V.F.5 Air-Cooled Stack Freeze Tolerance

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Ballard Power Systems, Burnaby, British Columbia, Canada

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Fiscal Year (FY) 2011 Objectives

- Advance the state of the art in technology for air-cooled proton exchange membrane (PEM) fuel cell stacks and related GenDrive™ material handling application fuel cell systems.
- Demonstrate FCvelocity™ 1020ACS stack durability of 5,000 hours (2.5x nominal durability) through enhanced system operational strategies or utilization of advanced fuel cell stack materials.
- Determine a stack/system concept that is suitable for sub-zero operation down to -30°C.
- Determine a stack/system concept that achieves a total cost that is competitive with incumbent materials handling fuel cell technology solutions.
- Develop, evaluate and trade-off the stack and system to meet materials handling requirements for freeze and cost.
- Develop an understanding around integrating air-cooled stack technology into a dynamic materials handling system.
- Perform life-cycle cost analyses for freeze tolerance strategies.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Durability (with respect to start-up, freezing and low relative humidity operation)
(B) Cost (with respect to stack and balance of plant [BOP] trade-off)
(C) Performance (with respect to voltage degradation, low relative humidity and sub-zero performance)

Technical Targets

- Stack/system concept that is suitable for sub-zero operation down to -30°C.
- Durability for an air-cooled fuel cell stack ≥5,000 hours operating under material handling conditions including start-stop cycles; a 2x improvement over baseline testing.
- GenDrive™ product cost reduction of 25% or greater using air-cooled stack design over baseline liquid-cooled GenDrive™ product.

FY 2011 Accomplishments

- Conducted screening tests on 27 membrane electrode assembly (MEA) technologies, stack durability tests on five MEA technologies and system compatible testing on three MEA technologies.
- Built a system test bench to test all system interactions, especially the fuel cell and battery, before final packaged design solution was complete. Prior testing was performed on three stack module test benches where the system interactions are managed within an analytical model.
- Completed testing of advanced system operating strategies for the FCvelocity™ 1020ACS air-cooled stack with over 6,000 hours of operation using two advanced operating strategies. These operating strategies focus on reducing cathode catalyst dissolution and corrosion and chemical and mechanical stress on the membrane. System operating strategies provide a 2x extension in durability compared to previous tests.
- Built a prototype system and performed system level high and low ambient temperature testing. Test results demonstrate an air-cooled stack system can operate continuously at both high and low ambient temperature conditions however system improvements are required to optimize performance to ensure long life.

- The project Go/No-Go review was held with the DOE in December 2010. The project cost metric was met and the DOE approved the recommendation to continue the project and advance to Phase 2.

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Introduction

Plug Power's objective is to advance the state-of-the-art fork-lift technology by using air-cooled fuel cell stacks and improving related GenDrive™ material handling systems to improve function and reduce cost. This will be accomplished through a collaborative work plan to reduce overall system cost by simplifying the system BOP through the use of an air-cooled stack as well as improve freeze tolerance and mitigate freeze-thaw failure modes through innovative fuel cell system design.

The fuel cell system, derived from Plug Power's commercially available GenDrive™ platforms, is providing battery replacement for equipment in the material handling industry. The fuel cell stacks are Ballard's commercially available FCvelocity™ 9SSL (9SSL) liquid-cooled PEM fuel cell stack and FCvelocity™ 1020ACS air-cooled PEM fuel cell stack. Stack modifications to the FCvelocity™ 1020ACS will be explored through this project. Plug Power will lead design-build-test and design-of-experiment efforts for GenDrive™ systems with support from Ballard Power Systems for the fuel cell stack and stack integration.

Approach

In this project the fuel cell stack, system and fuel cell stack operation will be designed together in order to trade off stack durability and freeze function with overall stack-system cost. Both stack and system level mitigation of freeze failure modes will be explored. The project will develop an understanding of market needs, system requirements, stack-system limitations, historical data, models and small-scale testing to define stack/system operating strategies that achieve required freeze function and durability.

Multiple design, build, test cycles will be employed to increase learning through iteration. Analytical models for durability and freeze will be developed and verified on stacks and system modules. Accelerated testing will be used where possible to reduce testing time. Stacks and systems will be operated under material handling freezer conditions, failure analysis will be performed to understand the root cause of failures, stacks and systems will be designed to mitigate the failure modes, then built and tested. Trade-off analysis will be used to determine the design solutions that are built and tested.

Results

The FCvelocity™ 1020ACS (ACS) stack must first demonstrate performance and durability targets to be considered a viable GenDrive™ product solution. Specifically, the ACS must demonstrate 5,000 hours running a representative load profile including start-stop cycles. The self-humidifying ACS stack is an "open cathode" design where cooling and reactants are supplied by a single fan. This offers system simplicity by eliminating the liquid cooling system, humidifiers, air compressor and on-board water management; providing a significant cost reduction compared to a liquid-cooled, closed cathode stack. As a result the MEA operates very dry, all start-ups are air-air start-ups and, under freeze conditions, the cooling power of the air stream is high making low current density operation difficult. All of these conditions increase the stack degradation and make function under freezing conditions a challenge.

Based on stack/MEA failure modes, two advanced system level operating strategies were developed to mitigate the known failure mechanisms:

- Air-air starts degrade the catalyst and cause voltage degradation.
- Time at open-circuit voltage (OCV) degrades the membrane and causes transfer leaks.
- High currents and stack temperatures stress the membrane.
- Mixed potentials (at start-up and shutdown) degrade the catalyst.

Figure 1 shows stack module bench test results of two system tests for average cell voltage, cumulative number of air-air starts and transfer leak rate versus operating hours; one operating strategy focused on reducing membrane degradation (time at high cell potential) while the other focused on reducing voltage degradation (number of air-air starts). The system strategy to reduce the number of air-air starts demonstrates a lower degradation rate compared to the system strategy that reduces the time at OCV. In the approach to reduce the number of air-air starts, hydrogen is kept on the anode for long periods; the result is more time spent at high cell potentials (or OCV) which has the side effect of increasing the membrane stress. To reduce membrane stress, time at high potentials can be minimized with a possible side effect of increasing the number of air-air starts. A trade-off is required between the two cases because in most cases reducing the number of starts and reducing the time at OCV are linked. The strategy to reduce OCV inherently has more air-air starts and as a result has a higher voltage degradation rate. Less time spent at OCV can increase the time for the MEA to develop a leak because there is less time spent in a state that is damaging to the membrane. Figure 1 also illustrates that although the reduced OCV strategy has the highest voltage degradation rate, it went over 6,000 hours without any indication of a transfer leak. By comparison the reduced starts operating strategy shows signs that a transfer leak was initiated after 5,000 hours due to the time spent at high cell potentials. In this system the end of life criteria is more related to voltage

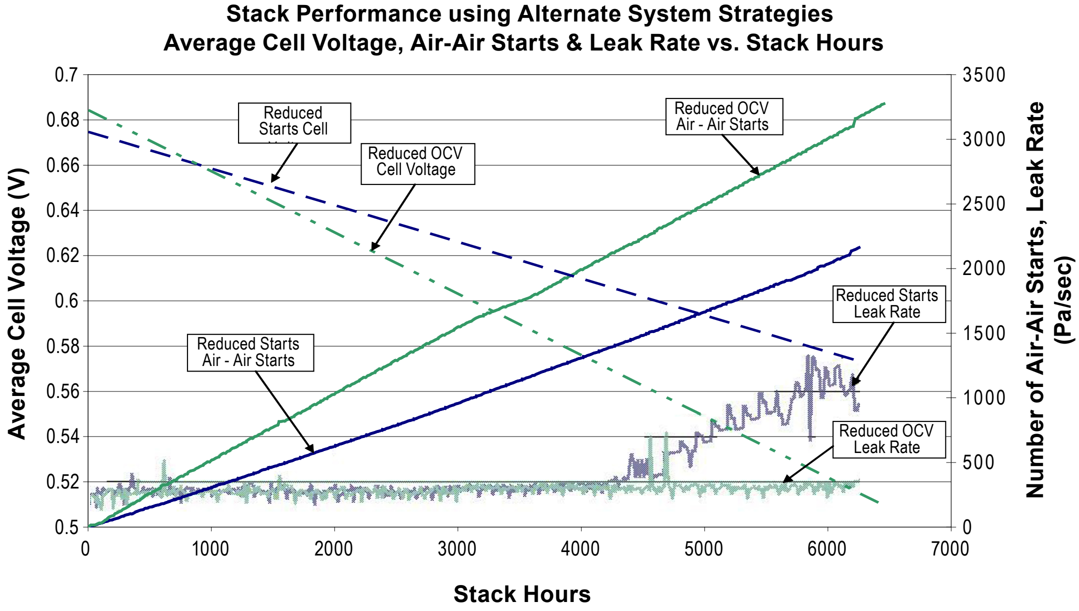

FIGURE 1. Stack Life Test Results

so managing low levels of hydrogen leaks will be accepted in order to extend life.

A prototype system using an air-cooled stack was built and instrumented for purposes of evaluating an air-cooled stack operating at low ambient temperature conditions. All development needed to build a prototype system was undertaken so that a proper system level evaluation could be made. This included activities such as battery hybrid integration, high pressure hydrogen storage integration and controls software development.

Multiple system features for low ambient temperature operation were designed into the prototype system in order to evaluate how each influences performance. A high ambient temperature test was performed first to evaluate any negative effects of system design features intended to allow low ambient temperature operation. The initial high ambient temperature testing indicated excessive pressure drop across the inlet air filter selected for the prototype design. Initially, the stack temperature exceeded the set point even with the fan at maximum speed. Removal of the filter during the test demonstrated the optimal stack temperature could be achieved with the fan operating below 60% capacity. An inlet air filter with lower pressure drop will need to be designed for the next level of tests.

The ambient temperature was then reduced to -30°C while operating a low load profile, reference Figure 2. Although stack temperature is near optimum under freezer conditions, the asymmetry of the air recirculation path produces a non-optimal gradient in stack inlet air temperature (T1, T2 and T3 are different inlet locations). Also discovered during the -30°C testing was ice formation in the air recirculation stream. As the warm exhaust air entered the cold air inlet chamber some of the moisture would condense then freeze. Uniform air temperatures across the stack inlet and control of the condensing moisture are critical for sustained -30°C operation. These issues are slated to be addressed during the design mitigation phase of the project.

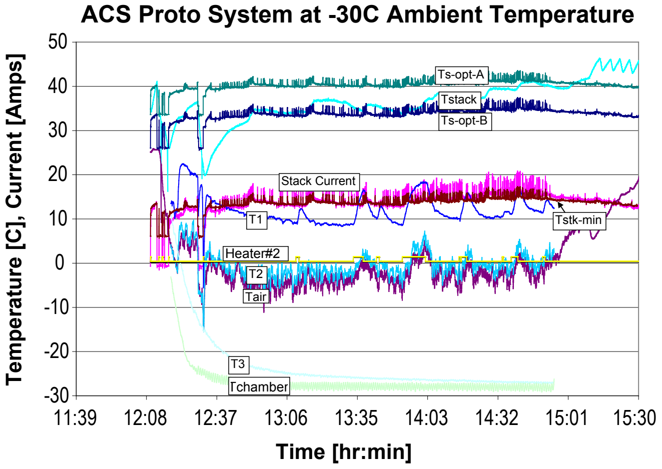

FIGURE 2. Low Ambient Temperature System Test Results

The project Go/No-Go is based on a cost metric of a product utilizing the air-cooled stack technology. Inherent in developing the product cost is that the air-cooled fuel cell stack solution must meet minimum performance and durability requirements to even be considered for a commercial product. The metric states that a GenDrive™ product cost reduction must be 25% or greater using air-cooled stack design over baseline liquid-cooled GenDrive™ product. A comparison of initial product cost and lifecycle cost is shown in Figure 3. Several product comparisons are made using the 2009 liquid-cooled (9SSL Technology) GenDrive^{TM} product as the baseline. Cost reductions for the 9SSL in 2010 are primarily from supply chain initiatives. An additional 9SSL cost reduction is projected based on continued supply chain initiatives plus concept system architecture.

The first air-cooled stack comparison is made with Ballard Power System's ACS second generation MEA with 5,000 hour durability. The product cost was estimated using both a top down and bottom up approach; both estimates resulted in very similar (<4% difference) cost estimates. The top down approach started with the existing liquid-cooled product and subtracted and added component differences. The bottom up approach assumed a clean sheet design and cost estimates were applied to each subsystem based on the system process and instrumentation diagram and the actual prototype system. The second air-cooled stack comparison was made with Ballad Power Systems Advanced ACS MEA.

As can be seen, reductions in initial product cost utilizing liquid-cooled technology are starting to level out whereas product cost projections utilizing the air-cooled stack technology indicate a possible step change for the order picker product. All costs are shown normalized to the baseline. A Go/No-Go review was held with the DOE and the project was approved to advance to the next phase of design mitigation to issues uncovered during freeze testing.

One of the major issues uncovered during freeze testing was a non-uniform stack inlet air temperature gradient. Warm exhaust air is re-circulated to the stack inlet and mixed with the cold inlet air to reduce the effects of freezing air on the cathode. Computation fluid dynamics was used extensively to optimize the stack inlet air velocity and temperature gradients in the freezer (-30°C ambient temperature) environment. The initial air recirculation duct work had decent velocity gradients but large temperature gradients at the stack inlet. The air recirculation duct work was then evaluated and re-designed to reduce the air temperature gradients. Figure 4 shows the temperature profile after refinements were made to the air recirculation. The velocity profile is now very uniform; however there is still an area of the stack inlet that has a lower temperature than the rest of the stack. Some additional refinement is still required to reduce the stack inlet air temperature gradient while operating in the freezer.

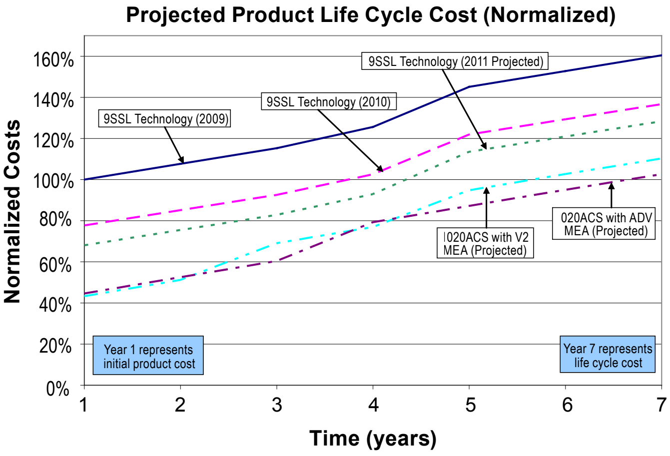

FIGURE 3. Life Cycle Cost Analysis

Conclusions and Future Directions

- Ballard's FCvelocity™ 1020ACS can meet the durability and cost requirements of the order picker GenDrive^{TM} with modified system operating strategies designed to reduce the number of air-air starts.
- With Ballard's FCvelocity™ 1020ACS, the order picker GenDrive^{TM} cost is lower than the liquid-cooled solution even with system strategies to handle freeze condition.
- Complete the design mitigation strategies for issues discovered during the low and high ambient temperature testing.
- Build prototype systems with mitigation strategies.
- Test prototype systems with mitigation strategies at low and high ambient temperatures.

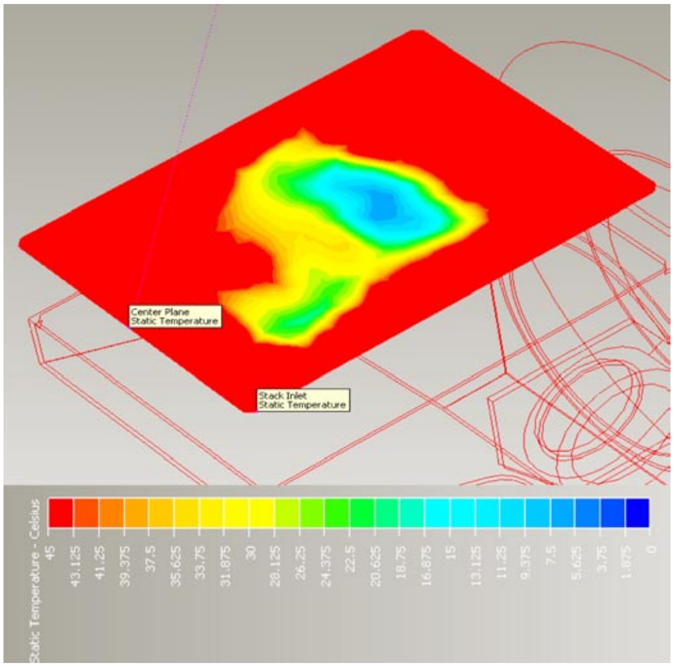

FIGURE 4. Air Temperature Profile at Stack Inlet