



A Comparison of Flow-Through Versus Non-Flow-Through Proton Exchange Membrane Fuel Cell Systems for NASA's Exploration Missions

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NASA/TM—2010-216107



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May 2010

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Background

As part of the Exploration Technology Development Program (ETDP) under the auspices of the Exploration Systems Mission Directorate (ESMD), NASA is developing both primary fuel cell power systems and regenerative fuel cell (RFC) energy storage systems within the fuel cell portion of the Energy Storage Project. This effort is being led by the NASA Glenn Research Center (GRC) in partnership with the NASA Johnson Space Center (JSC), Jet Propulsion Laboratory (JPL), NASA Kennedy Space Center (KSC), and industrial partners. The development goals are to improve fuel cell and electrolysis stack electrical performance, reduce system mass, volume, and parasitic power requirements, and increase system life and reliability.

A major focus of this effort has been the parallel development of both flow-through and non-flow-through proton exchange membrane (PEM) primary fuel cell power systems. The plan has been, at the appropriate time, to select a single primary fuel cell technology for eventual flight hardware development. Ideally, that appropriate time would occur after both technologies have achieved a technology readiness level (TRL) of six, which represents an engineering model fidelity PEM fuel cell system being successfully tested in a relevant environment. Budget constraints in fiscal year 2009 and beyond have prevented NASA from continuing to pursue the parallel development of both primary fuel cell options. Because very limited data exists for either system, a top-level, qualitative assessment based on engineering judgement was performed expeditiously to provide guidance for a selection. At that time, the non-flow-through technology was selected for continued development because of potentially major advantages in terms of weight, volume, parasitic power, reliability, and life. This author believes that the advantages are significant enough, and the potential benefits great enough, to offset the higher state of technology readiness of flow-through technology. This paper summarizes the technical considerations which helped form the engineering judgement that led to the final decision.

Introduction

Space fuel cell systems were first used to generate power during the Gemini program, and are presently in use on the Shuttle. For future Exploration Missions, NASA's development approach has been to leverage the extensive commercial development of PEM fuel cell systems, while also addressing the unique NASA requirements for space applications. These more stringent space requirements include operation with pure oxygen (instead of air), and water management in reduced and zero-gravity environments. 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.

System-Level Description

Both the stack and balance-of-plant are considerably different between the flow-through and non-flow-through PEM fuel cell systems. In order to highlight the major differences between these two options, a summary description at the system level is presented below.

Flow-Through PEM Fuel Cell Technology

Flow-through PEM fuel cell technology is characterized by a recirculating oxygen reactant stream that removes product water generated at the cathode surface within each individual cell of the fuel cell stack. Figure 1 depicts this recirculating oxygen stream. Depending on the operating characteristics of the stack for a particular fuel cell vendor, a duplicate hydrogen recirculating stream may also be required for removal of small amounts of water which inadvertently accumulate within the anode chamber of each individual cell. Periodic venting of each reactant stream may also be required to remove inert gases, depending on the purity of the reactants.

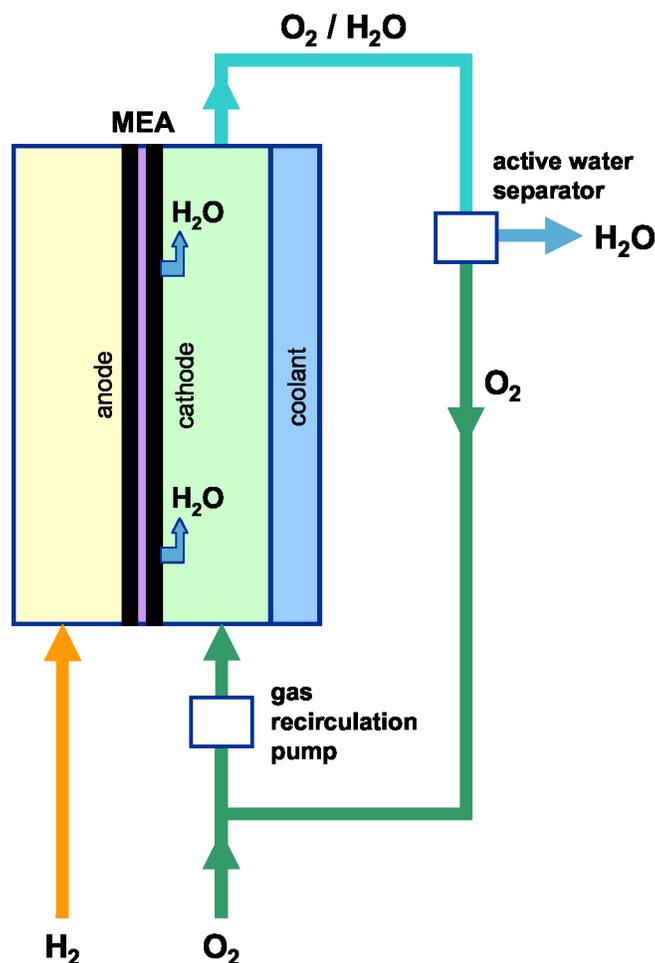


Figure 1.—Flow-Through PEM Fuel Cell Schematic (active components).

Recirculating reactant streams dictate 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 (Refs. 1 and 2). Any fuel cell system using these active components bears their weight, volume, parasitic power, reliability, life, and cost penalties. 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, various combinations of injectors, ejectors, solenoid valves, and pressure regulators have been investigated as passive replacements for pumps. In the area of product water separation, membrane separators, vortex separators, and meniscus separators have all been investigated as passive replacements for active motorized water separators.

Even though the flow-through PEM fuel cell technology was not selected for continued development, it is still considered a viable back-up option for Exploration missions. Therefore, ongoing work to complete the assessment of passive components will continue through 2008. The results of these efforts will be documented at that time.

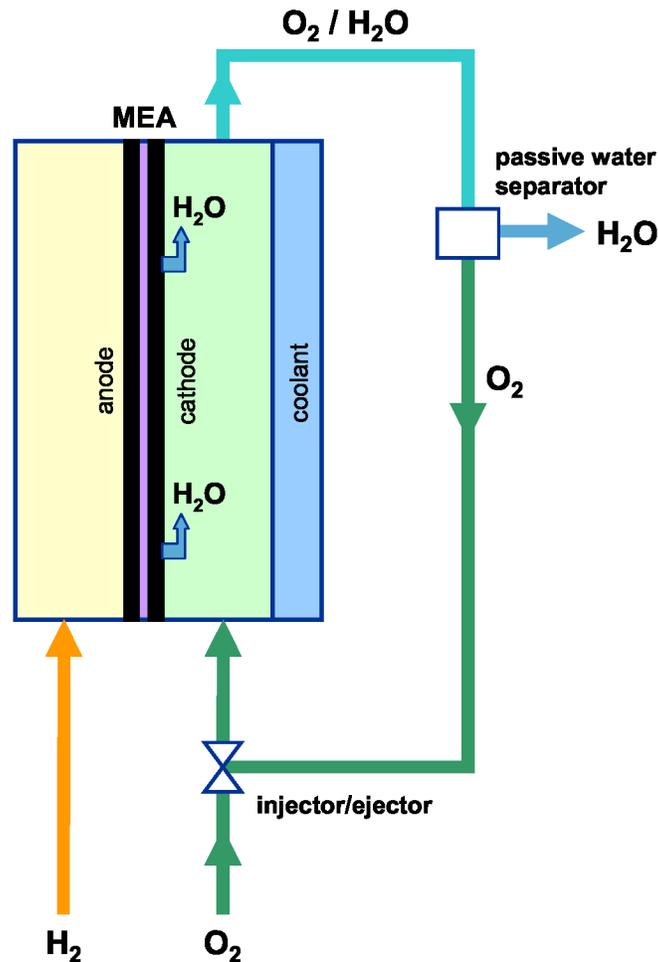


Figure 2.—Flow-Through PEM Fuel Cell Schematic (passive components).

Non-Flow-Through PEM Fuel Cell Technology

Non-flow-through PEM fuel cell technology is characterized by product water generated at the cathode surface wicking through a support structure across an adjacent gas cavity, through a hydrophilic membrane, into a water cavity within each cell of the stack, as shown in Figure 3. As with flow-through technology, periodic venting of each reactant cavity may be required to remove inert gases, depending on the purity of the reactants.

There are no recirculating reactants, and hence no requirement for providing either recirculation or product water separation from two-phase reactant streams. Therefore, there is no need for components that provide these functions, whether they are active or passive. The only ancillary component in a non-flow-through system that is not needed in a flow-through system is a back-pressure regulator needed to maintain the proper differential pressure between the oxygen and water/coolant cavities. This back-pressure regulator is critical for water removal within the non-flow-through system.

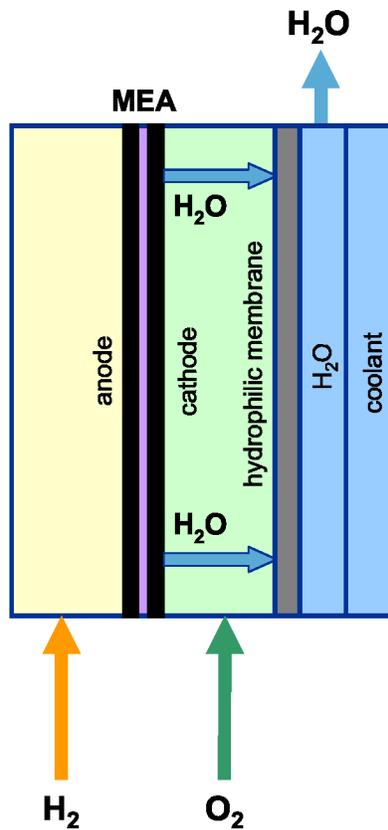


Figure 3.—Non-Flow-Through PEMFC Schematic.

Stack-Level Comparison

Even though there are many similarities between a flow-through PEM fuel cell stack and a non-flow-through stack, there are minor differences that potentially justify the selection of one technology over the other. The important design parameters that impact this selection at the stack level are efficiency, weight, volume, life, cost, and TRL. Table 1 highlights these parameters, with a check mark indicating the technology option having the advantage based on a qualitative assessment by the author.

TABLE 1.—STACK-LEVEL COMPARISON OF FLOW-THROUGH
VERSUS NON-FLOW-THROUGH

Design parameter	Flow-through	Non-flow-through
Efficiency		
Weight		✓
Volume		✓
Life		
Cost		
TRL	✓	

Assuming identical cell performance for both flow-through and non-flow-through PEM fuel cell stacks, the required active electrode area is inherently the same for both technologies. One difference between these options is the separate water cavity required in a non-flow-through stack, however it is possible that this water cavity could also serve as the coolant cavity. Another difference between these options is the thicker cathode (and possibly anode) reactant chamber needed to accommodate discreet flow channels in a flow-through stack. It is these flow channels that provide the required high-velocity recirculating reactant stream within each cell of the stack, thereby sweeping away the product water droplets generated across the entire active area of each cathode surface. In comparison, the water droplets generated in a non-flow-through stack are not swept away by a high-velocity recirculating reactant stream. These droplets travel passively across a support structure in the cathode cavity, then through a hydrophilic membrane into a water cavity within each cell of the stack. A slight pressure differential across the hydrophilic membrane drives the water transfer. Simple diffusion is sufficient to provide reactants to the electrode surfaces in a non-flow-through stack, so this allows the reactant chambers to be much thinner than those required in a flow-through stack. Diffusional flow is more likely to be acceptable at lower operating current densities where possible gas transport limitations in non-flow-through stacks are less likely to occur.

In spite of the possibly separate water chamber in a non-flow-through stack, the difference between relatively thick flow channels (flow-through) and thin support structures (non-flow-through) accounts for the minor weight and volume advantage of the non-flow-through stack in Table 1. Preliminary estimates by this author indicate a possible 5 to 20 percent weight advantage, and a possible 5 to 10 percent volume advantage at the stack level. Preliminary values have yet to be determined for the other design parameters in Table 1, however from an electrochemical standpoint, no major differences are anticipated between the two technology options. Therefore, efficiency and life are not expected to be discriminators. There is also little or no difference projected between the costs of the systems. Future development and testing will validate the accuracy of these assessments.

The single major advantage of the flow-through PEM fuel cell stack over the non-flow-through stack is its higher TRL. Even though an older vintage of non-flow-through fuel cell technology provided power for the Gemini missions, the technology has seen little development over the past several decades, even for commercial applications, when compared to flow-through fuel cell technology (Ref. 3). This is because non-flow-through technology is not applicable to fuel cells with air as the oxidant due to the continuous purge required to remove inert gases from the oxygen cavities in the cells. Inert gases

comprise approximately 80 percent of the air stream, and the continuous purge required to remove these inert gases essentially dictates flow-through operation—hence the minimal development of non-flow-through technology over the past several decades. Flow-through PEM fuel cell technology for space applications using pure oxygen as the oxidant has been under development by NASA since the late 1990s, while non-flow-through development was not initiated until 2005. Non-flow-through PEM fuel cell technology (presently at the laboratory/breadboard level) therefore lags flow-through technology (presently at the breadboard/engineering model level) by at least several years in terms of readiness for flight hardware development.

Balance-of-Plant-Level Comparison

There are very few similarities between a flow-through PEM fuel cell balance-of-plant and a non-flow-through balance-of-plant. The differences are significant, and clearly favor non-flow-through systems. A summary comparison of these two options at the balance-of-plant level, based on a qualitative assessment by the author, is presented in Table 2.

TABLE 2.—BALANCE-OF-PLANT-LEVEL COMPARISON OF FLOW-THROUGH VERSUS NON-FLOW-THROUGH

Design parameter	Flow-through	Non-flow-through
Weight		✓
Volume		✓
Parasitic power		✓
Reliability		✓
Life		✓
Cost		✓
TRL	✓	

The differences between the flow-through PEM fuel cell system and non-flow-through system are more significant at the balance-of-plant level than at the stack level. The major contributors are product water separation internal to the stack and the lack of reactant recirculation with non-flow-through PEM fuel cell technology (Fig. 3), which lead to the elimination of a number of ancillary components in the balance-of-plant when compared to flow-through technology (Figs. 1 and 2).

This reduction should result in an advantage for the non-flow-through balance-of-plant in terms of weight, volume, parasitic power, reliability, life, and cost. Preliminary estimates by this author indicate a 50 to 70 percent weight and volume advantage at the balance-of-plant level could be achieved. Preliminary values have yet to be determined for the other design parameters, but can be discussed at a summary engineering level. Parasitic power would likely be slightly less for a non-flow-through system compared to a passive flow-through system because of fewer ancillary components, and significantly less when compared to an active flow-through system because of no motorized active components. Reduced numbers of ancillary components would likely translate directly into increased life and reliability of the entire balance-of-plant because there are fewer components capable of failing, whether they be active or passive. Similarly, reduced numbers of components may also translate into lower costs for a non-flow-through balance-of-plant. Future development and testing will validate the accuracy of these assessments.

Just as with the stack-level comparison, the single major advantage of the flow-through PEM fuel cell balance-of-plant over the non-flow-through balance-of-plant is its higher TRL. Even though an older vintage of non-flow-through technology has flown previously on Gemini missions, flow-through technology for space applications has been under development by NASA for many more years than the newer vintage of non-flow-through technology. It therefore has the schedule advantage in terms of readiness for flight hardware development.

Summary

Over the past several years, NASA has been pursuing parallel development of flow-through and non-flow-through PEM primary fuel cell power systems under the ETDP Energy Storage Project. Both systems consist of a stack which generates electrical power and produces water, and a balance-of-plant which performs the appropriate fluid and thermal management functions of the system. At the stack level, non-flow-through PEM fuel cell systems have a potentially minor weight and volume advantage over flow-through systems because of thinner individual cells within the stack. The potential weight and volume advantage is more significant at the balance-of-plant level because of fewer ancillary components. The reduced number of ancillary components also likely leads to a reduction in parasitic power and an increase in reliability and life for non-flow-through PEM fuel cell systems. Costs are also anticipated to be less because of fewer ancillary components.

The lone major advantage of flow-through PEM fuel cell systems over non-flow-through systems is the higher level of technology readiness. Flow-through systems for space applications have been under development by NASA since the late 1990s and have reached the breadboard/engineering model level. Non-flow-through system development was not initiated until 2005 and this technology is presently at the laboratory/breadboard level. At least several more years of development will be required to bring non-flow-through PEM fuel cell hardware to the same level of technology readiness as existing flow-through hardware.

The original plan was to select a single primary fuel cell technology for eventual flight hardware development once both systems had reached an engineering model hardware fidelity. Budget constraints in fiscal year 2009 and beyond have led NASA to make an early selection of a single primary PEM fuel cell technology. A top-level, qualitative assessment was performed expeditiously to provide guidance for the selection, and based on this assessment; non-flow-through technology was selected for further development. The justification is based on a number of qualitative technical advantages with respect to weight, volume, parasitic power, reliability, life, and cost of non-flow-through technology when compared to flow-through technology. Some of these individual advantages may be minor, but in aggregate have the potential to be significant. It was this significant potential that drove the selection. Future development and testing will validate the accuracy of the assessments and the wisdom of the selection.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 01-05-2010		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A Comparison of Flow-Through Versus Non-Flow-Through Proton Exchange Membrane Fuel Cell Systems for NASA's Exploration Missions			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Hoberecht, Mark, A.			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-17186		
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-2010-216107		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 20 and 44 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT As part of the Exploration Technology Development Program (ETDP) under the auspices of the Exploration Systems Mission Directorate (ESMD), NASA is developing both primary fuel cell power systems and regenerative fuel cell (RFC) energy storage systems within the fuel cell portion of the Energy Storage Project. This effort is being led by the NASA Glenn Research Center (GRC) in partnership with the NASA Johnson Space Center (JSC), Jet Propulsion Laboratory (JPL), NASA Kennedy Space Center (KSC), and industrial partners. The development goals are to improve fuel cell and electrolysis stack electrical performance, reduce system mass, volume, and parasitic power requirements, and increase system life and reliability. A major focus of this effort has been the parallel development of both flow-through and non-flow-through proton exchange membrane (PEM) primary fuel cell power systems. The plan has been, at the appropriate time, to select a single primary fuel cell technology for eventual flight hardware development. Ideally, that appropriate time would occur after both technologies have achieved a technology readiness level (TRL) of six, which represents an engineering model fidelity PEM fuel cell system being successfully tested in a relevant environment. Budget constraints in fiscal year 2009 and beyond have prevented NASA from continuing to pursue the parallel development of both primary fuel cell options. Because very limited data exists for either system, a top-level, qualitative assessment based on engineering judgement was performed expeditiously to provide guidance for a selection. At that time, the non-flow-through technology was selected for continued development because of potentially major advantages in terms of weight, volume, parasitic power, reliability, and life. This author believes that the advantages are significant enough, and the potential benefits great enough, to offset the higher state of technology readiness of flow-through technology. This paper summarizes the technical considerations which helped form the engineering judgement that led to the final decision.					
15. SUBJECT TERMS Fuel cells; Fuel cell power plants; Hydrogen oxygen fuel cells; Energy conversion; Energy storage					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
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