Tools for Teaching About Hydrogen and Fuel Cells," describes the curriculum and equipment and is illustrated with photographs showing students performing hydrogen experiments.
- Creation of web page: The web page, hydrogencurriculum.org, was created to provide a single online location for promoting the curriculum and providing downloadable versions of all written curriculum materials, including lecture presentation slideshow, lab handouts, and instructor guides. We later expanded the website to include links to the instructional videos we produced.

- Creation of videos: During year two of the project, we received feedback from faculty at other campuses that they felt uncomfortable using the H_2E^3 equipment, particularly the fuel cell test stations, without on-site technical support. Not having the means to provide this support at distant campuses, we decided to produce a series of videos demonstrating use of the equipment. As the curriculum grew, we produced additional videos. For example, when students expressed confusion about the design and operation of the fuel cell stacks used on the test stations, we created a video showing the parts of a fuel cell and the assembly process. We also created a video "virtual tour" of the HSU Hydrogen Fueling Station, which will enable faculty at campuses lacking their own fueling station to have their students perform the fueling station analysis exercise we developed as part of the curriculum.
- Coordination with campus-based fuel cell projects: During the second year of the project, we learned that California electric utilities PG&E and SCE were granted permission by the state Public Utilities Commission to use ratepayer funds to install fuel cell power systems at several public university campuses. However, the PUC denied the utilities' requests to use additional ratepayer funds to work with these universities to tie the fuel cell projects in with campus curriculum. We saw an opportunity to help fill this educational gap using H_2E^3 curriculum. We approached the utilities, which in turn referred us to staff and faculty at the universities hosting fuel cell projects. This eventually led to participation in H_2E^3 curriculum by San Francisco State University, which is the site of a 1.4 MW molten carbonate fuel cell and a 200 kW solid oxide fuel cell. At the time of writing this report, both of these fuel cell systems, including heat recovery for campus use, are complete and operational. The project web page for the SFSU fuel cell project is: www.sfsu.edu/~build/construct/fuelcell.htm.
- In-person visits to campuses: After identifying interested faculty at other campuses, project staff visited faculty at UCB, Sonoma State University, San Francisco State University, and University of California Santa Cruz. We discussed the curriculum with them, toured their energy education facilities, and demonstrated our fuel cell/electrolyzer kits (see Figure 6).

Figure 6. Faculty at UC Santa Cruz try out H_2E^3 curriculum

- Providing sample fuel cell/electrolyzer kits to interested faculty: The fuel cell/electrolyzer kits are engaging, highly portable, safe, and easy to use, making them an ideal way to market the curriculum to faculty who may have little prior experience with fuel cells and hydrogen. We provided one or more demonstration kits to interested faculty at the following campuses:
    - UC Berkeley (Dr. Michelle Douskey, Berkeley Center for Green Chemistry)
    - UC Santa Cruz (Dr. Ali Shakouri and Dr. Tamara Ball, Dept. of Electrical Engineering and Sustainability Engineering and Ecological Design [SEED] Project)
    - UC Riverside (Dr. Kawai Tam, Dept. of Chemical and Environmental Engineering)
    - CSU San Bernardino (Dr. Joe Scarcella, College of Education)
    - San Francisco State University (Dr. Ahmad Ganji and Dr. Ed Cheng, Dept. of Mechanical Engineering)
    - CSU Los Angeles (Dr. David Blekhman, Dept. of Power, Energy,and Transportation)
    - Sonoma State University (Dr. Alexandra von Meier, Dept. of Environmental Studies and Planning)

  After having an opportunity to try out these kits, faculty from several of these campuses went on to adopt the curriculum for use in one or more courses (see Figure 7).

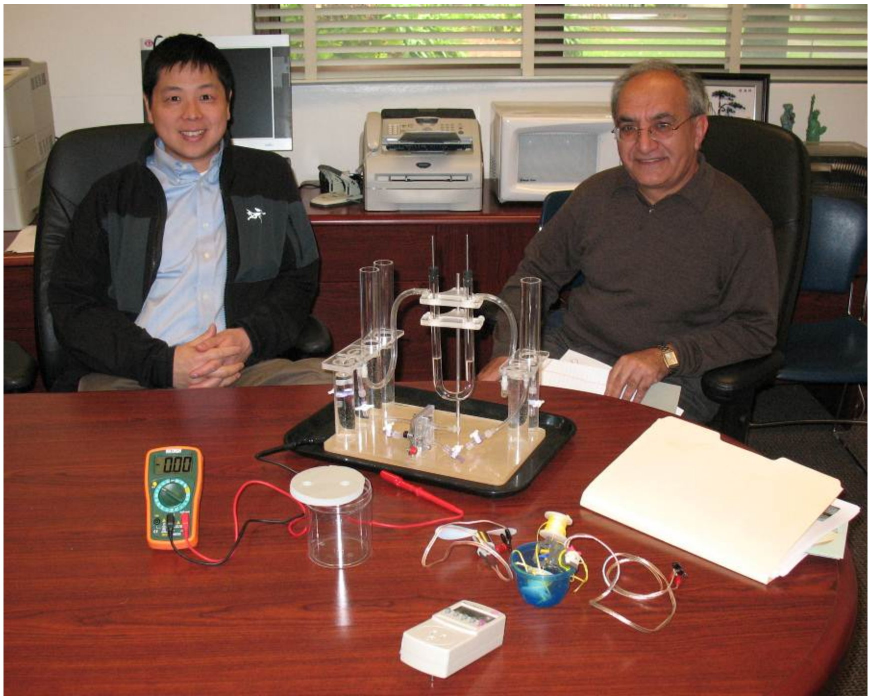

Figure 7. Faculty at San Francisco State University evaluate fuel cell/electrolyzer kit

Task 5. Conduct internships for UCB and HSU students at industry partners. At the time we developed our project proposal, we recruited four fuel cell companies as partners: Jadoo Power Systems, Inc., Protonex Technology Corporation, UTC Power, and IdaTech LLC. Each of these companies offered to provide student internships as part of the project. Our plan was to create internships in summer 2010 for UCB and HSU students who had previously participated in the curriculum.

Early in 2010, we contacted each of these companies with the intention of setting up summer 2010 internships. However, given the global financial downturn and the resulting attrition in the fuel cell industry, we were unable to create any internships that year. As we neared the end of the project in spring 2011, we re-evaluated our remaining project funds and determined that we could reallocate a portion of our travel budget to offer the partner companies a 50% cost share on student stipends. Two of the companies, Jadoo and Protonex, expressed interest in this arrangement.

We facilitated recruiting of applicants among students at UCB and HSU who had participated in the curriculum. Both companies interviewed applicants, but in the end only Protonex was able to identify students whose qualifications met their needs. Two students, Ryan Dunne and Brett Selvig, both undergraduate Environmental Resources Engineering majors at HSU, were hired by Protonex. They relocated temporarily to Protonex headquarters in Massachusetts, where they worked on PEM and solid oxide fuel cell projects for ten weeks from May-August 2011 (See Figure 8).

Figure 8. Interns assembling a test setup around a Protonex PEM fuel cell (photo courtesy of Protonex Technology Corporation)

As discussed below under "Products Developed," our follow-up assessment interviews with the interns and their supervisor demonstrated that all parties were satisfied with the outcome of the internships.

Task 6. Monitor and analyze hydrogen fueling stations as class projects. We developed curriculum that ties two operating hydrogen fueling stations in California to the H_2E^3 curriculum, with the potential to adapt these curriculum activities to other fueling stations.

At HSU, we created the "hydrogen fueling station data analysis" activity described under Task 1 above, making use of operating data collected at the Humboldt State University Hydrogen Fueling Station. The fueling station is the first rural facility on the California Hydrogen Highway system and the northernmost station in the network (see Figure 9). The station uses an on-site electrolyzer and utility power to generate up to 2.5 kg of hydrogen per day. A data acquisition system monitors multiple operating parameters (see Table 2). HSU/SERC operate a fleet of two hydrogen-powered vehicles that make use of the station.

Figure 9. Humboldt State University Hydrogen Fueling Station

Table 2. Fueling Station Data Monitored (Allen 2009)

Measurement	Range	Units
Time Stamp	00:00:00 -1:00:00	HH:MM:SS
Program Run Hours	none	Hours
Compressor Suction Temperature	-100 - 260	°C
Compressor Discharge Temperature	-100 - 260	°C
Tank A Pressure	0 - 7,000	psig
Tank B Pressure	0 - 7,000	psig
Hydrogen Flow	0 - 100	slm
Suction Pressure	0 - 250	psig
Electrolyzer Power	0 - 20,000	Watts
Compressor Power	0 - 6,000	Watts

The curriculum assignment used operating data from the fueling station to assess the difference in electrolyzer efficiency associated with an electrolysis module upgrade. Students in an engineering statistics course reviewed data over several cycles of fuel production before and after module replacement (see example in Figure 10) and determined that there was a statistically significant improvement in module efficiency.

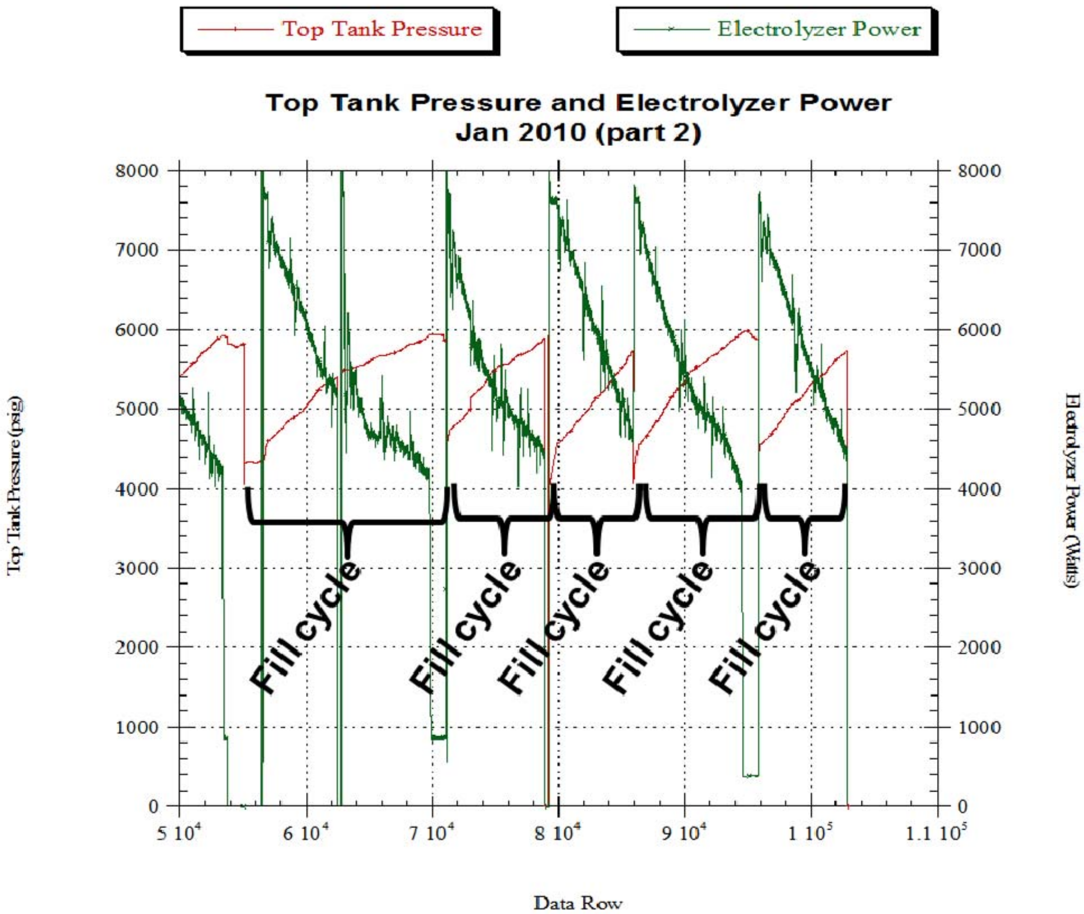

Figure 10. Hydrogen fueling station fill/dispense cycles

At UCB, project partner Dr. Tim Lipman collaborated with SERC to develop a hydrogen safety training at UCB's new hydrogen fueling station. The training was designed with emergency first responders as a principal audience, but a number of graduate students were included in the training in order to learn about hydrogen safety.

Task 7. Implement the curriculum at other UC and CSU campuses. The efforts made under Task 4 bore fruit at several campuses where faculty chose to adopt the H_2E^3 curriculum.

- At San Francisco State University, mechanical engineering professors A.S. (Ed) Cheng and Ahmad Ganji adopted the curriculum, including lab activities with the fuel cell/electrolyzer kits, for use in their Engineering 300 (Engineering Experimentation) class during fall semester 2011.
- At Sonoma State University, Dr. Alexandra von Meier's ENSP 201 (Energy Forum) class is using the curriculum, including lab activities with the fuel cell/electrolyzer kits.

- At University of California Riverside, Dr. Kawai Tam of the Chemical and Environmental Engineering Department is using the fuel cell/electrolyzer kits and associated curriculum in her Green Engineering (CEE 132) course.

Task 8. Conduct internships for UC and CSU students at industry partners. As noted above under Task 5, we were delayed one year in creating internships for UCB and HSU students. Due to this unavoidable setback in the project timeline, we were not able to facilitate internships for students from other UC and CSU campuses as part of this project. However, both Protonex Technology Corporation and Jadoo Power expressed interest in future hiring of student interns, especially if we are able to provide a cost share on the student stipends as we did using reallocated DOE project funds in summer 2011.

Task 9. Conduct project monitoring and evaluation. We developed a process for monitoring key aspects of the project, including student learning outcomes, instructors' impressions of the curriculum, and outcomes for the student interns and their mentor/supervisors. See "Assessment Tools" under "Products Developed" below for a more detailed account of our monitoring and evaluation process. Outcomes from the monitoring and evaluation process were actively used throughout the project to iteratively improve the content and delivery of the curriculum.

Task 10. Conduct project management and reporting. Project principal investigator Peter Lehman designated SERC senior research engineer Richard Engel as project manager. We created and managed a project budget and schedule. VertaBase project management software was used for tracking personnel time, completion of tasks, and expenditures. All periodic deliverables to DOE, including quarterly and annual reports, Annual Merit Review presentations, and financial reporting forms, were delivered complete and on time. Peter Lehman or Richard Engel attended the Annual Merit Review meetings in 2009, 2010, and 2011 to give oral presentations on project status. The presentations were well received by the reviewers.

An ancillary activity was added to the project in response to comments from reviewers at the May 2011 Merit Review meeting. Reviewers noted that the curriculum should be adapted for use with high school students. During summer 2011, we held a workshop in which high school students from an Upward Bound program in Lower Lake, CA were given a lecture on hydrogen and fuel cells and performed experiments similar to those used in our introductory engineering module. The workshop was a success, getting positive feedback from the students and their teachers.

Products Developed

Curriculum

The curriculum was designed in the form of modules that can be used to replace a single lecture or multiple lecture and lab periods in a variety of engineering courses. The curriculum simultaneously teaches hydrogen and fuel cell concepts while addressing existing teaching objectives (e.g., laws of thermodynamics, experimental design, electrical circuits) of the courses in which it is used. All lecture presentations and laboratory activities are available on our project website (hydrogencurriculum.org/downloads).

Lecture presentations. We developed a total of 17 lecture presentations that to date have been used in 16 different courses at the five participating campuses (and internationally at two universities in El Salvador).

Laboratory activities. We created seven different lab activities that to date have been used in eleven different courses at the five participating campuses and at the two universities in El Salvador.

Equipment

Test stations. SERC built two complete test stations, identical apart from some minor differences in the data acquisition hardware (see Figure 11). These compact test stations include many of the features found on research-grade test stations built by SERC and others, while emphasizing simplicity and safety for inexperienced operators. Test station specifications are provided in Appendix E.

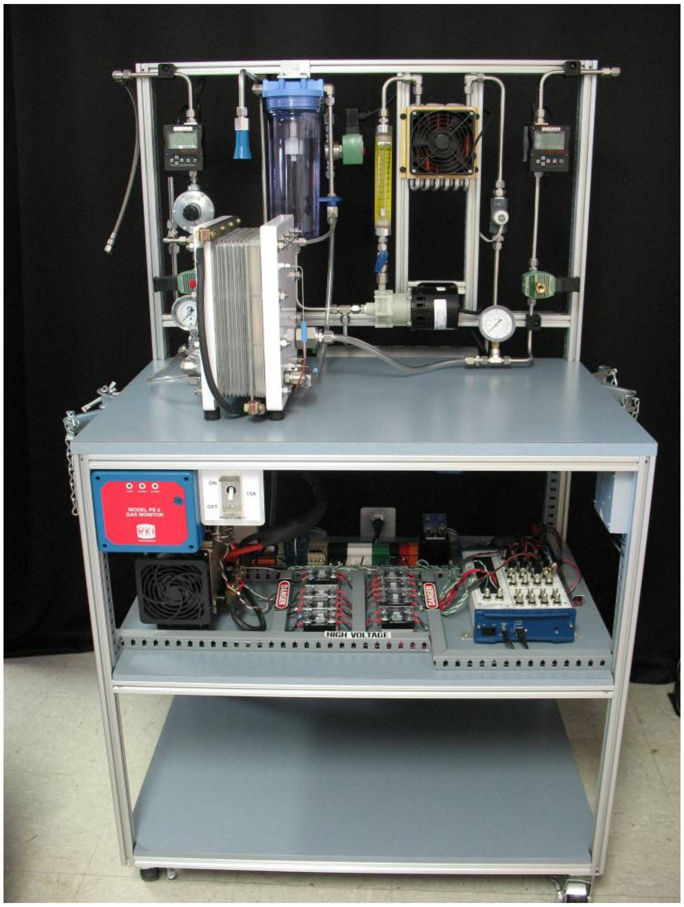

Figure 11. SERC fuel cell test station

The test stations are designed only for attended operation over short periods (e.g., a three-hour lab period). The test stations are designed to accommodate low pressure, dead-ended hydrogen fuel cells at a maximum power of 500 W. They are designed specifically for operation with an eight-cell, 300 cm^2 stack made by SERC and provided with each test station (see Figure 12). Stack specifications are provided in Appendix F.

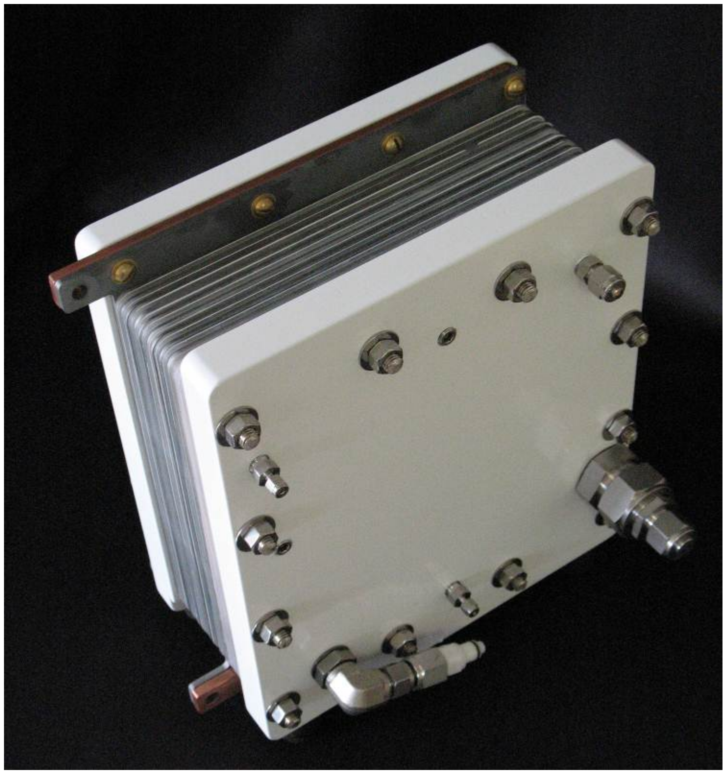

Figure 12. SERC 500W fuel cell stack

The test stations are operated with a user-supplied computer loaded with software that interfaces with the test station's data acquisition and control hardware. A graphical user interface allows the test station operator to view real-time indicators and make changes to operating parameters while data are written to a file for later analysis (see Figure 13). The test station allows the user to perform automated operations such as generating current-voltage polarization curves for each cell (see Figure 14).

Figure 13. Test station user interface

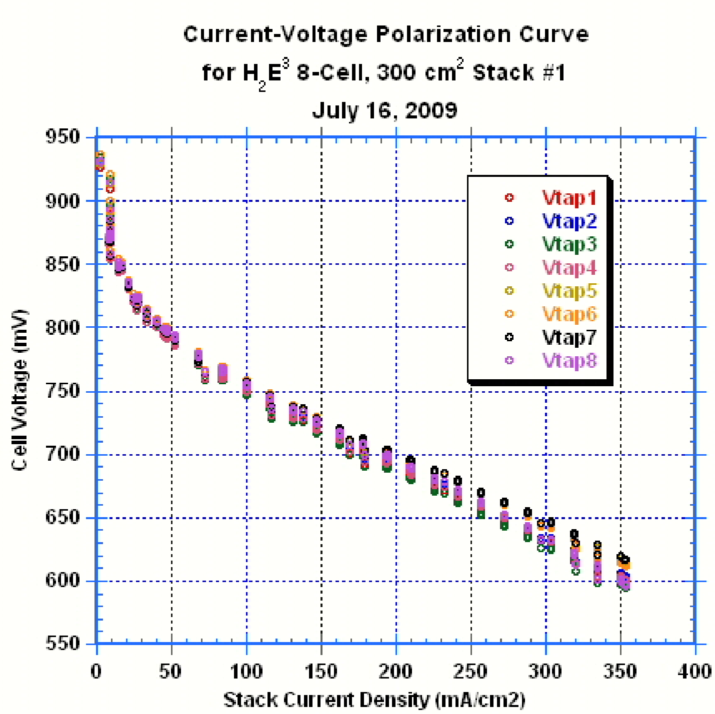

Figure 14. Current-voltage polarization curve generated using H_2E^3 test station

Fuel Cell/Electrolyzer Experiment kits. SERC built a total of 54 fuel cell/electrolyzer experiment kits (see Figure 15). The benchtop kits include an alkaline electrolyzer, gas storage columns, and a proton exchange membrane fuel cell. Students use simple techniques and instrumentation to measure electrolyzer and fuel cell performance and calculate efficiency of each component and the system overall. Electric load, 12V power supply, and instructor's manual are also included. The electrolyzer can alternatively be powered by a user-supplied solar module or other low-voltage DC power source. Twenty-four of these kits were built under the original project budget; an additional thirty were built using $15,000 in supplemental funds from DOE, allowing us to deploy kits simultaneously at more campuses. Specifications for the kits are provided in Appendix D.

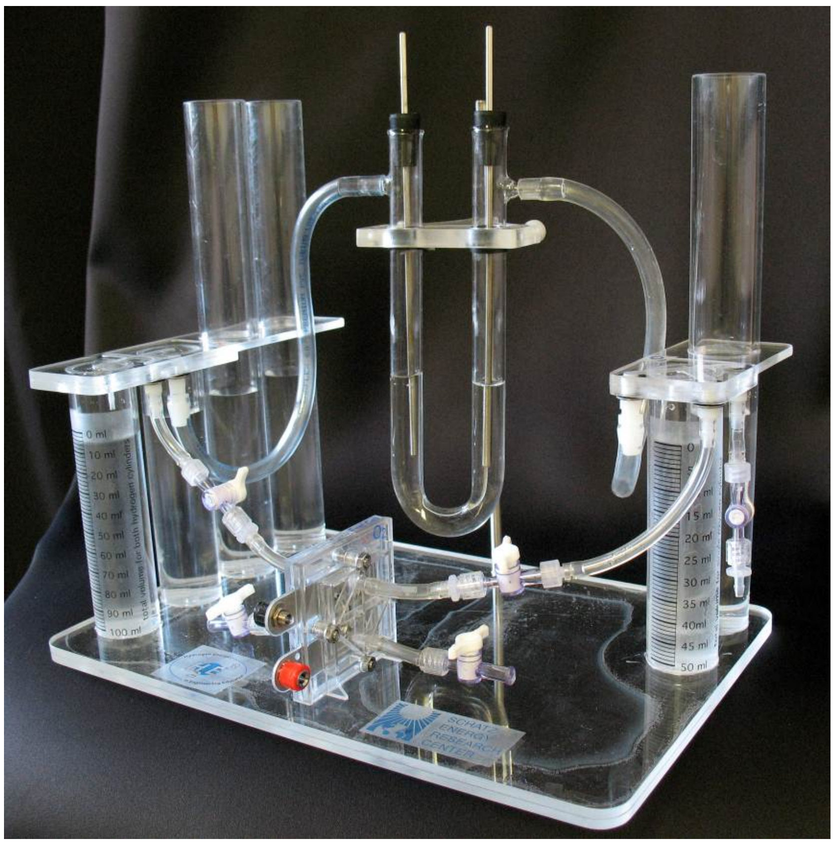

Figure 15. SERC fuel cell/electrolyzer experiment kit

Marketing/outreach tools

Web site. The project web site, hydrogencurriculum.org, was created by SERC staff using Joomla content management system. The site provides a portal to general information about the H_2E^3 project, access to downloadable curriculum materials (lecture presentations, labs, and instructional support tools), a list of recommended readings, links to the websites of project partners, and links to H_2E^3 videos that have been posted on YouTube (see Figure 16).

The web site has enjoyed significant levels of visitor traffic. For example, during a one-week period in August 2011, the site had 158 unique visitors who viewed a total of 521 pages. SERC intends to keep the site active indefinitely.

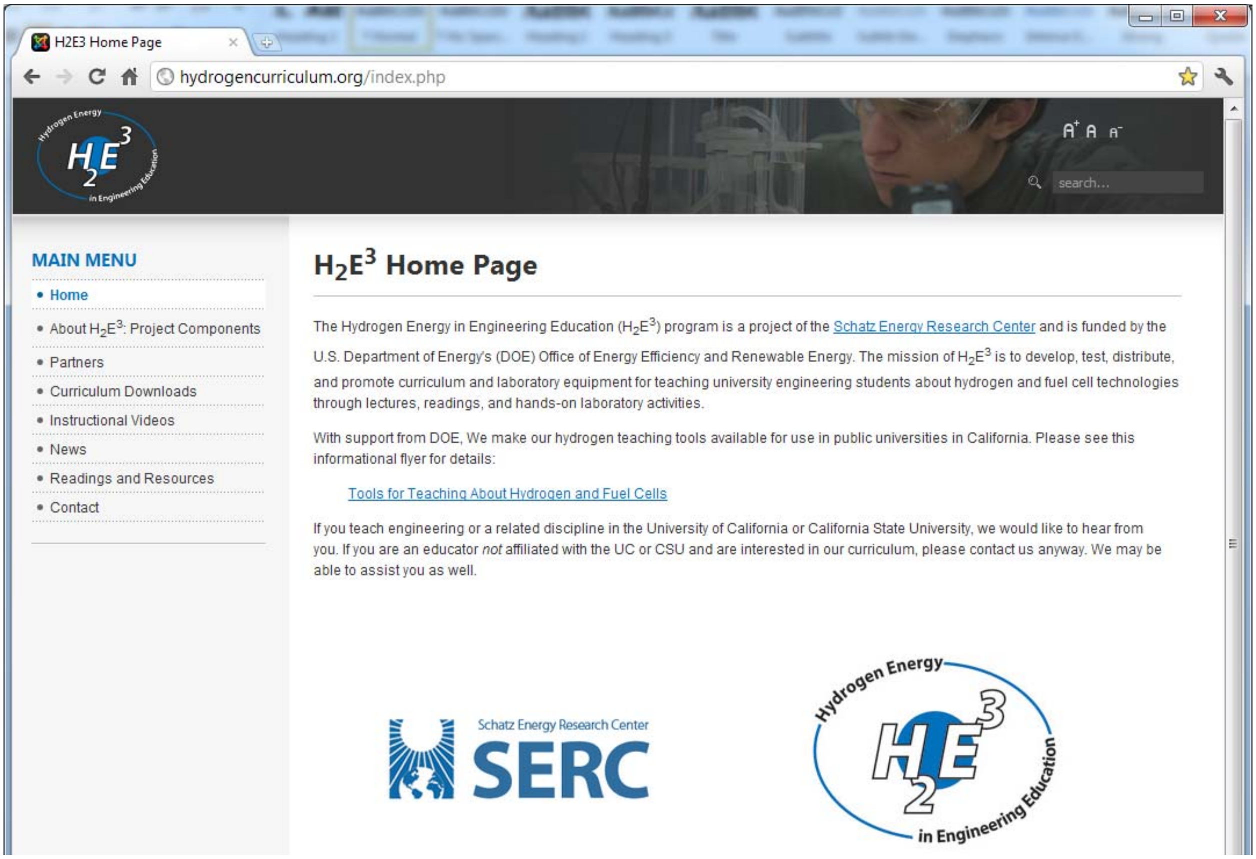

Figure 16. Project website, hydrogencurriculum.org

Flyer. Project staff produced and distributed a two-page flyer (available at hydrogencurriculum.org/images/documents/h2e3%20flyer.pdf) that describes the curriculum and equipment made available as part of the project. The flyer was made available online and distributed in printed form to instructors who expressed interest in the curriculum.

Instructional support tools

Test station O&M manual. A comprehensive manual for using the test stations is available online at: hydrogencurriculum.org/images/documents/h2e3%20test%20station%20version%201%20om%20manual.pdf

The manual provides a component-by-component description of the test station, laboratory resources required for operating the station, detailed instructions on operating and maintaining the station, a troubleshooting guide, and safety guidelines. As a supplement to the manual, a single-sheet laminated “Quick start guide” is attached to each test station to remind users of the basic start-up and shut-down procedures.

Instructor guide for fuel cell/electrolyzer kit. A ten-page instructor guide (hydrogencurriculum.org/images/documents/h2e3%20kit%20instructor%20guide%20feb%202011.pdf) provides instructors with guidance on using the fuel cell/electrolyzer kits with students in the lab. The guide explains the kit contents and nomenclature and offers tips on caring for the kit components. A sheet on lab safety and a set of wiring diagrams for setting up the kits are also included.

Videos. SERC staff produced a series of eleven videos as part of the curriculum package (see Figure 17). Nine of the videos provide detailed instructions on using the test stations and hydrogen experiment kits. These videos were originally produced with instructors as the intended audience, as some instructors had expressed uncertainty about using the H_2E^3 equipment using only written instructions. However, we have found that instructors also like to have their students view these videos prior to performing the labs in order to be better prepared.

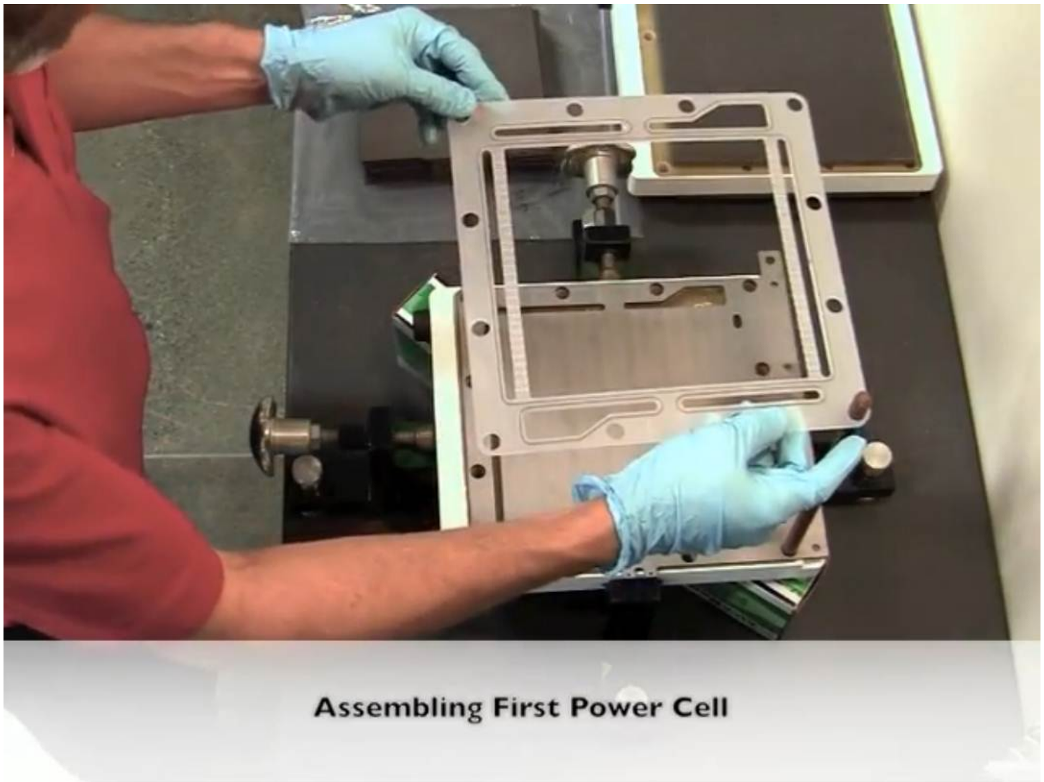

Figure 17. Still from video “H_2E^3: Building a Fuel Cell Stack”

Another video in the series is a virtual tour of the Humboldt State University Hydrogen Fueling Station. This video is intended to supplement the curriculum activity in which students analyze performance of the fueling station’s electrolyzer.

We also produced a video that shows the process of building a PEM fuel cell stack. This video was developed in response to comments from upper division students who generally felt comfortable operating the fuel cell test station under supervision but said they considered the stack itself to be a “black box.” The video shows and discusses the stack parts in some detail, which should help to demystify stack design and operation.

All of the videos are posted on YouTube on the Schatz Energy Research Center’s channel (www.youtube.com/ SchatzLab) and are linked to the H_2E^3 project website (hydrogencurriculum.org/instructional-videos). The videos are drawing viewers. Of the ten videos posted by October 2011, the average number of “views” per video was 115, with the most popular video having been watched 337 times.

Assessment tools

As described above, Task 9 consisted of developing and using monitoring and evaluation tools to assess the success of the project and make iterative improvements in the curriculum over the course of the project. Specific assessment tools developed included:

- Pre- and post-activity student assessments in the form of one- or two-page written “quizzes.” For any given lecture or lab activity where assessments were used, the students were asked the same set of learning assessment questions pre- and post-activity in order to estimate the learning impact of the activity. In addition, students were asked for their opinions and suggestions regarding the activity in each post-activity assessment.
- Assessment of instructors using focus groups and written assessments. Instructors unable to participate in a focus group meeting were asked to complete a written assessment as an alternative. In addition, instructors participated in a final written survey near the end of the project.
- Direct monitoring of lectures and labs by project staff. We attended numerous lecture and lab sessions where the curriculum was used, taking notes and meeting afterward to discuss among project staff our observations and opportunities to improve the curriculum or its delivery.
- Assessment of interns and intern mentor/supervisors. The interns participated in face-to-face interviews to assess their experiences as interns. Their mentor/supervisor at Protonex Technology Corporation was interviewed by phone.

Pre- and post- assessment questions that queried students on key learning objectives were developed for each of the following curricular activities.

- Introductory fuel cell kit lab
- Advanced fuel cell kit lab
- Data analysis of hydrogen fueling station

- Introductory test station lab

These survey instruments are provided in Appendix B.

Summary of assessment for fuel cell kits. The feedback given by the students who used the fuel cell kits in lab was overwhelmingly positive, with nearly 100% of the students agreeing that the curriculum and instrumentation were effective learning tools. Students enjoyed being able to set up their experiments and see how fuel cells worked first hand. Many students commented that the labs where they used the fuel cell test kit or the test station were "fun", "awesome", and that they "liked", "enjoyed" or "loved" this lab. In addition, the pre- and post- surveys indicated that students were gaining knowledge with regards to the specific learning objectives identified and gaining confidence in their abilities to conduct experiments using the laboratory equipment.

Although student and instructor feedback has been strongly positive throughout the project, we also received useful critique. We used the assessment outcomes to make iterative improvements to the curriculum, the equipment, and the assessment tool itself. Several questions were reworded or modified on the assessment surveys to better address the specific learning objective of interest.

In addition to improving the assessment tool, the most valuable lessons learned from the pre/post assessments of the fuel cell kits included: 1) parallel and series circuits remain confusing for the students and care must be taken in presenting the wiring set-up for the kits; 2) there is confusion about the system components and terminology, specifically the boundary between gas production (i.e. the electrolyzer) and gas storage, and 3) presenting introductory material prior to the lab session rather than at the beginning of the lab will facilitate greater understanding of the exercise and allow for more time on the experiment and efficiency calculations. The project team did make minor hardware changes to the fuel cell kits to facilitate easier connections. We also modified the curriculum to more clearly present and explain the wiring diagrams and lab handouts.

Summary of assessment for test station. Although the majority of the students using the fuel cell test station agreed the test station was an effective learning tool (90%), it was clear from the open-ended comments that the curriculum associated with the test station is more difficult to integrate into traditional engineering coursework. Approximately 50% of the students providing open-ended responses commented on ways to make the activity more effective. There was a higher level of satisfaction with this lab activity with each successive implementation. It seems clear that the added complexity of using the test station requires more careful development and implementation of the curriculum. In addition, the limitations of having only one test station for students to use require careful planning for access.

Summary of assessment for hydrogen fueling station curriculum. The assessment of the data analysis conducted on the hydrogen fueling station data indicated overwhelming positive responses from students. It was clear the students gained an increased understanding of how the hydrogen fueling station worked and appreciated the relevance of the data analysis they completed for the course. In our pre- and post- assessment surveys we realized that the focus of the survey was on one of the learning objectives (learning about hydrogen fueling and vehicles) and much less on the course-specific primary learning objectives of applying hypothesis testing and calculating confidence intervals. In the second implementation, we queried students on their perception of the learning objectives. The results indicated the students did not view the concepts of hypothesis testing and confidence intervals as main objectives. The surveys should be expanded to include questions asking them to conduct hypothesis testing and calculate confidence intervals operations to assess their learning.

Final project survey. A survey was launched at the end of this funded project period to all faculty, staff, and teaching assistants who utilized any of the curriculum or lab equipment developed as part of the H_2E^3 project. Detailed results are in Appendix A.

The respondents were very positive about their ability to integrate this curriculum in their on-going courses and found the material helpful in achieving course objectives. The majority of respondents agreed that the use of this curriculum and laboratory instrumentation either somewhat increased or greatly increased the inclusion of the topic of hydrogen energy in their curriculum. Greater than half the respondents utilized the slide presentations in one or more lectures in their courses and stated they were very likely to keep using these slides. The majority of the respondents (83%) who used the fuel cell laboratory kits in their classes found the curriculum and kits very helpful in achieving their course objectives. Only a slightly smaller majority (73%) of the respondents who used the test stations in their courses ranked the curriculum as very helpful for achieving course objectives.

Assessment of internships. Assessment interviews demonstrated that both interns and their mentor/supervisor were pleased with the outcomes of the internships. Both students, Brett Selvig and Ryan Dunne, noted that their participation in the H_2E^3 curriculum at HSU helped them arrive prepared at Protonex. Their mentor, Nate Palumbo, stated that he hopes to re-hire Ryan as a summer intern in 2012 and invited Brett, who is graduating in the current academic year, to apply for permanent employment at Protonex. This is a powerful testament to the success of these internships. Notes on the assessment interviews are included in Appendix C.

Relating our assessment effort back to the expected outcomes stated in the SOPO, the assessments were aimed principally at evaluating outcomes 1 and 2 (increased use of hydrogen curricula and increased understanding of hydrogen energy among students). Outcome 3 (an increase in students pursuing careers or post-graduate studies in hydrogen energy) will only become apparent over a time scale beyond the scope of the current project, though the positive outcomes for the project interns suggest prospects are good.

The monitoring and evaluation process turned out to be a very useful tool in measuring and improving the success of the project. It was encouraging to see that the assessments by students and faculty were generally positive and improved over time with iterative changes made to both the assessment tools and the curriculum itself.

Future directions

SERC intends to maintain the momentum created by this project. We hope to:

- provide continuing support for campuses that have already adopted the curriculum
- continue to create new curriculum modules and update existing ones
- expand adoption of the curriculum geographically beyond California. (Dr. David Blekhman of California State University Los Angeles has taken two of the kits with him to Russia, where he is serving as a visiting Fulbright Scholar while on sabbatical from CSULA.)
- pursue business opportunities to provide lab equipment based on the H_2E^3 equipment designs to other universities and colleges.
- identify a private-sector partner with whom we can work to commercialize the equipment developed under H_2E^3, enabling us to cost-effectively bring these learning tools to more users.

While near-term prospects for hydrogen education funding through DOE EERE appear limited, program staff and fellow awardees have pointed us toward other financial resources that may be of help in maintaining and expanding H_2E^3.

Conclusion

The Hydrogen Energy in Engineering Education project has been a great success on many levels. We have achieved or exceeded all of our project objectives, and the expected outcomes expressed in our original statement of project objectives are being realized. Both our formal monitoring and evaluation process and our casual face-to-face contacts have shown that students and instructors who participated are enthusiastic about the curriculum. The project found a wide audience, with faculty in mechanical, electrical, chemical, and environmental engineering, as well as non-engineering disciplines and high school teachers adopting the curriculum. SERC staff have enjoyed the support and collaboration we have received from DOE EERE staff in implementing this project.

Publications and Presentations

Lehman, Peter and Engel, Richard. "Hydrogen Education for California's Public Universities: Project Overview." Presentation for project kickoff meeting. Oct. 30, 2008.

Engel, Richard. "University H_2 Curriculum Project Gets Underway," *SERC Energy News*. Winter 2008.

Engel, Richard. "Project Update: University Hydrogen Curriculum," *SERC Energy News*. Spring 2009.

Schatz Energy Research Center. *Fuel Cell Test Station Operation and Maintenance Guide.* 2009.

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,"[1] 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," AASEE Annual Conference & Exposition, Louisville, KY.

Cashman, E., Engel, R., and Lehman, P. (2010) "Hydrogen Energy in Engineering Education," Proceedings of the 40th ASEE/IEEE Frontiers in Education Conference, October, Arlington, VA, IEEE Catalog number: 978-1-4244-6262-9/10.

Lehman, Peter A. "Hydrogen Energy in Engineering Education (H2E3)." Presentation for U.S. Department of Energy Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. May 21, 2009.

Lehman, Peter A. "Hydrogen Energy in Engineering Education (H2E3)." Presentation for U.S. Department of Energy Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. June 10, 2010.

Engel, Richard. "Hydrogen Energy in Engineering Education (H2E3)." Presentation for U.S. Department of Energy Hydrogen Program Annual Merit Review and Peer Evaluation Meeting. May 10, 2011.

Schatz Energy Research Center. "Tools for Teaching About Hydrogen and Fuel Cells." 2010.

Petroske, Jared. "Positive Energy: The Schatz Energy Research Center is Building a Renewable Future Today." Humboldt Magazine. Spring 2011. http://magazine.humboldt.edu/spring11/positive-energy/

Lipman, Timothy. "Hydrogen Production and Storage for Fuel Cells: Current Status." webinar presentation for DOE/Clean Energy States Alliance/Technology Transition Corporation Brown Bag Series on hydrogen and fuel cells. February 2, 2011 www.cleanenergystates.org/resource-library/resource/hydrogen-production-and-storage-for-fuel-cells-current-status-presentation-by-tim-lipman

Zoellick, James I. "First Responder Training for UC Berkeley Richmond Field Station Hydrogen Fueling Station." May 2011.

Dunne, Ryan and Brett Selvig. "Project Updates: Hydrogen Energy In Engineering Education (H2E3)." *SERC Energy News.* Fall 2011.

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[1] Selected for best paper in the Energy Conversion and Conservation division for the 2010 ASEE Annual Conference & Exposition, Louisville, KY.

Curriculum Materials:

Lab handout, blank wiring diagram, and safety guidelines for use in ENGR 115, introduction to environmental resources engineering (HSU)

Lab handout, blank wiring diagram, and safety guidelines for use in ENGR 331, introduction to thermodynamics (HSU)

PowerPoint presentation for E100, energy and society (UCB)

Monitoring and evaluation report on ENGR 331 (HSU) and E100 (UCB)

Lab handouts for use in ENGR 471, advanced thermodynamics (HSU):

- Lab Experiment #1 – Operating the Fuel Cell Test Station
- Lab Experiment #2 – Evaluating the Performance of a PEM Fuel Cell

Materials for Probability and Statistics Course

- Pre-lab lecture presentation: "The HSU Hydrogen Fueling Station"
- Assignment handout: "Performance of the Electrolyzer at the HSU Hydrogen Fueling Station"

Materials for Test Station Lab for Renewable Energy Power Systems Course

- Lecture Presentations: "Hydrogen and Fuel Cells" and "Using the Fuel Cell Test Station"
- Assignment handout: "Performance and Design of PEM Fuel Cell Stacks"

Materials for Test Station Lab for Transport Phenomena

- Assignment handout: "Fuel Cell Heat Balance Lab"

Materials for Energy Forum senior/graduate level course

- Lecture presentations: "Hydrogen, Electrolyzers, and Fuel Cells" and "Fuel Cell and Electrolyzer Lab Activity"

Materials for Graduate Level Hydrogen Safety Seminar

- Lecture presentations: "The Promise of Hydrogen" and "First Responder Training for UC Berkeley Richmond Field Station Hydrogen Fueling Station"

Spanish language publications:

- "Juego para Experimentos con Hidrógeno: Celda de Combustible y Electrolizador. Guía para docentes para uso en cursos introductorios en ingeniería y termodinámica" (translation/adaptation of "Hydrogen Fuel Cell / Electrolyzer Kit Instructor Guide for Use in Introductory Engineering and Introductory Thermodynamics Courses" from H_2E^3 curriculum collection)
- "Actividad: Diseño de Celda de Combustible" (translation/adaptation of "Fuel Cell System Design Activity" originally created as part of the DOE-funded HyTEC high school hydrogen curriculum development project)

Videos:

H2E3 - Using and Caring for the H2E3 Fuel Cell/Electrolyzer Kits. http://youtu.be/I6i3Z_WLyjM

H2E3 - Introduction to Engineering Fuel Cell and Electrolyzer Lab. http://youtu.be/Rx_lcFp-mzs

H2E3 - Introductory Thermodynamics Lab I and Lab II. http://youtu.be/7BKxYyKH2eU

H2E3 - Fuel Cell Test Station Software Overview. http://youtu.be/IFooNsV8eqs

H2E3 - Fuel Cell Test Station Orientation and Care. http://youtu.be/3xDSjetWob4

H2E3 - Fuel Cell Test Station Startup and Shutdown Part I. http://youtu.be/GoywLP40e1I

H2E3 - Fuel Cell Test Station Startup and Shutdown Part II. http://youtu.be/1mOfgnxqs-w

H2E3 - Fuel Cell Test Station Startup and Shutdown Part III. http://youtu.be/Vm_uxl1222o

H2E3 - Fuel Cell Test Station Startup and Shutdown Part IV. http://youtu.be/IvxjrIgMzzU

H2E3 - Building a Fuel Cell Stack. http://youtu.be/GcbrHAPmoh8

H2E3 - HSU Hydrogen Fueling Station Tour. http://youtu.be/pwT2kVEgD_w

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Allen, Andrea L. *Efficiency and Performance Measurements of a PDC Inc. Single Stage Diaphragm Hydrogen Compressor.* A Thesis Presented to The Faculty of Humboldt State University In Partial Fulfillment Of the Requirements for the Degree Master of Science In Environmental Systems: Environmental Resource Engineering. August, 2009.

Appendices

A. Analysis of Final Survey of Instructors

B. Student and Instructor Survey Instruments

C. Notes on Internship Assessment Interviews with Interns and Mentor

D. Hydrogen Experiment Kit Specifications

E. Test Station Specifications

F. Fuel Cell Stack Specifications

Appendix A: Analysis of Final Survey of Instructors

A survey was launched through Google Docs to all faculty, staff and teaching assistants who utilized any of the curriculum or lab equipment developed as part of the H2E3 project. The survey was issued in August, 2011 to 22 potential participants. We received responses from 14 of the 22 resulting in a 64% response rate.

The survey was issued on August 7, 2011 and a second reminder sent out on August 14, 2011. Figure 1 below illustrates the responses per day during that period. The survey questions along with a summary of the responses are presented in the following sections.

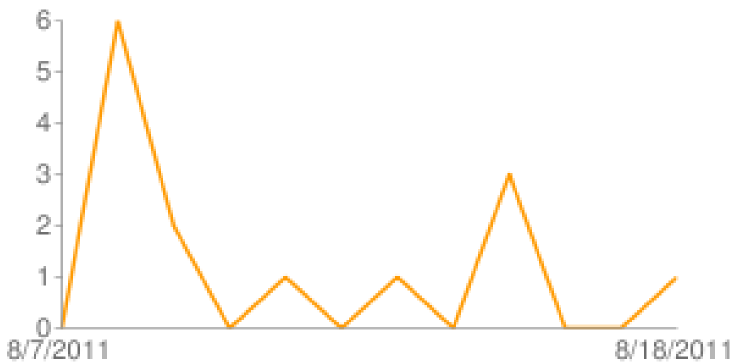

Figure 1: Daily response counts to Google survey.

H2E3 Project Final Survey

Dear Instructor:

The Schatz Energy Research Center operated the Hydrogen Energy in Engineering Education (H2E3) project during 2008-2011 with financial support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. The program consisted of development of hydrogen curriculum and associated laboratory equipment, including hydrogen fuel cell/electrolyzer experiment kits and fuel cell test stations.

The project is now approaching its scheduled end. As a user of the curriculum and lab equipment, your feedback is important to us. We are documenting input from instructors and students and will use this helpful information as we seek future support to distribute the curriculum more broadly and business partners to commercialize the lab equipment. Please take a few minutes to respond to the following voluntary survey.

Your responses to this survey will be aggregated with other instructors' responses for analysis and reporting. Your responses may also be quoted or referred to anonymously in our final report to DOE and in other documents, but your identity will not be revealed in connection with your responses.

Depending on your responses, you may be asked to complete a maximum of five screens of questions. We expect your participation to take 5-15 minutes.

Question 1: How important do you consider the topic of hydrogen energy for inclusion in your courses?

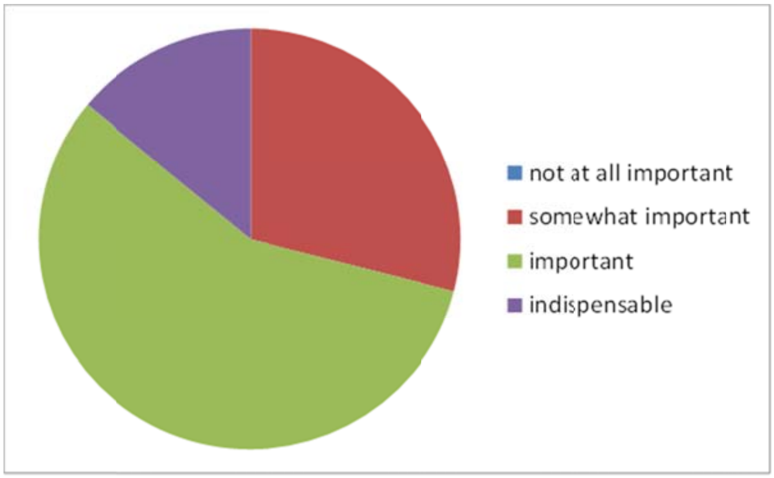

Figure 2: Responses to Question 1 of the H2E3 final survey.

Table 1: Percentage of answers by category in response to Question 1

category	% of answers
not at all important	0
somewhat important	29
important	57
indispensable	14

Question 2: What effect did the H2E3 curriculum have on the inclusion of the topic of hydrogen energy in the course(s) in which you used it (in comparison with previous quarters or semesters before you used this curriculum)?

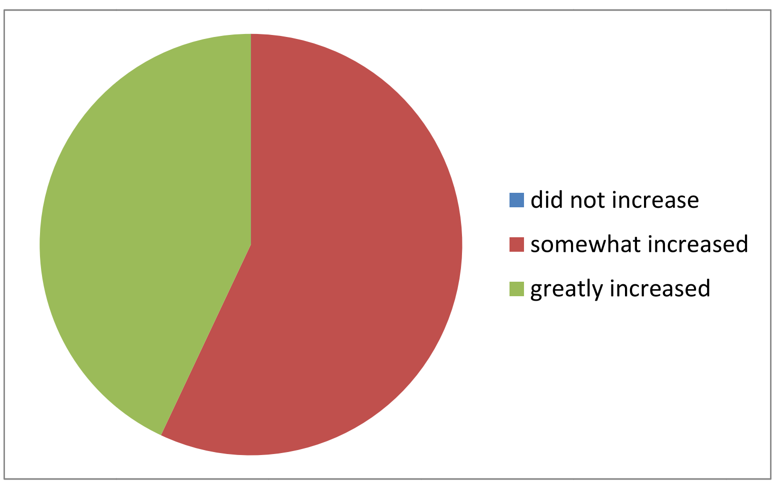

Figure 3: Responses to Question 2 of the H2E3 final survey.

Table 2: Percentage of answers by category in response to Question 2

category	% of answers
did not increase	0
somewhat increased	29
greatly increased	57

Question 3: Did you use the lecture slides that were developed as part of the H2E3 curriculum in your class or lab? If you select "NO" and did not use the lecture slides, the survey will automatically skip all questions related to this topic.

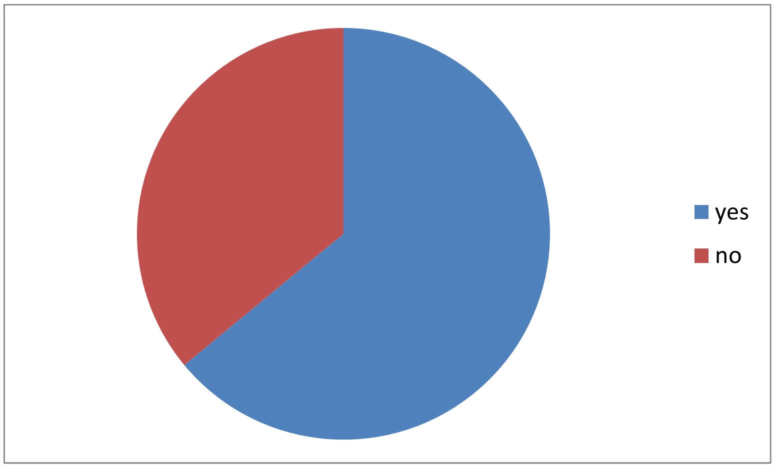

Figure 4: Responses to Question 3 of the H2E3 final survey.

The majority of the survey respondents (64%) used lecture slides in their classes. Questions 3a-3e were answered only by the those who self-identified as having used the lecture slides in their student activities, and the percentages are based on that number of responses.

Question 3a: How much use have you made of H2E3 lecture/slide shows (in total for all courses you teach)?

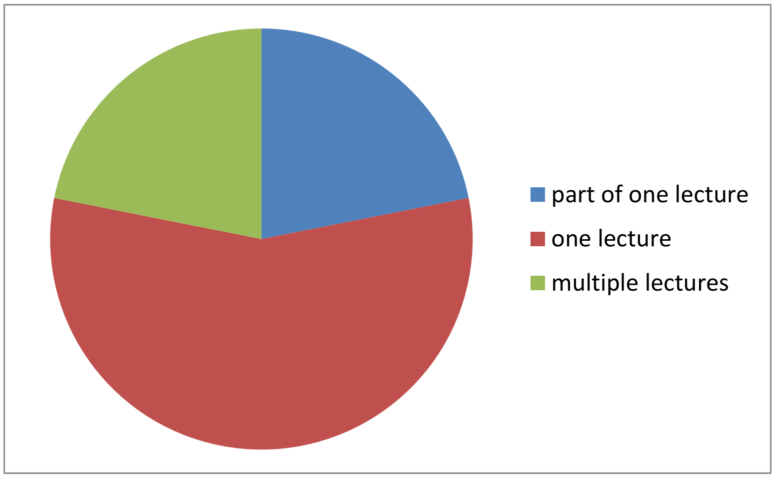

Table 3: Percentage of answers by category in response to Question 3a

category	% of answers
part of one lecture	22
one full lecture	56
multiple lectures	22

Figure 5: Responses to Question 3a of the H2E3 final survey.

Question 3b: How did you use the lecture/slide shows?

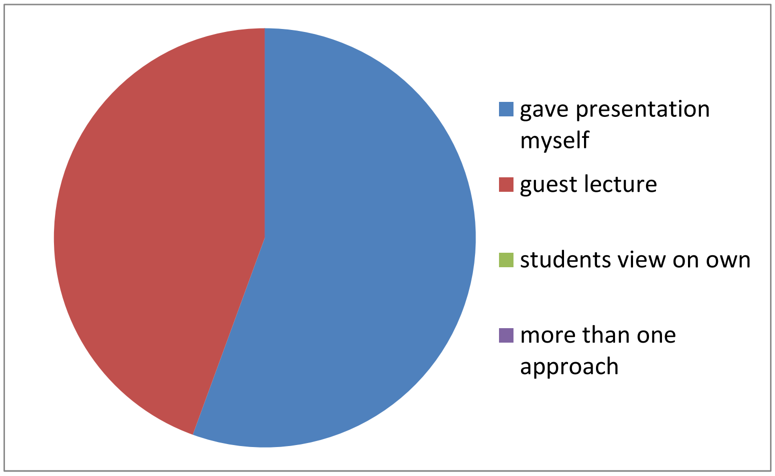

Table 4: Percentage of answers by category in response to Question 3b

category	% of answers
gave presentation myself	56
guest lecture	44
students view on own	0
more than one approach	0

Figure 6: Responses to Question 3b of the H2E3 final survey.

Question 3c: Were the lecture/slide shows helpful in meeting your course objectives?

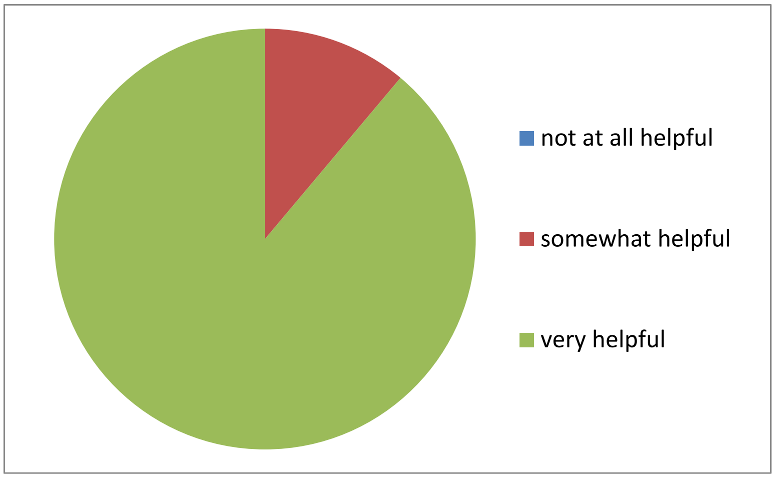

Table 5: Percentage of answers by category in response to Question 3c

category	% of answers
not at all helpful	0
somewhat helpful	11
very helpful	89

Figure 7: Responses to Question 3c of the H2E3 final survey.

Question 3d: How likely are you to continue using the H2E3 lecture/slide shows in your course?

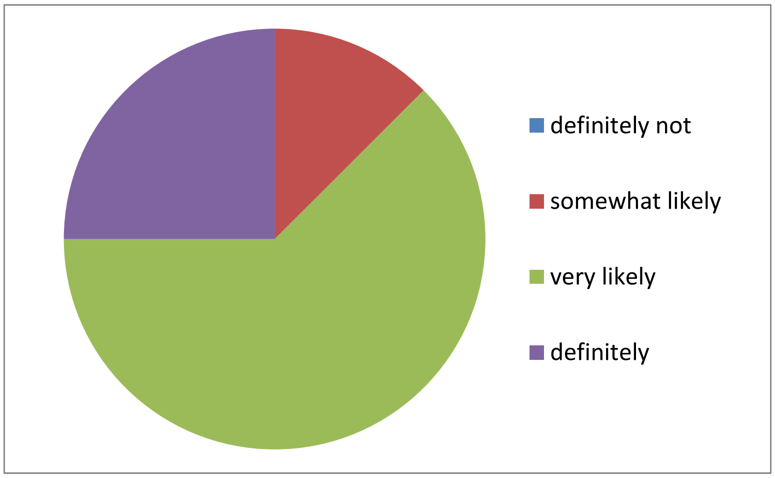

Figure 8: Responses to Question 3d of the H2E3 final survey.

Table 6: Percentage of answers by category in response to Question 3d

category	% of answers
definitely not	0
somewhat likely	13
very likely	63
definitely	24

Question 3e: Please share any comments you have on the lecture/slide shows.

- I used them in only one lecture.
- I think next time I would take over that task [delivering the lecture as opposed to a guest lecture].
- Should be further developed to apply more specifically to the course in which they are be ing used and help meet that course's overall objectives.
- I will not be teaching the course in the immediate future, so I am speculating on what the next instructor will do. That said, I expect they will make use of the H2E3 lecture slides.
- Excellent work on curriculum by project team!
- The lecture materials and slides were very useful. They were especially helpful for presenting concepts related to the first law of thermodynamics (conservation of energy; relationship between chemical, electrical, heat, and mechanical energy).
- We are still adding some refinement to these in collaboration with HSU.

Question 4: Did you use the Fuel Cell Electrolyzer Lab Kits in your class or lab? If you select "NO" and did not use the fuel cell lab kits, the survey will automatically skip all questions related to this topic.

The majority of the survey respondents (86%) used the Fuel Cell Electrolyzer Lab Kits in their classes. Questions 4a-4f were answered only by the 86% who self-identified as having used these kits in their student activities.

Question 4a: How much use have you made of the fuel cell/electrolyzer kits (in total for all courses you teach)?

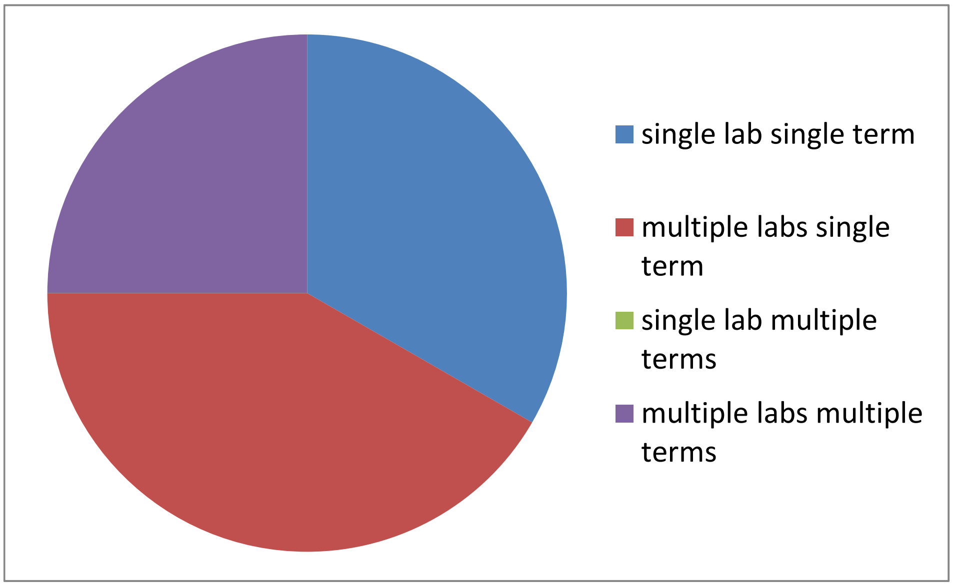

Figure 9: Responses to Question 4a of the H2E3 final survey.

Table 7: Percentage of answers by category in response to Question 4a

Category	% of answers
Single lab period during one quarter/semester	33
Multiple lab periods during one quarter/semester	22
Single lab period during multiple quarters/semesters	0
Multiple lab periods during multiple quarters/semesters	45

Question 4b: How did you use the fuel cell/electrolyzer kits?

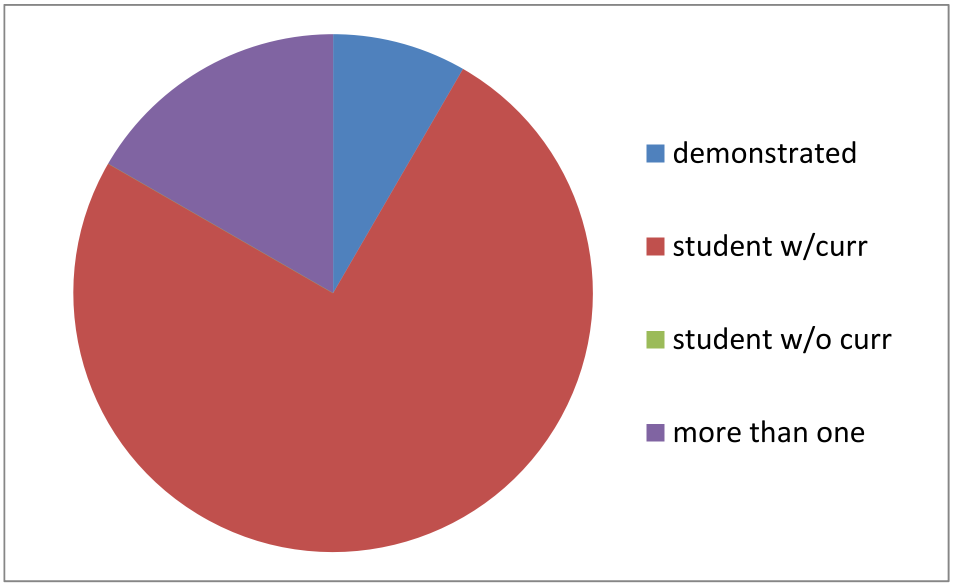

Figure 10: Responses to Question 4b of the H2E3 final survey.

Table 8: Percentage of answers by category in response to Question 4b

Category	% of answers
Demonstrated a kit for students	8
Had students perform one or more of the lab activities provided as part of the curriculum	75
Had students use the kits for an activity not provided as part of the curriculum	0
More than one of these approaches	18

Question 4c: Were the kits helpful in meeting your course objectives?

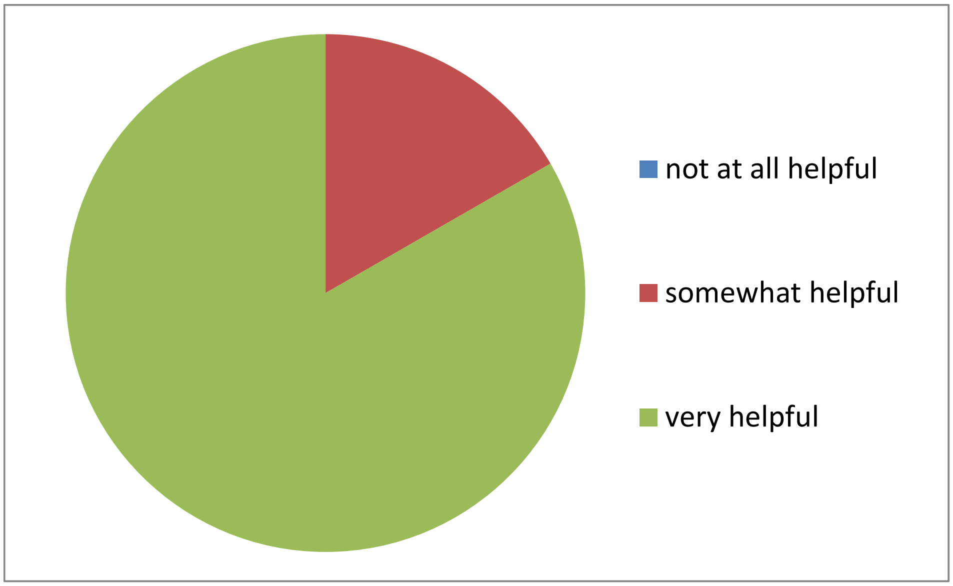

Figure 11: Responses to Question 4c of the H2E3 final survey.

Table 9: Percentage of answers by category in response to Question 4c

Category	% of answers
not at all helpful	0
somewhat helpful	17
very helpful	83

Question 4d: What specific recommendations do you have for changes or improvements that could be made to the kit hardware and/or the associated curriculum?

- Perhaps the connections and connectors could be something more robust and obvious than alligator clips . (2 comments)
- Improve measurement precision (especially for temperature and for volume of hydrogen)
- My students were very interested in the chemistry of the membranes. It would be interest ing to systematically switch out membranes and test the results.
- Finding ways to reduce heat loss from the reservoir would improve students' ability to measure interconversion of the various forms of energy.
- I modified the experiment to use an electric resistance element as the load for the fuel cell in some of the runs; this allowed for runs that involved greater amounts of hydrogen consumption. This was important in order to improve the precision of the hydrogen consumption. In the original version of the lab the precision of these measurements was very low in a way that reduced the quality of the lab.

Question 4e: Would you use this lab activity again? Why or why not?

Respondents all indicated they would use this lab activity again.

- Yes. It was an effective demonstration of the conversion of electrical energy to chemical and then back to electrical and finally to mechanical energy.
- My favorite part was the demonstration and measuring of work done by lifting a known mass a measured distance.
- Yes, students respond positively and seem to take the activity seriously.
- Yes, students enjoyed the hands-on approach to a concept to which they had already learned from previous courses.
- Yes, the students learned a lot and enjoyed the kits.
- No longer teaching the course - otherwise yes
- Yes and also worked with HSU for more active inclusion in Chem. classes and will keep working on that along with Eng. Classes
- Yes, as noted in the notes associated with Q3, the lab was very useful for explaining key t hermodynamic concepts.

Question 4f: Please share any other comments on the kits and associated curriculum.

- One of the more challenging (and ultimately rewarding) aspects of the lab was connecting the FCs in series to power the lift motor. Making the connections use a patch panel instead of alligator clips might be an improvement.
- Great contribution to energy education that should be widely replicated.
- This was a very good workshop for high school students. It kept them engaged and active and is in the direction that we need for future leaders.

Question 5: Did you use the Fuel Cell Test Station in your class or lab? If you select "NO" and did not use the fuel cell test station, the survey will automatically skip all questions related to this topic

Four out of the fourteen respondents (12%) used the fuel cell test stations. Questions 5a-5f represent the distribution of those four responses.

Question 5a: How much use have you made of the test station (in total for all courses you teach)?

Table 10: Percentage of answers by category in response to Question 5a

Category	% of answers
Single lab period during one quarter/semester	50
Multiple lab periods during one quarter/semester	25
Single lab period during multiple quarters/semesters	25
Multiple lab periods during multiple quarters/semesters	0

Question 5b: How did you use the test station?

Table 11: Percentage of answers by category in response to Question 5b

Category	% of answers
Demonstrated a test station for students	25
Had students perform one or more of the lab activities provided as part of the curriculum	50
Had students use the test station for an activity not provided as part of the curriculum	0
More than one of these approaches	25

Question 5c: Was the test station helpful in meeting your course objectives?

Table 12: Percentage of answers by category in response to Question 5c

Category	% of answers
not at all helpful	0
somewhat helpful	25
very helpful	75

Question 5d: What specific recommendations do you have for changes or improvements that could be made to the test station and/or the associated student handouts, lab procedures, or operation and maintenance manual provided for use with the test station?

Improve safety mechanisms to reduce possibility of overheating stack or otherwise damaging the test station.
The software can be a bit challenging but once it is working it is a great tool.

Question 5e: Would you use this lab activity again? Why or why not?

- Yes. It was an effective demonstration of a non-heat engine. The students had fun and were excited by the opportunity to work with a large Fuel Cell.
- Yes. Many students showed a lot of interest, and it's something new for just about everyone.
- Yes. It is incredibly valuable for students to get their hands on the technology and to be able to operate and test a fuel cell and see for themselves how it performs. Giving them an opportunity to generate an IV curve is much more instructive than simply giving them the data. The lab also allows them to see how a fuel cell test system, with it's data acquisition and control system, is set up and operated.

Question 5f: Please share any other comments on the test station and associated curriculum.

- I like the way the data collection activity (generating the IV curve) is integrated with the design activity where they size a fuel cell for a particular application and answer questions related to it's expected operation and performance.

Question 6: Did you draw upon the H2E3 curriculum in exams that you gave your students?

Table 13: Percentage of answers by category in response to Question 6

Category	% of answers
not at all	69
somewhat	31
heavily	0

Question 7: What H2E3 instructional support resources have you made use of? (check all that apply)

Table 14: Percentage of answers by category in response to Question 7

Category	% of answers
project web page (hydrogencurriculum.org)	45
online H2E3 videos (web page or YouTube)	36
fuel cell test station O&M manual	36
fuel cell/electrolyzer kit instructor guide	91

Question 8: How helpful were the instructional support resources you used (if any)?

Table 15: Percentage of answers by category in response to Question 8

Category	% of answers
not at all helpful	0
somewhat helpful	38
very helpful	62
not applicable	

Question 9: Safety Do you feel the curriculum and equipment as used by your students are safe? Please explain any safety concerns you may have and any ideas you have for making the H2E3 curriculum safer for students.

- Yes I felt my students were safe.
- Yes
- Be sure to make students wear safety glasses.
- Yes, I felt that the safety guidelines were well documented.
- Yes, for the most part. Some students were interested in changing electrolyte solution and you do have to careful that you don’t' accidentally make any toxic gases.
- No concerns
- It was safe provided the instructor enforced safety guidelines.
- Students only used data, so there were no safety concerns.

- Yes; I feel that the safety issues were adequately addressed in the materials provided.
- I suppose if a safer solution than the 4 mol KOH could be found that would be good, but it just requires careful handling.

Question 10: Please list any other courses and/or faculty at your campus where this curriculum might be adopted

- Dr. David Vernon, Humboldt State University, Environmental Resources Engineering
- Dr. Wes Bliven, Humboldt State University, Physics
- Currently being used in a technical elective course (Green Engineering), considering using this in a course with 60 students.
- Dr. Kawai Tam, UC Riverside
- Chemistry Departments
- Thermo II – Advanced thermodynamics course

Question 11: Please identify your teaching role in association with this curriculum.

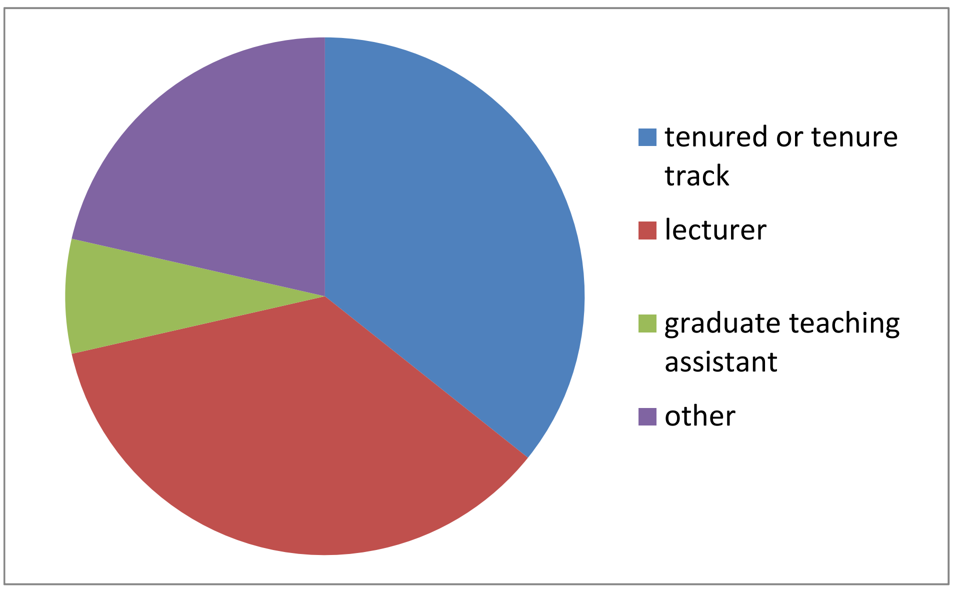

Figure 12: Responses to Question 11 of the H2E3 final survey.

Table 16: Percentage of answers by category in response to Question 11.

category	% of answers
tenure or tenure track	36
lecturer	36
graduate teaching asst	7
other	21

Question 12: Is there anything else you would like to comment on? Thank you for participating in this survey.

- Nice work.
- Thanks for letting me participate.
- I really enjoyed working with Richard Engel. He was very helpful in providing materials and answering questions from students. He even attended our end of semester poster session.

Student and Instructor Survey Instruments

Fuel Cells and Hydrogen Energy

A Pre-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell lab kits you will be using. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *before* reading your lab handout for the fuel cell and hydrogen lab and *before* performing the lab activities.

1) The efficiency of a fuel cell can be calculated as
   a) power generated multiplied by time operated
   b) chemical energy in divided by electrical energy out
   c) electrical energy out divided by chemical energy in
   d) useful energy out divided by time operated

2) A fuel cell stack produces 5.0 Amps of current at a voltage of 12.5 Volts. If the stack is operated for 15 hours at this constant output, how many kilowatt-hours of energy will it generate?
   a) 940 kWh
   b) 9.4 kWh
   c) 0.94 kWh
   d) 0.0375 kWh

3) What are the oxidation-reduction (redox) half-reactions that take place in a fuel cell?
   a) $2H_2 \rightarrow 4H^+ + 4e^-$ and $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$
   b) $4H^+ + 4e^- \rightarrow 2H_2$ and $2H_2O \rightarrow O_2 + 4e^- + 4H^+$
   c) $CH_4 + 2H_2O \rightarrow CO_2 + 8H^+ + 8e^-$ and $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$
   d) $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ and $2H_2O \rightarrow O_2 + 4e^- + 4H^+$

4) What is the role of an electrolyzer in a renewable hydrogen energy system?
   a) to split water into hydrogen and oxygen using electrical energy
   b) to convert electric output from the fuel cell from DC to AC
   c) to purify oxygen required to operate the fuel cell
   d) to store hydrogen for later use in a fuel cell

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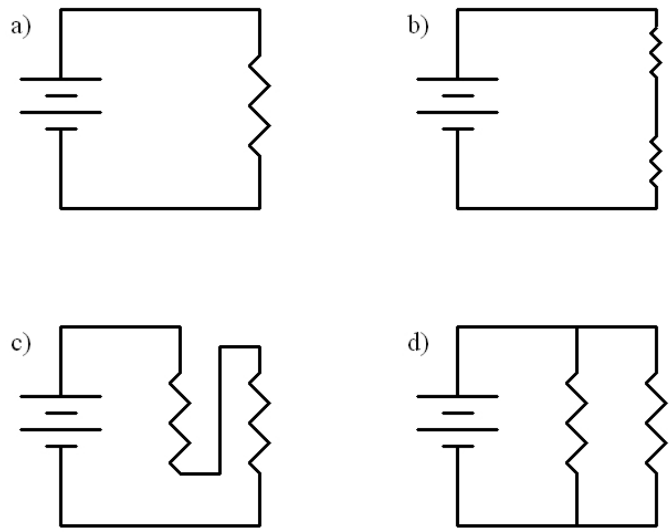
5) Which of the following drawings represents a circuit with resistive loads in parallel?
(circle one)



6) Name three practical applications for fuel cell technology.

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7) How high is your confidence that you can successfully perform a lab exercise working with hydrogen and fuel cells? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

Fuel Cells and Hydrogen Energy

A Post-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell lab kits you will be using. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *after* performing the fuel cell and hydrogen lab activities.

1) The efficiency of a fuel cell can be calculated as
   a) power generated multiplied by time operated
   b) chemical energy in divided by electrical energy out
   c) electrical energy out divided by chemical energy in
   d) useful energy out divided by time operated

2) A fuel cell stack produces 5.0 Amps of current at a voltage of 12.5 Volts. If the stack is operated for 15 hours at this constant output, how many kilowatt-hours of energy will it generate?
   a) 940 kWh
   b) 9.4 kWh
   c) 0.94 kWh
   d) 0.0375 kWh

3) What are the oxidation-reduction (redox) half-reactions that take place in a PEM fuel cell?
   a) $2H_2 \rightarrow 4H^+ + 4e^-$ <u>and</u> $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$
   b) $4H^+ + 4e^- \rightarrow 2H_2$ <u>and</u> $2H_2O \rightarrow O_2 + 4e^- + 4H^+$
   c) $CH_4 + 2H_2O \rightarrow CO_2 + 8H^+ + 8e^-$ <u>and</u> $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$
   d) $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ and $2H_2O \rightarrow O_2 + 4e^- + 4H^+$

4) What is the role of an electrolyzer in a renewable hydrogen energy system?
   a) to split water into hydrogen and oxygen using electrical energy
   b) to convert electric output from the fuel cell from DC to AC
   c) to purify oxygen required to operate the fuel cell
   d) to store hydrogen for later use in a fuel cell

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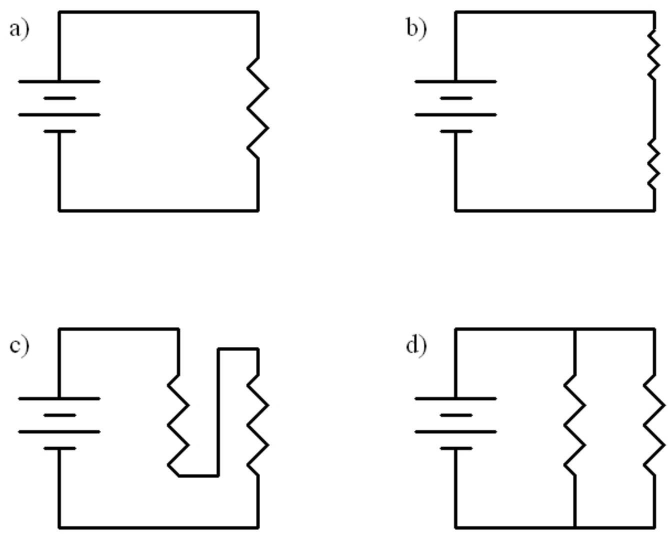
5) Which of the following drawings represents a circuit with resistive loads in parallel? (circle one)



6) Name three practical applications for fuel cell technology.

____

____

____

7) How high is your confidence that you could successfully perform a future lab exercise working with hydrogen and fuel cells? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

Electrolyzers, Fuel Cells and Hydrogen Energy

A Pre-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell lab kits you will be using. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or do not tell the person issuing the survey your name.**

This assessment should be completed *before* performing the lab activities.

1. The use of an electrolyzer, hydrogen storage, and a fuel cell together in a power system constitute an alternative to using:
    a. Solar photovoltaic modules
    b. Alternating current electricity
    c. A battery
    d. Oxygen
2. The efficiency of a fuel cell can be calculated as
    a. power generated multiplied by time operated
    b. chemical energy in divided by electrical energy out
    c. electrical energy out divided by chemical energy in
    d. useful energy out divided by time operated
3. For a given process, if the change in enthalpy is ***less*** than the amount of energy lost to the environment as heat, the process is:
    a. inefficient
    b. spontaneous
    c. endothermic
    d. non-spontaneous
    e. efficient
4. In an electrolysis reaction, total electric energy supplied to the electrolyzer is equal to
    a. chemical energy in the hydrogen generated plus heat lost to the surroundings
    b. heat lost to the surroundings minus chemical energy in the hydrogen generated
    c. chemical energy in the hydrogen generated minus chemical energy in the oxygen generated
5. How high is your confidence that you can perform the lab exercise correctly? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

Electrolyzers, Fuel Cells and Hydrogen Energy

A Post-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell lab kits you will be using. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or do not tell the person issuing the survey your name.**

This assessment should be completed *after* performing the lab activities.

1. The use of an electrolyzer, hydrogen storage, and a fuel cell together in a power system constitute an alternative to using:
    a. Solar photovoltaic modules
    b. Alternating current electricity
    c. A battery
    d. Oxygen
2. The efficiency of a fuel cell can be calculated as
    a. power generated multiplied by time operated
    b. chemical energy in divided by electrical energy out
    c. electrical energy out divided by chemical energy in
    d. useful energy out divided by time operated
3. For a given process, if the change in enthalpy is ***less*** than the amount of energy lost to the environment as heat, the process is:
    a. inefficient
    b. spontaneous
    c. endothermic
    d. non-spontaneous
    e. efficient
4. In an electrolysis reaction, total electric energy supplied to the electrolyzer is equal to
    a. chemical energy in the hydrogen generated plus heat lost to the surroundings
    b. heat lost to the surroundings minus chemical energy in the hydrogen generated
    c. chemical energy in the hydrogen generated minus chemical energy in the oxygen generated
5. How high is your confidence that you can perform the lab exercise correctly? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

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6. Have you used this kit or similar equipment before this class?

   yes   no

7. Was the use of the fuel cell/electrolyzer kit an effective learning tool in this lab?

8. Do you have suggestions for improvements to the equipment or the lab curriculum?

9. Any other comments or suggestions?

Hydrogen Fueling Station Performance

A Pre-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for use with the HSU hydrogen fueling station. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *before* reading your handout for the fueling station assignment.

1) Which of the following technologies is used for generating hydrogen at the HSU hydrogen fueling station? (circle one)
   a) reformation of natural gas
   b) biological hydrogen production
   c) electrolysis of water
   d) hydrogen is not generated at the station; it is only stored and dispensed

2) What are the four main components of the HSU hydrogen fueling station in process order? (circle one)
   a) digester → compressor → storage → dispenser
   b) electrolyzer → storage → compressor → dispenser
   c) inverter → electrolyzer → compressor → dispenser
   d) reformer → electrolyzer → compressor → dispenser
   e) electrolyzer → compressor → storage → dispenser

3) In what form is hydrogen dispensed to vehicles at the HSU hydrogen fueling station? (circle one)
   a) hydrogen gas at 5,000 PSI gauge
   b) hydrogen gas at atmospheric pressure for compression on board the vehicle
   c) liquid hydrogen at -253° C
   d) natural gas that is reformed on board the vehicle

4) Refueling a hydrogen-powered vehicle… (circle one)
   a) is much slower than refueling an ordinary vehicle at a gas station (takes a few hours)
   b) takes about as long as refueling an ordinary vehicle at a gas station (takes a few minutes)
   c) is much faster than refueling an ordinary vehicle at a gas station (takes only a couple of seconds)

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5) In order to calculate hydrogen production at the fueling station, we need to know (circle one)
   a) hydrogen mass flow rate at each time step and time interval between data points
   b) total station power consumption and time interval between data points
   c) total station power consumption and hydrogen mass flow rate
   d) efficiency of each station component

6) What is the key technological difference between the two vehicles that currently use the HSU hydrogen fueling station?

7) How high is your confidence that you can successfully perform an exercise to assess the performance of a hydrogen fueling station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

Hydrogen Fueling Station Performance

A Post-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for use with the HSU hydrogen fueling station. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *after* completing the fueling station assignment.

1) Which of the following technologies is used for generating hydrogen at the HSU hydrogen fueling station? (circle one)
   a) reformation of natural gas
   b) biological hydrogen production
   c) electrolysis of water
   d) hydrogen is not generated at the station; it is only stored and dispensed

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5) In order to calculate hydrogen production at the fueling station, we need to know (circle one)
   a) hydrogen mass flow rate at each time step and time interval between data points
   b) total station power consumption and time interval between data points
   c) total station power consumption and hydrogen mass flow rate
   d) efficiency of each station component

6) What is the key technological difference between the two vehicles that currently use the HSU hydrogen fueling station?

7) How high is your confidence that you can successfully perform an exercise to assess the performance of a hydrogen fueling station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

8) Was the fueling station an effective learning tool in this assignment? (circle one)

Yes No

9) Did you feel the assignment was relevant to this course? (circle one)

Yes No

10) Do you have suggestions for improvements to this assignment?

11) Any other comments or suggestions?

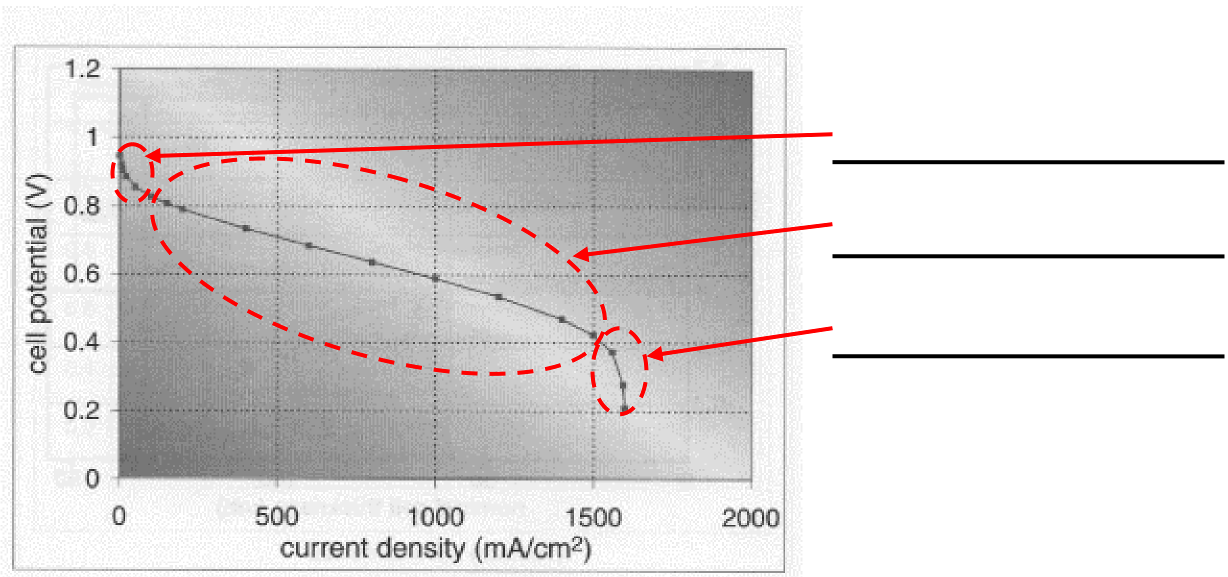
Fuel Cells and Hydrogen Energy

A Pre-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell test station. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or do not tell the person issuing the survey your name.**

This assessment should be completed *before* reading your lab handouts or any material related to the fuel cell test station and *before* performing the lab activities.

1) Match the following terms to the portions of the fuel cell polarization (voltage vs. current) curve shown.
   ohmic region   mass transport limited region   activation region



2) How does increased air flow affect fuel cell performance?
   a) generally increases the performance
   b) generally decreases the performance
   c) has no effect on the performance
   d) impossible to determine without additional information

3) In order for a fuel cell to play a role in storage of electricity generated from intermittent renewable resources, what other major components are needed?
   a) programmable electronic load and electrolyzer
   b) electrolyzer and hydrogen storage
   c) reformer and inverter
   d) reformer and electrolyzer
   e) battery and electrolyzer

4) What is the purpose of using a fuel cell test station?

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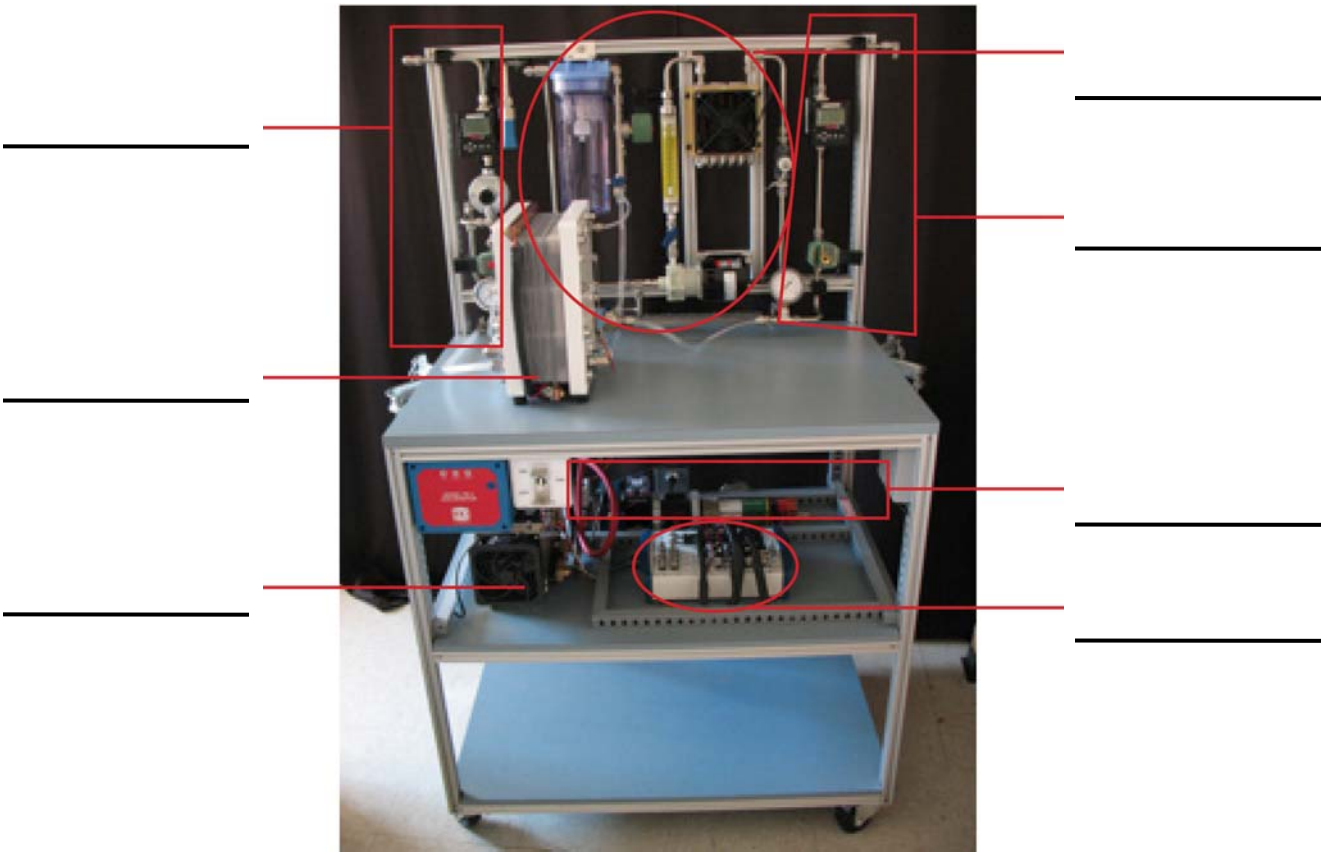
5) Label the fuel cell test station shown below using the following:
hydrogen system, water system, air system, fuel cell stack, electronic load, electrical system, and data acquisition system.



6) How confident are you in your ability to operate a fuel cell test station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

Fuel Cells and Hydrogen Energy

A Post-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for the fuel cell test station. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or do not tell the person issuing the survey your name.**

This assessment should be completed *after* reading your lab handouts or any material related to the fuel cell test station and *after* performing the lab activities.

1) Match the following terms to the portions of the fuel cell polarization (voltage vs. current) curve shown.
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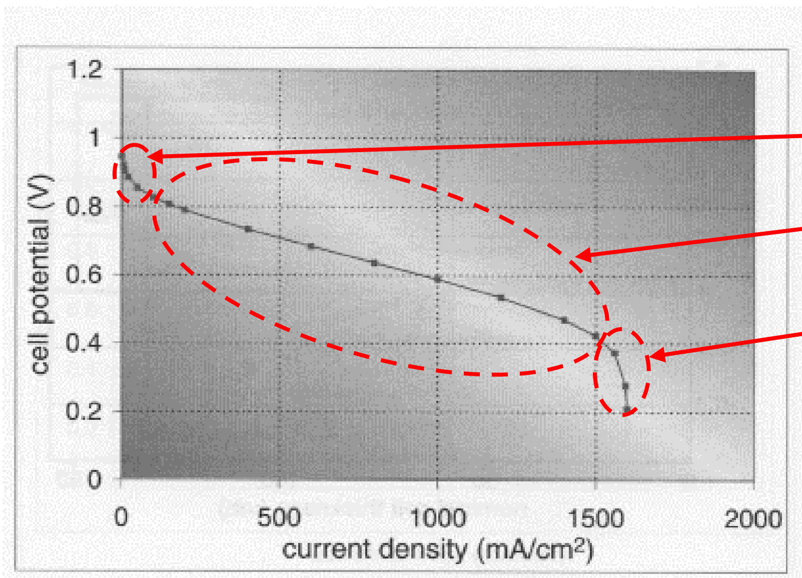

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2) How does increased air flow affect fuel cell performance?
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3) In order for a fuel cell to play a role in storage of electricity generated from intermittent renewable resources, what other major components are needed?
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   c) reformer and inverter
   d) reformer and electrolyzer
   e) battery and electrolyzer

4) What is the purpose of using a fuel cell test station?

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5) Label the fuel cell test station shown below using the following:
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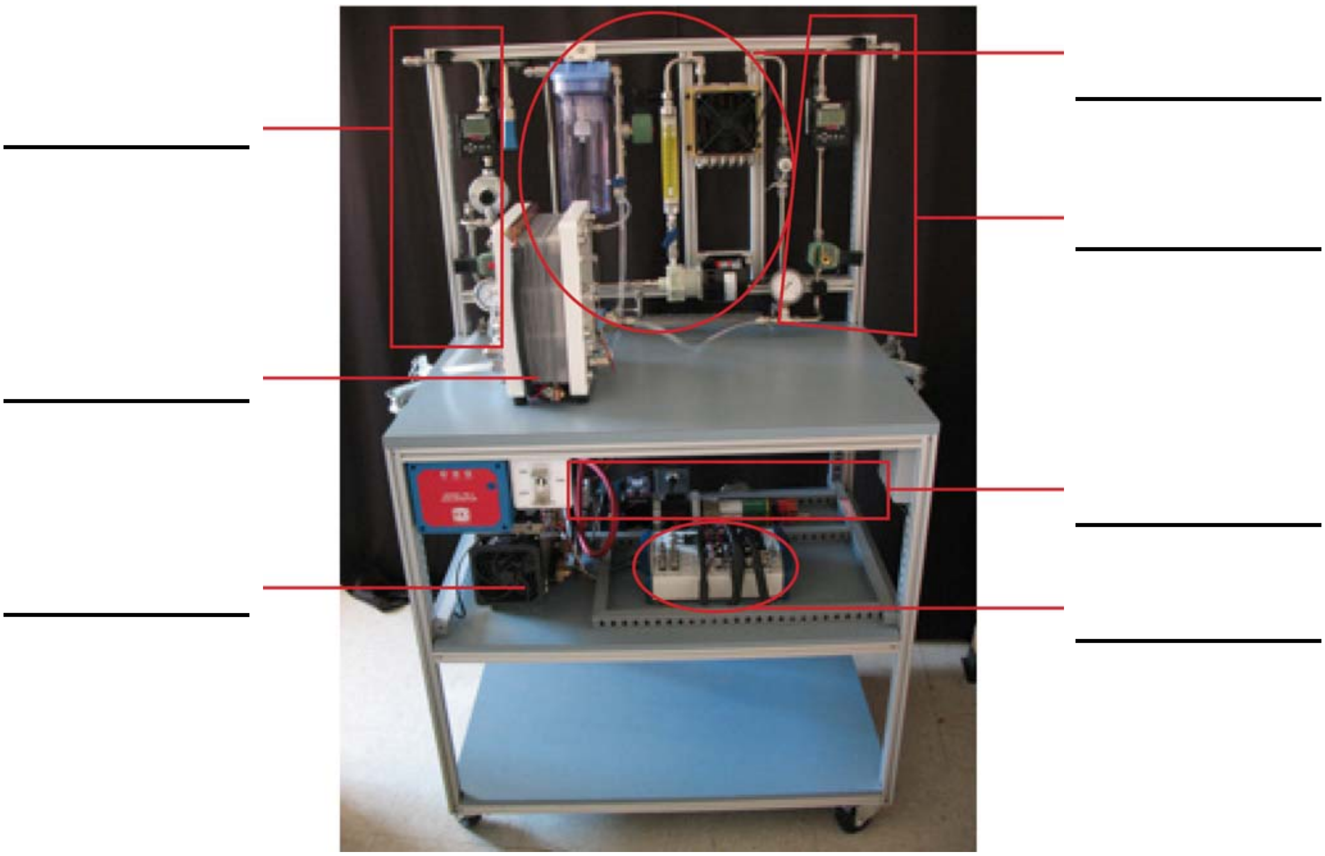


6) How confident are you in your ability to operate a fuel cell test station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

CONTINUED ON NEXT PAGE

7) Have you used this or similar equipment before this class?

yes no

8) Was the use of the fuel cell test station an effective learning tool in this lab?

9) Do you have suggestions for improvements to the equipment or the lab curriculum?

10) Any other comments or suggestions?

Fuel Cells, Hydrogen Energy, and Transport Phenomena
A Pre-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for hydrogen education. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *before* performing the lab activities.

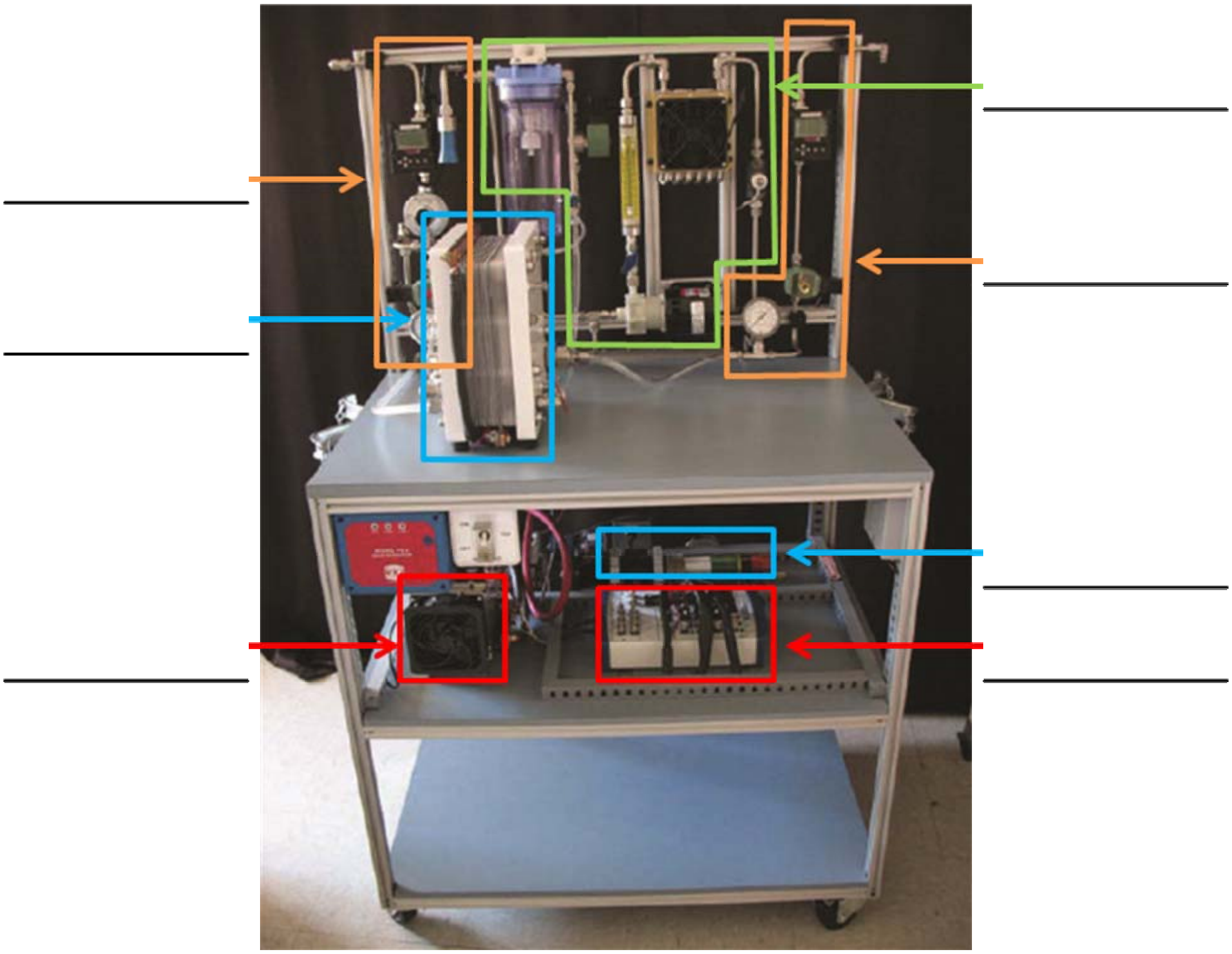
1) The purpose of humidification of the fuel cell stack is to (circle correct answer)
   a) remove impurities from the air in the stack
   b) heat the fuel cell stack to optimal operating temperature
   c) prevent the proton exchange membranes from drying out
   d) cool the stack to optimal operating temperature

2) Which of the following parameters' values must be known or assumed in order to calculate an energy balance on an operating fuel cell stack? (circle all that apply)
   a) hydrogen, air, and water flow rates
   b) water pump and water heater power consumption
   c) relative humidity of the air entering and leaving the stack
   d) temperatures of the reactants and the water as they enter and exit the stack
   e) stack power output

3) Which of the following is normally the dominant mode of heat transfer of an operating PEM fuel cell stack to its surroundings? (circle correct answer)
   a) conduction
   b) convection
   c) radiation

4) Under a given electrical load, with increased operating temperature a fuel cell will produce (circle correct answer)
   a) higher voltage than when operated at lower temperatures
   b) lower voltage than when operated at lower temperatures
   c) the same voltage as when operated at lower temperatures

5) Label the fuel cell test station shown below using the following:
hydrogen system, water system, air system, fuel cell stack, electronic load, electrical system, and data acquisition system.



6) How confident are you in your ability to operate a fuel cell test station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

7) In order to help us assess the effectiveness of the assigned readings: Did you read the assigned material for this lab prior to taking this assessment? ___ yes ___ no

Fuel Cells, Hydrogen Energy, and Transport Phenomena
A Post-Activity Knowledge Assessment

The results of this survey will be used to assess the effectiveness of the curriculum being developed for hydrogen education. Participation in the survey is strictly **voluntary** and will not be used for credit in this course. **If you are under the age of 18 please do not participate in this survey**. **Do not write your name anywhere on the survey or tell the person issuing the survey your name.**

This assessment should be completed *after* performing the lab activities.

1) The purpose of humidification of the fuel cell stack is to (circle correct answer)
   a) remove impurities from the air in the stack
   b) heat the fuel cell stack to optimal operating temperature
   c) prevent the proton exchange membranes from drying out
   d) cool the stack to optimal operating temperature

2) Which of the following parameters' values must be known or assumed in order to calculate an energy balance on an operating fuel cell stack? (circle all that apply)
   a) hydrogen, air, and water flow rates
   b) water pump and water heater power consumption
   c) relative humidity of the air entering and leaving the stack
   d) temperatures of the reactants and the water as they enter and exit the stack
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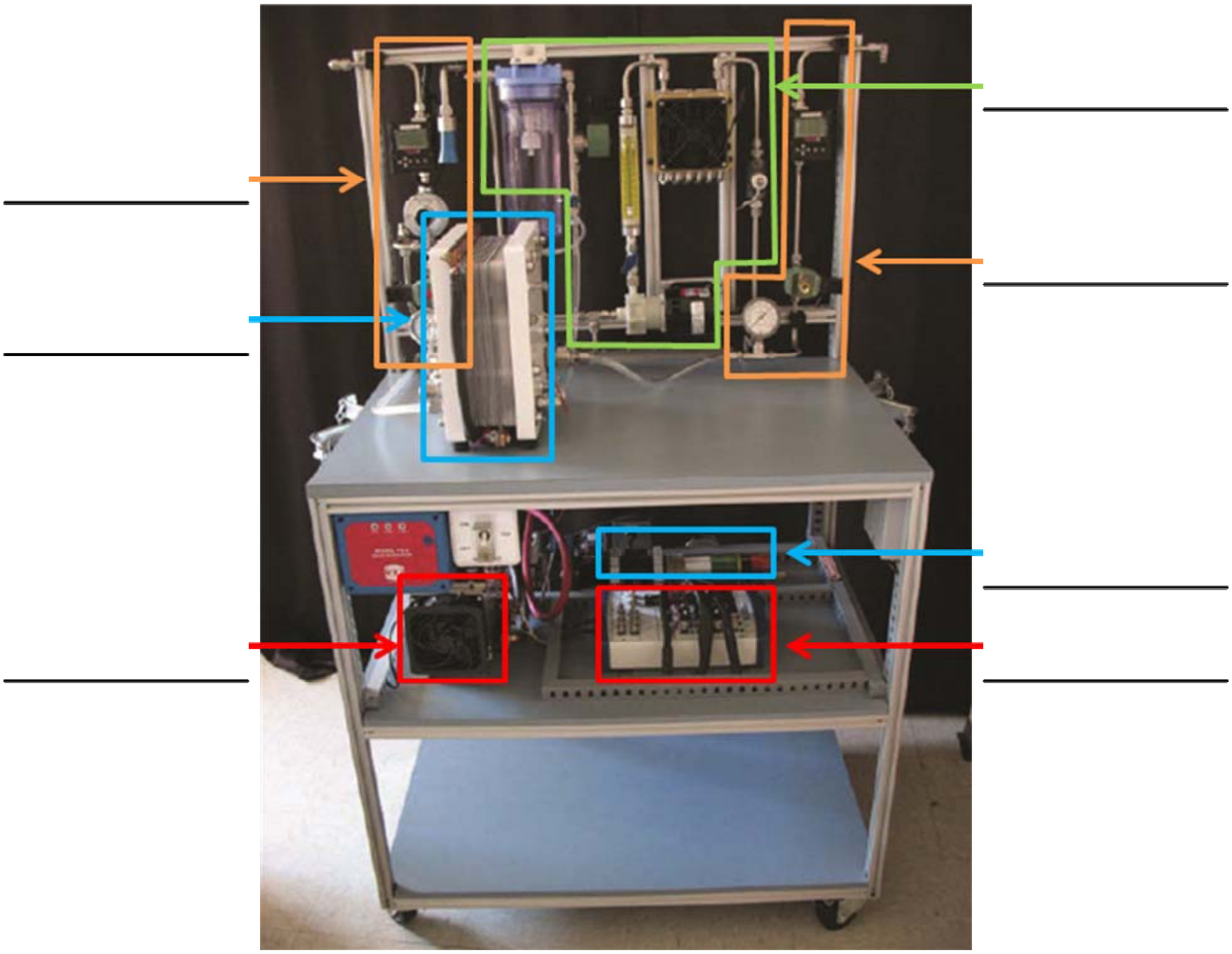

6) How confident are you in your ability to operate a fuel cell test station? (circle the appropriate number)

1	2	3	4	5
very low	low	moderate	high	very high

7) In order to help us assess the effectiveness of the assigned readings: Did you read the assigned material for this lab prior to taking this assessment? ___ yes ___ no

8) Have you used this or similar equipment before this class? ___ yes ___ no

9) Was the use of the fuel cell test station an effective learning tool in this lab?

10) Do you have suggestions for improvements to the equipment or the lab curriculum?

11) Any other comments or suggestions?

Instructor's Evaluation: Fuel Cell/Electrolyzer Lab Activity
ENGR 115, Humboldt State University, Fall 2009
Hydrogen Energy in Engineering Education (H_2E^3) Project

Instructor/TA/Lab Tech Name ____

Thank you for helping us to test and evaluate this lab activity.

The objectives of this lab as stated in the student handout are to:

- Explore the relationship between energy and power and learn to make measurements and calculations of energy and power.
- Gain understanding of energy efficiency and the Second Law of Thermodynamics.
- Learn about hydrogen energy, fuel cells, and systems for generating and storing hydrogen fuel.

1. Overall how successful do you feel this lab was in achieving these learning objectives?

(circle one)

1	2	3	4	5	6
very unsuccessful	mostly unsuccessful	somewhat unsuccessful	somewhat successful	mostly successful	very successful

2. What specific recommendations do you have for changes or improvements that could be made to the equipment used in this lab?

3. What specific recommendations do you have for changes or improvements that could be made to the student handouts and lab procedure used in this lab?

4. Would you like to use this lab activity again in this course? Why or why not?

5. Do you feel that a single three-hour lab period is adequate for completing this lab activity? How much time do you think is required to complete the activity? What specific recommendations do you have for modifying the lab activity so it can be completed in a single lab period?

6. Is there a different engineering course offered at HSU in which you would recommend use of the fuel cell/electrolyzer kits? Which one? What learning objectives would it help to meet?

7. What do you consider to be the ideal number of students per kit during the lab activity?

(circle one)

1 student 2 students 3 students 4 students 5 or more students

8. Please share any other comments on this lab activity and equipment.

Please return your completed evaluation to Richard Engel at the Schatz Lab. Thank you.

Appendix C

Follow-Up Interviews on Protonex Internships

Interviewee: *Brett Selvig, Intern*

1. Describe the work you did at Protonex.

   Test stand plumbing – MeOH fuel cells. M300 w/ reformer. 4 hr cartridge. FAT (Factory acceptance testing). Rearranging equipment. Power manager testing, submersion. Software engr. training. Machining. Bread board testing, training users.

2. What were some important skills (if any) you learned through this internship?

   Using vertical mill, machine shop skills, wiring, safety (labeling), spill sensors, TIG welding. Working in a professional environment on a team.

3. Did the hydrogen and fuel cell activities you did in HSU engineering courses help you prepare for your internship? If so, how?

   Yes – new software specialist didn't know how fuel cells worked, so we were able to explain them to her. Onboard reforming was new (for him) and interesting.

4. More broadly, how well did your engineering education in general prepare you for the work you were asked to do at Protonex? Were there specific skills you've learned as an engineering student that came in handy?

   General problem solving approach learned in ERE helped. Mechanics, electronics (working with solenoids). Math (design of float-controlled valve).

5. Was the stipend adequate to meet your living and travel expenses this summer?

   OK

6. Apart from pay, were there ways Protonex and SERC could have better supported you as an intern?

   Housing situation – had to ride bike 1.5 hrs (10 miles) each way to work. Neighborhood and household were good, but living closer to work would be better.

7. Would you recommend an internship with Protonex to your classmates or friends? Why or why not?

   Yes

8. Do you plan to keep working with hydrogen and fuel cells as part of your career?

   Not sure

9. Is there anything else you would like to add?

   Staff were helpful at Protonex, willing to explain their work

Interviewee: *Ryan Dunne, Intern*

1. Describe the work you did at Protonex.

   SOFCs – job shadowing initially. Fixing wiring and plumbing. Test stand troubleshooting. Machine shop, parts fabrication. Using straight H2 at first, troubleshoot wiring problem. Operation using JP8 did not work, went back to straight H2. Ran FC on his own. Generated VI curves, startup voltage curves. Optimizing H2/O2 mix.

2. What were some important skills (if any) you learned through this internship?

   Machine shop, mechanical, wiring, test station setup, circuit boards, seeing in a business how engineers manage multiple tasks, purchasing/ordering, troubleshooting approaches including high temperature pressure testing – can't make changes while system operating at high temperature

3. Did the hydrogen and fuel cell activities you did in HSU engineering courses help you prepare for your internship? If so, how?

   Our H2E3 test station helped, because it's basic and transparent by design. Protonex's equipment is harder to understand, very "black box"

4. More broadly, how well did your engineering education in general prepare you for the work you were asked to do at Protonex? Were there specific skills you've learned as an engineering student that came in handy?

   ENGR 115 and 215 gave good experience with Excel. Lonny's class and AutoCAD. Protonex uses SolidWorks, but AutoCAD experience helped. Math, chem and physics classes helped. Having some Powerpoint experience helped with developing his final presentation to staff.

5. Was the stipend adequate to meet your living and travel expenses this summer?

   OK – had to pay rent in Arcata and Boston simultaneously. Great roommate experience. He didn't have any better job opportunities he passed up to do this.

6. Apart from pay, were there ways Protonex and SERC could have better supported you as an intern?

   Housing – would have liked to live closer to work and get more help with finding housing

7. Would you recommend an internship with Protonex to your classmates or friends? Why or why not?

yes

8. Do you plan to keep working with hydrogen and fuel cells as part of your career?

   Maybe. His own experience working at Protonex was a nice mix of working with hands, analysis, data collection. However, another intern who was a mech engr. major spent the whole summer doing drafting – he's not into that.

9. Is there anything else you would like to add?

   Nate said he'd rehire either of them. Ryan gave a final presentation about his work to Protonex staff. Everyone at Protonex was approachable. Getting TIG welding experience was great.

Interviewee: *Nate Palumbo, Intern Mentor/Supervisor*

1. Please comment on your impressions of Brett and Ryan as individual interns.

   Very good considering their level of experience coming in. They behaved very professionally and were fully functional by the end of the summer.

2. Did the interns live up to your expectations and needs?

   Initially they didn't have much lab skills, but they learned fast. Their personalities were a good fit for the unstructured, fast-paced environment.

3. Did the interns come to Protonex with the skills and knowledge they needed to succeed?

   Yes. Basic engineering principles. Brett is farther along, but Ryan caught up quickly. Their tasks required multidisciplinary skill sets. Needed to learn about fluid flow.

4. How did the interns contribute to Protonex?

   Testing – both got involved in testing, where they were needed. Competent at running hardware and reporting results.

5. Do you feel the internships were a good investment for Protonex? Why or why not?

   Yes – pleased with both. Got up and running quick. Protonex had shied away from summer internships before because it seemed too much trouble to train students for such a short work period, but this worked out well.

6. Would you be willing to partner with Schatz Energy Research Center in the future on internships?

   Yes. Offered to re-hire Ryan as intern and asked Brett to submit a resume when he graduates if interested in working @ Protonex.

7. Is there anything else you would like to add?

   It was altogether a positive experience.

Hydrogen Experiment Kit Specifications

- Electrolyzer
  - Type: alkaline
  - Electrolyte: 4M KOH solution
  - Electrodes: 1/8" diameter 316 stainless steel, surface roughened
  - Power supply: 12VDC, 2000 mA
- Gas Storage
  - Hydrogen: 100 ml
  - Oxygen: 50 ml
- Fuel Cell
  - Type: Heliocentris single-cell PEM
  - Active area: 9 cm^2
  - Power capacity: ~350 mW

Test Station Specifications

SCHATZ ENERGY RESEARCH CENTER

Specifications

Fuel Cell Test Station

Stack testing capacity	
Voltage monitoring (cells)	8
Power rating	600 W
Current range	0-150 A
Voltage range	0-50 V
Stack pressure control	2.7-5.5 psig
Stack temperature (max)	70˚C
Hydrogen System	
Hydrogen flow range	0-20 slm
Hydrogen flow configuration	dead-ended
Hydrogen gas purge	automatic/manual
Purge knockout drain	manual
Air System	
Air flow	0-50 slm
Operating air pressure	0 - 4 psig
Stoichiometry software controlled	0-450%
· Stoichiometrically load following	
DI Water Cooling/Heating System	
Heater	600 W
Fan/heat exchanger cooling capacity	880 W @ 0.5 GPM, 40˚C ΔT
DI reservoir fill	automatic/manual
Stack temperature	software controlled
Water flow rate control	manual
Computer Control	
Signal conditioning	National Instruments USB DAQ
Data acquisition	National Instruments USB DAQ
Software	LabVIEW™ Runtime Engine 7.1
Platform/operating system	Windows 7 (software also supports Windows XP and Vista)
Data logging	Automated
Electronic Load	
Load capacity	600 W maximum
Configuration	2 electronic load modules in parallel
Input voltage range	0-50 VDC
Input current range	0-160 A
· Software based IV curve testing	

(continued next page)

Data Monitoring	
· Automatic longterm data logging	
· Individual cell voltages (up to 8 cells)	
· H2 inlet flow	
· Air inlet flow	
· Fuel cell current	
· 5-point Fuel cell operating temperatures	
· Ambient air temperature	
Software Safety Triggers, with alarms	
· Low cell voltage	
· High stack current	
· High stack temperature	
· Reservoir filling error	
Hardware Safety Triggers, with alarms	
· Station H2 sensor	
· Load over-temperature protection	
Test Stand Requirements	
Voltage	1-phase 120 VAC
Frequency	60 Hz
Current	15 Amps
DI water resistivity	> 200 kOhm-cm
Pressurized H2	100 psig
Pressurized Air	60 psig
Air/Water drains	to drain
H2 vent	to outdoors, fume hood
Software	
· National Instruments LabVIEW™- based	
· Standalone Executable Program	
· Test sequence selection and modification	
· Test profiling or configuring	
· Parallel manual and automated control	
· Alarming, auto-shutdown and standby modes	
· Real-time user displays include discrete data displays	
· Historical trending	
· Data channel selection	
· ASCII text file data storage	
Stack Requirements	
Max air inlet pressure	5 psig
Min air inlet temp	10˚ C
Max air inlet temp	70˚ C
Air stoichiometry range	200% - 400% (2 to 4 x 0.01659 slm/amp-cell)
Min. airflow rate	0.5 slm/cell
Min. H2 purity	99.95%
Max H2 delivery pressure	6 psig
H2 purge requirement	1 sec. every 1-20 minutes depending on current density
H2O flow rate	0.4 - 4 lpm (0.1 - 1.0 gpm), depending on current density and H2O pressure
H2O temp. range	40 - 65˚ C
Min. H2O temp @ fuel cell inlet	10˚ C
Max. stack temp.	70˚ C
Max. H2O pressure @ fuel cell inlet	3 psig

Fuel Cell Stack Specifications

Fuel Cell Type: Proton Exchange Membrane (PEM)
Power Cells: 8
MEA: Gore 5620, Gore-Tex gasket
GDM:
Humidification Cells: 4
Humidification Membrane: Gore Select, Gore-tex gasket
Cell Active Area: 300 cm^2
Maximum Rated Power: 500 W