



Proton Exchange Membrane Fuel Cell Engineering Model Powerplant

Test Report: Benchmark Tests in Three Spatial Orientations

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Summary

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 continued under Constellation Systems in the Exploration Technology Development Program. Initially, the engineering model (EM) powerplant was evaluated with respect to its performance as compared to acceptance tests carried out at the manufacturer. This was to determine the sensitivity of the powerplant performance to changes in test environment. In addition, a series of tests were performed with the powerplant in the original standard orientation. This report details the continuing EM benchmark test results in three spatial orientations as well as extended duration testing in the mission profile test. The results from these tests verify the applicability of PEM fuel cells for future NASA missions. The specifics of these different tests are described in the following sections.

Proton Exchange Membrane (PEM) Fuel Cell Engineering Model (EM) Powerplant Description

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

The fuel cell stack comprises 117 individual cells divided into 3 subsections. Each subsection comprises 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 a voltage regulation range of 33 to 27 volts of direct current (VDC). The fuel cell product water is removed from the stack using recirculation pumps and gravity-independent water separators and is rejected outside of the powerplant. All powerplant ancillary components are powered external to the fuel cell powerplant. Waste heat is removed from the stack via an internal cooling loop. The powerplant cooling system, in turn, rejects the heat to a facility cooling system external to the powerplant. Additional powerplant design goals are outlined in Table I.

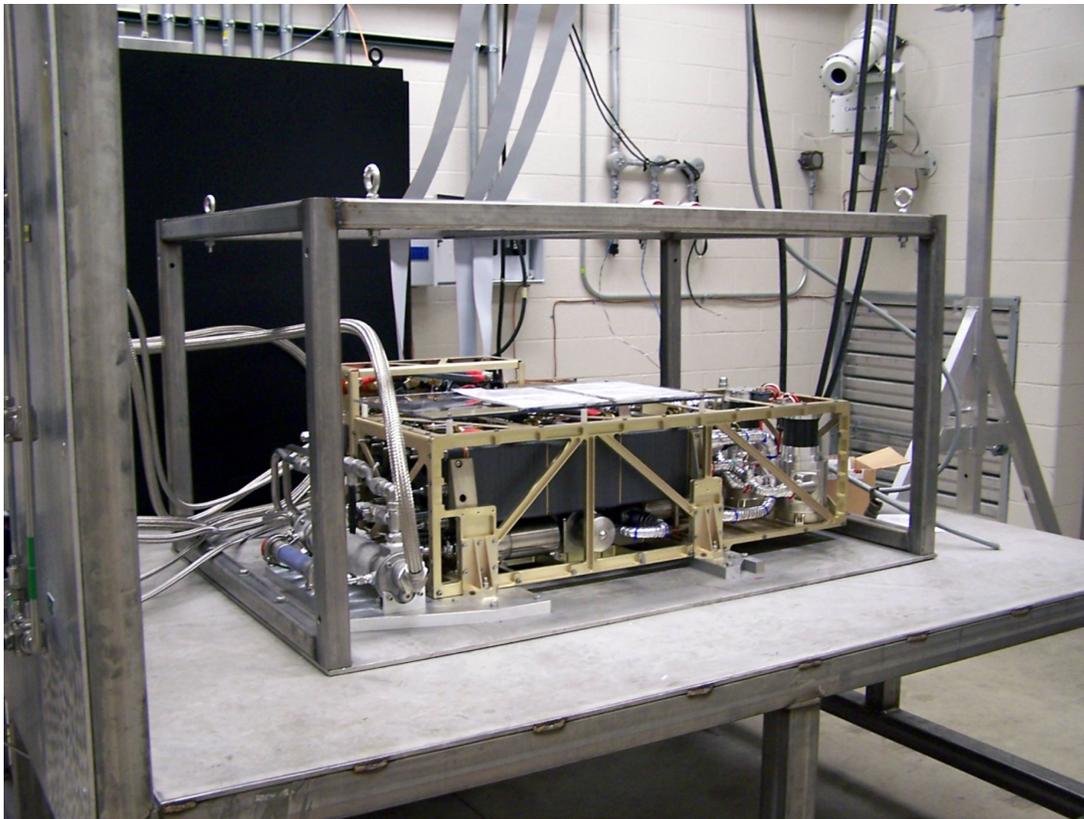


Figure 1.—Teledyne proton exchange membrane fuel cell engineering model powerplant in its original orientation.

TABLE I.—POWERPLANT 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 and orientation independent operation	Operation under three physical orientations
Maintenance-free operation for 3000 hr	All tests
90 percent of the final change in voltage after a change in load shall occur within 0.2 s	Performance load profile calibration series
Shall be capable of automatic startup to 3 kW in less than 5 s if reactants are present, initial stack temperature is greater than 40 °F, and no inerts are present	50 percent of capability test
Shall be capable of shutdown in less than 1 min	All tests
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
Shall be capable of operation for 9 min at 7 kW without cooling from a secondary coolant loop	Loss of coolant test
Shall be capable of a minimum 250 stop/start cycles	All tests

Test Summaries

The stability, performance, life, gravity independence, and response time of the Teledyne EM Powerplant were evaluated using a series of tests under three physical orientations. These performance tests were conducted upon the Teledyne EM 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. A brief description of each test type follows. Detailed information regarding operating parameters of each test is included in the appendix.

Calibration Series Test

The calibration series test is a reference test for the EM. The series is composed 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 EM at Teledyne, NASA Glenn Research Center (NASA Glenn), and NASA Johnson Space Center. The calibration series test quantifies performance changes of the EM caused by shipping, orientation effects, and damage as a result of testing and age. Voltage transitions are 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.

Performance Load Profile Test

The performance load profile test is a benchmark test for the EM. This test evaluates the performance of the EM under different operational conditions, such as orientation and vibration. The performance load profile test was carried out at Teledyne and NASA Glenn. 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.

Fifty Percent of Capability Test

The 50 percent of capability test evaluates the response speed of the EM to loads after a rapid startup. The rapid startup procedure is used to start the EM. This procedure includes purging the unit of nitrogen and the introduction of reactants but does not include a warmup of the powerplant. The powerplant ancillaries and heaters use a power source external to the powerplant. Under normal startup conditions, the powerplant ancillaries are started and then the plant is prewarmed to 45 °C prior to applying a power load. During this test, the ancillaries are started but no prewarming takes place. To meet the requirements of this test, within 5 s of the start, the powerplant must be able to respond to a load approximately 50 percent of the rated power. After completion of this test, the powerplant is shut down, and the normal startup procedure is used to bring the powerplant online for the remainder of the day's testing.

Mission Profile Test

The mission profile test measures the performance of the EM powerplant over a power profile and duration representative of a typical Shuttle mission. The test is run uninterrupted for the entire 240 hr.

Loss of Coolant Test

The loss of coolant test evaluates the performance of the EM powerplant when the cooling system external to the powerplant is interrupted.

Constant Load Test

During the initial mission profile test, a slow degradation of the fuel cell stack voltage was observed. The constant load tests were performed to evaluate the fuel cell stack voltage changes over time. The tests also were performed using ultrapure hydrogen and oxygen gas to help explain the voltage degradation observed while performing the Mission Profile under the same load condition with the gas supply coming from the hydrogen and oxygen tube trailers.

Orientation Effects

Description

A fuel cell powerplant designed for space applications must not rely upon gravitational effects to facilitate movement or removal of reactants or products. The EM was designed with this requirement in mind. To evaluate the effectiveness of the gravity-independent design, the EM was tested in three different physical orientations as part of the initial performance evaluation at NASA Glenn. Figures 2 through 4 show the powerplant in the A, B, and C orientations, respectively. A series of tests were performed in each of these orientations. These tests include the calibration series, the performance load profile, the 50 percent capability test, and the mission profile test.

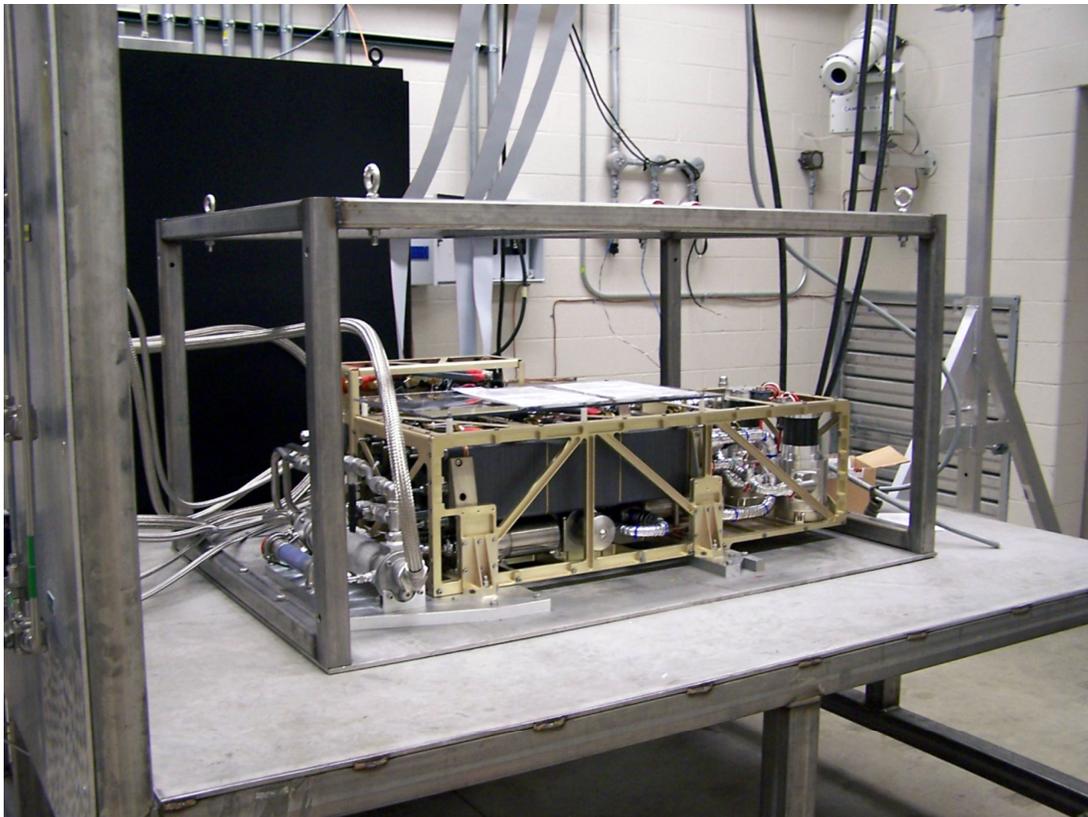


Figure 2.—Teledyne engineering model in orientation A.

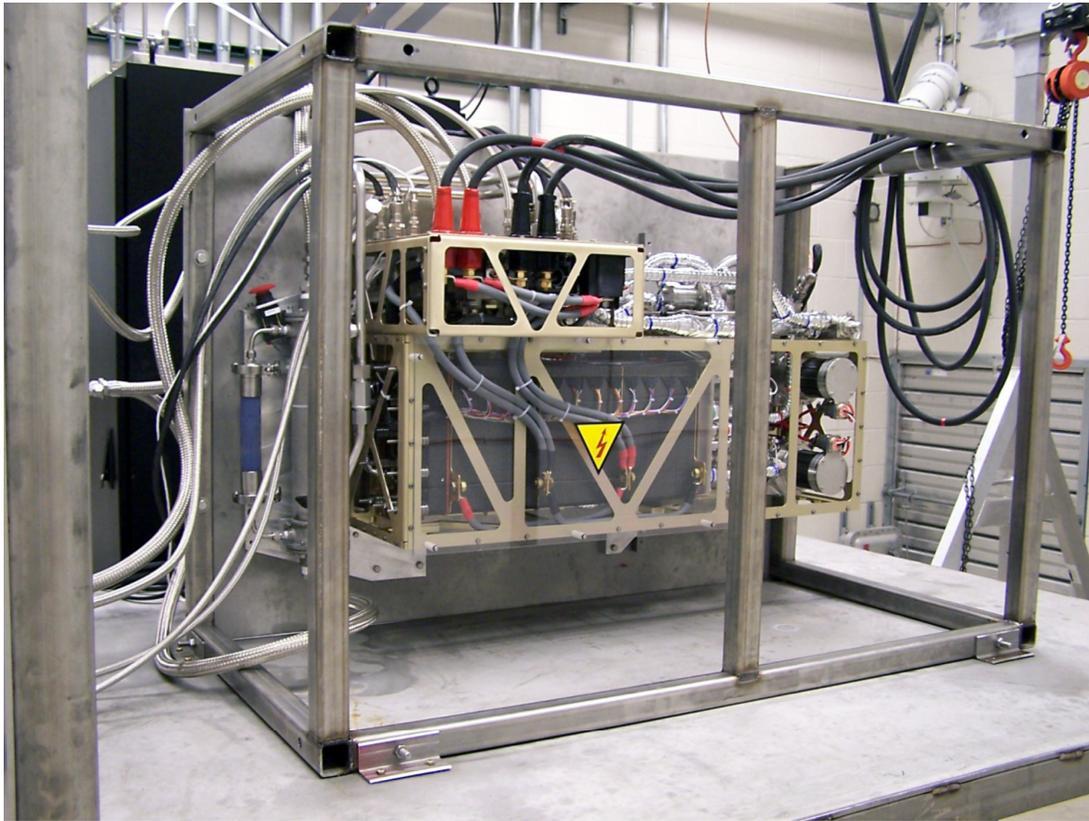


Figure 3.—Teledyne engineering model in orientation B.

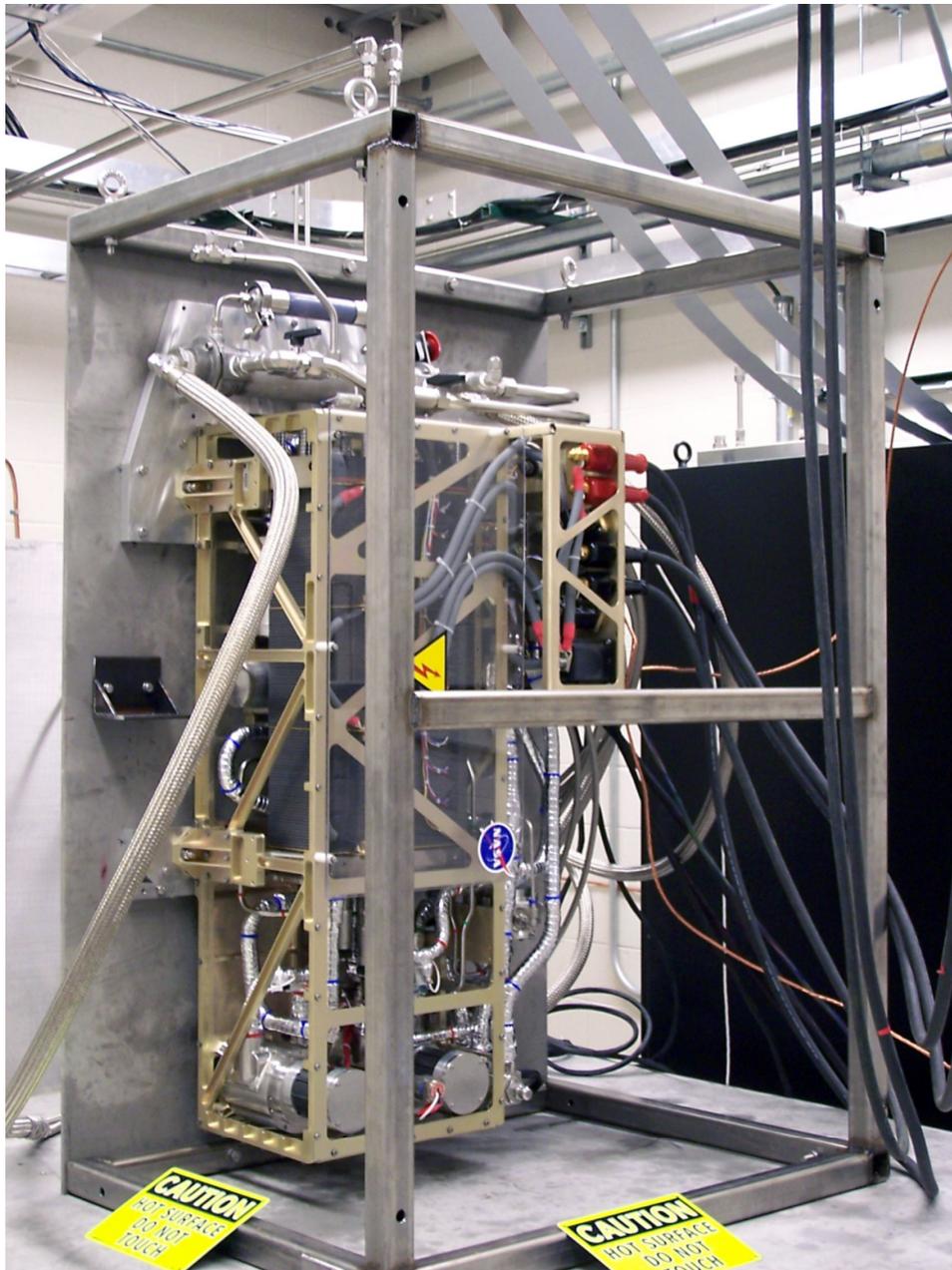


Figure 4.—Teledyne engineering model in orientation C.

Test Results

Calibration Series

The calibration series test was conducted upon the EM powerplant in each of the three orientations. After each orientation, the powerplant was returned to orientation A, and the calibration series was performed. This was performed to monitor any performance changes in the powerplant and to identify the cause of any variations such as age, operational conditions, or damage as a result of operation in one of the orientations.

The stack voltage performance curves obtained during the calibration series for the three different orientations are shown in Figure 5. Only minor variations in the voltage performance were observed in the three physical orientations. The sawtooth pattern evident in the 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 venting 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.

Figure 5 shows that the largest variation between the three orientations occurred within the first 45 min of the test, that is, during the iV curve. After this period, the performance variation between orientations diminished greatly.

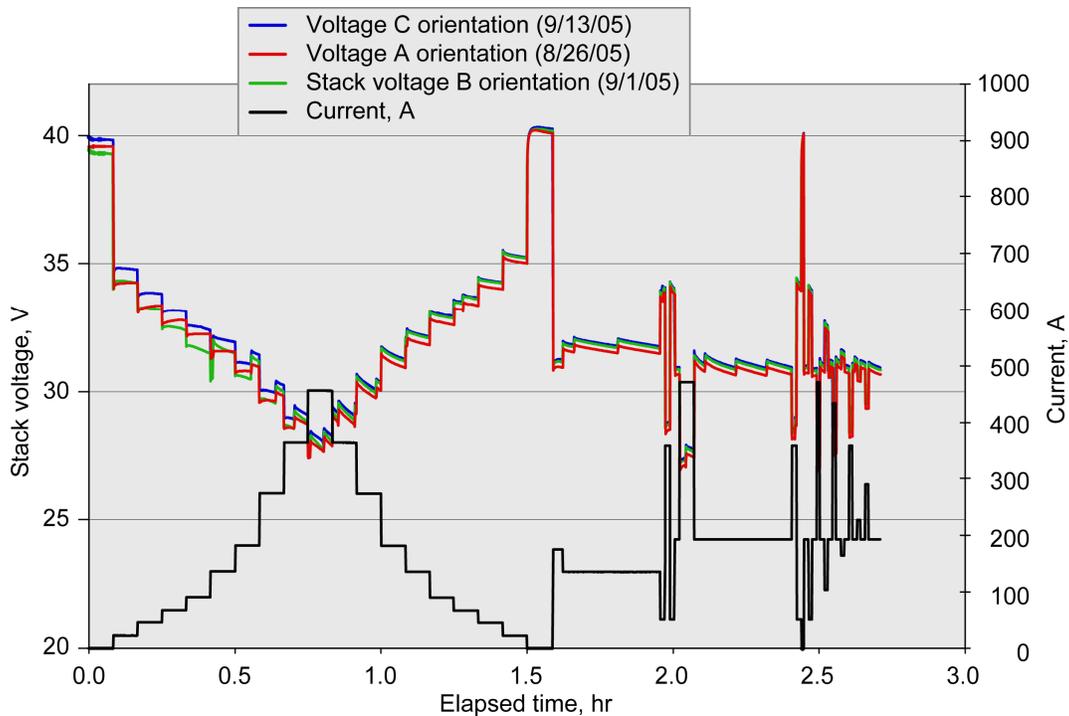


Figure 5.—Stack performance in three orientations: A, B, and C (calibration series).

To change the orientation of the powerplant, the powerplant was first taken through its shutdown sequence and allowed to cool prior to reorientation. During this time, small amounts of product water that had not been removed during the shutdown and purge sequence could condense within the fuel cell stack or the balance of plant components. Since the powerplant is predominantly a closed-loop system, until the water is separated out of the reactant stream, it could cause some temporary performance degradation.

The reactant recirculation pumps act to recirculate unused reactants back into the fuel cell stack after the product water has been removed. The power required to operate the reactant recirculation pumps is dependent upon the overall density of the gas or liquid being pumped. A higher density fluid, resulting from more humid gases or small slugs of water will require more power for pump operation. In Figure 6, the hydrogen recirculation pump current is plotted with the voltage curves for the three orientations. The pump currents observed during the three orientations are substantially different during the first 45 min of the calibration series test, indicating varying levels of liquid product water or humidification between the tests.

Other conditions that can have a significant effect upon powerplant performance are the temperature of the reactants entering the powerplant. The reactants used during the evaluation of the EM powerplant were stored outside. As the outside temperature varied, so too did the temperature of the stored reactants. As is evident from Figures 7 and 8, the incoming hydrogen and oxygen gas temperatures varied greatly during the first 45 min of the calibration series test. The combination of initial variations in inlet reactant temperatures with the higher humidity or presence of liquid product water accounts for the variation in powerplant performance observed during the first 45 min of the test. Figure 5 shows that after this initial period of adjustment, the performance curves in each of the three orientations overlapped. No significant effect was observed in the performance of the EM powerplant as a function of physical orientation.

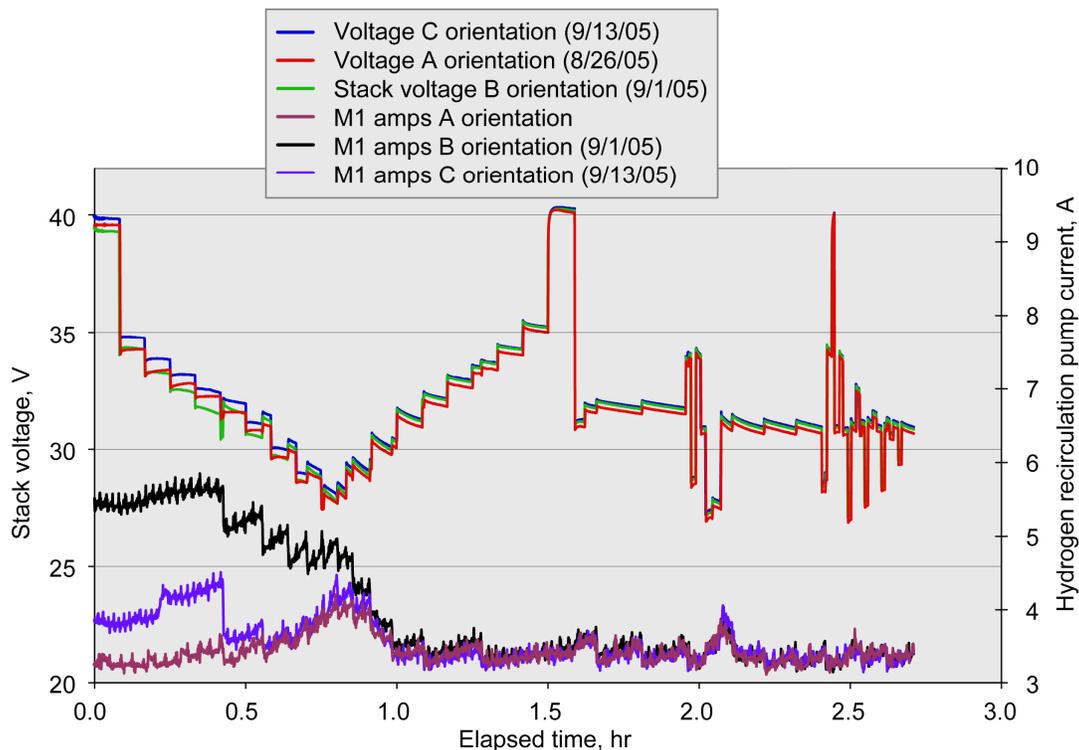


Figure 6.—Stack performance versus hydrogen recirculation pump current in three orientations: A, B, and C, (calibration series).

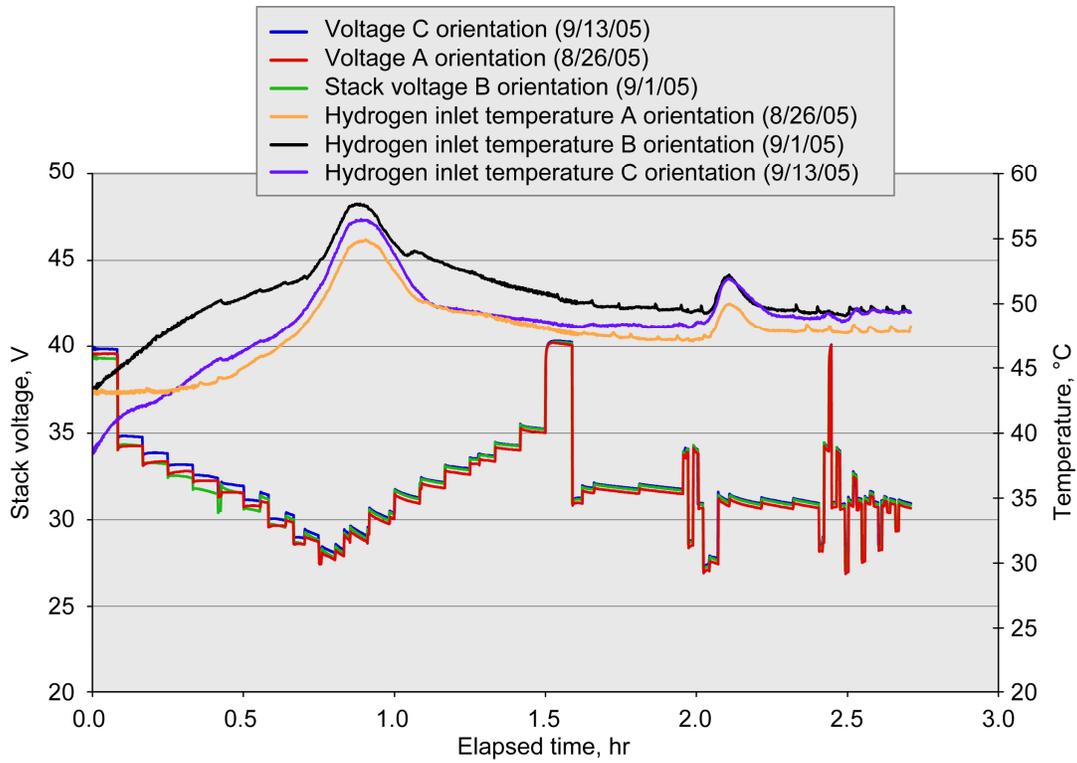


Figure 7.—Calibration series, hydrogen inlet temperature, in three orientations: A, B, and C.

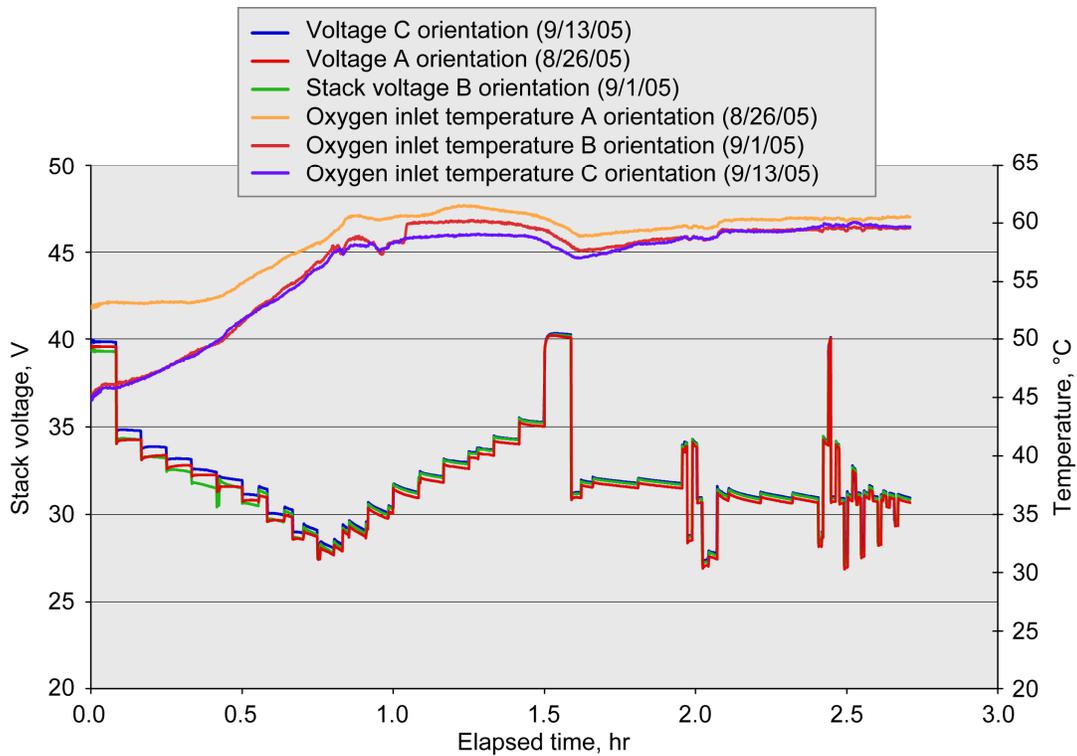


Figure 8.—Calibration series, oxygen inlet temperature, in three orientations: A, B, and C.

After each series of performance tests in each orientation, the powerplant was reoriented back into orientation A. The calibration series was then performed upon the powerplant in orientation A. The reason for this was two-fold. If any performance changes were observed in any of the orientations, the preceding and following orientation A calibration series test would act as a standard. If the powerplant operational performance changed in a specific orientation, the following orientation A calibration series test results would show if the change was truly a function of orientation or because of damage or performance changes to the powerplant over time.

Figure 9 shows the orientation A calibration series test conducted after each of the orientation test series. As was observed in the three orientations, the first 45 min shows some variations between the three tests. After the initial 45 min, the performance curves of the three orientation A's overlapped for the remainder of the test.

In the tests in the three orientations, the reactant recirculation pump operating current exhibited variability during that initial timeline. The variation in the oxygen recirculation pump current can be observed in Figure 10. The pump current in the A-after-B test was higher than that observed for the other two tests. This is likely due to liquid water being recirculated and moved out of the powerplant. After the initial 45 min, the excess water is removed, and the pump current dovetails and matches the pump currents observed during the other tests. At the same time, the performance (voltage) in the A-after-B test converges with the other two tests. Again, the performance differences observed were not due to damage as a result of operation in other orientations or age-related performance changes, but rather temporary, reversible differences in the starting conditions of the powerplant.

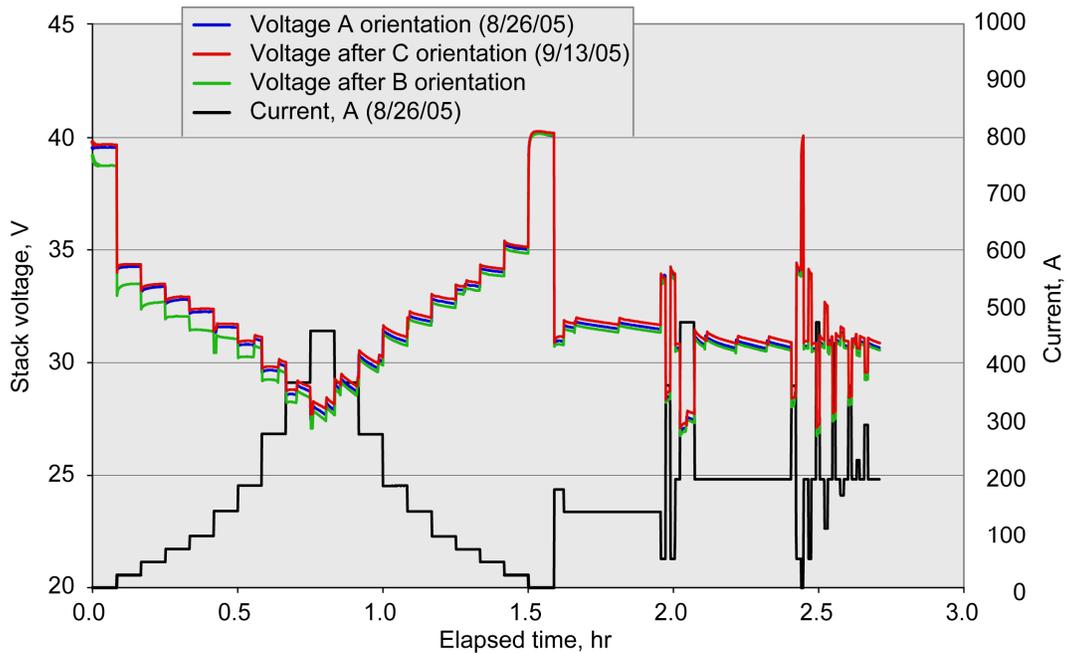


Figure 9.—Calibration series in orientation A after operating in other orientations (stack current).

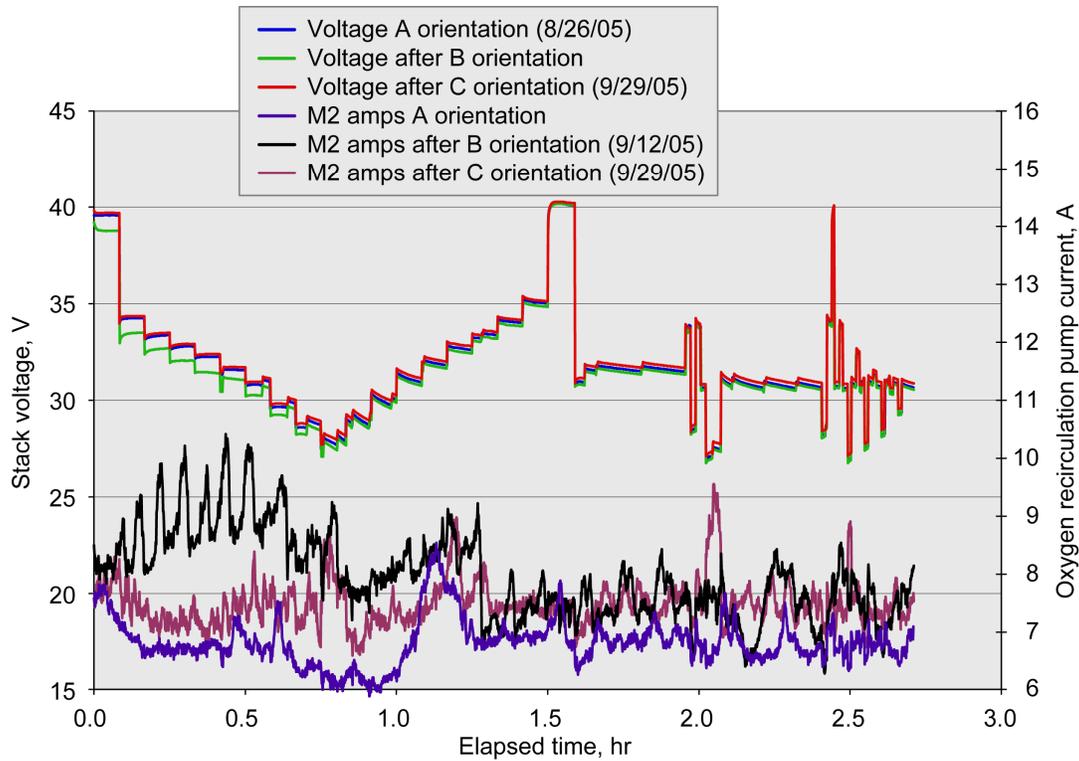


Figure 10.—Calibration series in orientation A after operation in other orientations (oxygen recirculation pump current).

Performance Load Profile Test

The performance load profile test is used as a standard test of powerplant performance over an uninterrupted 8-hr period. During the test, power levels and durations are varied. In addition, the transient response to a change in load was also evaluated during the transition from 51 to 357 A, and again at the transition from 357 to 51 A. The performance load profile results for all three orientations are shown in Figure 11. The performance voltage curves overlap for all three orientations, with very little variation between the three curves.

Transient Response of the Powerplant to Changes in Load

During the course of the performance load profile tests, 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 (see Fig. 12) and (2) from 357 to 51 A (see Fig. 13). The transient response of the powerplant was evaluated in all three orientations. A high-speed data acquisition system operating at 200 kHz monitored the applied load current and the stack voltage during these transitions.

During the transition from 51 to 357 A, the powerplant performed the same in all three of the physical orientations. No change in performance was observed as a function of physical orientation (see Fig. 12). In the transition from 51 to 357 A, the electronic load initially overshoot the requested current, but stabilized quickly. The fuel cell stack voltage followed the load current but also overshoot and followed a ringing pattern until it stabilized in less than 2 ms. 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 or due to some type of electrical interference in the signal, although this was not observed in the current signal. Currently the cause is unknown, but the

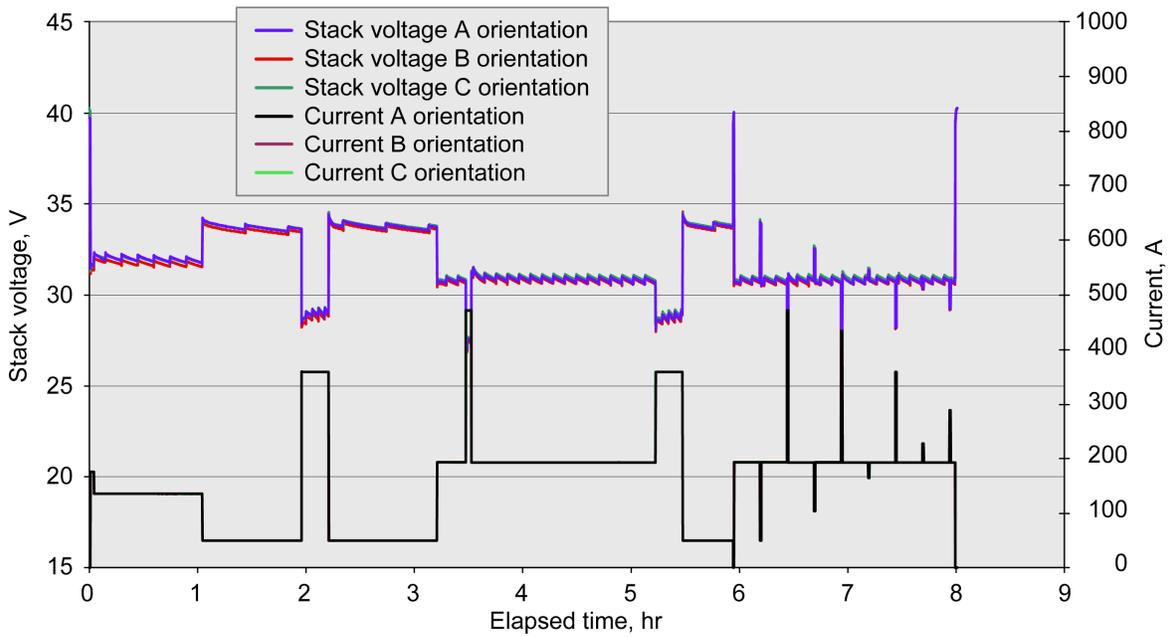


Figure 11.—Performance load profile in three orientations: A, B, and C.

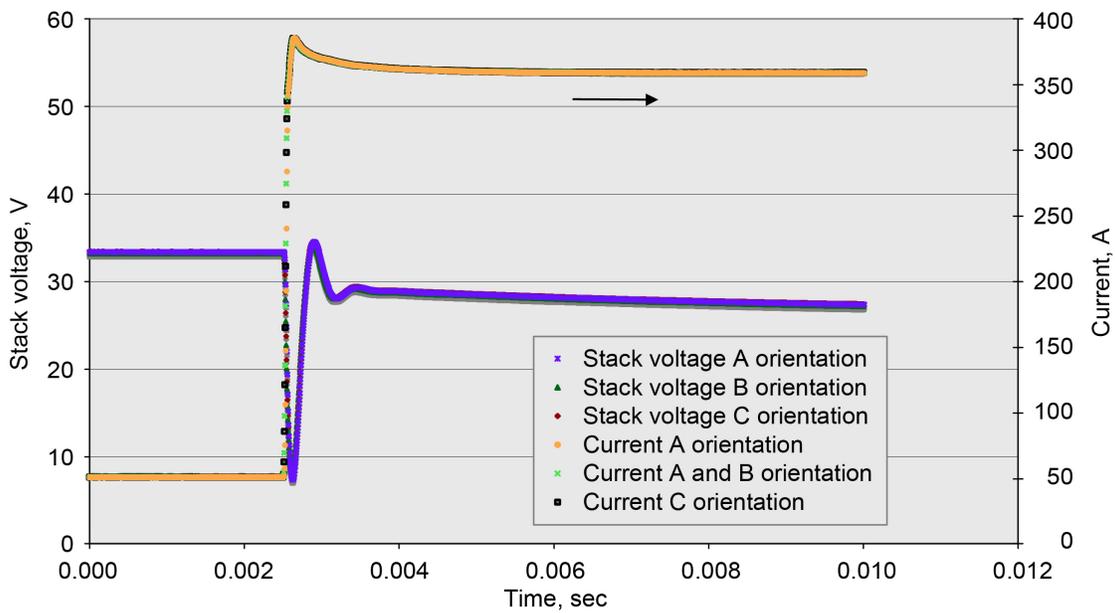


Figure 12.—Transient performance in orientations A, B, and C, from 51 to 357 amps.

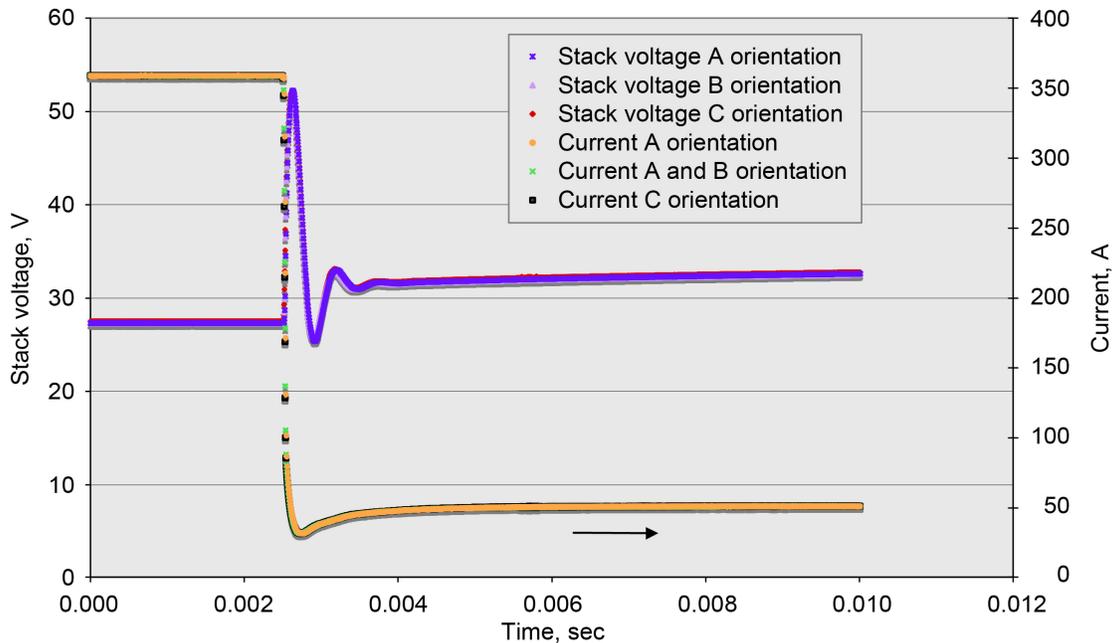


Figure 13.—Transient performance in orientations A, B, and C, from 357 to 51 amps.

phenomenon lasted less than 2 ms. 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; a slight increase in resident product water will result in a slight decrease in the stack voltage.

As can be seen in Figure 12, after approximately 8 ms, 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 ms. 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 s.

During the transition from 357 to 51 A, the powerplant again responded and stabilized rapidly (see Fig. 13). Again no difference in the transient response of the powerplant was observed for the three physical orientations. During the transition to a lower power draw (51 A), the stack voltage continued to increase slightly before stabilizing and 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 13, after approximately 8 ms, 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 ms. 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 s.

Fifty Percent of Capability Test

The 50 percent of capability test demonstrated the ability of the powerplant to deliver 50 percent of rated capacity within 5 s after the start of the powerplant. Under normal startup conditions, the powerplant is preheated to a set temperature prior to the imposition of a power load. During rapid startup, the inerts (i.e., nitrogen) were purged from the powerplant system prior to start; however, no prewarming 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 s of start. As can be seen in Figure 14, a load equivalent to 50 percent of its capability was applied to the powerplant 5 s 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 startup and operation.

Initial rapid startup or 50 percent of capability tests were performed in orientation A. The EM was then reoriented into the orientation B and then the orientation C. Figure 14 provides the stack voltage and applied current observed for the tests performed in all three orientations.

There were variations in stack voltages observed between the three orientations. This correlates to a similar variation in the hydrogen recirculation pump currents required (see Fig. 15). As described previously, as the density of the gas or fluid increases, more power is required to maintain recirculation. The powerplant in orientation B exhibited the worst performance; this corresponded to orientation B having the highest pump currents during the test. These higher pump currents are likely due to increased humidification or liquid water within the powerplant that required higher pump currents to recirculate. The presence of liquid water or high levels of humidification within the reactant streams act to dilute the reactant concentration within the fuel cell, resulting in a depressed fuel cell stack voltage.

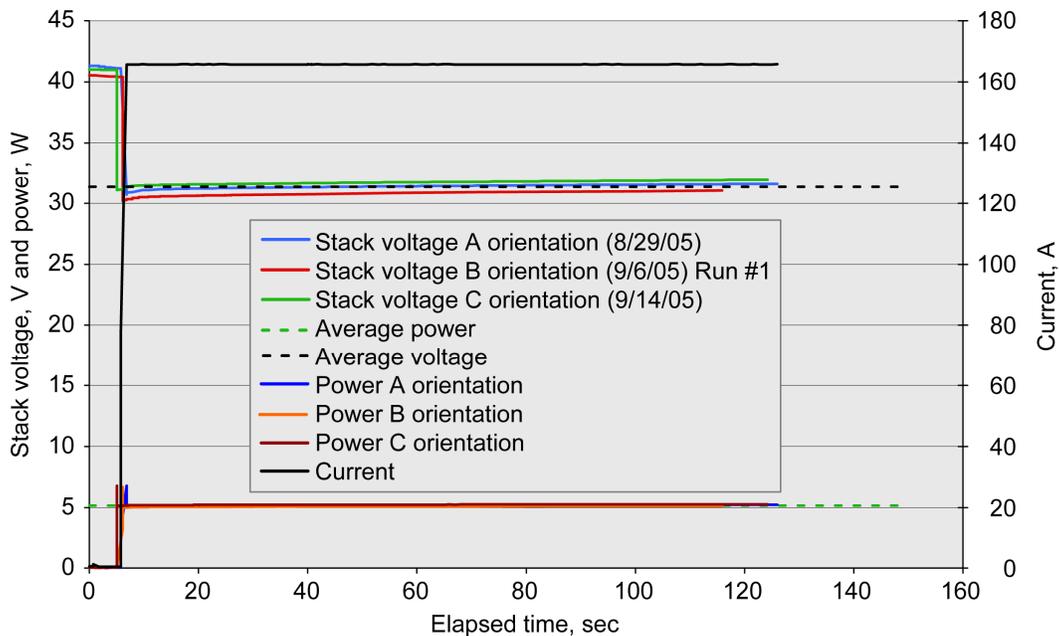


Figure 14.—Rapid startup stack voltage and stack current test results in all three orientations (50 percent capability, 5 s after start).

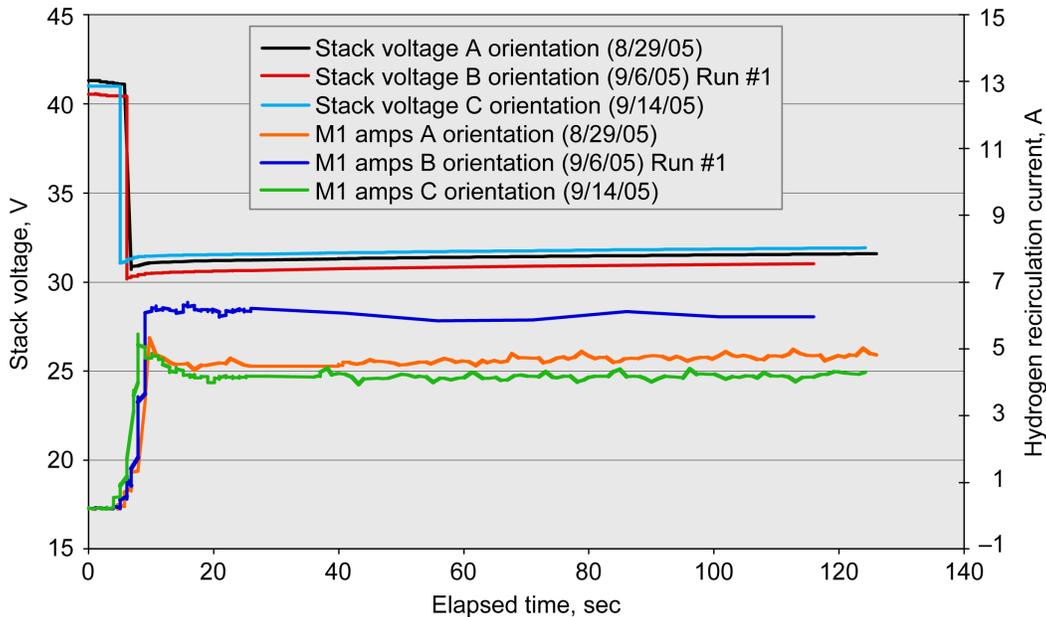


Figure 15.—Hydrogen pump currents during rapid startup testing in all three orientations (50 percent capability, 5 s after start).

Mission Profile Test

The mission profile test was a 10-day mission simulation used to address stability and performance during extended periods of operation as would be required during a typical Shuttle mission. There were two, 10-day mission profile tests completed during the course of initial performance evaluation testing. The first test was performed in orientation A, and the second test was performed in orientation C the following month. The first mission profile test shut down 15.5 hr short of completion because the oxygen pump current was less than 1 A. This is one of the built-in shutdown parameters for the EM powerplant. It indicates that some part of the powerplant supporting ancillary subsystem is not operating correctly. In the case of ancillary failure, the powerplant goes into shutdown mode to prevent potential damage to the fuel cell stack. In this case, the shutdown message indicated that the oxygen recirculation pump had stopped operating. The Teledyne EM powerplant computer was rebooted to clear the error code and the powerplant was restarted without incident. The mission profile test was continued, backtracking 4 hr previously into the test to ensure overlap.

Overall, EM performance was comparable for both tests, shown by the stack voltages plotted in Figure 16. The mission profile test was not able to be conducted in orientation B because of a necessary repair to the oxygen recirculation pump. The mission profile test could not be conducted after the repair as the powerplant was delivered to the Johnson Space Center for additional environmental tests. One significant finding to note is the degradation of the stack voltage during the constant-power-level portions of the test. Upon examination, none of the system parameters of temperature or pressure mirrored this change. As a result, some other factor is affecting the long-term performance of the powerplant. Two possible causes include a buildup of impurities in the powerplant system over time due to insufficient purge time or frequency, or a slow buildup of water within the powerplant system due to incomplete removal of the water during powerplant operation. Figure 17 shows this voltage degradation is completely reversible upon system purge. After the powerplant unexpectedly shut down in the latter portion of the mission profile test, the system automatically went into a system purge. When the powerplant was restarted, and the power profile backed up 6 hr to ensure overlap, it was seen that a significant voltage recovery occurred that cannot be accounted for by variations in the powerplant system operational parameters.

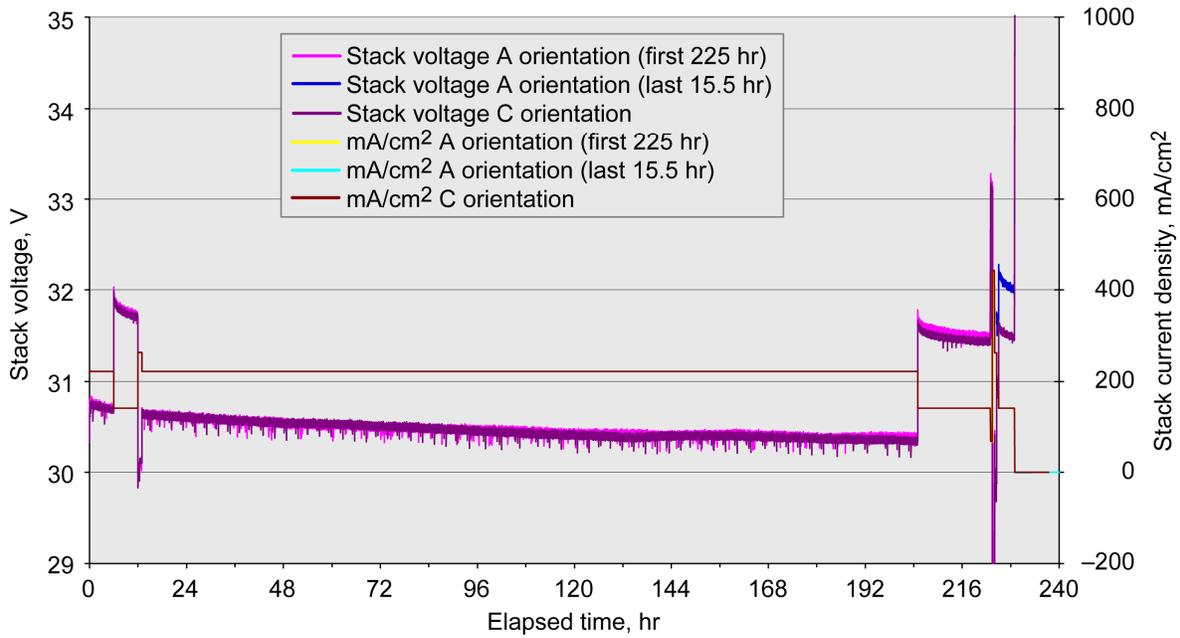


Figure 16.—Mission profile stack voltage and stack current densities for orientations A and C.

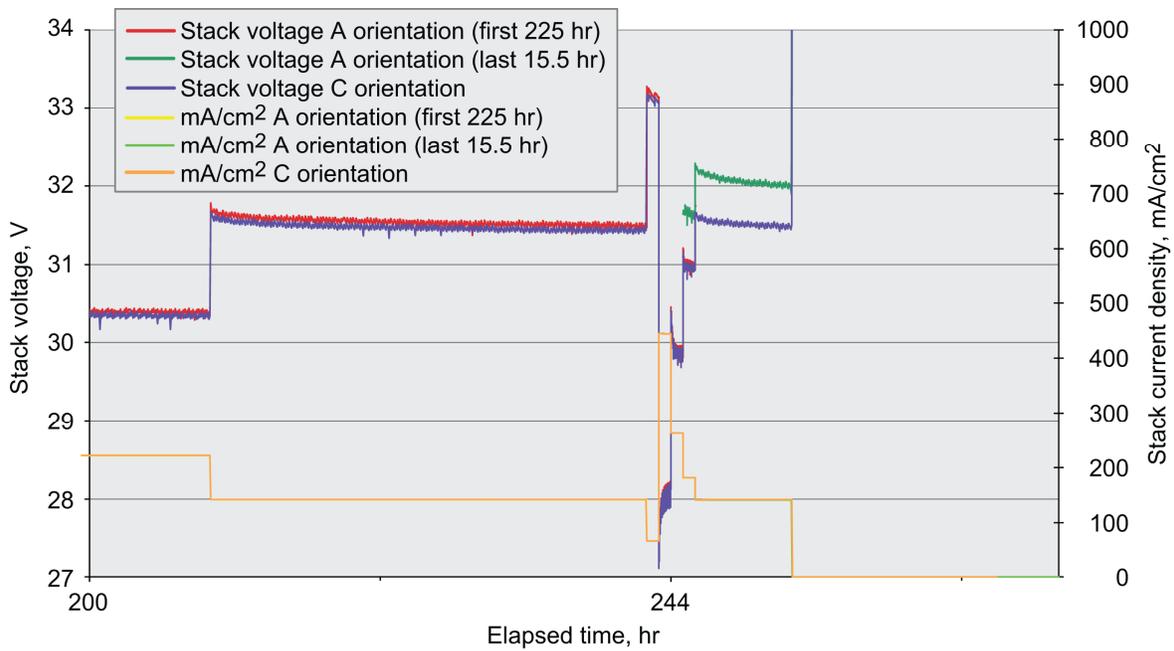


Figure 17.—Mission profile, last portion for orientations A and C.

During the tests in both orientations, water was observed percolating through the fuel cell stack. This was indicated by subtle drops and recoveries in the cell voltages, which started at the front of the stack and percolated through to the end of the stack. These cell voltage variations were not captured by the data acquisition system because of the collection interval, which was every 2 min. However, the percolation of water can be observed in the response of the hydrogen and oxygen recirculation pump currents (see Figs. 18 and 19). The large variation in pump currents indicates variable density fluids being moved through the powerplant, that is, water entrained within the reactant streams.

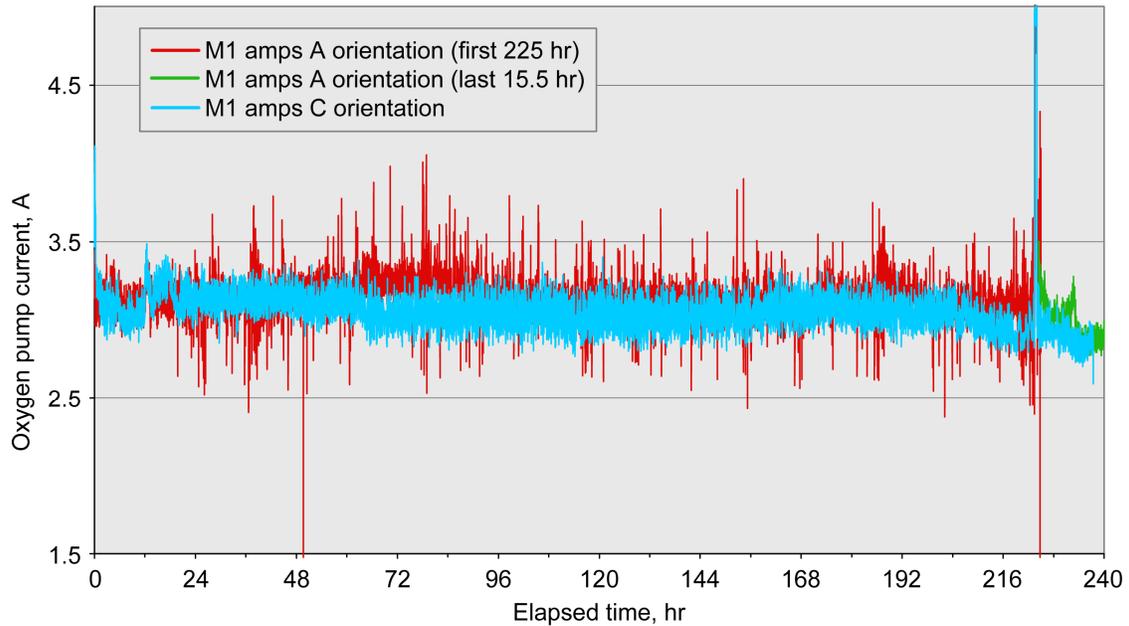


Figure 18.—Mission profile hydrogen pump currents for orientations A and C.

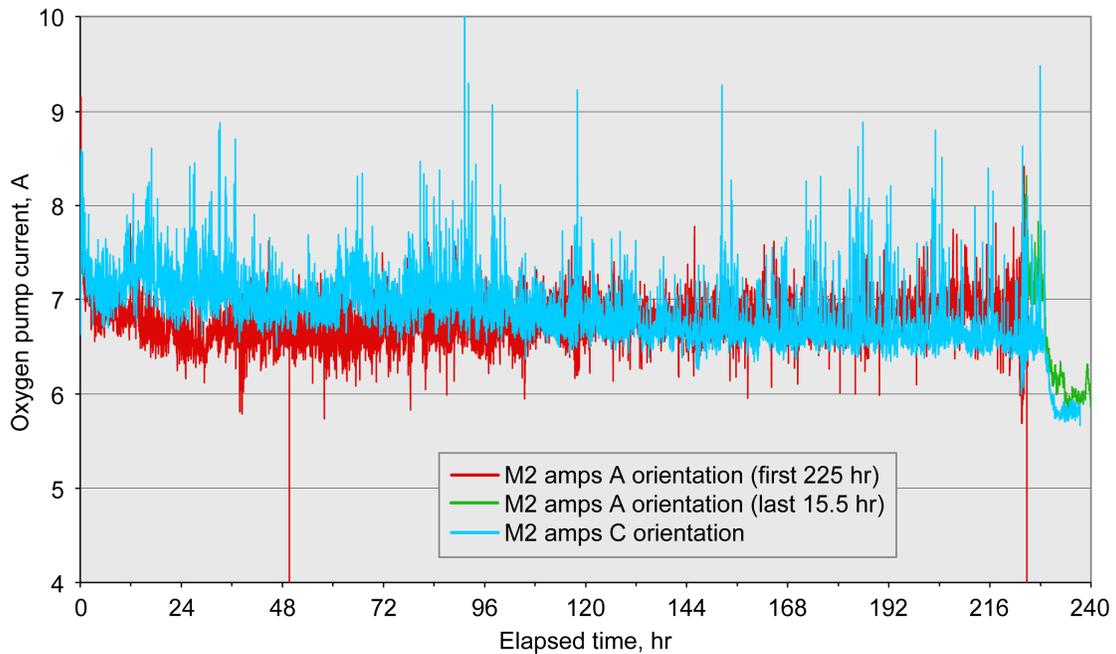


Figure 19.—Mission profile oxygen pump currents for orientations A and C.

Reactant Supply Gas Effects

A portion of the EM tests were performed at NASA Glenn Research Center with hydrogen and oxygen gas that varied in concentration or overall purity. The purpose of these tests was to see how the varying reactant gas concentrations affect overall stack performance as well as performance of balance of plant components over time. The majority of the tests were run with gas supplied from tube trailers with purity levels of 99.997 percent for hydrogen and 99.5 percent for oxygen. (Propellant-grade hydrogen and oxygen purity levels are 99.995 and 99.6 percent, respectively.) There were a select number of tests performed with ultrahigh purity (UHP) gas for both reactants. UHP gas concentrations were 99.999 percent for hydrogen and 99.995 percent for oxygen.

The calibration series test was conducted using the UHP reactants. Figure 20 shows a significant difference in the powerplant's performance when operating with propellant-grade reactants. The overall fuel cell stack voltage was higher for the higher purity reactants; this is expected as fuel cell performance is a function of reactant concentration. The impurities found in propellant-grade reactants act as a diluent, thus lowering the hydrogen and oxygen concentration. Another significant difference to note is the lack of the sawtooth pattern exhibited by the test run using UHP reactants. As discussed before, this pattern is a result of intermittent burping of the powerplant to release built up impurities. The interval period for burping the powerplant remained the same for the higher purity reactant test. Since a much lower concentration of impurities built up during that time, no significant change in voltage was observed when the system was burped.

There was a more significant difference between the propellant-grade and high purity reactants early in the test. Figure 21 shows this variation is likely due to the difference in oxygen inlet temperature observed during the two tests. The reactants are stored outside and are subject to significant variations in temperature from day to day. These two tests were performed on different days.

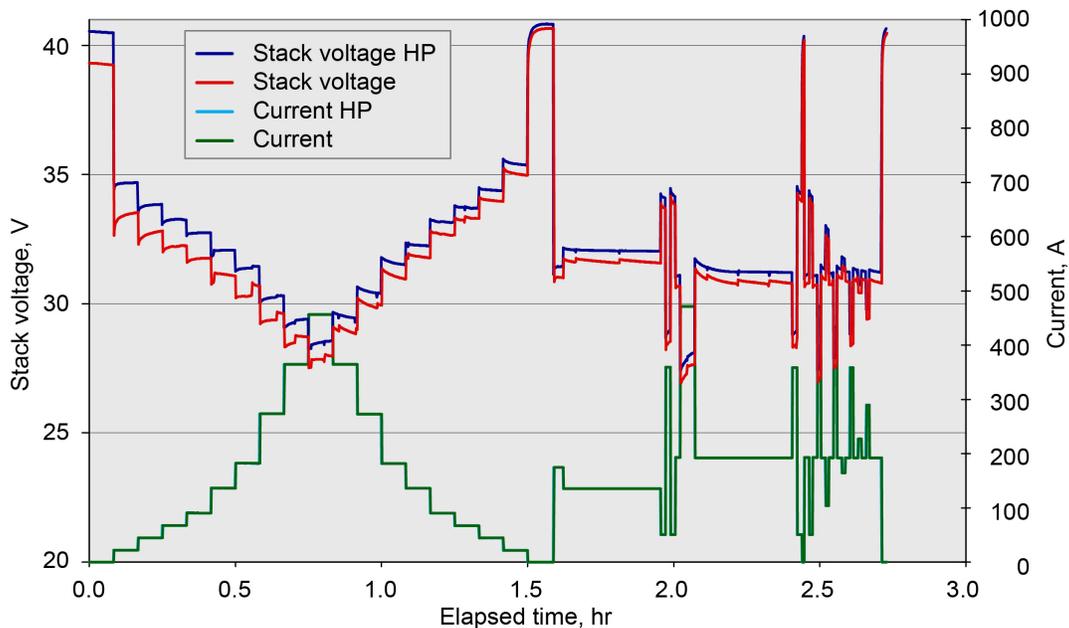


Figure 20.—Calibration series test comparison using normal reactant purity gas versus ultrahigh purity gas.

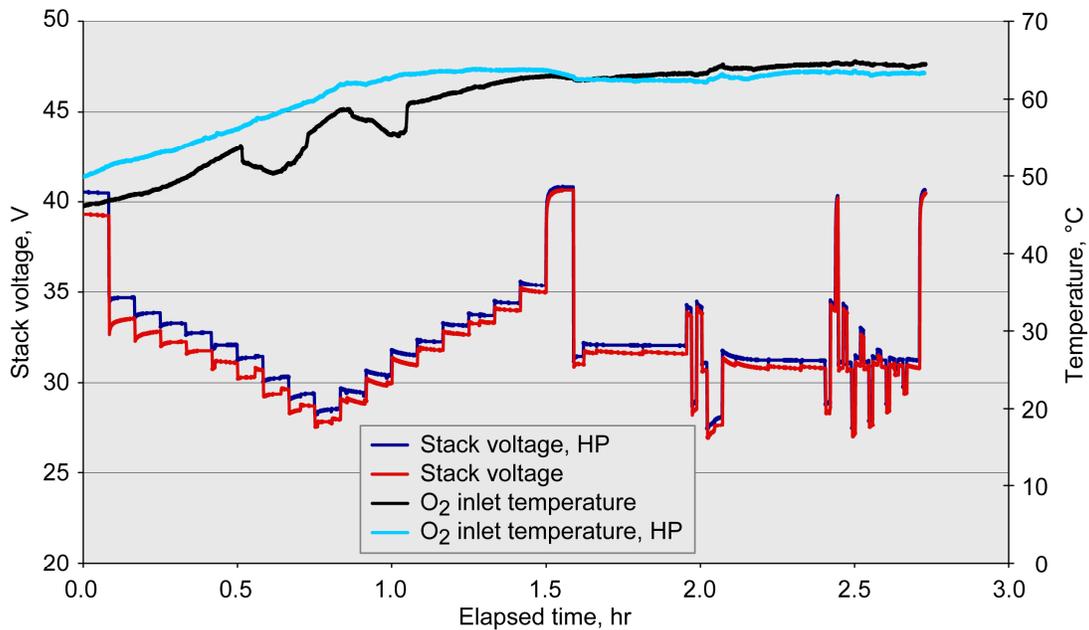


Figure 21.—Calibration series test comparison using normal reactant purity gas versus high purity oxygen reactant inlet temperature.

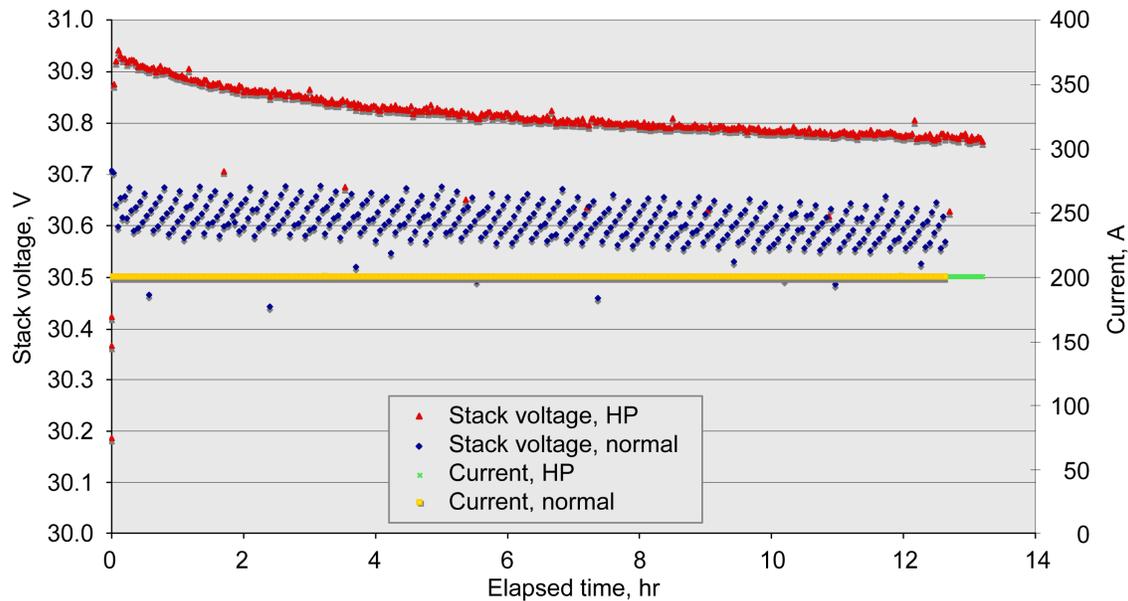


Figure 22.—Constant load, high purity versus normal grade hydrogen and oxygen reactants in orientation A.

As a result of the voltage degradation observed over time during the mission profile test, an additional test using propellant-grade reactants and high purity reactants was conducted using a constant current power profile. This was performed to differentiate between two potential causes for the voltage degradation observed, that is, a buildup of impurities that were not entirely purged from the powerplant system during the intermittent burps and the buildup of water in the system over time. As can be seen in Figure 22, during the duration of the test, using an identical power load, the test utilizing high purity reactants showed significantly more degradation than the test utilizing propellant-grade reactants.

The noisier voltage response for the propellant-grade reactants is again the result of the intermittent burping of the system and the concomitant voltage recovery. As a result of this test, it is obvious that the buildup of impurities is not the cause of the reversible degradation. Rather, it is likely because of the slow buildup of product water in the system that has not been entirely removed from the powerplant. Typically, the higher the oxygen concentration, the higher quantities of water produced.

Overall Performance Effects

Loss of Coolant Test

The loss of coolant test was intended to measure the response of the powerplant in the event of the external thermal loop shutting down. The test is a variation of the performance load profile test. Approximately 6 hr into the performance load profile test, at a power load of 226 A (7 kW), the external coolant loop is turned off for 9 min. After 9 min, the external coolant loop is turned back on and the performance load profile is continued at 192 A. Success is measured by the ability of the EM powerplant to maintain temperatures below 70 °C during the interval while the facility (external) coolant loop is shut off. The EM powerplant temperatures exceeded the upper temperature limit of 70 °C, 7 min and 37 s into the 9-min interval (see Figs. 23 and 24). The EM powerplant did not have sufficient thermal mass to absorb the waste heat produced by the fuel cell stack during the 9 min at 7 kW.

Powerplant Performance

The EM powerplant was extensively tested at NASA Glenn over a variety of conditions, including orientation, varying power profiles, and varying incoming reactant conditions. Nine months of total performance testing was conducted at NASA Glenn prior to delivery to NASA Johnson Space Center for environmental testing. Overall, the powerplant performed very well.

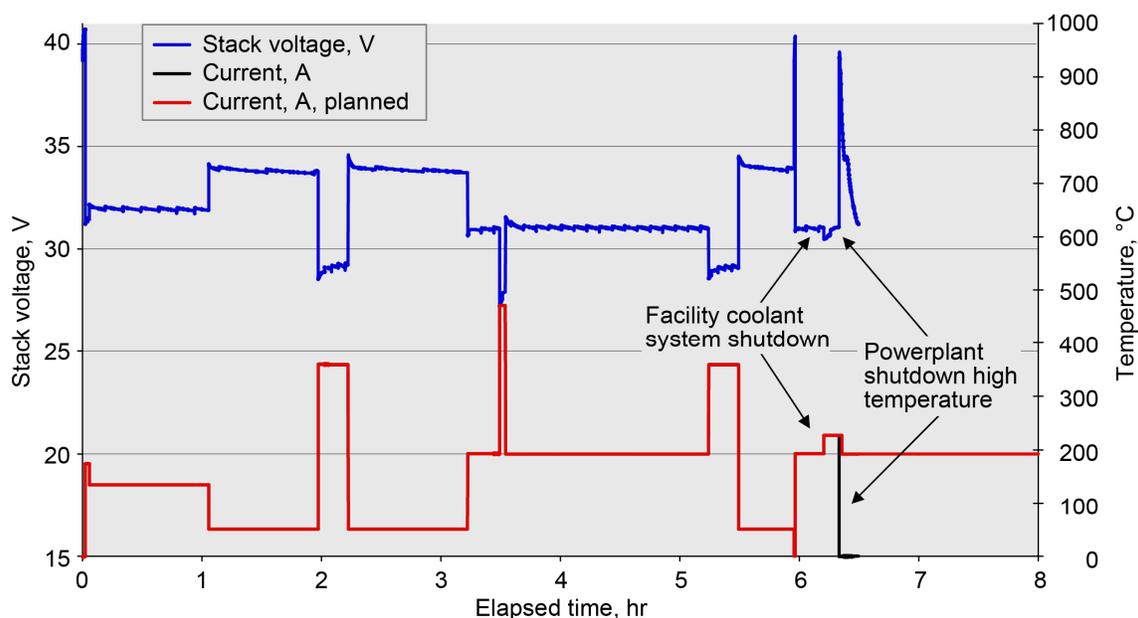


Figure 23.—Loss of coolant test in orientation A.

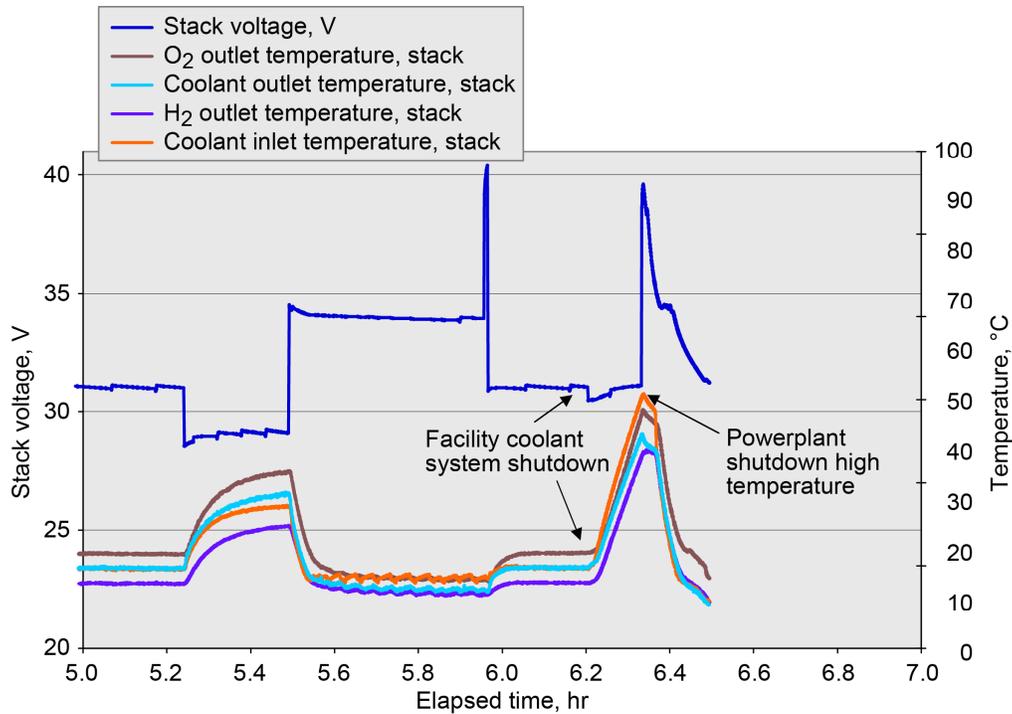


Figure 24.—Loss of coolant test in orientation A (stack voltage and temperatures).

TABLE II.—OPERATIONAL CHARACTERISTICS OF THE ENGINEERING MODEL FOR THE FIRST AND LAST CALIBRATION SERIES TESTS

Operational characteristics	Calibration series test 8/26/05	Calibration series test 5/25/06
Hydrogen in (TP1), °C	43.0 to 54.9	38.3 to 55.6
Hydrogen out (TP2), °C	40.9 to 57.8	40.6 to 56.8
Oxygen in (TP3), °C	52.7 to 61.5	44.4 to 62.0
Oxygen out (TP4), °C	43.7 to 66.2	42.8 to 65.5
Coolant in (TP5), °C	44.7 to 61.1	45.1 to 60.4
Coolant out (TP6), °C	42.9 to 63.4	42.3 to 62.4
Hydrogen temperature into powerplant, °F	66.6 to 77.9	66.3 to 72.5
Oxygen temperature into powerplant, °F	67.0 to 72.8	66.4 to 70.5
Stack voltage, V	26.8 to 40.2	27.1 to 40.6
Average cell voltage, V	0.688 to 1.030	0.697 to 1.041
Cell differential, V	0.011 to 0.043	0.009 to 0.031

Table II compares data between the first and last test run with Figure 25 providing the stack voltage trends for each calibration series test. The EM stack achieved about 1114 hr of operation, and overall the stack performed well with no observed dropoff in performance being noted. This was an approximate run time because the system operational hours had, at one point, reset during operation.

During the 9-mo test period, persistent problems occurred with regards to the operation of the reactant recirculation pumps and the water separator units. These problems manifested themselves almost exclusively during startup of the powerplant, often necessitating manual intervention to transition the ancillaries to operational status. However, almost without exception, once the ancillaries were operational, they performed well without problems. The root of the problems was found to be a function of quality control as well as motor controller function. As an example, significant issues were encountered during startup of the oxygen recirculation pumps. These problems escalated as testing continued. Eventually, the recirculation pump became nonoperational. It was disassembled, and after discussions with the manufacturer, it was found that the internal “wetted” surfaces had been manufactured with materials incompatible with oxygen use. As the material degraded, the performance of the recirculation pump was compromised.

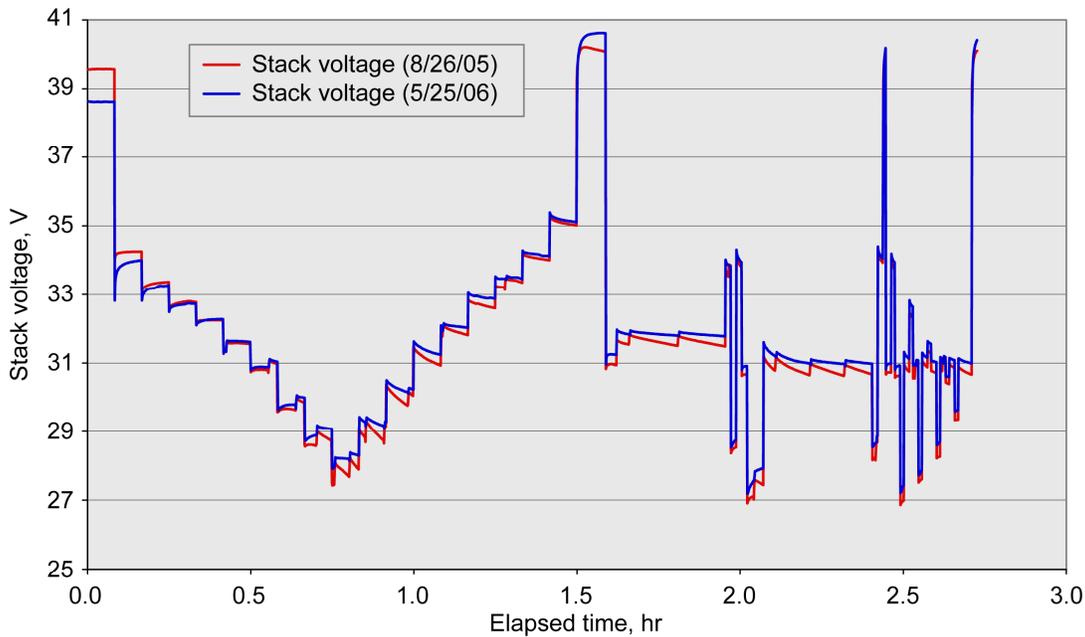


Figure 25.—Engineering model stack voltage comparison between the first and last calibration series tests in orientation A.

Conclusion

The performance of the fuel cell stack and the ancillary components was insensitive to changes in the orientation of the powerplant. Gravitational effects did not affect the performance of the fuel cell powerplant.

System ancillaries, specifically the gas circulation pumps and gas and water separators, experienced the most variability in performance and required the most maintenance to sustain operations. The hydrogen water separator had to be manually rotated numerous times, and the oxygen pump with controller went through several replacements. In general, the problems encountered with the ancillary components were mainly one of quality control, being issues of incompatible materials, bad controllers, and manufacturing tolerances. Once the powerplant system was fully operational for each test run, the stack performed exceptionally well with little variation in the cell-to-cell voltages. This was indicative of a good powerplant design in that the performance of each cell within the 117-cell stack (39 cells per substack) performed nearly the same. Each cell was provided adequate reactants, and the product water removed efficiently.

The EM design goals that were met have been summarized in Table III. System ancillaries were temperamental and would at times not start as designed. The ancillaries generally did not allow a clean startup to occur on each testing day. Once the system was operational though, the EM was generally seen to complete each test. This resulted in the maintenance-free operation for 3000 hr goal not being met. The loss of coolant test was intended to measure the response of the powerplant in the event of the external thermal loop shutting down. The EM powerplant did not have sufficient thermal mass to absorb the waste heat produced by the fuel cell stack during the 9 min at 7 kW; hence, the loss of a secondary coolant loop goal was not satisfied.

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

Engineering model design goals	Verification status
Produce 2 to 12 kW of electrical power within a voltage range of 33 to 27 VDC	Met at Glenn Research Center
Gravity and orientation independent operation	Met at Glenn Research Center
Maintenance-free operation for 3000 hr	Did not meet at Glenn Research Center
90 percent of the final change in voltage shall occur within 0.2 s	Met at Glenn Research Center
Shall be capable of automatic startup to 3 kW in less than 5 s if reactants are present, initial stack temperature is greater than 40 °F, and no inerts are present	Met at Glenn Research Center
Shall be capable of shutdown in less than 1 min	Met at Glenn Research Center
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	Met at Glenn Research Center
Operating life shall be greater than 3000 hr	Not yet met
Shall be capable of operation for 9 min at 7 kW without cooling from a secondary coolant loop	Did not meet at Glenn Research Center
Shall be capable of a minimum 250 stop/start cycles	Not yet met

Follow-On Research

Follow-on efforts will utilize passive system components in place of the active circulation pumps and gas and water separators. An upgraded breadboard stack with thinner membranes and lighter bipolar plates will also be utilized in the overall passive fuel cell system. Both stack and system performance will be closely monitored throughout each individual test. Specifically, the upgraded breadboard stack’s performance will be observed to see if any changes in performance occur over time, and the passive components will be monitored throughout to document how they respond to changes in load and under steady-state conditions. Direct performance comparisons to the active components will then be able to be made.

Appendix A.—Calibration Series Test

The calibration series test was a reference test of the engineering model (EM). The series was composed 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 EM at Teledyne, NASA Glenn, and NASA Johnson Space Center. The calibration series test was used to quantify performance changes of the EM as a function of shipping, orientation effects, and 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.

TABLE IV.—ENGINEERING MODEL CALIBRATION SERIES TEST CONDITIONS

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Stack voltage, V	Total time, s	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
^a 23b	5	51	5	1	-----	7100	57
^a 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
^a 29b	5	357	5	1	-----	8720	394
^a 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
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

TABLE IV.—Concluded.

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Stack voltage, V	Total time, s	Current density, mA/cm ²
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

^aVoltage transients occurred at the element numbers marked, and at these locations data was recorded at 200 kHz using the DataMax software.

Appendix B.—Performance Load Profile Test Description

The performance load profile test was a benchmark test of the engineering model (EM). This test was used to evaluate the performance of the EM under different operational conditions, such as orientation and vibration. The performance load profile test was carried out at Teledyne and NASA Glenn. 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 V.—ENGINEERING MODEL PERFORMANCE LOAD PROFILE TEST CONDITIONS

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Stack voltage, V	Total time, s	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
^a 4b	5	51	5	1	-----	7050	57
^a 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
^a 10b	5	357	5	1	-----	19710	394
^a 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
13	860	192	5	5	30.75	22280	212
14	40	51	5	5	33.89	22320	57
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

^aVoltage transients occurred at the element numbers marked, and at these locations data was recorded at 200 kHz using the DataMax software.

Appendix C.—Fifty Percent of Capability Test

The 50 percent of capability test was an evaluation of the speed of the response of the engineering model (EM) to loads after rapid startup. The EM was started using the rapid start procedure, which included purging the unit of nitrogen but did not include a warmup of the fuel cell or powerplant. After completion of this test, the powerplant was shut down and restarted using the normal startup 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 VI.—ENGINEERING MODEL 50 PERCENT OF CAPABILITY TEST CONDITIONS

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Stack voltage, V	Total time, s	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

Appendix D.—Mission Profile Test

The mission profile test is used to measure the performance of the engineering model (EM) powerplant over a power profile and duration representative of future missions. The test is run uninterrupted for the entire 240 hr.

TABLE VII.—ENGINEERING MODEL MISSION PROFILE TEST

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Total time	Current density, mA/cm ²	Comments
1a	5 hr 55 min	200	300	150	5 hr 55 min	221	Restart
1b	5 min	200	300	5	6 hr	221	Restart
2a	5 min	128	300	5	6 hr 5 min	142	Prelaunch
2b	5 hr 50 min	128	300	150	11 hr 55 min	142	Prelaunch
2c	5 min	128	300	5	12 hr	142	Prelaunch
3a	5 min	237	300	5	12 hr 5 min	262	Launch
3b	50 min	237	300	150	12 hr 55 min	262	Launch
3c	5 min	237	300	5	13 hr	262	Launch
4a	5 min	200	300	5	13 hr 5 min	221	Mission
4b	191 hr 50 min	200	300	150	204 hr 55 min	221	Mission
4c	5 min	200	300	5	205 hr	221	Mission
5a	5 min	128	300	5	205 hr 5 min	142	Landing and calibration
5b	17 hr 50 min	128	300	150	222 hr 55 min	142	Landing and calibration
5c	5 min	128	300	5	223 hr	142	Landing and calibration
6	0.5	61	300	5	223.5	67	Calibration
7	0.5	400	300	5	224	442	Calibration
8	0.5	237	300	5	224.5	262	Calibration
9	0.5	164	300	5	225	180	Calibration
10a	5 min	128	300	5	225 hr 5 min	142	Landing and calibration
10b	3 hr 50 min	128	300	150	228 hr 55 min	142	Landing and calibration
10c	5 min	128	300	5	229 hr	142	Landing and calibration
11a	5 min	0	300	5	229 hr 5 min	0	Cooldown
11b	10 hr 55 min	0	300	150	240 hr	0	Cooldown

Appendix E.—Loss of Coolant Test

The loss of coolant test is used to evaluate the performance of the engineering model (EM) powerplant when the cooling system external to the powerplant is interrupted. During this test, the facility cooling system is interrupted at the beginning of element no. 14 and then restarted at the beginning of element no. 15.

TABLE VIII.—ENGINEERING MODEL LOSS OF COOLANT TEST

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Stack voltage, V	Total time, s
1	30	0	5	5	30	0
2	120	174	5	5	150	192
3	3600	135	5	5	3750	149
4	3300	51	5	5	7050	56
5	900	357	5	5	7950	394
6	3600	51	5	5	11550	56
7	960	192	5	5	12510	212
8	180	468	5	5	12690	517
9	6120	192	5	5	18810	212
10	900	357	5	5	19710	394
11	1680	51	5	5	21390	56
12	30	0	5	5	21420	0
13	860	192	5	5	22280	212
14	540	226	5	5	22820	249
15	5980	192	5	5	28800	212

Appendix F.—Constant Load Test

The constant load tests were performed in order to see if improvements would be made in performance with the engineering model (EM) stack warmed up prior to changing its orientation as well as immediately following the change to its new orientation. The tests also were performed using ultrapure hydrogen and oxygen gas to help explain the voltage degradation observed while performing the mission profile under the same load condition with the gas supply coming from the hydrogen and oxygen tube trailers. Each test's profile is provided in Table IX.

TABLE IX.—CONSTANT LOAD PROFILE TEST WITH VARYING REACTANT GAS CONCENTRATIONS

Element no.	Increment time, s	Current, A	Teledyne data recording interval, s	NASA Glenn data recording interval, s	Total time, s	Current density, mA/cm ²
1	Varied for individual runs	200	5	5	Varied for individual runs	221

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14. ABSTRACT 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 continued under Constellation Systems in the Exploration Technology Development Program. Initially, the engineering model (EM) powerplant was evaluated with respect to its performance as compared to acceptance tests carried out at the manufacturer. This was to determine the sensitivity of the powerplant performance to changes in test environment. In addition, a series of tests were performed with the powerplant in the original standard orientation. This report details the continuing EM benchmark test results in three spatial orientations as well as extended duration testing in the mission profile test. The results from these tests verify the applicability of PEM fuel cells for future NASA missions. The specifics of these different tests are described in the following sections.					
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