V.F.1 Air-Cooled Stack Freeze Tolerance

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Fiscal Year (FY) 2012 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. This plan can be accessed at http://www.eere.energy.gov/hydrogenandfuelcells/mypp/).

(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

Characteristic (DOE Barrier)	Project Target	Project Results
Cost	≥25% cost reduction compared to liquid cooled stack solution (simultaneously meeting durability and performance targets)	Projected 57% initial product cost reduction and projected 32% product life cycle cost reduction
Durability	5,000 hour stack life with >0.54 volts/cell at 51.7 amps	Validated 5,000 hour durability on 6 air-cooled fuel cell stacks (average durability 5,700 hours)
Performance	Sustained operation in -30°C ambient temperature with stack inlet air temperature >0°C and stack temperature gradient <10°C	Designed and validated sustained operation at -30°C ambient temperature; stack inlet temperature >2°C and stack temperature gradient <6°C

FY 2012 Accomplishments

- Completed testing of next generation membrane electrode assembly (MEA) designs with operating strategies with advanced system operating strategies. The operating strategies focus on reducing cathode catalyst dissolution and corrosion and chemical and mechanical stress on the membrane.
- Developed mitigation strategies for issues found in the prototype system testing.
- Built a system with all mitigation designs and performed system level high and low ambient temperature testing.

Test results demonstrate all issues were successfully mitigated.

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Introduction

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

The fuel cell system was derived from Plug Power's commercially available GenDrive™ platforms, which were used to provide battery replacement for equipment in the material handling industry. The fuel cell stacks were Ballard's commercially available FCvelocity™ 9SSL (9SSL) liquid-cooled PEM fuel cell stack and FCvelocity™ 1020ACS air-cooled PEM fuel cell stack. Plug Power lead the design-build-test and design-of-experiment efforts for the GenDrive™ systems with the support of 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 were 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 were explored. The project developed an understanding of market needs, system requirements, and stack-system limitations and used historical data, models and small-scale testing to define stack/system operating strategies that achieved the required freeze function and durability.

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

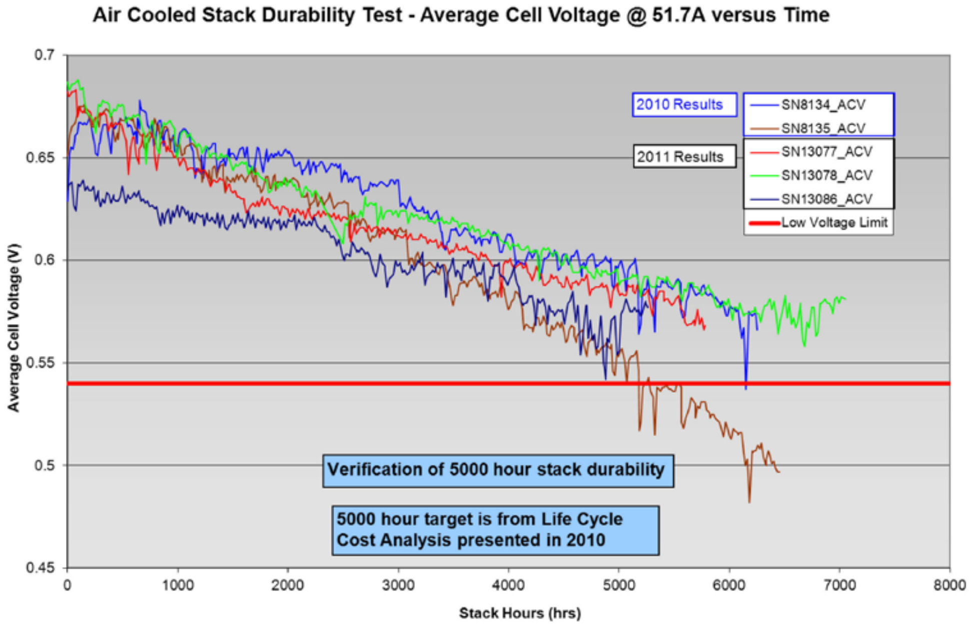
Results

Durability tests for the current design (V2) MEA and an advanced concept (V2-A) MEA were completed and are compared against the prior test results of the original (V1) MEA. The V2 MEA has a catalyst which is more resistant to carbon corrosion than the V1. The V2-A MEA has the additional feature of a membrane that is more resistant to transfer leaks (cross leaks from anode to cathode). System operating strategies were developed in collaboration with Ballard to mitigate stressors linked to cell and stack failure modes. The following stressors were identified: A) Air-air starts degrade the catalyst and cause voltage degradation; B) Time at open-circuit voltage (OCV) degrades the membrane and causes transfer leaks; C) High currents and stack temperatures stress the membrane; D) Mixed potentials (at start-up and shutdown) degrade the catalyst. Table 1 identifies the MEA type and system strategy and also summarizes the test results.

The stacks were tested using a simulated material handling load profile; the stack load was modeled analytically for the stack durability tests. Figure 1 shows the average cell voltage over time for the stacks and system strategies tested. Figure 2 illustrates when a transfer leak (cross leak from anode to cathode) occurs in the stack at one or more cells. A pressure decay measurement is taken with the anode loop closed. Stack SN 8135 which operated with a system control strategy to reduce the time at OCV ran over 6,400 hours and did not develop a transfer leak. Stack SN 13086, which incorporates a membrane more resistant to transfer leaks, operated over 5,200 hours without a transfer leak. Note that for stack SN 13086, large leaks were measured several times between 2,200 and 2,800 hours that were due to test stand issues; once these leaks were repaired the stack leakage rate returned to normal. Stack SN 8134, 13077 and 13078 all show transfer leak initiation started around 4,200 hours. This was expected for the V2 MEA (13077 and 13078) compared

TABLE 1. Summary of Stack Test Results

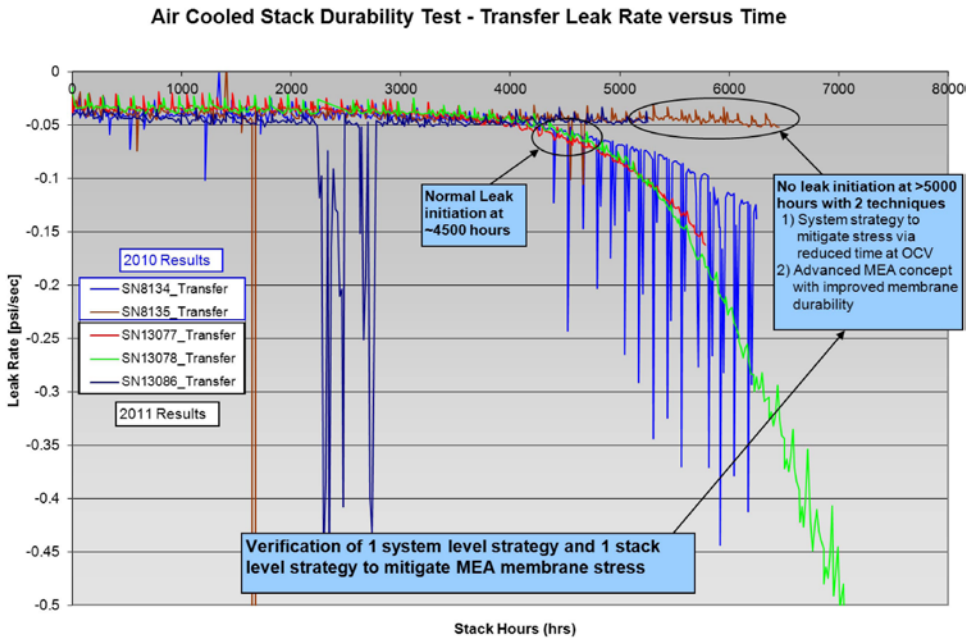
Stack	Cells	MEA	Strategy	Hours	Cycles	Deg Rate at 51.7A (μV/hr)	Transfer Leak	Completed
SN8134	36	V1	A, C, D	6253	2163	-16.2	Yes	2010
SN8135	36	V1	B, C	6456	3275	-27.1	No	2010
SN13077	36	V2	A, C, D	5785	1119	-16.8	Yes	2011
SN13078	36	V2	A, C, D	7054	1354	-15.6	Yes	2011
SN13086	36	V2-A	A, C, D	5261	1019	-13.3	No	2011



Verification of 5000 hour stack durability

5000 hour target is from Life Cycle Cost Analysis presented in 2010

FIGURE 1. Average Cell Voltage versus Time



Normal Leak initiation at ~4500 hours

No leak initiation at >5000 hours with 2 techniques
1) System strategy to mitigate stress via reduced time at OCV
2) Advanced MEA concept with improved membrane durability

Verification of 1 system level strategy and 1 stack level strategy to mitigate MEA membrane stress

FIGURE 2. Stack Transfer Leak Rate versus Time

to the V1 MEA (8134) because the membrane durability was not addressed in the V2 design. Specific membrane improvements were made on the V2-A MEA (13086) and the test results demonstrate the effectiveness of those improvements.

The final system built with freeze mitigation strategies was tested at both low and high ambient temperatures. All issues found during the initial test phase were addressed and mitigation strategies selected are as follows.

Initial testing at high ambient temperature indicated the system pressure drop was too high on the cathode to properly cool the stack at a +40°C ambient temperature. A lower pressure drop filter was developed during the design mitigation phase. System level high ambient temperature testing proved the fan was able to maintain the target stack temperatures at a +40°C ambient temperature.

Initial testing indicated a high inlet air temperature gradient across the stack and that moisture was condensing and freezing is some areas. Computational fluid dynamics (CFD) modeling was used to improve the inlet air temperature gradient. It proved so effective that auxiliary heaters were not required to the obtain target air inlet temperatures even while operating in a -30°C ambient temperature environment. CFD models were validated by module level testing in an environmental test chamber. Additional duct work refinements plus manufacturing changes to allow simpler duct fabrication were again tested at the module level to verify the final design configuration. In addition to not needing auxiliary heaters, the ducting improvements also demonstrated that no moisture was condensing or freezing in the recirculation loop. In a low ambient temperature environment, warm stack exhaust air is efficiently moved to the stack inlet and then mixed with the cold ambient air. Target stack inlet temperatures as well as temperature gradients are maintained over the entire operating regime.

FIGURE 3. Final System Shown in Plug Power Environmental Testing Chamber

Additionally, air-cooled stack durability was investigated in more detail because even though initial stack testing proved the 5,000 hour life target could be met; any gains in durability only stand to improve the product life cycle cost. The startup controls and idle time were modified to create a 46% reduction in the number of air-air starts (strategy A improvement). Additionally a cathode air starve technique was developed to minimize oxide layer growth on the catalyst; this improves cell performance because it allows the MEA to operate at a higher potential. If an oxide layer builds on the catalyst the performance is suppressed and the stack will reach end of life sooner. The strategy to minimize mixed potentials on shutdown was optimized to minimize carbon corrosion (strategy D optimization).

Final system verification testing at a low ambient temperature of -30ºC was performed in the environmental testing chamber at Plug Power. Figure 3 shows the test set up and Figure 4 shows the test results. The system was operated at both high and low loads over an 8-hour period.

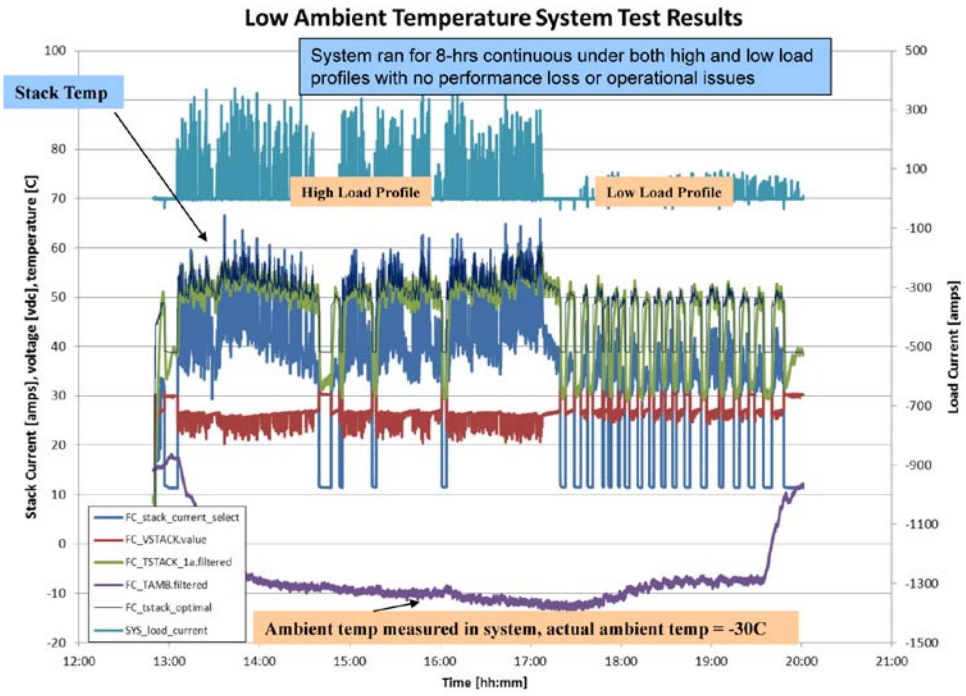


FIGURE 4. System Test Results from -30°C Ambient Temperature Testing

No performance or operation issues were observed and the system was able to maintain the optimal stack temperature. This test data is the culmination of all the freeze tolerance operation strategies developed and optimized over the course of this project.

The Air-Cooled Stack Freeze Tolerance project with DOE support was a success for Plug Power on multiple fronts. First, several technical achievements were realized through the work of this project; from proving 5,000 hour durability with an air-cooled stack, to understanding and addressing failure modes for both durability and freeze tolerance to the operation of an air-cooled stack in a -30°C ambient temperature environment without the use of heaters. And second, Plug Power demonstrated commercial success by releasing a new, 30% lower cost, fuel cell product that incorporated the learning from this project. The new GenDrive Class 3 fuel cell would not have been able to drive a step change in the cost structure without all the achievements from the Air-Cooled Stack Freeze Tolerance project. This project was able to translate research and development into commercial success.

Conclusions and Future Directions

- 5,000 hour durability target met with advanced MEA designs developed to improve corrosion resistance and membrane durability operating with system strategies developed to reduce air-air starts, OCV time and mixed potentials at shut down.
- Sustained operation at -30°C possible with system mitigation strategies employed and without the use of heaters.
- Product cost and life cycle cost analysis demonstrates significant lower cost utilizing ACS technology for material handling order picker applications.

This project is complete. Plug Power would like to express thanks to the DOE and Ballard Power Systems for the work and contributions that helped make this project a success.

FY 2012 Publications/Presentations

1. **PEM Cathode Catalyst Layer Degradation with Ambient and Freeze-Thaw Cycling**; Joanna Kolodziej P.Eng and Cara Startek; Ballard Power Systems, ASME Conference – August 2011.

2. **PEMFC MEA and System Design Considerations;** S. Knights, R. Bashyam, P. He, M. Lauritzen, C. Startek, V. Colbow, T. T. H. Cheng, J., Kolodziej, and S. Wessel, meeting abstract, Electrochemial Society 1102, 774 (2011).

3. **Durability Approach for Air Cooled Stack Integration in a Materials Handling Application;** Cara Startek and Shanna Knights, Ballard Power Systems, Small Fuel Cells Conference 2011.