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

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Fiscal Year (FY) 2012 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
- 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:

(G) Cost - Capital Cost
(H) System Efficiency

Technical Targets

Giner Progress toward Meeting DOE Targets for Distributed Electrolysis Hydrogen Production

Characteristics	Units	2017–2020 Targets	Giner 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	TBD

*Using H2A model rev 2.1.1; LHV – lower heating value

FY 2012 Accomplishments

Membrane

- Developed high-pressure, high-strength membranes compatible with 5,000 psi operation

Completed Electrolyzer Stack Fabrication for 5,000 psi Operation

- Innovative design to reduce stack material costs:
  - Cell Frames
    - Completed cell frame stress analysis and method for high pressure reinforcement
    - Utilizes thermoplastics vs. metal (high-cost)
  - Reduce parts count/cell
  - Carbon cathode support structures
    - Multi-functional part
    - Eliminates 20+ component parts
    - Enables high pressure operation
  - Single piece separator
    - Eliminates hydrogen embrittlement
- Evaluated overboard and crossover sealing to 1.25X operating pressure (6,250 psi)

Electrolyzer System Fabrication Initiated, Near Completion

- Integrated electrolyzer subsystems to minimize the number of balance-of-plant (BOP) components
- Improved safety and reliability

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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. 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.

The project focuses on the development of high-pressure, low-cost electrolyzer stack and BOP components. Giner has a matured proton exchange membrane (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 anode (O_2) side of the electrolyzer at near atmospheric pressure; high-pressure hydrogen is removed from the cathode or product side. In addition to reliability, and long maintenance intervals, safety is also a primary concern in this design due to the flammability and reactivity concerns of hydrogen and oxygen.

Approach

Giner is currently conducting a multi-year development project for DOE 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 differential hydrogen/oxygen pressure mode. Based on an innovative electrolyzer stack concept and recent developments in high strength membrane, Giner 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. High-pressure hydrogen can be generated in low-cost moderate-pressure electrolyzer stacks by means of external reinforcement to the individual cell frames. Utilizing external cell reinforcement eliminates the need for bulky and costly stack parts and facilitates a method for fabricating an electrolyzer stack and system that can safely operate at a high pressure. In addition, a reduction of major system components and system cost is realized.

Results

Membrane Evaluation: PEM electrolyzer gas permeation models developed by Giner and based on single-cell testing at various operating pressures, temperatures, and membrane thicknesses, show that improved stack efficiency is obtained while operating the electrolyzer stack in a differential pressure mode (hydrogen pressure over oxygen pressure) as opposed to balanced pressure in which both hydrogen and oxygen gases are generated at the same pressure. As illustrated in Figure 1**,** Faradaic losses, in terms of current density, during differential pressure operation of a 10 mil thick 1100 equivalent weight (EW) perfluorosulfonic acid (PFSA) membrane, is lower than that of a similar membrane tested at balanced pressure. Although not shown, this is true for all membrane thicknesses, operating pressures, and temperatures. The decrease in efficiency at balanced pressure operation is directly related to increased oxygen concentrations gradients across the membrane. Utilizing engineered membranes developed at Giner, the performance of the electrolyzer is optimized for the selected operating pressure (and temperature).

Electrolyzer Stack Fabrication: The HRA has been designed for on-demand operation. The system is designed with a small 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. Differential pressure operation required redesign of the electrolyzer stack hardware. Giner's initial design included the use of a pressure containment dome; the gas pressure in the pressure dome is matched to that of the electrolyzer's hydrogen and oxygen product streams to provide external stack reinforcement. In 2012, Giner developed a modified stack design that utilizes a metal containment ring externally attached to the electrolyzer-stack's cathode (H_2) cell frames. The simplified design eliminates the need for a containment dome; in addition, this technique enables high pressure operation with the use of low- and moderate-pressure PEM-based electrolyzer stacks without the need for expensive internal cell reinforcement or metal frames. Low-cost is maintained by utilizing previously designed injection molded thermoplastic cell frames and cell components.

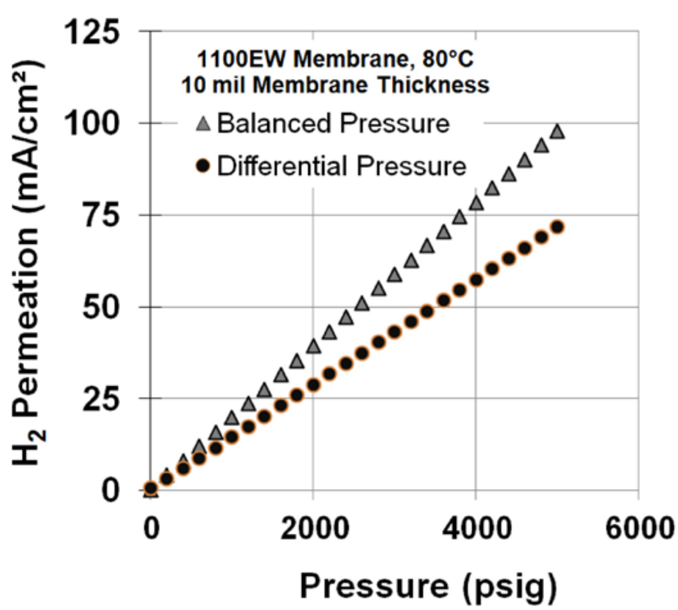

FIGURE 1. Faradaic Losses: Balanced vs. Differential Pressure Operation

In addition to the use of external cell-frame reinforcement, the electrolyzer stack includes several modifications developed under a separate DOE project (PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane) that further reduce stack cost. This includes (1) an overall decrease in the parts count per cell (2) a 75% reduction in anode and cathode catalyst loadings, (3) molded thermoplastic cell frames, resulting in a cost reduction of 95% as compared to machining this component, (4) a reduction in cell frame thickness, thus reducing the anode and cathode support materials and costs, and (6) and a modified anode membrane support material that enables high-pressure operation that can exceed 5,000 psi. The design and fabrication of the electrolyzer stack, utilizing the external cell reinforcement, has been completed and is shown in Figure 2. The electrolyzer stack was successfully proof pressure tested to 6,250 psi.

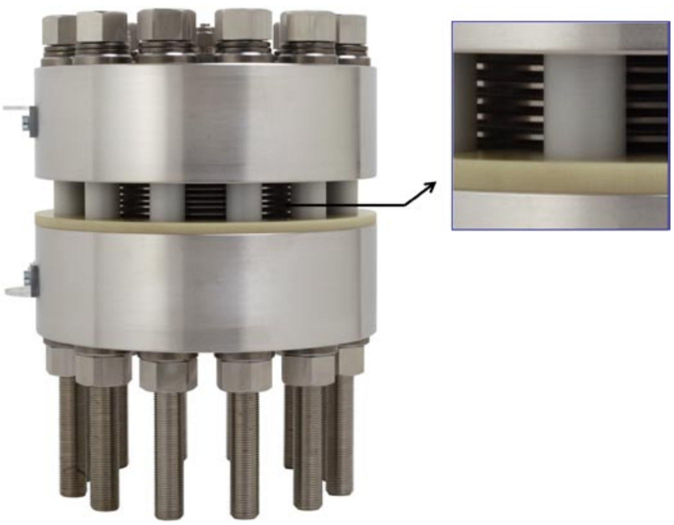

FIGURE 2. High Pressure Electrolyzer Stack with Reinforced Cell Frames

Preliminary Design of a 5,000 psi "Unitized" Electrolyzer System for Home Refueling: The HRA depicted in Figure 3 features: (1) a 2-kW differential pressure electrolyzer stack that produces hydrogen at up to 5,000 psi and oxygen at ambient pressure, (2) a water tank, sized for approximately 12 hours of electrolyzer operation at rated power levels, (3) an integrated deionized water loop used to maintain water purity and temperature control of the electrolyzer stack during operation, (4) a small hydrogen dryer to maintain a hydrogen gas dew point of <-40°C, (5) sensors for monitoring the production gases to prevent/detect formation of flammable mixtures, and (6) the integration, where feasible, of electrolyzer subsystems to minimize the number of BOP components. An automated control system also provides safe automated operation.

The reactant water is supplied to the anode side of the electrolyzer stack at ambient pressure. Oxygen generated on the anode side of the electrolyzer stack is then separated from water in the oxygen gas separator which also serves as the water reservoir. Water is circulated from the oxygen gas separator to the anode of the electrolyzer stack and back to the oxygen gas separator. The circulating pump operates at low differential pressure, as it must only overcome the pressure drop in the feed loop. During electrolyzer operation water is transferred from the anode side of the electrolyzer stack to the cathode side due to electrically-osmotic transport. Water loss due to electro-osmotic drag is collected in the hydrogen gas phase separator and returned to the electrolyzer feed loop after it has been degassed. Cooling to the electrolyzer stack is provided by the heat exchanger located in the electrolyzer water feed loop. The cooling loop

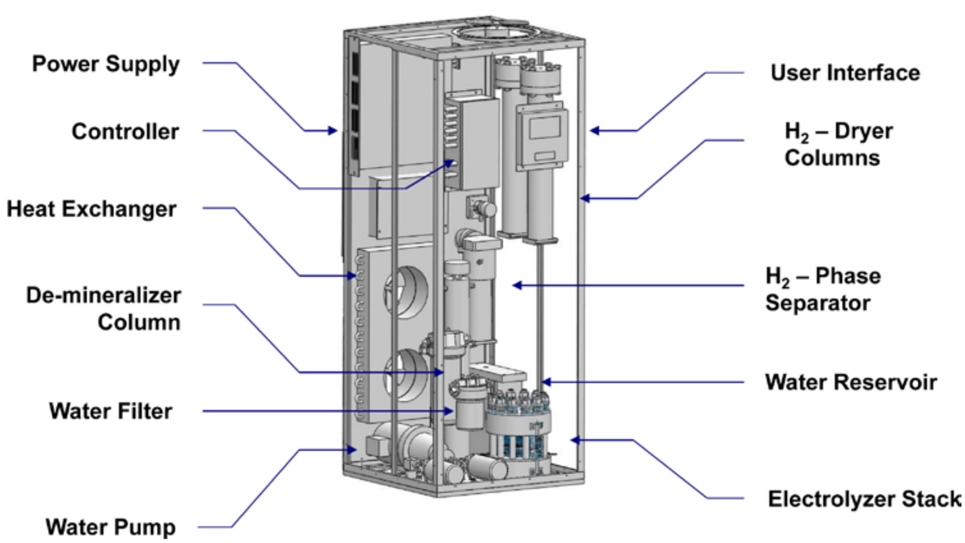

FIGURE 3. Electrolyzer (HRA) System Layout

and the heat exchanger are common between the electrolyzer stacks and the de-ionized water loop. Hydrogen generated on the cathode side is separated from crossover water in the hydrogen gas phase separator prior to entering the drying hydrogen unit.

At the end of the electrolysis cycle, which occurs when the water in the HRA system is nearing depletion, power is no longer available, or at a predetermined time or pressure, the electrolyzer subsystem is shut down. In addition to the normal end-of-cycle operation, the control system automatically shuts down electrolyzer operation when abnormal conditions are detected. The conditions that trigger electrolyzer subsystem shut down include: low water in the electrolyzer feed loop, low water flow rate, high temperatures (>80°C), over pressure (>5,000 psig), and gas detection alarms. In addition, any cell in the electrolyzer stack exhibiting a low or high voltage will activate a system shutdown.

Performance: The specific energy consumption of the electrolyzer stack, based on a 10-mil membrane is shown in Figure 4. Although Figure 4 includes the affect of a Nernstian voltage penalty due to pressurization from 300 psi to 5,000 psi, the higher power consumption is largely due to faradaic losses related to hydrogen permeation. As shown in Figure 4, an additional 5 kWe per kg of H_2 is required

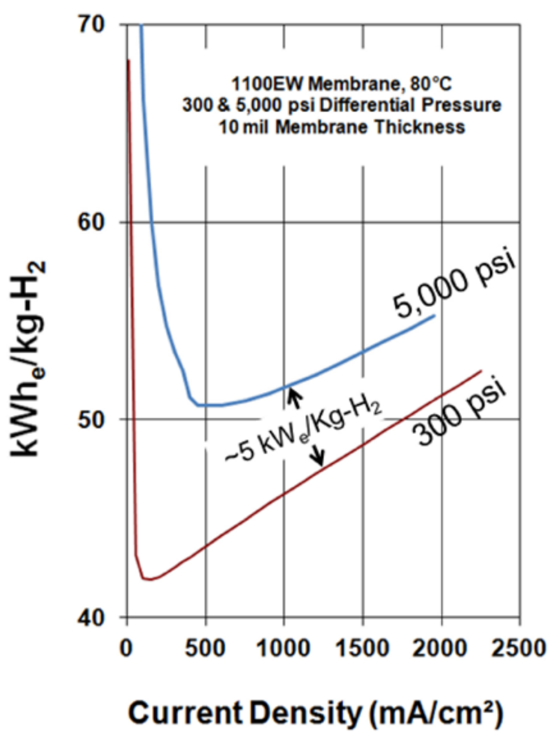

FIGURE 4. Specific Energy Consumption of Electrolyzer Stack

when operating the electrolyzer stack from 300 to 5,000 psi with a 10-mil thick 1100 EW PFSA membrane. At operating current densities above 500 mA/cm², internal resistance losses become dominate. This can be reduced by properly engineering the membrane thickness for pressure and temperature conditions. Giner's current membrane design is expected to result in an electrolyzer stack power consumption of 51-52 $kWh_e/kg\text{-}H_2$ at an operating at a current density of between 1,000 and 1,500 mA/cm².

Conclusions and Future Directions

The technology will be able to provide onsite residential hydrogen refueling at a cost that meets the DOE target of \$2.00–\$4.00/kg-H_2 by 2017. In addition to unitizing the major components, the design incorporates numerous cost-saving (and reliability enhancing) simplifications. 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 fabrication of the full-scale HRA system sized for a hydrogen production rate of 0.5 kg H_2 (at 5,000 psi) per 12-hour operational period
- Conduct performance and durability testing of HRA prototype
- Conduct optimization studies: stack and system
- Complete a preliminary design and economic analysis of a future commercial HRA system
- Develop marketing strategy and partnerships for wide scale adoption of technology.

FY 2012 Publications/Presentations

1. T. Norman, and M. Hamdan, *Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi.* 2012 Hydrogen Annual Program Merit Review Meeting, Presentation #pd_065 norman, May 15, 2012.