Round Trip Energy Efficiency of NASA Glenn Regenerative Fuel Cell System

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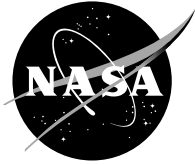
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Abstract

NASA Glenn Research Center (GRC) has recently demonstrated a Polymer Electrolyte Membrane (PEM) based hydrogen/oxygen regenerative fuel cell system (RFCS) that operated for a charge/discharge cycle with round trip efficiency (RTE) greater than 50 percent. The regenerative fuel cell system (RFCS) demonstrated closed loop energy storage over a pressure range of 90 to 190 psig. In charge mode, a constant electrical power profile of 7.1 kWe was absorbed by the RFCS and stored as pressurized hydrogen and oxygen gas. In discharge mode, the system delivered 3 to 4 kWe of electrical power along with product water. Fuel cell and electrolyzer power profiles and polarization performance are documented in this paper. Individual cell performance and the variation of cell voltages within the electrochemical stacks are also reported. Fuel cell efficiency, electrolyzer efficiency, and the system RTE were calculated from the test data and are included below.

Introduction

The hydrogen-oxygen RFCS has been promoted as one of the most favored energy storage technologies for solar electric power in aerospace applications, mainly due to its high (300 to 1000 Whr/kg) specific energy. A RFCS could provide much higher specific energies than any advanced battery system and potentially the highest storage capacity and lowest weight of any non-nuclear device. Due to irreversible heat generation the RTE, that is, the fraction of energy put into the system that actually gets delivered back to the user, is limited to about 75 percent.

Round trip efficiency is one of the most important attributes for the user since it dictates, along with the energy density, how much storage media, or storage installation size, will be required in order to accommodate user energy demands and how much power from the primary source will be required to replenish that storage. For many mechanical, and some magnetic and electrochemical storage devices, the round trip efficiencies can be as high as 80 percent. However, they do not compete with the RFC on energy content per unit weight basis.

Performance estimates made for recent hydrogen oxygen PEM RFCS conceptual designs have predicted round trip efficiencies of roughly 50 to 60 percent depending on stack polarization performance and current densities applied. This paper presents electrochemical stack performance and round trip energy storage efficiencies from closed cycle hydrogen - oxygen PEM RFCS which is being operated as an energy storage device at NASA GRC.

System Description

The RFC system is a completely closed loop test bed for the cyclic operation of fuel cell systems up to 60 kWh (5 kWe times 12 hr). The NASA GRC RFCS is shown in figure 1. Closed loop means the system with its electrochemical reactants and products is completely sealed; nothing goes into the system other than electrical power and there are no discharges or emissions from the system other than electrical power and waste heat. The RFC system can accommodate a fuel cell stack up to 5.25 kWe (100 A at 52.5 V) capacity and an electrolyzer stack up to 15 kWe (150 A at 100 V). The system has a maximum operating pressure of 400 psig with hydrogen and oxygen storage capacities of 40 and 20 ft^3, respectively. The electrolyzer operates at the system pressure while the fuel cell reactant feeds and recirculation loops are regulated down to 50 psig. During the charge cycle the electrolyzer charges the reactant tanks to full pressure (400 psig) while running under a current profile that is either fixed, or shaped to simulate the output of a flat plate solar array. During the discharge cycle, the fuel cell delivers electrical power and product water from the stored reactants.

Figure 1.—PEM RFCS at NASA GRC.

Figure 2.—Hydrogen and oxygen reactant pressure profile.

A DC power supply simulates the solar input to the electrolyzer and a DC load is used to sink the fuel cell current. The closed loop water supply provides source and cooling water for the electrolyzer, humidification, and product collection for the fuel cell. Data acquisition and control for the RFC is provided by a multithreading suite of NASA GRC developed software using the National Instruments LabVIEW™ programming language. A more detailed discussion of the NASA GRC RFCS can be found in references 1 to 4.

Test Summary

The test for round trip efficiency was performed July 14th and 15th of 2005. The test consisted of an electrolysis (charge) cycle and a fuel cell (discharge) cycle. The electrolysis cycle began with the hydrogen and oxygen reactant storage tanks each at a pressure of 90 psig, temperatures of 83 and 85 °F, respectively and the system fully charged with deionized water. Charging of the reactant storage tanks was completed over a time period of 3 hr and 45 min, with the hydrogen and oxygen storage tanks each reaching a pressure of 190 psig and temperatures of 86 and 88 °F, respectively. While charging the reactant storage tanks the RFC absorbed a constant electrical power input of 7.1 kW and the operating temperature of the electrolyzer was maintained at 140 °F.
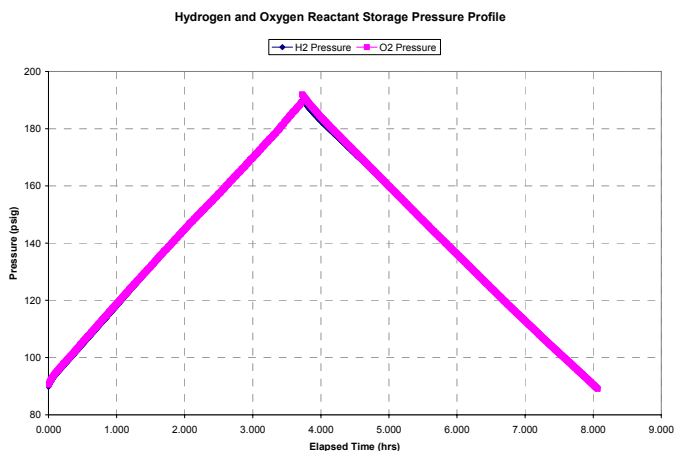
The fuel cell cycle began with the hydrogen and oxygen reactant storage tanks each at a pressure of 190 psig and temperatures of 82 and 85 °F, respectively. Discharge or fuel cell mode was completed over a time period of 4 hr and 22 min. During discharge the hydrogen and oxygen storage tanks were depleted to a pressure of 90 psig and the temperatures of the storage tanks rose to 85 and 87 °F, respectively. A plot showing the reactant pressure profiles during both the charge and discharge cycles is presented in figure 2. While discharging the reactant storage tanks the RFC delivered an electrical power output of 3.0 to 4.0 kW and the operating temperature of the fuel cell was maintained at 135 °F.

Results and Discussion

During the charge cycle the electrolyzer operating pressure followed the pressure of the reactant storage tanks, varying from 90 to 190 psig. Initially, the electrolyzer operating temperature was set to 140 °F but was increased (to get better cell voltage performance) throughout the charge cycle to a maximum of 147 °F. While charging the reactant storage tanks the RFCS absorbed a constant electrical power input of 7.1 kW and electrolyzer current was maintained at 75 A. The power versus time profile for the electrolyzer during the charge cycle is presented in figure 3. Integration of the area under this curve yields the total kilowatt-hours input into the RFCS during the electrolysis cycle. While absorbing 27.23 kWhr of electrical energy the RFCS generated 317 moles of gaseous hydrogen and 158 moles of gaseous oxygen, raising the pressure in reactant storage tanks from 90 to 190 psig.

During the discharging of the reactant storage tanks the RFCS delivered an electrical power output of 3.0 to 4.0 kW, corresponding to a fuel cell current range of 60 to 85 A and a stack voltage that varied from 51 to 48 V. The fuel cell operating pressure was 63 psig and its operating temperature was maintained at 135 °F. The power versus time profile for the fuel cell during the discharge cycle is presented
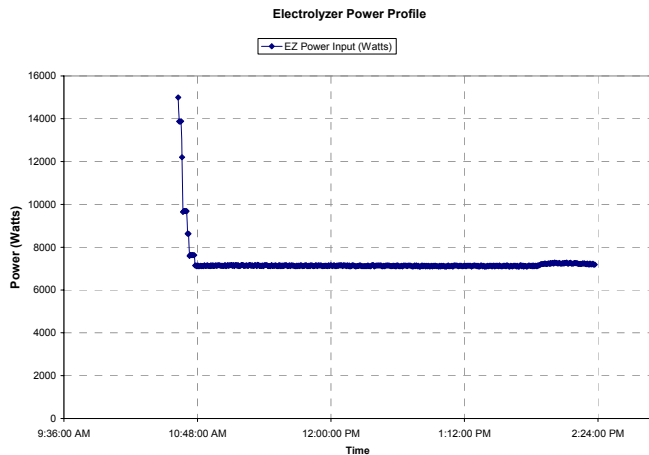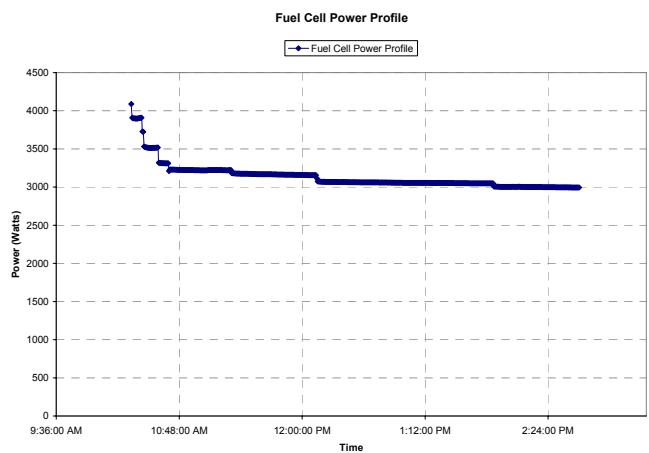
Figure 3.—Electrolyzer power profile.

Figure 5.—Electrolyzer polarization performance.

Figure 4.—Fuel cell power profile.
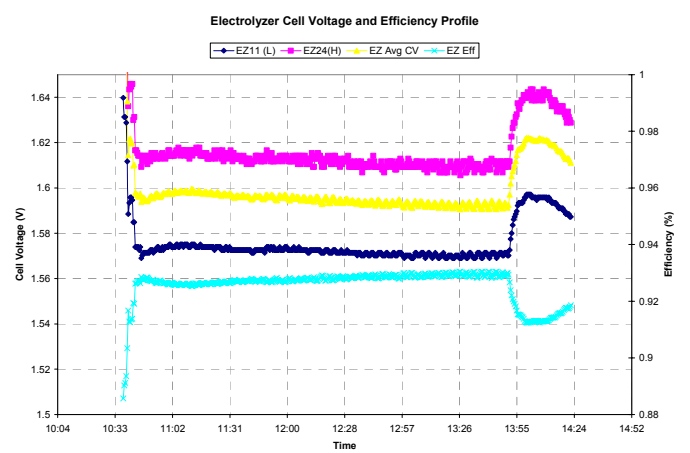
Figure 6.—Electrolyzer cell voltage and efficiency profile.

in figure 4. Integration of the area under this curve yields the total kilowatt-hours delivered by the RFCS during the fuel cell cycle. While discharging the reactant storage tank pressures from 190 to 90 psig the actual energy output from the RFCS was 13.73 kWhr.

The round trip efficiency (RTE) of the NASA GRC RFCS was calculated for this charge/discharge cycle which covered a pressure range of 100 psig. The total energy input to the system while the electrolyzer charged the reactant storage tanks was 27.23 kWhr. While discharging the reactant storage tanks the fuel cell was able to deliver 13.73 kWhr of energy. This resulted in RTE of 50.4 percent. Comparing the energy potential of the mass of hydrogen produced during electrolysis to the actual power delivered by the fuel cell yields a similar RTE. The electrolysis cycle produced 640 gms of hydrogen, which under ideal conditions could yield 25.42 kWhr of electrical energy. Despite the amount of potential energy available, the fuel cell was only able to deliver 13.73 kWhr of energy, resulting in a theoretically determined RTE of 54 percent.

Prior to beginning the charge cycle at de-rated power, the electrolyzer was ramped up to full power (to aid in getting the
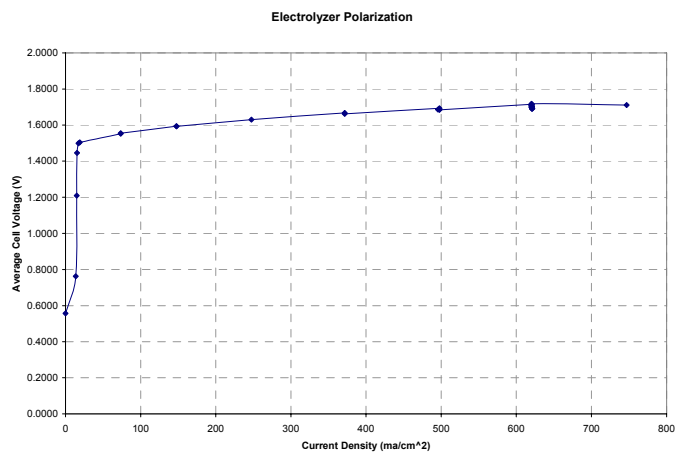
stack to its operating temperature) and a polarization plot was generated. This plot, shown in figure 5, was taken at a system pressure of 70 psig. The polarization data shown is not at constant temperature, but over a range of operating temperatures that rose from 68 to 115 °F as current was ramped up.

The average cell voltage of the electrolyzer throughout the charge cycle was 1.6 V which compared to the 1.48 V thermo neutral point, leads to an operating efficiency greater than 92 percent. Figure 6 shows the electrolyzer high, low, and average cell voltages along with the operating efficiency versus time.

Prior to beginning the discharge cycle at de-rated power the fuel cell was ramped up to full power (to aid in getting the stack to its operating temperature) and a polarization plot was generated. System pressure was 200 psig. Since the stack is actively cooled, the performance recorded was not at constant temperature but over a range of operating temperatures that varied from 68 to 140 °F roughly corresponding to load current applied. This polarization performance is shown in figure 7.
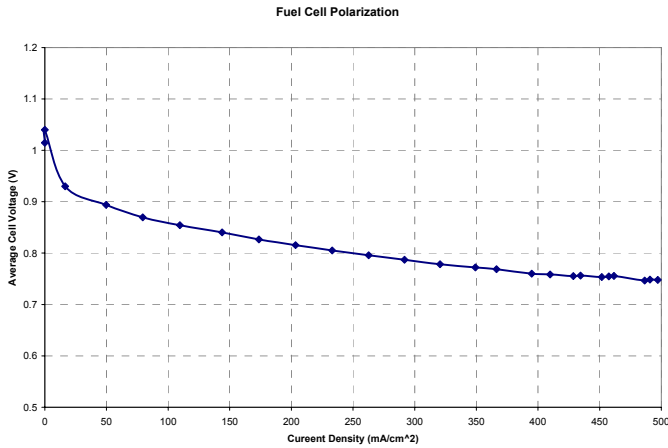
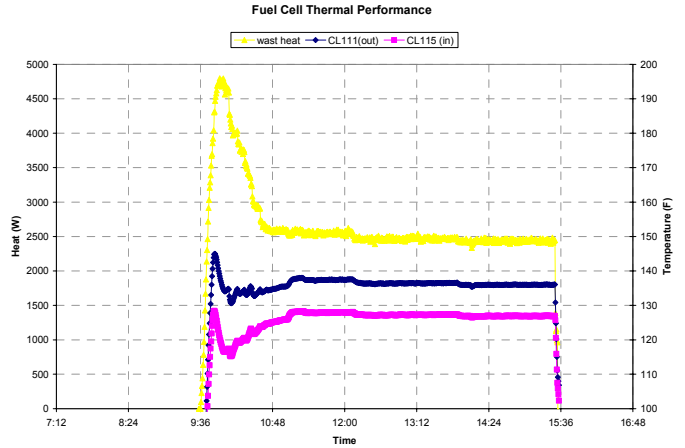Figure 7.—Fuel cell polarization performance.

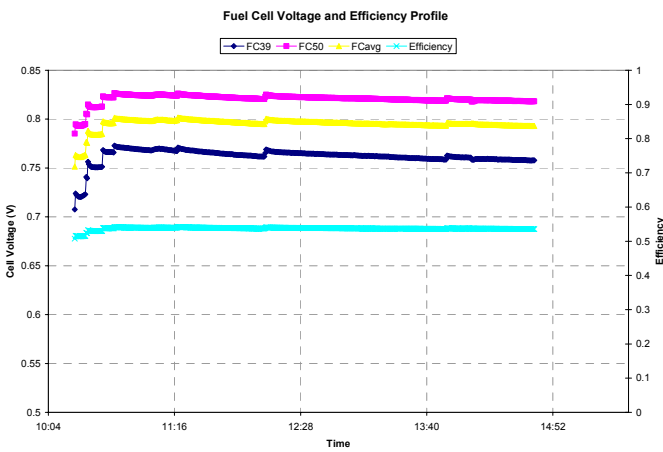Figure 9.—Fuel cell thermal performance.

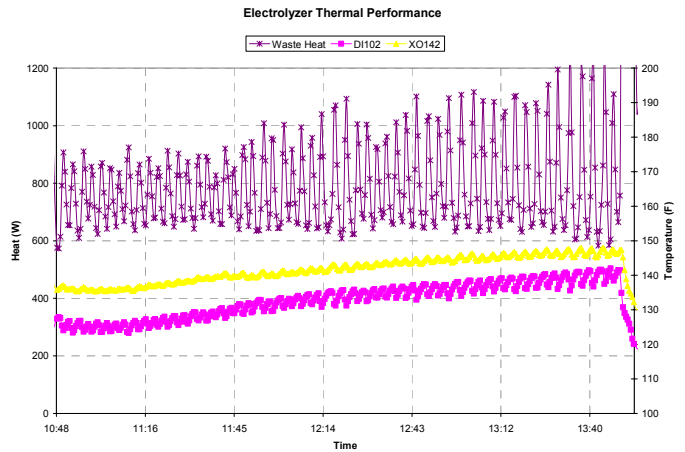Figure 8.—Fuel cell voltage and efficiency profile.

Figure 10.—Electrolyzer thermal performance.

During the discharge cycle a load current of 70 A was sustained, which corresponds to a stack current density of 350 mA/cm^2. The average cell voltage of the fuel cell throughout the discharge cycle was 0.80 V which, compared to the 1.48 V thermo neutral point, leads to an operating efficiency of 54 percent. Figure 8 shows the fuel cell high, low, and average cell voltages along with the operating efficiency versus time.

The change in Gibbs free energy and the change in enthalpy can be used to determine the maximum possible operating efficiency of the fuel cell; in this case the efficiency limit of the fuel cell was calculated to be 80 percent. Table 1 gives the thermodynamic values used to determine the efficiency limit, relative to the HHV, for a fuel cell operating at 135 °F.

TABLE 1

Form of water product	Temp (°F)	$\Delta \overline{h_f}$ $\dfrac{kJ}{mol}$	$\Delta \overline{g_f}$ $\dfrac{kJ}{mol}$	Max EMF (V)	EFF Limit
Liquid	135	−287	−231	1.20	80 %

The actual operating efficiency of the fuel cell, 54 percent, was much less than this ideal value because of voltage and current losses. The major factors that contribute to bringing down the open circuit and operating voltages of fuel cells are mass transport losses, ohmic losses, activation losses, and fuel crossover. It is evident from looking at the overall energy balance that the fuel cell was the major contributor to the overall system inefficiency. During fuel cell operation the irreversibility's mentioned above appear as waste heat.

Figure 9 shows the fuel cell coolant inlet and outlet temperatures during the discharge cycle. Also shown in the plot is the waste heat, calculated based on temperature rise and coolant flow rate. The amount of waste heat calculated accounted for the fuel cell inefficiency.

Figure 10 shows a similar plot for the electrolyzer. As expected from its higher operating efficiency, the amount of waste heat generated was much lower than that of the fuel cell.

For RTE comparison it is instructive to consider performance that was observed during a recent five day endurance run (ref. 5) where the electrolyzer input power profile was time-varied to duplicate the power delivery of a flat plate solar collector and the fuel cell was run at its maximum power. While charging the reactant storage tanks

during the endurance test, the electrolyzer operated with an efficiency between 88 and 92 percent, depending on the current input, which varied from 50 to 150 A. The fuel cell, drawing a constant current of 100 A, discharged the reactant storage tanks with an efficiency of 48 percent. In this case the fuel cell was operating at a current density of 500 mA/cm^2, and an average cell voltage of only 0.71 V per cell. This is 0.09 V less than the 0.80 V per cell observed during the efficiency run, when load current was limited to 350 A. For the five day endurance run the RTE of the system (operating over the same storage tank pressure range as the July 14th and 15th tests) was no better than 37 percent. Since the fuel cell stack was operating at a higher current density, the cell voltages were lower, resulting in a lower RTE.

Obviously, running the RFC system at maximum capacity without de-rating has the advantage of delivering more power, but the RTE suffers. However, efficiency often gets traded away in favor of reduced mass in aerospace applications.

Considering the entire charge/discharge cycle, the energy losses (hence, efficiency losses) can be attributed mainly to the fuel cell stack. These losses are exacerbated by running the stack at high current density in order to achieve rated power. This can be seen not only in the polarization curve (fig. 7) which shows the stacks average cell voltage, but also in the individual cell voltages which are captured in figure 11 and figure 12. Figure 11 is a snapshot of the stacks individual cell voltages taken during the five day endurance run, at a stack current of 100 A, which corresponds to a current density of 500 mA/cm^2. Figure 12 shows individual cell voltages at a stack current of 60 A, taken during the July 14th and 15th efficiency run. Here the stack current of 60 A corresponds to a current density of 300 mA/cm^2. When current density is reduced, the cell voltages are much higher and the performance is more stable with less variation in voltage from cell to cell. This implies getting more power from the RFCS while trying to maintain a system RTE greater than 50 percent with the current fuel cell stack will require an increase in active area. This can be achieved through increased cell count, more active area per cell, or both. Increasing active area enlarges the stack which means the RFCS will increase in size, cost, and weight correspondingly.

Conclusions

NASA Glenn performance measurements on the RFCS indicate that contemporary hydrogen-oxygen PEM hardware operating in the current density regime of 300 to 500 mA/cm^2 (fuel cell) and 500 to 900 mA/cm^2 (electrolyzer) can yield round trip energy storage efficiencies from 35 up to 50 percent. Reducing stack current density improves efficiency at the expense of power throughput, with the fuel cell being the most sensitive component subject to the greatest variation.
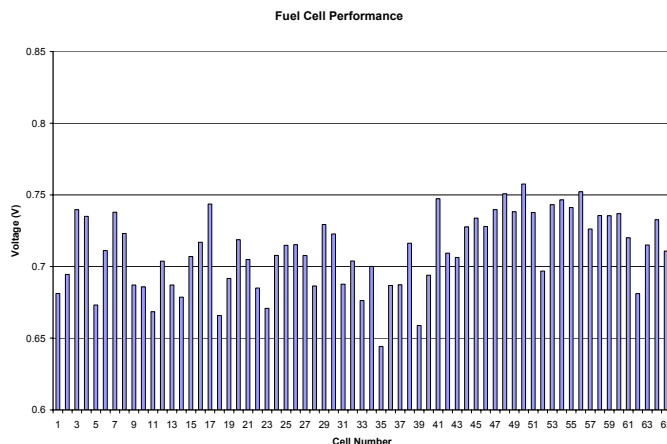

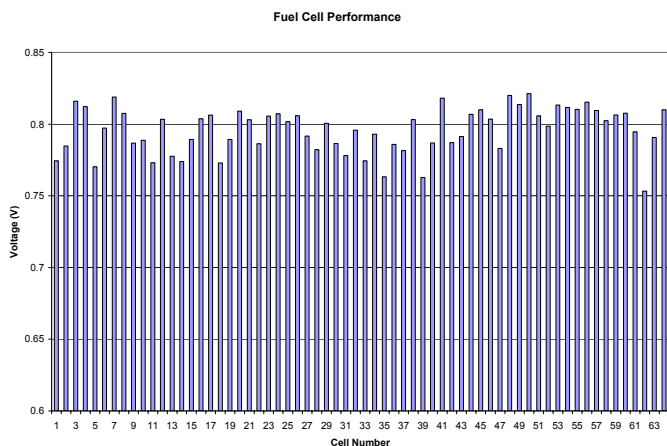Figure 11.—Fuel cell performance at 100 A, 65 psig, and 135 °F.

Figure 12.—Fuel cell performance at 60 A, 65 psig, and 135 °F.

In the future the fuel cell stack will be replaced with more advanced stacks to achieve higher round trip efficiencies. The system has also recently completed a contiguous five-cycle endurance demonstration at rated pressure and power (ref. 5). Future plans include fully autonomous operation and demonstration of tens of charge/discharge cycles. Currently, the RFCS is programmatically part of the NASA Low Emissions and Alternative Power (LEAP) Program to further develop aerospace regenerative fuel cells for high altitude applications and as a surface power source for planetary missions.

Reference

1. D.J. Bents, V.J. Scullin, B.J. Chang, D.W. Johnson, and C.P. Garcia "Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System," 2004 Fuel Cell Seminar, San Antonio, TX, Nov. 1–5, 2004, NASA/TM—2005-213381.

2. V.J. Scullin, D.J. Bents, et al, "Closed Loop H2/O2 Fuel Cell Test Facility at NASA Glenn," Proc. Hydrogen and Fuel Cell Futures Conference," Perth, Australia, Sept. 12–15, 2004.

3. B.J. Chang, D.W. Johnson, C.P. Garcia, I.J. Jakupca, V.J. Scullin, and D.J. Bents "Regenerative Fuel Cell Test Rig at Glenn Research Center," Proc. First International Energy Conversion Engineering Conference (AIAA, ASME, IEEE), Portsmouth, VA, Aug. 17–21, 2003, AIAA–2003–5942, NASA/TM—2003–212375.

4. D.J. Bents, V.J. Scullin, B.J. Chang, D.W. Johnson, and C.P. Garcia "PEM Hydrogen-Oxygen Regenerative Fuel Cell at NASA Glenn Research Center," Proc. 8th ANSE Electrochemical Power Sources R&D Symposium, Portsmouth, VA, July 21–24, 2003.

5. D.J. Bents, V.J. Scullin, J.E. Freeh, D.A. Jacqmin, B.J. Chang, D.W. Johnson, C.P. Garcia, and I.J. Jakupca "Regenerative Fuel Cell Development at NASA Glenn Research Center," to be presented at 2005 Fuel Cell Seminar, Palm Springs, CA Nov. 14–15, 2005.

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NASA Glenn Research Center (GRC) has recently demonstrated a Polymer Electrolyte Membrane (PEM) based hydrogen/oxygen regenerative fuel cell system (RFCS) that operated for a charge/discharge cycle with round trip efficiency (RTE) greater than 50 percent. The regenerative fuel cell system (RFCS) demonstrated closed loop energy storage over a pressure range of 90 to 190 psig. In charge mode, a constant electrical power profile of 7.1 kWe was absorbed by the RFCS and stored as pressurized hydrogen and oxygen gas. In discharge mode, the system delivered 3 to 4 kWe of electrical power along with product water. Fuel cell and electrolyzer power profiles and polarization performance are documented in this paper. Individual cell performance and the variation of cell voltages within the electrochemical stacks are also reported. Fuel cell efficiency, electrolyzer efficiency, and the system RTE were calculated from the test data and are included below.

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