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

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Objectives

Develop conceptual design for a unitized electrolyzer system for residential refueling at 5,000 psi to meet DOE targets for a home refueling apparatus:

- Complete preliminary system and stack design of a unitized proton exchange membrane (PEM) electrolyzer.
- Evaluate PEM membrane up to 2,500 psi.
- Complete economic feasibility studies.

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) Capital Cost
(H) System Efficiency

Technical Targets

TABLE 1. GES Progress toward Meeting DOE Targets for Distributed Electrolysis Hydrogen Production

Characteristics	Units	2012/2017 Targets	GES Status
Hydrogen Cost	$/kg H_2	3.70/<3.00	2.99*
Electrolyzer Capital Cost	$/kg H_2	0.70/0.30	0.99
Electrolyzer Energy Efficiency	% (LHV)	69/74	73.6**

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

Accomplishments

- Preliminary Electrolyzer Stack and System Design
  - Completed preliminary design of a 5,000 psi "unitized" stack.
    - Designed, fabricated, and tested electrolyzer stack hardware to 2,500 psi.
  - Completed preliminary design for unitized PEM electrolyzer system for home refueling applications.
  - Completed economic feasibility studies.
  - Completed survey of applicable domestic and international hydrogen generation/refueling safety codes and standards.
- Membrane Evaluation
  - Six-cell short stack built with advanced dimensionally stable membrane (DSM™).
  - Conducted testing of DSM™ at pressures of 100, 600, and 2,500 psi.

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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 their widespread use, 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, the DOE has recommended that high-pressure hydrogen generation for home refueling of fuel cell vehicles be implemented as an intermediary approach.

GES has developed 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. A 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 non-military 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 balance 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 can deliver hydrogen at pressures of 5,000 psi. The design concept demonstrates a method for the generation of high-pressure hydrogen by means of "unitizing" the electrolyzer stack and a high-pressure hydrogen/water phase-separator. 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 Home Refueling Appliance (HRA) has been designed for on-demand operation. The system is designed with a small six-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 production 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 equipment. The simplified major subsystems of the high-pressure electrolyzer system include the electrolyzer; the electricity feed sub-system; a user accessible deionized water feed and deionized water handling system. Note that the oxygen/water phase-separator is eliminated in

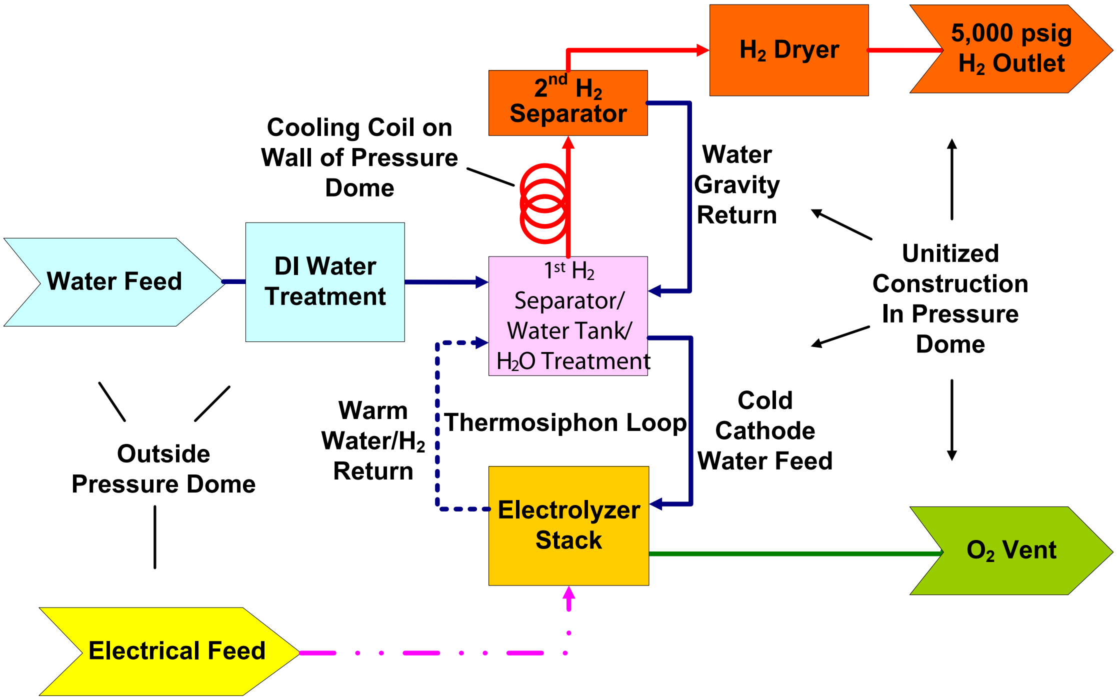

FIGURE 1. Cathode Feed Process Flow Diagram

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. Figure 2 illustrates a conceptual layout of the HRA pressure dome containing the major items of equipment (electrolyzer stack, water separators, hydrogen cooling coil, and hydrogen dryer).

Liquid-Gas Phase Separators: As they will not be subject to any significant differential pressures, the hydrogen/water phase separators located within the dome are designed from low-cost polypropylene material. They do need to be gas-tight; to meet this requirement they will be rotationally molded in a single piece, or injection molded in two pieces, then ultrasonically welded.

Pressure Dome: Section VIII of the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code [3] was used to calculate preliminary material thickness for the HRA pressure dome. Two primary calculations were completed – for the cylindrical shell of the dome, and for the flanged-and-dished heads used to seal both ends of the dome. The cylindrical shell of the dome requires a 2.5″ carbon steel metal thickness to contain the 5,000 psig pressure within the dome.

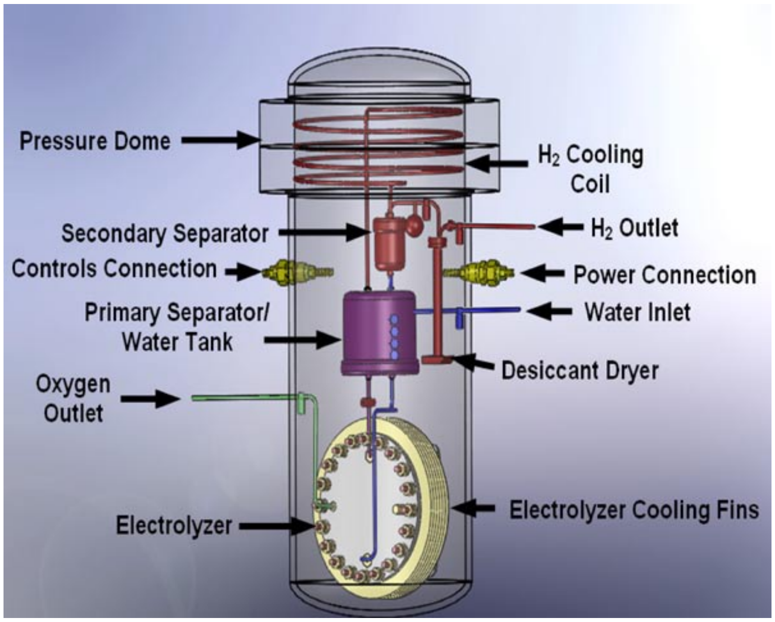

FIGURE 2. HRA Conceptual Design

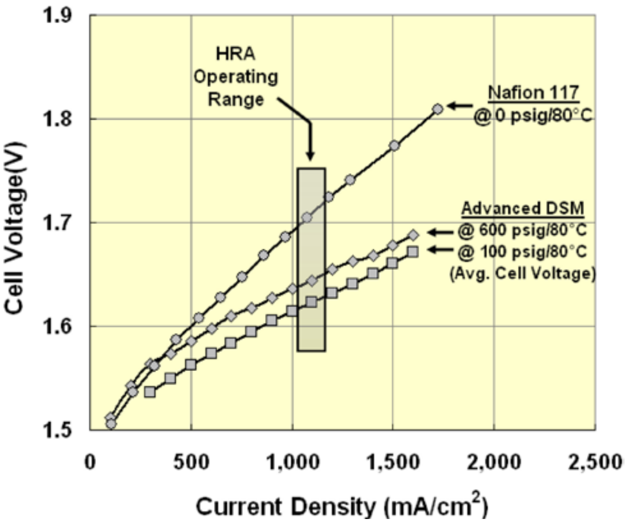

FIGURE 3. Supported Membrane Demonstration of DSM^{TM} in Cathode-Feed 50-cm^2 Cell

Membrane Evaluation at High Pressure Operation: Polarization scans were obtained in an operating cathode-feed six-cell electrolyzer stack with an active area of 50 cm^2. The membrane used for this test was DSM™, fabricated by GES personnel. Utilizing a unique structure, DSM™ is a high-performance membrane having excellent dimensional stability over a wide range of temperatures and relative humidities. Compared to conventional ionomer membranes, the supported membrane is stronger, more ionically conductive, and can be optimized for specific applications. The DSM™ used in these tests had a total dry thickness of 2.2 mils, with a polyimide reinforcement layer. Figure 3 illustrates a polarization scan obtained with this electrolyzer, with data taken while operating at 80°C and 100 and 600 psi. The DSM^{TM} demonstrated stable short-term operation and performance superior to that of Nafion® 117 [4]. The voltage ranged from 1.512 V at 100 mA/cm^2, to 1.688 V at 1,600 mA/cm^2. At the HRA design current density of 1,200 mA/cm^2, the operating voltage of 1.655 V translates into a stack voltage efficiency of 75.6% LHV (89.4% higher heating value, HHV). In separate testing using the same hardware, the cell voltage measured during single-cell testing at a balanced operating pressure of 2,500 psi is 1.695 V. Although hardware development is required for 5,000 psi operation, a cell voltage of 1.701 V is achievable (accounting for the Nernst penalty loss at 5,000 psi balanced-pressure-operation) or a cell efficiency of 73.6% LHV (87.0% HHV).

System Feasibility Studies: The main challenge to producing commercially viable hydrogen is cost reduction. To determine the feasibility of using a ‘unitized electrolyzer’ as an HRA, it was necessary to examine the individual contributors to the cost of hydrogen production, such as the capital, feedstock (electrical costs), and fixed operating and maintenance costs (See Tables 1 and 2).

TABLE 1. System Capital Costs

Cumulative Number of Units	**1**	**10**	**100**	**1 k**	**10 k**	**100 k**	**1,000 k**
Electrolyzer Stack	19.14	8.64	4.98	2.90	1.69	0.98	0.57
BOP	17.85	8.06	4.64	3.53	1.57	0.91	0.53
System Assembly Labor	3.70	1.67	0.96	0.56	0.32	0.19	0.11
Total Cost of System ($,000)	**40.69**	**18.37**	**10.58**	**6.99**	**3.59**	**2.09**	**1.22**

BOP = balance of plant

TABLE 2. H2A Model Analysis of HRA

Cumulative Number of Units	**1**	**10**	**100**	**1 k**	**10 k**	**100 k**	**1,000 k**
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*Compression, Storage, and Dispensing Cost Contribution = 0.00 ($/kg-$H_2$)

A comparison was made between the GES HRA cost estimates and the DOE Hydrogen Program 2015 system cost goal of $30/kWe for light-duty vehicle fuel cells [5]. Using this DOE cost basis, and a scaling factor of 0.60 [6,7], a 2 kWe HRA system would be predicted to cost $234 at a unit production volume of 1,000,000 units. Alternately, a different comparison can be made to the DOE forecourt electrolyzer cost breakdown for 2017 of $125/kWe [8]. Using this alternate DOE cost basis, and a scaling factor of 0.60, a 2 kWe HRA system would be predicted to cost $4,617 at a unit production volume of 1,000. These can be compared to the GES predicted capital costs to verify that the GES costs ($1,220/$6,994) are well above the DOE 2015/2017 scaled costs ($234/$4617). As the modeled GES costs are a factor of 1.5 to 5 above the scaled DOE costs, the magnitude of the GES capital cost predictions appear to be conservative, relative to the DOE 2015/2017 costs.

The total cost of delivered hydrogen ($/kg-$H_2$) via DOE's H2A analysis model (rev 2.1.1) is shown in Table 2. Our studies indicate that the most significant cost contributions are in two areas: feed stock and capital costs. The feedstock (electricity required to generate H_2) contribution of an electrolyzer system operating with a 3-mil DSM™ membrane, average efficiency of 84.1% HHV and a power cost of 4 cents per kWh, is $1.98/kg-$H_2$. Although limited by durability at elevated temperature operation, for comparison the feed stock cost of an electrolyzer system operating with Nafion® 117 (average cell efficiency of 73.7% HHV), is calculated to be >$2.30/kg-$H_2$.

Conclusions and Future Directions

The Phase I project yielded a practical preliminary design for a 5,000-psi "Unitized" design that will be able to provide on-site residential hydrogen refueling at a cost that meets the DOE target of $3.00/kg-$H_2$ in 2017. 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:

- 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.
- Perform in-depth reviews of codes and standards pertinent to hydrogen generation.
- Performance testing of unitized system prototype.
- Develop marketing strategy and partnerships for wide scale adoption of the technology.

FY 2010 Publications/Presentations

1. T. Norman, *Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi*. DOE HPTT Presentation, October 14, 2009.

2. T. Norman, *Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi*. 2010 Hydrogen Annual Program Merit Review Meeting. Presentation #pd_065_norman, June 10, 2010.

References

1. Multi-Year Research, Development and Demonstration Plan. Hydrogen Production. DOE, 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.

3. ASME B31.12, Hydrogen Piping and Pipelines, American Society of Mechanical Engineers, 2008.

4. Nafion® and Kapton® are registered trademarks of E.I. du Pont de Nemours and Company.

5. U.S. Department of Energy Hydrogen Program Fact Sheet, March, 2009a, retrieved from http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_program.pdf on 4/23/10.

6. U.S. DOE Guideline G 430.1-1 Chapter 20, "Estimating Specialty Costs" (Mar 28, 1997), retrieved from https://www.directives.doe.gov/directives/current-directives/430.1-EGuide-1-Chp20/view on 4/23/10.

7. "Equipment Design and Cost Estimation for Small Modular Biomass Systems, Synthesis Gas Cleanup, and Oxygen Separation Equipment, Task 2: Gas Cleanup Design and Cost Estimates – Black Liquor Gasification;" Nexant Inc. San Francisco, California, Subcontract Report, NREL/SR-510-39944, May 2006.

8. "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan, Planned Program Activities for 2005-2015," U.S. DOE Office of Energy Efficiency and Renewable Energy, April, 2009b, retrieved from http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf on 4/23/10.