NASA/TM—2011-216783

Characterization Testing of the Teledyne Passive Breadboard Fuel Cell Powerplant

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July 2011

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Summary

NASA's Exploration Technology Development Program (ETDP) is tasked with the development of enabling and enhancing technologies for NASA's exploration missions. As part of that initiative, the return to the Moon requires a reliable, efficient, and lightweight fuel cell powerplant system to provide power to the Altair Lunar Lander and for lunar surface systems. Fuel cell powerplants are made up of two basic parts; the fuel cell itself and the supporting ancillary subsystem. This subsystem is designed to deliver reactants to the fuel cell and remove product water and waste heat from the fuel cell. Typically, fuel cell powerplant ancillary subsystems rely upon pumps and active water separation techniques to accomplish these tasks for closed hydrogen/oxygen systems. In a typical system, these components are the largest contributors to the overall parasitic power load of the fuel cell powerplant. A potential step towards the development of an efficient lightweight power system is to maximize the use of "passive" or low-power ancillary components as a replacement to these high-power load components.

Introduction

The Teledyne proton exchange membrane (PEM) fuel cell breadboard powerplant was designed to address alternatives to two subsystems within the powerplant: the gas and water separator and the reactant gas recirculation pumps. Both the recirculation pumps and the active water separation methods are the major contributors to the parasitic power load of a fuel cell powerplant (Ref. 1, internal report). As such, the development of alternative, low-power ancillary components for these tasks were chosen. The powerplant consists of a water-cooled, hydrogen/oxygen PEM fuel cell stack along with supporting ancillaries (Fig. 1) and a separate control and data acquisition system. Facility power is used to initially start the powerplant, that is, the opening of reactant valves and initiation of the coolant and heating loop. After the powerplant is operational, the ancillary components, except for the data acquisition and control, are powered by the powerplant itself.

The breadboard powerplant uses a unique water separation mechanism to separate the product water from the oxygen reactant stream. In the past, for variable gravity water separation, a centrifugal method of separating the water from the reactant gas stream had been used. The method integrated within the breadboard powerplant has no moving parts but rather relies upon the separation of water from gas via a porous membrane. This membrane allows the passage of water but not the reactant gas. Within the breadboard, this passive water separator was used on the oxygen reactant stream. A backup, gravity-dependent water separator was placed in series with the passive unit to collect any water not separated from the oxygen gas stream. This was done to prevent damage to the fuel cell stack in the instance that the passive system did not work sufficiently. A gravity-dependent water separator was used to separate any small quantities of water carried by the hydrogen reactant stream.

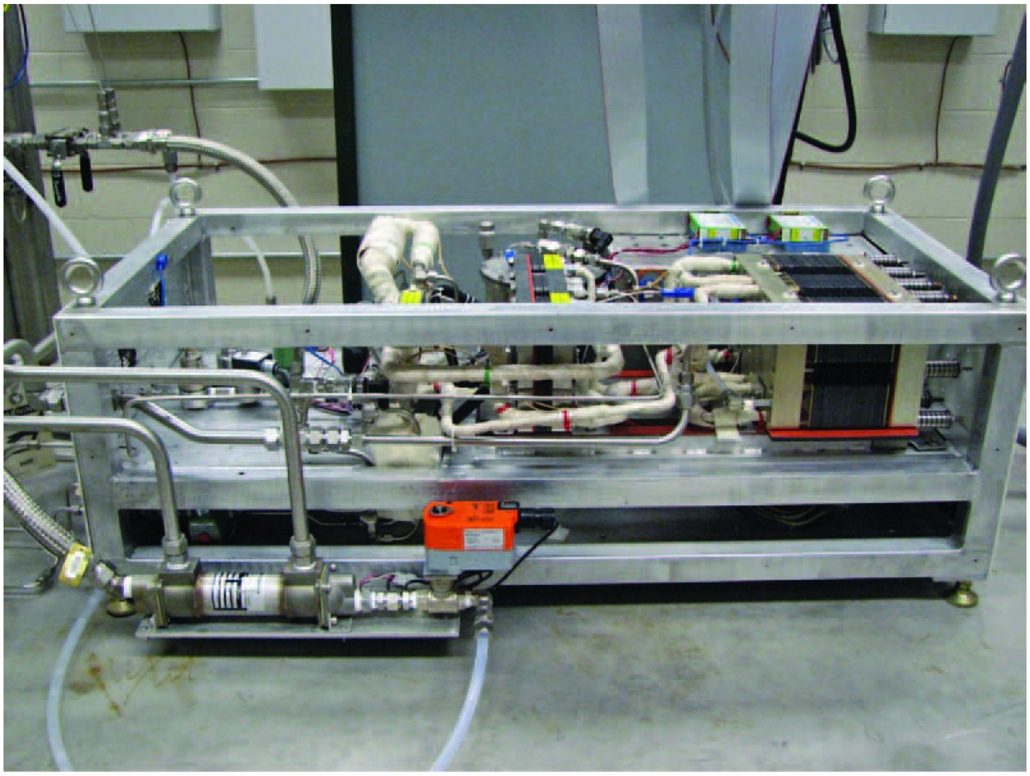

Figure 1.—Teledyne proton exchange membrane fuel cell breadboard powerplant.

The breadboard powerplant uses a low-power alternative to the stand recirculation pumps used in the past. The role of the active gas reactant recirculation pumps normally used for reactant recirculation, has been replaced by a combination of a fuel injector/ejector on the hydrogen side and a solenoid/ejector on the oxygen side (Ref. 2, internal report). The gas recirculation rate is a function of the pulse rate of the fuel injector/ejector or solenoid valve/ejector. The parasitic power required to operate the injector/ejector or solenoid valve/ejector is on the order of approximately 10 W as opposed to the 100 to 200 W used by gas recirculation pumps.

The fuel cell stack comprised 32 individual cells in a series configuration. The fuel cell stack was designed to provide 1.5 kW (nominal) and up to 1.8 kW peak. The passive water separator is located downstream of the fuel cell (Ref. 2, internal report). While the fuel cell product water is removed from the stack using a passive gravity independent water separator, a backup gravity-dependent water separator on the oxygen side is also installed (Ref. 2, internal report). On the hydrogen side, any water is removed from the gas stream via a gravity-dependent water separator. Waste heat is removed from the stack via an internal liquid cooling loop. The powerplant cooling system in turn rejects the heat to a facility cooling system external to the powerplant.

Test Summaries

The stability, performance, life, and response time of the Teledyne breadboard powerplant were evaluated using a series of tests. These performance tests were conducted to assess performance and stability over conditions anticipated to be encountered during operation under mission scenarios. A brief description of each test type follows below. Detailed information regarding operating parameters of each test is included in Appendix C.

Calibration Series Test

The calibration series test was a reference test for the breadboard powerplant. The series comprised 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 breadboard powerplant at NASA Glenn Research Center. The calibration series test was used to quantify performance changes of the breadboard model as a function of damage resulting from shipment, testing, or age. Voltage transitions were recorded at a rate of 200 kHz during the various transitions in current.

Performance Load Profile Test

The performance load profile test was a benchmark test for the breadboard model powerplant. This load profile was developed to approximate a typical power load on the Space Shuttle orbiter. Voltage transitions were recorded at a rate of 200 kHz during some of the transitions in current.

Transient Load Profile Test

The utilization of passive components could negatively impact the ability of the powerplant system to follow rapid changes in power load demand. The transient load profile test was used to assess the performance and response of the passive ancillary components to multiple, rapid changes in power demand.

Water Separator Evaluation

The gravity-independent, passive water separator was evaluated by applying a constant power load to the powerplant for 20 hr. During that time, the water collected by the oxygen gravity-independent, passive water separator, the oxygen gravity-dependent backup water separator and the hydrogen gravity-dependent water separator was collected and measured. Several power levels were applied to the breadboard powerplant to evaluate the water separator.

Test Results and Discussion

Calibration Series Tests

During the course of the evaluation testing of the Teledyne breadboard powerplant, a power profile calibration series was applied at regular intervals to the powerplant (Figs. 2 and 3). The aim of this test was to not only monitor current performance of the powerplant but also capture changes in the performance over time as a result of age, extended testing or any environmental effects.

Figure 3 shows, even as the power load level drawn from the fuel cell changes from 0 to 1800 W, the ancillary component parasitic power remains relatively constant, varying between 130 and 150 W. Within the powerplant, only the injector/ejector recirculation system varies with fuel cell power. The parasitic power required by this combination is constant with only the duty cycle (how many on/off pulses per minute) varying as the rate at which the fuel injector/solenoid pulse changes.

In Figure 4, the results of the calibration testing carried out during the test regime are presented. There is some minor variation within the stack voltages. The variation observed can be a result of several factors, including coolant temperature, reactant temperature, and internal hydration content of the membranes. The stack voltage variation observed is minor and within reason given the day-to-day variation of environmental conditions.

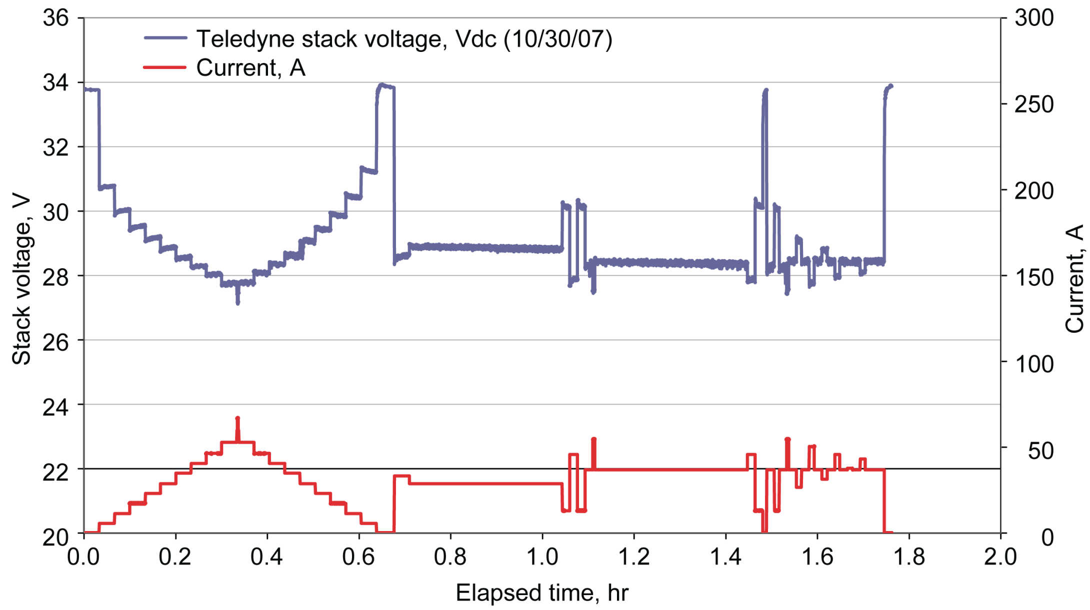

Figure 2.—Calibration series test—stack voltage and applied current load (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

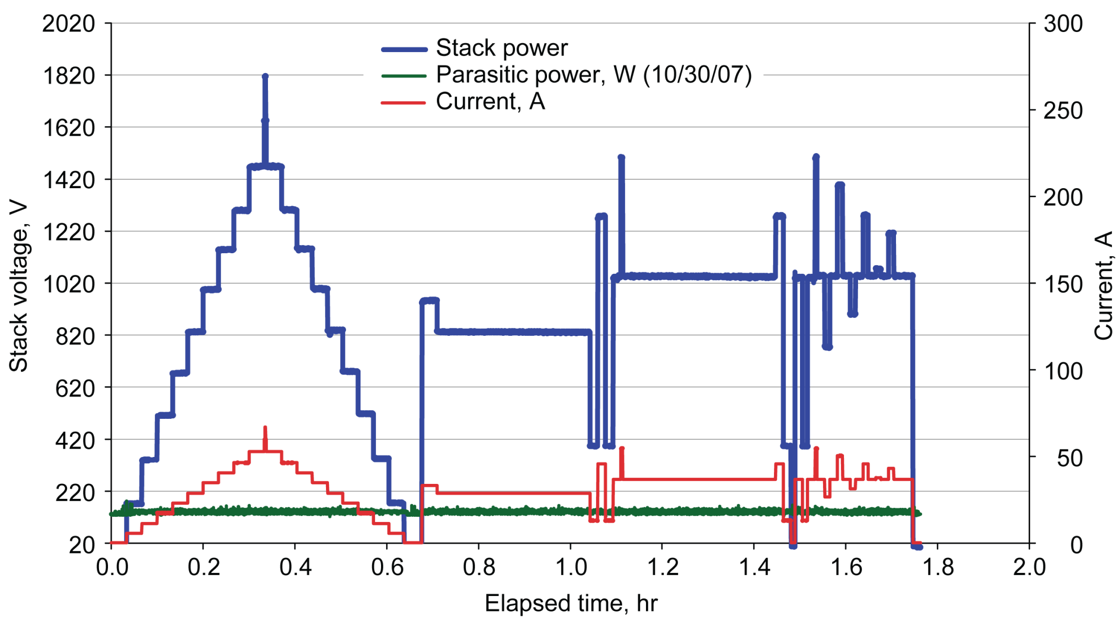

Figure 3.—Calibration series test—stack power and ancillary component parasitic power (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

Figure 5 shows the first and last calibration series collected, approximately 3 months apart, are not significantly different. However, there are some minor variations in the stack voltage. In this instance, the performance of the last calibration series collected was actually slightly better than the initial performance observed. A number of factors could be responsible for the slight performance change. These include temperatures of the reactants or the fuel cell and the relative hydration level of the membranes within the fuel cell.

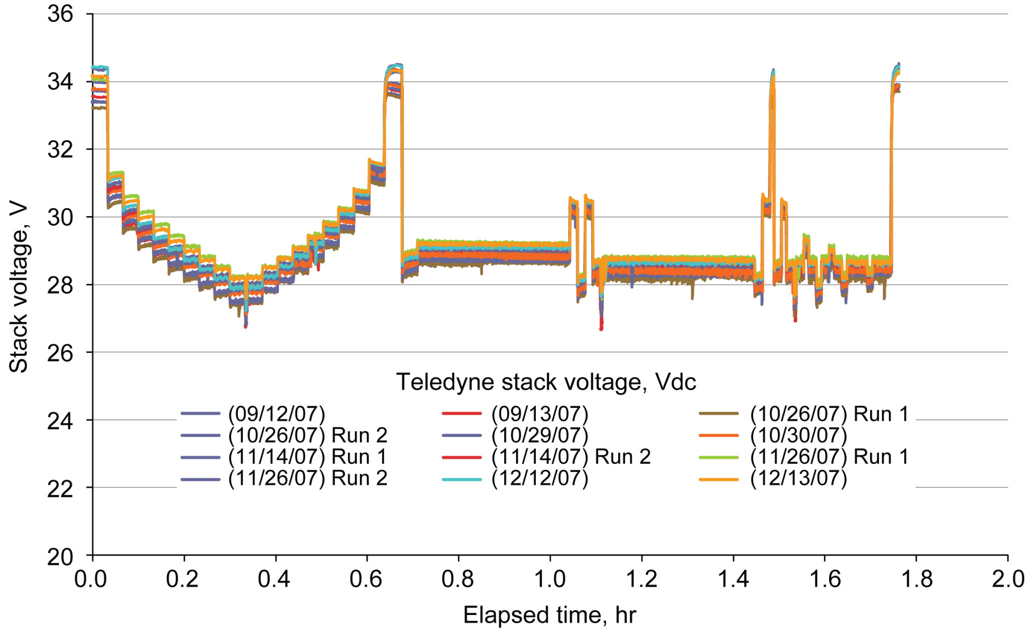

Figure 4.—Calibration series test—stack voltages from all calibration series collected (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

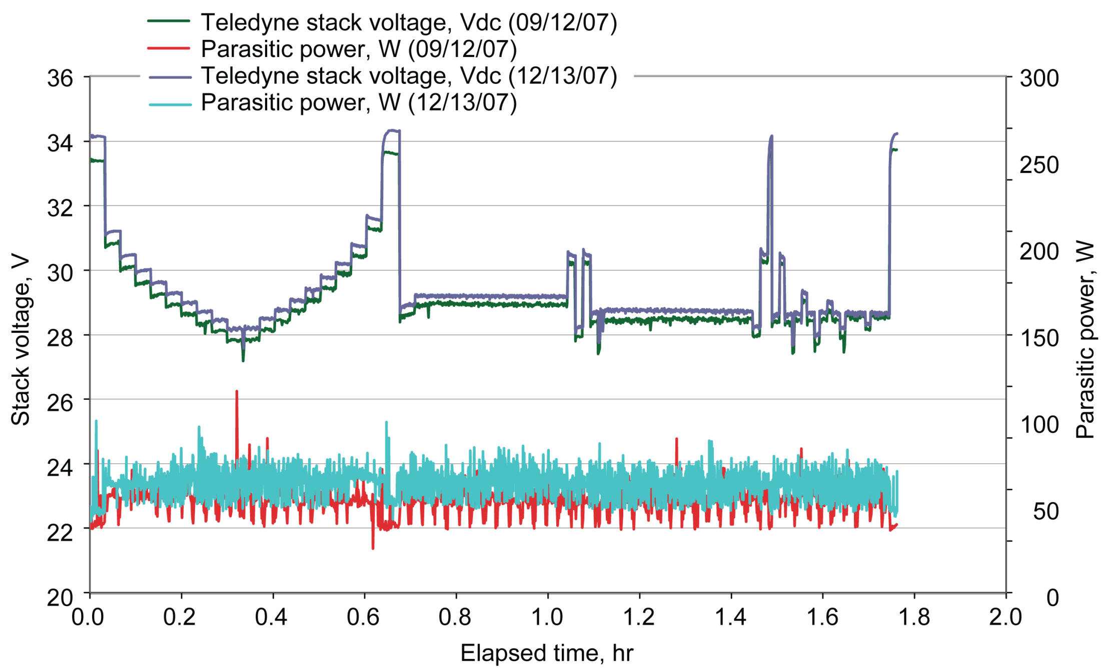

Figure 5.—Calibration series test—first and last calibration series collected (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

In Figure 6, there is a similar performance variation seen between separate calibration series run on the same day. Minor variations in coolant temperature and variable internal water content of the membranes is likely responsible for the slight voltage variation observed.

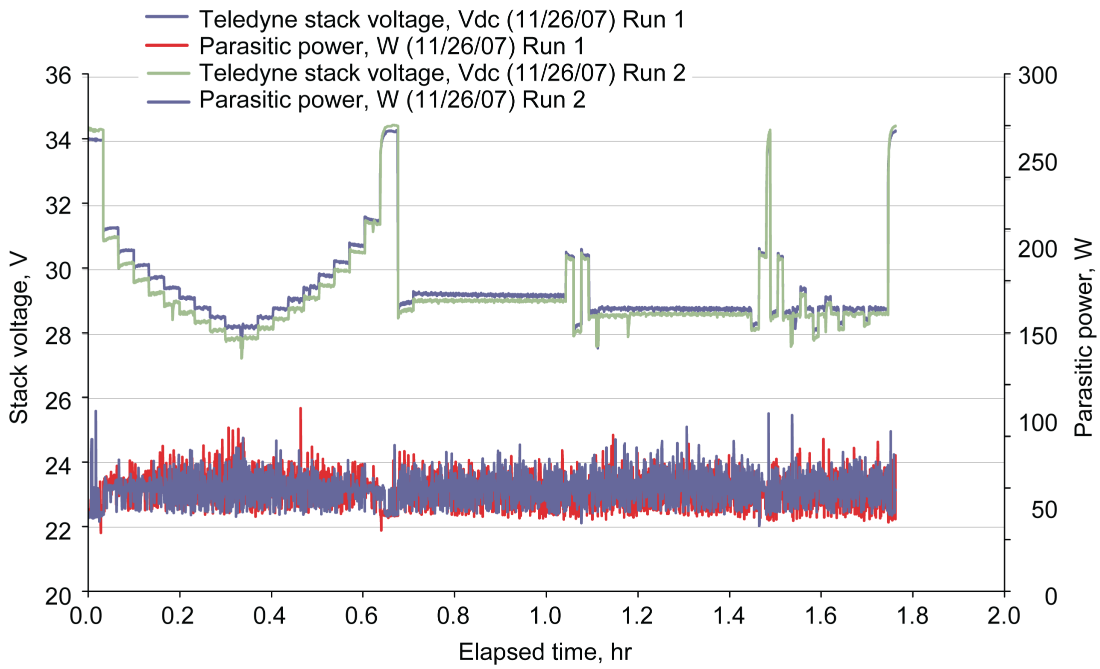

Figure 6.—Calibration series test—stack voltage and parasitic power of calibration series run on the same day (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

Performance Load Profile Test

Performance load profiles are measures of the performance and stability of the fuel cell powerplant over an 8-hr period. Performance load profile results from approximately 1 month apart can be seen in Figure 7. During this month, the breadboard powerplant had been operated for 322 hr. (The powerplant was operated for a total of 850 hr while at the Glenn Research Center.) Only minor variations in the stack voltage and power are present. As was seen for the calibration series results, small changes in temperature can result in these minor performance changes.

Transient Load Profile Test

The transient load profile was intended to evaluate the performance of the breadboard powerplant to rapid changes in power demand. The change from active recirculation pumps that quickly recirculate unused reactants to injector/ejector or solenoid valve/ejector may limit the response of the powerplant to rapid load changes. The power profile combines several instances of longer times at different power levels to several rapid changes in power load over the course of a few minutes. The applied current load and resulting powerplant power output can be seen in Figure 8. The parasitic power remains essentially constant regardless of the power output of the breadboard powerplant. This reflects the largely passive design of this powerplant.

Figure 9 displays an expanded view of the profile. This portion includes several rapid power transitions. The fuel cell powerplant is able to follow the current demands applied to it. After each transition, the power level delivered rapidly follows the current draw and remains constant and stable until the next load step. However, it should be noted that all load steps were within the design power delivery range of the powerplant. If the load steps were above or below the design range, the performance stability would likely degrade. Beyond this range, the reactant delivery and recirculation may not be adequate to meet the power demand or provide enough circulation to move the water from within the stack to the water separator.

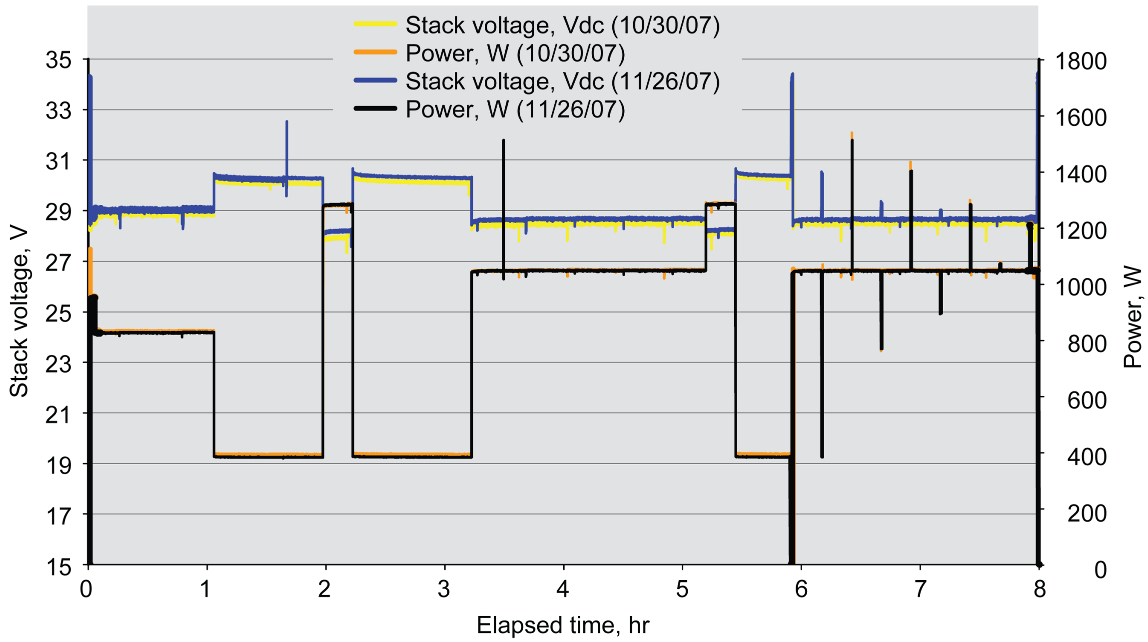

Figure 7.—Performance load profile test—stack voltage and power collected a month apart (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

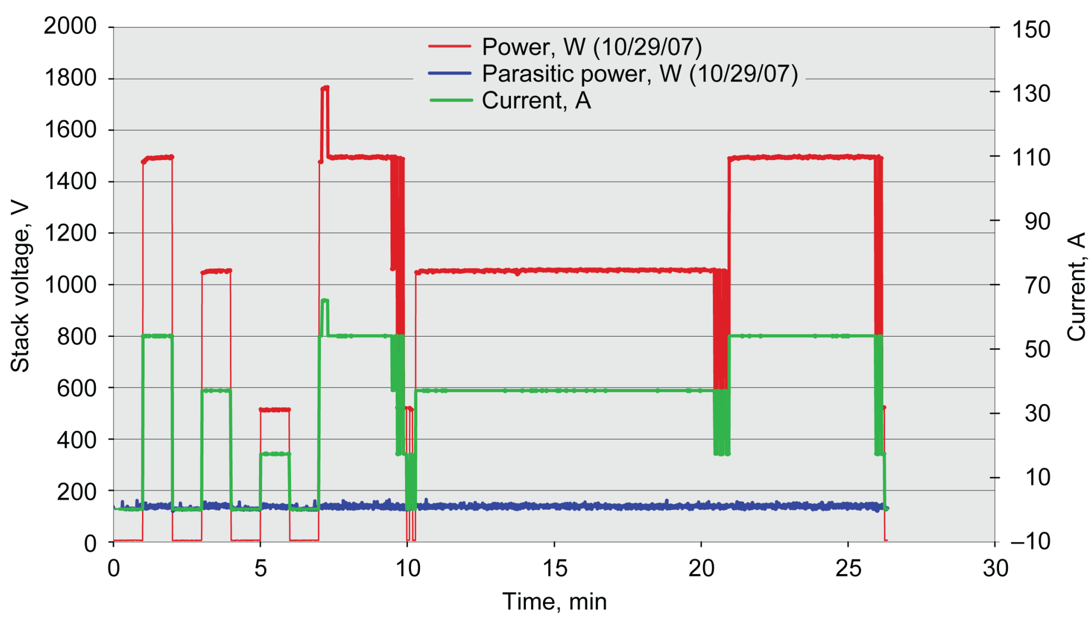

Figure 8.—Transient load profile test—stack power and parasitic power (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

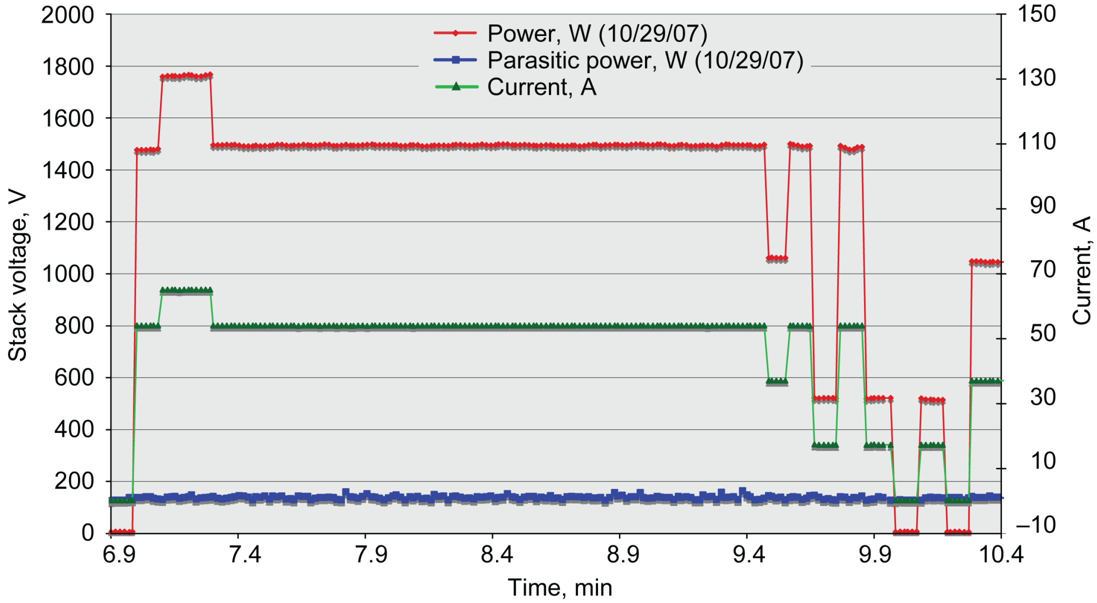

Figure 9.—Transient load profile test—expanded view of rapid changes in load demand (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

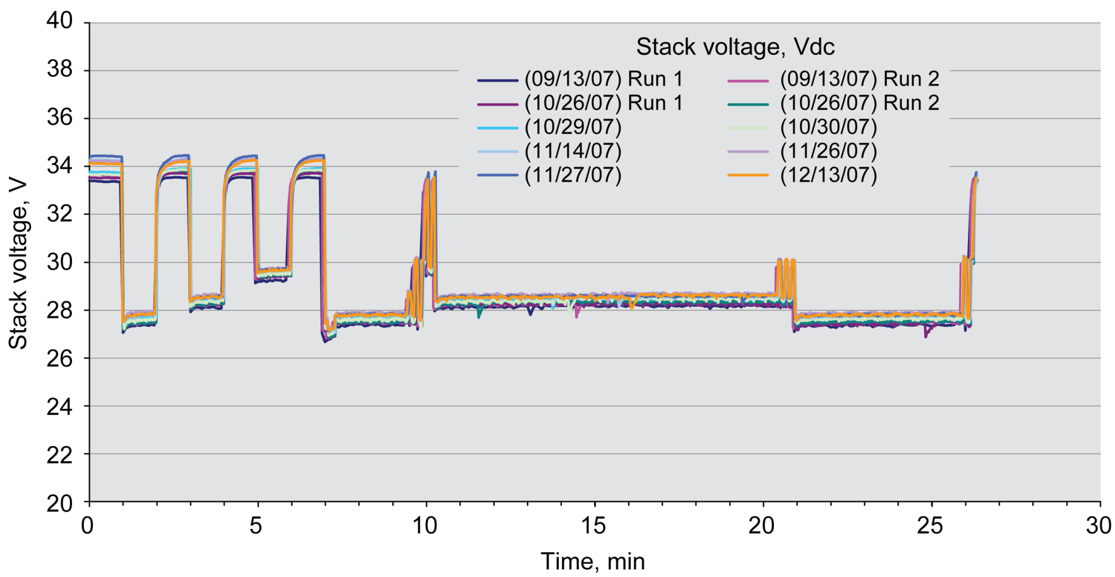

Figure 10.—Transient load profile test—all profiles collected during test periods (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

Transient load profile tests were carried out at various times during the overall test regime. The results of these tests can be seen in Figure 10. There is some variation in stack voltage between the various test runs. As previously discussed, this variation can be caused by a number of factors, including the temperature of the fuel cell from run to run. In Figure 11, the coolant inlet temperature for the various transient load profile runs is plotted. The coolant inlet temperature also varies from run to run with the higher temperature runs corresponding to the slightly higher stack voltages.

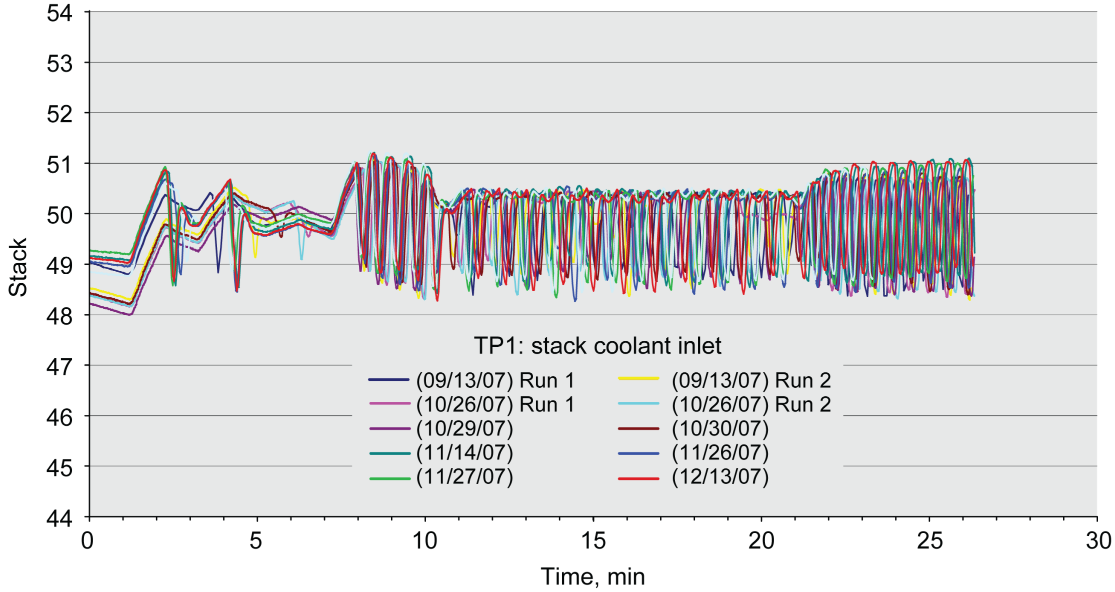

Figure 11.—Transient load profile test—inlet coolant temperatures (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

Water Separator Evaluation Test

The Teledyne breadboard powerplant uses a unique water separation mechanism to separate the product water from the oxygen-reactant stream. In the past, for variable gravity water separation, a centrifugal method of separating the water from the reactant gas stream has been used. The method integrated within the breadboard powerplant has no moving parts but rather relies upon the separation of water from gas via a porous membrane. This membrane allows the passage of water but not the reactant gas. Within the breadboard, this passive water separator was used on the oxygen reactant stream. A backup gravity-dependent water separator was placed in series with the passive unit to collect any water not separated from the oxygen gas stream. This was to prevent damage to the fuel cell stack in the instance that the passive system did not work sufficiently. A gravity-dependent water separator was used to separate any small quantities of water carried by the hydrogen reactant stream.

To evaluate the performance of the passive water separator, the powerplant was run at several power levels (Fig. 12) for a set period of time of 20 hr. During that time, product water was collected from the passive water separator on the oxygen reactant loop and the gravity dependent water separators on the hydrogen and oxygen reactant loop. At the end of each time period, the water collected in each water separator was measured. The results of the water separator test can be seen in Figure 13.

Figure 13 shows the quantity of water collected by the gravity-independent passive water separator follows a linear relationship with increasing current. Small quanities of water were also collected within the gravity-dependent separators on both the hydrogen and oxygen lines. The quantity of water collected in those separators was less than 1 percent of the water collected by the gravity-independent separator. It is likely that the water collected by the backup gravity-dependent separator is due to condensation as the temperature of the gas stream is reduced. The gravity-independent separator removed the water produced by the fuel cell over the entire range of power levels applied to the breadboard fuel cell powerplant.

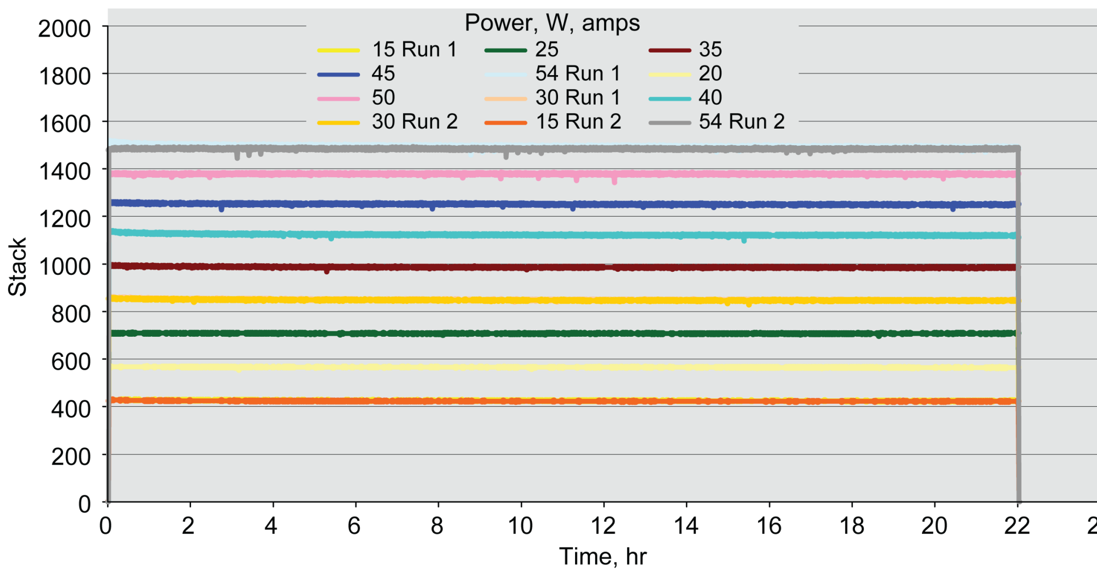

Figure 12.—Water separator test—individual power levels for the duration of each test (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

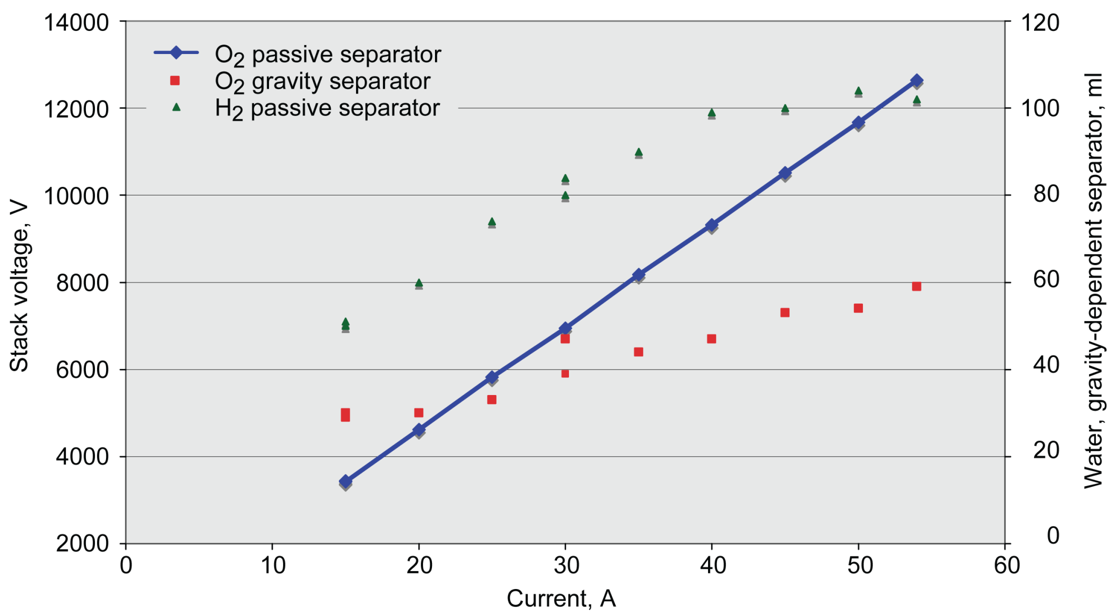

Figure 13.—Water separator test—water collected within the water separators at various levels of current load (TESI 1.5-kW option 5 breadboard H_2O_2 proton exchange membrane (PEM) fuel cell system).

Mission Profile Test

A 240-hr mission profile test profile was applied to the Teledyne breadboard powerplant. This test serves the purpose of an abbreviated life test of the powerplant. The profile is an approximation of the typical power load experienced by the Shuttle orbiter fuel cell powerplant. Figure 14 shows the test is primarily composed of a long-duration steady-state power load, with load variations in the beginning and end of the profile. Over extended periods of time, the stack voltage degrades slightly. This had been observed before in other powerplants evaluated (Ref. 3). It is likely this is due to a buildup of impurities

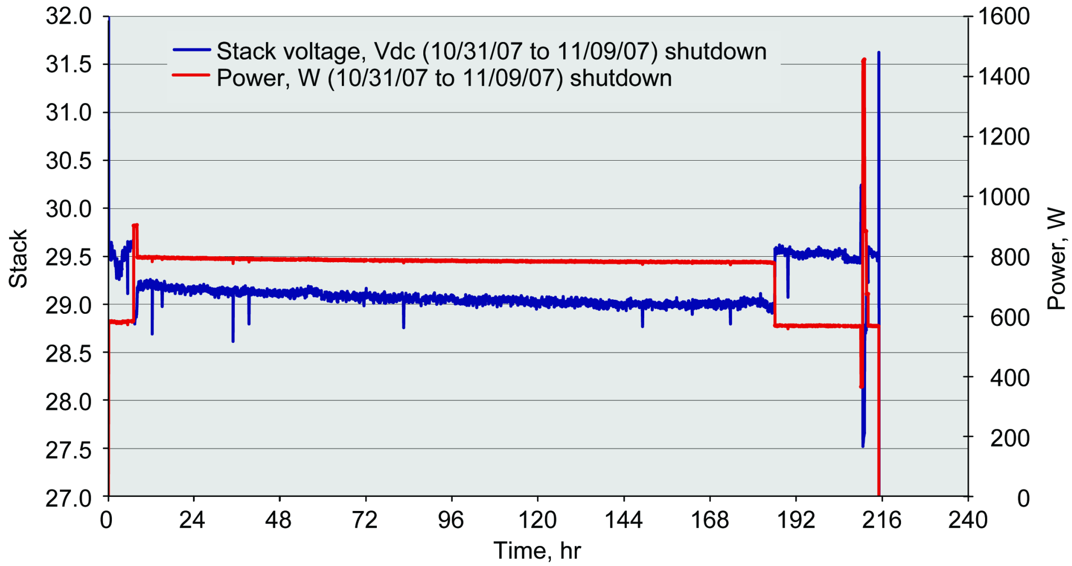

Figure 14.—Mission profile test of the Teledyne option 5 breadboard fuel cell powerplant.

and/or excess water vapor within the powerplant. Unfortunately, the powerplant shut down 72 hr short of the planned 240-hr test. The powerplant was shut down automatically by the powerplant controller as a result of a pressure differential between the oxygen and hydrogen inlet lines exceeding 8 psi. This pressure differential was caused as a result of intermittent burping of the reactant systems to vent accumulated impurities combined with the timing of the recirculation system pulses.

Conclusion

The Teledyne passive breadboard fuel cell powerplant has been evaluated with regard to its performance and stability. Repeated tests over time were conducted and evaluated. Minor variation in performance between test runs was noted, however, these variations could be attributed to temperature changes within the fuel cell, not degradation or instability. In general, the powerplant exhibited consistent and reproducible performance over time. The passive, gravity-independent water separator was evaluated during extended operation over a variety of power loads. Over the entire range of power levels applied, the passive water separator effectively separated the product water from the oxygen stream exiting the fuel cell maintaining stable performance over the entire 20-hr test period at each power level.

References

1. Teledyne Energy Systems, Inc.: PEM Fuel Cell Engineering Model Critical Design Review (CDR). December 7, 8, and 9, 2004 (internal report).
2. TESI 1.5kW Option 5 Breadboard H2/O2 PEM Fuel Cell System User Manual & System Documentation Rev 04, December 2007 NASA contract no. NAS3-02093 (internal report).
3. Loyselle, P.L.; and Prokopius, K.P.: Proton Exchange Membrane Fuel Cell Engineering Model Powerplant. Test Report: Benchmark Tests in Three Spatial Orientations. NASA/TM—2011-216224, 2011.

Appendix A.—Test Matrix

A.1 Test Schedule—2007

- Verify reproducible performance over a 3-day period
  - October 26, 2007
- Calibration series, transient test, calibration series, transient test
  - October 29, 2007
- Calibration series, transient test
  - October 30, 2007
- Calibration series, transient test

October 30, 2007

- Performance Load Profile Test
- Verify long-term behavior of powerplant/stack; verify reproducibility with respect to testing at Teledyne
  - October 31, 2007, to November 9, 2007
  - Mission Profile Test
- Evaluate any performance changes after 240-hr mission profile test
  - November 26, 2007
  - Calibration Series Test, Transient Test, Performance Load Profile Test

November 30, 2007, to December 12, 2007

- Water Separator (Teledyne Unit) Test

December 12, 2007

- Calibration Series Test, Transient Test

December 13, 2007, to December 18, 2007

- Mission Profile Test

Appendix B.—Operating Procedure for Teledyne's Upgraded Breadboard Computer

Updated: 3 January 2008

Date: ___________

1.0 Start up Procedure

______ Double click on the 20071116_NASA BB INTERFACE.vi icon on the desktop of the Teledyne Computer.

______ Select a data storage rate for the test profile to be run (Fig. B1, green circle). Selecting a storage rate of zero will collect data at a rate of about 7 samples/second.

______ Change the Delta V Shutdown Limit from 0.08 to 0.12 V.

______ Press the white arrow at the top left of the screen to start up the program.

______ Click "OK" to proceed with startup.

______ Click "OK" to keep default file name for data storage or modify the file name and then click "OK." If "CANCEL" is clicked data will not be stored.

______ Click "OK" at Confirm Nitrogen Supply prompt to begin purging and leak testing.

______ Click "OK" at Confirm Reactant Supply prompt to open reactants.

______ When the TEST STATUS display indicates "STARTUP COMPLETE: FUEL CELL SYSTEM FULLY OPERATIONAL," the power plant is at open circuit and load currents can now be applied.

______ Begin test profile using the LabVIEW system.

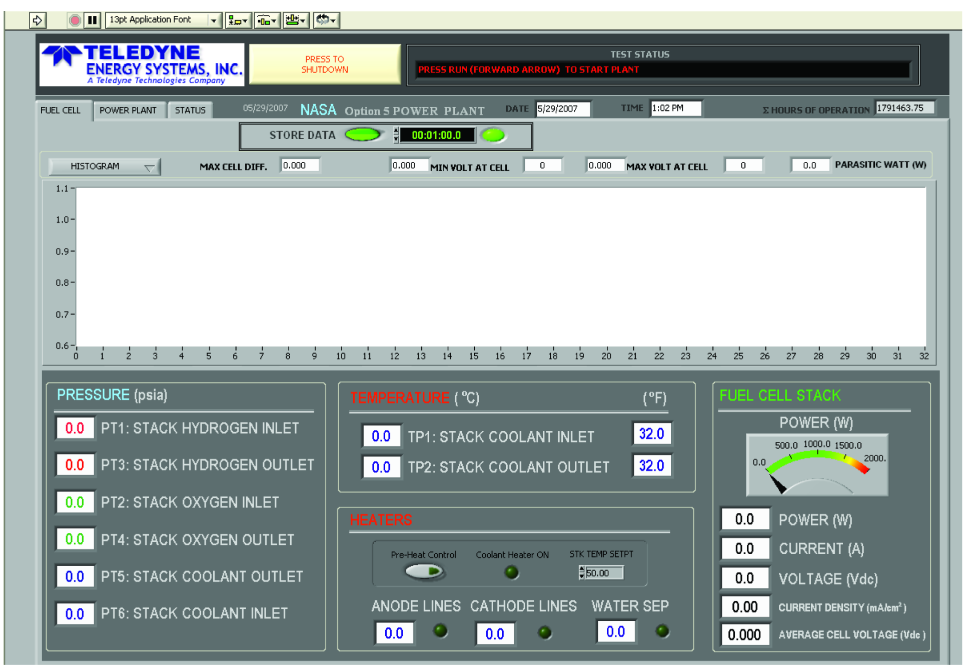

Figure B1.—Teledyne fuel cell interface screen.

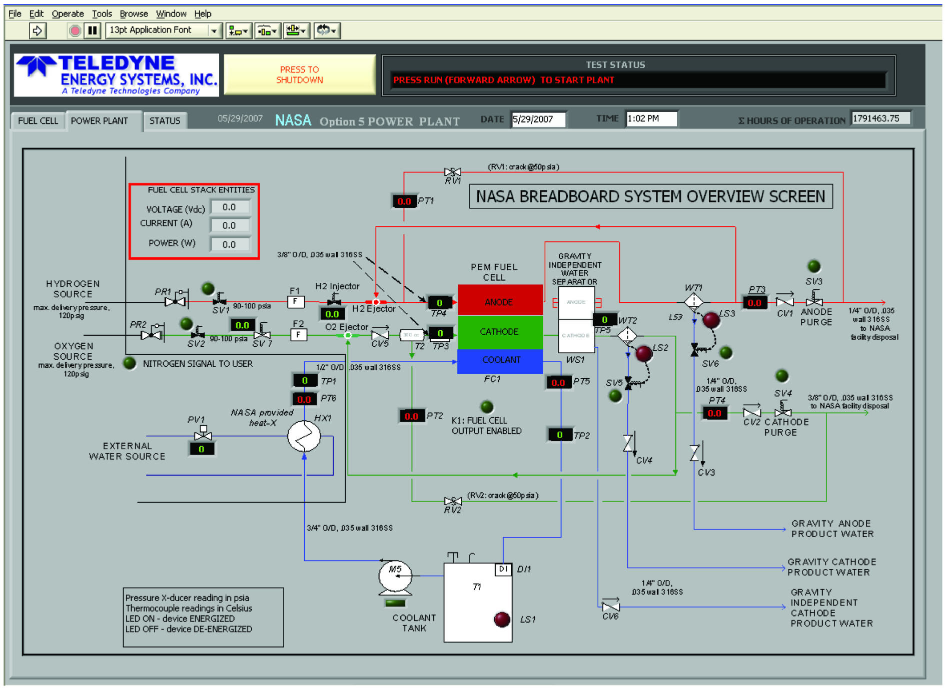

Figure B2.—Teledyne powerplant P&ID screen.

2.0 Normal Shutdown Procedure

______ Click the PRESS TO SHUTDOWN button located at the top of the Fuel Cell Interface Screen (Fig. B1, red circle). This will initiate a normal sequenced shutdown. Do not attempt to intercede or interrupt the shutdown since purging and cooling performed during shutdown is very important to maximize stack life.

3.0 Emergency Shutdown Procedure

______ Push in one of the red E-STOP buttons in the control room. This will immediately shut down the power plant.

______ Once the emergency circumstance has been resolved, close the Teledyne program, reopen it, and restart it. Proceed with a normal startup until just after the nitrogen purging begins and then click the PRESS TO SHUTDOWN button (Fig. B1, red circle). This will cause the breadboard to go through a normal shutdown allowing any residual reactant gases to be consumed and to assure the stack voltage is brought down to a safe level.

4.0 Miscellaneous Notes

______ The graph in Figure B1 is set up to show the voltage of all 32 cells. This graph can be changed to digital display or sweep graph. It is displayed currently in histogram mode (Fig. B1, yellow circle).

______ Figure B1 is currently set to the fuel cell interface screen. The screen can be changed to show the power plant P&ID screen (Fig. B2) as well as the power plant status display screen (Fig. B3).

______ If the maximum cell voltage difference becomes greater than 0.1 V, the system will automatically shut down.

______ If the minimum voltage at any individual cell is less than 0.75 V, the system will automatically shut down.

______ Do not apply peak loads in excess of 1.5 kW on a continuous basis. Peak loads between 1.5 and 1.8 kW must not exceed 15 seconds in duration.

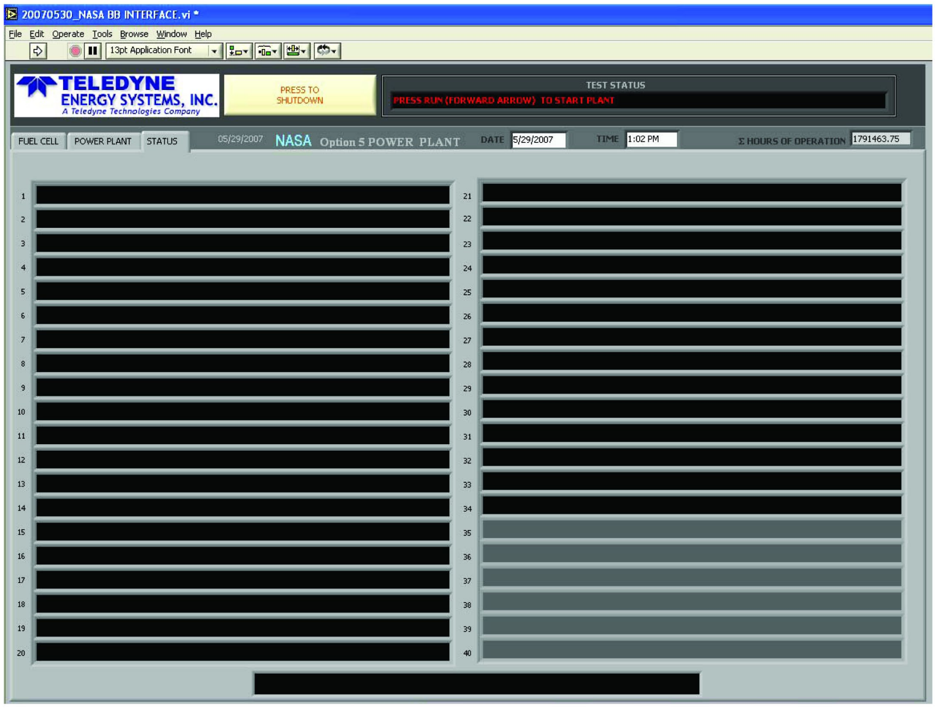

Figure B3.—Teledyne powerplant status display screen.

Appendix C.—Test Description Tables

Element no.	Increment time, sec	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time, sec	Current density, mA/cm^2	Comments
1a	115	0.0	1	1			115	0	Voltage transient
1b	5	0.0	1	1	200		120	0	
2a	5	5.8	1	1	200		125	20	
2b	115	5.8	1	1			240	20	Between Elem. 1, 2
3a	115	11.7	1	1			355	40	Voltage transient
3b	5	11.7	1	1	200		360	40	
4a	5	17.5	1	1	200		365	60	
4b	115	17.5	1	1			480	60	Between Elem. 3, 4
5	120	23.4	1	1			600	80	
6	120	29.2	1	1			720	100	
7	120	35.0	1	1			840	120	
8	120	40.9	1	1			960	140	
9	120	46.7	1	1			1080	160	
10	120	53.2	1	1			1200	182.2	
11	5	60.0	1	1			1205	205.4	
12	5	67.0	1	1			1210	229.4	
13	5	60.0	1	1			1215	205.4	
14	120	53.2	1	1			1335	182.2	
15	120	46.7	1	1			1455	160	
16	120	40.9	1	1			1575	140	
17	120	35.0	1	1			1695	120	
18	120	29.2	1	1			1815	100	
19	120	23.4	1	1			1935	80	
20	120	17.5	1	1			2055	60	
21	120	11.7	1	1			2175	40	
22	120	5.8	1	1			2295	20	
23	120	0.0	1	1			2415	0	
24	20	0.0	1	1			2435	0	
25	120	33.6	1	1			2555	115.2	
26	1200	29.0	1	1			3755	99.3	
27a	55	13.3	1	1			3810	45.6	Voltage transient
27b	5	13.3	1	1	200		3815	45.6	
28a	5	46.0	1	1	200		3820	157.6	
28b	55	46.0	1	1			3875	157.6	Between Elem. 27, 28
29	60	13.3	1	1			3935	45.6	
30	60	37.1	1	1			3995	127.2	
31	15	54.9	1	1			4010	188	
32	1200	37.1	1	1			5210	127.2	
33a	55	46.0	1	1			5265	157.6	Voltage transient
33b	5	46.0	1	1	200		5270	157.6	
34a	5	13.3	1	1	200		5275	45.6	
34b	55	13.3	1	1			5330	45.6	Between Elem. 33, 34
35a	25	0.0	1	1			5355	0	Voltage transient
35b	5	0.0	1	1	200		5360	0	
36a	5	37.1	1	1	200		5365	127.2	
36b	55	37.1	1	1			5420	127.2	Between Elem. 35, 36
37	40	13.3	1	1			5460	45.6	
38	60	37.1	1	1			5520	127.2	
39	15	54.9	1	1			5535	188	
40	60	37.1	1	1			5595	127.2	
41	40	26.9	1	1			5635	92	
42	60	37.1	1	1			5695	127.2	
43	40	50.6	1	1			5735	173.4	
44	60	37.1	1	1			5795	127.2	
45	40	31.5	1	1			5835	108	

Element no.	Increment time, sec	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time, sec	Current density, mA/cm^2	Comments
46	60	37.1	1	1			5895	127.2	
47	40	46.0	1	1			5935	157.6	
48	60	37.1	1	1			5995	127.2	
49	40	38.0	1	1			6035	130	
50	60	37.1	1	1			6095	127.2	
51	40	43.3	1	1			6135	148.4	
52a	145	37.1	1	1			6280	127.2	Voltage transient
52b	5	37.1	1	1	200		6285	127.2	
53a	5	0.0	1	1	200		6290	0	
53b	55	0.0	1	1			6345	0	Between Elem. 52, 53

C.1 Performance Load Profile

Element no.	Increment time, sec	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time, sec	Current density, mA/cm^2	Comments
1	60	0.0	1	1			60	0	
2	150	33.6	1	1			210	115.2	
3	3600	29.0	1	1			3810	99.3	
4a	3295	13.3	1	1			7105	45.6	Voltage transient
4b	5	13.3	1	1	200		7110	45.6	
5a	5	46.0	1	1	200		7115	157.6	
5b	895	46.0	1	1			8010	157.6	Between Elem. 4, 5
6	3600	13.3	1	1			11610	45.6	
7	960	37.1	1	1			12570	127.2	
8	15	54.9	1	1			12585	188	
9	6120	37.1	1	1			18705	127.2	
10a	895	46.0	1	1			19600	157.6	Voltage transient
10b	5	46.0	1	1	200		19605	157.6	
11a	5	13.3	1	1	200		19610	45.6	
11b	1675	13.3	1	1			21285	45.6	Between Elem. 10, 11
12a	55	0.0	1	1			21340	0	Voltage transient
12b	5	0.0	1	1	200		21345	0	
13a	5	37.1	1	1	200		21350	127.2	
13b	855	37.1	1	1			22205	127.2	Between Elem. 12, 13
14	40	13.3	1	1			22245	45.6	
15	885	37.1	1	1			23130	127.2	
16	15	54.9	1	1			23145	188	
17	860	37.1	1	1			24005	127.2	
18	40	26.9	1	1			24045	92	
19	860	37.1	1	1			24905	127.2	
20	40	50.6	1	1			24945	173.4	
21	860	37.1	1	1			25805	127.2	
22	40	31.5	1	1			25845	108	
23	860	37.1	1	1			26705	127.2	
24	40	46.0	1	1			26745	157.6	
25	860	37.1	1	1			27605	127.2	
26	40	38.0	1	1			27645	130	
27	860	37.1	1	1			28505	127.2	
28	40	43.3	1	1			28545	148.4	
29a	220	37.1	1	1			28765	127.2	Voltage transient
29b	5	37.1	1	1	200		28770	127.2	
30a	5	0.0	1	1	200		28775	0	
30b	55	0.0	1	1			28830	0	Between Elem. 29, 30

C.2 Transient Tests

Element no.	Increment time, sec	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time, sec	Current density, mA/cm^2	Comments
1a	55	0.0	1	1			55	0.0	
1b	5	0.0	1	1	200		60	0.0	Voltage transient
2a	5	54.0	1	1	200		65	184.9	Between Elem. 1b, 2a
2b	50	54.0	1	1			115	184.9	
2c	5	54.0	1	1	200		120	184.9	Voltage transient
3a	5	0.0	1	1	200		125	0.0	Between Elem. 2c, 3a
3b	50	0.0	1	1			175	0.0	
3c	5	0.0	1	1	200		180	0.0	Voltage transient
4a	5	37.1	1	1	200		185	127.1	Between Elem. 3c, 4a
4b	50	37.1	1	1			235	127.1	
4c	5	37.1	1	1	200		240	127.1	Voltage transient
5a	5	0.0	1	1	200		245	0.0	Between Elem. 4c, 5a
5b	50	0.0	1	1			295	0.0	
5c	5	0.0	1	1	200		300	0.0	Voltage transient
6a	5	17.5	1	1	200		305	59.9	Between Elem. 5c, 6a
6b	50	17.5	1	1			355	59.9	
6c	5	17.5	1	1	200		360	59.9	Voltage transient
7a	5	0.0	1	1	200		365	0.0	Between Elem. 6c, 7a
7b	55	0.0	1	1			420	0.0	Voltage transient
8	6	54.0	1	1	200		426	184.9	Between Elem. 7b, 8
9	12	65.0	1	1	200		438	222.6	Voltage transient between Elem. 8, 9
10a	6	54.0	1	1	200		444	184.9	Voltage transient between Elem. 9, 10a
10b	120	54.0	1	1			564	184.9	
10c	5	54.0	1	1			569	184.9	Voltage transient
11	6	37.1	1	1	200		575	127.1	Between Elem. 10c, 11
12	6	54.0	1	1	200		581	184.9	Voltage transient between Elem. 11, 12
13	6	17.5	1	1	200		587	59.9	Voltage transient between Elem. 12, 13
14	6	54.0	1	1	200		593	184.9	Voltage transient between Elem. 13, 14
15	6	17.5	1	1	200		599	59.9	Voltage transient between Elem. 14, 15
16	6	0.0	1	1	200		605	0.0	Voltage transient between Elem. 15, 16
17	6	17.5	1	1	200		611	59.9	Voltage transient between Elem. 16, 17
18	6	0.0	1	1	200		617	0.0	Voltage transient between Elem. 17 18
19	6	37.1	1	1	200		623	127.1	Voltage transient between Elem. 18, 19
20a	5	37.1	1	1			628	127.1	
20b	600	37.1	1	1			1228	127.1	Voltage transient
20c	5	17.5	1	1	200		1233	59.9	Between Elem. 20b, 20c
21	6	37.1	1	1	200		1239	127.1	Voltage transient between Elem. 20c, 21
22	6	17.5	1	1	200		1245	59.9	Voltage transient between Elem. 21, 22
23	6	37.1	1	1	200		1251	127.1	Voltage transient between Elem. 22, 23
24	6	17.5	1	1	200		1257	59.9	Voltage transient between Elem. 23, 24
25	300	54.0	1	1	200		1557	184.9	Voltage transient between Elem. 24, 25
26	6	17.5	1	1	200		1563	59.9	Voltage transient between Elem. 25, 26
27	6	54.0	1	1	200		1569	184.9	Voltage transient between Elem. 26, 27

Element no.	Increment time, sec	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time, sec	Current density, mA/cm^2	Comments
28	6	17.5	1	1	200		1575	59.9	Voltage transient between Elem. 27, 28
29	6	0.0	1	1	200		1581	0.0	Voltage transient between Elem. 28, 29

C.3 Mission Profile Test

Element no.	Increment time	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time	Current density, mA/cm^2	Comments
1a	55 min	20.0	300	300			55 min	68.5	Restart, transient from OCV to 20 A
1b	5 min	20.0	300	5			1 hr	68.5	Restart
2a	5 min	20.0	300	5			1 hr 5 min	68.5	Prelaunch
2b	5 hr 50 min	20.0	300	300			6 hr 55 min	68.5	Prelaunch
2c	5 min	20.0	300	5			7 hr	68.5	Prelaunch
3a	5 min	31.5	300	5			7 hr 5 min	107.9	Launch
3b	50 min	31.5	300	300			7 hr 55 min	107.9	Launch
3c	5 min	31.5	300	5			8 hr	107.9	Launch
4a	5 min	27.6	300	5			8 hr 5 min	94.5	Mission
4b	177 hr 50 min	27.6	300	300			185 hr 55 min	94.5	Mission
4c	5 min	27.6	300	5			186 hr	94.5	Mission
5a	5 min	20.0	300	5			186 hr 5 min	68.5	Landing
5b	23 hr 50 min	20.0	300	300			209 hr 55 min	68.5	Landing
5c	5 min	20.0	300	5			210 hr	68.5	Landing
6	0.5 hr	12.9	300	5			210.5 hr	44.2	Calibration 1
7	0.5 hr	53.2	300	5			211 hr	182.2	Calibration 2, transient from 12.9 to 53.2 A
8	0.5 hr	31.5	300	5			211.5 hr	107.9	Calibration 3, transient from 53.2 to 31.5 A
9	0.5 hr	23.8	300	5			212 hr	81.5	Calibration 4
10a	5 min	20.0	300	5			212 hr 5 min	68.5	Landing
10b	23 hr 50 min	20.0	300	300			235 hr 55 min	68.5	Landing
10c	5 min	20.0	300	5			236 hr	68.5	Landing
11a	5 min	0.0	300	5			236 hr 5 min	0.0	Cooldown, transient from 20.0 to 0.0 A
11b	3 hr 55 min	0.0	300	300			240 hr	0.0	Cooldown

C.4 Water Separator Test

Element no.	Increment time, min	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time	Current density, mA/cm^2	Comments
1	10	0	5	5					
2	5	0	5	5					Collect water
3	60	5	5	5					Collect water
4	60	5	5	5					Collect water
5	10	0	5	5					
6	5	0	5	5					Collect water
7	60	10	5	5					Collect water

Element no.	Increment time, min	Current, A	Teledyne data recording interval, sec	GRC data recording interval, sec	High speed data recording rate, kHz	Stack voltage, V	Total time	Current density, mA/cm^2	Comments
8	60	10	5	5					Collect water
9	10	0	5	5					
10	5	0	5	5					Collect water
11	60	15	5	5					Collect water
12	60	15	5	5					Collect water
13	10	0	5	5					
14	5	0	5	5					Collect water
15	60	20	5	5					Collect water
16	60	20	5	5					Collect water
17	10	0	5	5					
18	5	0	5	5					Collect water
19	60	25	5	5					Collect water
20	60	25	5	5					Collect water
21	10	0	5	5					
22	5	0	5	5					Collect water
23	60	30	5	5					Collect water
24	60	30	5	5					Collect water
25	10	0	5	5					
26	5	0	5	5					Collect water
27	60	35	5	5					Collect water
28	60	35	5	5					Collect water
29	10	0	5	5					
30	5	0	5	5					Collect water
31	60	40	5	5					Collect water
32	60	40	5	5					Collect water
33	10	0	5	5					
34	5	0	5	5					Collect water
35	60	45	5	5					Collect water
36	60	45	5	5					Collect water
37	10	0	5	5					
38	5	0	5	5					Collect water
39	60	50	5	5					Collect water
40	60	50	5	5					Collect water
41	10	0	5	5					
42	5	0	5	5					Collect water
43	60	55	5	5					Collect water
44	60	55	5	5					Collect water
45	10	0	5	5					
46	5	0	5	5					Collect water

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14. ABSTRACT NASA's Exploration Technology Development Program (ETDP) is tasked with the development of enabling and enhancing technologies for NASA's exploration missions. As part of that initiative, the return to the Moon requires a reliable, efficient, and lightweight fuel cell powerplant system to provide power to the Altair Lunar Lander and for lunar surface systems. Fuel cell powerplants are made up of two basic parts; the fuel cell itself and the supporting ancillary subsystem. This subsystem is designed to deliver reactants to the fuel cell and remove product water and waste heat from the fuel cell. Typically, fuel cell powerplant ancillary subsystems rely upon pumps and active water separation techniques to accomplish these tasks for closed hydrogen/oxygen systems. In a typical system, these components are the largest contributors to the overall parasitic power load of the fuel cell powerplant. A potential step towards the development of an efficient lightweight power system is to maximize the use of "passive" or low-power ancillary components as a replacement to these high-power load components.					
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