NASA/TM—2011-217107

Development Status of PEM Non-Flow-Through Fuel Cell System Technology for NASA Applications

Mark A. Hoberecht
Glenn Research Center, Cleveland, Ohio

Ian J. Jakupca
QinetiQ North America, Inc., Cleveland, Ohio

November 2011

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Glenn Research Center
Cleveland, Ohio 44135

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Level of Review: This material has been technically reviewed by technical management.

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Background

Today's widespread development of proton-exchange-membrane (PEM) fuel cell technology for commercial users owes its existence to NASA, where fuel cell technology saw its first applications. Beginning with the early Gemini and Apollo programs, and continuing to this day with the Shuttle Orbiter program, fuel cells have been a primary source of electrical power for many NASA missions. This is particularly true for manned missions, where astronauts are able to make use of the by-product of the fuel cell reaction, potable water. But fuel cells also offer advantages for unmanned missions, specifically when power requirements exceed several hundred watts and primary batteries are not a viable alternative.

In recent years, NASA's Exploration Technology Development Program (ETDP) funded the development of fuel cell technology for applications that provide both primary power and regenerative fuel cell energy storage for planned Exploration missions that involved a return to the moon. Under this program, the Altair Lunar Lander was a mission requiring fuel cell primary power. There were also various Lunar Surface System applications requiring regenerative fuel cell energy storage, in which a fuel cell and electrolyzer combine to form an energy storage system with hydrogen, oxygen, and water as common reactants. Examples of these systems include habitat modules and large rovers. In FY11, the ETDP has been replaced by the Enabling Technology Development and Demonstration Program (ETDDP), with many of the same technology goals and requirements applied against NASA's revised Exploration portfolio.

NASA has a unique set of requirements for fuel cells when compared to commercial PEM fuel cell technology. These requirements result from the space environment, and include operation with pure oxygen (instead of air), and water management in reduced and zero-gravity. Because these requirements are so unique, commercial PEM fuel cell technology is not directly applicable to NASA's needs. However, over the past decade NASA pursued a development path to modify commercial PEM fuel cell technology for NASA applications, and recently focused specifically on non-flow-through PEM fuel cell development. This paper addresses the status of that development. The goals for the technology development effort are depicted in Table 1, which identifies the key performance parameters for the various mission users.

TABLE 1.—FUEL CELL KEY PERFORMANCE PARAMETERS

Customer Need	Performance Parameter	SOA (alkaline)	Current Value* (PEM)	Threshold Value** (@ 3 kW)	Goal** (@ 3 kW)
Altair: 3 kW for 220 hours continuous, 5.5 kW peak. Lunar Surface Systems: TBD kW for 15 days continuous operation Rover: TBD	System power density Fuel Cell RFC (without tanks)	49 W/kg n/a	n/a n/a	88 W/kg 25 W/kg	136 W/kg 36 W/kg
	Fuel Cell Stack power density	n/a	n/a	107 W/kg	231 W/kg
	Fuel Cell Balance-of-plant mass	n/a	n/a	21 kg	9 kg
	MEA efficiency @ 200 mA/cm^2 For Fuel Cell Individual cell voltage For Electrolysis Individual cell voltage For RFC (Round Trip)	 73% 0.90V n/a n/a n/a	 72% 0.89V 86% 1.48 62%	 73% 0.90V 84% 1.46 62%	 75% 0.92V 85% 1.44 64%
	System efficiency @ 200 mA/cm^2 Fuel Cell Parasitic penalty Regenerative Fuel Cell**** Parasitic penalty High Pressure penalty	 71% 2% n/a n/a n/a	 65%*** 10% n/a n/a n/a	 71% 2% 43% 10% 20%	 74% 1% 54% 5% 10%
Maintenance-free lifetime Altair: 220 hours (primary) Surface: 10,000 hours (RFC)	Maintenance-free operating life Fuel Cell MEA Electrolysis MEA Fuel Cell System (for Altair) Regenerative Fuel Cell System	 2500 hrs n/a 2500 hrs n/a	 13,500 hrs n/a n/a n/a	 5,000 hrs 5,000 hrs 220 hrs 5,000 hrs	 10,000 hrs 10,000 hrs 220 hrs 10,000 hrs

*Based on limited small-scale testing.

**Threshold and Goal values based on full-scale (3 kW) fuel cell and RFC technology.

***Teledyne passive flow through with latest MEA

****Includes high pressure penalty on electrolysis efficiency 2000 psi

Introduction

All fuel cell systems, whether for space or commercial applications, consist of one or more fuel cell stacks in combination with appropriate balance-of-plant hardware. The fuel cell stack performs the electrochemical function of breaking down hydrogen and oxygen to form water and electrical power, and the ancillary components comprising the balance-of-plant perform the necessary fluid and thermal management functions of the system. The goals of NASA’s development effort are to improve fuel cell stack electrical performance, reduce balance-of-plant mass, volume, and parasitic power requirements, and increase overall system life and reliability. The effort is being led by NASA Glenn Research Center (GRC) in partnership with NASA Johnson Space Center (JSC), NASA Jet Propulsion Laboratory (JPL), NASA Kennedy Space Center (KSC), and vendor partners. A comparison of PEM flow-through fuel cell technology with non-flow-through technology was addressed by this author in a recent paper (Ref. 1). A brief summary of that work is presented here.

Commercial PEM fuel cell technology is flow-through in nature, where a recirculating oxygen reactant stream removes product water generated at the cathode surface within each individual cell of the fuel cell stack. A recirculating reactant stream dictates the need for some type of device to initiate and sustain the recirculating flow, and another device to separate the product water from the two-phase stream exiting the stack. In the case of existing state-of-the-art (SOA) flow-through PEM fuel cell systems, these devices are typically active mechanical components such as the pump and water separator in Figure 1. Any fuel cell system using these active components bears their weight, volume, parasitic power, reliability, life, and cost penalties.

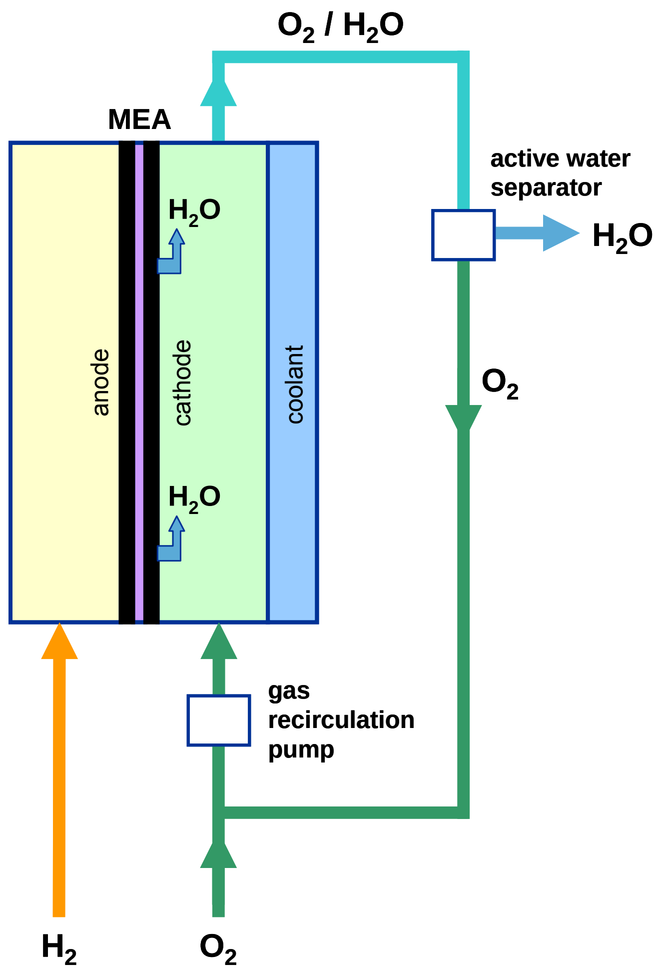

Figure 1.—Flow-through PEM fuel cell schematic (active components).

Replacing the active components with passive components can minimize some of the resulting penalties. Figure 2 depicts the same flow-through technology schematic as in Figure 1, but with passive components replacing active mechanical components. For reactant recirculation, injectors or ejectors could serve as passive replacements for pumps. In the area of product water separation, membrane separators could replace motorized centrifugal separators.

The penalties associated with these balance-of-plant components can be minimized even further with non-flow-through PEM fuel cell technology, as shown in Figure 3. Here, product water generated at the cathode surface wicks through a support structure across an adjacent gas cavity, through a hydrophilic membrane, into a water cavity within each cell of the stack. There are no recirculating reactants, and hence no requirement for providing either recirculation or product water separation from a two-phase reactant stream. Therefore, there is no need for components that provide these functions, whether they are active or passive. Eliminating these components therefore eliminates the penalties associated with them.

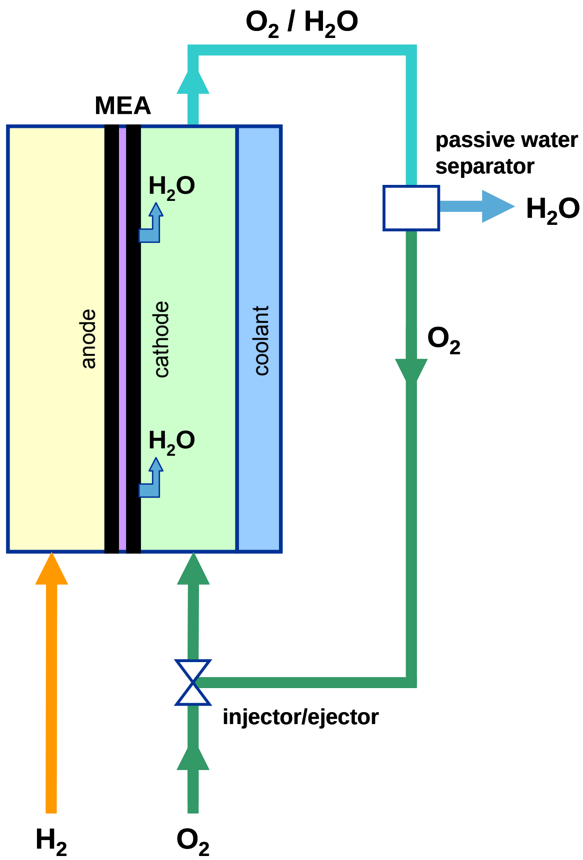

Figure 2.—Flow-through PEM fuel cell schematic (passive components).

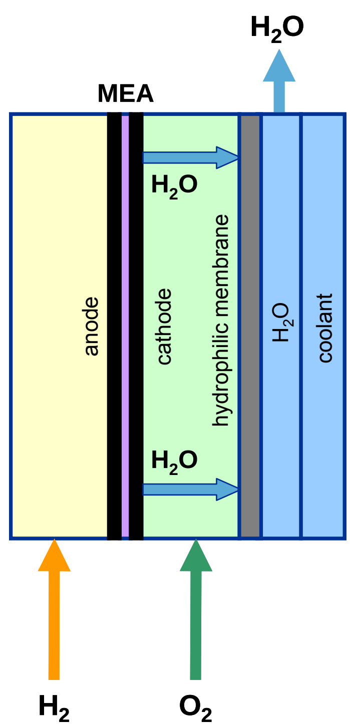

Figure 3.—Non-flow-through PEM fuel cell schematic.

TABLE 2.—SYSTEM-LEVEL COMPARISON OF FLOW-THROUGH VERSUS NON-FLOW-THROUGH TECHNOLOGY

Design parameter	Flow-through	Non-flow-through
Efficiency	–	–
Mass		✓
Volume		✓
Parasitic power		✓
Reliability		✓
Life		✓
Cost		✓
TRL	✓	

The projected advantages (marked by a ✓) for NASA applications of non-flow-through PEM fuel cell technology over flow-through technology at the system level are numerous, as shown in Table 2.

There is little difference in efficiency between the two systems because voltage performance is similar. The sole advantage of the flow-through technology is its higher technology readiness level (TRL), but this advantage has diminished with the recent success of non-flow-through development at several vendors. The many projected advantages of the non-flow-through PEM fuel cell technology are the reason why NASA continues to actively pursue its development. However, the major challenge remains water management within the gas cavities of the non-flow-through cell. Because non-flow-through technology by definition is dead-ended in terms of reactant flow, there is no bulk flow of gas available to flush liquid water away from reactant sites within the cells. Proper design of internal cell structures, along with their surface properties and pore characteristics, is critical to achieving effective water management within non-flow-through cells. It should be noted, however, that brief purging of reactants through the cell remains an effective method of water management. These purges are always necessary in a non-flow-through fuel cell to remove gaseous inerts that accumulate over time. During purging, a non-flow-through fuel cell is operating in a flow-through mode. To maintain the advantages of non-flow-through technology over flow-through technology, the quantity and duration of these purge events should be minimized.

Vendor Stack Development Status

NASA is presently developing PEM non-flow-through fuel cell stack technology at four different vendors, each of whom has their own unique proprietary approach to stack design and system operation. Each vendor uses different materials for cell frames, gas-cavity support structures, and the hydrophilic membrane separating the oxygen cavity from the water cavity (see Fig. 3). Each vendor has also chosen a cell active area based on already-existing hardware. One of the vendors is considered the baseline vendor to supply PEM non-flow-through fuel cell stacks for the systems under development as part of ETDDP , while the other three are considered alternates, each competing for the role of back-up vendor.

Infinity Fuel Cell and Hydrogen, Inc. is the baseline vendor, and is presently developing their stack technology under a Phase III Small Business Innovative Research (SBIR) contract with NASA GRC. Infinity's stack technology is based on their design approach developed under previous Phase I and II SBIR contracts. They have built several short stacks (less than 10 cells) with active areas of both 50 cm^2 and 150 cm^2. Larger active areas of greater than 100 cm^2 are necessary for multi-kW sized stacks, while active areas less than 100 cm^2 are more appropriate for stacks under 1 kW. The existing Phase III contract culminates in the summer of 2012 with the delivery to NASA of two 40-cell 150 cm^2 breadboard stacks (30 V, 1 kW) which when tested successfully, will demonstrate a NASA Technology Readiness Level (TRL) of 5. At that time, and with the availability of sufficient funding, development of engineering model stacks will be initiated with the goal of demonstrating a TRL of 6 through testing in a relevant environment.

TABLE 3.—NON-FLOW-THROUGH PEM FUEL CELL TECHNOLOGY VENDOR COMPARISON

Parameter	Infinity	ElectroChem	Proton	Teledyne
Active area (cm^2)	50 and 150	200	86	69
Operating temperature (°C)	60	75	75	55
Operating pressure (psig)	30	30	50	10
Max oxygen/Water ΔP (psig)	8	30	4	5
Pressure Control Sensitivity	Medium	Low	Very high	High
Peak steady state current density (mA/cm^2)	500	350	400	200
Pass load profile test?	Yes	No	No	No
Orientation sensitivity	None	TBD	TBD	TBD

The first alternate vendor is ElectroChem, Inc., who provided their stack under a Phase III Small Business Innovative Research (SBIR) contract through NASA JSC. The ElectroChem stack technology was also developed under previous Phase I and II SBIR contracts, and is now at an active area of 200 cm^2. The next alternate vendor is Proton Energy Systems, Inc., whose non-flow-through stack technology was developed under a Phase II SBIR contract with NASA KSC. Proton's development is derived from previous NASA unitized regenerative fuel cell (URFC) SBIR work, and is presently at an active area of 86 cm^2. The last alternate vendor is Teledyne Energy Systems, Inc., who developed non-flow-through stack technology under funding from two sources, company internal research and development (IR&D) and the NASA Innovative Partnership Program (IPP). Teledyne stack technology is presently at an active are of 69 cm^2.

Each vendor has conducted in-house testing of their non-flow-through stack technology, and successfully demonstrated its performance. Testing by the baseline vendor has been extensive, while testing by all the alternate vendors was more limited. NASA has conducted a series of tests on stacks from all four vendors, and a comparison of various parameters based on these tests is shown in Table 3.

The first three parameters in the table are stack characteristics specific to each vendor's technology, with no impact on performance. An assessment of performance begins with the fourth and fifth parameters, which represent operating pressure and pressure control sensitivity. A higher number for the differential pressure between the cell oxygen and water cavities reflects a more robust cell design, and also allows less stringent pressure control. The sixth and seventh parameters, peak steady state current density and ability to pass the load profile test, are in this case most likely a reflection of the effectiveness of the water removal process for the various stacks. Although several factors could contribute to lower current density capability, in these tests it was noted that cell flooding was readily observed while operating at higher current densities. Only the vendor's stack with the highest current density value, the baseline vendor, was capable of passing the NASA load profile test by completing the entire load profile with no low-voltage shutdowns, as shown in Figure 4. An example of an alternate vendor's stack failing the test because of a low-voltage shutdown is also shown. An assessment of the last parameter, orientation sensitivity, was only conducted on stacks from the baseline vendor, where orientation had no impact. Orientation sensitivity for stacks from the three alternate vendors will be determined in the near future.

More detailed testing of all the vendor stacks will be conducted over the coming months. Key parameters to be evaluated during that time include stack efficiency, mass and volume, manufacturability, and stable long-term operation. At the conclusion of these detailed evaluations, the NASA fuel cell team will down-select a back-up vendor. At some point in the future, and should additional funding be available, NASA will initiate a parallel development effort for TRL-6 engineering model stacks.

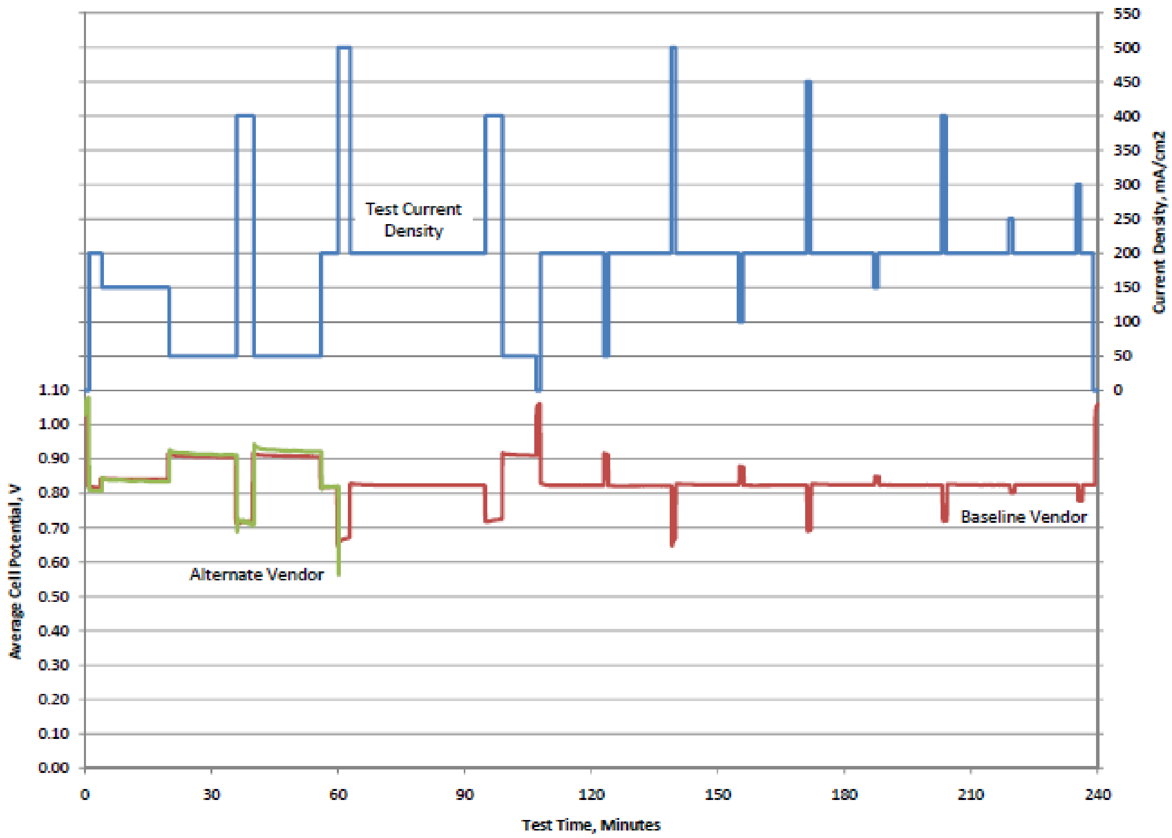

Figure 4.—NASA load profile test.

NASA Balance-of-Plant Development Status

The PEM non-flow-through fuel cell balance-of-plant hardware is being developed in-house at NASA GRC. The present focus of the effort is development of a common system architecture, shown in Figure 5, which can be used to test hardware from the component level through the system level. The balance-of-plant effort is proceeding along two fronts; a versatile common test platform to test fuel cell stacks from multiple vendors, and a compact balance-of-plant design to evaluate mass and volume reduction options using the fuel cell stack design from the baseline vendor.

The common system architecture consists of various modules, each with specific functions. At the core of the architecture is the Fuel Cell Stack. The kinetics within the stack determines the system architecture. These kinetics include electrical, fluidic, hydraulic, and thermal phenomenon. The Reactant Manifold Module is required to control three fluids (hydrogen reactant gas, oxygen reactant gas, liquid product water), in this case using a pair of pressure control components for each fluid. The Cooling Module removes any excess heat generated by the fuel cell stack, and is the dominant parasitic load in the system. The Power Interface Module distributes power between the Fuel Cell Stack and both the External System and Cooling Module through some combination of power conditioning and switching. Delivery of the hydrogen and oxygen gaseous reactants to the system is accomplished with the Reactant Supply Module. An Electronics Module is used to monitor several system operating parameters to safely control the system, and an internal Power Conditioning Module provides regulated power to ensure high quality sensor data and uninterrupted computer control. The separate nature of these modules provides flexibility in terms of scale-up for larger stacks or higher power capabilities as the non-flow-through fuel cell system technology matures.

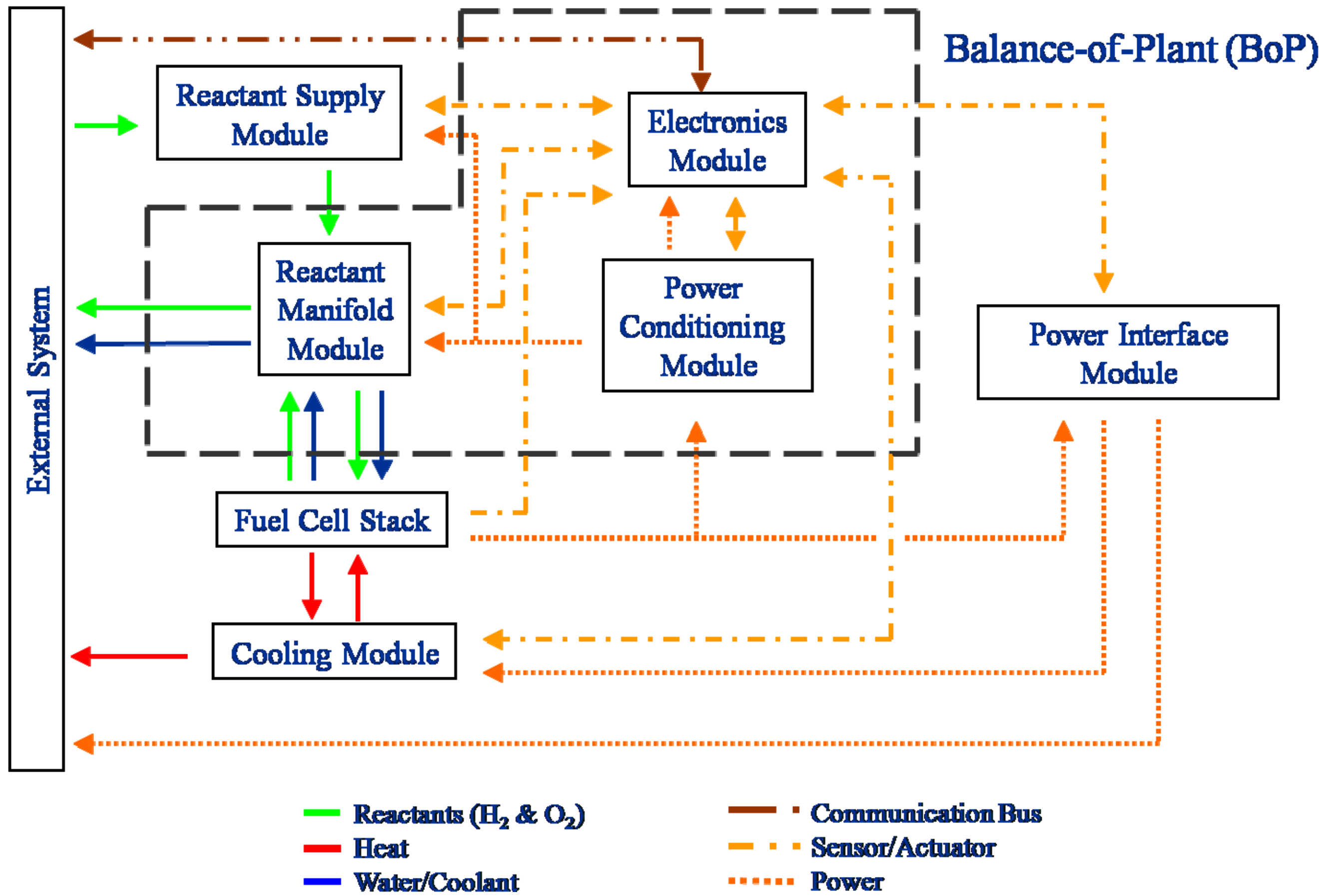

Figure 5.—Common system architecture.

Based on the common system architecture, a versatile common test platform has been designed, built, and certified to test non-flow-through PEM fuel cell stacks from multiple vendors. The test platform, shown in Figure 6, incorporates all modules from the common system architecture with the exception of the Reactant Supply Module. It is capable of testing a stack up to 1 kW in power, with up to 40 cells. Using NASA customized software, the common test platform controls absolute and differential pressures, as well as stack temperature within user-defined limits. The computerized safety system autonomously initiates a shut down in the event that any selectable safety parameter has exceeded its permitted range.

The compact balance-of-plant design, shown in Figure 7, is a model of the common system architecture re-packaged for field applications. The entire Reactant Manifold Module has been incorporated into the fuel cell stack end plate. By maintaining the common system architecture, all system fluidic, structural, and thermal aspects are simplified. This results in increased volumetric efficiency without modifications to the electronic hardware, software, or operational procedures. A field demonstration of the compact balance-of-plant integrated into an actual fuel cell system is planned for the near future.

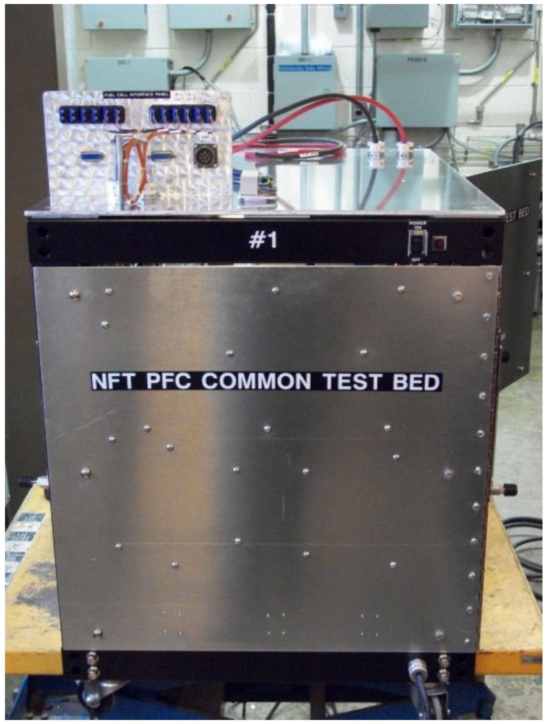

Figure 6.—Versatile common test platform.

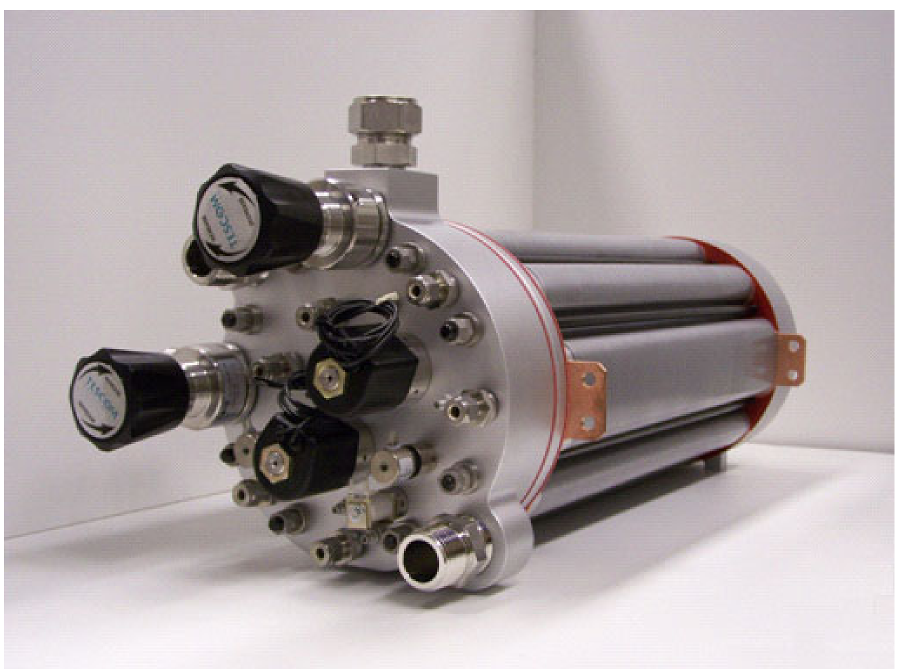

Figure 7.—Compact balance-of-plant design.

Summary

Fuel cells have a successful history of supplying electrical power for many past NASA missions, including Gemini, Apollo, and the Shuttle Orbiter. For use in future missions, NASA has been developing advanced PEM fuel cell technology for the past decade by leveraging past commercial development and adapting it to NASA's unique set of space requirements. Initially this development was concentrated on flow-through PEM fuel cell technology because of its commercial legacy. Over the past several years, however, the focus has shifted to non-flow-through PEM fuel cell technology because of its many projected system advantages, which include mass, volume, parasitic power, reliability, life, and cost.

Four different vendors, one baseline and three alternates, are presently developing non-flow-through PEM fuel cell technology for future NASA missions. Each vendor has a unique, proprietary approach. The baseline vendor, Infinity Fuel Cell and Hydrogen, Inc., has delivered several short stacks to NASA over the past two years for test and evaluation, and is presently under contract to deliver two 40-cell 150 cm^2 breadboard stacks to NASA GRC in the summer of 2012. The three alternate vendors—ElectroChem, Inc., Proton Energy Systems, Inc., and Teledyne Energy Systems, Inc.—have each delivered short stacks to NASA over the past year for test and evaluation. Initial testing has now been performed on stacks from all four vendors, and a preliminary evaluation has been conducted. Following more detailed testing over the coming months, a more complete assessment can be conducted allowing a back-up vendor to be selected. Going forward, and should additional funding be available, both the baseline and back-up vendors will be awarded contracts to develop engineering model fuel cell stacks to a NASA TRL of 6, which will require testing in a relevant environment.

References

1. Hoberecht, M.A., NASA Glenn Research Center, "A Comparison of Flow-Through Versus Non-Flow-Through Proton Exchange Membrane Fuel Cell Systems for NASA's Exploration Missions," NASA/TM—2010-216107.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-11-2011

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Development Status of PEM Non-Flow-Through Fuel Cell System Technology for NASA Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Hoberecht, Mark, A.; Jakupca, Ian, J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 038957.04.06.01.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17783

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-217107

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 15, 20, and 44
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Today’s widespread development of proton-exchange-membrane (PEM) fuel cell technology for commercial users owes its existence to NASA, where fuel cell technology saw its first applications. Beginning with the early Gemini and Apollo programs, and continuing to this day with the Shuttle Orbiter program, fuel cells have been a primary source of electrical power for many NASA missions. This is particularly true for manned missions, where astronauts are able to make use of the by-product of the fuel cell reaction, potable water. But fuel cells also offer advantages for unmanned missions, specifically when power requirements exceed several hundred watts and primary batteries are not a viable alternative. In recent years, NASA’s Exploration Technology Development Program (ETDP) funded the development of fuel cell technology for applications that provide both primary power and regenerative fuel cell energy storage for planned Exploration missions that involved a return to the moon. Under this program, the Altair Lunar Lander was a mission requiring fuel cell primary power. There were also various Lunar Surface System applications requiring regenerative fuel cell energy storage, in which a fuel cell and electrolyzer combine to form an energy storage system with hydrogen, oxygen, and water as common reactants. Examples of these systems include habitat modules and large rovers. In FY11, the ETDP has been replaced by the Enabling Technology Development and Demonstration Program (ETDDP), with many of the same technology goals and requirements applied against NASA’s revised Exploration portfolio.

15. SUBJECT TERMS
Fuel cells; Electrochemical cells; Spacecraft propulsion; Energy conversion

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	16	443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18