

DEPARTMENT OF ENERGY

A Low-Cost High-Pressure Hydrogen Generator

Final Report

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EXECUTIVE SUMMARY

Electrolysis of water, particularly in conjunction with renewable energy sources, is potentially a cost-effective and environmentally friendly method of producing hydrogen at dispersed forecourt sites, such as automotive fueling stations. The primary feedstock for an electrolyzer is electricity, which could be produced by renewable sources such as wind or solar that do not produce carbon dioxide or other greenhouse gas emissions. However, state-of-the-art electrolyzer systems are not economically competitive for forecourt hydrogen production due to their high capital and operating costs, particularly the cost of the electricity used by the electrolyzer stack.

In this project, Giner Electrochemical Systems, LLC (GES) developed a low-cost, high-efficiency proton-exchange membrane (PEM) electrolysis system for hydrogen production at moderate pressures of 300 to 400 psig (2170 to 2860 kPa). The electrolyzer stack operates at differential pressure, with hydrogen produced at moderate pressure while oxygen is evolved at near-atmospheric pressure, reducing the cost of the water feed and oxygen handling subsystems. The project included basic research on catalysts and membranes to improve the efficiency of the electrolysis reaction, as well as development of advanced materials and component fabrication methods to reduce the capital cost of the electrolyzer stack and system. The project culminated in delivery of a prototype electrolyzer module to the National Renewable Energy Laboratory for testing at the National Wind Technology Center.

Electrolysis cell efficiency of 72% (based on the lower heating value of hydrogen) was demonstrated using an advanced high-strength membrane developed in this project. This membrane would enable the electrolyzer system to exceed the DOE 2012 efficiency target of 69%. GES significantly reduced the capital cost of a PEM electrolyzer stack through development of low-cost components and fabrication methods, including a 60% reduction in stack parts count. The estimated cost of the present stack design in large-scale production is less than \$1000/kW. A future development path has been identified that would decrease the capital cost to less than \$550/kW. Economic analysis indicates that hydrogen could be produced for \$3.79 per gge at an electricity cost of \$0.05/kWh by the lower-cost PEM electrolyzer developed in this project assuming high-volume production of large-scale electrolyzer systems.

1.0 INTRODUCTION

Electrolysis of water to produce hydrogen and oxygen was first demonstrated in 1800 and was developed commercially for large-scale hydrogen production in the 1920s and 1930s (Kroposki, et al., 2006). However, commercial electrolyzers have relatively low efficiency and high capital cost, which limits their use to areas with inexpensive electricity or to applications, which require high-purity hydrogen. The present cost of hydrogen produced by large-scale electrolysis systems is \$5.00/kg, according to Department of Energy (DOE) estimates. This is considerably higher than the 2012 DOE target cost of \$3.70/kg for hydrogen production by electrolysis.

DOE has identified hydrogen production by electrolysis of water at forecourt stations as a critical technology for transition to the hydrogen economy, and as the hydrogen economy matures, for hydrogen production at centralized locations using renewable energy sources. This hydrogen would be a clean, domestic, carbon-free fuel. In a recent study, the National Renewable Energy Laboratory (NREL) reported that hydrogen production by electrolysis using the United States wind and solar resources could replace the Nation's present gasoline requirements (Kroposki et al., 2006).

The two major electrolyzer technologies are alkaline and proton-exchange membrane (PEM). Giner Electrochemical Systems, LLC (GES) is developing a differential-pressure PEM electrolysis system. The GES electrolyzer consists of a number of bipolar cells stacked in electrical series, with each cell containing a membrane-electrode assembly (MEA) formed by bonding anode and cathode electrodes to opposing sides of the membrane. The MEA is in contact with electrically conductive anode and cathode support structures located in the oxygen and hydrogen chambers, respectively. An electrically conductive cell separator is located between the anode and cathode chambers of adjacent cells. In the process, high-purity water is pumped to the anode, where it is electrochemically decomposed to oxygen gas, hydrogen ions and electrons. The hydrogen ions move through the PEM and the electrons move through the external circuit to the cathode, where they recombine to form hydrogen. An excess of water is supplied to the oxygen side of the cell and is recirculated to remove waste heat from the MEA. A portion of the excess water is electro-osmotically transported across the PEM with the hydrogen ions. The electrochemically-transported water is separated from the product hydrogen and returned to the water stream.

The GES PEM electrolyzer technology is much more efficient than the more mature alkaline electrolyzer technology. GES PEM cells operate efficiently at current densities of 2000 to 3000 mA/cm², compared to alkaline electrolyzers that typically operate at less than 300 mA/cm². At this current density the alkaline cell voltage is typically 1.9 V or higher. In contrast, the operating cell voltage of the present 15-kW GES electrolyzer is lower, 1.85 V, at a current density nearly an order of magnitude higher, 2000 mA/cm² at 300 psig (2170 kPa) H₂. In this project GES demonstrated a PEM electrolysis cell based on an advanced membrane that operates at 1.7 V at 2000 mA/cm². Since the cost of electricity is the major contributor to the cost of hydrogen produced by electrolysis, efficient operation is a key to low-cost hydrogen production for large applications. Although the capital cost of PEM electrolyzer stacks is higher than that of alkaline stacks on an area basis, the much higher current density of PEM cells allows the stacks to be smaller by a factor of 5 to 10, while achieving high efficiency. Thus, in large-scale

production, and with development of lower-cost materials and manufacturing methods for key components, the capital cost of a PEM stack is expected to be competitive with alkaline stacks, while the electricity consumption of the PEM stack will be significantly lower than that of the alkaline stack.

Another key advantage of the GES PEM technology is the ability to operate the stack at a high differential pressure, allowing hydrogen to be produced at high pressure, while oxygen is produced, and the reactant water is supplied, at near atmospheric pressure. Production of hydrogen in the electrolyzer at elevated pressure provides some systems advantages, decreasing the number of stages of mechanical compression required to store the product hydrogen at greater than 5000 psig (34.6 MPa), the DOE goal for hydrogen fueling stations. However, these advantages must be weighed against the increased capital cost of the higher pressure stack and electrolyzer balance of plant (BOP).

The GES differential pressure PEM electrolyzer technology is based on the design of the PEM oxygen generating plants (OGP) used onboard the SeaWolf class submarines. GES manufactured the stack components for six OGP plants. In these balanced-pressure systems, oxygen and hydrogen are both produced at 3000 psig (20.8 MPa). GES subsequently developed the technology for a 1000-psig (7 MPa) differential-pressure electrolyzer. However, the technology is based on the very reliable, but very expensive, electrolyzer stack designs required for submarine applications. The challenge in this DOE project was to modify the differential pressure stack design to significantly reduce stack and system cost, while improving process efficiency, to meet the DOE cost targets for hydrogen production.

2.0 PROJECT OBJECTIVES AND TECHNICAL APPROACH

The overall objective of this project was to develop and demonstrate a cost-effective renewable energy-based system for hydrogen generation via water electrolysis. To meet this objective, GES designed a focused project to increase the pressure capability of the PEM electrolyzer, decrease system costs to meet DOE targets, and increase system electrical efficiency. The project plan consisted of a sequential progression of laboratory experiments and engineering prototypes with each generation of prototype demonstrating increased pressure and/or improved designs, lower-cost materials and increased efficiency. This development was conducted for the 0.17-ft² (160 cm²) active area GES electrolyzer platform. Under this project, GES made improvements to a first generation electrolyzer stack and system that produces hydrogen at 1000 psig (7 MPa) and developed a second generation prototype electrolyzer stack and system (EP-2) that produces hydrogen at 2000 psig (13.9 MPa). A third generation stack was designed for operation at 3000 psig (20.8 MPa). However, economic studies conducted under this program using the DOE H2A analysis model indicated that an electrolysis system designed for operation in the 300- to 1200-psig (2.1 to 8.4 MPa) range, with a mechanical compressor to increase the pressure to greater than 5000 psig (34.6 MPa), will produce hydrogen at a significantly lower cost than an electrolysis system designed for direct electrochemical production of hydrogen at 5000 psig (34.6 MPa). Based on these results, the project objective was modified, with DOE permission, to development of a low-cost, high-efficiency electrolysis system for hydrogen production at moderate pressures up to 1200 psig (8.4 MPa).

The GES approach to decreasing the electrolyzer stack capital cost was to develop lower-cost materials and/or less expensive fabrication methods for the repeating cell components. A major thrust was reducing the parts count/cell, which yielded significant savings in stack assembly labor as well as in stack materials cost. GES also focused on reducing the amount of the expensive precious metal catalyst required for high-efficiency stack operation through development of higher activity catalysts, improved electrode structures and methods of forming the membrane-electrode assemblies (MEAs).

Another approach to decreasing both the stack capital and operating costs was to improve the electrolyzer performance, allowing the stack to operate at high efficiency at high current density. Operation at higher current density decreases the stack active area required to produce a given amount of hydrogen, thus reducing the capital cost. In this project, electrolyzer performance was improved through development of an advanced membrane as well as improvements to the MEA structure.

An important objective of this project was to demonstrate operation of a low-cost electrolyzer in conjunction with a renewable energy system. This objective was met by testing a GES 13-kWe electrolyzer module at the National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (NREL).

3.0 RESULTS

3.1 Decreased Catalyst Loading

The GES OGP electrolyzer stacks use electrodes containing high noble metal loadings of 4 mg/cm² noble metal (Pt plus Ir) on the anode and 4 mg/cm² Pt black on the cathode. These electrodes provide high performance and reliability, but are very expensive, particularly with the present high cost of platinum. At these noble metal loadings, the catalyst cost is a significant fraction of the total electrolyzer stack cost, and is too high to meet the DOE cost targets. Another concern is that the unsupported noble metal catalysts contain large individual particles, on the order of 10 micrometers (µm), which can protrude into the membrane. This was not a problem in the OGP stacks, which used 250-µm- (0.010-inch-) thick Nafion®¹ 120 membrane², but is a concern for the thinner membranes being developed under this project to achieve higher electrolyzer efficiency. With thinner membranes, large catalyst particles protruding into the membrane from the electrodes on opposite sides can touch, resulting in electrical shorting of the electrolyzer cell.

In this project, GES applied recent developments in fuel cell catalyst technology to the electrolyzer electrodes. The resulting cathode consists of Pt supported on carbon black catalyst blended with Nafion ionomer, similar to the composition used successfully in PEM fuel cells. This electrode has a total Pt loading of 0.4 mg/cm², a reduction of 90% compared to the OGP cathode. The smaller particle size of the carbon supported catalyst also helps prevent electrical shorting of the electrolyzer cells.

Carbon catalyst supports can not be used on the electrolyzer anode due to carbon corrosion at the oxygen-evolution potentials. To decrease the anode catalyst cost, GES evaluated alternate compositions and methods of preparing the Pt-Ir catalyst. This development resulted in an anode structure having a Pt-Ir loading of 0.62 mg/cm².

Single-cell electrolyzer performance of Nafion 112 (50 µm (0.002 inch) thick) MEAs having low-loaded electrodes is compared in **Figure 1** with baseline electrode structures having anode and/or cathode loadings of 4 mg/cm². The performance of the MEA having a total noble metal loading of 1.02 mg/cm² was comparable to that of the baseline MEA having a total noble metal loading of 8 mg/cm² at current densities up to 4000 mA/cm².

¹ Nafion is a registered trademark of E.I. duPont deNemours & Co.

² All thicknesses referenced are for dry membrane

Electrolysis Cell Performance- Low Catalyst Loadings

80°C Ambient Pressure, NAFION 112, 8cm²

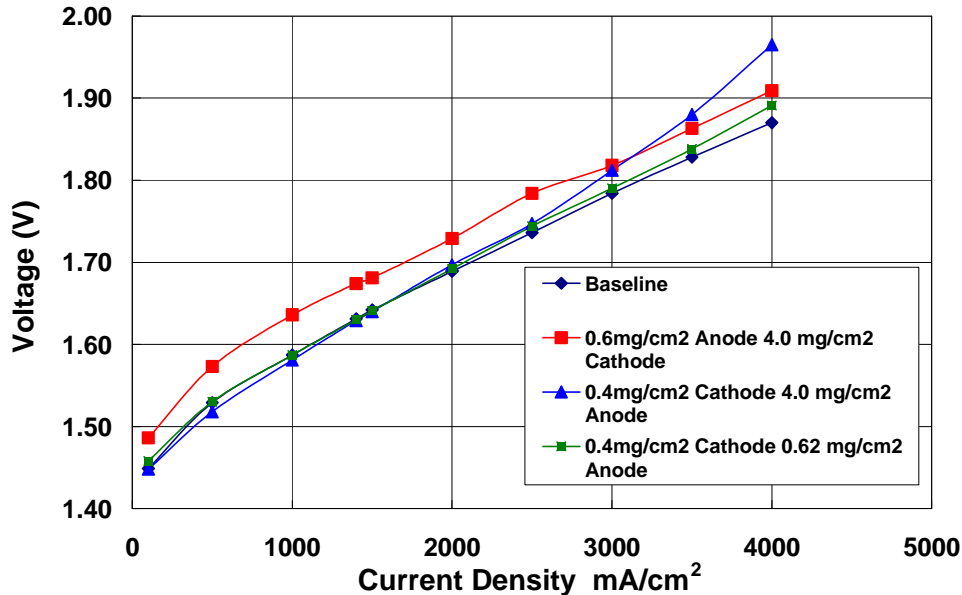


Figure 1. Effect of Catalyst Loading on Single-Cell Performance

3.2 Development of a High-Efficiency Membrane

3.2.1 Thin Nafion Membranes

The proton-exchange membrane (PEM) is the heart of the PEM electrolyzer. The membrane serves as the electrolyte, as well as the barrier between the hydrogen and oxygen. To achieve high cell efficiency the electrolyte must have high protonic conductivity, which is generally achieved using a perfluorocarbon sulfonic acid membrane with a high charge density (milliequivalents of H⁺/g dry membrane) or low equivalent weight (EW) and making the membrane as thin as possible. However, to achieve high reliability and long-life, the membrane must be chemically stable and must be strong enough to resist punctures, deformation, and pinhole formation. Standard thin Nafion-based membranes have high protonic conductivity, but have poor mechanical properties, and are prone to early failure from chemical and mechanical degradation. This is particularly an issue for electrolyzers designed for differential pressure operation, in which the thin membrane must be able to support the differential pressure. Another concern with thin membranes is reduced current efficiency for hydrogen production due to permeability of hydrogen and oxygen across the membrane.

For highly reliable operation at 3000 psig (20.8 MPa) the OGP electrolyzers used Nafion 120 membrane, a 1200 EW membrane with a thickness of 250 μm (0.010 in.) GES subsequently demonstrated high-pressure stacks using Nafion 110 membrane, an 1100 EW membrane that is also 250 μm (0.010 in.) thick. During this project we developed methods of supporting Nafion 117 (1100EW, 175 μm (0.007 in.) thick) for use in stacks having a differential pressure of up to 3000 psig (20.8 MPa). This membrane was used in the 1000-psig (7 MPa) differential-pressure stack contained in the EP-1 electrolyzer module delivered to NREL.

To further improve electrolyzer efficiency, Nafion 115, 1135 and 112 membranes, having thicknesses of 125 μm (0.005 in.), 88 μm (0.0035 in.), and 50 μm (0.002 in.), respectively, were evaluated in single-cell hardware at pressures up to 1000 psig (7 MPa). As expected, the cell voltage decreased with decreasing membrane thickness. The stack with Nafion 117 (N117) membrane operates at approximately 1.81 V/cell at 1100 mA/cm², or 69% efficiency based on the LHV of hydrogen. In single-cell testing, shown previously in Figure 1, the performance of a Nafion 112 membrane at 80°C was less than 1.7 V at 2000 mA/cm², which corresponds to a cell efficiency of 73% (LHV). However, the poor mechanical properties of the Nafion 112 and other thin Nafion membranes caused difficulties in assembling and operating the cells, so N117 was used in the deliverable stack.

3.2.2 Dimensionally Stable Membranes

Under this project, GES initiated development for electrolyzers of an advanced high-strength membrane combining the conductivity and electrochemical performance of Nafion 112 with the mechanical properties of engineering plastics. GES initially developed this membrane concept for PEM fuel cell applications, and is continuing development of fuel cell membranes based on this concept under DOE Contracts DE-FG36-06GO16035 and DE-FG02-05ER84322.

The GES advanced membrane, known as a dimensionally stable membrane (DSM), is an ionomer membrane incorporated in a high-strength supporting structure having a definable pattern. A preliminary sample support employed polyimide (Kapton[®], from DuPont) as the base material. The Young's modulus of Kapton is 2900 MPa, compared to 70 MPa for wet Nafion 112 membrane. Laser micromachining technology was used to drill holes 30 μm in diameter in the 8- μm -thick support structure, shown in **Figure 2**. To form the membrane, the support was sprayed with multiple thin coats of liquid Nafion solution, which is pulled into the pores by capillary action. A cross-section of a filled DSM having a total thickness of 30 μm is shown in **Figure 3**.

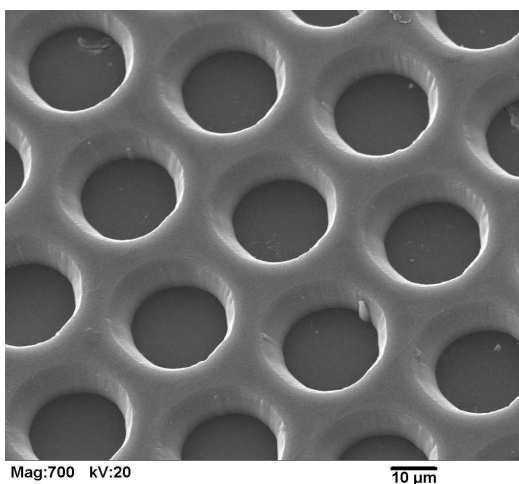


Figure 2. Scanning Electron Microscope (SEM) micrograph of the polymer membrane support structure with definable straight hole pattern.

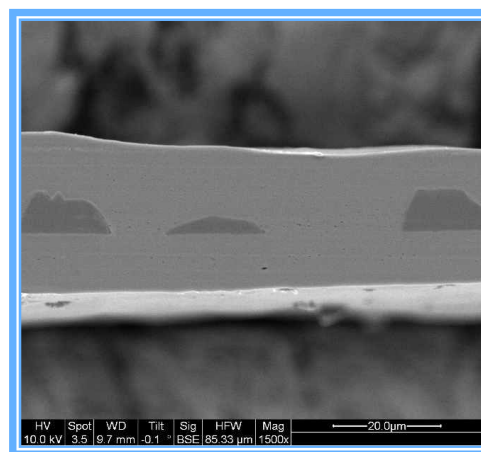


Figure 3. Cross-Section of Dimensionally Stable Membrane (30- μm -thick membrane)

Nafion EW1100 can expand ~30% in-plane when in contact with liquid water or high-humidity air. When Nafion EW1100 solution is incorporated into the support matrix, the supported membrane shows negligible in-plane dimensional expansion when in contact with liquid water, hence the name dimensionally stable membrane. This unique property will drastically alleviate the stress induced in Nafion membranes during wet/dry and temperature cycling.

The data in **Figure 4** shows that the modulus of the supported membrane is approximately 100 times higher than N112 when dry or wet. The creep of the N112 membrane was 20% during the test while the supported membrane showed 0% creep.

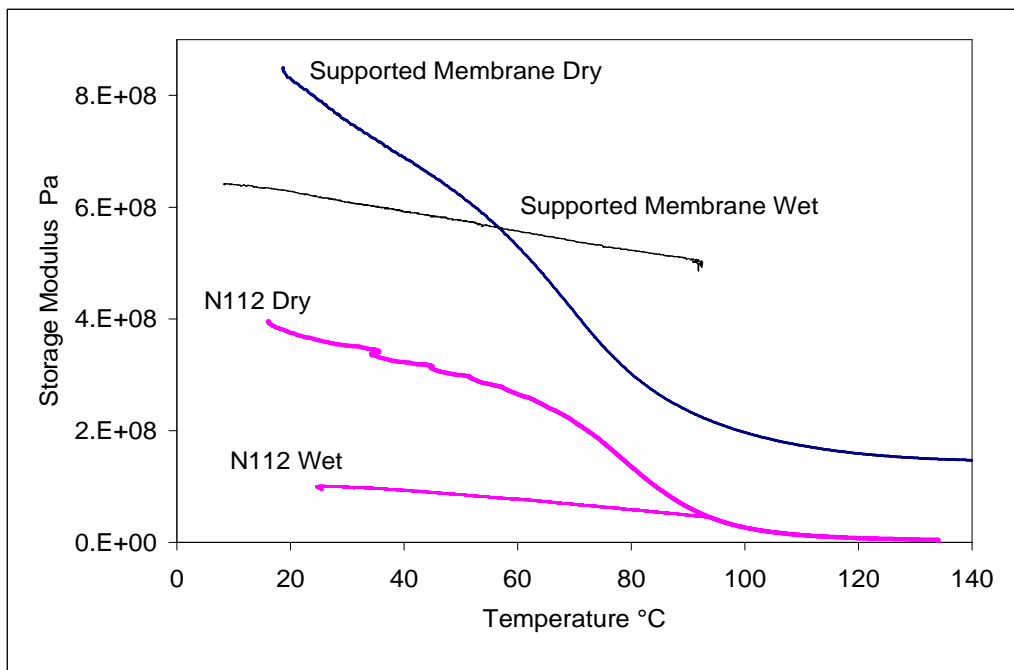


Figure 4. Dynamic Mechanical Analysis (DMA) of DSM vs. Nafion

A laser-drilled Kapton-Nafion EW1100 membrane having a thickness of approximately 30 μm was tested in a 160-cm² electrolysis cell. The electrolyzer performance of the DSM membrane was significantly better than that of Nafion 117 (**Figure 5**) at 60°C. Performance of a cell with the DSM membrane after 300 hours of operation (**Figure 6**) was slightly better than initial performance, indicating that the membrane is stable in short-term testing.

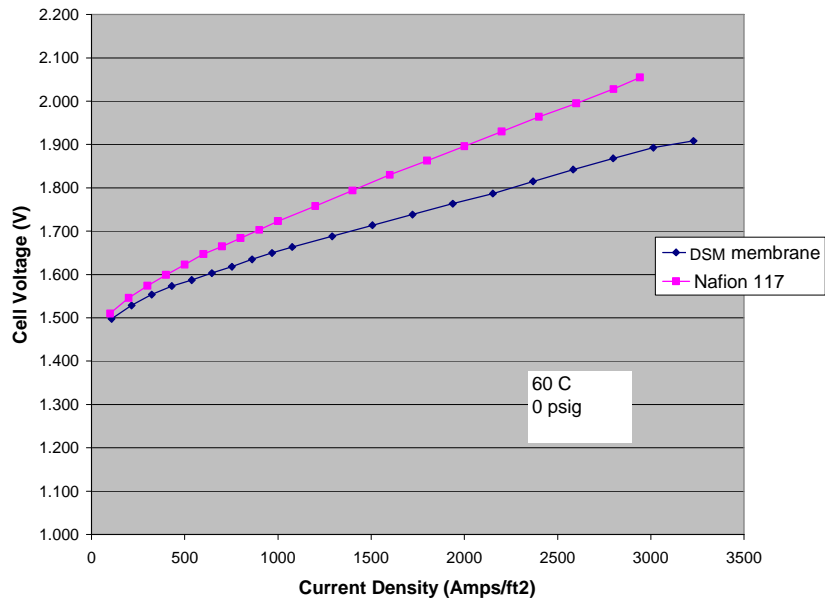


Figure 5. Electrolyzer Performance of DSM

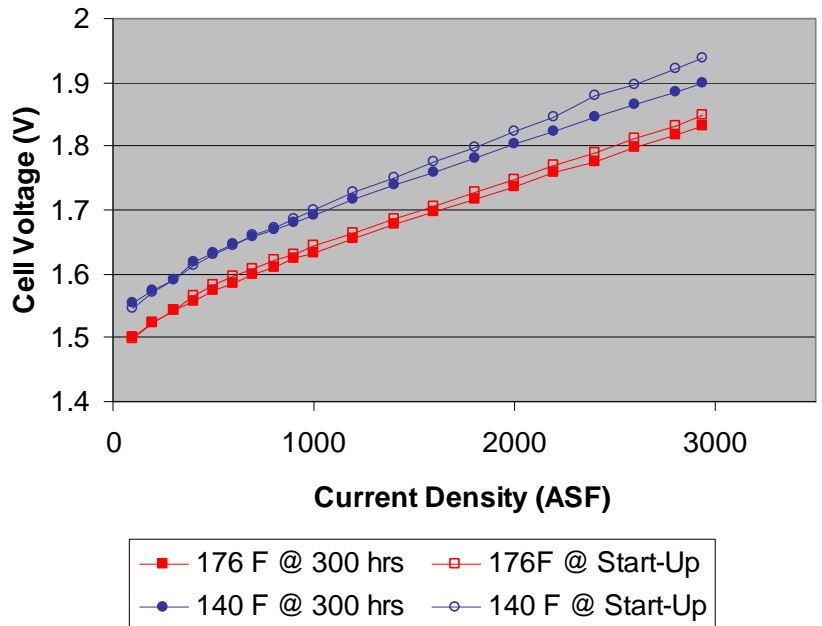


Figure 6. Performance of DSM Following 300 Hours of Operation

3.3 Stack Cost Reduction

The GES PEM electrolysis stacks used in the Navy OGP systems used a 3000-psig (20.8 MPa) balanced pressure design developed in the early 1980s. This design was developed to provide very high reliability for the critical life-support application, but was very expensive. The repeating cells consisted of over 40 parts, with many parts fabricated from expensive and specialized metals, such as zirconium or niobium. One of the major tasks of this project was redesign of the electrolyzer stack to significantly reduce the parts count and to use less expensive materials of construction.

The repeating cells in the electrolyzer stack consist of four main types of hardware components: anode-side membrane support structure (ASMSS), cathode-side membrane support structure (CSMSS), cell frames for both the anode and cathode side, and the cell separator. GES evaluated lower-cost designs and/or materials for each of these elements, as described in the following sections. Component designs were evaluated in single-cells or short-stacks, often integrated with other advanced components. Designs providing the best combination of low cost, high performance and high reliability were incorporated in the electrolyzer stack that was delivered to NREL as part of the EP-1 system.

3.3.1 Anode-Side Membrane Support Structure (ASMSS)

The ASMSS is located between the anode side of the cell separator and the anode of the MEA, and is placed inside of the anode-side cell frame. The ASMSS is a complex component that performs a myriad of functions: (1) support the MEA to enable electrical contact and sealing at high differential pressures; (2) provide high electrical conductivity between the cell separator and the anode; (3) distribute the deionized water that serves as both reactant and coolant equally across the anode compartment; and (4) provide egress for the product oxygen. In addition to providing these functions, the ASMSS must be stable in the presence of pure oxygen at high anodic potentials.

In prior designs, the ASMSS was a complex structure consisting of nine layers of valve metal components, with each layer processed and assembled by hand. Each metal layer was treated to minimize contact resistance. This structure had the highest parts count and labor requirements of the repeating cell components.

To reduce the parts count and decrease electrolyzer stack cost, GES developed a preliminary design for a single-piece component having the required properties and tolerances. Several methods of fabricating the single-piece ASMSS were evaluated, and one ASMSS demonstrated acceptable pressure drop and good performance in a full-size (160-cm² active area) single-cell test. However, specialized tooling beyond the scope of this project was required for cost-effective fabrication of this component, so this design was not evaluated in larger stacks. Further development of the single-piece ASMSS is recommended.

3.3.2 Cathode Side Membrane Support Structure (CSMSS)

The functions of the CSMSS are similar to those of the ASMSS, except that water distribution is not required. However, the CSMSS must provide egress of the product hydrogen and water that is protonically dragged to the cathode. Since hydrogen is evolved at high pressures on the cathode, the CSMSS must be resistant to hydrogen embrittlement.

In prior designs, the CSMSS was a very expensive component comprised of multiple layers of zirconium parts. Zirconium, an expensive valve metal, was chosen due to its high resistance to hydrogen embrittlement. The prior design also required a separate hand-woven electrically-conductive component to provide compliance between the cells. This compliant member, which was incorporated in the cell separator, maintained sealing and electrical contact as parts contracted and expanded due to changes in operating temperature or aging of components. A major accomplishment of this project was development of a single-piece CSMSS/compliant member fabricated from a low-cost material. GES worked with a vendor to develop the processing steps to yield a material with the required density, electrical conductivity and mechanical properties. The single-piece design functioned very well in the stack and reduced the contact resistance of the cathode side, resulting in improved cell performance. This single-piece CSMSS was used in the electrolyzer stack delivered to NREL.

3.3.3 Low-Cost Cell Frames

Each cell contains thermoplastic frames on the anode and cathode to conduct fluids into and out of the active parts of the cell and to help contain the pressure loads. Although the material is relatively inexpensive, the frames used in previous electrolyzer designs required extensive high-precision and time-consuming machining, resulting in a very high cost per part.

In this project, GES initiated development of an inexpensive frame fabrication method that does not require machining. The design consists of joining two or three parts that could be fabricated by cutting and molding stock plastic, or possibly by injection molding for high-rate fabrication. The major challenge was identification and development of a method of joining the plastic parts that retained the fine features of the parts and did not introduce materials that could contaminate the MEA.

Several fabrication methods, including ultra-sonic and laser welding, were evaluated. The development focused on selection of a high-strength non-contaminating joining compound. GES worked with vendors of the welding equipment to identify and prepare test coupons of suitable materials. The coupons were tested for bonding properties and for leaching of chemicals that could contaminate the MEA.

GES also designed and procured a mold to enable partial molding of the frames, as a step toward eliminating the machining requirement. Sample parts were successfully molded. Further development of the molding process and post-molding fabrication steps is recommended.

The molding and welding development resulted in demonstration of preliminary feasibility of a low-cost method for fabricating cell frames, eliminating the labor-intensive machining steps. Successful development of a low-cost frame is expected to reduce the cost/cell by 40%.

3.3.4 Cell Separator

The cell separator is a gas-impermeable conductive sheet that separates the hydrogen and oxygen compartments in the bipolar stack. The separator must be highly conductive, as well as resistant to hydrogen embrittlement and to corrosion in an oxidizing environment. The proven GES high-pressure naval electrolyzer uses a complex multi-layer separator incorporating a conductive compliant member and sheets of niobium and zirconium metal. Zirconium is used due to its high resistance to hydrogen embrittlement.

In the EP-2 stack, the complex cell separator was replaced with a single piece of titanium. The compliance function was incorporated in the cathode-side membrane support structure (CSMSS) rather than the separator. This new design significantly reduced the stack parts count and the cost of stack fabrication. However, hydrogen embrittlement of the titanium is expected to limit the separator life to several thousand hours of operation.

A straight-forward, but expensive approach, is a two-piece separator, consisting of a layer of titanium and a layer of zirconium. This required development of a method of minimizing contact resistance between the two metal pieces. Preliminary testing demonstrated that cell performance of the dual separator and the single-piece titanium separator was comparable. However, pitting corrosion of the zirconium sheet occurred in some test builds, but not in others. The pitting corrosion appeared to be due to impurities introduced into the stack from other components.

An alternative, and more promising approach for long-term implementation, is coating titanium with a low-cost electrically conductive, embrittlement-resistant material. The challenge is development of a pinhole-free, highly adherent coating with the required characteristics. Two coatings, a carbon-based material and a metal oxide, were evaluated, but neither coating was pinhole free, resulting in hydrogen embrittlement of the underlying titanium. Further development is required to eliminate porosity of the electrically conductive coatings to protect titanium from embrittlement.

3.3.5 Impact of Component Cost Reduction on Stack Cost

The materials and manufacturing methods developed in this program have significantly decreased the electrolyzer capital cost. As a result of the component and membrane development conducted in this program, the overall projected capital cost of the electrolyzer stack (designed for 330-psig (2.38 MPa) operation) has decreased from greater than \$2500/kW in 2001 to less than \$1000/kW in 2007, with a further projected decrease to \$600/kW in 2010, assuming successful commercialization of the low-cost manufacturing methods and large-scale production of electrolyzer stacks.

The overall decrease in parts count per cell is a major factor in the stack cost reduction. The parts count/cell has been reduced from more than 40 parts at the beginning of this program in 2002 to the present design of 16 parts, as shown in **Figure 7**. In addition to reducing the cost of the individual components, the reduced parts count is expected to decrease the labor required to assemble the stack by 60%.

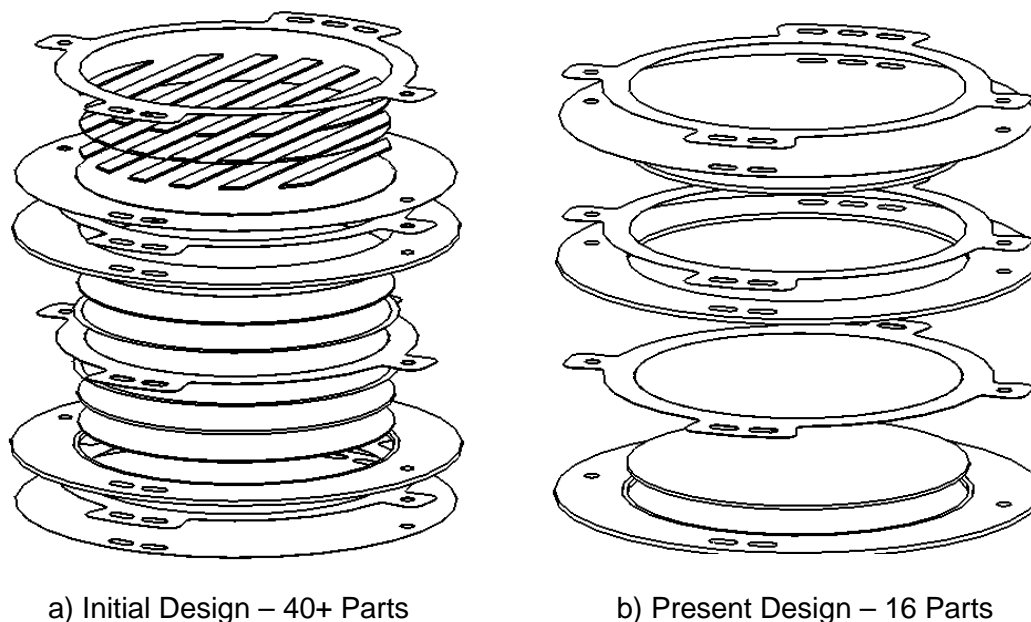


Figure 7. Decreased Electrolyzer Part Count/Cell

3.4 Economic Analysis

The DOE H2A model was used to project the cost of hydrogen production with the GES electrolysis technology and to determine the lowest cost system design. Tradeoffs of operating pressure, system efficiency and capital costs were conducted using a standard set of assumptions and cost parameters.

The H2A model was run for production of 1500 kg H₂/day at a forecourt filling station. The cost inputs used projected capital costs for the 500th station, applying volume production and learning curves to estimate the capital costs. The capital and operating costs include a compressor for increasing the hydrogen pressure from the stack operating pressure to the DOE target storage pressure of 6250 psig (43.2 MPa).

In one study, the cost of hydrogen was determined for the “present” design, the 1000-psig (7 MPa) differential-pressure stack and system contained in the EP-1 module delivered to NREL for testing. This stack uses a Nafion 117 membrane and is operated at 1600 mA/cm² at a moderate temperature of 60°C. For a system of this design, the H2A forecourt model projects a hydrogen cost of \$4.77/gge, based on an electricity cost of \$0.039/kWh. As shown in **Figure 8**,

the major contributors to the hydrogen cost are the electricity (feedstock) cost, followed by the capital cost.

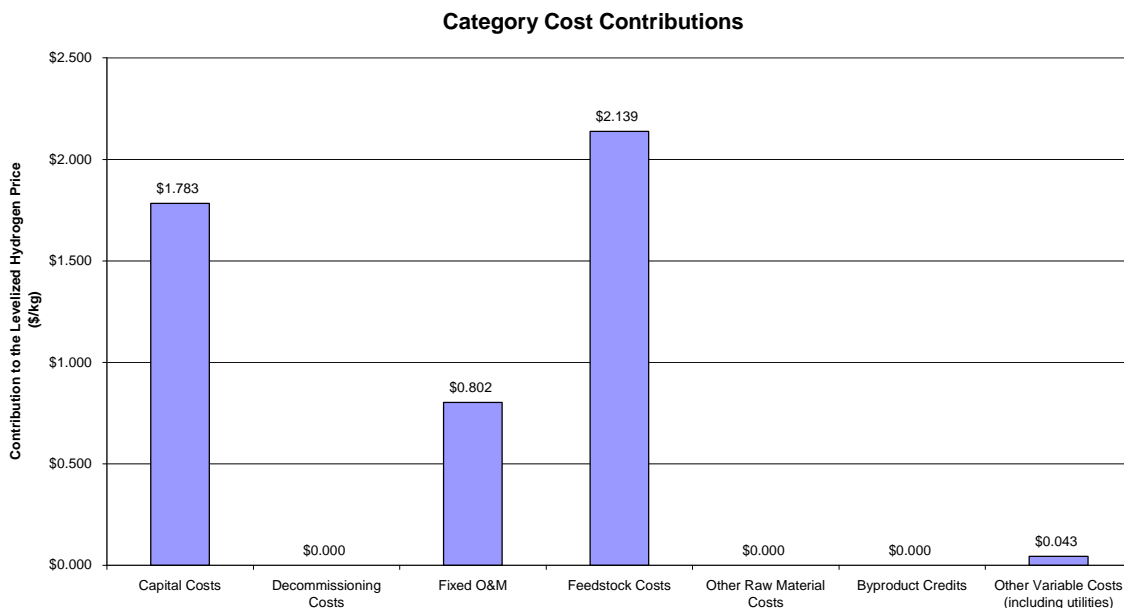


Figure 8. H2A Model Cost Contributions for Present-Design GES Electrolyzer (electricity cost = \$0.039/kWh)

In another study, the cost of hydrogen produced using the GES electrolysis technology was analyzed as a function of four operating pressures, ranging from 100 psig (0.79 MPa) to 5000 psig (34.6 MPa), and three current densities: 1000, 2000 and 3000 amps/ft² (ASF) (929, 1858 and 2787 mA/cm², respectively). The H2A model used for this study was an earlier version than that used in the study described above, so the results can not be directly compared with the results for the “present” design. The stack performance and cost data used in this analysis were based on results obtained in this project for a stack incorporating the lower cost components, including the advanced membrane, demonstrated at the single-cell level in this project. The membrane type and operating temperature used in the model were varied depending on the operating pressure, with the membrane thickness increasing and operating temperature decreasing with increasing operating pressure.

Analysis was conducted for two electricity rates: (1) \$0.05/kWhr for industrial electricity; and (2) a lower cost of \$0.035/kWhr. Detailed results of the analyses are presented in **Table 1** and graphically in **Figure 9** (except for the 100-psig (0.79 MPa) data). At the higher electricity cost (\$0.05/kWhr), the lowest projected cost for hydrogen production is \$3.77/kg, for an electrolyzer designed to operate at 100 psig (0.79 MPa) and a moderate current density of 2000 ASF. At an electricity cost of \$0.035/kWhr, the lowest projected cost of hydrogen is \$2.84/kg.

The effect of operating current density on hydrogen cost involves a tradeoff between: (1) electricity cost, which increases as the stack efficiency decreases at higher current densities; and (2) stack capital cost, which decreases with increasing current density as the required stack active area decreases. The model results show that operation at a low current density of

1000 ASF is more expensive at all pressures than operation at higher current density, but that the cost of operating at 2000 or 3000 ASF is comparable at all pressures, and at both electricity cost points, due to the offsetting effects of increasing electricity cost and lower capital costs with increasing current density.

Table 1. H2A Model Results for GES Electrolysis System

DOE H2A Model Results

Electricity at H2A Industrial Value of 5 cents/kWhr

Pressure psig	cd ASF	cell voltage V	cell power kWhr/kg H2	Projected Capital Costs(\$K)			H2 cost(\$/kg)			
				stack	compressor	total	capital	elec	O&M	total
100	1000	1.635	44.3	380	518	2011	0.9	2.57	0.47	3.79
100	2000	1.732	46.7	190	518	1726	0.77	2.72	0.44	3.77
100	3000	1.821	49	125	518	1636	0.74	2.87	0.42	3.87
333	1000	1.652	45.7	775	432	2582	1.16	2.65	0.55	4.2
333	2000	1.749	47.6	405	432	2003	0.9	2.76	0.47	3.97
333	3000	1.838	49.8	253	432	1800	0.8	2.91	0.44	3.99
1200	1000	1.714	47.9	1869	259	4438	1.97	2.74	0.67	5.22
1200	2000	1.853	50.7	918	259	2875	1.27	2.93	0.5	4.54
1200	3000	1.984	53.9	606	259	2376	1.06	3.13	0.45	4.48
5000	1000	1.807	52.9	2204	0	5050	2.23	3.02	0.86	5.95
5000	2000	2.016	56.5	1054	0	3085	1.37	3.26	0.59	5.06
5000	3000	2.218	61.2	691	0	2474	1.1	3.56	0.51	5.01

Electricity at 3.5 cents/kWhr

100	1000	1.635	44.3	380	518	2011	0.88	1.72	0.47	2.91
100	2000	1.732	46.7	190	518	1726	0.75	1.82	0.44	2.84
100	3000	1.821	49	125	518	1636	0.71	1.91	0.42	2.89
333	1000	1.652	45.7	775	432	2582	1.13	1.77	0.55	3.29
333	2000	1.749	47.6	405	432	2003	0.86	1.85	0.46	3.01
333	3000	1.838	49.8	253	432	1800	0.78	1.94	0.44	3.00
1200	1000	1.714	47.9	1869	259	4438	1.94	1.83	0.67	4.29
1200	2000	1.853	50.7	918	259	2875	1.25	1.95	0.51	3.55
1200	3000	1.984	53.9	606	259	2376	1.03	2.09	0.45	3.41
5000	1000	1.807	52.9	2204	0	5050	2.2	2.01	0.86	4.92
5000	2000	2.016	56.5	1054	0	3085	1.34	2.17	0.59	3.95
5000	3000	2.218	61.2	691	0	2474	1.07	2.37	0.51	3.8

H2 Cost Breakdown (elec= \$.05/kWh)

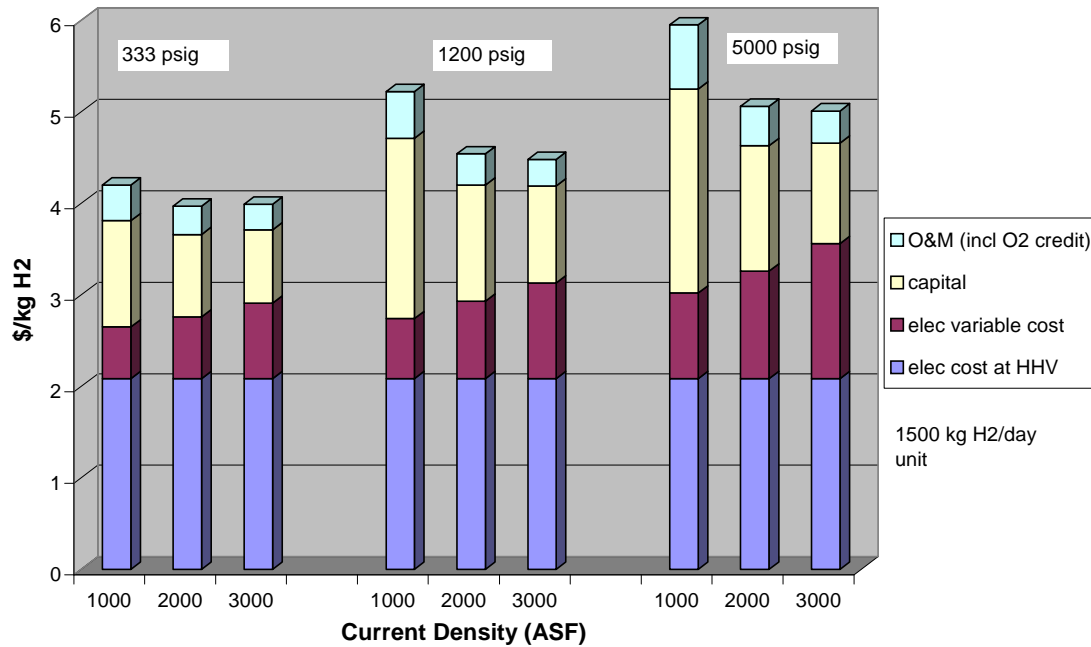


Figure 9. H2A Model Results for Cost of H₂ Production by Electrolysis as a Function of Pressure and Current Density for Advanced GES Stack Design

The projected cost of hydrogen increases with increasing stack and system operating pressure. For an electrolyzer stack producing hydrogen at 5000 psig (34.6 MPa), the lowest projected hydrogen cost is approximately \$5.00/kg, a 25% increase over the 333-psig (2.4 MPa) case. Higher pressure operation reduces the compressor costs, but significantly increases the capital cost of the electrolyzer stack and system. This is particularly true for operation at 5000 psig (34.6 MPa), where the high pressure limits the practical size (active area) of the individual cells and reinforced sealing is required for each cell. The larger number of cells and the higher cost per cell, as well as a higher cost for the balance-of-plant components rated for 5000-psig (34.6 MPa) operation, result in a significantly higher capital cost for the 5000-psig (34.6 MPa) electrolyzer compared to lower pressure designs.

The H2A model results indicate that the keys to achieving low-cost hydrogen by electrolysis are to increase electrolyzer efficiency to enable efficient operation at current densities of 2000 to 3000 mA/cm² and to design a stack having a large active area per cell operating at moderate pressures.

3.5 Electrolyzer System Development

Prior to this project, GES developed the first-generation high-differential-pressure electrolyzer prototype module, designated EP-1. This system was originally designed for hydrogen production of 0.25 kg/hr at 1200 psig (8.4 MPa). The system included a 28-cell stack having an active area of 160 cm²/cell. The nominal system power input was 20 kW, with a maximum of 15 kW delivered to the electrolyzer stack.

The major subsystems of the EP-1 high-pressure electrolyzer system include the electrolyzer, the electricity feed subsystem, the deionized (DI) water feed and DI water handling system, low-pressure DI water pump, oxygen gas/liquid separator and oxygen vent subsystem, and the hydrogen gas train (hydrogen separator, dryer and high-pressure hydrogen outlet.) In this system a non-regenerable hydrogen dryer was used, consisting of replaceable desiccant bags housed in a pressure vessel.

In this project, GES developed a second generation engineering prototype, designated EP-2, which produces 0.33 kg/hr hydrogen at 2000 psi (13.9 MPa) using 25 kW of power. This system, shown in **Figure 10**, was designed to be a test bed for stack and BOP components, and thus is more open than EP-1 to allow components to be readily replaced.



Figure 10. 2000-psig (13.9 MPa) Electrolyzer System (EP-2)

The EP-2 system incorporated a high-pressure regenerative hydrogen gas dryer developed in this project. GES developed an improved method of heating the dryer during regeneration to improve regeneration efficiency. With this method, GES demonstrated drying of a wet nitrogen stream to a dew point of -40°C and successful regeneration of the bed. We also made improvements to the dryer subsystem valving, sensors and control system to improve safety and efficiency.

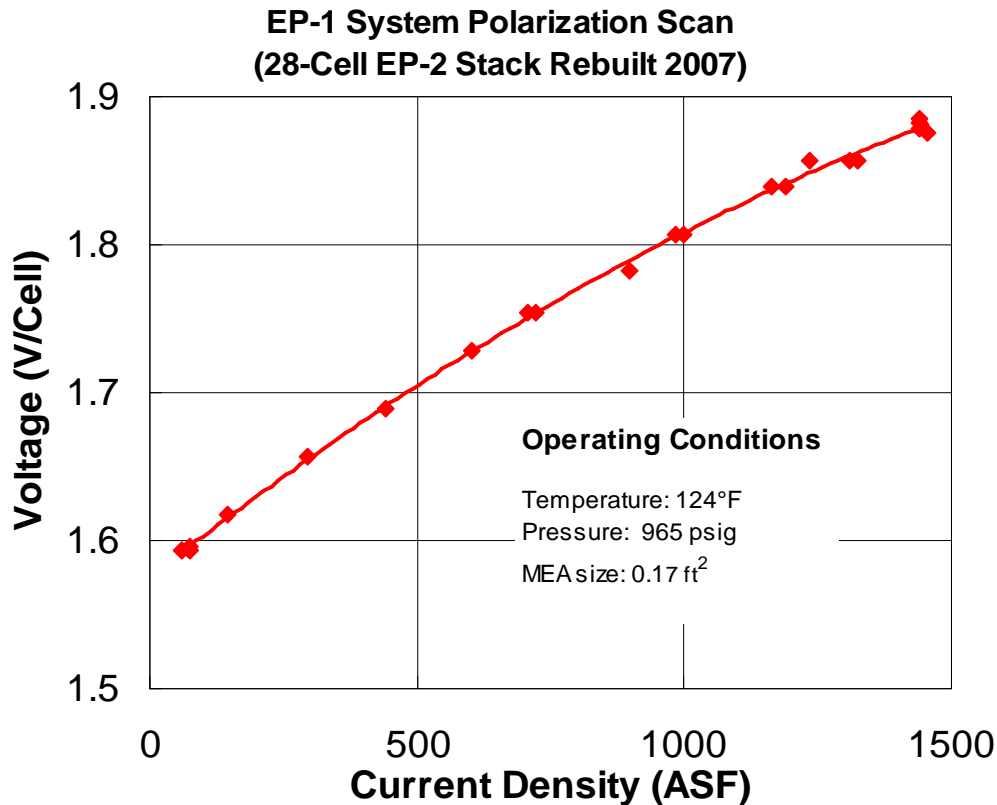
3.6 Electrolyzer Module Evaluation at NREL

To demonstrate the advancements made in electrolyzer design and efficiency under this project, the project concluded with testing of a GES electrolyzer module at the NREL NWTC facility. For this demonstration, the EP-1 electrolyzer module was fitted with a modified stack incorporating low-cost components developed in this project. The modified stack was designed for hydrogen production at 1000 psig (7 kPa), with oxygen production at atmospheric pressure. The modified EP-1 module was tested at GES, then shipped to NREL for testing. **Figure 11** is a photograph of the EP-1 unit installed at NREL, with the side panels removed to show system components. NREL tested the electrolyzer module in September 2007 and January-March 2008.



Figure 11. GES EP-1 Electrolyzer Installed at NREL Test Facility
(Photo courtesy of Kevin Harrison, NREL)

The stack in the delivered system contains 28 cells, with an active area of 160 cm^2 (0.17 ft^2) /cell. The rated input power to the stack was 13.2 kW at a design current density of 1562 mA/cm^2 (1470 ASF), resulting in rated hydrogen production of $0.26\text{ kg H}_2/\text{hr}$. A stack polarization scan, presented as average voltage/cell, at approximately 1000 psig (7 MPa) hydrogen in the EP-1 system is shown in **Figure 12**. This testing was conducted at 52°C (124°F), which is lower than the design operating temperature of 60°C .



**Figure 12. Polarization Scan of Low-Cost Electrolyzer Stack
Incorporated into EP-1 System Delivered to NREL**

GES assisted with installation and commissioning of the EP-1 module at the NWTC Hydrogen Test Facility. NREL conducted preliminary testing of the EP-1 module and reported electrolysis stack performance of 52.8 V at 250 A, or 1.89 V/cell at a current density of 1562 mA/cm², for hydrogen production at 950 psig (6.7 MPa) and stack operation at an average of 50.8°C. This performance was very similar to the stack performance obtained at GES. Based on this data, NREL reported that the electrolyzer stack efficiency was 67% (Harrison, 2007). The stack power consumption was 13.2 kW, and the total system power consumption was 16.5 kW.

During testing of the EP-1 module, NREL measured the flow rate of high-pressure hydrogen product. To obtain an accurate flow measurement, the moist gas stream was passed through a freshly charged desiccant bed to dry the gas prior to the mass flow meter. NREL reported that the average hydrogen flow was 2.1-2.4 Nm³/hr, significantly lower than the expected 3.1 Nm³/hr. From the data obtained at NREL, it appears that hydrogen is being lost from the EP-1 system during the periodic draining of water from the high-pressure hydrogen/water separator. GES is working with NREL to diagnose and correct this problem.

4.0 PROJECT ACCOMPLISHMENTS

In this project GES developed a low-cost, high-efficiency proton-exchange membrane (PEM) electrolysis system for hydrogen production at moderate pressure.

Electrolysis cell efficiency of 72% (based on the lower heating value of hydrogen) was demonstrated using an advanced high-strength membrane developed in this project. This membrane would enable the electrolyzer system to exceed the DOE 2012 efficiency target of 69%. GES significantly reduced the capital cost of a PEM electrolyzer stack through development of low-cost components and fabrication methods, including a 60% reduction in stack parts count. The estimated cost of the present stack design in large-scale production is less than \$1000/kW. A future development path has been identified that would decrease the capital cost to less than \$550/kW. Economic analysis indicates that hydrogen could be produced for \$3.79 per gge at an electricity cost of \$0.05/kWh by the lower-cost PEM electrolyzer developed in this project assuming high-volume production of large-scale electrolyzer systems.

The project culminated in delivery of a prototype electrolyzer module to the National Renewable Energy Laboratory for testing at the National Wind Technology Center. NREL reported that the electrolyzer stack efficiency was 67% based on the hydrogen LHV.

5.0 PRODUCTS DEVELOPED

5.1 Hardware Prototypes

A second-generation prototype electrolyzer system designated EP-2, which produces 0.33 kg/hr hydrogen at 2000 psi (13.9 MPa) using 25 kW of power, was developed under this project. In addition, an earlier prototype electrolyzer system, EP-1, which produces 0.26 kg/hr hydrogen at 1000 psig (7 MPa), was modified to incorporate the low-cost cell components developed under this project. This electrolyzer system was delivered to NREL for testing.

5.2 Publications

C. Cropley and T. Norman, “A Low-Cost High-Pressure Hydrogen Generator,” (15) Quarterly Progress Reports for Work Performed Under U.S. Department of Energy Cooperative Agreement No. DE-FC36-04GO13029 (July 2003 – Jan. 2008).

Cropley, C., and T. Norman, “A Low-Cost High-Pressure Hydrogen Generator,” U.S. Department of Energy Cooperative Agreement No. DE-FC36-04GO13029, (4) Hydrogen Program Annual Reports and Presentations at *Hydrogen Fuel Cells Technology Infrastructure Review Meetings* (2004-2007).

5.3 Inventions/Patent Applications

“Electrolyzer System Including Combination Gas Storage Vessel and Gas/Water Separator,” T. Norman and E. Schmitt; Patent Application S/N 11/274040; Filed: Nov. 14, 2005.

6.0 REFERENCES

Harrison, K.W., “Preliminary Test Report on Giner EP1 PEM Electrolyzer,” *DOE Hydrogen and Fuel Cell Program*, NREL Renewable Electrolysis Task 3.7, Milestone 3.7.4, Deliverable Report 3.7.12, U.S. Dept. of Energy, National Renewable Energy Laboratory Contract No. DE-AC36-99-GO10337, Sept. 2007.

Kraposki, B., J. Levene, K. Harrison, P.K. Sen., and F. Novachek, “Electrolysis: Information and Opportunities for Electric Power Utilities,” Technical Report NREL/TP-581-40605, U.S. Dept. of Energy, National Renewable Energy Laboratory Contract No. DE-AC36-99-GO10337, Sept. 2006.