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**Metal Hydride**  
**Hydrogen Storage**  
**Backup Power**  
**Electrolysis**

**Retention:**  
**Permanent**

**SAVANNAH RIVER NATIONAL LABORATORY  
REGENERATIVE FUEL CELL PROJECT**

**T. Motyka**

**NOVEMBER 2008**

Savannah River National Laboratory  
Savannah River Site  
Aiken, SC 29808

Prepared for the U.S. Department of Energy Under Contract Number  
DEAC09-08-SR22470



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## REVIEWS AND APPROVALS

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Manager, Level 3 Manager, Energy Security and Engineering Department

Date

## TABLE OF CONTENTS

<b>LIST OF FIGURES .....</b>	<b>iv</b>
<b>LIST OF TABLES .....</b>	<b>iv</b>
<b>LIST OF ACRONYMS .....</b>	<b>v</b>
<b>EXECUTIVE SUMMARY .....</b>	<b>1</b>
<b>1.0 INTRODUCTION.....</b>	<b>2</b>
<b>2.0 BACKGROUND AND MARKET ASSESSMENT .....</b>	<b>5</b>
<b>3.0 RFC TEST SYSTEM COMPONENTS AND CONFIGURATION .....</b>	<b>9</b>
<b>4.0 RFC TEST PLAN AND DISCUSSION OF RESULTS .....</b>	<b>12</b>
<b>4.1 SERIES 1 RESULTS: METAL HYDRIDE VESSEL TESTS .....</b>	<b>12</b>
<b>4.1.1 Charging Tests.....</b>	<b>12</b>
<b>4.1.2 Discharge Tests.....</b>	<b>15</b>
<b>4.2 SERIES 2 RESULTS: BACKUP POWER SIMULATION TESTS.....</b>	<b>19</b>
<b>4.2.1 Step Change Tests .....</b>	<b>19</b>
<b>4.2.2 Impulse Tests .....</b>	<b>20</b>
<b>4.2.3 Vessel Changeover Test .....</b>	<b>21</b>
<b>4.2.4 Series Grid Loss Events .....</b>	<b>21</b>
<b>4.2.5 Thermal Management: Fuel Cell and Metal Hydride Vessels.....</b>	<b>22</b>
<b>5.0 SUMMARY OF RESULTS AND CONCLUSION.....</b>	<b>24</b>
<b>6.0 REFERENCES.....</b>	<b>26</b>

## LIST OF FIGURES

Figure 1. Regenerative Fuel Cell System Operation .....	2
Figure 2. Probable Fuel Cell Adoption Curve [1].....	5
Figure 3. RFC Backup Power System [4].....	9
Figure 4. Schematic of Single Tube in Metal-Hydride Storage Assembly.....	10
Figure 5. Metal Hydride Hydrogen Storage System Testing Configuration .....	11
Figure 6. MH Charging Isotherms using the HOGEN RE .....	13
Figure 7. Passive Charge Started at 45°C as a Function of MH Pressure and Temperature	13
Figure 8. Passive Charge Started at 45°C as a Function of Time .....	14
Figure 9. MH Pressure vs. H <sub>2</sub> Total Desorbed at 2kW DC Bus Load.....	16
Figure 10. MH Pressure vs. H <sub>2</sub> Total Desorbed at 3.5kW DC Bus Load.....	16
Figure 11. Bus Load: 3.5kW MH Setpoint Temperature: 35°C .....	17
Figure 12. Bus Load: 3.5kW MH Setpoint Temperature: 30°C .....	17
Figure 13. MH Pressure vs. H <sub>2</sub> Total desorbed at 5kW DC Bus Load.....	18
Figure 14. MH Characterization at 5kW bus load and 60°C Setpoint Temperature .....	18
Figure 15. Comparison of Step Changes for MH Vessel Temperatures of 35°C and 45°C	19
Figure 16. Step Change Test for 35°C MH Setpoint Temperature.....	20
Figure 17. Power levels for Impulse Test @ 35°C .....	20
Figure 18. MH Vessel Temperatures and Pressure for Impulse Test @ 35°C .....	21
Figure 19. Vessel Changeover Test .....	22
Figure 20. Fuel Cell and Electrolyzer Cell Stack Power During Series Grid Loss Events ..	22
Figure 21. DC Bus Load: 3.5kW, MH Vessel Temperature Setpoint: 35°C.....	23

## LIST OF TABLES

Table 1. Economic Evaluation of a Fuel Cell vs. VRLA Battery over 10-year Period [3] ....	7
Table 2. Charging Statistics .....	15

## LIST OF ACRONYMS

AC	Alternating Current
ATC	Aiken Technical College
CHP	Combined Heat and Power
CHR	Center for Hydrogen Research
E-STOP	Emergency Stop
DAQ	Data Acquisition
DC	Direct Current
DOE OE.	Department of Energy, Office of Electricity Delivery and Energy Reliability
FC	Fuel Cell
FCC	Federal Communication Commission
H <sub>2</sub>	Hydrogen
HCI	Hydrogen Components Inc.
HVAC	Heating Ventilation and Air Conditioning
PEM	Proton Exchange Membrane
RFC	Regenerative Fuel Cell System
RTD	Resistance Temperature Detectors
SRNL	Savannah River National Laboratory
UPS	Uninterruptible Power Supply
VRLA	Valve-Regulated Lead Acid

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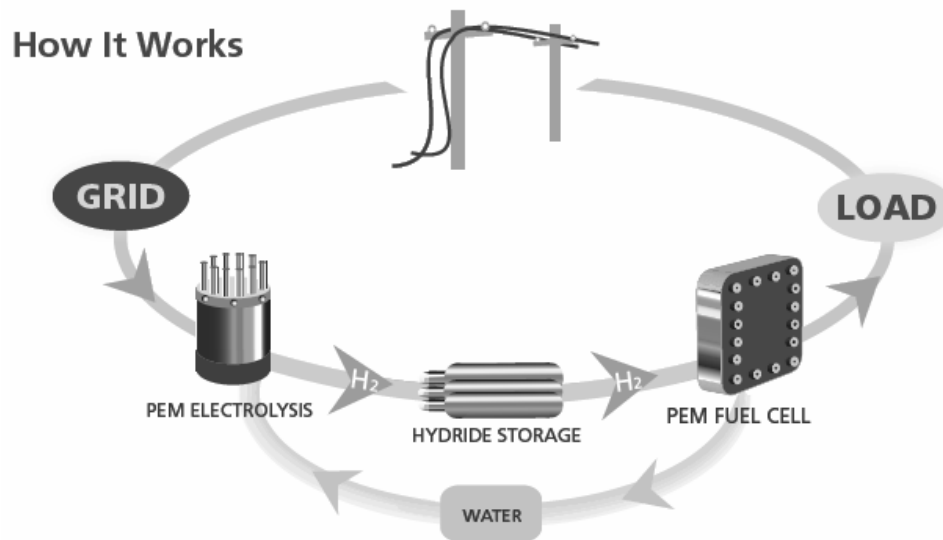


## EXECUTIVE SUMMARY

A team comprised of governmental, academic and industrial partners led by the Savannah River National Laboratory developed and demonstrated a regenerative fuel cell system for backup power applications. Recent market assessments have identified emergency response and telecommunication applications as promising near-term markets for fuel cell backup power systems. The Regenerative Fuel Cell System (RFC) consisted of a 2 kg-per-day electrolyzer, metal-hydride based hydrogen storage units and a 5 kW fuel cell. Coupling these components together created a system that can produce and store its own energy from the power grid much like a rechargeable battery. A series of test were conducted to evaluate the performance of the RFC system under both steady-state and transit conditions that might be encountered in typical backup power applications. In almost all cases the RFC functioned effectively. Test results from the demonstration project will be used to support recommendations for future fuel cell and hydrogen component and system designs and support potential commercialization activities. In addition to the work presented in this report, further testing of the RFC system at the Center for Hydrogen Research in Aiken County, SC is planned including evaluating the system as a renewable system coupled with a 20kW-peak solar photovoltaic array.

## 1.0 INTRODUCTION

The Savannah River National Laboratory (SRNL) has led a project team to develop and demonstrate a regenerative fuel cell system for backup power applications. The Regenerative Fuel Cell (RFC) system combines a proton exchange membrane (PEM) fuel cell capable of generating electricity from hydrogen fuel, an electrolyzer utilizing grid electrical energy to produce hydrogen, and a solid state hydrogen storage system for storing the hydrogen. This combination of systems was demonstrated to provide a rugged, compact, quick-response, reliable emergency power supply for occasions where grid power is temporarily cut off. These systems can replace high maintenance battery and generator-set systems and offer a higher degree of reliability. A regenerative fuel cell system can also be combined with renewable energy sources such as wind and solar systems for unlimited power generation. Figure 1 shows a schematic of a regenerative fuel cell system and how it might operate as a backup power system.



**Figure 1. Regenerative Fuel Cell System Operation**

The overall goal of the RFC project was to evaluate the technical and economic challenges and opportunities facing market adaptation of regenerative fuel cell systems for backup power applications. Safe and efficient hydrogen storage is one of the key requirements in making these systems commercially viable. This project attempted to address not only the hydrogen storage requirements but also many of the other requirements and the integration issues involved in adapting a regenerative fuel cell backup power system to existing energy networks.

The SRNL-led RFC Project, which formally began in September of 2006, was a cost-shared project sponsored by the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability (DOE OE). SRNL's principal cost-share partner was the Center for Hydrogen Research (CHR), a regional non-profit organization whose mission is to promote technology transfer and commercialization of hydrogen technology coming primarily from the national laboratory. Other project partners included Proton Energy Systems (PES), a leader in proton exchange membrane (PEM) electrolyzers and the integration of these devices into overall backup and continuous power systems; Aiken Technical College (ATC), a regional technical and vocational school that is active in developing educational outreach and technical training curriculum in the area of hydrogen and fuel cell technology and Clemson University and the South Carolina Institute for Energy Studies, active in hydrogen and other alternative energy projects.

The overall RFC project was organized into the following tasks:

- 1) Literature Review and Market Assessment
- 2) Hydrogen Storage Technology Assessment and Development
- 3) Regenerative Fuel Cell System Development and Integration
- 4) System Evaluation and Testing
- 5) Education and Outreach.

Under Task 1, Clemson University and the South Carolina Institute for Energy Studies performed a literature review and market assessment on stationary fuel cell systems to help guide and focus the overall project. The results from the Clemson and other market studies [1-3] led to the project team to select a 5 kW regenerative fuel cell to evaluate as a backup power system. More information on the Clemson and other market assessment studies can be found later in this report.

SRNL took the lead in Task 2, the assessment and development of hydrogen storage technology for this project. SRNL has over 50 years of expertise in hydrogen and hydrogen storage systems with over 25 years of expertise in storing hydrogen on metal hydrides and other solid materials. In addition to our ongoing development of novel, high-capacity, hydrogen storage materials, SRNL adapted a 2 kg of hydrogen metal hydride-based storage system for use in this project.

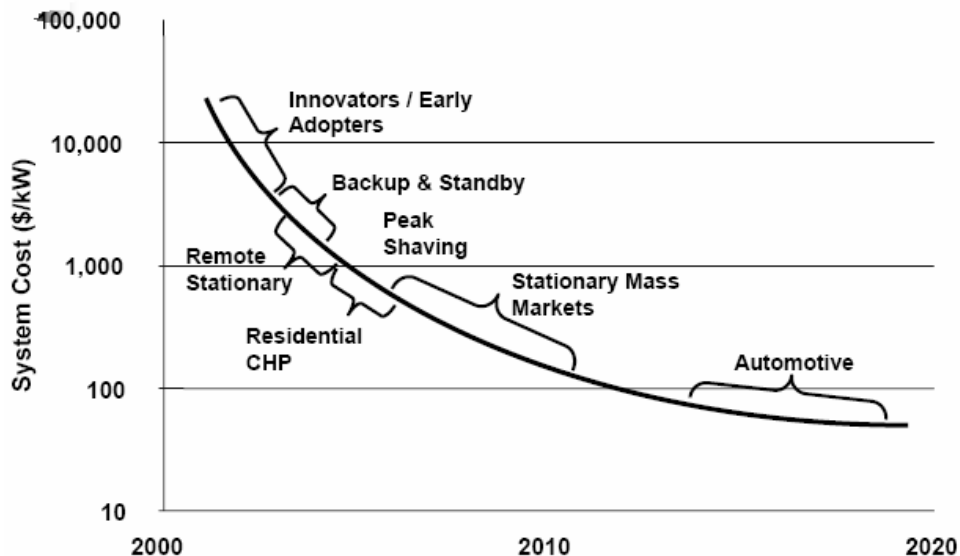
PES working with SRNL and the CHR was responsible for performing the majority of the fuel cell system development and integration, Task 3. Due to delays encountered during completion of the CHR facilities, the majority of the initial electrolyzer, fuel cell and storage system testing was performed by PES in their Connecticut facilities as Task 4. PES also provided the electrolyzer, which was able to charge the SRNL metal hydride storage vessel in less than 24 hours.

The CHR and ATC are jointly responsible for education and outreach portion of this project. ATC has been integrating hydrogen technology into their technical college curriculum for over two years and as part of that program they have provided additional sensors and data acquisition capabilities to the RFC system so that data and results can be sent from the CHR to the ATC classrooms and laboratories in real time. The CHR purchased the Plug Power<sup>TM</sup> fuel cell and the PES electrolyzer from Proton Energy and will be responsible for continued testing of the system for backup power applications. As a follow on to this project the CHR will be adding 20kW of photovoltaic panels to the system to be able to evaluate and operate the RFC as a renewable power system.

Several detailed reports covering Tasks 1 to 4 are available and referenced in this report. These include interim reports that were initiated as part of this overall project [3-4]. Therefore, no attempt will be made to repeat all the information contained in these other reports. The emphasis of this report will be to discuss and summarize the overall project findings and results and to draw out discussions and some conclusions on the applicability of regenerative fuel cells for near-term and long-term backup power applications.

## 2.0 BACKGROUND AND MARKET ASSESSMENT

A hydrogen economy is often viewed as the commercialization of hydrogen and fuel cell vehicles. In his 2003 State of the Union Address, President George W. Bush initiated a 5-year, \$1.2 billion program to promote hydrogen and fuel cell technology. At the end of that program, many substantial improvements and advances in fuel cells and hydrogen technology were achieved, however, the cost and performance targets required to adapt hydrogen and fuel cell technology to the transportation market still had not yet been realized. The expected cost of fuel cells for automotive applications is often quoted to be on the order of \$50/kW. This cost is 10 to 20 times less than what may be needed for portable, stationary and other applications (Figure 2).



**Figure 2. Probable Fuel Cell Adoption Curve [1]**

Today, there is an increasing demand for highly reliable power for critical applications such as telecommunications, hospitals, financial and emergency response. The costs and lost revenue associated with power disruptions to these applications can be disastrous. Recent hurricanes in the southeast U.S. have revealed limitations with traditional battery and genset systems. Competition for gasoline and diesel fuel during disasters, along with poor battery life, has made many of these systems ineffective.

A recent comprehensive assessment on fuel cell markets was performed for the Department of Energy by Battelle [2]. The April 2007 study by Battelle focused on identifying near-term market opportunities for direct hydrogen PEM fuel cells in pre-automotive applications that could support future fuel cell industry commercialization. The study found that the most promising near-term opportunities were in specialty vehicle and backup power applications.

In backup power, the study found that for applications such as emergency response radio towers, PEM fuel cells can be competitive with battery-generator systems on a lifecycle cost basis. The cost saving for fuel cell systems were found to be greater for systems with runtimes of 1 to 3 days where the high cost of hydrogen storage was minimized. Costs savings for fuel cell systems over battery systems were also found for harsh operating environments where battery lifetimes were shortened. The study identified financial incentives, demonstration projects and reductions in the high cost of hydrogen storage to be critical for PEM fuel cells if they are to compete effectively in the backup power and capture a profitable near-term market share.

As part of this project, a market assessment on regenerative and stationary fuel cells was performed by Clemson University and the South Carolina Institute for Energy Studies. The Clemson study [3] focused primarily on the 1-5 kW range. The report detailed the market, business strategy, competing technologies and barriers to commercialization of stationary fuel cell technology. The study concluded that while life cycle costs of fuel cell systems can be less than batteries, the major draw back is the initial costs for fuel cells. A secondary finding was that the lack of reliability data and user experience hindered commercialization efforts.

Major observations of the study include:

- There is an increasing need for reliable backup power solutions.
- Stationary Fuel cells are a promising technology to meet this need.
- Stationary fuel cells that target the telecom backup market appear to be the most promising.
- Regenerative fuel cells are an attractive option, but face technology and market challenges.
- Stationary fuel cell manufacture's are at varying stages of development and commercialization.
- Most products are in the prototype stage and sales data are not available at the current time.
- There are a variety of backup power systems that all strive to provide power when grid power is unavailable.
- No single technology will provide the complete solution and trends in backup power point to a mosaic of alternative technologies.
- Prospects for the commercial success of stationary fuel cells remain uncertain for internal (industry specific) and external reasons - nominally high fuel cell cost, high manufacturing cost, limited access to capital markets, lack of interconnection rules, codes and standards, lack of product performance data, lack of adequate technical training courses, failure of collaborative partners, reliance on government funding and intense competition from energy technology companies.
- Demonstration projects and government support are crucial for success in the market.

Both the Battelle [2] and the Clemson [3] studies arrived at similar conclusions with respect to fuel cells for near-term backup power applications. Both studies point to telecommunications segments as early adoptions markets and to lifecycle cost advantages of fuel cells over today's battery systems. Table 1 compares the 10-year costs of fuel cell systems versus Valve-Regulated Lead Acid (VRLA) battery systems. The table shows higher initial costs for fuel cell systems but because of lower maintenance and replacement costs the lifecycle costs for fuel cell systems are lower than VRLA batteries for runtimes between 24 and 72 hours. The majority of the 100,000 utility-owned substations in the U.S rely on VRLA battery-based backup power systems [5]. Battery systems typically provide 4-8 hours of backup coverage. Following Hurricane Katrina in 2005, new proposed FCC regulations would require a minimum of 24 hours of backup for all central cell towers and 8 hours minimum for remote sites [6].

**Table 1. Economic Evaluation of a Fuel Cell vs. VRLA Battery over 10-year Period [3]**

	<b>Run time (hours)</b>	<b>Initial Cost*</b>	<b>Maintenance Cost*</b>	<b>Replacement Cost*</b>	<b>Total Cost*</b>	<b>Fuel cell Saving</b>
<b>Battery</b>	8	13400	11900	5000	30300	-24.42%
<b>Battery</b>	24	18800	11900	9600	40300	6.45%
<b>Battery</b>	48	29000	15400	17500	61900	39.10%
<b>Battery</b>	72	39200	17100	25300	81600	53.80%
<b>Fuel cell</b>	72	31700	5100	900	37700	

\* All costs are in present value

Both studies point toward the need for additional demonstrations and development to further lower the capital cost of fuel cell systems and to obtain more operational and reliability data. The studies also encourage additional government support via tax credits and incentives as well as increased use by government facilities and installations thereby promoting early adoption and market entry.

In comparing the operating power available from many of today's fuel cell manufacturers, Clemson [3] found that most of the products concentrated around a sweet spot in the 5 kW range. This range corresponds to the most popular range for telecommunication backup power and UPS markets. One of the problems with fuel cells competing in this market is the cost and availability of supplying and storing hydrogen.

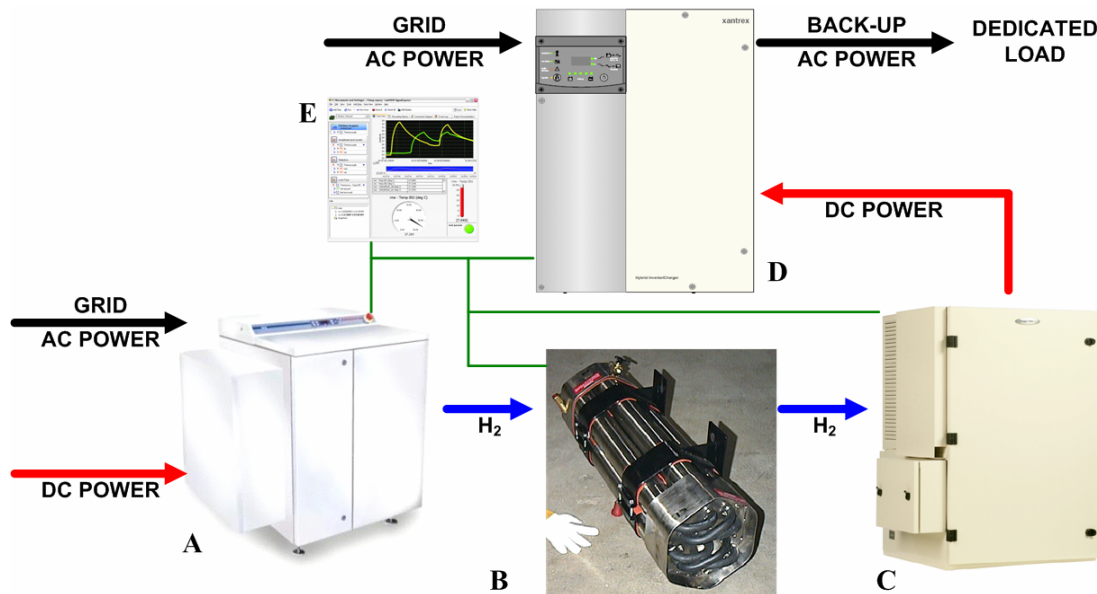
An attractive alternative for many backup power applications is an RFC. An RFC has the advantage in that it can supply its own hydrogen via electrolysis. Therefore, the RFC can be compared to an energy storage device like a rechargeable battery. But unlike a battery system, the RFC separates the power and the energy storage components of the system. Power output is determined by the size of the fuel cell stack and energy capacity is dictated by the size of the hydrogen storage system. By separating the power producing device from the energy storage capacity device, a RFC can increase its runtime simply by adding hydrogen storage. Only one fuel cell is needed to go from 8 hours to 24 hours of runtime. In a battery system, increasing the runtime from 8 to 24 hours typically requires tripling the size and cost of the system. One of the keys to success in the developing of a RFC system is low cost, safe, efficient and reliable hydrogen storage.



### 3.0 RFC TEST SYSTEM COMPONENTS AND CONFIGURATION

The fuel cell system chosen for this project was a regenerative fuel cell system. As described previously the advantage of this type of system for backup power applications is the ability of the system to produce its own hydrogen via an electrolyzer using grid power available during normal grid operation. Separate deliveries of hydrogen are not required. Remember for most backup power applications, normal grid power is available greater than 99% of the time. Only during 1% or less of the time during upsets to the grid is the backup system required. Another advantage of our RFC system is the use of low pressure metal hydride hydrogen storage. Not only does storing the hydrogen on metal hydrides improve safety over high pressure gas bottles but it also improves the systems overall efficiency and reliability by being able to load and store hydrogen at the 200 psig electrolyzer delivery pressure rather than having to compress and store the hydrogen to 2,000 psig or higher typical of most gas storage bottles. A more complete description of the RFC components and system developed for this project is described below and in reference [4].

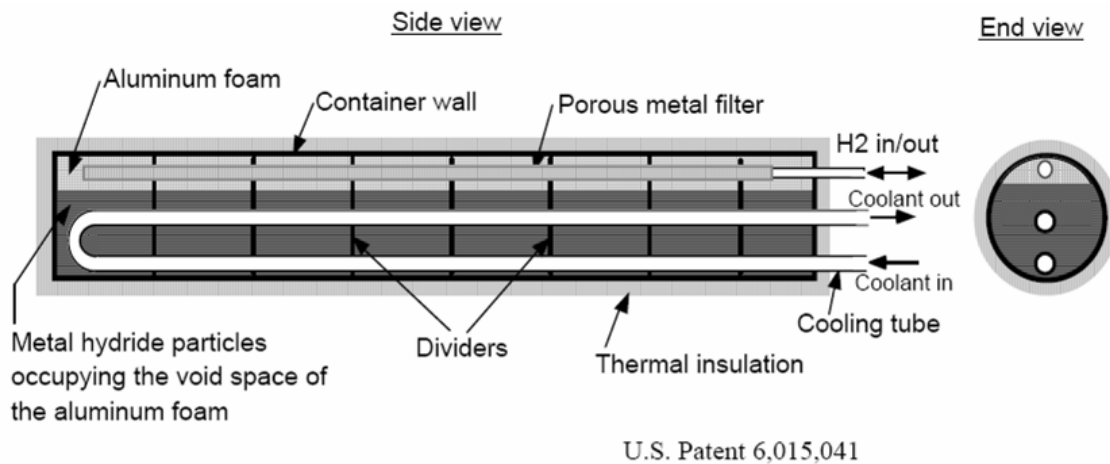
The RFC system is comprised of 5 major subsystems (Figure 3). The hydrogen generator or electrolyzer receives electrical power and de-ionized water to make pure hydrogen gas. The hydrogen generator is a HOGEN RE S40 capable of producing 2.27kg/day hydrogen with a purity better than 99.999%, <5 ppm H<sub>2</sub>O, and <1ppm other gases. The output pressure of the HOGEN RE is 200PSIG with a maximum flow rate of 18Ln/min.



(A) Hydrogen Generator, (B) Hydrogen Storage (one of two vessels shown), (C) Fuel Cell, (D) Power Management, (E) Data Acquisition System

Figure 3. RFC Backup Power System [4]

Two metal hydride vessels provided by SRNL, together store approximately 2 kg of hydrogen in the system. Each vessel stores 1 kg of hydrogen in an assembly containing an AB5 metal hydride material composed of a mischmetal-nickel-aluminum alloy (mischmetal is a mixture of lanthanum rich rare earth metals). The hydrogen storage assemblies are an SRNL patented design that were fabricated by Hydrogen Components, Inc. (HCI) in Littleton, CO, under contract to SRNL. Each metal hydride vessel contains seven bundled tubes and weighs approximately 143 kg. The individual tube is shown schematically in Figure 4. The design uses a thin stainless steel outer shell with high-heat-transfer aluminum foam and dividers to contain the metal hydride materials. Use of the metal hydride container not only allows for safe and compact low pressure storage but also eliminates the need and associated cost for a hydrogen compressor. The individual tube design shown in Figure 4 is assembled into a bundle of 7 tubes (each approximately 30 inches in length and 3 inches in diameter). More detailed information on the characteristics and performance of the SRNL storage bed can be found in various SRNL and partner publications [7-9].



**Figure 4. Schematic of Single Tube in Metal-Hydride Storage Assembly**

Two identical bundles were used for this project. Each was equipped with a manually operated isolation valve and a relief valve set to 435PSIG. Heating/cooling water was plumbed through each tube in the bundle in a series fashion. The water flow through both bundles was configured in parallel. A gas panel was developed for the metal hydride system to measure flow rates and pressures of the H<sub>2</sub> supply from the HOGEN RE and the output to the GenCore fuel cell. Hydrogen pressure was measured at the H<sub>2</sub> supply from the HOGEN RE, the metal hydride storage vessels, and the output to the fuel cell. Figure 5 shows the metal hydride vessel as they were configured for testing. In addition, a water panel measured the flow rate and incoming and outgoing temperatures of the water for the metal-hydride vessels to determine heat flow and energy.



**Figure 5. Metal Hydride Hydrogen Storage System Testing Configuration**

The fuel cell unit selected for this project was a GenCore™ 5B48 system capable of producing 5kW net of DC power at a maximum hydrogen flow rate of 75 SLPM. The fuel cell system included a 33Ah 48VDC battery bank in parallel with the fuel cell's DC/DC power converter. The fuel cell stack and battery bank were instrumented to provide data on the current, voltage, power, and energy of each. The battery current, power, and energy were bi-directional for charging and discharging. The fuel cell stack, recirculation pump outlet, and thermostatic valve outlet were instrumented with surface mount RTD temperature sensors. The recirculation pump outlet and thermostatic valve outlet temperatures were used in conjunction with a flow meter to measure the heat flow and energy rejected through the liquid to air heat exchanger.

Electrical power from the fuel cell was routed to a Xantrex™ XW6048 series inverter/charger with an integrated transfer switch. The function of the inverter/charger as its name implies is two-fold. When the electrical service is available, the inverter/charger functions as a battery charger maintaining charge in the battery and the dedicated AC load is supplied by the grid. During a grid loss, the AC load is switched over to the inverter in less than a half-cycle. This places a DC load on the batteries causing the DC bus voltage to drop. When the DC voltage drops below a preset level the fuel cell is turned on to maintain the load on the inverter/charger. How long the fuel cell can maintain this load depends on the load power level and amount of hydrogen stored.

The regenerative fuel cell system was instrumented with high quality sensors and transducers coupled to National Instruments Compact Data Acquisition System. Lab View™ software was used to interface the sensor signals with the computer and its peripherals. Power transducers were located at the AC input to the HOGEN RE, the AC service side of the inverter/charger, and on the output to the AC load.

## **4.0 RFC TEST PLAN AND DISCUSSION OF RESULTS**

A two step approach was used to test the regenerative fuel cell system. The first step involved a series of tests to establish a baseline of operation for the metal hydride vessel with the HOGEN RE hydrogen generator and the GenCore fuel cell. The second step involved a series of tests to evaluate the RFC as an actual backup power system under various realistic backup power startup and transient operating conditions.

One of the limitations of the system was the hydrogen supply pressure requirement for the GenCore of no less than 64 PSIG. This issue was discussed with the technical support of Plug Power and it was confirmed that the GenCore's customer Emergency Stop (E-Stop) circuit could be used to shut the fuel cell down on low hydrogen supply pressure. A pressure switch was installed on the system that would open at 49.5 PSIG and close again at 67 PSIG. When the switch opened, it triggered a customer E-STOP on the GenCore.

### **4.1 SERIES 1 RESULTS: METAL HYDRIDE VESSEL TESTS**

#### **4.1.1 Charging Tests**

These tests were aimed at evaluating how the metal hydride vessel functioned during hydrogen charging from the HOGEN RE electrolyzer. Initially, temperature setpoints of 10, 15, 25, and 40°C were programmed into the heater/chiller on the metal hydride cooling and heating loop. After reviewing the results, an additional test at 35°C was added. The results showing metal hydride vessel pressure vs. total hydrogen charged to the metal hydride vessels are plotted in Figure 6. The hydrogen flow rate during this charging test was approximately 15.4 SLPM (83g of H<sub>2</sub> per hour or 2.0kg/day). From these results, it was shown that the metal hydride vessels can be charge to 90% of their nominal full capacity at a temperature of 40°C. This graph also shows that since the metal hydride storage vessels was charged to roughly 95% at 25°C, there was very little advantage in cooling the metal hydride vessels down to 10°C in a practical application.

A charging test was also conducted without the use of the heater/chiller and at a starting temperature of approximately 45°C. The results of the passive charge without thermal management are shown in Figure 7.

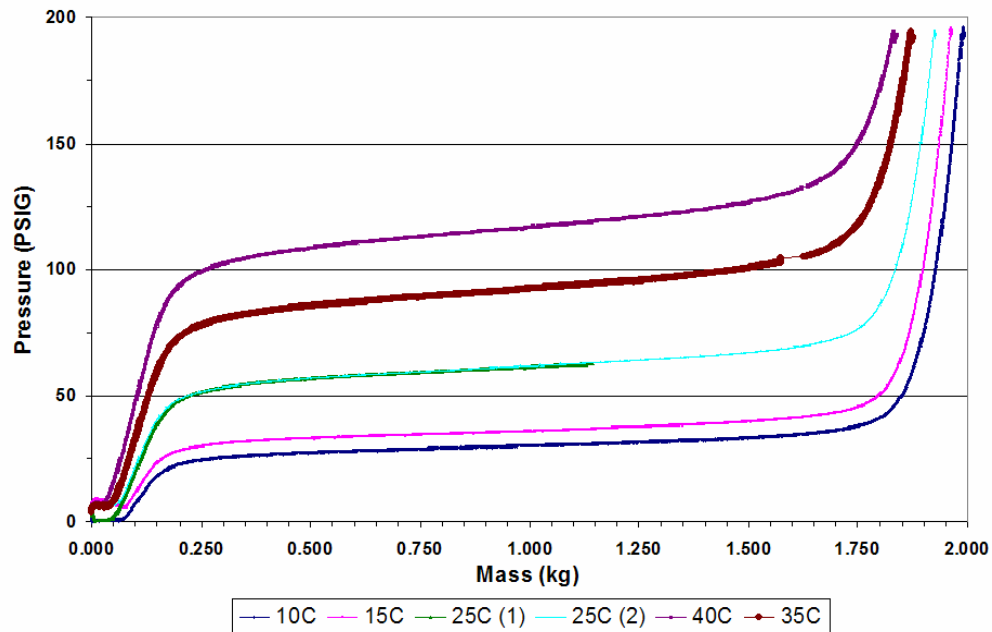


Figure 6. MH Charging Isotherms using the HOGEN RE

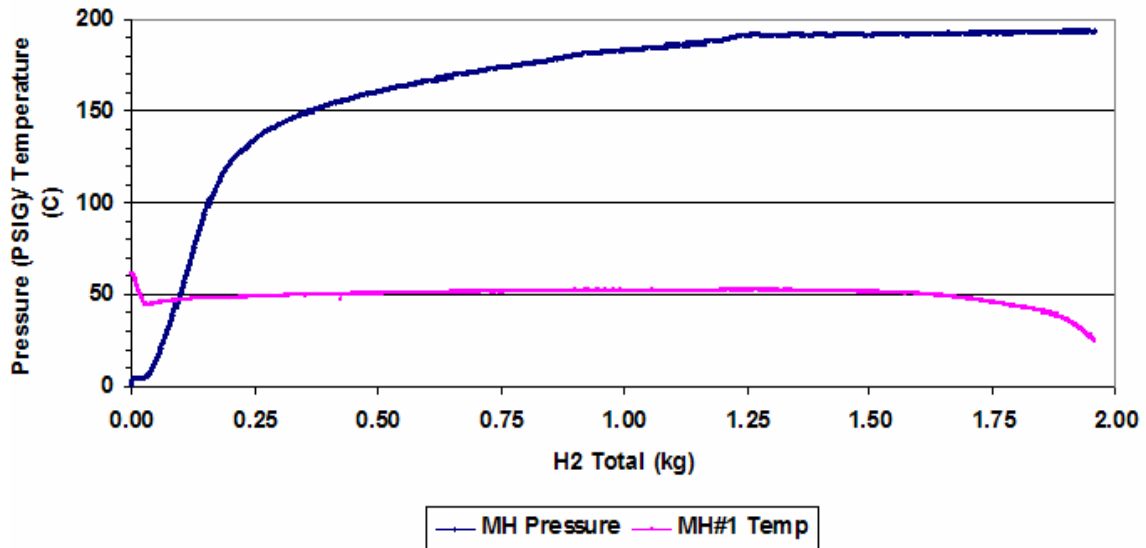
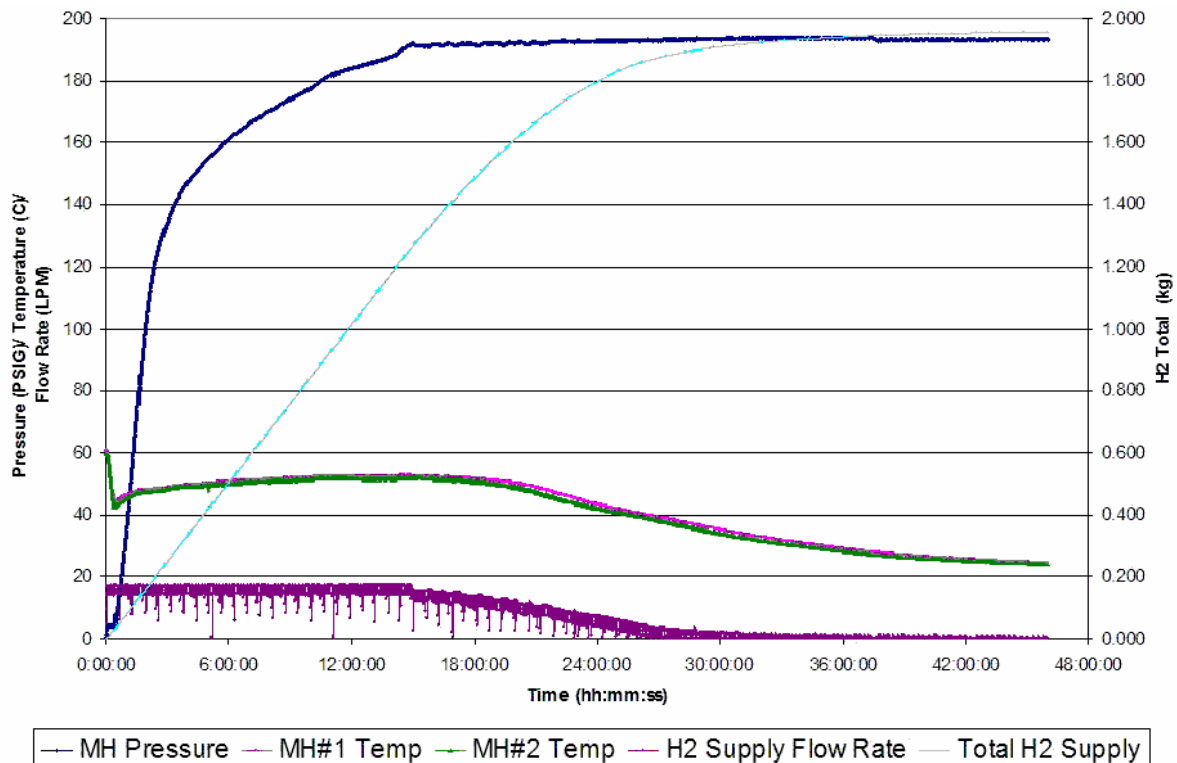


Figure 7. Passive Charge Started at 45°C as a Function of MH Pressure and Temperature

Figure 8 shows the passive charge curves over time. This perspective shows that the vessels were charged to approximately 90% of their nominal full capacity within 24 hours. It also shows that it took an additional 20 hours for the metal hydride vessel to reach a fully charged state. The reason that an additional 20 hours was needed to reach full charge is because after reaching 190 PSIG at the metal hydride vessels, the electrolyzer hydrogen generation rate was automatically reduced based on its pressure feedback and control setpoint. The 190 PSIG pressure at the metal hydride bed is very close to the equilibrium pressure for the metal hydride material in the vessel at about 50°C. To accept more hydrogen in the metal hydride material either the charging pressure has to be increased or the temperature of the material in the vessel decreased. Since the electrolyzer setpoint prevented any additional pressurization the metal hydride vessels had to cool down to accept more hydrogen. The lower hydrogen generation rate by the electrolyzer allowed the vessels to cool and slowly receive the last 0.750 kg of hydrogen.



**Figure 8. Passive Charge Started at 45°C as a Function of Time**

The performance of each charge cycle is shown side-by-side in Table 2. With the exception of the passive charge, the metal hydride vessels were filled to full capacity in 24 hours.

**Table 2. Charging Statistics**

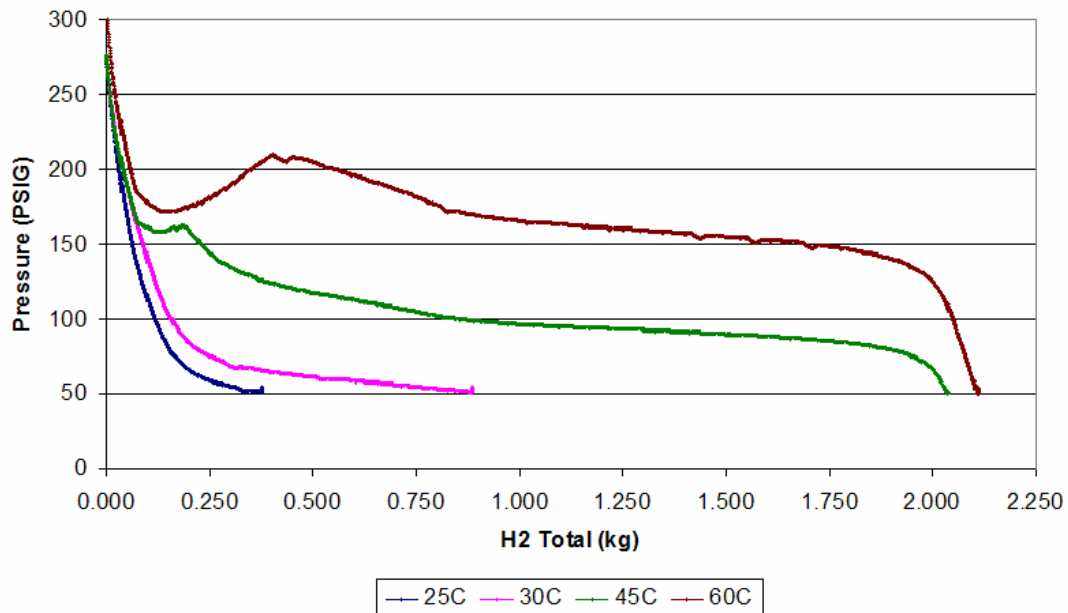
SetPoint Temperature	10	15	25	35	40	Passive	°C
Run Time	24:36:20	24:08:31	23:46:00	23:09:00	23:21:41	44:42:20	hh:mm:ss
H <sub>2</sub> Total	1.993	1.966	1.929	1.876	1.840	1.957	kg
Electrolyzer Stack Energy	137.269	135.358	131.941	128.701	126.946	140.587	kWh
Stack Utilization	68.89	68.84	68.41	68.60	68.99	71.83	kWh/kg

#### 4.1.2 Discharge Tests

A series of tests were conducted to evaluate the ability of the metal hydride vessel to provide an adequate amount of hydrogen to sustain a certain power level on the DC bus fed by the fuel cell. Tests were conducted at 2kW, 3kW and 5 kW DC bus loads and at metal hydride vessel chiller/heater setpoints of 25°C, 30°C, 45°C and 60°C. Typically, the power level of the fuel cell was about 10% higher than the power on the DC bus. This amount of additional power was needed for some power conditioning by the power management system as well as to handle some of the fuel cell system's auxiliary and hotel loads. At bus power levels of 1 kW and less, often the fuel cell was observed to operate at about 2kW to provide the needed hotel loads which could include electrical heating if the fuel cell was not yet at normal operating temperatures.

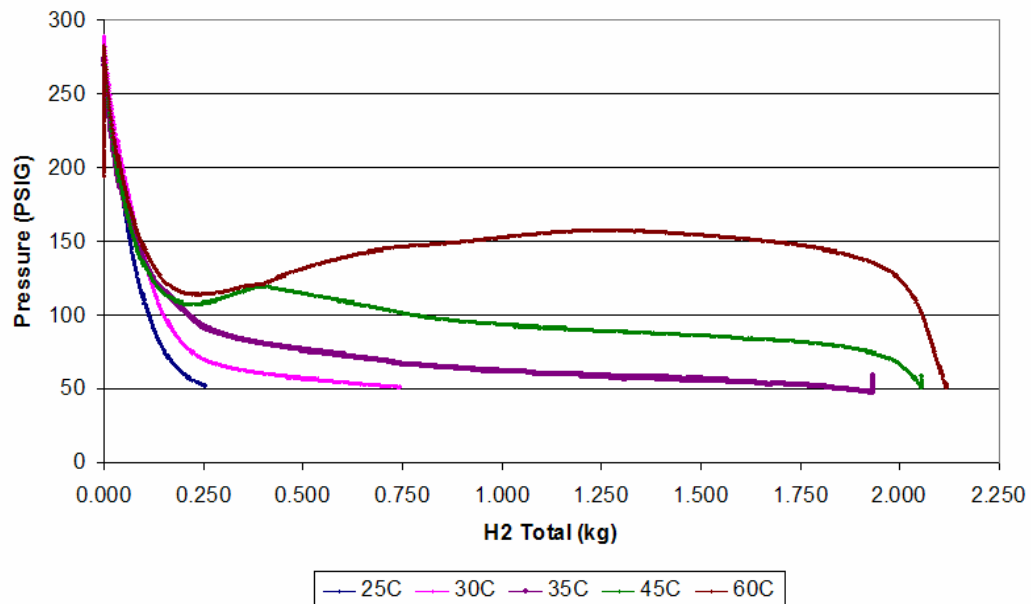
Figure 9 shows the results for the 2kW DC bus power level case. The graphs show a sharp decrease in metal hydride vessel pressure for the first 0.125kg of hydrogen desorbed. As the heater/chiller brought the temperature up toward the 45 and 60°C targets, the pressure climbed before reaching a plateau. The total hydrogen consumption at the end of the test was nearly the same for the 45°C and 60°C tests. The pressure levels for the 25°C and 30°C tests dropped below the 49.5 PSIG pressure switch cutoff before the chiller/heater could compensate for the rapid drop in temperature caused by the rapid desorption of hydrogen from the metal hydride vessels. At the higher chiller/heater temperatures there is enough heat transfer available to reverse the initial pressure drop and increase the pressure temporarily prior to reaching an approximate steady-state condition. This can be seen clearly in Figure 9. *Remember as hydrogen is desorbed from a metal hydride material it undergoes an endothermic reaction and requires heat to continue desorption. The opposite occurs as hydrogen is absorbed on a metal hydride. The exothermic absorption reaction requires cooling to maintain hydrogen absorption.*

Since the fuel pressure in the fuel cell stack is only about 2 PSIG, improvements can be made in the system to allow for a lower hydrogen fuel cell pressure requirement. This will allow the system to accommodate lower temperature metal hydride vessel operations, possibly 30°C or even 25°C at lower power levels.



**Figure 9. MH Pressure vs. H<sub>2</sub> Total Desorbed at 2kW DC Bus Load**

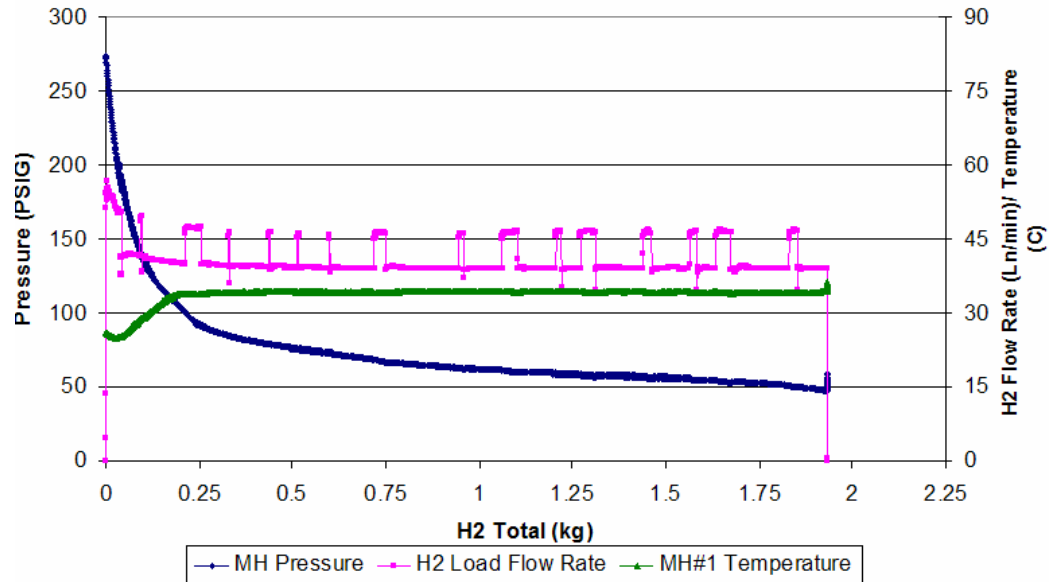
Figure 10 shows the results for a 3.5kW load on the DC bus for metal hydride temperature setpoints of 25, 30, 35, 45, and 60°C. An additional test was conducted at 35°C at this power level to compliment the charge test at this same temperature.



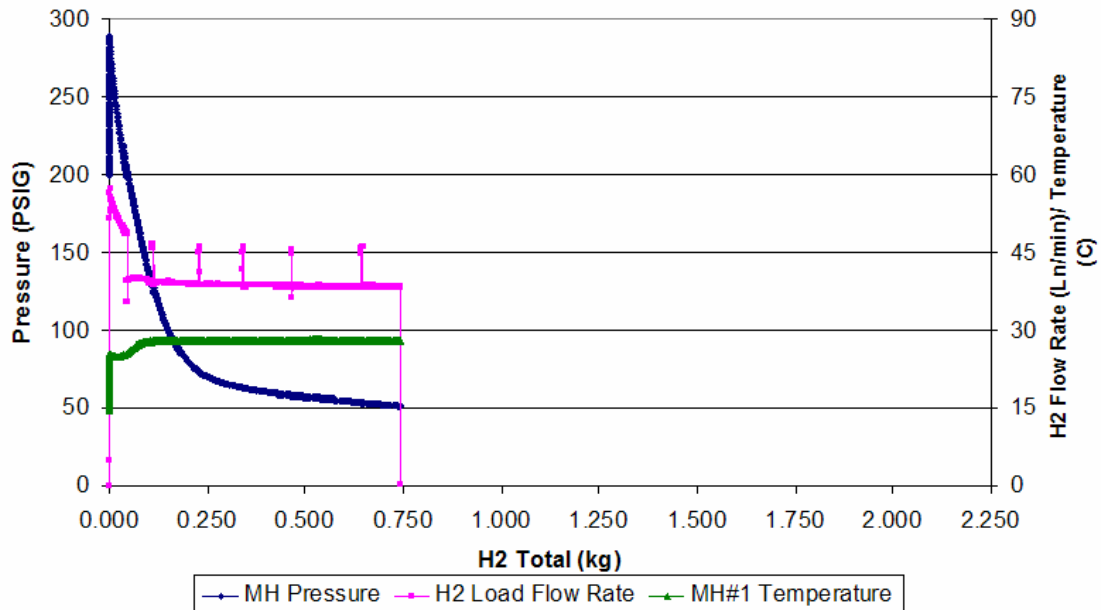
**Figure 10. MH Pressure vs. H<sub>2</sub> Total Desorbed at 3.5kW DC Bus Load**



Figure 10 shows that there is a significant increase in the total hydrogen consumption from 30°C to the 35°C setpoint. Only about 35% of the capacity is used at the lower temperature while nearly all of the available capacity is used by increasing the temperature by 5°C. The metal hydride pressure, H<sub>2</sub> Load Flow Rate, and MH#1 Temperature were charted versus total hydrogen consumed for both runs in Figure 11 and Figure 12.



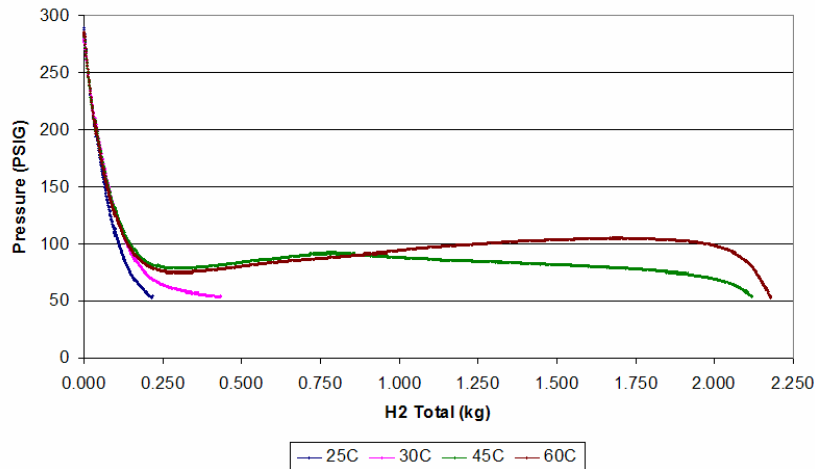
**Figure 11. Bus Load: 3.5kW MH Setpoint Temperature: 35°C**



**Figure 12. Bus Load: 3.5kW MH Setpoint Temperature: 30°C**

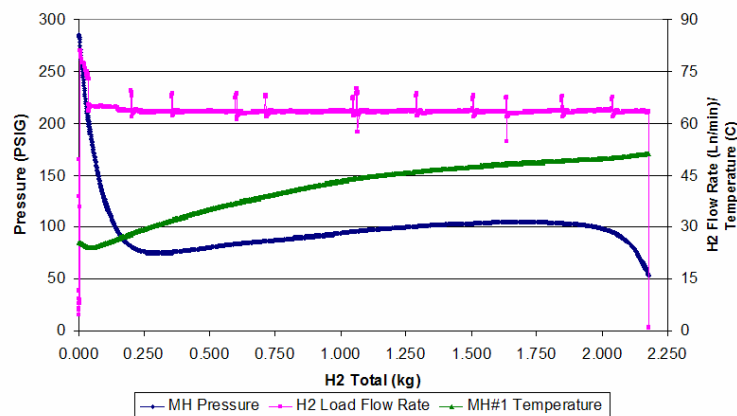
The 3.5kW discharge tests showed similar performance for 45 and 60°C as with the 2kW tests. At 25°C and 30°C, the amount of hydrogen consumed by the fuel cell is substantially less than for the 2kW tests. This is related to the higher desorption rate early in the test causing more rapid cooling and subsequent pressure drop.

The results for a 5kW load on the DC bus for metal hydride temperature setpoints of 25, 30, 45, and 60°C are plotted in Figure 13.



**Figure 13. MH Pressure vs. H<sub>2</sub> Total desorbed at 5kW DC Bus Load**

The 5kW discharge tests showed similar performance for the 45 and 60°C runs and further reduced performance at the lower temperatures compared to the tests at lower power levels. At the rate of desorption for the 5kW DC load, the heater/chiller used for the testing was not capable of raising the metal hydride vessels to 60°C during the duration of the test. The hydrogen flow rate, metal hydride vessel pressure, and MH vessel #1 temperature during the 5kW discharge at the 60°C setpoint temperature are shown in Figure 14.



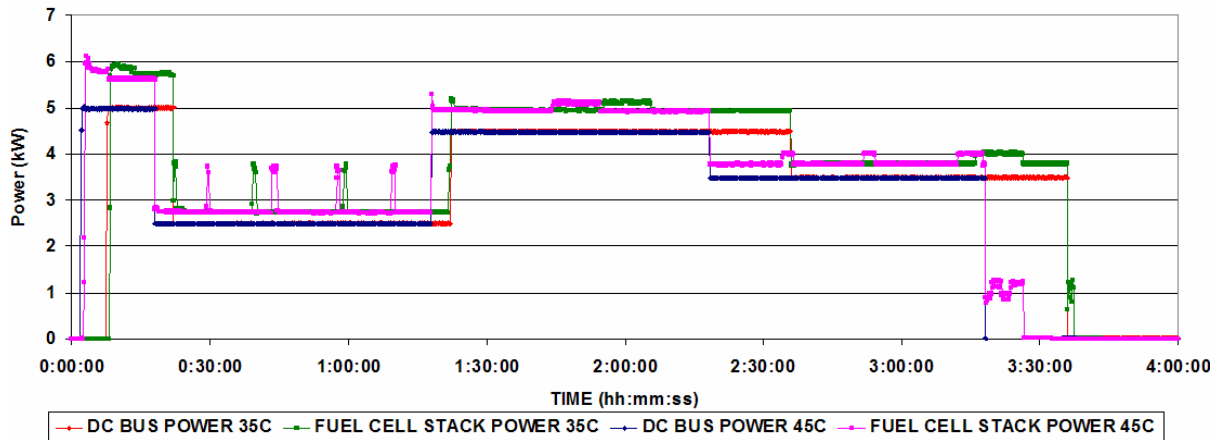
**Figure 14. MH Characterization at 5kW bus load and 60°C Setpoint Temperature**

## 4.2 SERIES 2 RESULTS: BACKUP POWER SIMULATION TESTS

Once the metal hydride characterizations were complete, testing on more general characteristics of the RFC system was conducted. These tests measured the performance and practical implementation of the RFC system in a back-up power role. Target temperatures of 35°C and 45°C were selected based the brief run-time at 25°C and the good performance at 45°C.

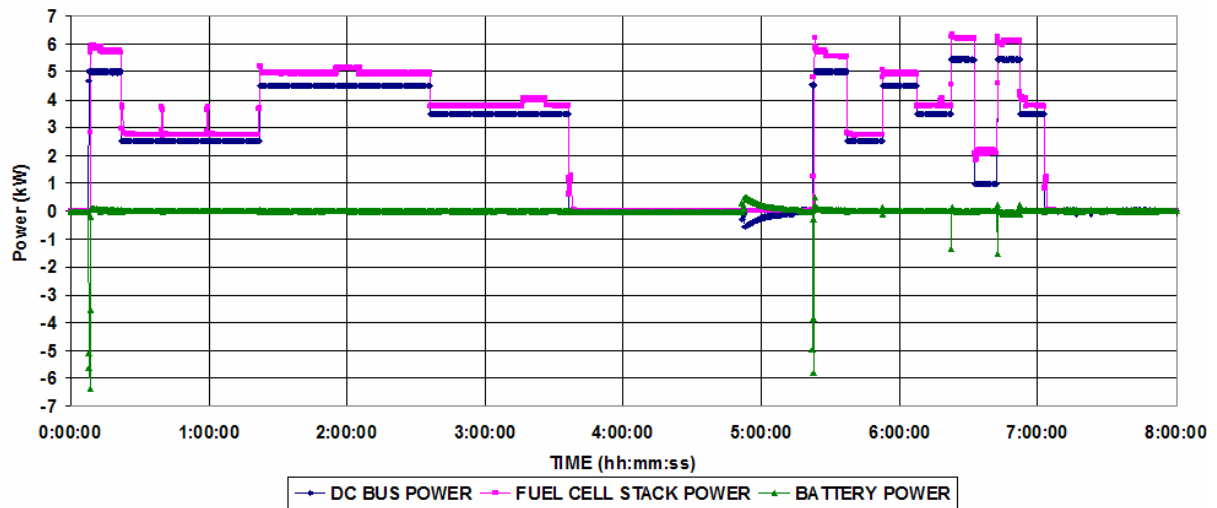
### 4.2.1 Step Change Tests

A series of step changes in the DC bus load were performed at metal hydride temperatures of 35°C and 45°C. The battery and fuel cell response were key parameters while the temperature of the metal hydride vessels did not affect the tests. The DC bus power and fuel cell stack power for both metal hydride temperature setpoints are shown in Figure 15. Aside from initial start, shutdown and time shifts, there was no noticeable difference in the response to a step change at the two temperatures.



**Figure 15. Comparison of Step Changes for MH Vessel Temperatures of 35°C and 45°C**

The step change test for 35°C operation, plotted in Figure 16, illustrates the role of the battery inside the fuel cell system. During start-up from a standby state, the battery responded to the initial power draw from the DC bus. The battery also responded to step changes noticeably when the DC bus load exceeded the 5kW net power rating of the fuel cell. The negative polarity for the battery power indicated that the battery was in discharge mode and the positive polarity near the 5 hour mark in the plot showed a bulk charge of the battery.

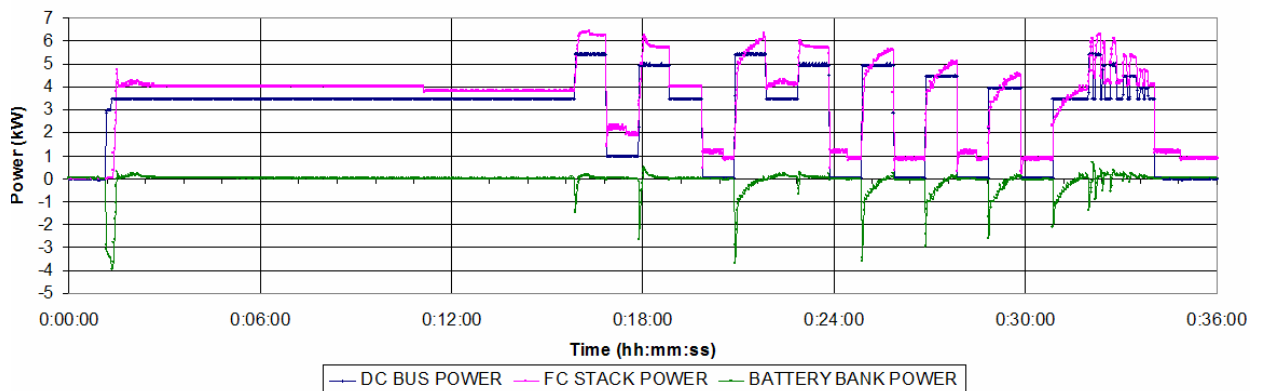


**Figure 16. Step Change Test for 35°C MH Setpoint Temperature**

#### 4.2.2 Impulse Tests

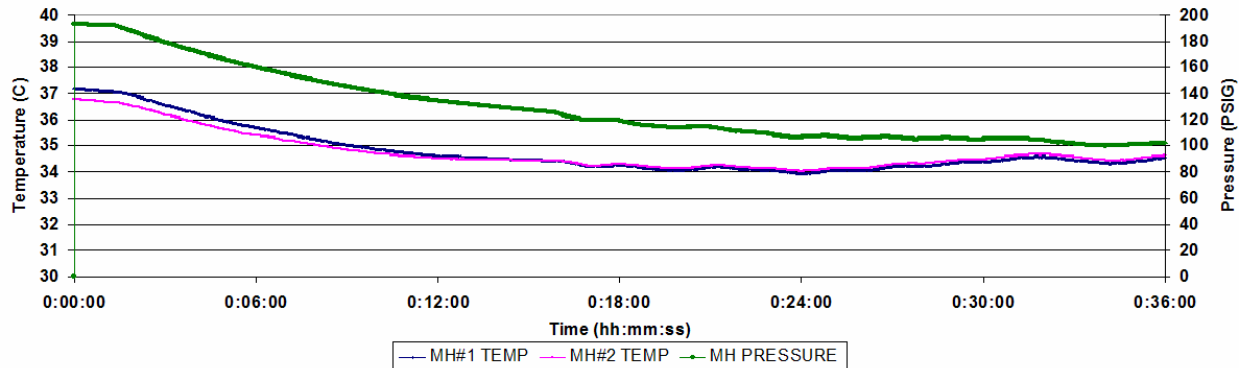
During the impulse tests, the fuel cell system response to DC load changes on the order of seconds, was measured and compared for 35°C and 45°C metal hydride setpoints. The effect of metal hydride temperature from 35°C to 45°C was indiscernible on the operation of the fuel cell system, as it was with the step change tests.

Figure 17 shows the power levels for the DC bus, fuel cell stack, and battery bank for the impulse test sequence at 35°C. The figure shows that the role of the battery is significant for quick response in maintaining the DC bus power during the impulses.



**Figure 17. Power levels for Impulse Test @ 35°C**

The temperature and pressure of the metal hydride vessels were examined to see how short duration load changes caused any affect in their performance. Small ripples in these two parameters that corresponded to load changes can be seen in Figure 18, but overall temperature and pressure changes were not substantial and the overall trend followed previous steady-state discharge tests.



**Figure 18. MH Vessel Temperatures and Pressure for Impulse Test @ 35°C**

#### 4.2.3 Vessel Changeover Test

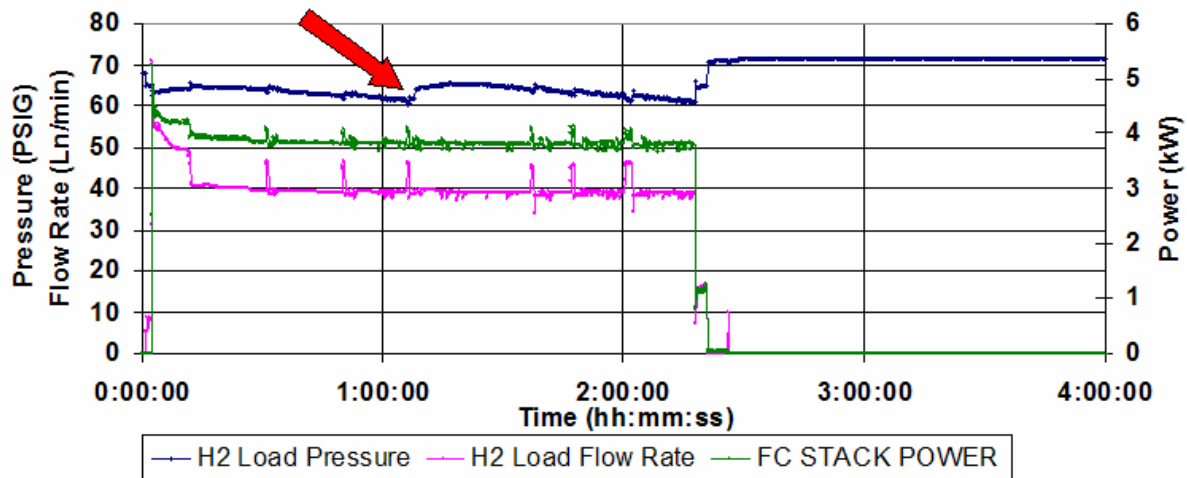
The vessel changeover test was conducted to gauge the effects on fuel cell system operation when switching over from a less than full metal hydride vessel to a full one. This test also demonstrated the ability of the RFC system to utilize hydrogen from multiple metal hydride vessels in sequence during operation for longer back-up power times.

These tests were conducted at 3.5kW and temperatures of 35°C and 45°C. The vessel changeover results at 35°C are shown in Figure 19. From these results it can be seen that the H<sub>2</sub> load pressure increased slightly just after the one hour time mark when the vessel was switched over. This was due to the higher pressure in the fully charged metal hydride vessel. Aside from the effect, the hydrogen load flow rate responded slightly but there was no noticeable effect on the fuel cell stack power level.

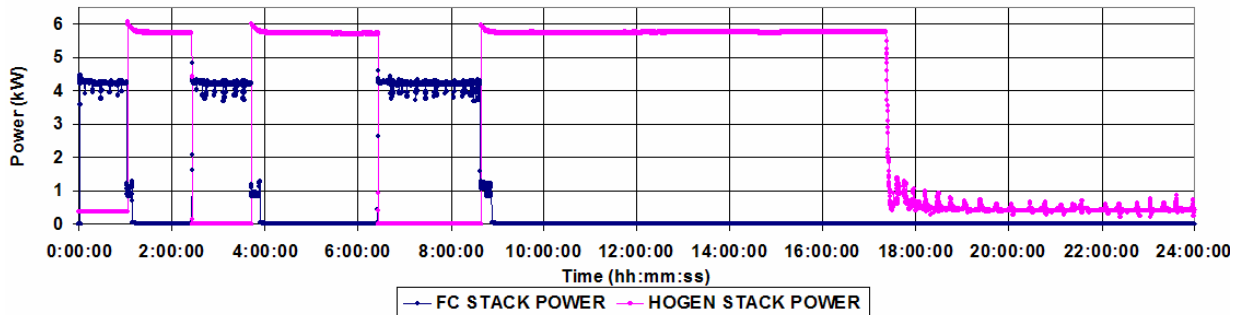
#### 4.2.4 Series Grid Loss Events

Simulated grid losses in series using the AC load were conducted to observe the RFC system during back-up power mode and hydrogen generation mode. The metal hydride vessels were initially charged to roughly 200 PSIG at 35°C and, at the end of the test, recharged to the same conditions. After each grid loss, the inverter/charger handled the transfer switch and inverting function to the 3.5kW AC load.

When the grid was restored, the hydrogen generator started supplying hydrogen to the metal hydride vessels. Note the continued operation of the fuel cell stack at 1kW after the hydrogen generator came back online, as shown in Figure 20. This is due to in part to an algorithm in the fuel cell controls that serves as a battery charging function. In this application, the inverter/charger was also charging the batteries and may have been interfering with the fuel cell's control algorithm.



**Figure 19. Vessel Changeover Test**

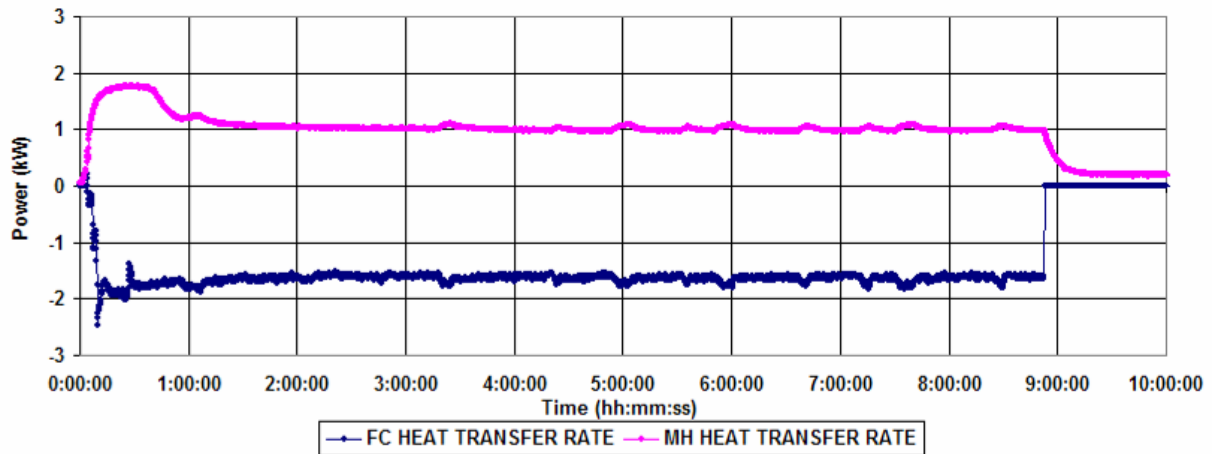


**Figure 20. Fuel Cell and Electrolyzer Cell Stack Power During Series Grid Loss Events**

#### 4.2.5 Thermal Management: Fuel Cell and Metal Hydride Vessels

During initial project discussions, it was anticipated that the fuel cell and the metal hydride vessel heating and cooling systems would be coupled. This would allow the waste heat from the fuel cell to heat up the metal hydride vessel to provide the needed hydrogen. Upon further discussions with the fuel cell vendor it was recommended not to modify the fuel cell's coolant/heating loop at this time. Thermally coupling the fuel cell and the metal hydride vessels would make the overall system more energy efficient. This may be important for a continuous renewable RFC fuel cell system, which requires wind or solar resources to produce its hydrogen but may not be as critical for a grid powered backup power system. Future test plans for the system as a renewable RFC are still underway and thermally coupling the units are still being considered. However, a test was conducted for the current RFC configuration to estimate the amount of waste heat available from the fuel cell.

Figure 21 shows the results of measurements and calculations made at a DC bus load of 3.5kW and 35°C. The results indicate that the fuel cell system rejected more heat through the radiator than was needed to maintain a temperature of 35°C at the metal hydride vessels. It took approximately one hour, during this test, for the metal hydride vessels to stabilize at 35°C. Therefore, for steady operations there appears to be more than enough waste heat from the fuel cell to heat up the hydride vessels. However, during startup before the fuel cell reaches its operating temperature either the battery in the fuel cell must be sized adequately to supply some on the initial load or the metal hydride vessels need to be fully charged so that they can provide enough initial hydrogen at suitable pressure before the fuel cell coolant flow heats up. Other alternatives may be to maintain the metal hydride vessels continuously at 35°C or to add a small gas volume to the system to initiate hydrogen flow to the fuel cell until the metal hydride vessel temperature and pressure increases enough to run the fuel cell.



**Figure 21. DC Bus Load: 3.5kW, MH Vessel Temperature Setpoint: 35°C**

## 5.0 SUMMARY OF RESULTS AND CONCLUSION

A regenerative fuel cell system was developed by combining a commercial fuel cell and electrolyzer with a pre-commercial metal hydride storage system. The metal hydride system held 2 kg of hydrogen and was able to provide 3.5 to 4 kW of DC power for 8 to 10 hours. Additional metal hydride storage vessels can be added to increase the backup times. As was mentioned previously, the present fuel cell configuration requires a minimum of 49.5 PSIG supply pressure. This will require approximately a gallon per minute of 35°C cooling/heating water flow through the metal hydride vessels to deliver all of the hydrogen to the fuel cell under a wide range of operating conditions. If the supply pressure can be reduced to 15 PSIG the cooling/heating temperature may be able to be reduced to 25°C or less. Another alternative that was evaluated during this study is to use the waste heat from the fuel cell cooling/heating loop to heat the metal hydride vessels.

Charging the metal hydride vessels directly from the electrolyzer at 200 PSIG was demonstrated without any issues. Because of the lower hydrogen flow rate coming from the electrolyzer (2kg/24hrs) the metal hydride vessels were able to absorb and store hydrogen at coolant water temperatures ranging from 10 to 40°C. Even passive charging without any coolant flow was demonstrated. The use of safe, low pressure metal hydrides for hydrogen storage opens the door for wider acceptance of fuel cell system because of the possibility of indoor installations. Metal hydrides also have a high hydrogen volumetric density allowing them to store more hydrogen in a smaller space than compressed gas systems.

The RFC system was tested under various simulated power outage scenarios. In all cases the system responded rapidly to provide the required electric load. The fuel cell system included a small 33Ah 48VDC battery which helped to provide intermittent power for a variety of startup, pulse and other transient operations. A more detailed study is recommended to determine if this amount of battery power (approx. 1.5kWh maximum) is optimal especially for cold starts with a partially charged metal hydride vessels.

The RFC tested here, even though not optimized, provided a good alternative to VRLA batteries. Lifecycle costs from Table 1 indicate that fuel cell systems can be cost effective over VRLA battery systems especially at higher run times (> 8hours). One of the variables that can dramatically affect the overall costs of a fuel cell system is the cost of delivered hydrogen. The use of an electrolyzer and low pressure metal hydride storage system eliminates the need for providing delivered hydrogen but at a higher capital cost. Additional studies are recommended to compare the long term lifecycle cost associated with providing delivered hydrogen versus the use of an electrolyzer for various backup and renewable power applications and scenarios. Work by Proton Energy and others continues in the development of a “unitized” solution that uses the same unit which functions both as an electrolyzer and as a fuel cell. Basically a PEM fuel cell is similar to a PEM electrolyzer except operated in reverse. The advantage of a unitized system would be to lower the overall capital cost of the system by having only one unit. The disadvantages include only being able to operate one unit at a time and lower possible operating efficiencies. Neither of these may be a serious problem for a backup power application.



One key aspect of this project was to evaluate the performance of solid-state hydrogen storage systems for fuel cell backup power and other stationary fuel cell applications. Overall the performance of the storage system evaluated for this project was judged to be excellent. The storage system easily and efficiently stored and delivered hydrogen from and to the electrolyzer and the fuel cell, respectively, under a wide range of operating conditions and scenarios. For this project a traditional, intermetallic, metal hydride (AB<sub>5</sub>) material was selected as the storage medium. This class of material has a good track record in storing hydrogen, especially, with respect to having favorable operating conditions, high volumetric hydrogen density and good cycle ability. The downside of this and other intermetallic materials historically has been their high gravimetric density (less than 2 wt% hydrogen) and to a lesser extent their cost. While weight is not a major concern for stationary hydrogen storage systems, low gravimetric densities do affect how much metal hydride material is needed to store a required amount of hydrogen, which adds to the overall hydrogen storage system cost. SRNL and others have been working with the DOE on their “Grand Challenge”, to find a workable hydrogen storage solution for automobile applications. While many new promising materials have been discovered over the past several years, with hydrogen capacities some greater than 20 wt%, none have met all of the DOE targets. Because weight is not as critical in stationary compared to mobile applications, a great potential still exists to significantly lower the cost and improve the efficiency of stationary storage systems. SRNL and our other project partners are hopeful that new practical and economical hydrogen storage systems can be developed for backup, portable and stationary applications in the next 5 years or less.

Following this phase of the project, the RFC system will be relocated to the Center for Hydrogen Research (CHR) in Aiken, South Carolina. In addition to more backup power testing the system also will be evaluated as a renewable power system. The CHR is installing a 20kW solar photovoltaic array to provide electricity to the grid as well as electricity to make hydrogen from the electrolyzer. The CHR will also use the RFC system for education, outreach and training. A program is currently underway at Aiken Technical College (ATC) to provide hydrogen and fuel cell operations into their HVAC and electrical energy curriculums. In addition to providing hands on experience for students, data from the RFC in the CHR will be transmitted to ATC for classroom use.

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