V.M.1 Air-Cooled Stack Freeze Tolerance

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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.
- GenDrive™ product cost reduction of 25% or greater using air-cooled stack design over baseline liquid-cooled GenDrive™ product.

Accomplishments

- Through detailed stack failure analysis the key stack failure modes were identified to be platinum loss and platinum crystal growth during start-stop and membrane leak induced cathode carbon corrosion. In extreme freeze events cathode catalyst fragmentation was also seen. Materials and operating strategies were selected to mitigate these failures.
- Advanced system operating strategies for the Mk1020 air-cooled stack have demonstrated 5,000 hours of operation to date (2.5 times initial durability), testing is still ongoing. These operating strategies focus on reducing cathode catalyst dissolution and corrosion and chemical and mechanical stress on the membrane.
- Advanced Mk1020 air-cooled stack membrane electrode assembly (MEA) concepts have demonstrated an improvement in both operating hours and start-stop cycles; 2,500 start-stops have been achieved and testing is on going. Advanced MEAs contain a membrane of lower ionic resistance and higher chemical stability as well as a better dissolution-resistant cathode catalyst.
- Stack-system modeling has been used to guide balance-of-plant design to achieve freeze targets. Validation of model output is ongoing.

- Although over 100 freeze-starts were demonstrated on the FCvelocity™ 1020ACS stack the variability in performance start-to-start was high and would still contribute to the dominant degradation mode of platinum dissolutions and agglomeration. To achieve the performance and durability targets for materials handling the system will be designed to provide the stack with optimal conditions where possible (within realistic BOP cost restrictions).

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Introduction

To be competitive with incumbent materials handling technologies there is a need to reduce the overall cost of the materials handling stack/system. The fuel cell stack incumbent technology is the liquid-cooled GenDrive™ system. The air-cooled stack offers a chance to reduce the cost of the system by eliminating the need for a humidifier and coolant loop. In order to be a viable option for materials handling applications the air-cooled stack must also demonstrate increased durability and freeze function.

Plug Power's objective is to advance the state of the art in technology for air-cooled fuel cell stacks and related GenDrive™ material handling application fuel cell systems. This will be accomplished through a collaborative work plan to improve freeze tolerance and mitigate freeze-thaw effect failure modes within innovative material handling equipment fuel cell systems designed for use in freezer forklift applications.

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. 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 each iteration. Stacks and systems will be operated to failure under material handling freezer conditions, failure analysis will be performed to understand the root cause, stacks and systems will be designed to mitigate the failure modes, then built and tested, and trade-off analysis will be used to determine the design solutions that are built and tested.

Results

The Mk1020 air-cooled stack must first demonstrate performance and durability targets to be considered a viable GenDrive™ product solution. Specifically, the Mk1020 must demonstrate 5,000 hours running a representative load profile including start-stop cycles. The Mk1020 stack offers system simplicity by eliminating the liquid cooling system; this is achieved through an "open cathode" design where cooling and reactants are supplied by a single fan. 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 freeze function a challenge.

The failure modes of the baseline Mk1020 stack were identified by running a stack through the standard Mk1020 ACS duty cycle and removing MEAs every 250 cycles for degradation analysis. The dominant voltage degradation modes were identified as catalyst dissolution, followed by membrane transfers (internal leaks). Results show that at the onset of internal membrane leaks the catalyst failure mechanism begins to include corrosion as well as dissolution as seen by a catalyst layer thickness reduction once the stacks begins to leak; this is thought to be due to air leaking to the anode during operation and on shutdown. Wet-dry cycling as well as operating at high potentials accelerate the membrane degradation, see Figure 1. To improve the durability by way of design changes, a more dissolution resistant cathode catalyst and leak-resistant membrane were explored.

In this report advanced stack concepts are represented by the following code: Ax Mx Cx, where A represents the anode, M represents the membrane and C represents the cathode. The baseline MEA is A1 M1 C1.

Advanced MEA concept durability is shown in Figure 2. The durability of the membrane, as seen by leak rate, has been significantly improved from the baseline (M1), both M2 and M3 have longer times to leak initiation. The voltage degradation rate is improved with the advanced catalyst design C3. The stack concept that provides a low degradation rate will be considered as the primary candidate.

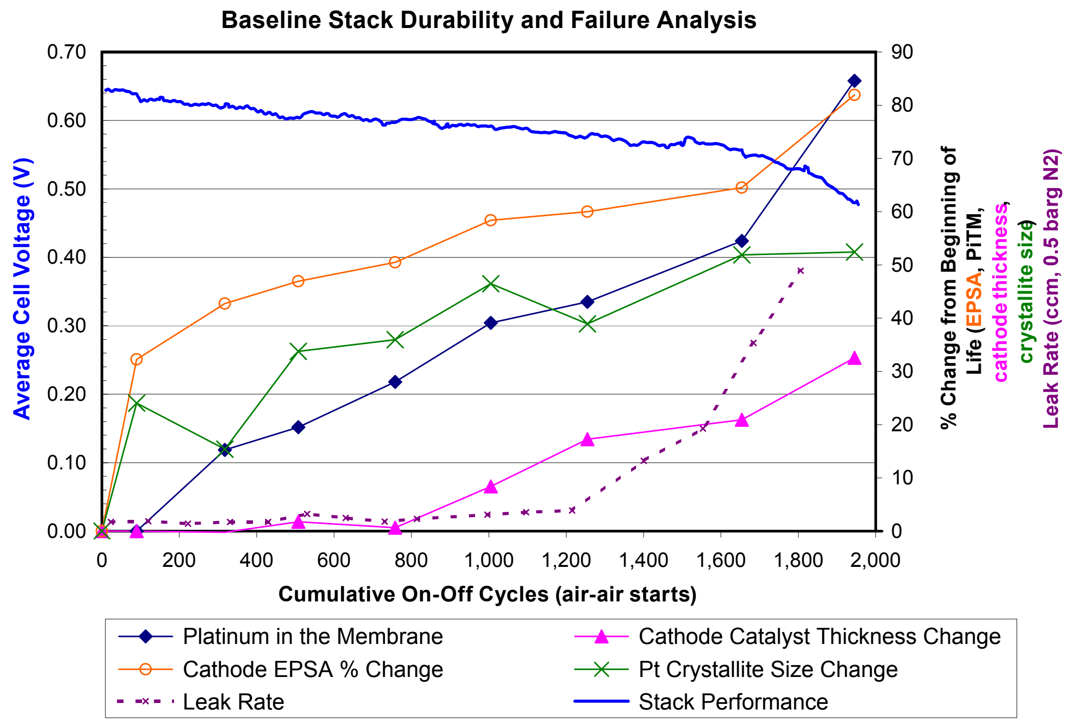


FIGURE 1. Degradation and Failure Analysis of Baseline Stack

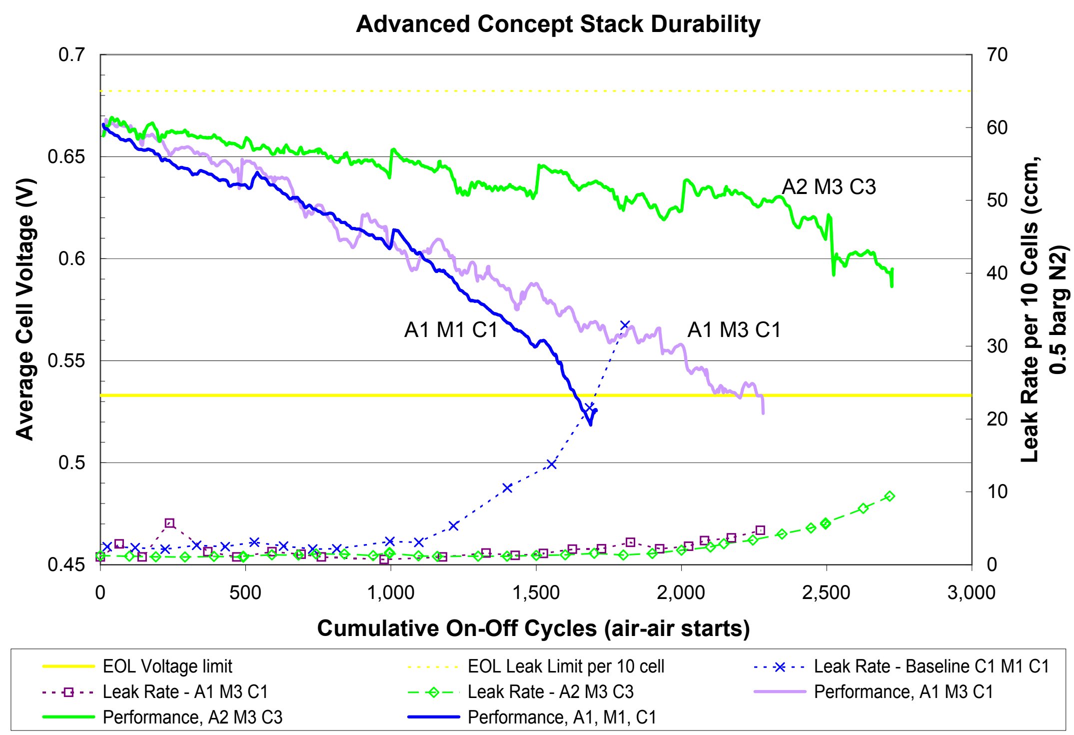


FIGURE 2. Advanced Stack Concept Durability Testing Results

Failure analysis of advanced concepts shows improvements can be made to the failure propagation of the catalyst and membrane. Results indicate lower crystallite growth, lower cathode catalyst thickness loss, and lower platinum dissolution. It was also noted that more durable membranes (M2 and M3) can lower the impact of cathode catalyst corrosion compared to the baseline. This further supports the link between localized transfers in the membrane and catalyst corrosion.

Based on the baseline stack durability testing and failure analysis the system can impact stack durability by controlling stack-critical parameters for performance and durability, including: stack temperature, relative humidity cycles, time at open circuit voltage, cathode potential, cathode potential cycles and mixed anode potentials.

System strategies designed to mitigate the known stressors and improve stack life were evaluated via screening tests and the best strategies were down-selected for long-term durability testing. Each system strategy was designed to control one or more of the above critical parameters. Figure 3 illustrates cell voltage degradation as a function of hours for the baseline system and two advanced operating strategies.

Air-cooled stack durability and start-stop cycles have been improved over the original design air-cooled stack when operating under material handling conditions via successful implementation of operating system architecture strategies. Stack life has been demonstrated at 2.5 times the original design; going from 2,500 hours to 6,300 hours. Air-Air starts have been improved by 1.6 times the original design; going from 1,000 to 1,600.

Performance test results for the baseline Mk1020 stack indicate a lower performing polarization curve at the extreme temperatures, 40°C and -10°C. This was a result of fan turn-down limitations resulting in non-optimal stack temperatures during the polarization. Stacks that run above the optimum temperature tend to experience drier conditions, while stacks that run below optimum temperature tend to run wetter; both situations can lead to performance loss. Although the freeze-start capability of the baseline ACS stack was variable from test to test, over 100 freeze-start cycles were completed. The end cells of the stack were particularly sensitive, failure analysis of the most sensitive cells showed typical freeze failure damage; i.e. catalyst cracking and fragmentation.

Based on previous Ballard design work, a MEA/stack solution for freeze and durability can significantly increase the cost of the stack. Therefore, the primary approach is to explore system options and operating strategies in order to manage a sub-zero environment with extended durability.

A stack thermal computational fluid dynamics model that combines fluid flow and heat transfer in a single air channel was developed to explore several stack-system related freeze function strategies related to increasing the rate of stack heating. The baseline operating strategy, heater use, fan turndown and cathode recirculation were explored to determine the

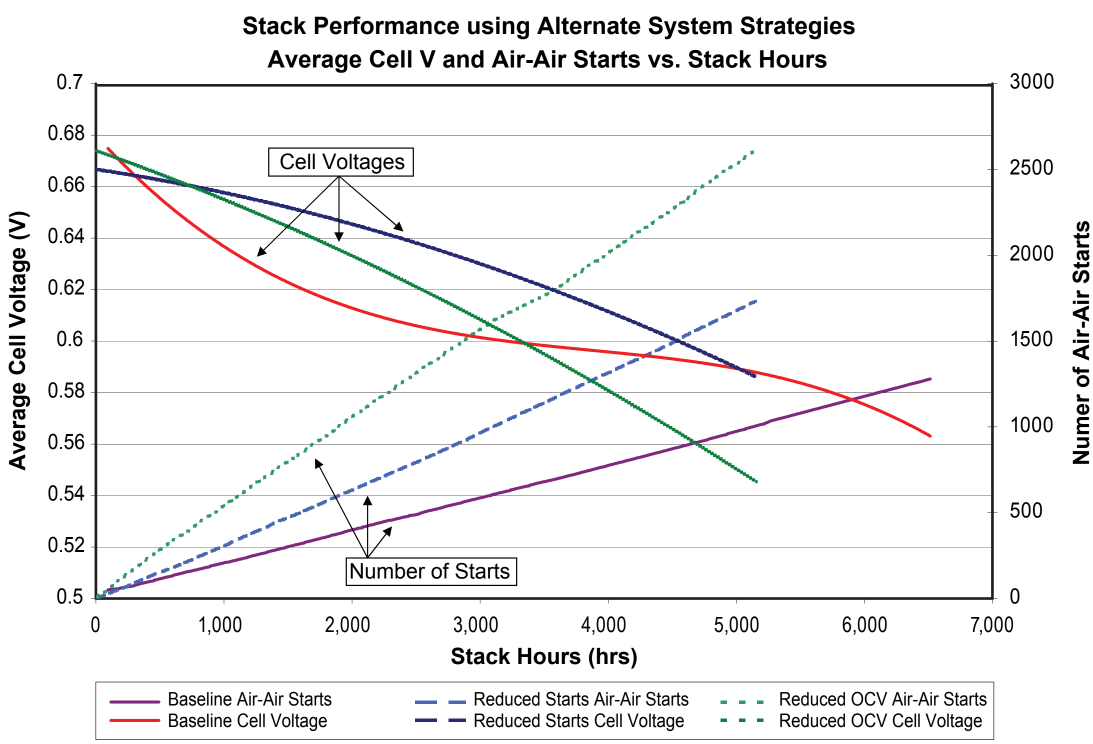
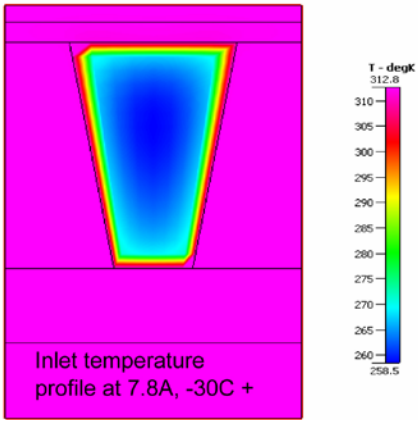


FIGURE 3. Stack Performance using Alternate System Strategies

TABLE 1. Results of Thermal Modeling of Stack with Inlet Air of 20°C, -10°C and -30°C



	Units	Nominal Conditions	-30°C Ambient Conditions + Heater	Target Ambient Conditions
Cathode/Air Inlet Temperature	C	20	-10	-30
Cooling Flow Rate Required for Optimum Temp at 7.8 A	slpm	319	129	88
Cooling Flow Rate Required for Optimum Temp at 51.7 A	slpm	1,968	1,007	781
Fan Turn Down Ratio[1]	-	6	15	22
Heat Required to Heat Air from -30 C to Required Inlet Temp	W	345	52	0

[1] Calculated from 51.7 A flow at 20C to 7.8 A flow at required inlet temperature

requirements for function at -30 C. In all cases explored the goal was to reach optimum temperature, to minimize the performance de-rate, as quickly as possible. Table 1 summarizes some of the results, validation of these results will happen at the system level.

Conclusions and Future Directions

- Both stack and system test data are tracking to show advanced MEA concepts and/or advanced system strategies can achieve the requisite stack-system durability.
- The baseline freeze function of the stack is not sufficient to meet the materials handling requirements. Stack-system solutions are being explored.
- Stack/system testing under material handling freezer application conditions has not been completed and is needed to understand the commercial viability of the air-cooled stack.
- Models have been developed for stack and system operation in freezer conditions and used as input for the concept air-cooled fuel cell system architecture.
- Concept air-cooled fuel cell systems will be built and tested under material handling freezer conditions.
- Failure analysis will be performed on stacks and systems to understand the freeze failure modes.
- Freeze prevention and mitigation design step following failure analysis and the best solution(s) will be down-selected using trade-off analysis.
- A product life cycle cost analysis will be used to evaluate the commercial viability of using an air-cooled fuel cell stack versus a liquid-cooled stack. The key parameters for the product life cycle cost analysis are the capital, maintenance, and operational costs. A GenDrive product with an air-cooled fuel cell stack must demonstrate a 25% lower capital cost and life cycle cost when compared to the 2009 end-of-year GenDrive with a liquid-cooled fuel cell stack.
- A Go/No-Go project decision review will be held with the DOE to evaluate the metric of a 25% GenDrive™ product cost reduction using an air-cooled fuel cell stack versus a liquid-cooled fuel cell stack.
- Air-cooled fuel cell stacks and systems will be built with freeze mitigation design strategies and re-tested to evaluate the improvements under material handling freezer conditions.