II.J.1 Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi

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Fiscal Year (FY) 2011 Objectives

- Detail design and demonstrate subsystems for a unitized electrolyzer system for residential refueling at 5,000 psi to meet DOE targets for a home refueling appliance (HRA).
- Fabricate and demonstrate unitized 5,000 psi system (Year 2).
- Identify and team with commercialization partner(s).

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan [1]:

(G) Cost

(H) System Efficiency

Technical Targets

TABLE 1. Giner Electrochemical Systems, LLC (GES) Progress toward Meeting DOE Targets for Distributed Electrolysis Hydrogen Production [1]

Characteristics	Units	2017–2020 Targets	GES Status
Hydrogen Cost	\$/kg H_2	2.00–4.00	2.99*
Electrolyzer Capital Cost	\$/kg H_2	0.30	0.99
Electrolyzer Energy Efficiency	% (LHV)	74	73.6**

*Using H2A model rev 2.1.1; **5,000 psi operation; LHV = lower heating value

FY 2011 Accomplishments

- Determined performance and operational limits of a cathode-feed electrolyzer that circulated water using a thermosiphon, rather than a circulating pump.
- Updated electrolyzer and compressed hydrogen safety codes and standards.
- Performed 50 cm^2 2,000 psig (pumped cathode feed) electrolysis tests in a pressure dome.
- Tested Dimensionally Stable Membrane (DSM™) in balanced-pressure 17-cell 50 cm^2 2,000 psig (pumped anode feed) stack in pressure dome.
- Completed first round of tests on protective coatings for pressure containment dome internals.
- Assembled pressure swing absorber dryer for sorbent testing.
- Began preliminary system layouts of proton exchange membrane (PEM) electrolyzer HRA breadboard system.

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Introduction

U.S. automakers have invested significant resources in the research and development of hydrogen fuel cell vehicles. However, to enable the widespread use of fuel cell vehicles, an additional major investment will be required to construct an infrastructure for hydrogen production and delivery to fueling stations. In order to facilitate this transition, it has been recommended that high-pressure hydrogen, generated at 5,000 psig for home refueling of fuel cell vehicles, be implemented as an intermediary approach.

GES has matured a PEM-based electrolyzer technology for producing hydrogen at moderate to high pressure directly in the electrolyzer stack, while oxygen is evolved at near-atmospheric pressure. In this system, liquid water, which is a reactant as well as coolant, is introduced into the oxygen side at near atmospheric pressure; high-pressure hydrogen is removed from the product side. An improved, low-cost process for producing high-pressure hydrogen from water by electrolysis will significantly advance the development of the hydrogen economy, providing hydrogen for fuel cell vehicles at a price competitive with that of gasoline on a per-mile basis. The ability to produce hydrogen economically, the relatively low capital cost of the electrolyzer unit, and the low maintenance cost of the unit will allow widespread distribution of hydrogen home fueling appliances deemed necessary for the introduction of fuel cell vehicles.

Approach

GES is currently conducting a multi-year development project for DOE (Contract DE-FC36-08GO18065) that aims to reduce commercial electrolyzer costs while simultaneously raising the efficiencies of the PEM-based water electrolyzer units operating in the range of 400 psi. Future extension of this technology to pressures of 5,000 psig is feasible with modifications to the electrolyzer stack, providing the ability to safely operate in a balanced hydrogen/oxygen pressure mode. Based on an innovative electrolyzer stack concept and recent developments in high strength membrane, GES has designed a PEM-based water electrolyzer system for home refueling applications that will be able to deliver hydrogen at pressures of 5,000 psi. The design concept generates high-pressure hydrogen by means of "unitizing" the electrolyzer stack with a high-pressure hydrogen/water phase-separator and other subsystems. The combination of components eliminates the need for bulky and costly stack parts and facilitates a method for fabricating an electrolyzer system that can safely operate at a balanced hydrogen pressure of 5,000 psi. In addition, a reduction of major system components and system cost is realized.

Results

Electrolyzer Stack Design: The HRA has been designed for on-demand operation. The system is designed with a small 6-cell 2 kWe electrolyzer stack, providing a vehicle tank fill of 0.5 kg of hydrogen over a 12-hour period. This will provide 30 miles of driving range based on current fuel cell vehicle fuel economy estimates of 60 miles/kg-H_2. The electrolyzer stack is totally enclosed in a pressure containment dome; the pressure in the pressure dome is matched to that of the electrolyzer's hydrogen and oxygen product streams. This pressure dome-based design markedly simplifies many of the stack design requirements. Operating in the dome at pressures up to 5,000 psig, the 6-cell stack has a design pressure of 100 psid, and a proof pressure of 150 psid, meeting the requirements of the draft International Organization for Standardization (ISO) Standard ISO_DIS_22734-2 [2].

Preliminary Design of a 5,000 psi "Unitized" Electrolyzer System for Home Refueling: A block diagram outlining the process configuration for the 5,000 psi (34.6 MPa) PEM HRA is shown in Figure 1. The direct production of high-pressure hydrogen in the electrolyzer is shown via combining the water storage tank, electrolyzer stack and hydrogen/water phase-separators inside a pressure-containment dome, eliminating the need for a high-pressure mechanical hydrogen compressor, along with its ancillary equipments. The simplified major subsystems of the high-pressure electrolyzer system include the electrolyzer; the electricity feed sub-system; a user-accessible de-ionized (DI) water feed and DI water handling system. Note that the oxygen/water phase-separator is eliminated in this cathode-fed design; product oxygen that is free of liquid water will be promptly reduced from its high pressure and vented safely from the system.

Electrolyzer Operation Without a Circulation Pump: The most important project task involved verifying the catholyte circulation rate that can be supported in a thermosiphon-based cathode-feed electrolyzer. If insufficient water is circulated to meet the stoichiometric reaction needs of the electrolyzer, the membrane electrode

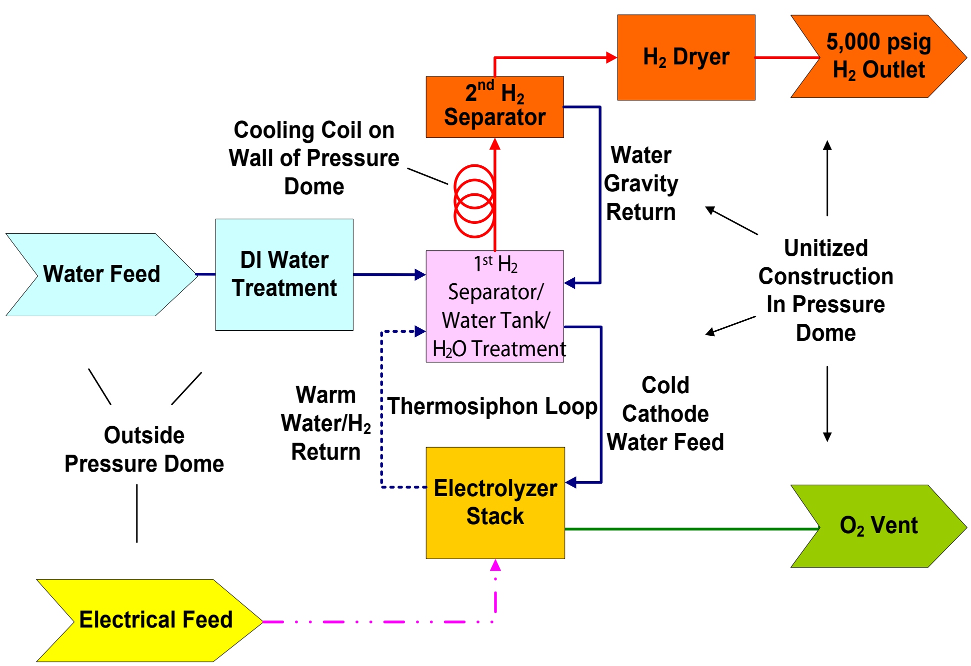

FIGURE 1. Cathode Feed Process Flow Diagram

assembly (MEA) can become water-starved, leading to membrane dry-out and inefficient electrolyzer operation, with eventual safety shutdown due to high voltage operation. Sufficient water circulation is also required for a second critical operational need: heat removal from the electrolysis reaction. As the electrolytic production of hydrogen and oxygen from water is not 100% efficient, byproduct waste heat is produced. The resultant waste heat must be removed from the electrolyzer. The standard GES electrolyzer design uses water circulation rates well in excess of the stoichiometric reaction requirements to remove the heat of reaction; the heat is then released to the surroundings through a separate heat exchange process.

Calculations during Phase I of this effort resulted in a thermosiphon water circulation rate prediction of 5.75 cc/min for a single 60-mil-thick, 160-cm^2 cathode-feed electrolyzer cell. Figure 2 illustrates the typical thermosiphon catholyte flow through a 90-mil cathode compartment. Flow measurements were quite consistent from ambient temperature up to 90°C. Thermosiphon flow ranged from a minimum of 36 cc/min. at 100 mA/cm^2, to a limit of 58 cc/min., reached over a range of 600–900 mA/cm^2. These flows are well in excess of the predicted flows: a factor of 6.3–10.1 times higher than the water circulation rate predicted in the project's earlier Phase I effort. Consequently, one of the most important HRA operational requirements, adequate thermosiphon flow, was validated for the 90-mil cathode compartment thickness.

Thermosiphon Electrolyzer Voltage Performance: After verifying the superior water circulation rates possible with the initial 90-mil thick, low-resistance cathode design, voltage performance data was collected at ambient pressure and operating temperatures up to 90°C. Figure 3 illustrates the resultant polarization scans at 80 and 90°C. As expected, the higher temperature, 90°C operating data provides better performance (lower voltage), relative to operation at 80°C. The performance benefit of 90°C operation ranges from a 21 mV improvement at 100 mA/cm^2, up to an 82-mV improvement at 850 mA/cm^2. Obviously, if electrolyzer performance can be proven to be reliable and stable at 90°C, the energy efficiency of hydrogen production will be increased.

Cathode Feed (Pumped) Operation in Pressure Dome: On a separate National Aeronautics and Space Administration-funded project developing high-pressure oxygen electrolysis for life support, successful differential-pressure operation of a 50-cm^2 1cell cathode-feed stack was conducted in a 2,000-psig pressure dome. Although not exactly in line with the goals of the HRA development project, this work demonstrated an advancement of state-of-the-art operations of high-pressure electrolyzers contained in pressure domes. Operation of both the 50-cm^2 1cell cathode-feed and a 50-cm^2 17cell anode-feed electrolyzer stacks was successful over a wide range of operating conditions. Figure 4 illustrates the resultant polarization scan from pumped anode-feed operation, for both 1,000- and 2,000-psig oxygen production pressures. (Cathode feed data is not shown.)

Data in Figure 4 illustrate the slight voltage penalty for producing oxygen gas at higher pressure, which occurs for all operating temperatures. At a constant 300 mA/cm^2, with

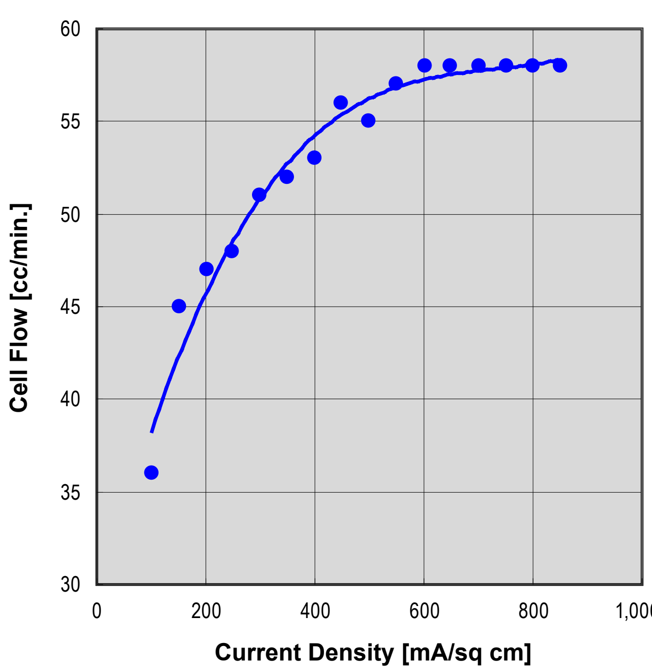

FIGURE 2. Cathode-Feed (Non-Pumped) 160 cm^2 Single-Cell Water Circulation Rate

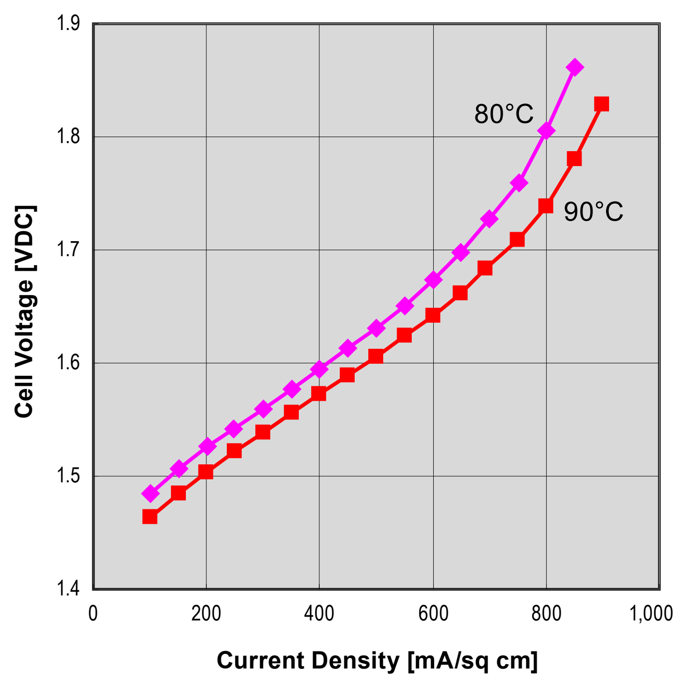

FIGURE 3. Cathode-Feed (Non-Pumped) 160 cm^2 Single-Cell Polarization Testing

40°C operation, raising the oxygen's production pressure from 1,000 to 2,000 psig requires an additional 42 mV. With 60°C operation, raising the oxygen pressure from 1,000 to 2,000 psig requires an additional 28 mV; at 80°C it requires an additional 20 mV.

Figure 4 also shows the advantages of raising the operating temperature from 40°C to 80°C. The primary advantage is to reduce the cell operating voltage, resulting in more efficient electrolyzer operation. For instance, at a constant 300 mA/cm^2 operation at 2,000 psig oxygen generation pressure, raising the cell temperature from 40 to 60°C reduces the voltage by 99 mV. In addition, further raising the cell temperature from 60 to 80°C reduces the voltage by an additional 57 mV. To summarize the cathode feed (pumped) tests in a pressure dome, the most efficient electrolyzer operation occurred at the highest temperature of 80°C.

Conclusions and Future Directions

The Phase II project is completing component tests that will lead to a practical design for a 5,000 psi "Unitized" breadboard system to be built and tested next year. The technology will be able to provide on-site residential hydrogen refueling at a cost that meets the DOE target of \$2.00–\$4.00/kg-H_2 in 2017–2020. In addition to unitizing the major components, the design incorporates numerous cost-saving (and reliability enhancing) simplifications, such as eliminating the need for any mechanical pumps, and utilizing passive cooling for low-cost, maintenance-free heat transfer. These design features eliminate the need for bulky and costly stack and system parts, and facilitate a method for producing a low-cost electrolyzer system that can safely operate at a hydrogen pressure of 5,000 psi in a residential setting. Future objectives are:

- Complete HRA component tests.
- Conduct a hazards and operational safety analysis/failure modes and effects analysis of the breadboard HRA system.
- Detail design and fabrication of a full-scale electrolyzer stack sized for a hydrogen production rate of 0.5 kg H_2 per 12-hour operational period.
- Detail design, component fabrication, and assembly of a "unitized" breadboard HRA electrolyzer system for 5,000 psi delivery pressure.
- Performance and durability testing of unitized breadboard system prototype.
- Complete a preliminary design and economic analysis of a future commercial HRA system.
- Develop marketing strategy and partnerships for wide scale adoption of technology.

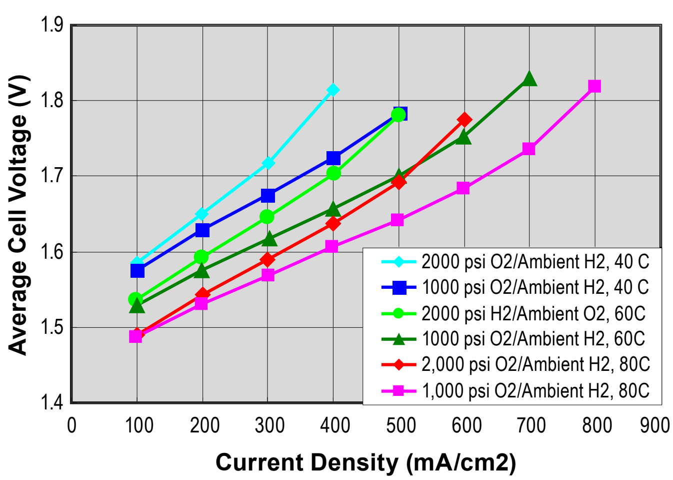

FIGURE 4. Cathode Feed (Pumped) Nafion® 117 Operation

FY 2011 Publications/Presentations

1. T. Norman, M. Hamdan and K. Patch, SBIR Phase II, *Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi*, DOE HPTT Presentation, November 2, 2010.

2. T. Norman, K. Patch and M. Hamdan, *Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi.* 2011 Hydrogen Annual Program Merit Review Meeting, Presentation #pd_065_norman, June 10, 2011.

References

1. Multi-Year Research, Development and Demonstration Plan, Hydrogen Production, Pg 3.1-14. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf.

2. ISO Draft International Standard ISO/DIS 22734-2, Hydrogen generators using water electrolysis process – Part 2: Residential applications, 2009.

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