VI.C.1 Hydrogen Filling Station*

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- UNLV Center for Energy Research, Las Vegas, NV
- UNLV Chemistry Department, Las Vegas, NV
- Distributed Energy Systems, Wallingford, CT
- National Renewable Energy Laboratory (NREL), Golden, CO
- Altairnano, Reno, NV
- Hydrogen Solar, Las Vegas, NV
- IF, LLC, Delray Beach, FL

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Project End Date: December 31, 2007
(Includes amendment 3)

*Congressionally directed project

Objectives

Design, install and analyze operation of a hydrogen generation and vehicle fueling system using electrical energy furnished by solar energy and grid power.

- Enter use agreement with selected host site property owner (Las Vegas Valley Water District).
- Construct infrastructure including site preparation and utilities extensions.
- Install proven and tested low pressure hydrogen production components and operate with conventional electrical energy.
- Convert two utility vehicles.
- Monitor operation of the fueling system and the converted vehicles and characterize system performance.
- Install a solar energy collection system and connect to electrical power grid.

Enhance the system by designing, testing and implementing a high pressure electrolysis hydrogen production and dispensing system and convert another vehicle.

- Validate high pressure electrolyzer design.
- Install high pressure production system with booster storage skid at host site.
- Monitor and analyze system performance data.
- Convert one conventional pickup to be a hybrid internal combustion engine/fuel cell (ICE/FC) (the latter for electrical load) vehicle, use it in everyday travels, and compare its various performance aspects to a compressed natural gas (CNG) (but otherwise conventional) vehicle of the same type.
- Consider the design of a true hydrogen ICE/FC hybrid vehicle.

Develop and optimize nano-crystalline thin films to maximize the efficiency of photo-catalytic reaction of sunlight to generate hydrogen at low manufacturing cost.

- Develop photocatalytic technology and produce carbon-free hydrogen via a sunlight splitting water pathway.
- Innovate cost-effective technologies to achieve DOE < $3/kg target.
- Conduct cell array engineering work along with enhancement of material photoelectrochemical (PEC) performance.
- Improve cell configuration including novel cell construction materials.
- Test array using solar simulator and sunlight.
- Conduct balance of plant engineering work including modeling and simulation.

Perform outreach activities to constituencies.

- Organize a workshop on hydrogen codes and standards and safety.
- Plan and carry out a roadmapping effort for hydrogen development in Nevada.

Photoelectrochemical hydrogen production using nanotechnology processes.

- Design, purchase and set up X-ray photoelectron-ultraviolet photoelectron spectroscopy (XPS-UPS) system.
- Characterization of photoelectrochemical devices.
- Develop and implement standardized testing protocols.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan as well as issues in production and safety:

(A) Lack of Fuel Cell Vehicle Performance and Durability Data

(C) Lack of Hydrogen Refueling Infrastructure Performance and Availability Data

(D) Maintenance and Training Facilities

(E) Codes and Standards

(H) Hydrogen from Renewable Resources

Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE Technology Validation milestones from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- Milestone 7: Validated refueling time of 5 minutes or less for 5 kg of H_2 (1 kg/min) at 5,000 psi through the use of advanced communication technology. (4Q, 2007
- Milestone 8: Fuel cell vehicles demonstrate the ability to achieve 250 mile range without impacting passenger cargo compartment. (4Q, 2008)
- Milestone 10: Validate fuel cell vehicle's 2,000-hour fuel cell durability, using fuel cell degradation data. (4Q, 2009)
- Milestone 23: Total of 10 stations constructed with advanced sensor systems and operating procedures. (1Q, 2008)
- Milestone 24: Validate a hydrogen cost of $3.00/gge (based on volume production) (4Q, 2009)
- Milestone 28: Validate the cost of compression, storage, and dispensing at refueling stations and stationary power facilities to be <$0.80/gge of hydrogen. (4Q, 2013)
- Milestone 35: Validate $1.60/gge hydrogen cost from biomass and $3.10/kg for renewable/electrolysis (untaxed) at the plant gate. (4Q, 2014)

Accomplishments

- Components of all Phase 1 systems have been installed and are successfully operating.
- Components of all Phase 2 systems have been installed and are successfully operating.
- A photovoltaic (PV) system to power these components was designed and installed by the Las Vegas Valley Water District (LVVWD) and is now in full operation.
- Phase 3 equipment is almost completed, including a high output electrolysis unit.
- An electric vehicle has been converted to be a hybrid fuel cell vehicle (FCV) that demonstrates an effective and relatively low cost method for this type of conversion. This has been incorporated and is being used at the new Las Vegas Springs Preserve attraction in Las Vegas.
- A locally designed direct cylinder injector for a hydrogen ICE has been successfully demonstrated and incorporated on a 1-cylinder vehicle. This vehicle is being used by the new Las Vegas Springs Preserve attraction in Las Vegas.
- A computation fluid dynamics (CFD) model for understanding performance of photocatalytic cells has been developed. Results have shown tradeoffs in performance that have been valuable in improved design directions.
- An on-sun facility for evaluation of photocatalytic cells has been installed. Data from this as well as from the CFD modeling, and from physical insights, continue to be used to develop a parametric prediction model for performance.
- Demonstrated bench-scale performance of a photocatalytic device of 35 mA @ 1.2 V. This is approximately three times the world's record.
- A roadmapping workshop was organized and was attended by a number of people with interests in hydrogen within the state.
- A hydrogen safety workshop was organized and was attended by individuals involved in hydrogen production and dispensing, including permitting authorities.
- The XPS-UPS system was received and installed.
- Work performed by NREL relating to standardization and characterization is ongoing and reported under the DOE funded PEC project.

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Introduction

This project addresses a number of important developments relative to moving forward the state-of-the-art of the hydrogen economy from generation technologies to transportation utilization. Both conventional electrolysis and thermophotocatalytic generation topics are being addressed. In addition, several efforts to aid the development and application of hydrogen technologies are included.

Of particular concern is improving the generation technologies for hydrogen, specifically oriented to production from renewable energy sources. Included are electrolysis and photocatalytic methods. In addition, the development of local expertise in vehicle conversions is being addressed, including fuel cell and ICE drives. For the latter, we are focused on development of direct cylinder injection approaches that could facilitate these kinds of conversions. It has been pointed out to us by DOE personnel that this is the only hydrogen project that involves both a commercial filling station as well as active research into improved generation and utilization technologies as well as renewable energy hydrogen production.

Approach

Because of the multi-thrust of the project, a variety of approaches are being used. Included are basic studies of high performance electrolysis, development of effective photocatalytic generation technologies and new approaches to hydrogen utilization technologies, including direct cylinder injection systems for ICE conversions and renewable energy hydrogen production.

Safety and permitting issues were also addressed as part of this project to provide a well-rounded overall approach to production, dispensing and vehicle integration.

Results

The Fueling Station

The installation of the fueling station (Figure 1) function was one of the primary thrusts of this project, and this is first described by phase for this project. The installation of a low pressure proton exchange membrane (PEM) electrolyzer fueling station has been completed and is operational, the basic thrust of Phase 1. The electrolyzer system was developed by Proton Energy and the design and installation of the compression/dispensing system was performed by Air Products. Output of this system is 2.0 kg/day. In addition, a site was identified at the LVVWD and permitting process was initiated.

In Phase 2, the system was to be enhanced with a high pressure electrolyzer, and this is complete and operational (Figure 2). This enhanced the hydrogen output rate compared to Phase 1 by 0.25 kg/day. The same companies that were involved in the Phase 1 system fabricated and installed this system.

An upgrade of the station to include a 400 psig large electrolyzer was the core of Phase 3. This system has been designed and fabricated. Installation is scheduled for the fall of this year. Operations will commerce shortly thereafter. Hydrogen output of this system is slated to be 12 kg/day.

Because of the plentiful solar resource, as well as utility encouragements, a photovoltaic array was added to the fueling station. This was purchased with funds furnished by the Southern Nevada Water Authority and the LVVWD. It was sized to furnish all of the power required for the Phase 1 and 2 systems. It consists of four single-axis tilted trackers at 4.2 kWe each, for a total output of 16.8 kW DC and 14 kW AC and an expected yearly energy generation of approximately 37,000 kWh. The LVVWD has established a net metering agreement with the local electrical utility for this production facility.

A key element to both the fueling system and the vehicles (the latter are discussed below) is a complete set of data acquisition hardware so that the full complexion

FIGURE 1. The Las Vegas Valley Water District/UNLV Solar Powered Hydrogen Filling Station

FIGURE 2. Equipment at the station includes: Unit 1 – the low pressure electrolyzer, Unit 2 – compressor/dispenser/storage, Unit 3 – high pressure electrolyzer, Unit 4 – compressor, chiller for Unit 4, buffer tank, with single-axis photovoltaic trackers in the background.

of performance can be assessed. For the fueling station, the following data are accessed and archived: ambient meteorological conditions including solar flux, power used by all components in the system, PV power generation, and hydrogen mass flow rates. Electrolyzer performance is monitored separately by Proton and the compression/dispensing station is monitored by Air Products.

Several significant events have been held related to the opening in the station, including operator and first responder training, and a formal station opening. The former of these was organized and presented by the manufacturers involved. We also held a DOE hydrogen safety review team meeting to critique the complete facility and vehicles.

A station opening ceremony and media demonstration was held on April 12 with 95 in attendance. Attendees represented a wide community cross section including congressional delegation representatives and members of the Clean Cities Coalition.

Finally, a web site has been developed for all aspects of this project. It is available at http://www.hydrogen.unlv.edu/.

Vehicles

Two utility vehicles provided by LVVWD including a Polaris Ranger (Figure 3) with an ICE were converted by students to run on hydrogen. The ICE uses locally developed, state-of-the-art, in-cylinder injection. Also, a Taylor-Dunn Electruck electric utility vehicle (Figure 3) was modified with the addition of a PEM fuel cell to demonstrate lower cost fuel cell vehicles. The vehicles are now in use at the LVVWD Desert Springs Preserve facilities which are near the filling station location.

FIGURE 3. Polaris Ranger Hydrogen ICE Vehicle Shown with the Taylor-Dunn Fuel Cell Vehicle Shown in the Background

In addition, we have garnered great interest from automotive companies since development of the vehicles and the station.

For the ICE vehicle, a conventional engine was modified for direct cylinder injection of hydrogen through a machined head. Crankcase venting was added. The timing system was modified and engine computer control was added. Electrical system modifications were made with the addition of the engine control computer and control system for the engine startup and shutdown. An onboard data acquisition system to monitor parameters is in testing. Modifications to the engine and dynamometer testing of the developed product were performed at Kell's Automotive and Marine.

For the electric vehicle conversion to a hydrogen fuel cell hybrid (initially a Taylor Dunn Electruk), the following were included:

- A Nuvera H2e 5.5-kW PEM fuel cell was added which provides power to recharge batteries and power the electric drive system.
- 6-VDC batteries were replaced with 12-VDC batteries to allow room for the fuel cell. A power conversion unit was installed to regulate voltage and regulate fuel cell load. Fuel cell sequence controls were added to control the fuel cell startup and shutdown. Onboard data acquisition was added to monitor parameters.
- A hydrogen fuel system was added including two 0.67-kg Dynatek L026 350-bar tanks with integral Teleflex TV-115 tank manifolds equipped with tank solenoids/check valves and pressure relief devices. An additional pressure relief device was added between pressure regulators and the fuel cell.
- Regenerative braking is being developed for this vehicle.

In the course of vehicle development on both units, safety aspects were of primary concern, with performance as a secondary concern. To address this, we used several approaches. The vehicles' modifications used components and procedures specifically designed for use with hydrogen vehicles wherever possible. When these were not available, we followed the latest CNG standards.

Any components fabricated locally, such as the in-cylinder injection check valve, went through materials testing for suitability, bench testing, dynamometer testing, and months of vehicle road testing at the university. Components were disassembled after testing and tolerances were checked.

Electrical components and assemblies, such as the FCV power conversion system and sequencing controls, were bench tested through multiple cycles, load tested, and road tested for months. Operational safety was considered for each component used. Components used for high pressures and hydrogen applications were checked for rating and suitability. Pressure ratings were carefully documented.

We are currently modifying a full-sized pickup that will have street use by the LVVWD. This vehicle uses a V8 engine modified with generally the same philosophy as the Polaris engine and will be including newly designed direct cylinder injection. Auxiliary electrical generation will be accomplished by a small on-board fuel cell, removing the necessity for a generator/alternator on the vehicle.

Basic PEM Electrolyzer Related Work

In this aspect of the work, membrane elements analysis, catalyst studies and membrane electrode assembly (MEA) development/testing have been taking place. The end goal of this involves the optimization of cost, conductivity, permeation, and durability. We have identified nine candidate materials for further evaluation and testing. These have gone through mechanical, chemical and permeation screenings. MEA testing is underway.

Catalysts are receiving attention in an attempt to minimize cost and maximize performance and durability. We have approached this effort with an initial survey and sample procurement from suppliers (these are quite limited), such that six identified candidates can undergo in-house synthesis. Single element, binary, and ternary systems are being considered. The focus is currently on Pt-group metals.

Another area of research activity is in issues related to low cost bipolar plate development. The approaches we have used for this include CFD modeling verification, design concepts brainstorming, CFD modeling optimization, and prototype testing (Figure 4).

Work has also addressed modeling of the overall electrolysis cell. A proposed simplified performance model has been shown to work quite well for parametric studies. Included in the model is a simple photoelectrochemical model for predicting the power requirements and hydrogen production rates from solar energy for PEM electrolyzer cells. As part of the work, we have developed a CFD model for simulating momentum and species transport and electrode kinetic reactions for an electrolyzer cell. We have also performed parametric studies of the effects of temperature, external power and illumination intensity on the operation of these cells. As a result of this study it has been revealed there is a strong non-uniformity in the distributions of channel velocities for the bipolar plate.

Another effort is a study of manufacturing aspects of electrolyzer cells. A major issue is the effect of scale-up of these components.

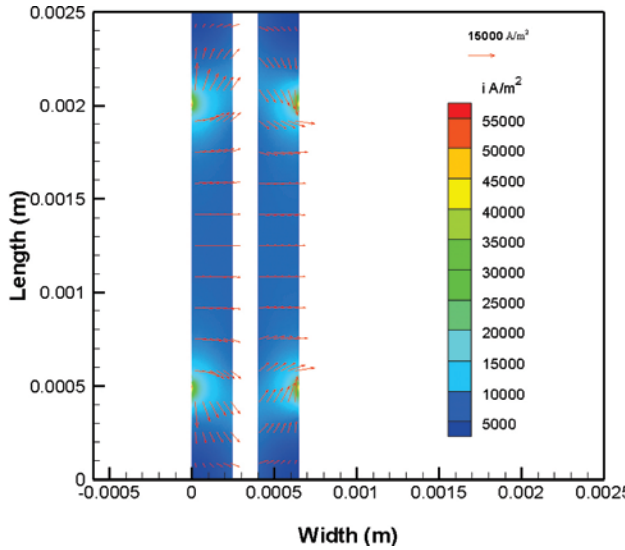

FIGURE 4. One example of many results of numerical computations that were performed. This shows current densities during unit operation. Comparisons to experimental data were generally very good.

Finally, work is ongoing related to a renewable energy interface development for electrolysis cells. While this work has recently begun, we began with baselining current systems for this application. The intent is to have an efficient and low cost device that will allow the direct powering of the electrolyzer by direct current from a source like photovoltaics.

Photocatalytic Cell Development

Two efforts remain on-going that are results of our earlier collaboration with Hydrogen Solar. We no longer work with this company (they removed their U.S. presence), but we continue work with one of their former employees using equipment that was purchased with federal funds for their work. We have demonstrated bench-scale performance of a photocatalytic device of 35 mA @ 1.2 V. This is approximately three times the world's record.

We have also developed a test facility on the roof of the engineering building at UNLV to provide on-sun testing of these types of devices. Two modules have been developed for evaluation in this facility, and most preliminary testing will be concluded at the end of summer 2007.

Summary

- The project is nearing a very successful completion.
- An excellent example of a renewable energy hydrogen filling station applicable to distributed application in the Southwest is now being demonstrated.

- Low cost vehicle conversions have been completed and are in operation.
  - Components designed here for these vehicles are being considered for use by major manufacturers.
  - Some of the components will simplify future conversions.
  - Expertise gained in the region in these technologies has been immense.
- A large number of students have been trained as a result of this project. These students have graduated at all levels from BS through PhD.
- The project has impacted a large number of fleet services throughout the Southwest, increasing awareness and interest in hydrogen technologies on a broad range of applications.
- This project has successfully brought together a significant public/private partnership, and this is one of the few projects in existence that combines a technical validation project with an active research component. This latter point was underlined to us when the DOE Safety Review Panel visited our project a few months ago.

Future Work

- Complete the installation of the 400 psi electrolyzer system.
- Continue to monitor station performance and vehicle characteristics.
- Complete the conversion of a Ford pickup with H_2 ICE and FC electrical power.
- Complete photoelectric cell studies for current configuration.
- Complete the Phase 4 work.
- Tabulate cost information comparisons.
- Continue to include a major component of student training in the project.
- Continue to support NREL's work for the PEC project.

FY 2007 Publications/Presentations

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2. Y. T. Chen, J. H. Nie, B. F. Armaly, H. T. Hsieh and R. F. Boehm, "Developing turbulent forced convection in two-dimensional duct," *Journal of Heat Transfer – Transactions of the ASME*, 2007 (in press).

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11. Y. Baghzouz, M. Popek, R. F. Boehm, R. Hurt, "Hydrogen APU electrical system analysis and bootstrap charging method," NHA Annual Hydrogen Conference, San Antonio, TX, March 19–22, 2007 (Poster).

12. Y. Baghzouz, R. Hurt, R.F. Boehm, "Evaluation of a fuel cell for powering the electric load of ICE vehicles," ICCEP, Capri, Italy, May 21–23, 2007.

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