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Teledyne Energy Systems, Inc., Proton Exchange Member (PEM) Fuel Cell Engineering Model Powerplant

Test Report: Initial Benchmark Tests in the Original Orientation

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August 2011

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1.0 PEM Fuel Cell Engineering Model (EM) Powerplant

Proton Exchange Membrane (PEM) fuel cell technology is the leading candidate to replace the aging alkaline fuel cell technology, currently used on the Shuttle, for future space missions. This test effort marks the final phase of a 5-yr development program that began under the Second Generation Reusable Launch Vehicle (RLV) Program, transitioned into the Next Generation Launch Technologies (NGLT) Program, and is now continuing under Constellation Systems in the Exploration Technology Development Program. This report details initial performance evaluation test results of the EM in its original orientation as shipped by the manufacturer. The specifics of these different tests are described in the following sections.

1.1 Description

The Teledyne Proton Exchange Membrane (PEM) Fuel Cell Engineering Model (EM) Powerplant consists of a water-cooled, hydrogen/oxygen PEM fuel cell stack along with supporting ancillaries and a separate control/data acquisition system (Figure 1).

The fuel cell stack is comprised of 117 individual cells divided into three subsections. Each subsection is comprised of 39 cells in a series configuration. The three subsections are connected in a parallel configuration. The fuel cell stack was designed to deliver between 2 and 12 kW of power within voltage regulation range of 33 to 27 VDC. The Fuel Cell product water is removed from the stack using recirculation pumps and gravity independent water separators and rejected outside of the powerplant. Waste heat is removed from the stack via an internal cooling loop. The powerplant cooling system in turns rejects the heat to a facility cooling system external to the powerplant. Additional powerplant design goals are outlined in Table 1.

2.0 Test Summaries

The stability, performance, life, gravity independence and response time of the Teledyne Engineering Model Powerplant were evaluated using a series of tests under three physical orientations. These performance tests were conducted upon the Teledyne Engineering Model Powerplant to assess performance and stability over conditions anticipated to be encountered during operation under mission scenarios. Initial evaluation tests were conducted under the standard “A” orientation, as seen in Figure 1, to form a baseline performance metric. The results of these tests are described in this paper. A brief description of each test type follows below. Detailed information regarding operating parameters of each test is included in the Appendix A.

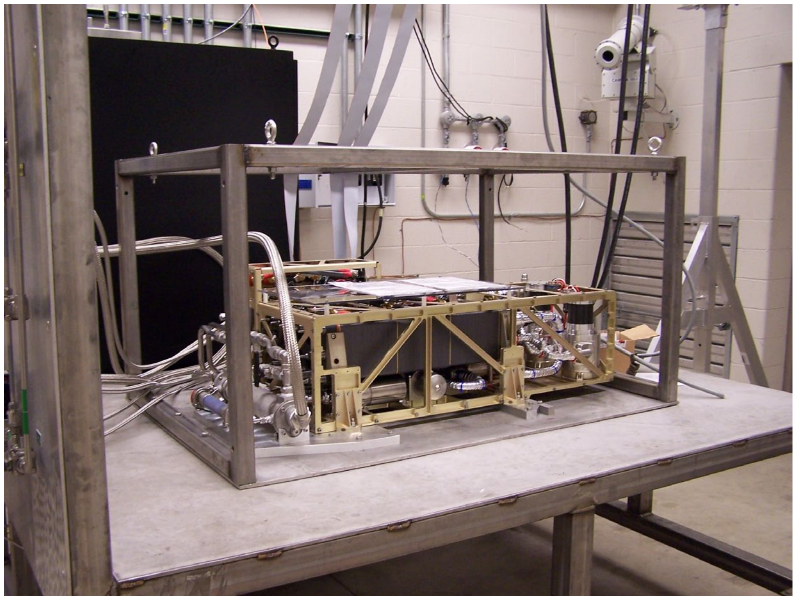

Figure 1.—Teledyne PEM fuel cell EM Powerplant in its original orientation.

TABLE 1.—ENGINEERING MODEL DESIGN GOALS

Engineering Model Design Goals	Verification Method
Produce 2 to 12 kW of electrical power within a voltage range of 33 to 27 VDC	All tests
Gravity/orientation independent operation	Operation under three physical orientations
Maintenance free operation for 3000 hr	All tests
90% of the final change in voltage after a change in load shall occur within 0.2 sec	Performance load profile calibration series
The power plant shall be capable of automatic startup to 3 kW in less than 5 sec if reactants are present, initial stack temperature is greater than 40 °F and no inerts are present.	50% of capability test
The power plant shall be capable of shutdown in less than 1 min	All tests
The power plant shall be capable of operating on propellant grade (MIL PRF-27201C) and higher purity hydrogen and propellant grade (MIL PRF-25508F) and higher purity oxygen.	All tests
Operating Life shall be greater than 3000 hr	All tests
Powerplant shall be capable of operation for 9 min at 5 kW without cooling from a secondary coolant loop	Loss of coolant test
The powerplant shall be capable of a minimum of 250 start/stop cycles	All tests

2.1 Calibration Series Test

The Calibration Series Test was a reference test for the Engineering Model. The series is comprised of a Polarization Test and an abbreviated version of the Performance Load Profile Test. This test was performed at specified intervals during the evaluation of the Engineering Model at Teledyne, the NASA Glenn Research Center (GRC) and the NASA Johnson Space Center (JSC). The Calibration Series Test was used to quantify performance changes of the Engineering Model as a function of shipping, orientation effects, and damage as a result of testing and age. Voltage transitions were recorded at a rate of 200 kHz during the transition from 51 to 357 A and again at the transition from 357 to 51 A.

2.2 Performance Load Profile Test

The Performance Load Profile Test was a benchmark test for the Engineering Model. This test was used to evaluate the performance of the Engineering Model under different operational conditions, i.e., orientation, vibration, etc. The Performance Load Profile Test was carried out at Teledyne and GRC. Voltage transitions were recorded at a rate of 200 kHz during the transition from 51 to 357 A and again at the transition from 357 to 51 A.

2.3 Fifty Percent of Capability Test

The Fifty Percent of Capability Test was an evaluation of the speed of the response of the Engineering Model to loads after rapid start-up. The Engineering Model was started using the rapid start-up procedure, which includes purging the unit of nitrogen and introduction of reactants but does not include a warm-up of the powerplant. Under normal start-up conditions, the powerplant is pre-warmed to 45 °C prior to applying a power load. Within 5 sec of the start, the powerplant must be able to respond to a load app. 50 percent of the rated power. After completion of this test, the powerplant was shutdown and restarted using the normal start-up procedure for the remainder of the day’s testing.

3.0 Test Results

3.1 Teledyne and GRC Acceptance Tests

Prior to delivery of the Engineering Model to the GRC, two acceptance tests were performed upon the unit at the Teledyne facility; a Calibration Series Test and Performance Load Profile Test. These tests were then repeated at the GRC Fuel Cell Test Laboratory (FCTL). The power load profiles applied (current drawn) during the two tests were identical at both facilities. As can be seen from Figure 2, the Calibration Series Tests performed at the two facilities were quite similar. The saw tooth pattern evident in the GRC data was the result of intermittent venting of impurities built up in the powerplant system. The powerplant was designed to operate “deadheaded” the majority of time, as the reactants were consumed the impurity concentration increased in the system. These impurities acted as a diluent to the reactants. As the impurity concentration in the system increased, the system performance reversibly degraded until the impurities were vented from the powerplant system. The powerplant impurity vent timing could be adjusted to reflect the purity of the incoming reactants. The lower the purity of the incoming reactant gases, the more frequently the vent was required. One of the design goals of the powerplant was operation under propellant grade reactants. This design goal enables the powerplant to share reactants from the propellant system rather than carrying reactants and tanks dedicated to the power subsystem. By eliminating the need for separate reactant tanks, this feature will result in significant mass savings. The reactant gases utilized at the GRC facility were propellant grade, a lower purity level than those used at the Teledyne facility.

GRC	O_2 = 99.5 percent
	H_2 = 99.997 percent
Teledyne	O_2 = 99.87 percent
	H_2 = 99.96 percent

The most significant difference observed in the tests at the two facilities occurred in the first half of the polarization curve. During the test at GRC, the stack voltage during the first half of the polarization curve was lower than that observed at Teledyne. However, during the second half of the polarization curve and for the remainder of the test, the stack voltages observed at the two facilities were nearly identical. The depressed voltage observed at the initiation of the Calibration Series Test was likely due to minor drying of the fuel cell stack. Approximately one month elapsed between the acceptance tests at Teledyne and the initiation of testing at GRC. During that time the powerplant was removed from the Teledyne test facility, shipped to GRC and installed in the GRC FCTL. It is likely during the time required for shipment and installation, the fuel cell stack dried out slightly resulting in a lower voltage at the initiation of the test. Shortly into the Calibration Series Test (app. 30 to 40 min), the stack had rehydrated and the stack voltage recovered to the levels observed at the Teledyne facility.

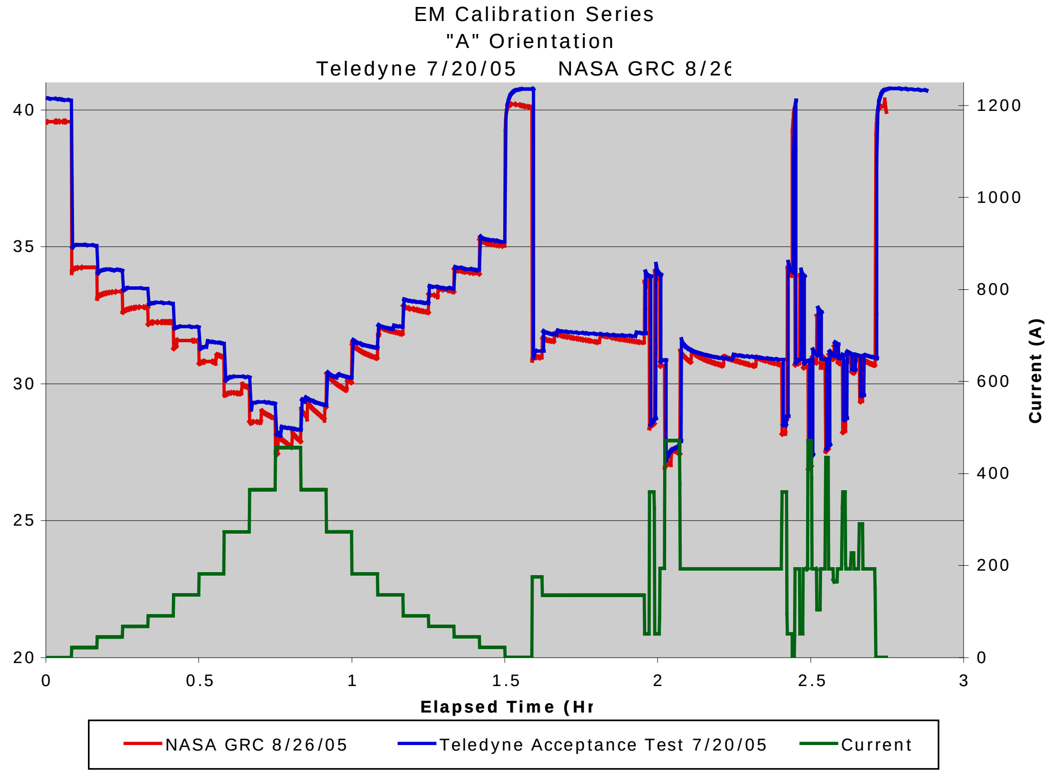

Figure 2.—Comparison of Teledyne Acceptance Calibration Series test with initial GRC Calibration Series test.

As can be seen from Figure 3, the Teledyne Engineering Model Powerplant has not met the design goal to produce 2 to 12 kW of electrical power within a voltage range of 33 to 27 VDC. At 2.28 kW, the stack voltage was 33.509 V and at 12.97 kW of electrical power, the stack voltage was 28.4 V. At higher power loads, the powerplant operates within the voltage range. However, at power loads below 3 kW, the fuel cell stack voltage was higher than 33 V. As a result, some voltage regulation would be required during mission operations.

As can be seen in Figure 4, the Performance Load Profile Tests performed at the Teledyne facility and the GRC FCTL were also quite similar. Again, the saw tooth pattern observed in the GRC data was a result of build-up and release of reactant impurities as was observed in the Calibration Series Test. The stack voltages observed at both facilities were nearly identical.

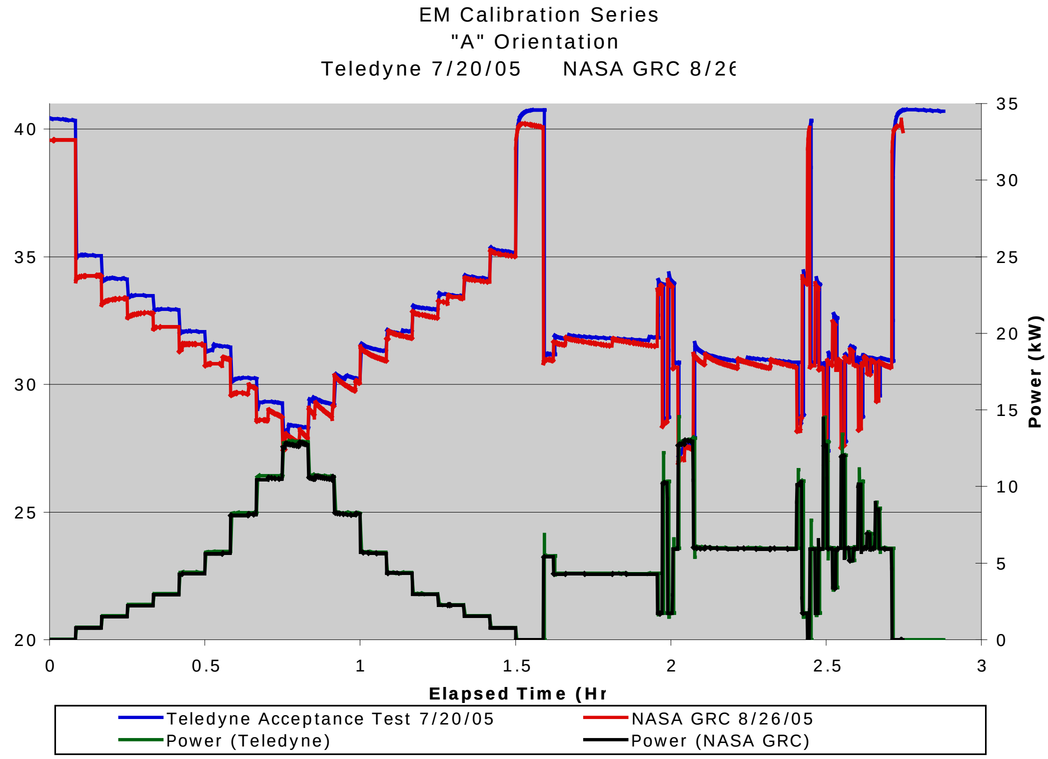

Figure 3.—Comparison of Teledyne Acceptance Calibration Series test with initial GRC Calibration Series test. Stack voltage at various power levels.

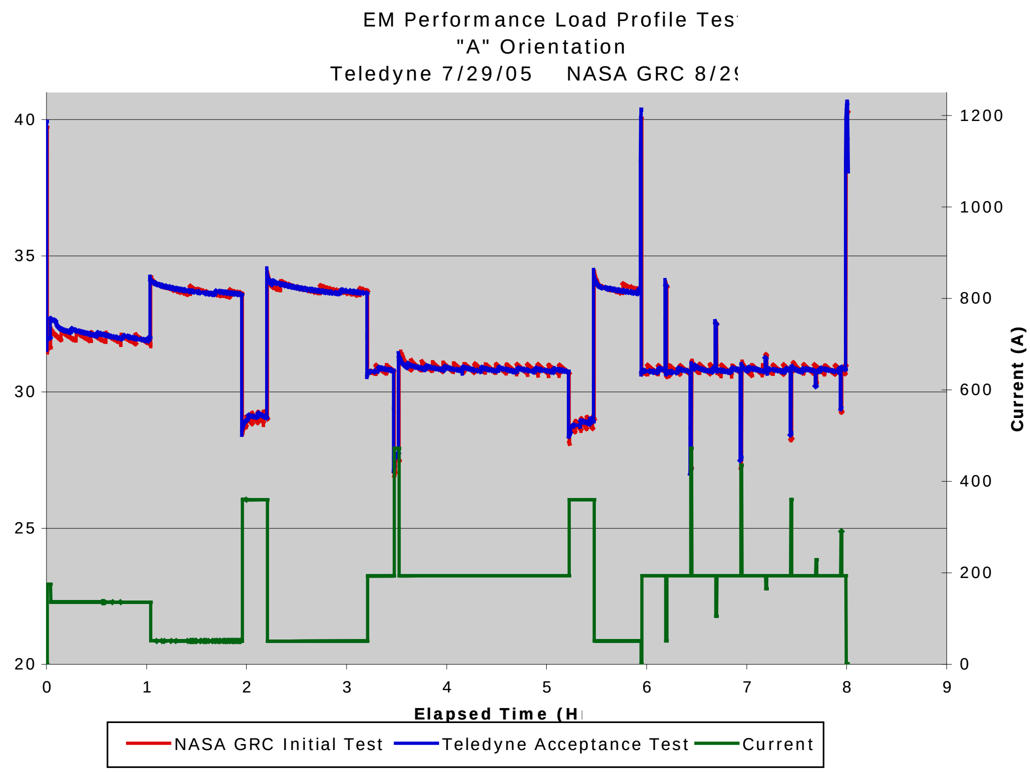

Figure 4.—Comparison of Teledyne Acceptance Performance Load Profile test with initial GRC Performance Load Profile test.

3.2 Transient Response of the Powerplant to Changes in Load

During the course of the Calibration Series Test and Performance Load Profile Test, the response of the powerplant to changes in load was monitored at two points during the test: (1) from an applied load of 51 to 357 A (Figure 5) and (2) from 357 to 51 A (Figure 6). A high-speed data acquisition system operating at 200 kHz was employed to monitor the applied load current and the stack voltage during these transitions. As can be seen in Figure 5, during the transition from 51 to 357 A, the electronic load initially overshoots the requested current, but stabilized quickly. The fuel cell stack voltage followed the load current but also overshot and followed a ringing pattern until it stabilized in less than 2 msec. The cause of the fuel cell stack voltage overshoot and ringing pattern is unknown. It could be due to pressure swings within the fuel cell stack caused by changes in reactant consumption, changes in flow rates of some type of electrical interference in the signal, although this was not observed in the current signal. Currently the cause is unknown, but the phenomenon lasted less than 2 msec.

As can be observed in Figure 5, the stack voltage continued to decrease after the ringing pattern subsided. The reactant flow rates did not change when the power load was changed from 51 to 357 A. However, the reactant consumption rate did change. Therefore, the stoichiometry of the reactant delivery to the fuel cell stack changed. At 51 A, the calculated hydrogen and oxygen stoichiometry was 14.8 and 28.5, respectively. At 357 A, the calculated hydrogen and oxygen stoichiometry was 3 and 5 respectively. At the higher power load (higher current), the reactant flow rate through the fuel cell stack was reduced relative to the lower power load (lower current). Product water was removed from the stack via reactant flow rates higher than required by the power demand. Therefore, when the power demand increased and the reactant flow rates did not, product water was not removed from the stack as well. The slight reduction in stack voltage over a few milliseconds was likely the result of a change in the product water remaining in the stack; i.e., a slight increase in resident product water will result in a slight decrease in the stack voltage.

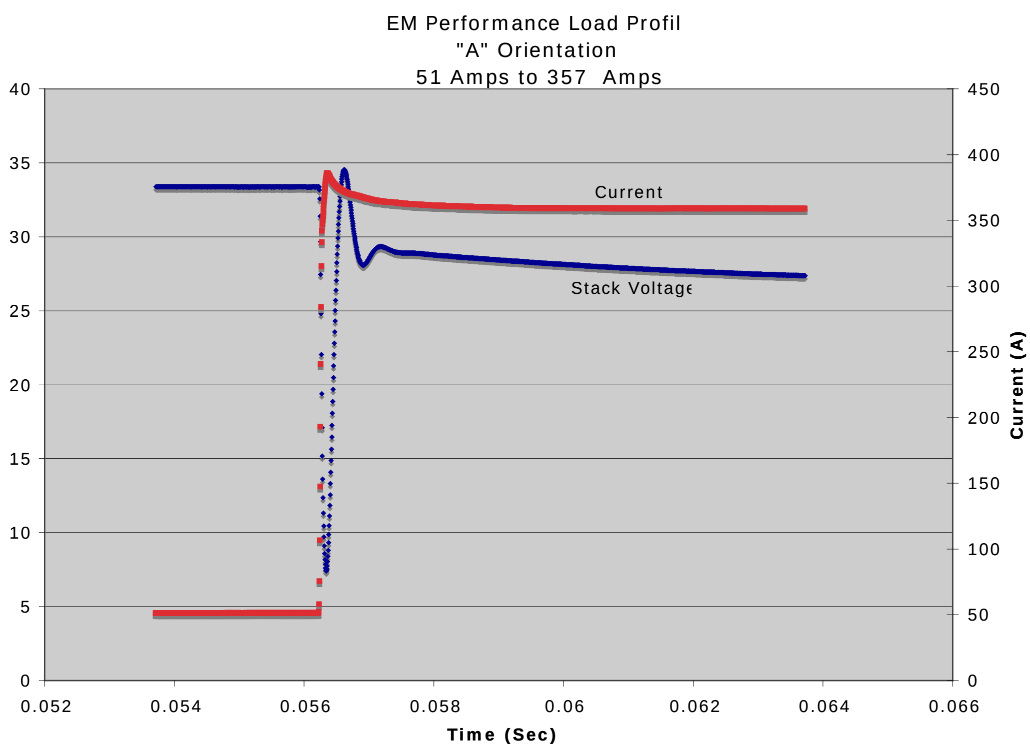

Figure 5.—Observation of the voltage response of the EM Powerplant during the transition from 51 to 357 A.

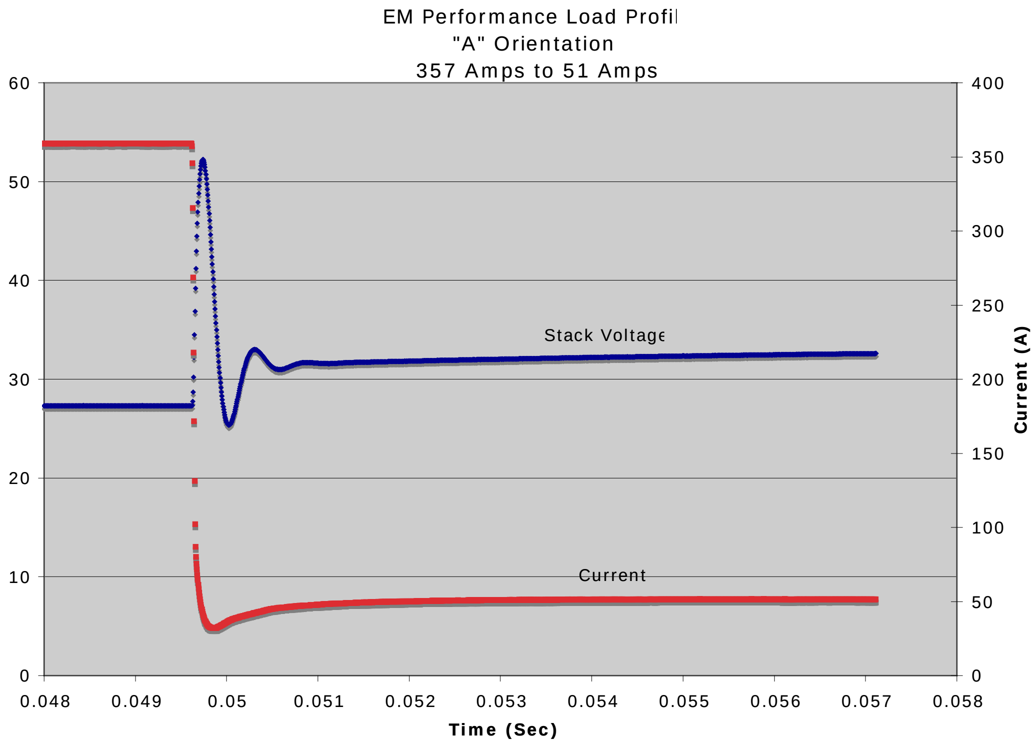

Figure 6.—Observation of the voltage response of the EM Powerplant during the transition from 357 to 51 A.

As can be seen in Figure 5, after approximately 8 msec, the stack voltage reached 27.4 V. The final voltage observed after this transition was 29.1 V. Therefore, the powerplant reached greater than 90 percent of the final voltage within 8 msec. The powerplant met the design requirement that the 90 percent of the final change in voltage after a change in load should occur within 2 sec.

During the transition from 357 to 51 A, the powerplant again responded and stabilized rapidly, as can be viewed in Figure 6. During the transition to a lower power draw (51 A), the stack voltage continued to increase slightly before stabilizing as discussed before, the reactant stoichiometry again changed, this time going to a higher level. As a result, more product water was being removed from the stack which resulted in a slightly higher stack voltage.

As can be seen in Figure 6, after approximately 8 msec, the stack voltage was 32.6 V. The final voltage observed after this transition was 33.7 V. Therefore, the powerplant reached greater than 90 percent of the final voltage within 8 msec. Again, the powerplant met the design requirement that 90 percent of the final change in voltage after a change in load should occur within 2 sec.

3.3 Calibration Series Tests

As discussed previously, the Calibration Series Test was a reference test of the performance of the powerplant over time and after any system modifications, repairs or relocations. During this initial series of benchmark tests in the "A" orientation, it was not likely that changes in the performance of the powerplant occurred as a result of degradation or age between the two Calibration Series Tests. Only four days and a run time of approximately 12 hr had elapsed. However, as can be seen in Figure 7, slight differences were evident in the Calibration Series Tests collected on August 26, 2005, and August 30, 2005. All controllable test conditions were the same for both test runs; however, small variations of the operational conditions were possible. In order to determine the cause of the variance between the two test runs, the operating conditions for each test run were evaluated.

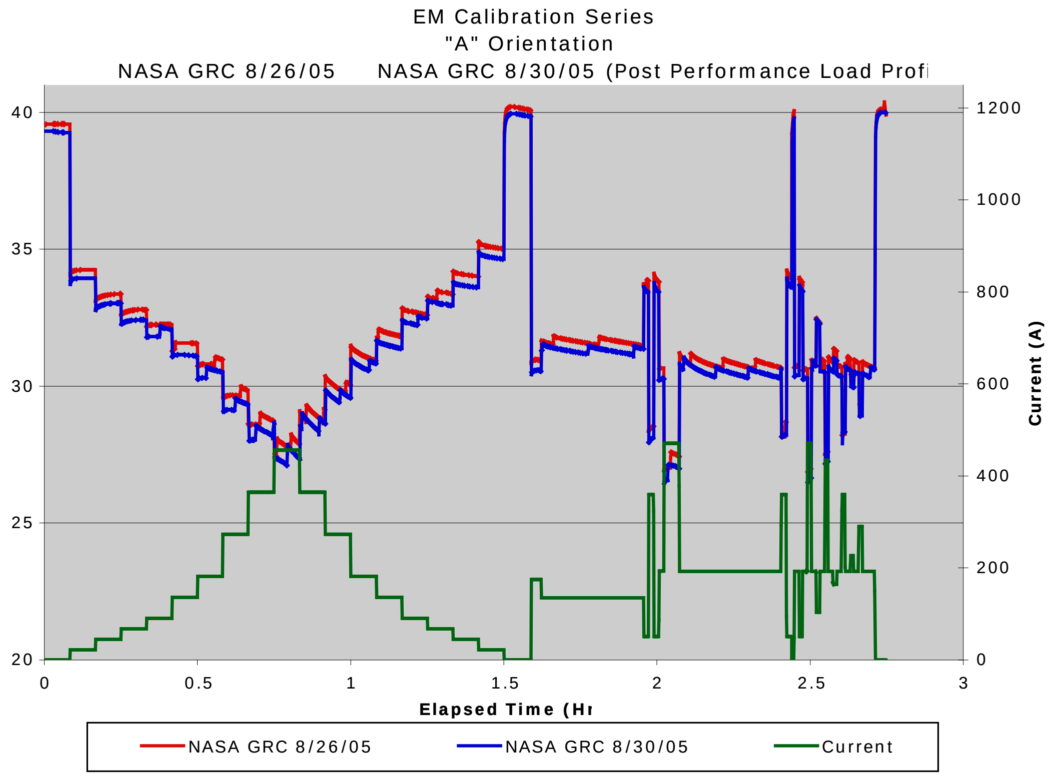

Figure 7.—Comparison of the Calibration Series test in the "A" orientation before and after the Performance Load Profile test.

Fuel cell performance is dependent upon the temperature at which the reaction occurs with a higher temperature enhancing performance. At the GRC FCTL, hydrogen and oxygen reactants were stored outside of the test facility in tube trailers. The temperature of the reactants as they enter the test facility can vary depending upon the outside ambient temperature. As can be seen in Figure 8 and Figure 9, the hydrogen and oxygen inlet temperatures observed varied slightly between run days. The fuel cell powerplant was primarily operated "dead-ended", therefore hydrogen and oxygen are only added to the powerplant to replace the reactants consumed in the fuel cell reaction. The remainder of the reactant gas that is unconsumed was recirculated throughout the powerplant. The outlet reactant gas temperature was a good measure of the temperature within the fuel cell stack. As can be seen in Figure 8 and Figure 9, the outlet temperature of reactant gases closely followed the load applied to the fuel cell powerplant. As the load was increased, the efficiency of the fuel cell reaction decreased, resulting in the generation of more waste heat. This waste heat is partially removed from the fuel cell stack via the exiting reactant gases. The hydrogen and oxygen temperatures, as they exited the fuel cell stack, were nearly identical between the two days. Therefore, the differences in performance were not a result of reactant temperature.

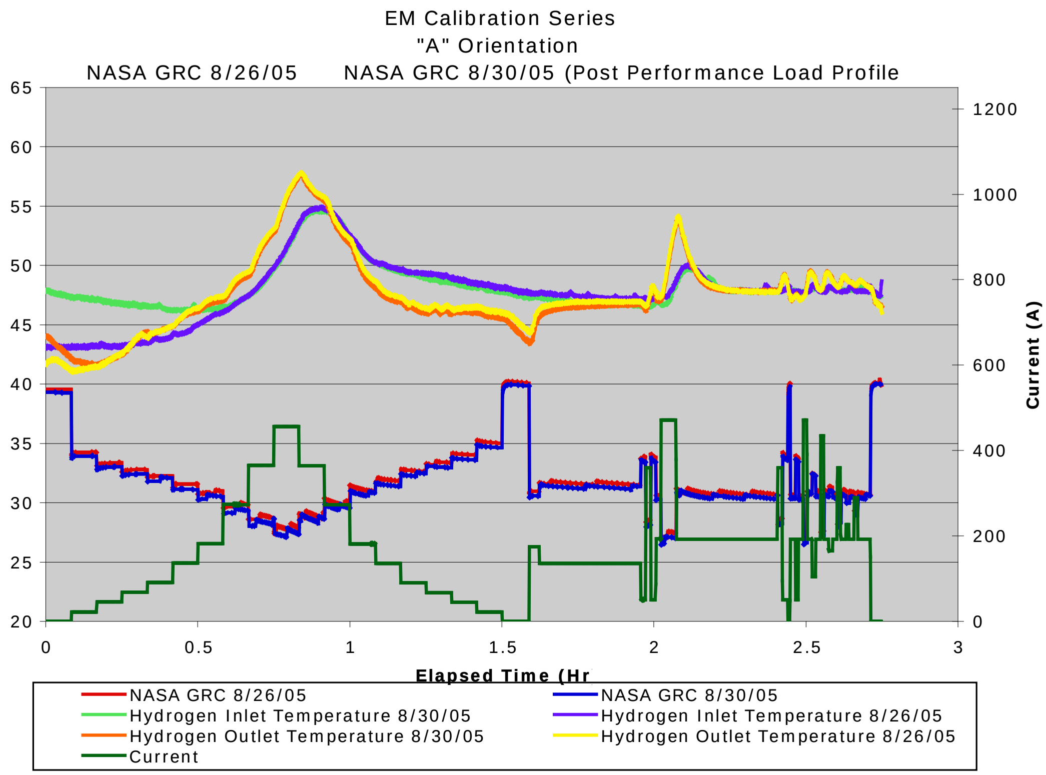

Figure 8.—Comparison of the Calibration Series test in the “A” orientation before and after the Performance Load Profile test. Inlet and outlet hydrogen temperatures.

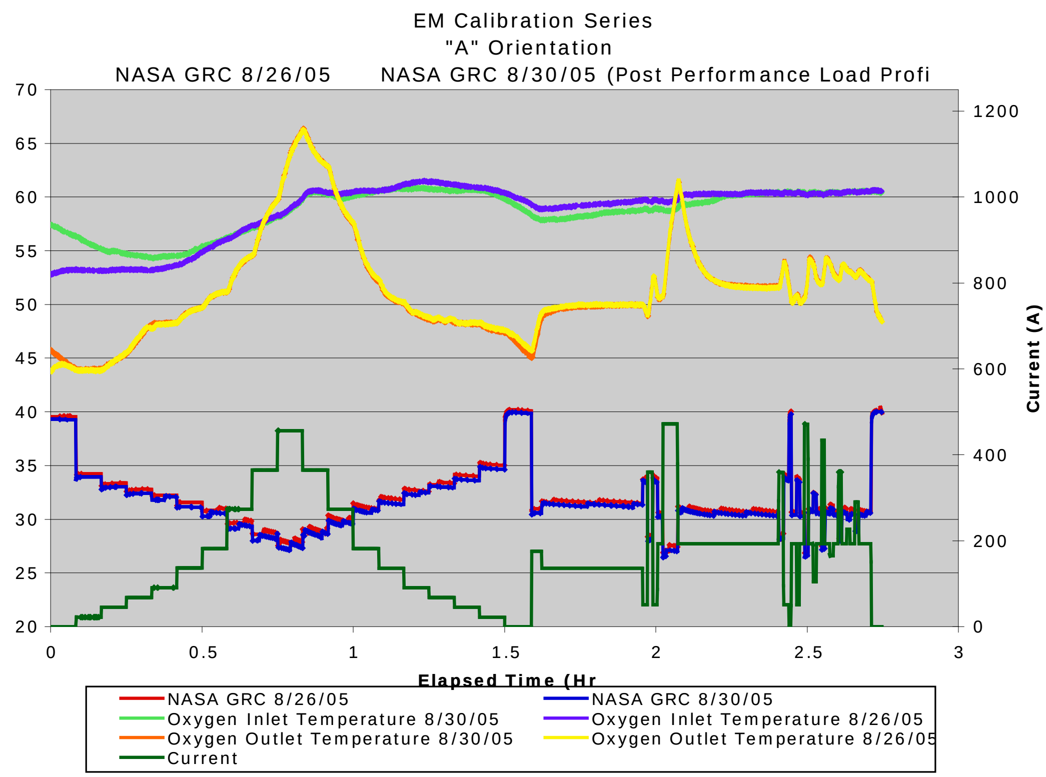

Figure 9.—Comparison of the Calibration Series test in the “A” orientation before and after the Performance Load Profile test. Inlet and outlet oxygen temperatures.

Likewise, the coolant temperature also influences the temperature at which the fuel cell reaction occurs. The powerplant coolant system was a recirculating loop which transferred heat from the fuel cell to a heat exchanger. The heat exchanger in turn rejected heat to an external cooling loop (the fuel cell facility chiller system). As can be seen in Figure 10, the coolant loop temperatures also closely followed the power load profile as did the reactant gas temperatures. In a similar fashion to the reactant outlet temperatures, the inlet and outlet temperatures of the coolant system were consistent between the Calibration Series Tests runs on August 26, and August 30. Therefore, it is not likely that temperature variations between the two days were responsible for the performance variation observed.

Fuel cell performance is also dependent upon reactant pressures, with higher pressures generally improving overall performance. In Figure 11 and Figure 12, the inlet and outlet reactant pressures are plotted with the voltage and current data. As can be seen, in Figure 11, the hydrogen pressure was slightly higher during the August 26 Calibration Series test than was observed on August 30. The reactant operating pressure was 6 psig. The hydrogen inlet pressure was approximately 0.3 to 0.6 psig higher on August 26, 2005, than on August 30, 2005. This 5 to 10 percent difference in inlet hydrogen pressure resulted in a 0.4 to 0.6 V difference in the stack voltages. The higher hydrogen pressure improved the fuel cell performance resulting in the slightly higher stack voltage observed during the August 26 Calibration Series Test run.

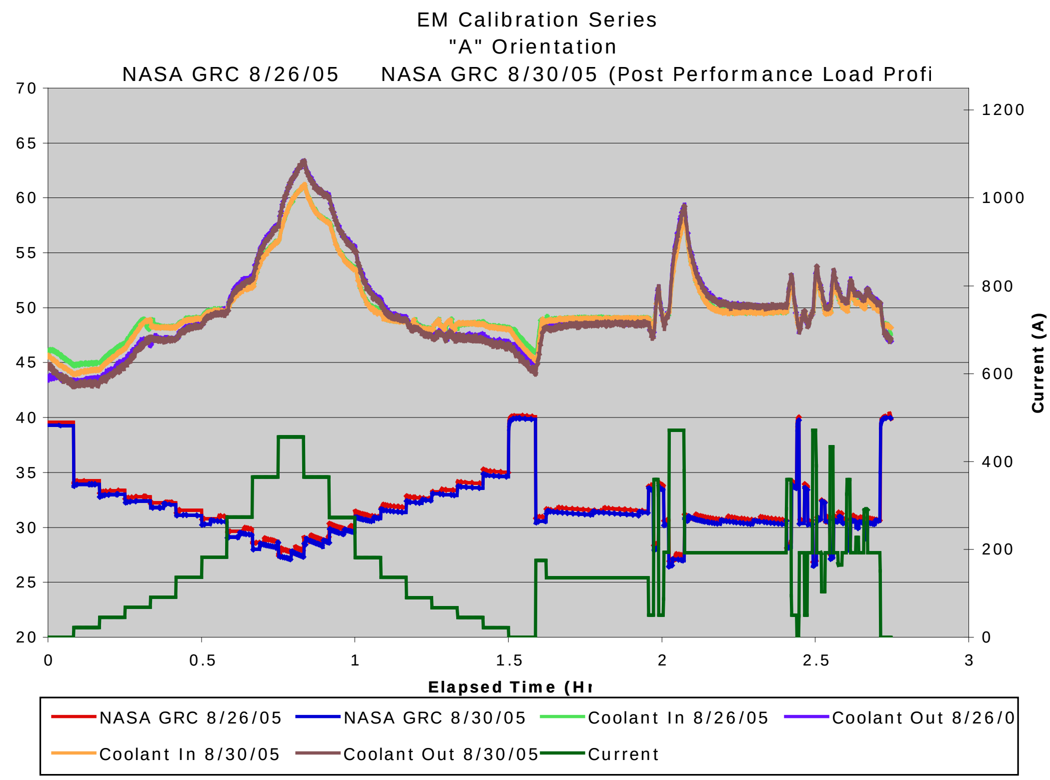

Figure 10.—Comparison of the Calibration Series test in the “A” orientation before and after the Performance Load Profile test. Coolant inlet and outlet temperatures.

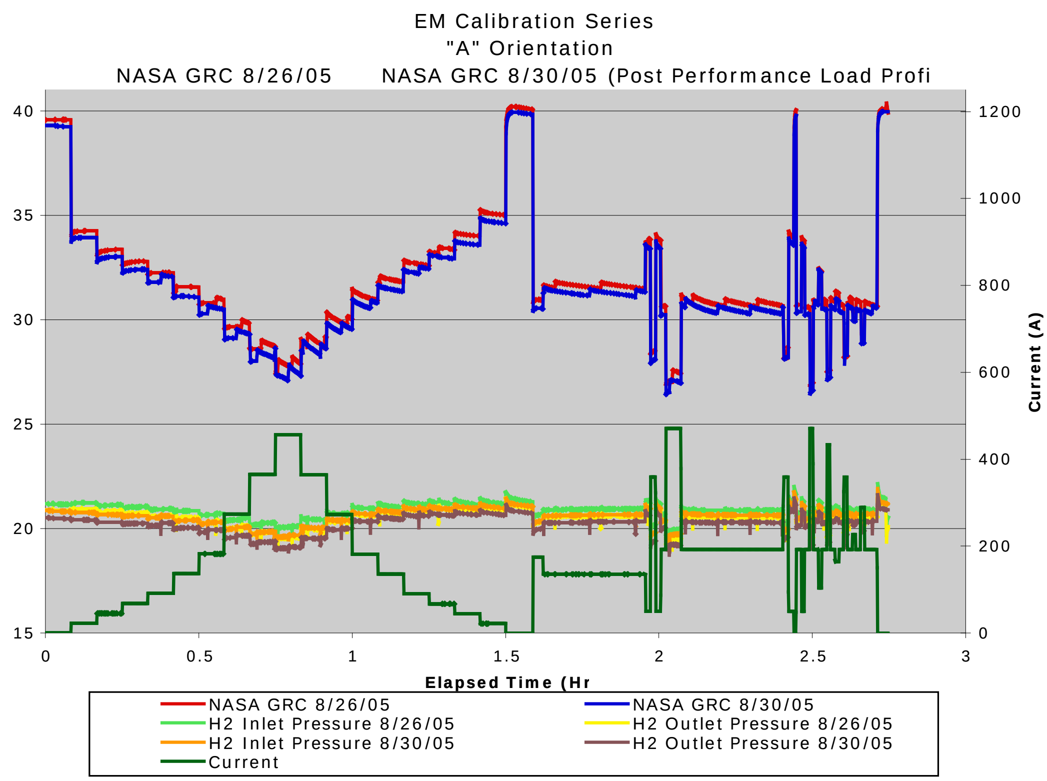

Figure 11.—Comparison of the Calibration Series test in the “A” orientation before and after the Performance Load Profile Test. Hydrogen inlet and outlet pressures.

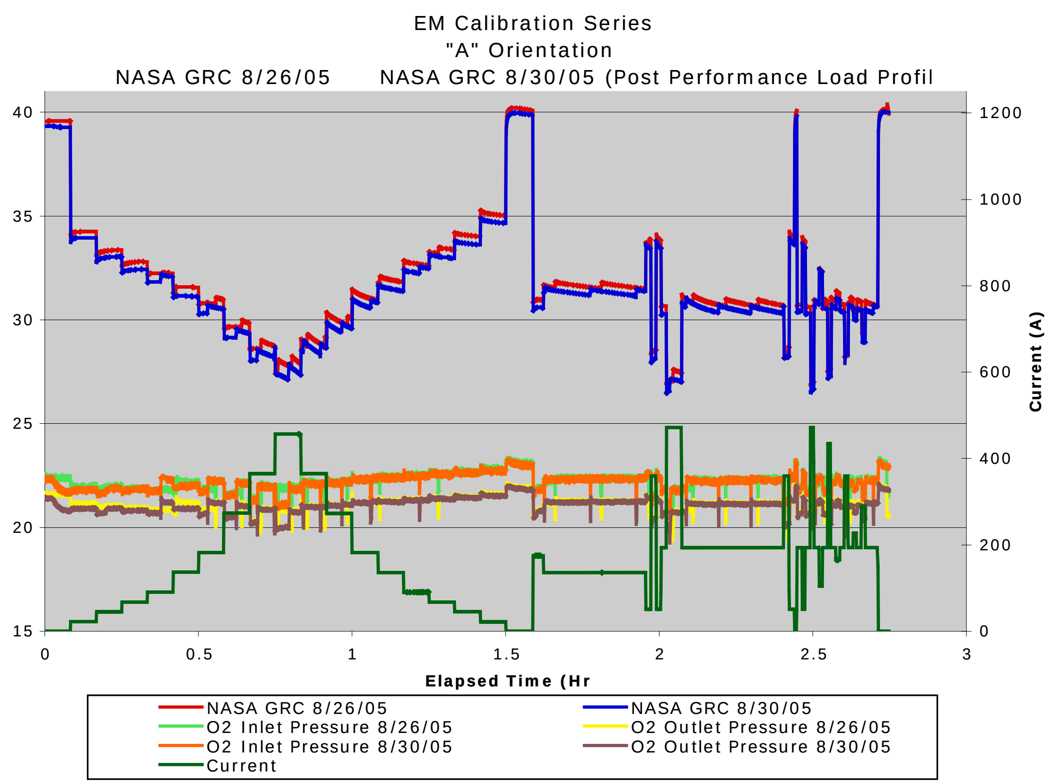

Figure 12.—Comparison of the Calibration Series test in the “A” orientation before and after the Performance Load Profile test. Oxygen inlet and outlet pressures.

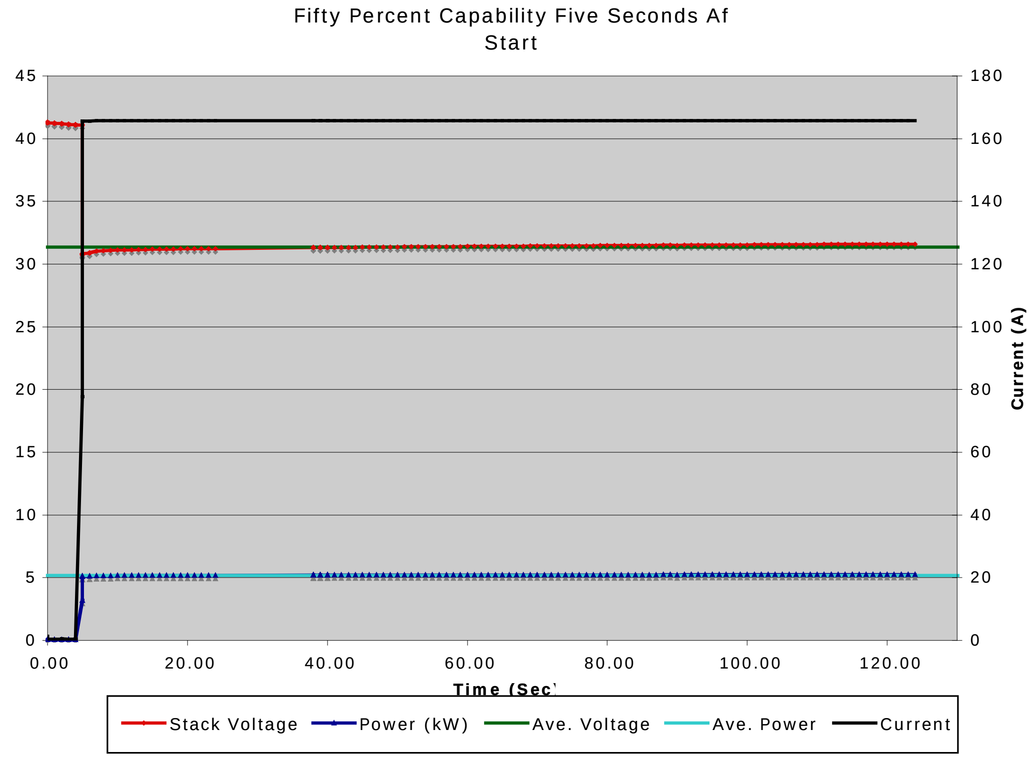

Figure 13.—Fifty percent of capability test in the "A" orientation.

The Fifty Percent of Capability Test demonstrated the ability of the powerplant to deliver Fifty Percent of rated capacity within 5 sec after the start of the powerplant. Under normal start-up conditions, the powerplant is preheated to a set temperature prior to the imposition of a power load. During rapid start-up, the inerts, i.e., nitrogen, were purged from the powerplant system prior to start; however, no pre-warming of the fuel cell stack or powerplant occurred. When the powerplant was started under this method, the ancillary system, i.e., the reactant recirculation pumps and water separators were started and the reactant supply solenoid valves were opened. The powerplant system was designed to bring the ancillary system online and to be ready to provide power within 5 sec of start. As can be seen in Figure 13, a load equivalent to 50 percent of its capability was applied to the powerplant 5 sec after start. The average power and average voltage plotted represent the levels seen during normal operation at the same power level. Upon application of the load, the powerplant voltage and power quickly rose to levels seen during normal start-up and operation.

In Figure 14, the individual cell voltages within the stack are plotted. As can be seen, within the first few seconds after start-up the cell voltages were closely spaced and maintained their spacing during the duration of the test. This indicates that even under rapid start-up conditions, the pressure and temperature was consistent across the stack. Cell 1 is the only outlier and may have exhibited decreased performance for a number of reasons including lower gas humidity or temperatures.

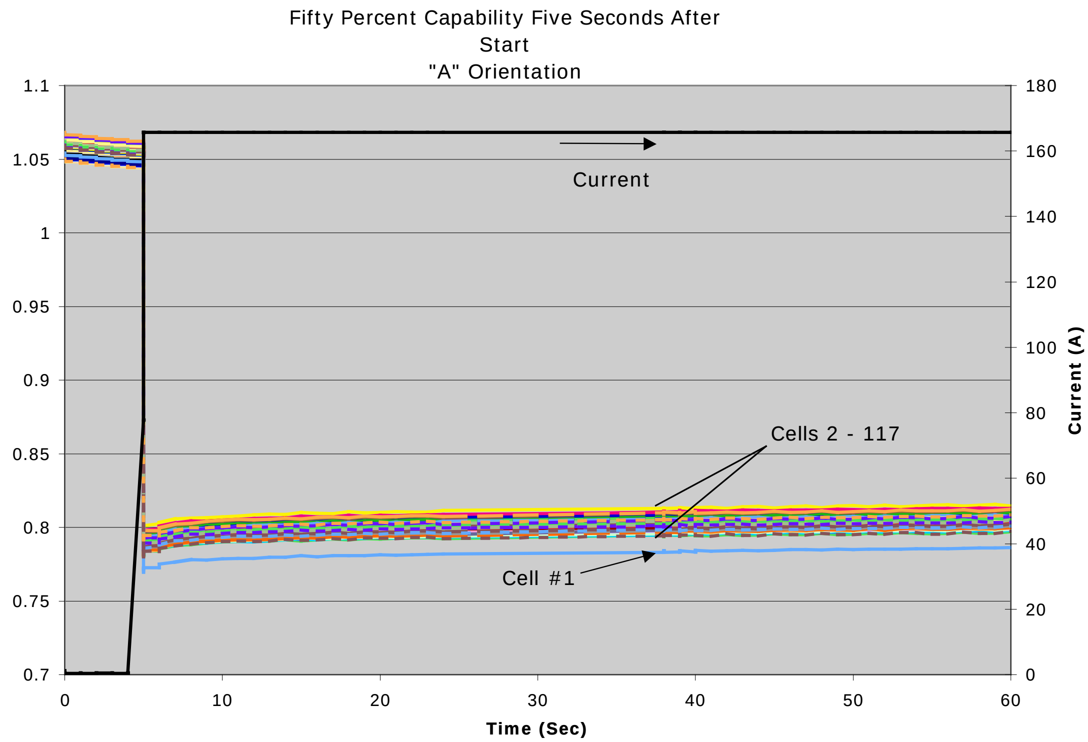

Figure 14.—Fifty percent of capability test in the “A” orientation. Individual cell voltages.

4.0 Conclusion

The initial evaluation of the Teledyne Engineering Model Powerplant was conducted to measure the performance over a variety conditions and power load profiles. This report details these initial performance evaluation test results of the EM in its original orientation as shipped by the manufacturer. Table 2 outlines the original design goals for the Teledyne Engineering Model and specifies the goals that were demonstrated during the initial evaluation testing. The remaining tests will be used to quantify:

- Performance and any changes in performance during operation under different physical orientations.
- Maintenance intervals, operating life, performance degradation, and cycle life.
- Stability over extended duration operations (240 hr).
- Powerplant response to loss of cooling.

TABLE 2.—DESIGN GOALS OF THE TELEDYNE ENGINEERING MODEL POWERPLANT

Engineering Model Design Goals	Tested?	Met?
Produce 2 to 12 kW of electrical power within a voltage range of 33 to 27 VDC	Tested	Did not meet
Gravity/orientation independent operation	Not tested	
Maintenance free operation for 3000 hr	Not tested	
90% of Final change in voltage shall occur within 0.2 sec.	Tested	Met
The power plant shall be capable of automatic startup to 3 kW in less than 5 sec if reactants are present, initial stack temperature is greater than 40 °F and no inerts are present.	Tested	Met
The power plant shall be capable of shutdown in less than 1 min	Not tested	
The power plant shall be capable of operating on propellant grade (MIL PRF-27201C) and higher purity hydrogen and propellant grade (MIL PRF-25508F) and higher purity oxygen.	Tested	Met
Operating life will be greater than 3000 hr	Not tested	
Powerplant shall be capable of operation for 9 min at 5 kW without cooling from a secondary coolant loop.	Not tested	
Minimum of 250 start / stop cycles life design goal	Not tested	

Appendix A.—Detailed Test Descriptions

The following tables and descriptions quantify the exact currents, durations and recording intervals used during the test described in this paper.

A.1 Calibration Series Test

The Calibration Series Test was a reference test of the Engineering Model. The series was comprised of a Polarization Test and an abbreviated version of the Performance Load Profile Test. This test was performed at specified intervals during the evaluation of the Engineering Model at Teledyne, GRC and JSC. The calibration series test was used to quantify performance changes of the Engineering Model as a function of shipping, orientation effects, damage as a result of testing and age. The stack voltage in the table was the average of the last four readings taken July 20, 2005, during the calibration series acceptance test at Teledyne. Voltage transients occurred at the element numbers marked with an asterisk and at these locations, data was recorded at 200 kHz using the DataMax software.

TABLE 3.—EM CALIBRATION SERIES TEST CONDITIONS

Element no.	Increment time (sec)	Current (A)	Teledyne data recording interval (sec)	GRC data recording interval (sec)	Stack voltage (V)	Total time (sec)	Current density (mA/cm^2)
1	300	0	5	5	40.34	300	0
2	300	22.65	5	5	35.04	600	25
3	300	45.3	5	5	34.13	900	50
4	300	67.95	5	5	33.47	1200	75
5	300	90.6	5	5	32.93	1500	100
6	300	135.9	5	5	32.06	1800	150
7	300	181.2	5	5	31.47	2100	200
8	300	271.8	5	5	30.23	2400	300
9	300	362.4	5	5	29.27	2700	400
10	300	453	5	5	28.31	3000	500
11	300	362.4	5	5	29.22	3300	400
12	300	271.8	5	5	30.22	3600	300
13	300	181.2	5	5	31.31	3900	200
14	300	135.9	5	5	32.07	4200	150
15	300	90.6	5	5	32.93	4500	100
16	300	67.95	5	5	33.46	4800	75
17	300	45.3	5	5	34.14	5100	50
18	300	22.65	5	5	35.17	5400	25
19	300	0	5	5	40.74	5700	0
20	20	0	5	5	40.74	5720	0
21	120	174	5	5	31.17	5840	192
22	1200	135	5	5	31.83	7040	149
23a	55	51	5	5	33.91	7095	57
*23b	5	51	5	1		7100	57
*24a	5	357	5	1		7105	394
24b	55	357	5	5	28.72	7160	394
25	60	51	5	5	33.96	7220	57
26	60	192	5	5	30.86	7280	212
27	180	468	5	5	27.91	7460	516
28	1200	192	5	5	30.87	8660	212
29a	55	357	5	5	28.80	8715	394
*29b	5	357	5	1		8720	394
*30a	5	51	5	1		8725	57
30b	55	51	5	5	34.06	8780	57
31	30	0	5	5	40.33	8810	0

TABLE 3.—EM CALIBRATION SERIES TEST CONDITIONS

Element no.	Increment time (sec)	Current (A)	Teledyne data recording interval (sec)	GRC data recording interval (sec)	Stack voltage (V)	Total time (sec)	Current density (mA/cm^2)
32	60	192	5	5	30.88	8870	212
33	40	51	5	5	33.92	8910	57
34	60	192	5	5	30.84	8970	212
35	40	468	5	5	27.40	9010	516
36	60	192	5	5	31.03	9070	212
37	40	104	5	5	32.60	9110	115
38	60	192	5	5	30.88	9170	212
39	40	431	5	5	27.76	9210	476
40	60	192	5	5	31.00	9270	212
41	40	164	5	5	31.42	9310	180
42	60	192	5	5	31.03	9370	212
43	40	357	5	5	28.73	9410	394
44	60	192	5	5	31.06	9470	212
45	40	226	5	5	30.49	9510	249
46	60	192	5	5	31.00	9570	212
47	40	288	5	5	29.56	9610	318
48	150	192	5	5	30.92	9760	212
49	60	0	5	5	40.37	9820	0

A.2 Performance Load Profile Test

The Performance Load Profile Test was a benchmark test of the Engineering Model. This test was used to evaluate the performance of the Engineering Model under different operational conditions, i.e., orientation, vibration, etc. The Performance Load Profile Test was carried out at Teledyne and GRC. The stack voltage in the table was the average voltage during each step as observed July 19, 2005, during the performance load profile acceptance test at Teledyne. Voltage transients occurred at the element numbers marked with an asterisk and at these locations, data was recorded at 200 kHz using the DataMax software.

TABLE 4.—EM PERFORMANCE LOAD PROFILE TEST CONDITIONS

Element no.	Increment time (sec)	Current (A)	Teledyne data recording interval (sec)	GRC data recording interval (sec)	Stack voltage (V)	Total time (sec)	Current density (mA/cm^2)
1	30	0	5	5	39.93	30	0
2	120	174	5	5	31.97	150	192
3	3600	135	5	5	32.11	3750	149
4a	3295	51	5	5	33.70	7045	57
*4b	5	51	5	1		7050	57
*5a	5	357	5	1		7055	394
5b	895	357	5	5	29.04	7950	394
6	3600	51	5	5	33.75	11550	57
7	960	192	5	5	30.77	12510	212
8	180	468	5	5	27.63	12690	516
9	6120	192	5	5	30.82	18810	212
10a	895	357	5	5	28.80	19705	394
*10b	5	357	5	1		19710	394
*11a	5	51	5	1		19715	57
11b	1675	51	5	5	33.75	21390	57
12	30	0	5	5	40.32	21420	0.0
13	860	192	5	5	30.75	22280	212
14	40	51	5	5	33.89	22320	57

TABLE 4.—EM PERFORMANCE LOAD PROFILE TEST CONDITIONS

Element no.	Increment time (sec)	Current (A)	Teledyne data recording interval (sec)	GRC data recording interval (sec)	Stack voltage (V)	Total time (sec)	Current density (mA/cm^2)
15	860	192	5	5	30.74	23180	212
16	40	468	5	5	27.13	23220	516
17	860	192	5	5	30.82	24080	212
18	40	104	5	5	32.48	24120	115
19	860	192	5	5	30.77	24980	212
20	40	431	5	5	27.57	25020	476
21	860	192	5	5	30.80	25880	212
22	40	164	5	5	31.21	25920	180
23	860	192	5	5	30.78	26780	212
24	40	357	5	5	28.48	26820	394
25	860	192	5	5	30.79	27680	212
26	40	226	5	5	30.20	27720	249
27	860	192	5	5	30.77	28580	212
28	40	288	5	5	29.38	28620	318
29	150	192	5	5	30.82	28770	212
30	60	0	5	5	40.40	28830	0

A.3 Fifty Percent of Capability Test

The Fifty Percent of Capability Test was an evaluation of the speed of the response of the Engineering Model to loads after Rapid Start-Up. The Engineering Model was started using the rapid start procedure, which included purging the unit of nitrogen but did not include a warm-up of the fuel cell or powerplant. After completion of this test, the powerplant was shutdown and restarted using the normal start-up procedure for the remainder of the day’s testing. The stack voltage in the table was the average voltage during each step as observed July 19, 2005, during the performance load profile acceptance test at Teledyne.

TABLE 5.—EM FIFTY PERCENT OF CAPABILITY TEST CONDITIONS

Element no.	Increment time (sec)	Current (A)	Teledyne data recording interval (sec)	GRC data recording interval (sec)	Stack voltage (V)	Total time (sec)	Current density (mA/cm^2)
1	5	0	1	1	39.93	5	0
2	120	164	1	1	31.21	125	181
3	5	0	1	1		130	0

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14. ABSTRACT
Proton Exchange Membrane (PEM) fuel cell technology is the leading candidate to replace the alkaline fuel cell technology, currently used on the Shuttle, for future space missions. During a 5-yr development program, a PEM fuel cell powerplant was developed. This report details the initial performance evaluation test results of the powerplant.

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