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Hydrogen-Oxygen PEM Regenerative Fuel Cell Development at the NASA Glenn Research Center

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Abstract

The closed-cycle hydrogen-oxygen PEM regenerative fuel cell (RFC) at the NASA Glenn Research Center (NASA Glenn) has successfully demonstrated closed cycle operation at rated power for multiple charge-discharge cycles. During charge cycle the RFC has absorbed input electrical power simulating a solar day cycle ranging from zero to 15 kWe peak, and delivered steady 5 kWe output power for periods exceeding 8 hr. Orderly transitions from charge to discharge mode, and return to charging after full discharge, have been accomplished without incident. Continuing test operations focus on:

(1) Increasing the number of contiguous uninterrupted charge discharge cycles
(2) Increasing the performance envelope boundaries
(3) Operating the RFC as an energy storage device on a regular basis
(4) Gaining operational experience leading to development of fully automated operation
(5) Developing instrumentation and in situ fluid sampling strategies to monitor health and anticipate breakdowns

Introduction

The RFC is beginning to demonstrate its potential as an energy storage device for aerospace solar power systems such as solar electric aircraft, lunar and planetary surface installations; any airless environment where minimum system weight is critical.

The closed-cycle hydrogen-oxygen PEM regenerative fuel cell (RFC) at the NASA Glenn Research Center (Refs. 1 and 2) has successfully demonstrated closed cycle operation at rated power for multiple charge-discharge cycles. During charge cycles the RFC absorbed input electrical power simulating a solar day cycle ranging from zero to 15 kWe peak. During discharge cycles it delivered steady 4.5 to 4.8 kWe output power for periods exceeding 8 hr. Orderly transitions from charge to discharge mode, and return to charging after full discharge, were accomplished without incident. Continuing test operations focus on:

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(5) Developing instrumentation and in situ fluid sampling strategies to monitor health and anticipate breakdowns

Table 1 presents a summary of test experience from August 2004 (date of last Fuel Cell Seminar publication) to the end of July 2005. In this table, "Power Absorbed" is the range of power levels sustained by the electrolyser in charging mode, and "Power Delivered" is the range of output powers delivered by the fuel cell stack and ancillaries during discharge mode. In the charge/discharge cycle tests, the electrolyser was normally driven by a power profile that approximates electrical output of a flat plate solar collector (hence the zero to 15 kWe peak), while the fuel cell was operated to deliver the maximum output power that could be sustained. The "longest elapsed run time" is defined as the longest elapsed time period during these tests that the RFC operated as an energy storage system uninterrupted for any reason other than orderly startup, shutdown or transitions between modes. For example, the test run of March 9–29, 2005, shown in Figure 1, reports a longest elapsed run time of 70 hr. This run contained two complete charge/discharge cycles which were carried out over a two week period, where electrolysis was accomplished in segments using a 4.5 kWe short stack. The segments were not contiguous but interrupted by normal (end of working day) shutdowns. The system however, was capable of resuming operation at any time during the shutdown period, hence the accumulation of elapsed hours from one segment to the next (elapsed hour accumulations ended when a test segment got curtailed).

TABLE 1.—NASA CLOSED CYCLE RFC TESTING SUMMARY AUGUST 2004 TO JULY 2005

Date(s) of Test	Test Objectives	Power absorbed	Power delivered	Longest elapsed run	Test Curtailed By:
Aug 3 - 4, 2004	Charge/Discharge cycles + transitions	2.1 - 11 kWe	4.5 - 4.8 kWe	21 hr	Pressure spike causes EZ stack failure
Oct 22 - 25, 2004	Non-venting Cell flooding prevention	(EZ stack not used)	3.0 - 4.5 kWe	2.5 hr	Cell flooding, vent/purge req'd
Nov 30 - Dec 1, 2004	New EZ short stack performance tests	zero to 6 kWe	(FC stack not used)	10 hr	Successful outcome
Dec 8 - 10, 2004	Charge/Discharge cycles, new EZ stack	zero to 15 kWe	4.5 - 4.8 kWe	9 hr	FC stack crossover
Dec 16 - 17, 2004	Multiple Chge/Dischge cycles + transitions	zero to 15 kWe	(FC stack not used)	10 hr	Computer SW platform failure
Feb 14 - Mar18, 2005	Safety Improvements new software checkout	3.2 - 4.5 kWe	2.5 - 4.5 kWe	8 hr	Successful Outcome
Mar 9 - 29, 2005	Charge/Discharge cycles + transitions	4.5 kWe	4.8 kWe	70 hr	Recirculation pump failures
May 2 - 5, 2005	Multiple Chge/Dischge cycles + transitions	6 kWe	3.2 kWe	4 hr	EZ stack failure (bad cell)
May 17-20, 2005	Multiple Chge/Dischge cycles + transitions	zero to 15 kWe	4.5 kWe	7 hr	FC stack cell flooding
June 21 - July 1, 2005	Multiple Chge/Dischge cycles + transitions	zero to 15 kWe	4.5 - 4.8 kWe	149 hr	Successful outcome

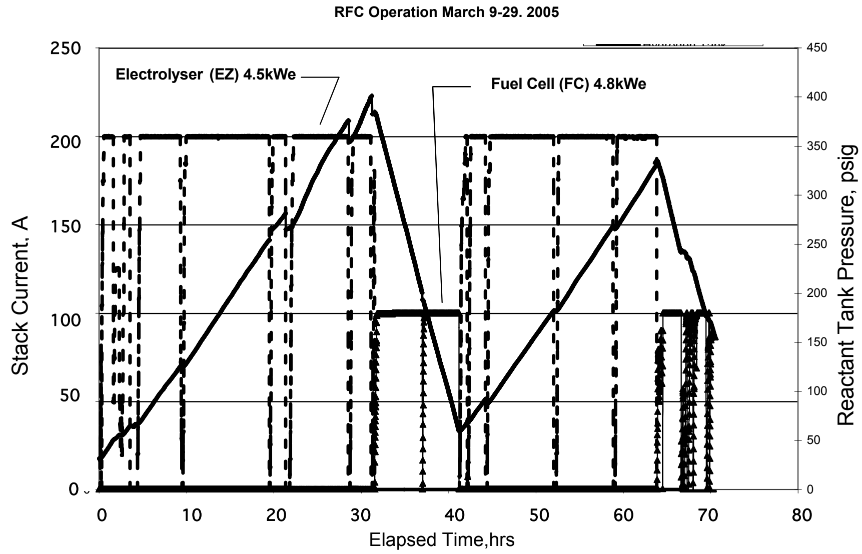

Figure 1.—NASA closed cycle RFC testing March 9–29, 2005.

Although the majority of the tests logged in Table 1 were curtailed by failures, the failures spawned hardware and software improvements which eventually rendered the system capable of longer operations at rated power. These improvements included: (1) methods to isolate and remove inert contaminants from the stack, thereby reducing to zero the amount of venting/purging that is required; (2) balanced void volumes within the recirculation loops, and carefully timed valves and orifices to minimize differential pressure swings due to mode transitions and reactant recombination; (3) "Fuzzy Logic" automated control for rapid power transitions while maintaining equilibrium within the fuel cell stack and recirculation loops (faster ramp up than a human operator); and (4) control strategies to identify and respond to individual cell dropoffs in an appropriate and timely manner (i.e., distinguish between flooding, dryout or inert contamination) leading to development of fully automatic controls.

A significant development milestone was achieved during the test series June 24 to July 1 when the RFC was operated for seven complete charge/discharge cycles without failure. Five of these cycles were run continuously over an uninterrupted 120 hr period, from June 26 to July 1. These five contiguous back-to-back charge/discharge cycles at full power, with transitions, are shown in Figure 2.

During charge cycles the RFC absorbed daytime solar electrical current profiles of 0 to 15 kWe storing the energy as pressurized hydrogen and oxygen gas. The RFC delivered back the stored energy during discharge as steady 4.5 to 5 kWe electrical power. Electrical energy delivered during each cycle ranged from 38 to 40 kW/hr. Full power was sustained during both charge and discharge modes throughout the duration of test demonstrating maximum system performance. Smooth transitions at the end of the electrolysis (charge) cycle to fuel cell (discharge) mode were repeatedly accomplished, and smooth transitions at the end of discharge (fuel cell) mode back to charge mode (electrolysis) were repeated. At the conclusion of testing the hardware remained fully capable of repeating another charge/discharge cycle without servicing or intervention. The RFC demonstrated fully closed cycle operation during the test period (hermetically sealed system, nothing goes in, nothing goes out other than electrical power and heat). Reactant inventory (water) losses measured at the end of the test period (seven full charge/discharge cycles including the five contiguous back-to-back cycles) were less than 1 percent.

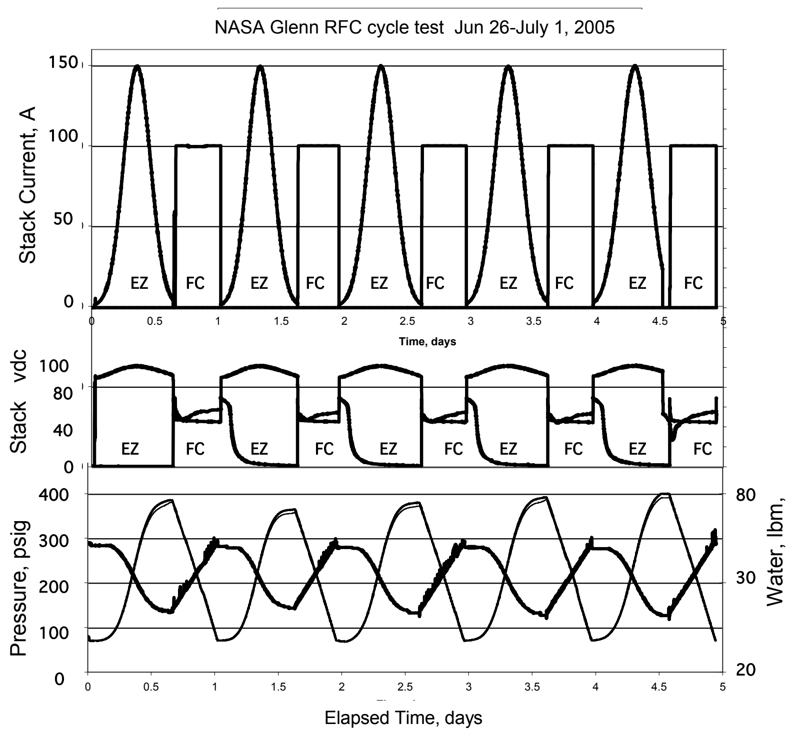

Figure 2.—NASA closed cycle RFC testing June 26 to July 1, 2005.

Figure 2 summarizes system performance over the five days operation. In the topmost plot "Stack Current," the $\sin^2$-shaped trace represents electrolyser current applied during charge (day) cycle, which is followed by a square wave shaped trace that represents fuel cell output current during the discharge (night) cycle, plotted over the entire five day period. The day/night cycle applied was 16/8 hr, respectively, roughly corresponding to local summertime day/night conditions. In the middle plot, the top trace is electrolyser stack voltage, while the lower trace is the fuel cell stack voltage. Note how stack voltages idle to open circuit then fall during recombination. The RFC system ran completely sealed closed cycle over the five day period (no venting no purging). The bottom plot depicts overall reactant balance over the five days, coincident with the power profiles. The wide amplitude traces correspond to (oxygen and hydrogen) reactant tank pressures, while the smaller amplitude trace corresponds to pounds of water remaining, as measured by the oxygen phase separator tank level. Water inventory is minimum when reactant tank pressures are at their peak. As hydrogen and oxygen are consumed the water level rises. Note how water level at the end of the five days is just about the same as it was in the beginning. Since the fuel cell stack was operating at maximum current during these tests, overall system round trip energy storage efficiency was less than 50 percent. This demonstration fulfilled NASA's Low Emissions Alternative Power Aircraft Fuel Cell Power System Regenerative Fuel Cell (LEAP AFCPS RFC) Task FY05 milestone criteria "Demonstrate repeatable system performance over multiple (4 to 10) repeated contiguous charge/discharge cycles" thus confirming the RFC's potential as an energy storage device for aerospace solar power systems such as solar electric aircraft, lunar and planetary surface installations; any airless environment where minimum system weight is critical.

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The closed-cycle hydrogen-oxygen PEM regenerative fuel cell (RFC) at the NASA Glenn Research Center has successfully demonstrated closed cycle operation at rated power for multiple charge-discharge cycles. During charge cycle the RFC has absorbed input electrical power simulating a solar day cycle ranging from zero to 15 kWe peak, and delivered steady 5 kWe output power for periods exceeding 8 hr. Orderly transitions from charge to discharge mode, and return to charging after full discharge, have been accomplished without incident. Continuing test operations focus on: (1) Increasing the number of contiguous uninterrupted charge discharge cycles; (2) Increasing the performance envelope boundaries; (3) Operating the RFC as an energy storage device on a regular basis; (4) Gaining operational experience leading to development of fully automated operation; and (5) Developing instrumentation and in situ fluid sampling strategies to monitor health and anticipate breakdowns.

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