Air-Cooled Stack Freeze Tolerance

Freeze Failure Modes and Freeze Tolerance Strategies for GenDrive™ Material Handling Application Systems and Stacks

Final Scientific Report

DE-EE0000473

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1 REPORT APPLICABILITY

Project Title:	Air-Cooled Stack Freeze Tolerance - Freeze Failure Modes and Freeze Tolerance Strategies for GenDriveTM Material Handling Application Systems and Stacks
Project Period:	June 1, 2009 to November 15, 2011
Reporting Period:	June 1, 2009 to November 15, 2011
Date of Report:	February 13, 2012
Recipient:	Plug Power Inc.
Award Number:	DE-EE0000473
Working Partners:	Plug Power Inc. Ballard Power Systems
Cost-sharing Partners:	Plug Power Inc. Ballard Power Systems
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2 EXECUTIVE SUMMARY

Air-cooled stack technology offers the potential for a simpler system architecture (versus liquid-cooled) for applications below 4 kilowatts. The combined cooling and cathode air allows for a reduction in part count and hence a lower cost solution. However, efficient heat rejection challenges escalate as power and ambient temperature increase. For applications in ambient temperatures below freezing, the air-cooled approach has additional challenges associated with not overcooling the fuel cell stack. The focus of this project was freeze tolerance while maintaining all other stack and system requirements.

Through this project, Plug Power advanced the state of the art in technology for air-cooled PEM fuel cell stacks and related GenDrive™ material handling application fuel cell systems. This was 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. Freeze tolerance remains an area where additional research and understanding can help fuel cells to become commercially viable. This project evaluated both stack level and system level solutions to improve fuel cell stack freeze tolerance. At this time, the most cost effective solutions are at the system level. The freeze mitigation strategies developed over the course of this project could be used to drive fuel cell commercialization.

The fuel cell system studied in this project was Plug Power's commercially available GenDrive™ platform providing 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 (Mk1020) air-cooled PEM fuel cell stack.

Ballard FCvelocity™ 1020ACS air-cooled PEM fuel cell stack

3 OBJECTIVES, GOAL AND ACCOMPLISHMENTS

The specific project objectives and accomplishments versus the project goals are outlined below.

1) Evaluate and develop the stack and system together to meet durability, cost, performance and freeze tolerance requirements

   a) The durability target set at >5000 hours for the air cooled stack based on a preliminary cost analysis to be a competitive solution to the incumbent liquid-cooled solution

   b) The cost target for an air cooled solution was set at 75% of the incumbent liquid-cooled solution to make the technology worth investing additional resources to develop. This was for both initial product cost and product life cycle cost and was used as the project Go / No-Go metric.

   c) The performance and freeze tolerance criteria were Plug Power customer application loads for F3 order picking units in -30°C distribution center freezers.

   d) The final stack-system solution met the project requirements for durability, cost, performance and freeze tolerance.

2) Develop understanding around integrating air cooled stack technology into a dynamic materials handling system; including frequent air to air start ups and operation in a freezer (-30°C ambient temperature) environment.

   a) The project included a subcontract with Ballard Power Systems to identify stack failure modes, develop stack specific improvements and to evaluate system mitigation strategies for integrating the air-cooled stack technology in a material handling system application.

3) Test and evaluate air-cooled stacks and system compatible operation developed for increased freeze tolerance and durability.

   a) A new stack MEA was developed to mitigate the stressors identified that reduce stack life in the material handling application

      i) Stack failure mode analysis was performed to identify end of life failure modes.

      ii) Accelerated stack stress tests were developed to reduce the time in testing alternate MEA concepts that addressed the identified failure modes.

      iii) Best MEA solutions were built into full stacks and placed on a durability test to prove the solutions addressed the failure mode hypothesis.

   b) System level strategies were developed to mitigate the stressors identified that reduce stack life in material handling applications.

      i) Multiple system level strategies were implemented on the stack durability test benches to prove the solutions addressed the failure mode hypothesis.

      ii) Best system level strategies were carried forward in subsequent tests.

4) Evaluate failure mechanism mitigation at MEA, stack and system level.

    a) The project evaluated MEA, stack and system level mitigation strategies. System level mitigation was determined to be the most cost effective solution.

5) Perform life-cycle cost analyses for freeze tolerance strategies.

    a) A life-cycle cost analysis was performed after initial prototype testing proved the selected stack-system solution could meet the required durability, performance and freeze tolerance.

    b) All costs were normalized and the incumbent liquid-cooled solution for order picking material handling applications was used as the baseline for the cost comparisons.

    c) The projected initial product cost of the air-cooled solution was 43% of the baseline.

    d) The projected life cycle cost of the air-cooled solution was 68% of the baseline.

    e) A Go / No-Go Review was held with the DOE to evaluate the project against the stated metrics. A Go decision was determined and the project continued in order to address issues that were found during the initial testing.

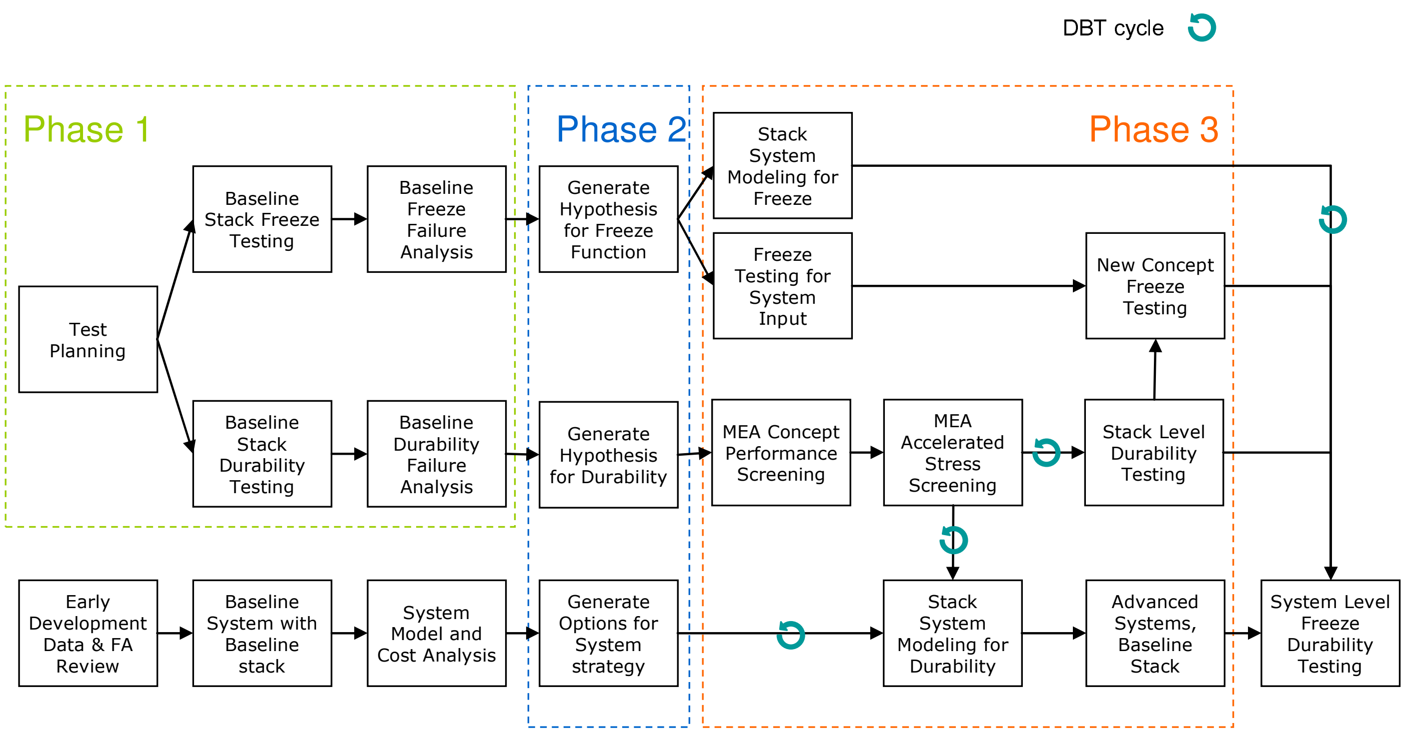
6) Document and publish summary of freeze failure analysis.

    a) Over the course of this 2 year project, all findings were reported in the 8 Quarterly Progress Reports (Q1 2010 through Q4 2011), 2 Annual Reports (2010 and 2011), 2 Annual Merit Reviews (2010 and 2011) and this Final Scientific Report.

4 PROJECT ACTIVITIES

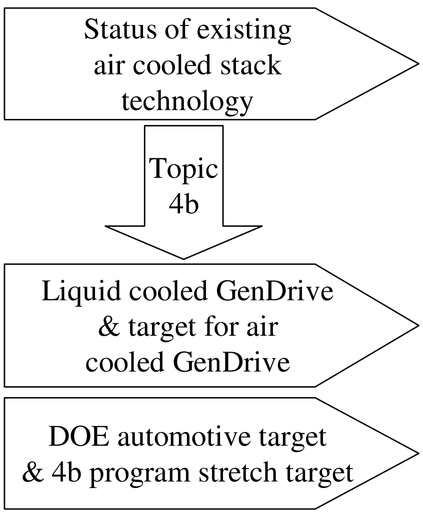
Approach

In this project the fuel cell stack, system and fuel cell stack operation were designed together. With this approach the goal was to trade-off stack durability and freeze function with overall stack-system cost. Multiple design, build, test (DBT) cycles were employed to capitalize on past knowledge and increase the learning through each iteration. Plug Power and Ballard utilized their understanding of market needs, system requirements, stack-system limitations, historical data, models and small scale testing to develop stack/system operating strategies to achieve the required freeze function and durability. Failure analysis was used to improve analytical models and used as input to develop mitigation strategies. Stacks and systems were built with mitigation strategies and tested against requirements. Note that for purposes of continuity of discussion; stack development is reviewed first followed by system development. In reality the stack-system development was in parallel as shown in the flowchart below.



Freeze Capability Levels & Technology Status

The following definitions were developed for consistent understanding when various freeze operations are discussed. Additionally, the status of the liquid cooled and air-cooled technology is shown below.



Term	Definition
Non Freezer Operable	Is not capable for operating at any time in a freezing environment.
Intermittent Freezer Operable	Has the ability to operate for a defined amount of time in a freezing environment of a defined temperature.
Freezer Operable	Has the ability to operate for any length of time in a freezing environment of a defined temperature.
Freeze Tolerant (subset of Freezer Operable)	Freezer Operable unit which has been designed to not sustain any component damage if it is inadvertently left in a freezer when not in operation.
Cold Startable (subset of Freeze Tolerant)	Freeze Tolerant unit that can be frozen without any incurred damage or need for additional protective devices or actions and can be restarted and returned to operation even if stored inside of a freezing environment.

Background

Some historical data was generated through the Ballard subcontract from Plug Power in support their development of a backup power system design under a DOD contract.

A Mk1020 stack was tested at subzero temperatures to investigate the effects of inlet temperature on performance and performance de-rate. The main conclusions from a set of tests run in 2008 are listed below:

- Low ambient temperatures down to -20°C had little impact on stack performance at 65.3 amps. Stack power output de-rates 2%, while it is 35% from -20°C to -45°C. See Figure 1.
- The Mk1020 stack can not operate at low power levels (<65.3 amps) at temperatures below -20°C. Operating temperature can not be maintained due to cooling systems turn-down ratio limitations.
- Stack performance is 100% recoverable as the ambient temperature increases.

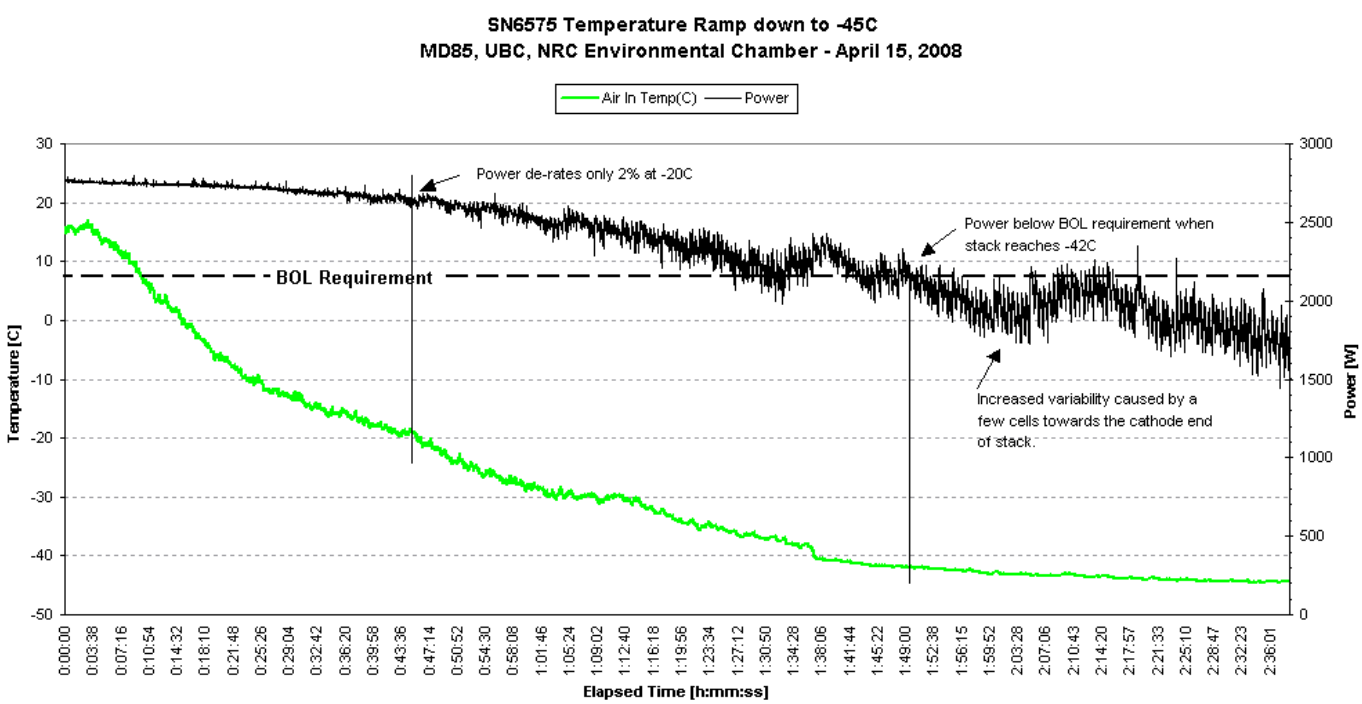


Figure 1: Power de-rate as stack air inlet temperature ramps to -45°C

**NOTE: This is taken from an existing Ballard report, power requirements are not linked to Plug Power application.*

A Mk1020 stack was also started from subzero temperatures to investigate the time required to start the stack. The main conclusions from this set of tests are listed below:

- Through and after all the freeze/thaw cycles the leak rate was unchanged.
- Stack performance was not affected greatly by the freeze/thaw cycles, see Figure 2. Durability testing must be done to verify impact on degradation rates (discussed later).
- Low ambient temperature start-ups down to -20℃ are possible though require a special procedure and an impractical extended amount of time. Maintaining the stack temperature above 0℃ is the best option for reliable start-ups. See Figure 3.

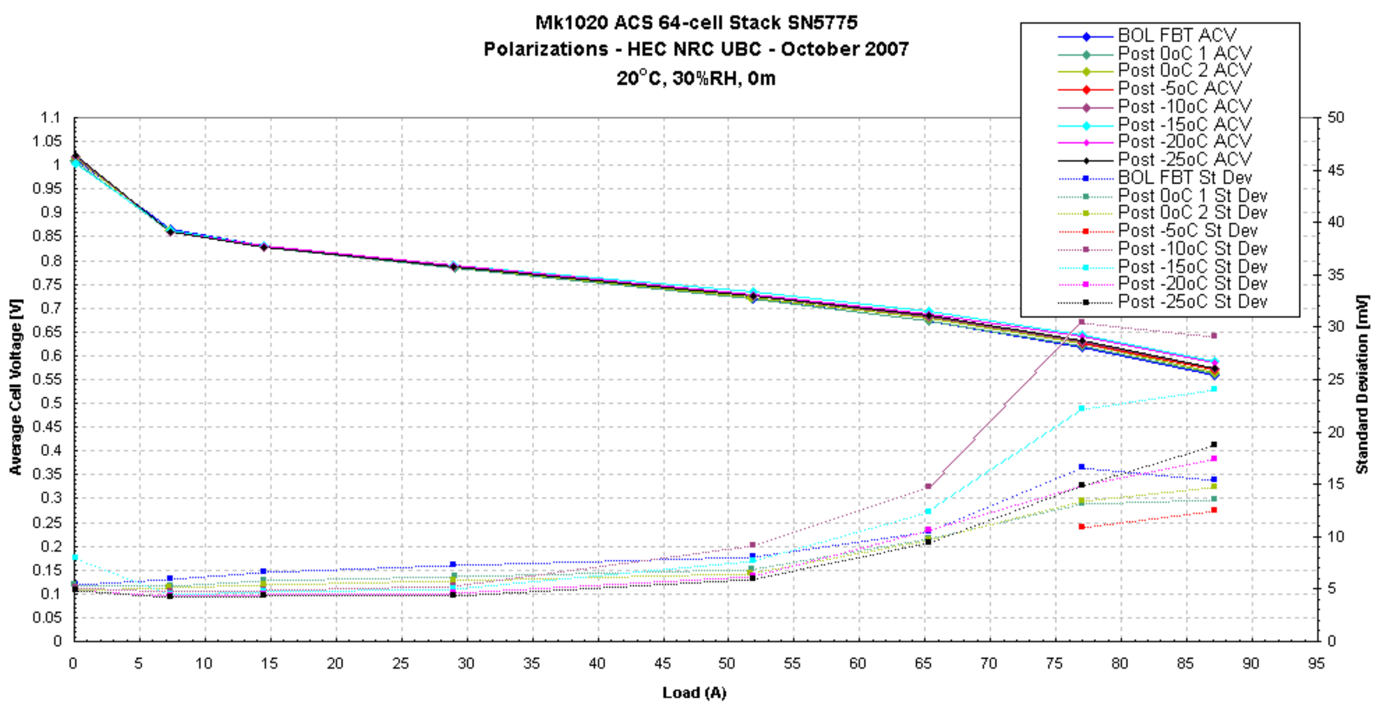


Figure 2: Stack polarizations at 20℃ after freeze thaw cycling

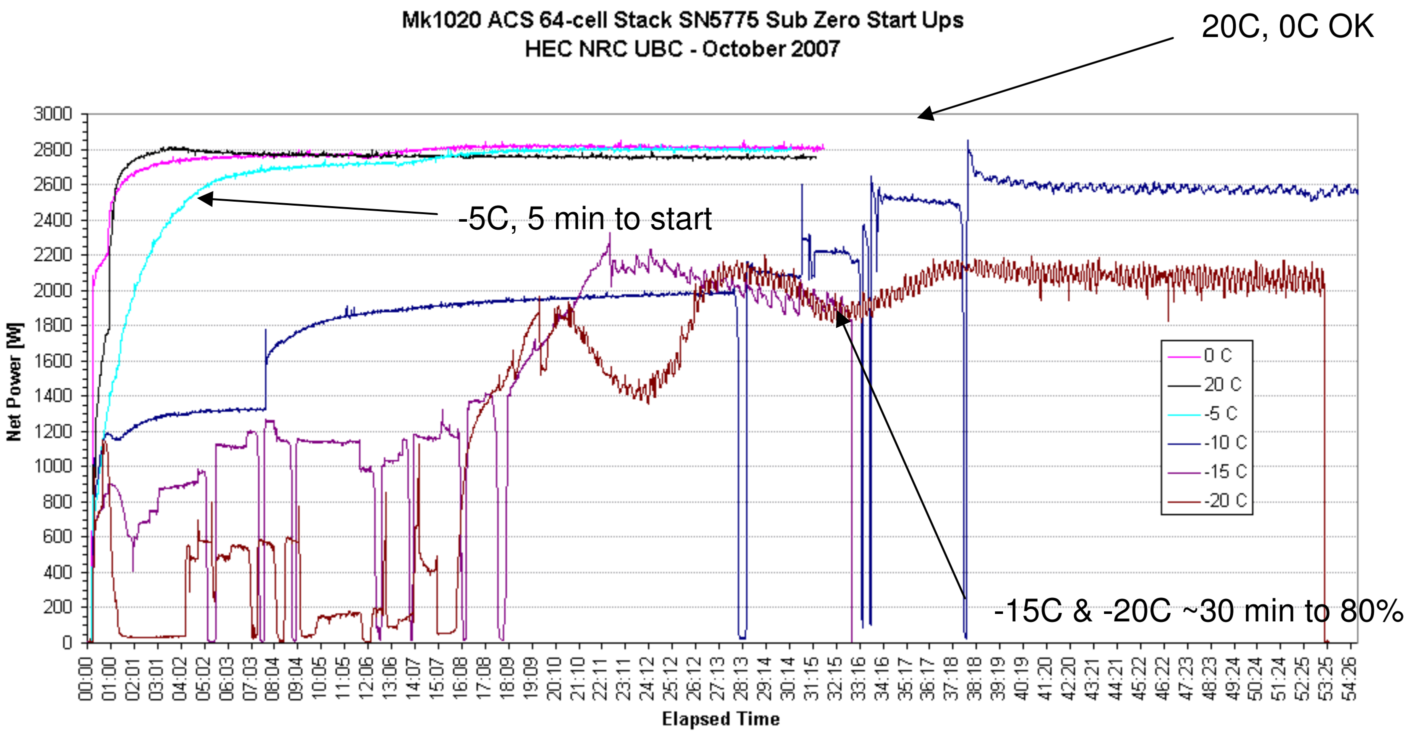


Figure 3: Power ramp up comparison for start-ups from subzero ambient temperatures

Figure 4 shows a typical degradation profile for a Mk1020 stack. Results indicate that the leak rate increased after 1,000 cycles; the increase in leak rate does not seem to be from general membrane thinning. Steady voltage degradation is exhibited through the lifetime of the stack; this seems to be due to corrosion and platinum loss.

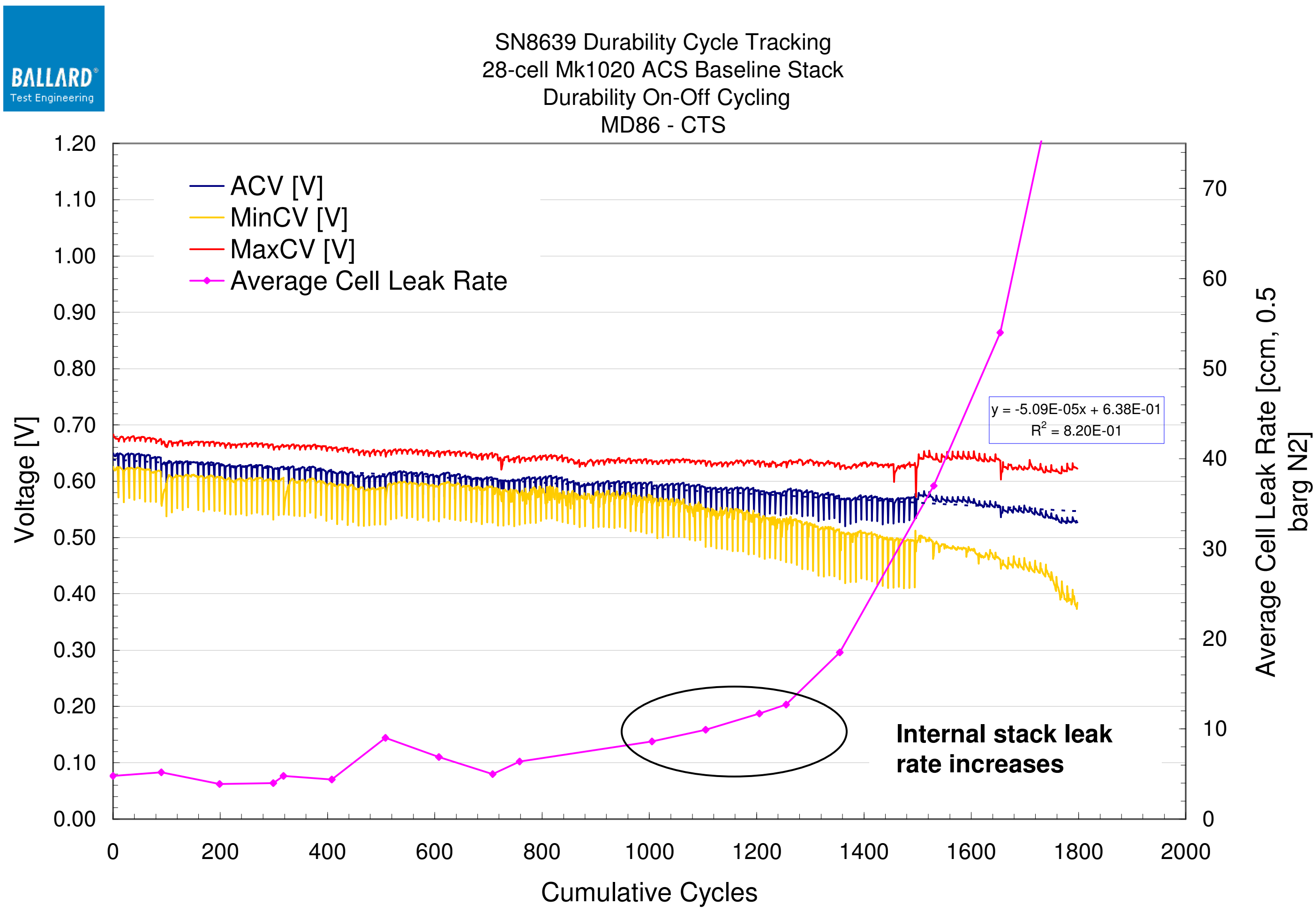


Figure 4: Performance and leak rate data over life

There was no significant membrane thinning observed in the MEA samples analyzed throughout life test, indicating that internal leaks are due to localized holes. An average of 12 thickness measurements were taken from each MEA pulled out. There was an increase in the standard deviation of membrane thickness and a slight thickness increase in some cases (within 5%).

Baseline Stack Performance

In this report CCM designs 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*.

The nominal and sub-zero performance for the baseline MK1020 stack (A1 M1 C1) is shown in Figure 5. The results indicate a lower performing polarization curve at the extreme temperatures, 40℃ and –10℃. 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. The 7.3A operating point of the -10°C polarization can not sustain performance because the temperature of the stack is near 0°C, this causes overcooling and likely flooding of the cell. To run the stack at this temperature and current, modifications need to be made to the system; modeling activities will determine the optimum air flow rate to achieve the optimum temperature and performance.

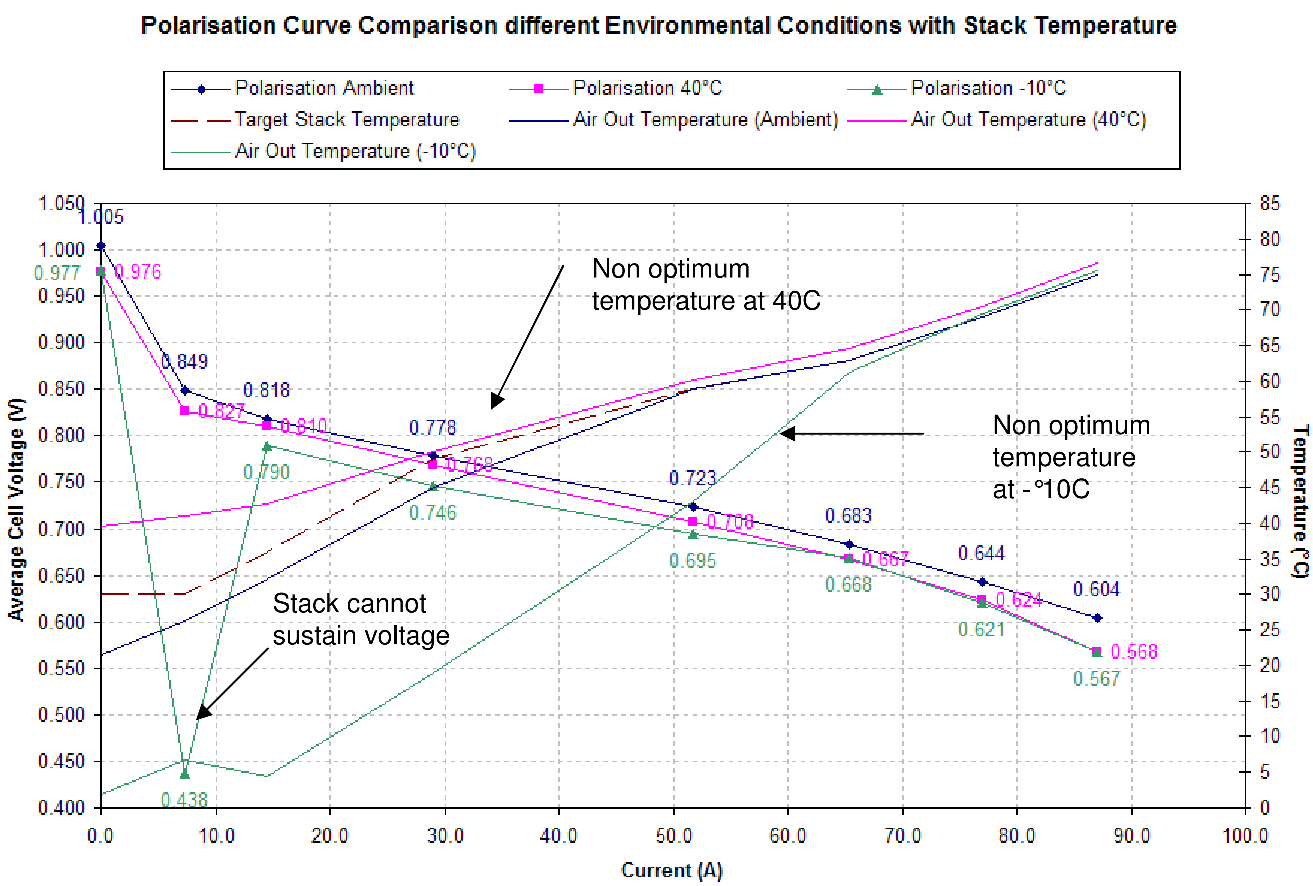


Figure 5: Polarization comparison across various environmental conditions, A1 M1 C1

Baseline Stack Durability

The failure modes of the baseline Mk1020 stack (MEA A1 M1 C1) were identified by running a stack through the standard Mk1020 ACS duty cycle and removing MEAs every 250 cycles for degradation analysis. The main finding of this activity is that the dominant voltage degradation mode is catalyst dissolution, followed by membrane transfers (internal leaks). It is thought that at the onset of internal membrane leaks the catalyst failure mechanism begins to include corrosion as well as dissolution and that wet-dry cycling as well as operating at high potentials accelerate the membrane degradation, see Figure 6. To improve the durability by way of design changes a more dissolution resistant cathode catalyst and leak resistant membrane is suggested.

Catalyst dissolution occurs when the cathode potential is cycled; it is most damaging when the cathode potential goes above 1.2V. The cathode potential can spike above 1.2V during an air-air start-up. It is for this reason that an operating strategy that minimizes the number of air-air starts is suggested. The voltage degradation and membrane leak signatures are similar to the historical performance of the Mk1020 ACS.

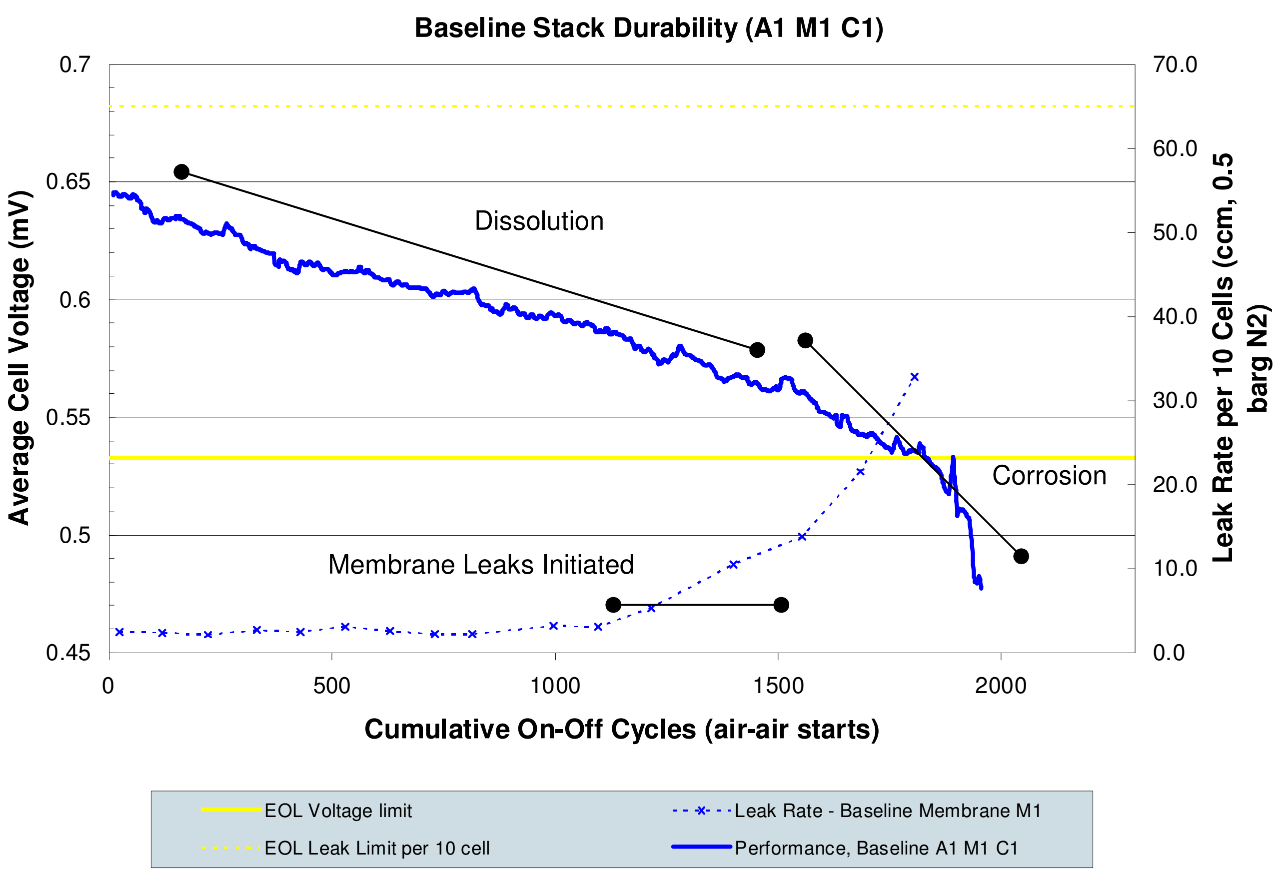


Figure 6: Degradation of Baseline Stack

Stack Failure Mode Investigation

The cathode effective platinum surface area (EPSA) loss, as measured by CO stripping voltammetry, shown in Figure 7, appears to decrease with an increase in number of cycles. This indicates a steady platinum surface area loss per cycle from the beginning of life. The EPSA CO peak maxima do not shift, indicating that there is no contamination (not shown).

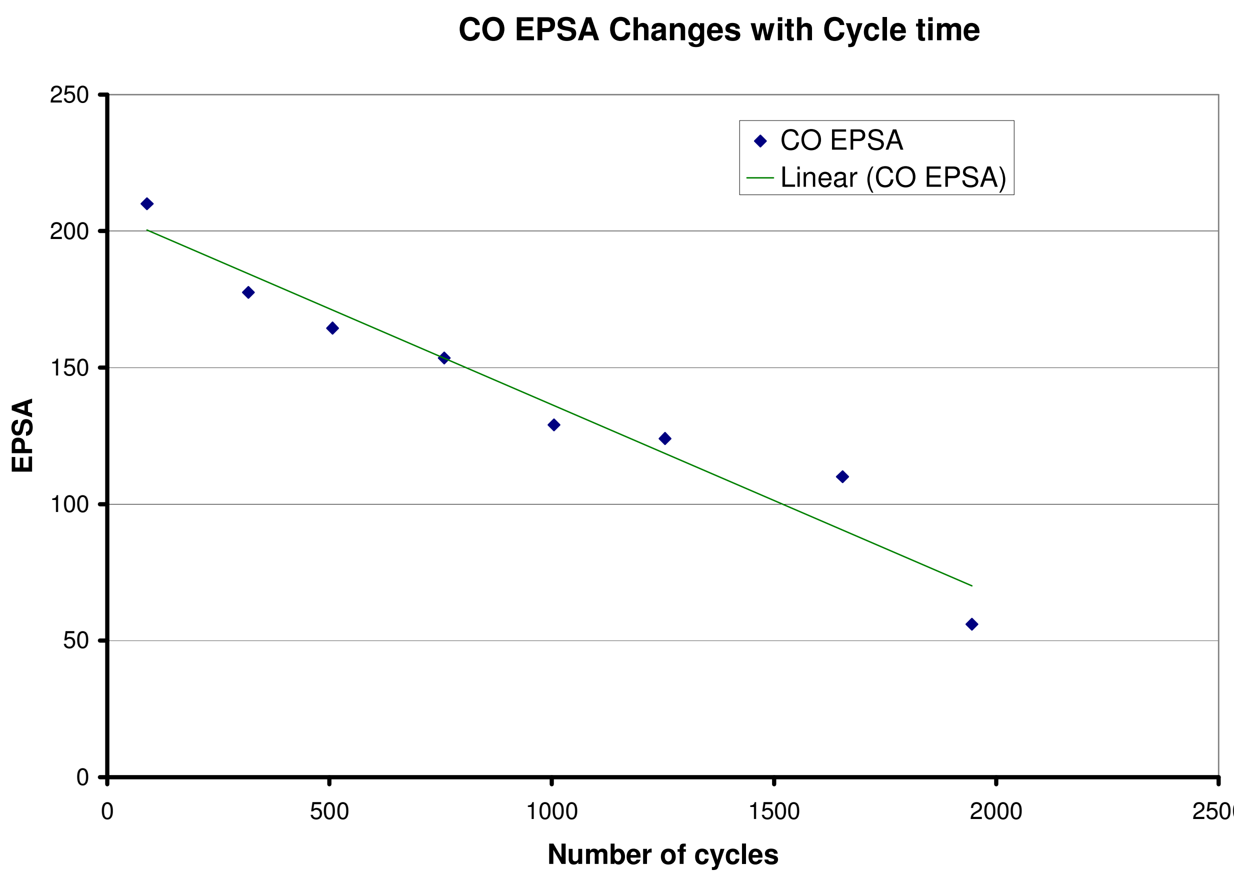


Figure 7: Change in EPSA verses cycle

An increasing trend in cathode catalyst thickness change over time is shown in Figure 8 (positive change represents a reduction in thickness); however this trend appears to have a step change around 1,000 cycles where the onset of cathode catalyst thinning is observed.

This result may indicate a shift in failure mechanism once the MEA starts to leak. Figure 7 shows the EPSA decreases steadily with cycle number; where Figure 8 indicates the catalyst thinning begins near the onset of leak initiation (Figure 6 showed an increase in leak rate after 1,000 cycles).

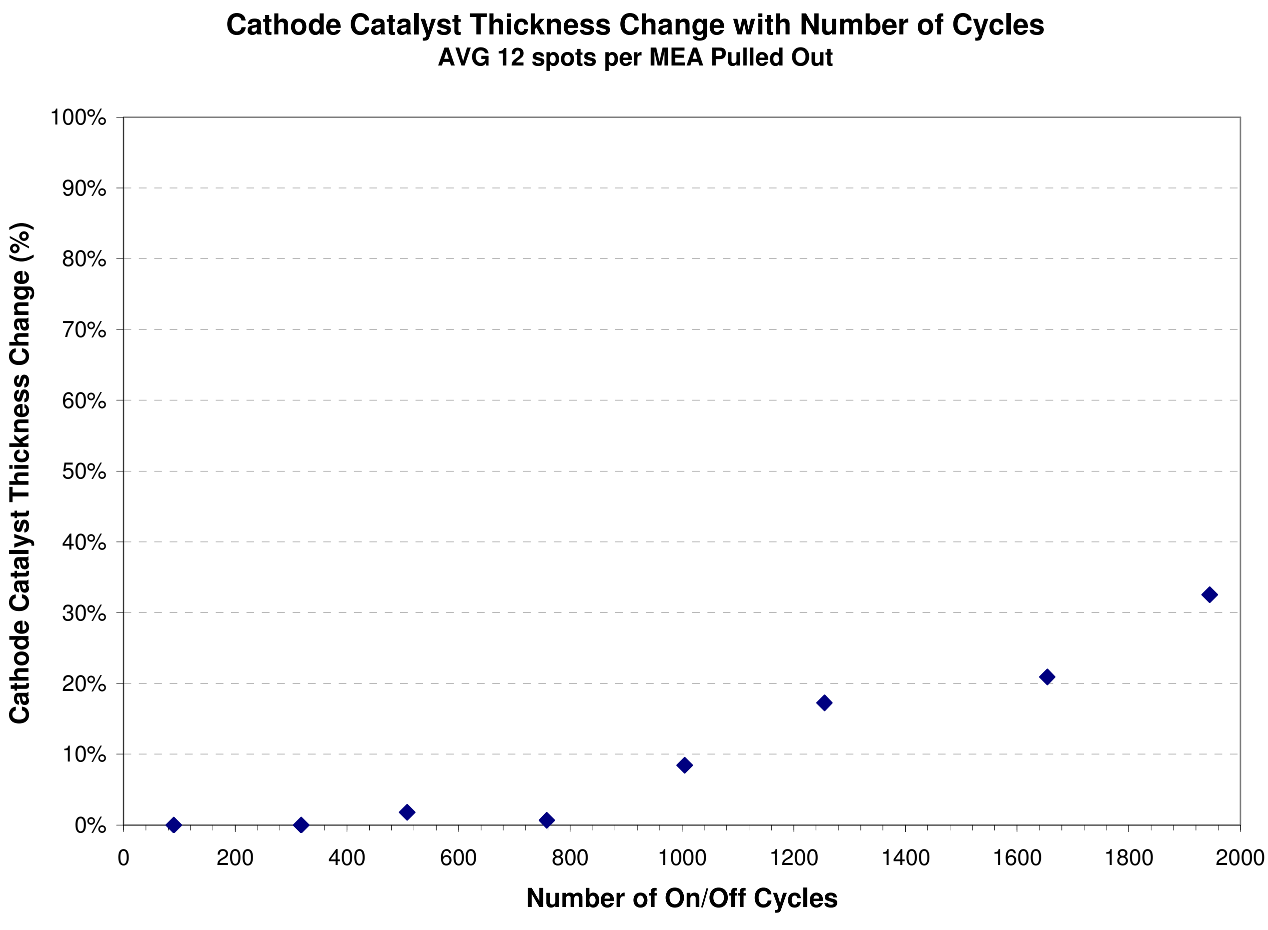


Figure 8: Change in cathode catalysis thickness verses cycle

Additional tests correlated the Effective Platinum Surface Area (EPSA), Platinum in the Membrane (PITM), cathode thickness and leak rate; reference figure 9 below. The initial voltage degradation failure mode hypothesis is platinum dissolution from potential cycling. The decrease in EPSA and the increase in PITM follow a similar trend as the voltage degradation rate. The hypothesis for membrane leak initiation is stress on the membrane caused by wet-dry cycles, operation at high current densities and operation at high temperature. Following the onset of leak initiation the voltage degradation rate changes; the hypothesis for the increased voltage degradation rate is a combination of platinum dissolution and corrosion.

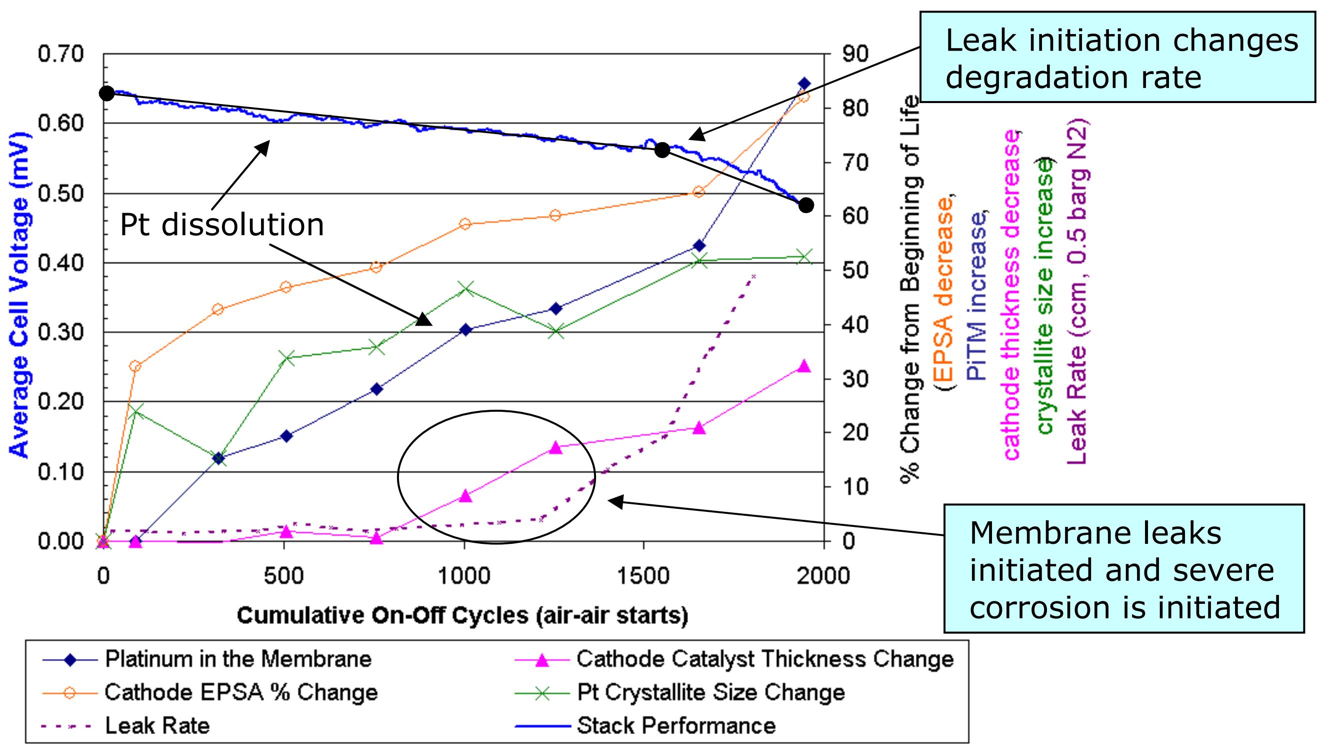


Figure 9 – Stack / MEA stress signatures

Freeze Tolerance Testing and Failure Mode Investigation at Stack Level

Freeze start-up testing revealed that the stack was capable of a limited number of start-ups from -10℃, however for a significant number of reliable freeze start events the stack would need significant design changes and/or system operating changes.

The main barriers to the air-cooled stack meeting freeze start-up requirements are as follows:

1. Standard fan turn down is not sufficient to allow the stack to heat up in an acceptable amount of time. This causes too much product water to freeze in the MEA resulting in increased performance loss over successive freeze-start cycles. Much of the performance loss is a recoverable performance loss (RPL).

2. Overcooled end cells result in a performance de-rate and significant cell performance variability and reversal after successive freeze start-up cycles. The stack was unable to complete more than 8 consecutive sub-zero starts at -10℃ without cell reversals of cathode end cells, in extreme cases this resulted in non-recoverable performance loss[1].

3. Increased time to rated power when starting from -10℃, resulting in a ~15x increase in required bridging energy when compared to ambient temperature start-up.

Much of the stack testing was focused on defining the stack limitations such that stack-system solutions could be explored. All stack freeze tolerance related testing was done in Ballard's Thermotron SE-1200-10-10 series environmental chamber. Follow up freeze testing work will focus on defining the limitations of the stack and suggest alternative system operational strategies for freeze start-up.

[1] these end cells were removed for failure analysis

In all, 120 freeze start-up cycles were done. The first stack start-up attempts from a -10°C was always successful, however, the second start-up attempt was consistently unsuccessful, see Figure 10. The failed start attempt was typically triggered by reversal of both the anode and cathode end cells. In Figure 2 the blocks of cycles labeled I, II, III, IV, V, and VI represent uninterrupted successive freeze start-up cycles that were performed using test station automation. Cells 27/28 (cathode end cells) were removed for failure analysis after 82 freeze start-up cycles because they had exhibited sufficient performance loss. Since the first start-up of the test would involve a relatively dry MEA this trend suggests that the state of the MEA upon freezing is important. The data also suggest that -5°C is a more manageable sub-zero start up temperature, indicating that the time operating in sub-zero or the time it takes the stack to reach above 0°C is critical.

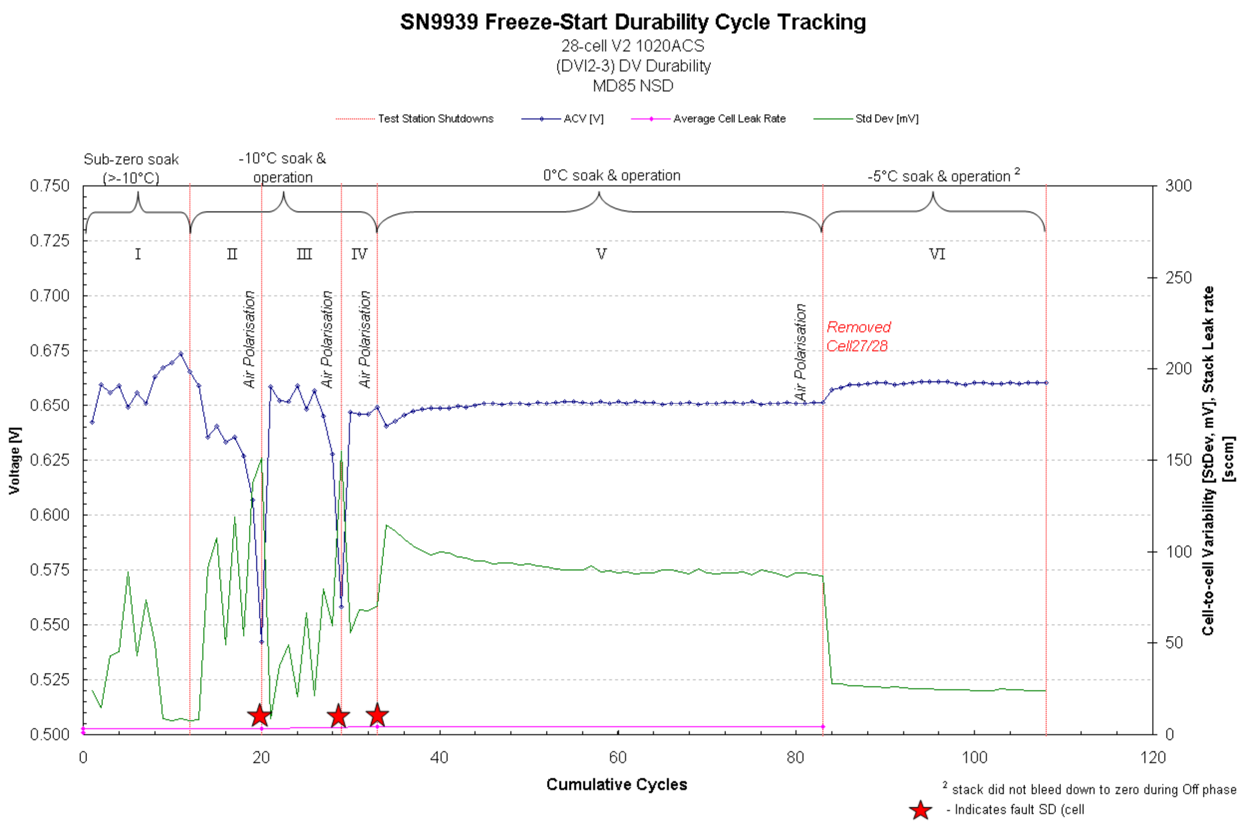


Figure 10: Overview of Freeze Start-up Testing Conducted on a 28-cell Baseline Stack

Figure 11 shows the 65A polarization data for a 28-cell stack taken after each start-up in block II. Results reveal consistent performance de-rate for cathode end cells during -10°C operation following freeze start-up. Other cells begin to show performance loss after 6 consecutive freeze start-up cycles. This suggests that although the anode end cell may experience reversals severe enough to trigger a shutdown (<-0.2V), it is the cathode end cells that are experiencing performance loss as a consequence of repeated -10°C FSU cycling.

Without changes to stack hardware, such as the addition of end-cell heating/insulation, or additional changes to the operating strategy the baseline design is not robust to more than 5-8 FSU cycles. The end cells are particularly sensitive to performance loss over consecutive cycles. This is likely due to the overcooling of the end cells.

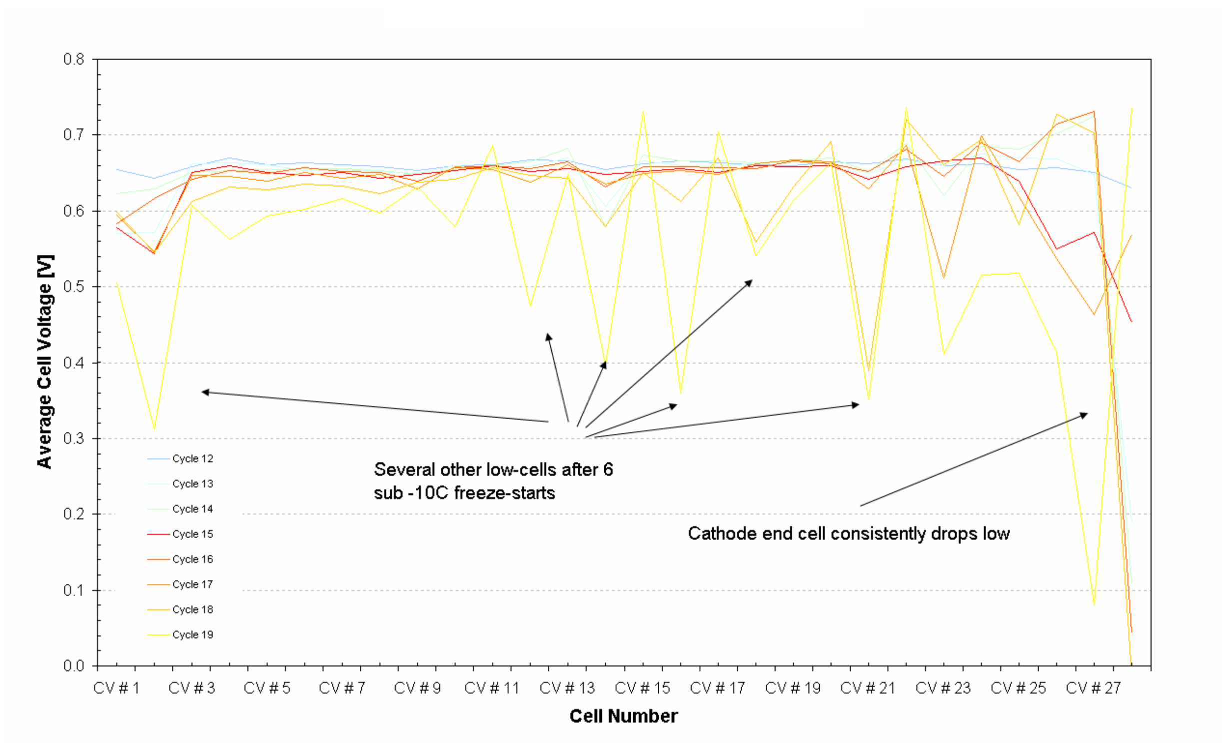


Figure 11: 65A Operation Cells Scans During Freeze Start-up Cycles (Block II, Figure 2)

Figure 12 shows an example of the severe damage of the end-cell MEA after freeze start cycling with reversals; catalyst separation from the membrane was noted, this was especially high under the landings where water has the tendency to collect.

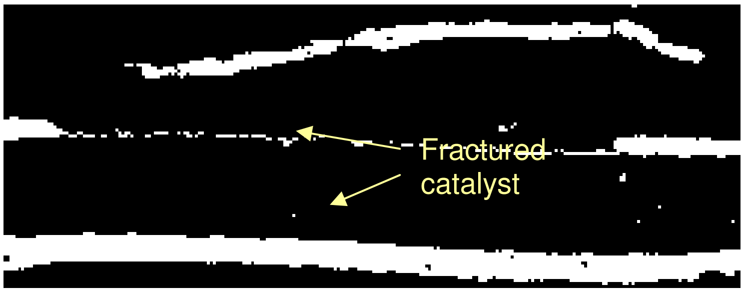


Figure 12: Example of Anode Catalyst Cracking on a Severely Damaged End-Cell

Analysis shows a significant increase in catalyst cracking of both the anode and the cathode. Figure 13 shows a comparison of the number of cracks found in damaged end cells compared to an un-run MEA, this observation is typical of freeze start-up stacks but may not be the cause of the performance loss. This is an example of the most extreme damage, more than expected for realistic operation.

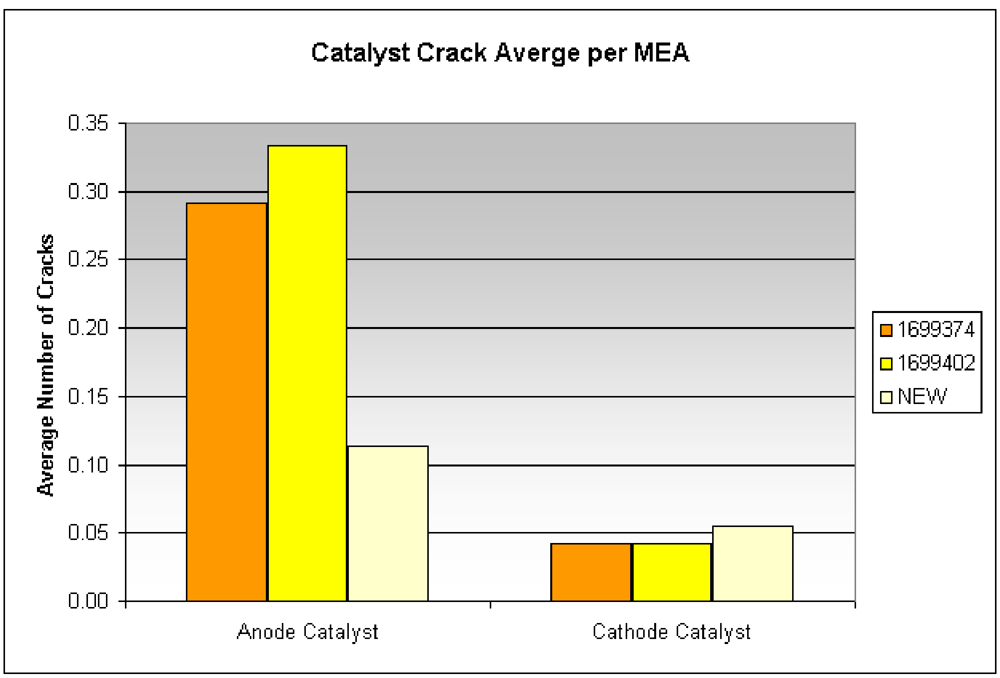


Figure 13: Crack Number Quantification of Severely Damaged End-Cells

MEA Development Approach

To assess the feasibility of meeting durability targets by unit cell or MEA changes, several MEA concepts were screened for basic dry performance. A subset of these materials will be further analyzed through small scale membrane and catalyst durability tests. Materials that passed basic performance and durability tests will be tested at the stack level for basic durability and then stack freeze durability. This approach, shown in Figure 14, was selected to provide empirical durability relationships to support development of a next-generation freeze-tolerant Mk1020 stack / system concept that has been optimized for lifetime by considering the key life-limiting failure modes of voltage and membrane degradation. All new materials considered were selected based on meeting the project objectives.

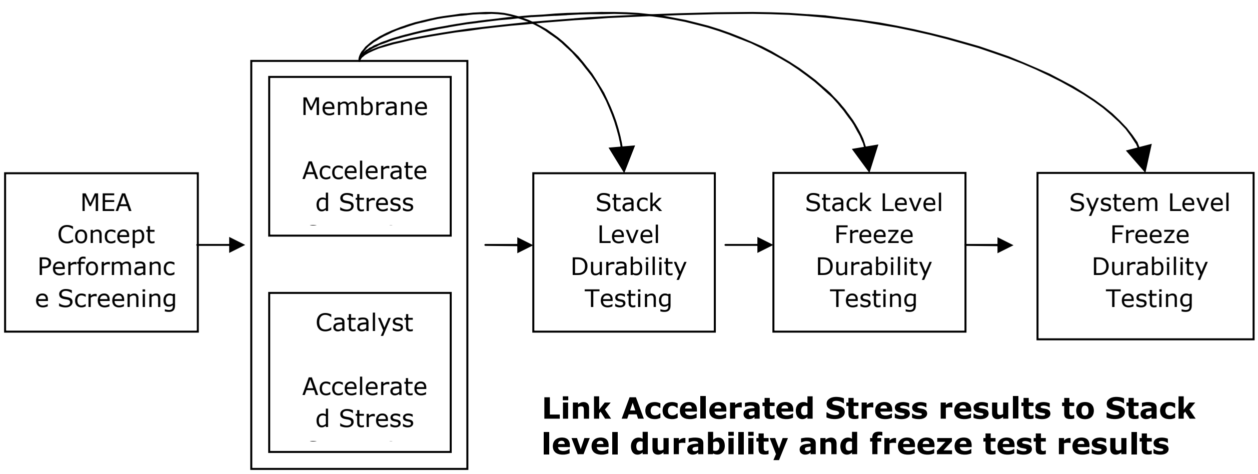


Figure 14: Approach for selecting new Stack concepts for DOE Project

Recall for this report CCM designs 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*.

For most of the small scale tests the anode catalyst remained constant with either the A1 or A3 design, one of the samples used a more corrosion resistant anode catalyst (A2). Nine membrane concepts were screened, including dense membranes (M5, M9), composite membranes (M1, M2, M3, M7, M8) and composite membranes with chemical stabilization (M4, M10). The cathode designs cover a wide range of functions; improved corrosion resistance (C2), improved platinum dissolution (C3) with the rest of the designs targeted at improved performance and durability. Not all materials are discussed in this summary.

Advanced Concept MEA Performance Screening

To assess the feasibility of meeting durability targets by unit cell or MEA changes several MEA concepts were screened for performance and durability at the small test cell level and a few unit cell changes assessed in full stack durability tests. A summary of results are shared, although some of this work was done outside of the project.

A total of 23 MEA concepts were screened for basic dry (40% RH) performance using the Ballard MEA Evaluation Tool. The goal was to meet or exceed the baseline (A1 M1 C1) performance. From the data gathered, several concepts were recommended for further assessment. The data also suggests that the cathode catalyst composition is the significant contributor to the MEA dry performance. Different membrane concepts will also affect the MEA dry performance, but to a lesser degree than the cathode catalyst composition.

Test articles run through the combined chemical/mechanical AST were subjected to chemical stress via a no-load (OCV) condition at high temperature, low relative humidity and elevated oxygen content. Mechanical stress is provided during a separate stage consisting of repeated wet-dry cycles under an inert nitrogen atmosphere. Following each AST cycle (comprised of a chemical and mechanical stage), the failure state of each MEA is determined using the open circuit voltage and an electrochemical leak detection method. Key durability metrics obtained in the course of testing included the fluoride release rate (calculated from a conductivity-fluoride calibration curve), number of AST cycles to failure, and the OCV decay rate. Figure 15 contains membrane durability AST data for the candidates being considered for improved durability of the Mk1020 stack.

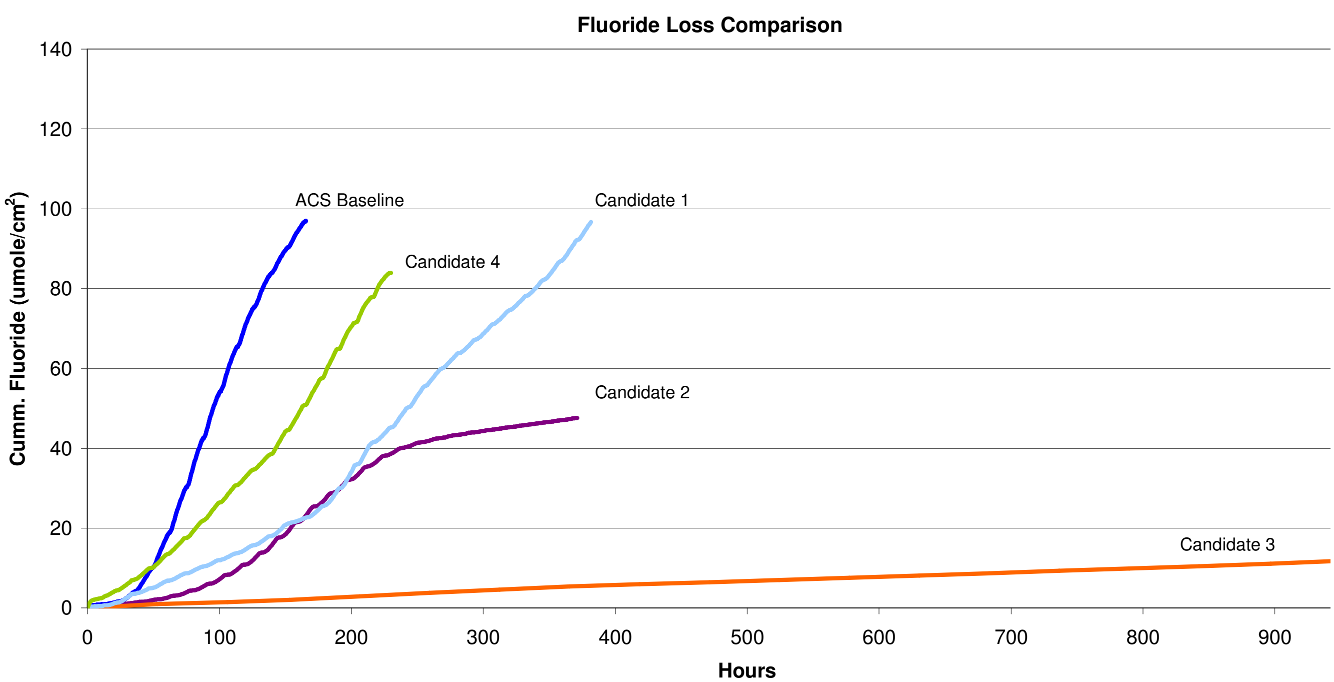


Figure 15: Membrane accelerated stress test results

Several MEA concepts were recommended for continued small scale durability testing; A1 M1 C4, A1 M2 C1, A1 M2 C2, A1 M3 C1, A2 M3 C3, A3 M5 C13 and A3 M5 C14, concepts relevant to this report are found in Figure 16.

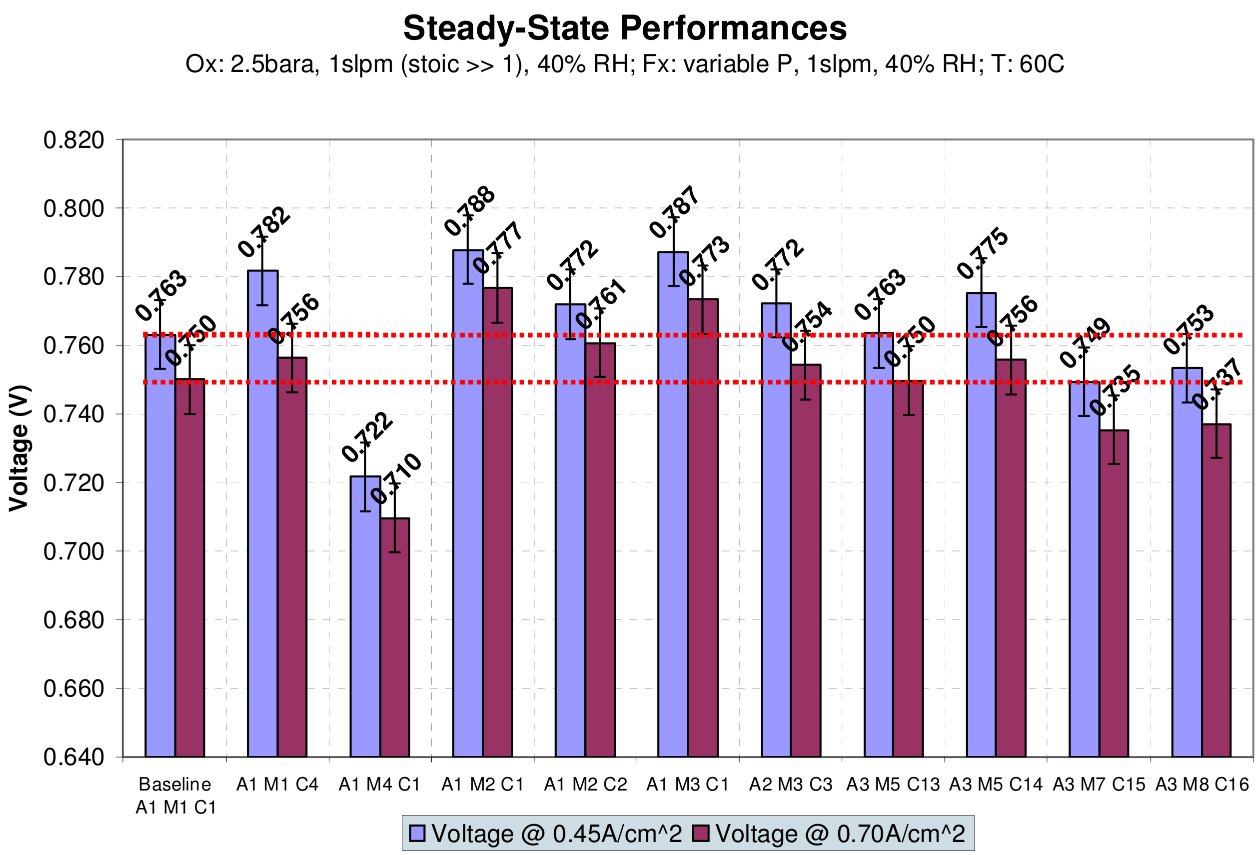


Figure 16: MEA Performance Evaluation of Next Generation Candidates

Small Scale Accelerated Stress Testing (AST) and Analysis

A total of eight membrane candidates were evaluated for chemical and mechanical durability using the Cyclic OCV AST. This AST investigates the effect of high temperature, OCV operation, and wet/dry cycles. It provides a means of rapid evaluation and also generates design curves to estimate the relative impact of operating parameter levels on the degradation mechanism. Both dense (M5 and M6) and composite membranes (all others) are represented as well as the effect of chemical stabilization (M4 and M6). Through this membrane durability study all other cell components remained constant, the anode catalyst use is the A3 design and the cathode catalyst is the C5 design.

A snapshot of the relative durability of these designs is provided by AST cycles to failure, Figure 17. Membrane concepts M2, M3, M4, M6 and M7 exceed the durability of the baseline (M1) material. The benefit of mechanically stabilized composite membranes is clear as the number of cycles increases from 6 cycles for a dense membrane to 23-24 cycles for many of the composite membranes. Only concepts M2 and M3 will proceed to stack testing due to the performance reduction seen with the M4, M6 and M7 (Figure 17, M6 not shown).

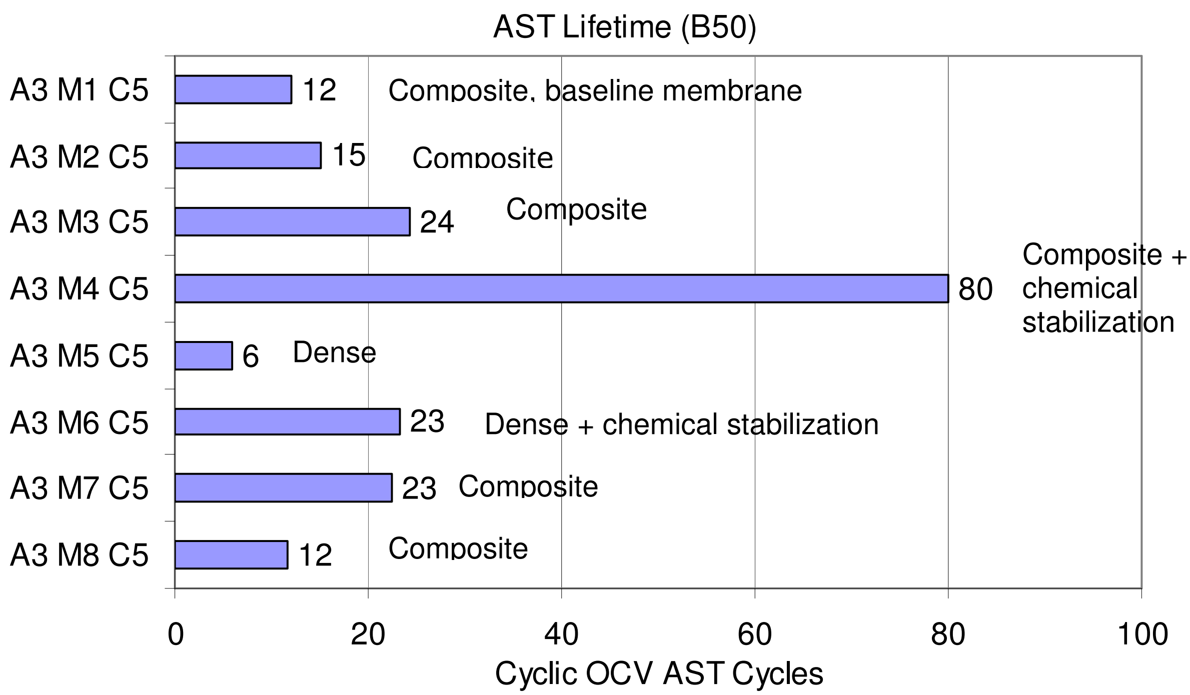


Figure 17: Cycles to failure for candidate membranes during Cyclic OCV AST testing

Stack Level Modeling

Stack level thermal modeling (single channel CFD), and reporting is complete. The main objective of this work was to use thermal models to analyze different approaches to operating a Mk1020 stack in sub-zero ambient temperatures. The results of modeling will guide system operating strategies in order to maintain stack function and maintain acceptable stack lifetime (based on the MK1020 stack manual) when sub-zero operation is required. The output of this model is an estimate of the fan flow rates required to achieve optimum stack operating temperatures and minimum performance de-rate with an inlet temperature of -30°C by:

- fan adjustments to reduce air flow rate to achieve optimum temperature
- using heaters to heat the air to -10℃

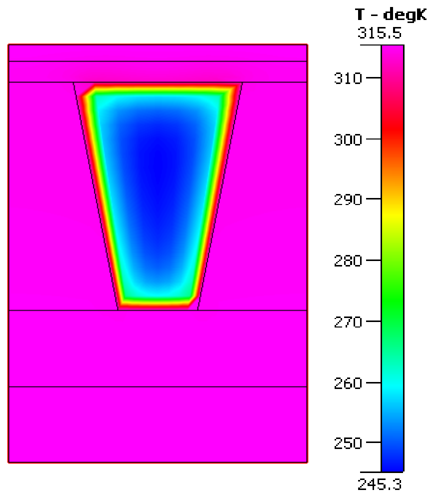


Figure 18 – CFD Model of a single cooling channel in the Mk1020 ACS

Table 1 below shows the required flow rates to achieve optimum stack temperature calculated using a CFD model (reference Figure 18 above). Results show the flow rate turn-down required for a stack with inlet temperatures ranging from 20℃ to -30℃ is 22. This fan turn down cannot be achieved with a regular fan, other options are to use two fans (one smaller than the other) or use inlet/outlet flow restrictions when operating at low current and low ambient temperature. If a 52 W heater is used to heat up the inlet air to -10℃ during low current operation the flow rate turn down can be reduced to 15, and if a larger heater is used then the flow rate turn down can be significantly lower.

Parameter	Units	Nominal Conditions	Sub-zero No Heater	-30℃ Ambient Conditions + Heater
Cathode/Air Inlet Temperature	°C	20	-30	-10
Fan Turn Down Ratio*	-	6	22	15
Heat Required to Heat Air from -30°C to Required Inlet Temp	W	345	0	52

Table 1: Results of Thermal Modeling of Stack with Inlet Air of 20℃, -10℃ and -30℃

Advanced Concept MEA Durability Screening

Voltage cycling causing platinum dissolution was found to be the most dominant voltage degradation stressor. Since every start-up of an air cooled stack is an air-air start-up (valid for both freeze-start and ambient start) the dominant failure mode is a voltage cycling mechanism. From previous failure analysis it was found that there was minimal corrosion before internal leaks were initiated, this focused efforts on platinum dissolution. A voltage cycling AST was used to screen options to target an increase in the number of air-air starts allowed to try to target a materials handling application.

From previous AST experience, several factors were considered in designing an appropriate AST to accelerate catalyst dissolution and understand degradation for this application. It has been found that the upper potential limit (UPL), time at upper potential, number of voltage cycles and relative humidity all impact the associated performance loss.

Previous work explored the feasibility of using the MEA evaluation tool (MET) for completing catalyst durability ASTs. Since Ballard's FCvelocityTM-1020ACS uses an open cathode air–cooled stack design, the MEA is operated under very dry conditions. For this reason the performance measurements were conducted using 40% RH gases (oxidant and fuel) to amplify the ohmic losses typically seen in a dry stack-system. However, to increase the voltage degradation signal the voltage cycling was conducted using oversaturated conditions.

The materials analyzed for catalyst durability are:

- Baseline (A1 M1 C1)
- A1 M1 C4 – cathode catalyst with lower corrosion resistance than baseline
- A1 M3 C1 – improved durability membrane over baseline
- A1 M4 C1 – improved durability membrane over baseline
- A2 M3 C3 – improved durability membrane and improved dissolution resistance cathode compared to baseline
- A3 M5 C14 - improved dissolution resistance cathode compared to baseline

CCM concept A1 M4 C1 was added despite not meeting the performance requirement to measure the effect of membrane chemical stabilization on cathode catalyst dissolution. The anode catalyst was not considered since the failure mode of interest is cathode catalyst dissolution.

Each sample was cycled 6000 times following the profile in Figure 19. A dry (40% RH) performance assessment is done at the beginning of the test and every 1000 cycles after that.

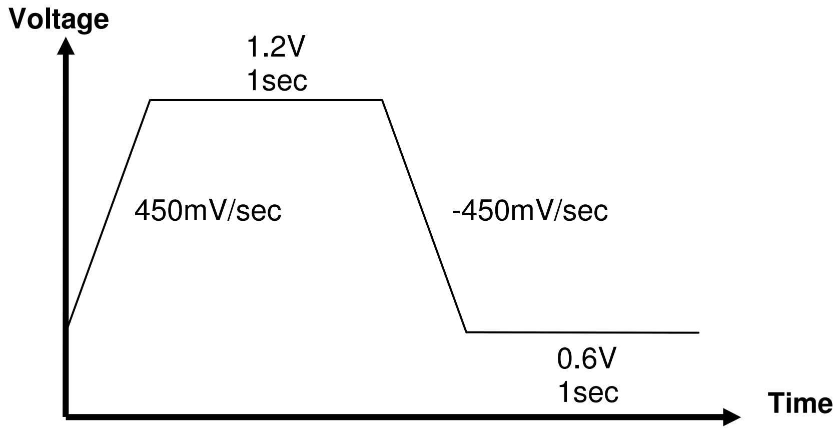


Figure 19: Voltage Cycling Profile

The degradation profiles for each measured samples is found in Figure 20 with degradation rates listed in Table 2. As expected, the cathode catalyst appears to be the most significant contributor to cathode catalyst dissolution. C4 stands out as a poor choice for catalyst dissolution. The improved platinum dissolution catalysts, C3 and C14, show significant improvement over the baseline C1 catalyst in terms of degradation rate. Taking into consideration the measurement error, the membrane type shows no contribution to platinum dissolution.

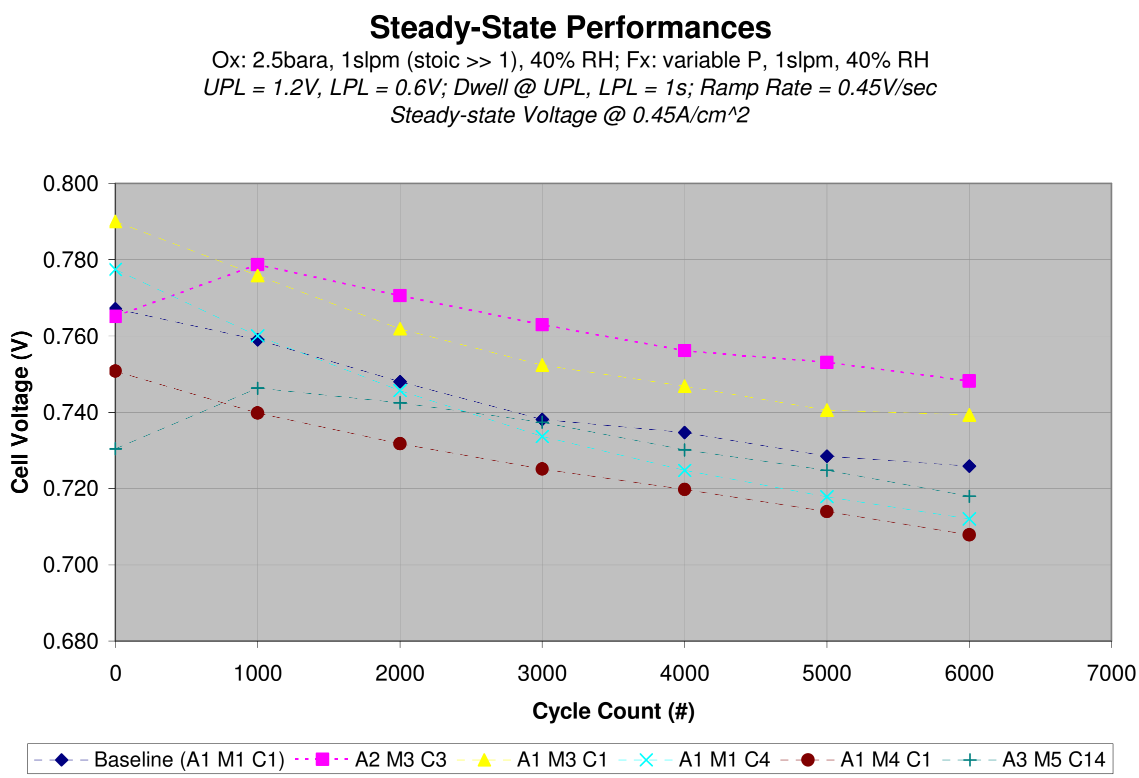


Figure 20: Cell Voltage at 0.45A/cm2 During the Catalyst Dissolution AST

CCM Concept	Degradation Rate *µV/cycle*	Improvement Over Baseline
A1 M1 C1 (Baseline)	-7	100%
A2 M3 C3	-4	57%
A1 M3 C1	-8	114%
A1 M1 C4	-11	157%
A1 M4 C1	-7	100%
A3 M5 C14	-3	43%

Table 2: Degradation Rates from Catalyst Dissolution AST

Figure 21 shows the end-of-test failure analysis of A1 M1 C1, this analysis was also done on the A1 M3 C1 and A2 M3 C3 samples. The analysis shows a platinum-in-the-membrane (PITM) band and no catalyst corrosion, indicating the dissolution failure modes have been isolated. The largest change in catalyst thickness, the A2 M3 C3 sample, was less than 1.5um which indicates minimal corrosion for all the samples. Without further analysis, the main evidence for platinum dissolution is the presence of the PITM band.

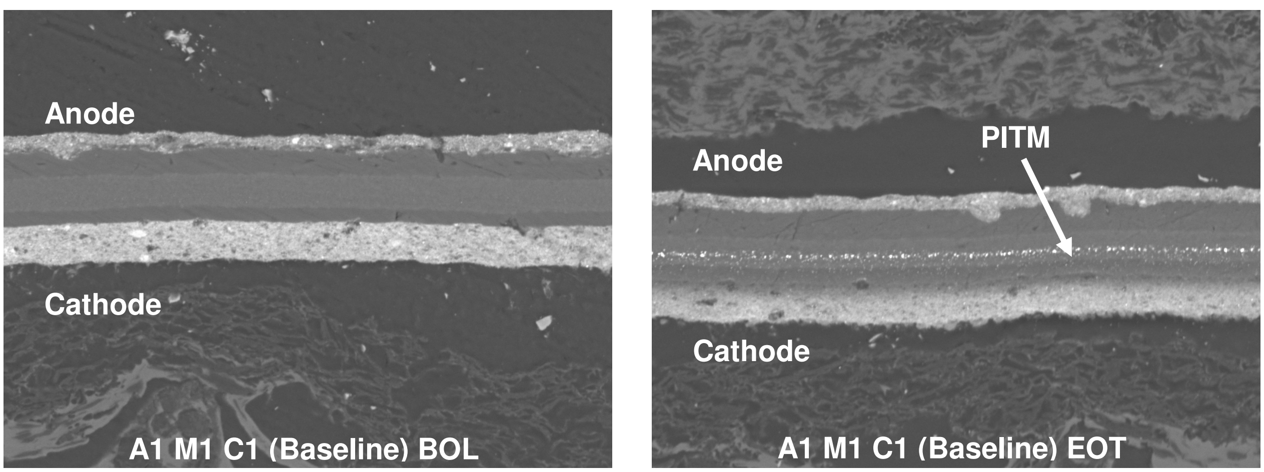


Figure 21: SEM Cross Section of the A1 M1 C1 CCM Concepts at 1600x Magnification

Results indicate that CCM candidates A2 M3 C3 and A3 M5 C14 stand out as most durable designs based on the MET dissolution testing when compared to the baseline. It is recommended to test these two concepts at the stack-level and compare to the baseline stack.

The A1 M3 C1 and A1 M4 C1 concepts offer the same degradation rate as the baseline; however the membrane AST shows improved membrane durability. It is recommended to test these at the stack level to gain further insight on the durability against membrane failure.

The degradation rates from the catalyst dissolution AST is significantly lower than the stack voltage degradation rates. It is recommended to conduct catalyst corrosion ASTs to determine if corrosion is significant at the early stages of stack voltage degradation.

Stack Performance Testing

Figure 22 shows the BOL performance for the 4 different MEA concepts and the baseline. The A2 M3 C3 and the A1 M2 C2 designs perform lower than the baseline concept, however the shape of the polarization curves using the M3 membrane indicates a lower resistance which may be beneficial for sub zero operation. It was also noted that the performance of the A2 M3 C3 design increases over the first 500 cycles, indicating that the end of life performance may be the most useful metric.

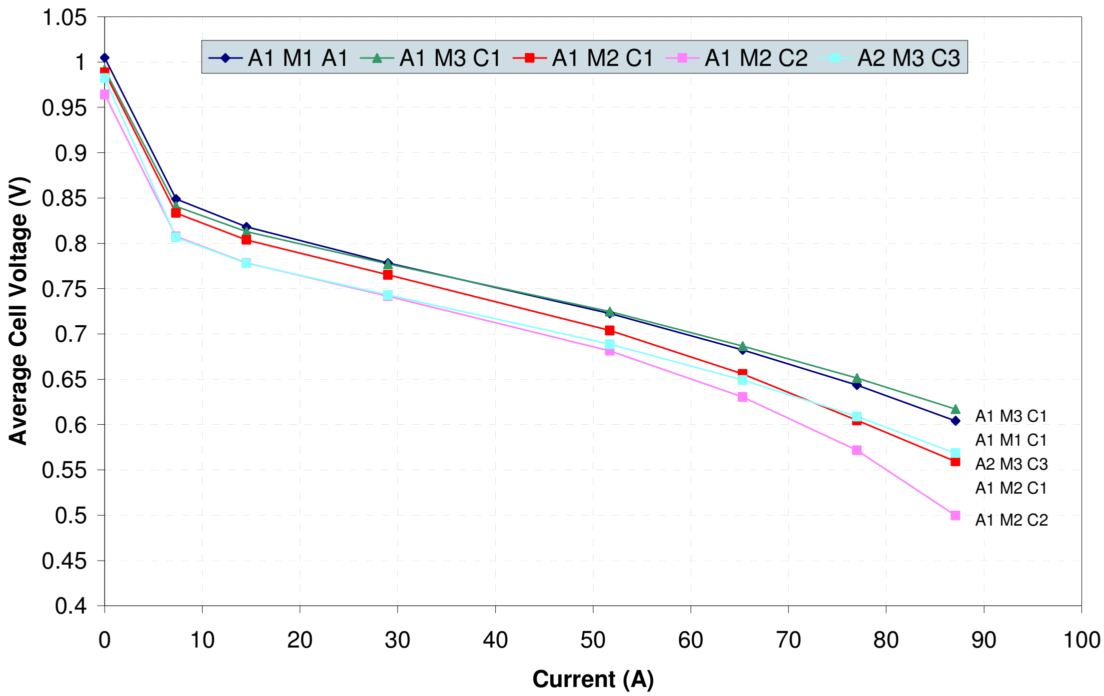


Figure 22: Advanced Concept Polarization Curves

Stack Durability Testing

Based on the durability test failures modes and the concepts screened, several concepts were selected for stack durability testing. These concepts are designed to minimize degradation rates due to operation to achieve materials handling requirements. The leading candidate is A2 M3 C3, and this concept will move on to freeze characterization testing and be compared to the baseline stack. Figure 23 shows the advanced concept durability data collected to date. The durability of the M3 membrane (as seen by leak rate) has been significantly improved from the baseline (M1), after 2500 cycles the leak rate appears to show the onset of leaks – more than 2x improvement. The voltage degradation rate is significantly improved with advanced catalyst C3. This stack concept meets the required 2500 cycles durability target of the materials handling application, with system improvements this stack concept expected to see a further increase in durability. The A2 M3 C3 concept will move to freeze characterization and testing in system benches.

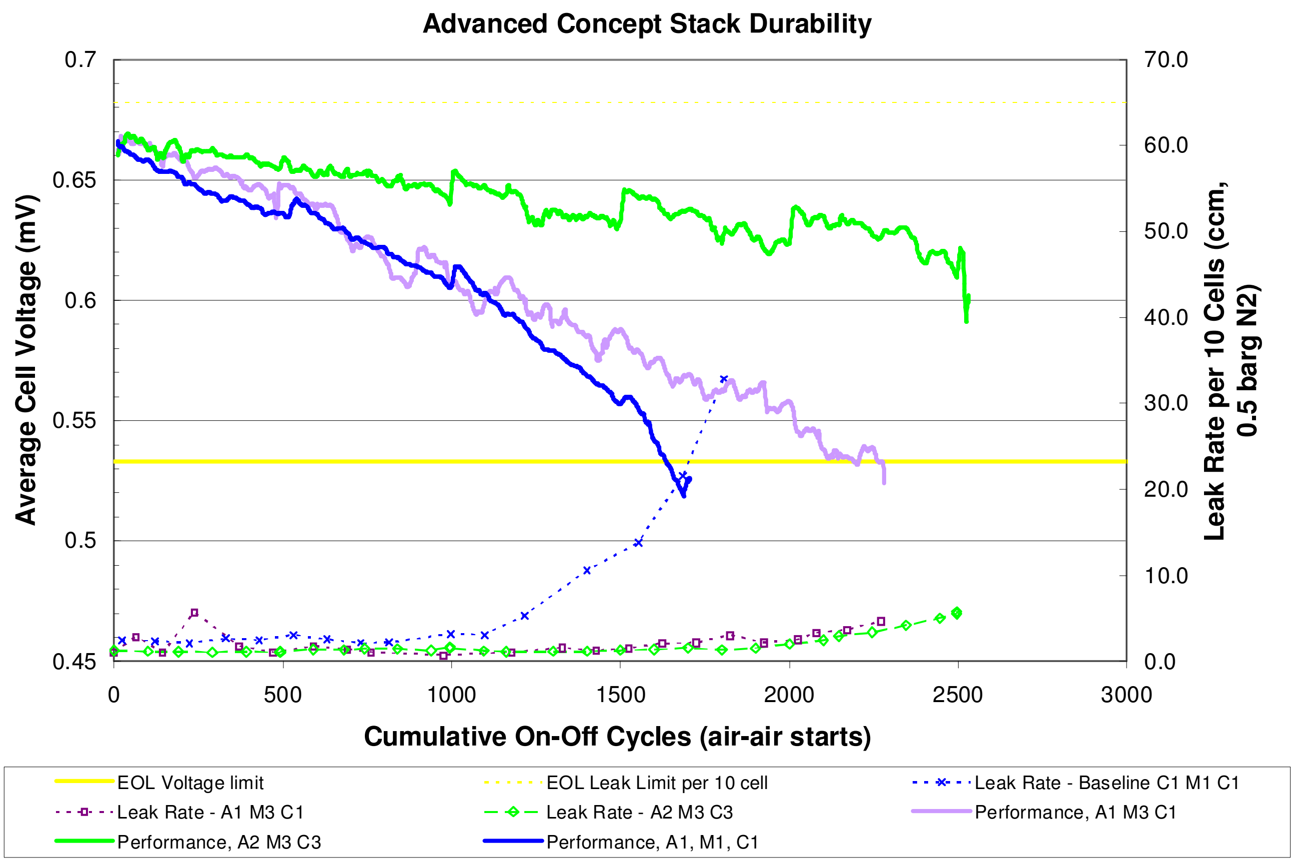


Figure 23: Advanced concept durability testing results

System Level Testing

The Mk1020 stack had to first demonstrate minimum performance and durability targets to be considered a viable GenDrive product solution. Specifically, the Mk1020 had to demonstrate 5,000 hours running a representative load profile including start-stop cycles. After 5,000 hours, both the stack performance and transfer leak must be within acceptable limits. Since the Mk1020 stack was not originally designed to meet the stated targets; Plug Power and Ballard collaborated to improve the stack-system durability. The system must maintain stack critical-parameters for performance and life, including:

- Stack temperature
- Relative humidity (RH) cycles
- Time at open circuit voltage (OCV)
- Cathode potential
- Cathode potential cycles
- Mixed anode potentials

There are two approaches for extending stack durability and improving the freeze characteristics of a stack-system; improve the structure/design of the stack or improve the stack-system interface. Based on Ballard design work, a MEA/stack solution for freeze and durability can significantly increase the cost of the stack. Therefore, the primary approach explored system options and operating strategies in order to manage a sub-zero environment with extended durability.

Stack concepts considered included material changes targeted at durability and freeze failure modes. System/operation strategies considered were linked to their impact on voltage cycling, open circuit voltage (OCV) time, and stack temperature at ambient and sub zero conditions.

Analytical models and accelerated stress tests (ASTs) were used to anticipate the impact of operating strategies and advanced materials on durability and freeze tolerance. Analytical model work included a transient model of the fuel cell behavior as hydrogen moves through the air-cooled stack under various conditions at start-up. The model is able to breakdown the total current response during the start-up transients into capacitance effects and corrosion currents and was used to set targets for the system response on start-up. In addition, a thermal model of the stack and some system components was developed.

The ASTs used focused specifically on cathode catalyst and membrane degradation. The stressors for cathode catalyst degradation are cathode potential and cathode potential cycling, whereas for membrane the degradation stressors are temperature, RH cycling and time at open OCV.

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. Stack testing simulating a material handling application demonstrated 5000 hours with 3 different system operating strategies. The success of these tests indicated the air cooled technology can meet the required performance and durability requirements to be considered a viable option for a commercial material handling application. However, there are still many additional factors to study such as air quality tolerance, shock and vibration tolerance and freeze tolerance. Freeze tolerance testing was the focus for this project.

SN: 4710 was the first Mk1020 stack tested at Plug Power for a material handling application. It ran an application representative load profile, employed the operating strategy from the Ballard Mk1020 manual and operated with a maximum stack current of 75 amps (the maximum recommended). A transfer leak developed at ~1,000 hours (Figure 24), and by ~2,500 hours the stack could not reach 75 amps (Figure 25) without pulling cells into reversal; after which the test was discontinued.

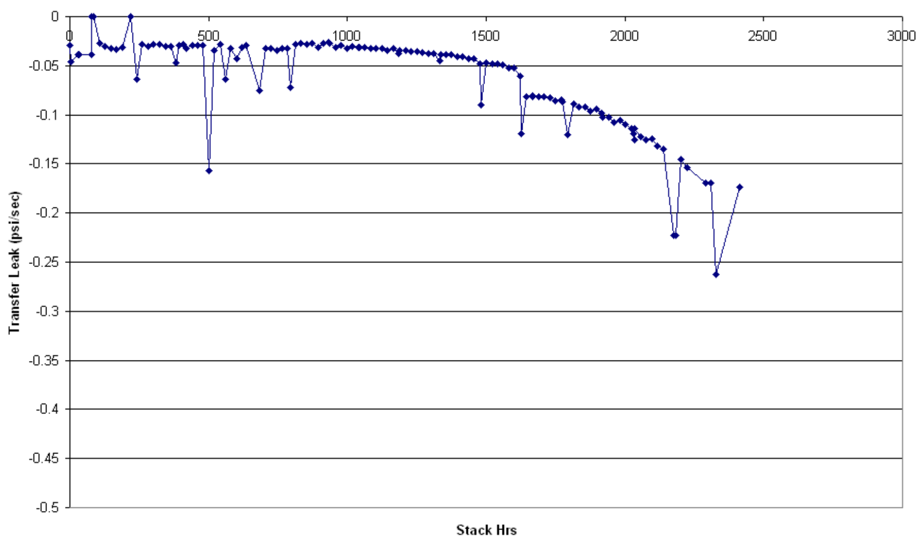


Figure 24: SN: 4710 – Transfer Leak

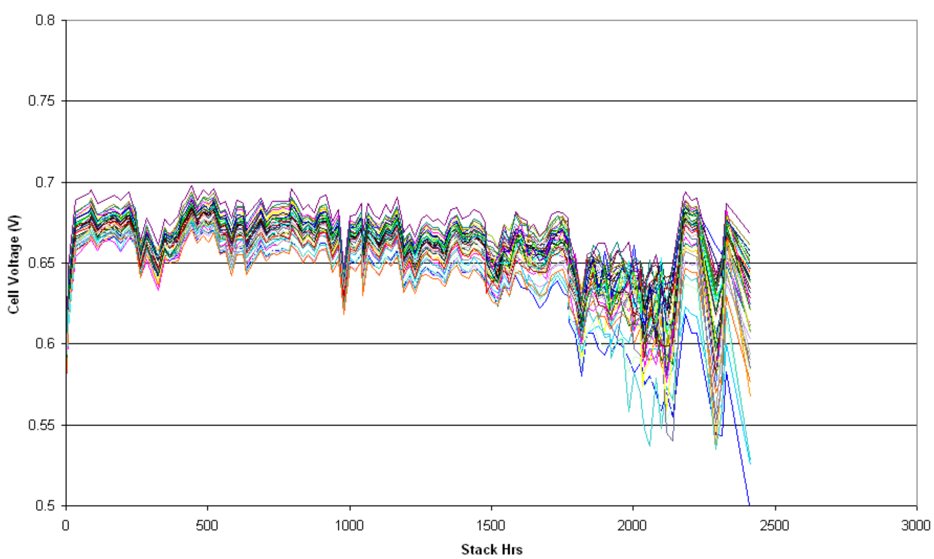


Figure 25: SN: 4710 – Cell Voltage

The next stack (SN 7077) was tested for a hauling application and employed the operating strategy from the Ballard Mk1020 manual. It was operated at a reduced maximum stack current in an effort to reduce the maximum operating temperature and therefore reduce the mechanical stresses on the membrane to increase the time to transfer leak initiation. The stack reached end of life at 6514 hours and 1279 air-air starts. This strategy demonstrated a ~5X increase in time to leak initiation ~2.5X increase in stack life to date as compared to stack SN 4710.

Two additional Mk1020 stacks were tested for an order picking material handling application. Both employ separate advanced system operating strategies, which build on the strategy employed for SN 7077 to mitigate catalyst and membrane degradation.

A reduced starts strategy was operated on SN 8134 and was targeted to reduce voltage degradation on start-up by reducing the number of air-air starts. A reduced OCV strategy was operated on SN 8135 and was targeted to reduce membrane degradation on shut down by reducing the time spent at OCV.

The figure below shows both the average cell voltage, the cumulative number of air-air starts and the transfer leak rate versus operating hours. The system strategy to reduce the number of starts demonstrates a lower degradation rate compared to the system strategy that reduces the time at OCV. Stack and MEA results indicate catalyst dissolution and corrosion is associated with air-air starts. Reducing the number of starts and reducing the time at OCV are mutually exclusive because if the stack is bleed down to avoid OCV then every start becomes an air-air start. Therefore the strategy to reduce OCV inherently has more air-air starts and as a result is also has a higher voltage degradation rate; this is seen below. However, 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 26 (below) illustrates that although the reduced OCV strategy has the highest voltage degradation rate it went over 6000 hours without any indication of a transfer leak. By comparison the reduced starts operating strategy shows signs that a transfer leak was initiated after 5000 hours.

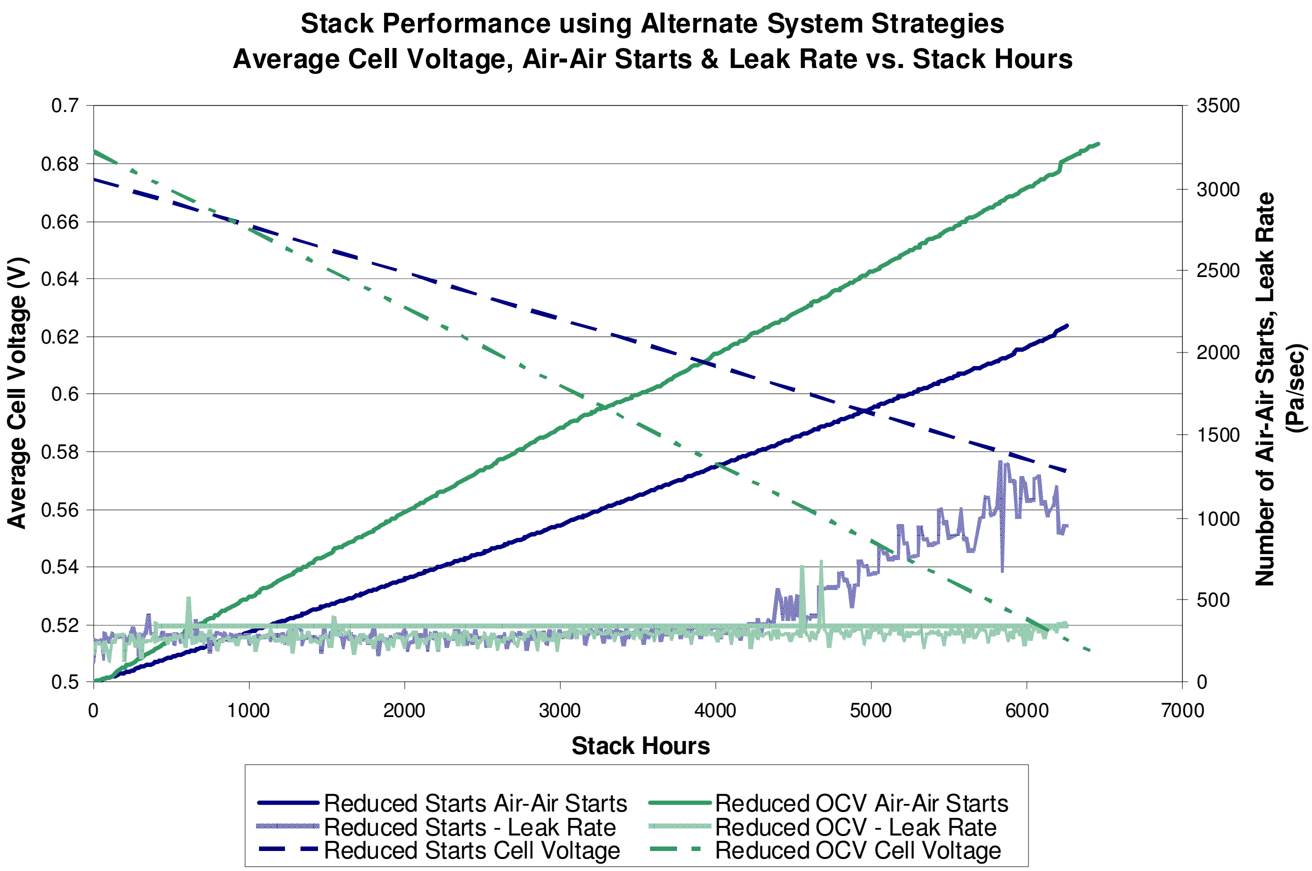


Figure 26 – Stack Average Cell Voltage, Number of Air-Air Starts & Leak Rate versus Time

System Freeze Tolerance Testing

A prototype system using an air cooled stack was built and instrumented for purposes of evaluating an air cooled stack operating at low ambient conditions. All development needed to build a prototype system was taken here 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. All system tests at high and low ambient temperatures were performed in Plug Power's environmental test chamber.

Multiple system features for low ambient operation were designed into the prototype system in order to evaluate how each influences performance. A high ambient test was performed first to evaluate any negative effects of system design features intended to allow low ambient operation. The initial high ambient 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 (100% command). Removal of the filter during the test demonstrated the optimal stack temperature could be achieved with the fan operating below 60% capacity. Reference Figure 27 below; this test was at high power and high ambient temperature and represents the highest heat rejection condition. An inlet air filter with lower pressure drop will need to be designed for the next level of tests.

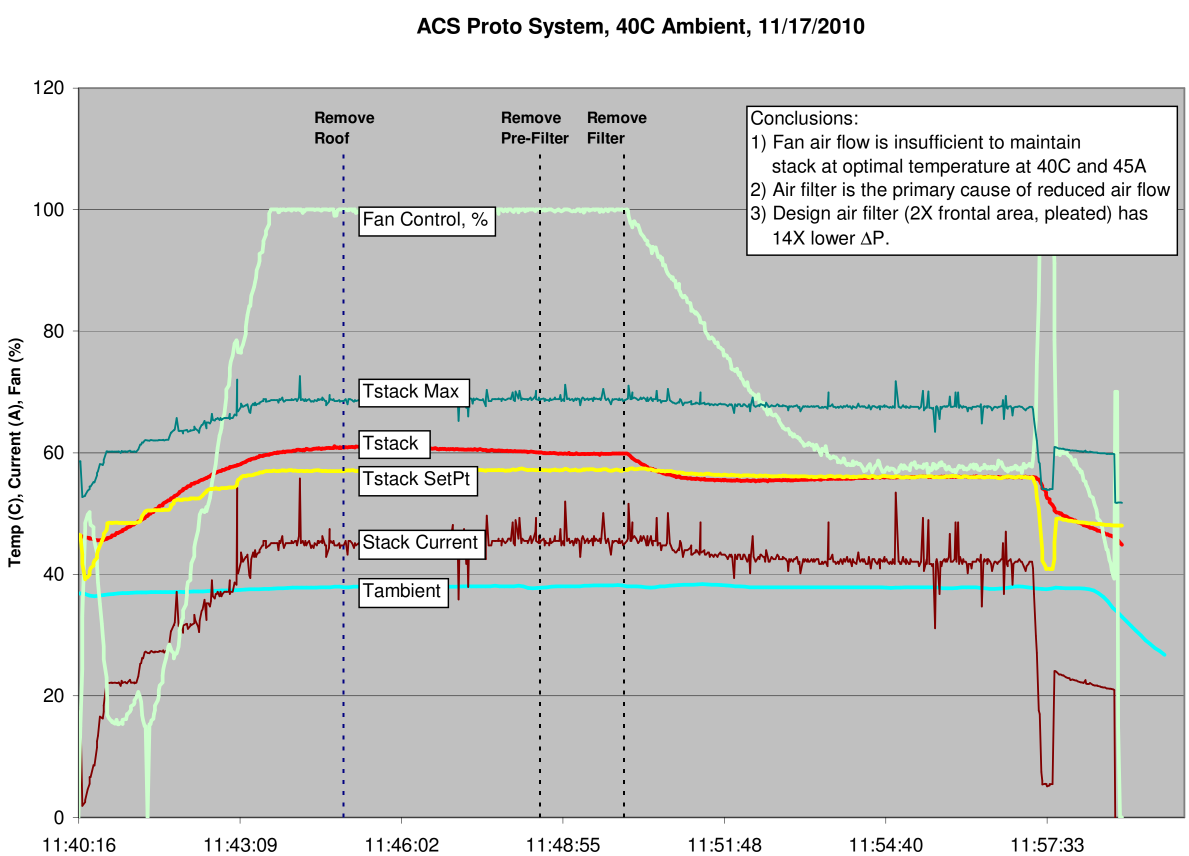


Figure 27 – System Test data at 40C Ambient

The next system level evaluation was performed under a low load profile at -15C ambient environment. Again, low loads are more challenging at low ambient conditions because less heat is generated by the stack. Here it can be seen that both exhaust air recirculation and heaters can influence the stack inlet air temperature. Stack performance is reduced as air inlet temperatures drop below freezing; therefore managing the inlet air temperature is critical for optimal stack performance. System test results are shown in Figure 28 below.

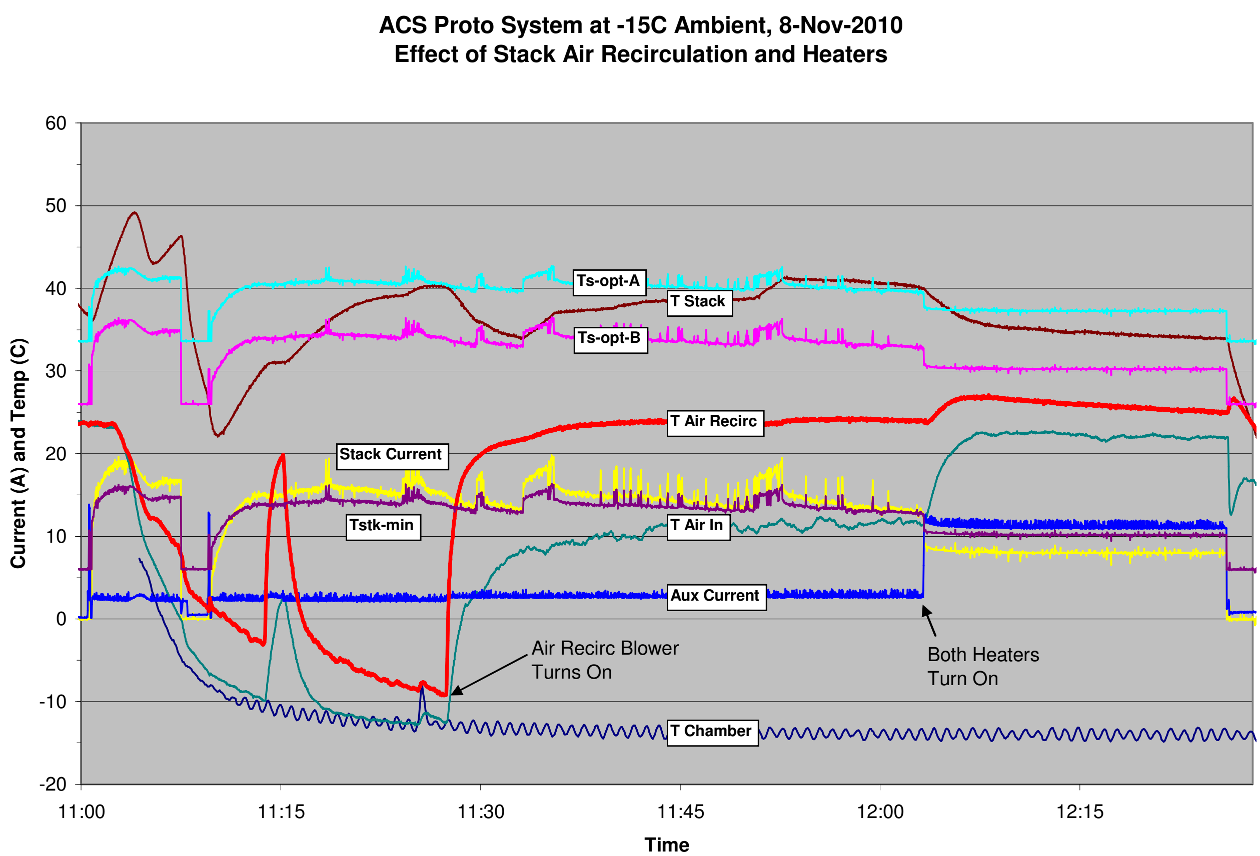


Figure 28 – System Test data at -15C Ambient

The ambient temperature was then reduced to -30C while operating a low load profile, reference Figure 29. 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.

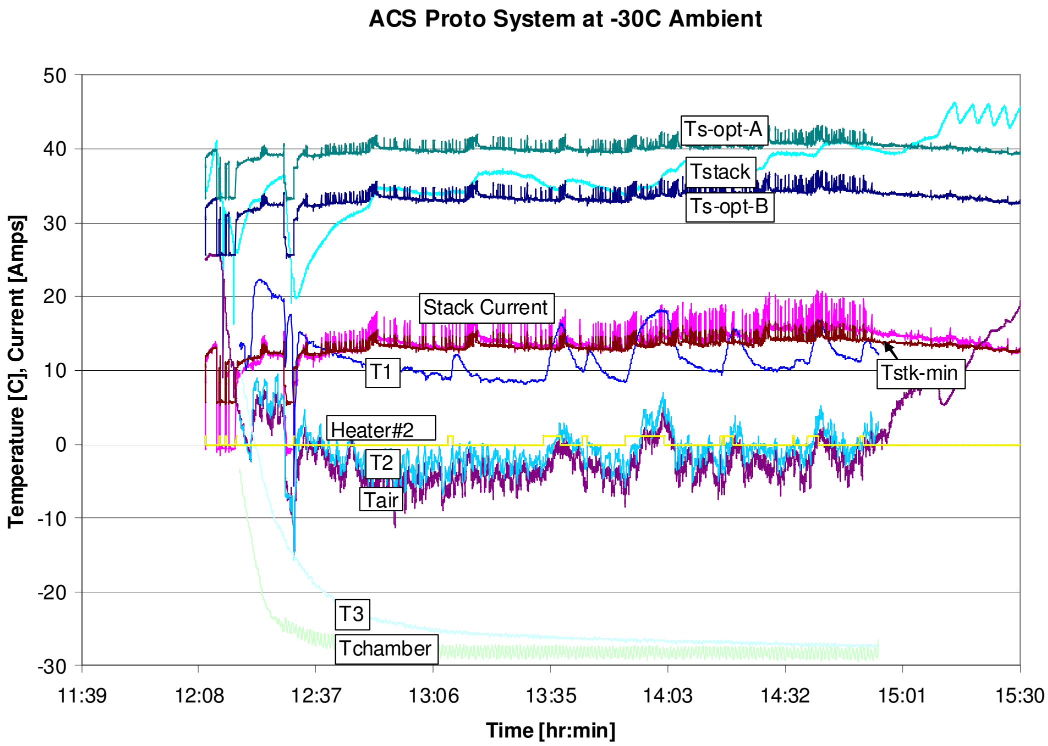


Figure 29 – System Test data at -30C Ambient

Another issue discovered during the -30C testing was ice formation in the air recirculation stream; see Figure 30 below. 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 -30C operation.

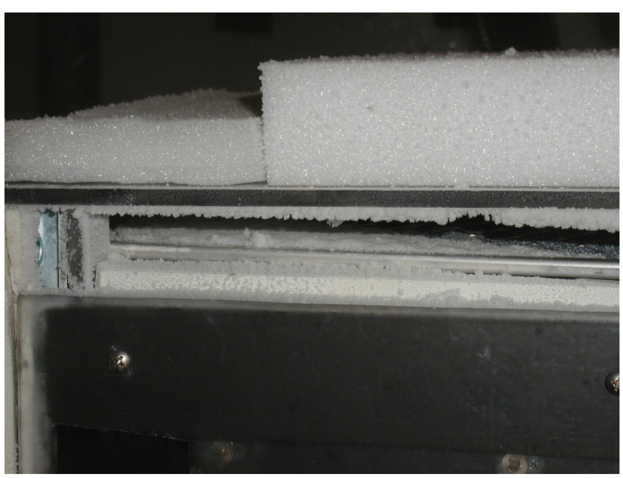


Figure 30 – Ice formation in air recirculation path

GenDrive™ system strategy is to keep the system running in below freezing ambient environments; however the products may be stored for long durations at conditions just above freezing. Additionally, GenDrive™ system strategy utilizes a battery hybrid design to take the peak load demands and to provide power to the forklift quickly until the fuel cell stack can turn on an generate power. The system voltage (fuel cell – battery hybrid) must stay above the forklift minimum voltage limit under all load conditions. The time for the air cooled stack to reach full power is longer in colder ambient conditions. A test was performed at 5C following a 5 hour soak at 5C. As seen in Figure 31, the air cooled stack is able to ramp up to power to ensure the battery voltage stays above the battery minimum voltage limit.

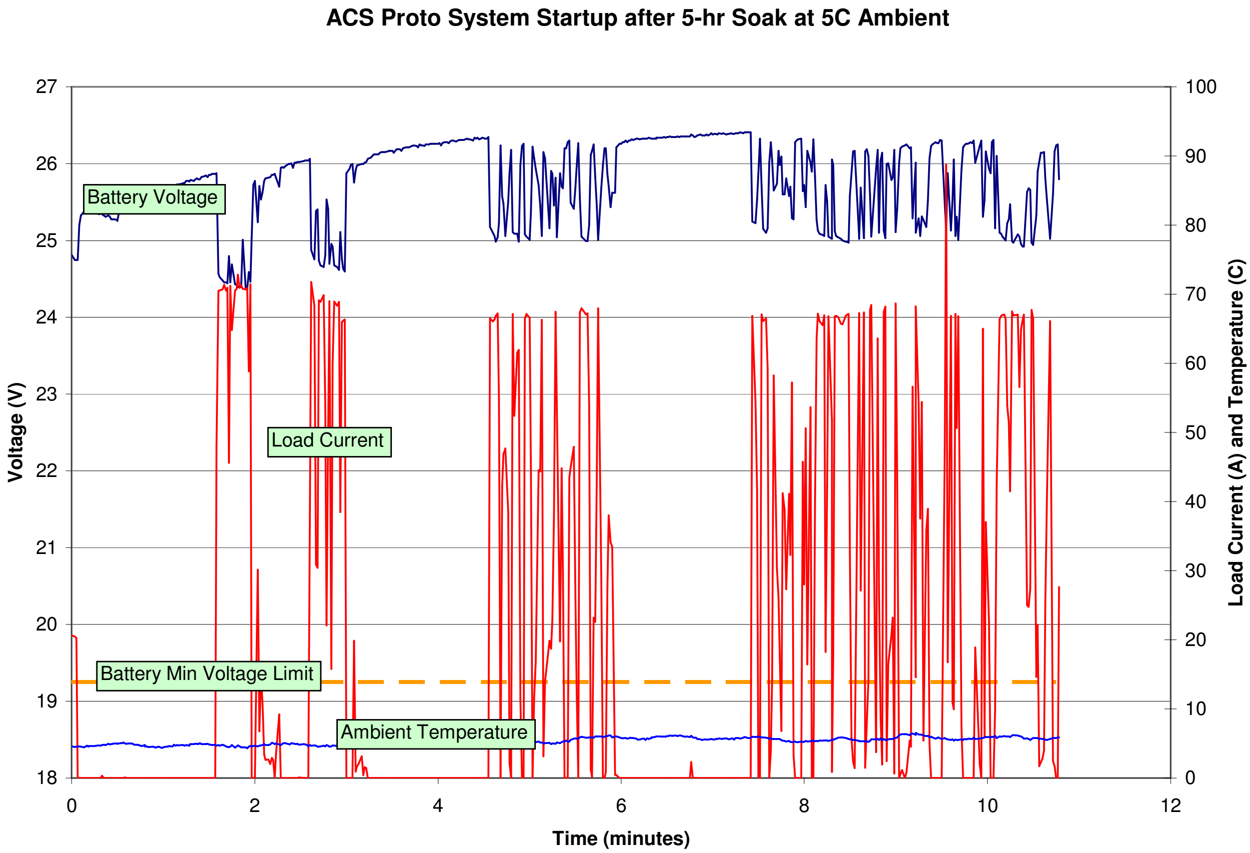


Figure 31 – System Startup following a 5 hour soak at 5C ambient

Initial Test Conclusions

An air-cooled stack system meets the performance and durability targets and can function in a -30°C ambient temperature environment. The major issues discovered during the -30°C ambient (freezer) testing are shown below along with the proposed modifications.

Issue	Proposed Modifications
ACS durability – excessive # starts over service life	- Optimize operating and control strategy to reduce # starts and improve ACS durability
Insufficient fan at +40C ambient	- Evaluate larger pleated filter
Inlet air temperature gradient	- Heater positioning and mounting - Air recirculation ducting changes - Ambient air inlet ducting
Moisture condensing/freezing in air filter	- Heater positioning and mounting - Air recirculation ducting changes - Ambient air inlet ducting

Go / No Go Metric

Background

The project Go / No Go decision 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 minimum air cooled fuel cell stack durability was set at 5000 hours which was met using 3 different system operating strategies as reported in the 2010 Q3 progress report. The minimum air cooled fuel cell stack performance was set for sustained operation at -30°C ambient under a low load profile from customer application data which represents a worst case material handling freezer environment. At low loads there is less heat generated by the stack to keep itself warm and system strategies must be employed to maintain fuel cell stack critical operating parameters. The product cost utilizing the air cooled fuel cell stack must include any devices required to achieve the 5000 hour durability and the -30°C ambient performance.

Go / No Go Cost Metric

GenDrive™ product cost reduction of 25% or greater using an air cooled fuel cell stack (1020ACS) when compared to 2009 end of year GenDrive™ with a liquid cooled fuel cell stack (9SSL)

Go / No Go Approach

The target market is material handling order picking applications. Plug Power markets its GenDrive™ product for this application and will use existing records to create the baseline product life cycle cost. The product life cycle cost consists of 3 main components; the initial product cost, maintenance costs and operating costs. The initial product cost is the cost of the customer to purchase the product. The maintenance costs are expenses associated with preventative maintenance, replacing wear items and servicing the product. Operating costs are the costs associated to fuel storage and delivery and the cost of the fuel itself.

The baseline was set as the 2009 end of year cost for Plug Power's GenDrive™ product; Plug Power's incumbent commercial solution for material handling order picking applications. The 2009 end of year cost was selected because this was the year the project was started. A cost metric was selected because development effort of an alternate technology would need to be justified by a considerable advantage over the existing commercial solution.

A high level bill of material was created for a product utilizing the air cooled fuel cell stack system architecture to develop the initial product cost. Maintenance costs were estimated based on Plug Power's experience servicing similar parts used on other fuel cell systems. Plug Power's analytical system model was used to predict system efficiency and used along with Plug Power's experience in the cost of hydrogen fuel infrastructure to derive the operating cost.

Plug Power evaluated both the initial product cost and the product life cycle cost of the air cooled fuel cell stack technology compared to the incumbent liquid cooled fuel cell stack technology. In addition, Plug Power has shown product life cycle cost reductions for the liquid cooled fuel cell product made in 2010, largely from supply chain activities, and an estimated product life cycle cost for a new concept liquid cooled system architecture. The additional comparisons illustrate that Plug Power maintains an open approach to finding the most cost effective solutions that meet customer requirements.

Initial product cost and life cycle cost will be shown normalized to the baseline product (2009 end of year GenDrive™). Additionally, a subsystem cost ratio will be presented for each of the product comparisons made.

Go / No Go Results

A comparison of initial product cost is shown in Figure 32. 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 a concept system architecture.

The first air cooled stack comparison is made with Ballard Power System's 1020ACS V2 MEA with 5000 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 1020ACS Advanced MEA.

As can be seen from the first 3 bars in Figure 8, 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. Costs are normalized to the baseline.

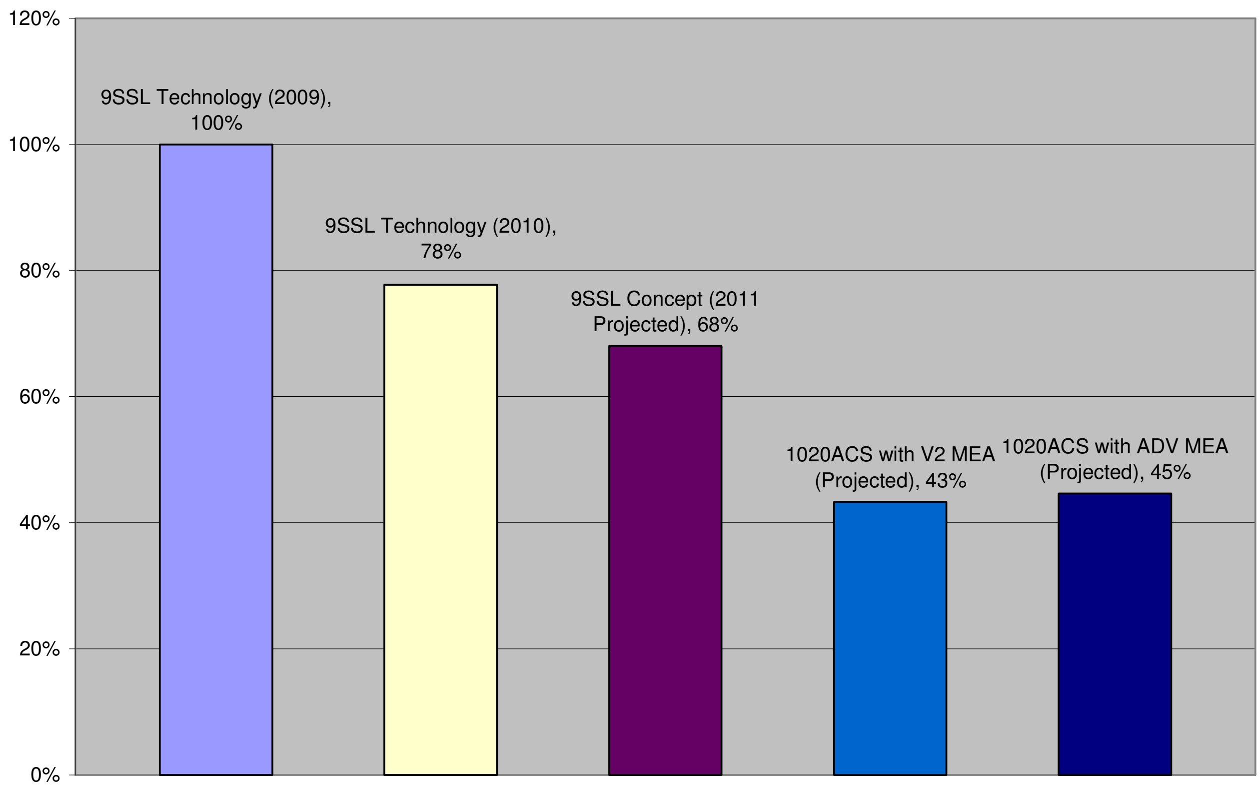


Figure 32 – Initial Product Cost Comparison (Normalized)

A product life cycle cost comparison is made in Figure 33. Cost at year 1 represents the normalized initial product costs as shown in Figure 8. The cost increase over the product life represents the maintenance and operational costs. Here it can be seen that while the 1020 advanced MEA product has a higher initial cost (1020ACS with ADV MEA), it achieves a lower product life cycle cost due to a more durable fuel cell stack. The projected higher durability is based on preliminary testing. Durability testing is ongoing but the value to the life cycle cost can be seen.

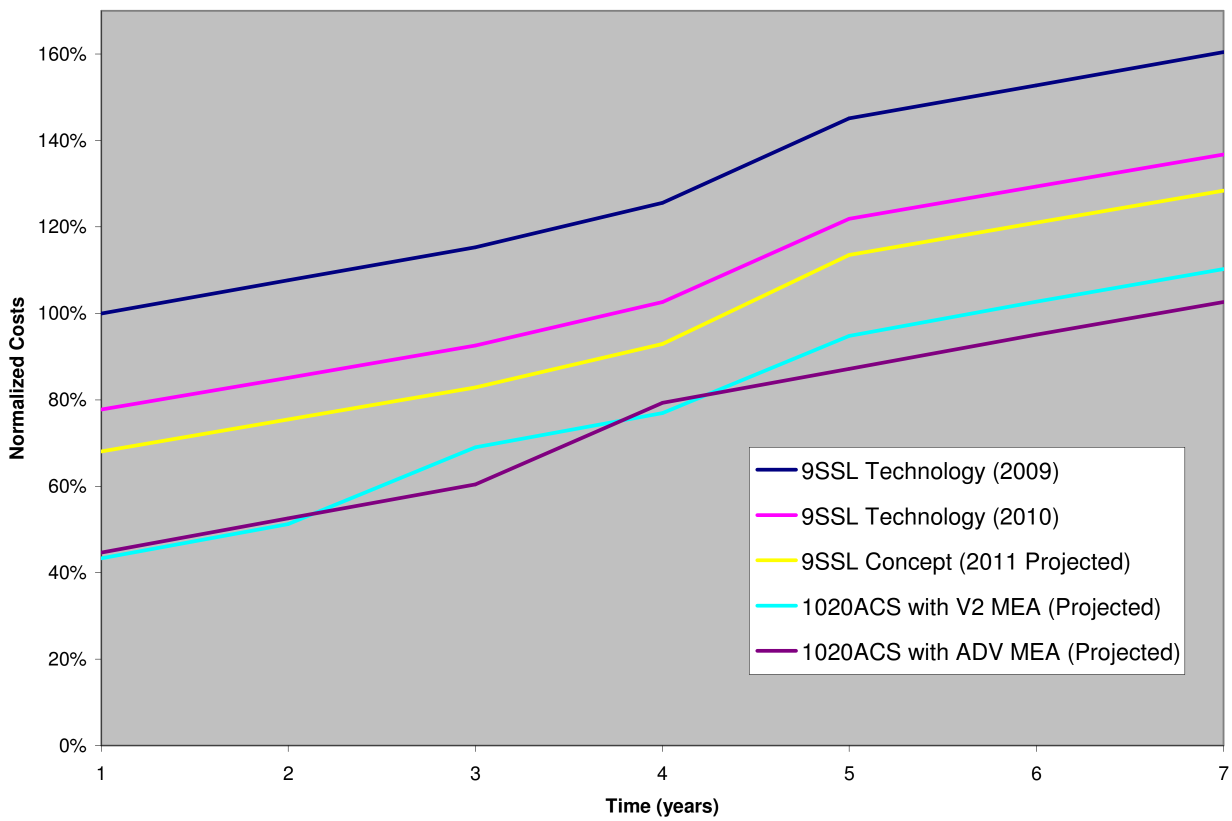


Figure 33 – Product Life Cycle Cost Comparison (Normalized)

A Go / No Go project review was held at Plug Power on December 14, 2010. A summary of the current project status was provided along with project details for each task and a copy of the presentation material was provided to the DOE. Additionally, a detailed Go / No Go Cost Metric report was then submitted to the DOE for review. Per Plug Power's recommendation, DOE approved continuing the project.

Stack Durability Test Results with System Level Operating Strategies Employed

Durability test results for the current design (V2) MEA and an advanced concept (V2-A) MEA are shown below 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). Figures 34 through 37 are stacks that were run using a simulated material handling load profile; the stack load was modeled analytically for these stack durability tests. The legend in Table 3 identifies the MEA type and system strategy for the test results shown in Figures 34 through 37.

Stack Serial Number	MEA	System Strategy*
SN8134	V1 (original)	A, C, D
SN8135	V1 (original)	B, C
SN9585	V2 (corrosion resistant catalyst)	A, C, D
SN13077	V2 (corrosion resistant catalyst)	A#, C, D
SN13078	V2 (corrosion resistant catalyst)	A#, C, D
SN13086	V2-A (adds leak resistant membrane)	A#, C, D

Table 3: Stack / System Configuration Table for Durability Tests

* System operating strategies were developed 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

   (A# represents control strategy refinements developed during the design mitigation)

B. Time at 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 4, shown below, summarizes the test data from all stacks that ran a durability test.

Stack	Cells	MEA	Hours	Cycles	Deg Rate at 51.7A (µV/hr)	Deg Rate at 29.0A (µV/hr)	Transfer Leak	Status
SN8134	36	V1	6253	2163	-16.2	-9.8	Yes	Finished
SN8135	36	V1	6456	3275	-27.1	-15.0	No	Finished
SN9585	36	V2	3253	1161	-23.4	-13.3	No	Finished
SN13077	36	V2	5785	1119	-16.8	-12.0	Yes	Finished
SN13078	36	V2	7054	1354	-15.6	-12.3	Yes	Running
SN13086	36	V2-A	5261	1019	-13.3	-6.9	No	Running

Table 4: Summary of Stack Test Results

Figure 34 below shows the average cell voltage over time for the stacks and system strategies tested. Note that for SN9585; the test was halted at 3250 hours because a fuel leak on the stack test stand had compromised the test. The remaining stacks ran beyond the 5000 hour target.

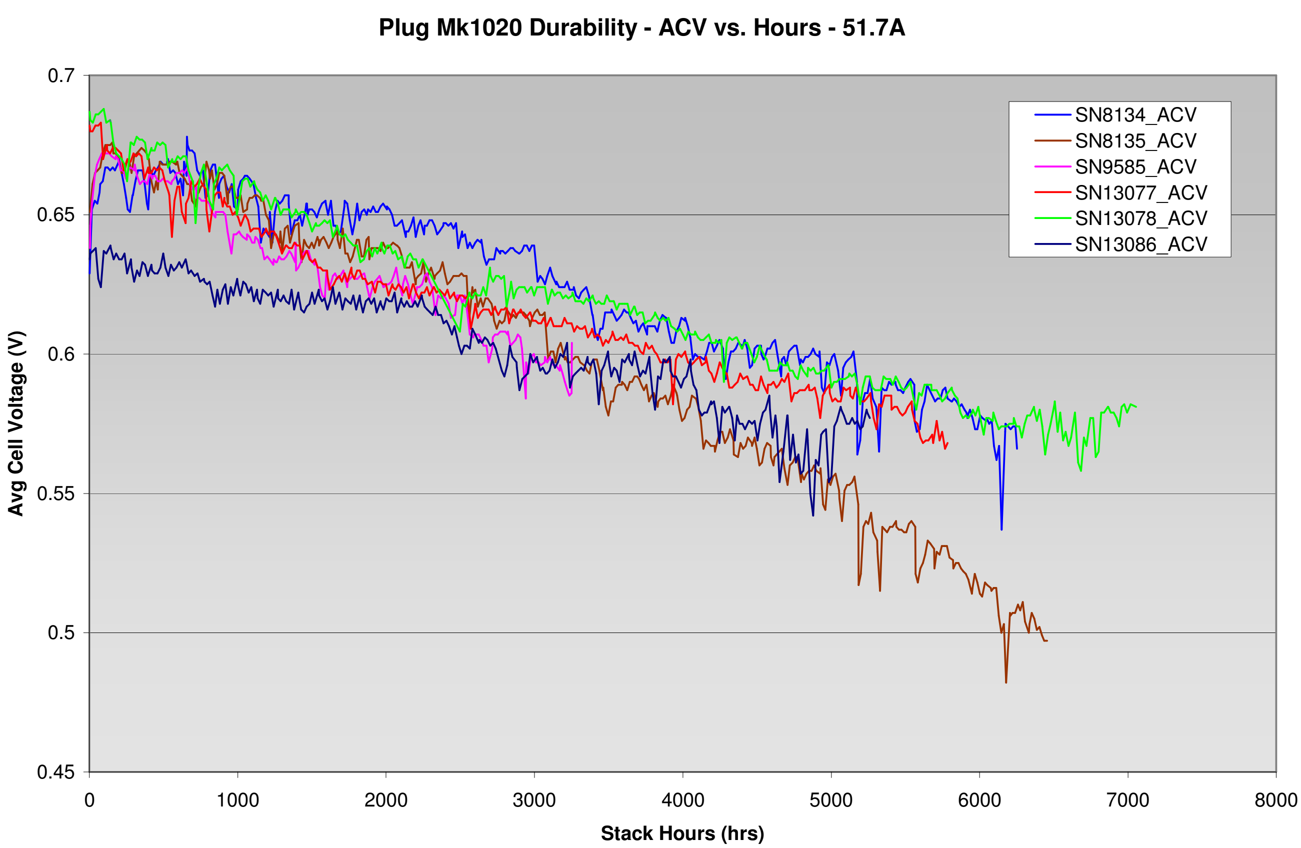


Figure 34: Average Cell Voltage versus Time

Figure 35 illustrates the number of air to air start stop cycles over time. Stack SN13077, 13078 and 13086 used a refined control strategy to reduce the number of air-air starts. Air-air starts cause carbon corrosion which can significantly reduce stack life. Since the stack is air cooled, the cathode channels are open which makes it challenging to eliminate mixed potentials across the stack at shut down.

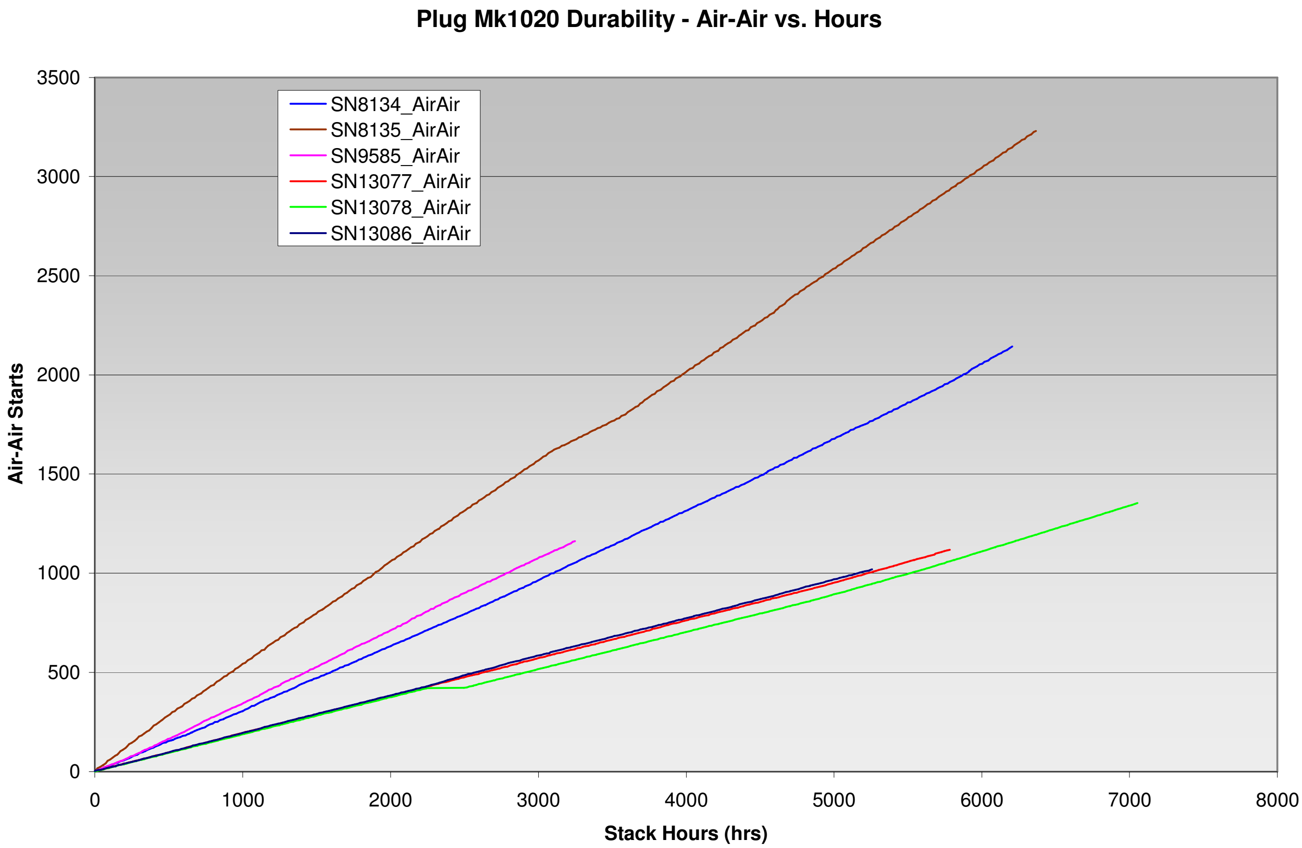


Figure 35: Number of Air-Air Starts versus Time

Figure 36 below 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 open circuit voltage (OCV) ran over 6400 hours and did not develop a transfer leak. Stack SN 13086, which incorporates a membrane more resistance to transfer leaks, has run for over 5200 hours without a transfer leak. Note that for stack SN 13086, large leaks were measured several times between 2200 and 2800 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 4200 hours. This was expected for the V2 MEA (13077 and 13078) compared to the V1 MEA (8134) because the membrane durability was not address in the V2 design. Specific membrane improvements were made on the V2-A MEA (13086) and the test results below demonstrate the effectiveness of those improvements.

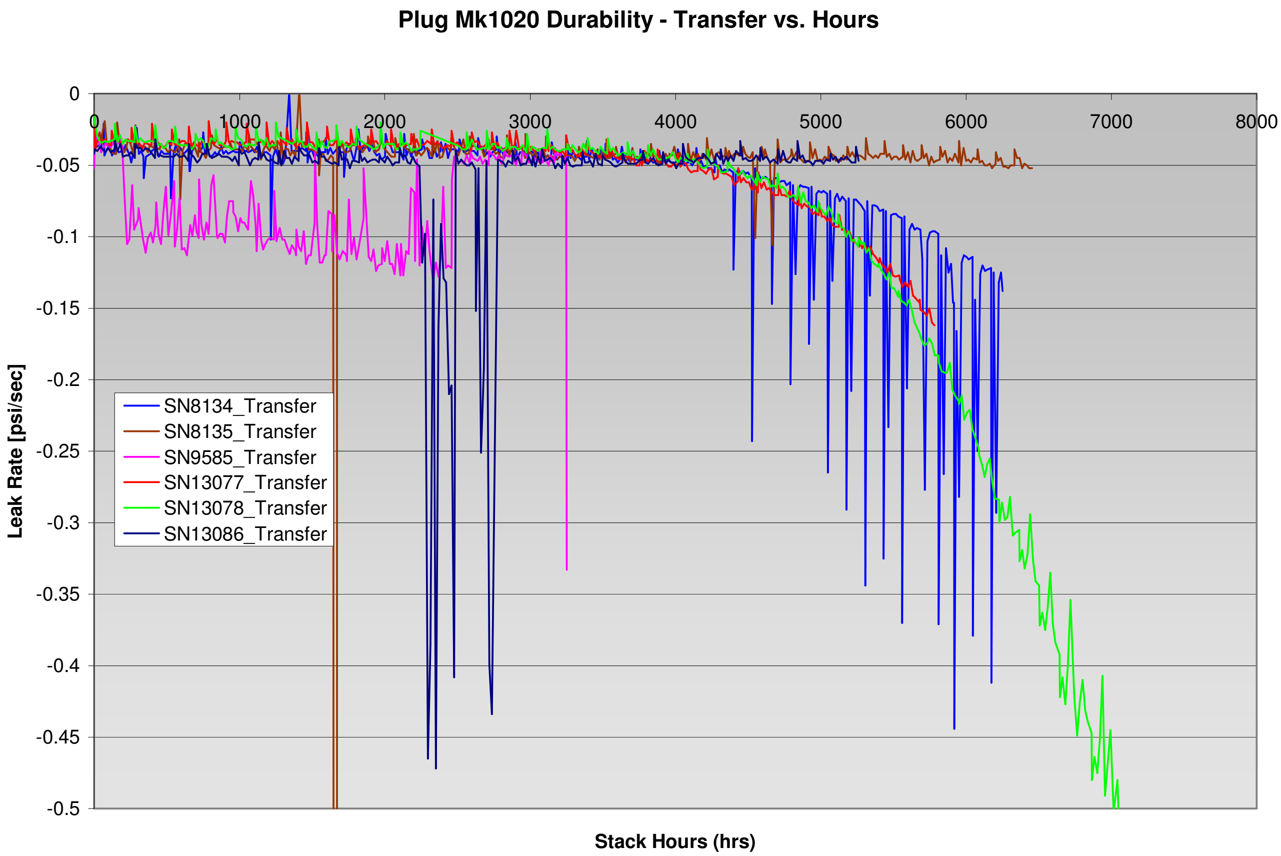


Figure 36: Stack Transfer Leak Rate versus Time

Figure 37 below illustrates how the transfer leak rate compares to the time at OCV. One of the stressors identified was time at open circuit voltage can damage the membrane and lead to transfer leaks. This graph starts to quantify the influence of time at OCV. However, for this sample set the transfer leak initiation is more consistent with operating hours (reference Figure 3). This suggests other influences, such as fuel inlet humidity, may be more dominant that the time spent at OCV.

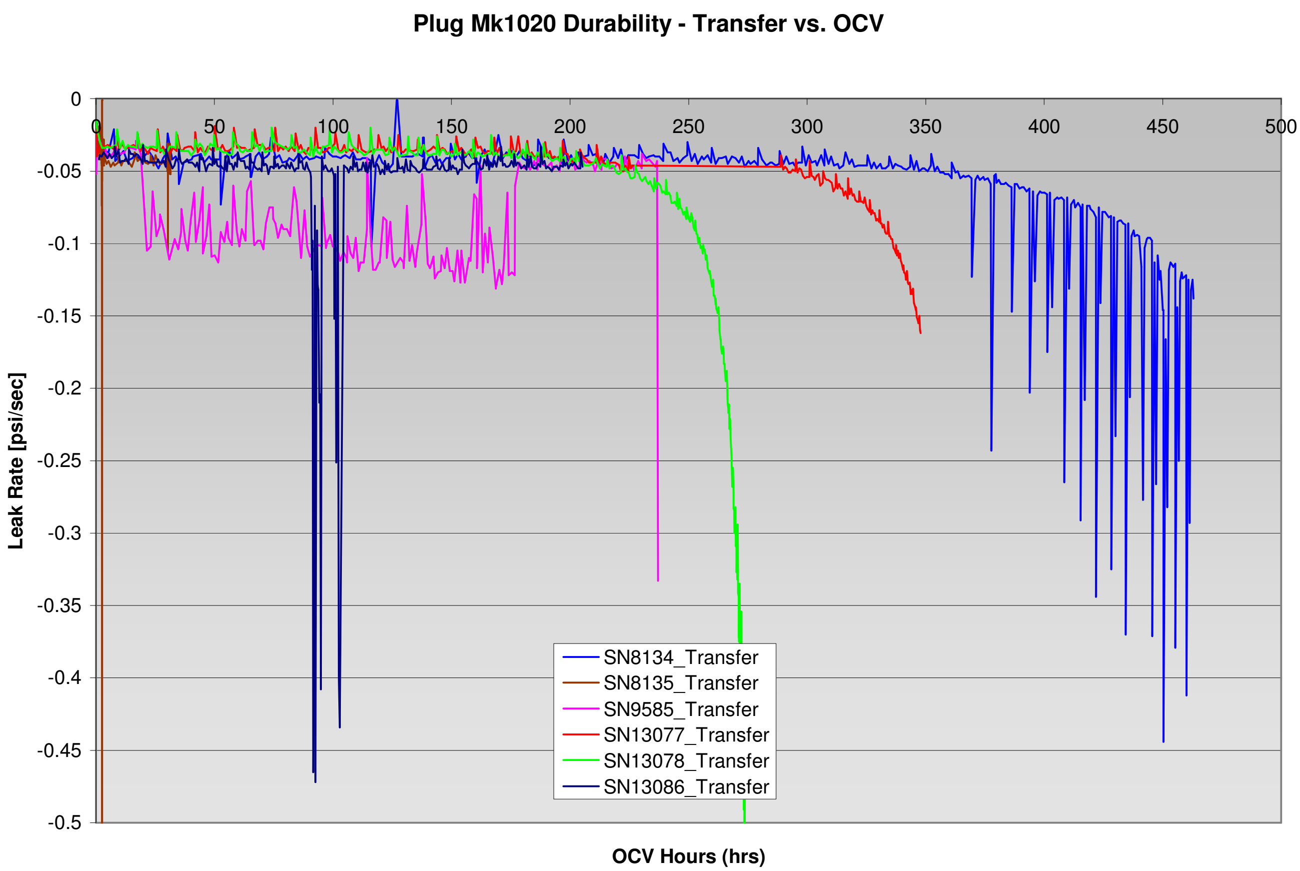


Figure 37: Stack Transfer Leak Rate versus Time at Open Circuit Voltage

System Strategy Improvements for Durability

Air Cooled Stack (ACS) durability was investigated in more detail because even though initial stack testing proved the 5000 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 tweaked to create a 46% reduction in the number of air-air starts. 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.

High Ambient Temperature Capability

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^{o}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^{o}C ambient temperature.

Air Inlet Temperature Gradient

One of the major issues uncovered during the initial freezer 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 (CFD) was been used extensively to optimize the stack inlet air velocity and temperature gradients in the freezer (-30^{o}C ambient) environment. A few graphic representations of the CFD model output are shown below. The initial air recirculation duct work had decent velocity gradients but large temperature gradients at the stack inlet as shown in Figures 38 and 39 below. The air recirculation duct work was then evaluated and re-designed to reduce the air temperature gradients. Figures 40 and 41 show the temperature and velocity profiles 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.

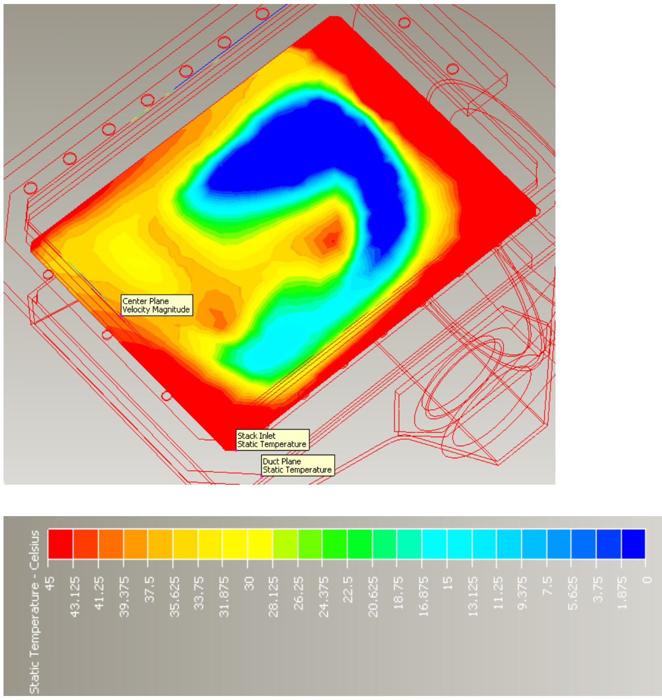


Figure 38: CFD Air Temperature Profile at stack inlet – initial duct modeling

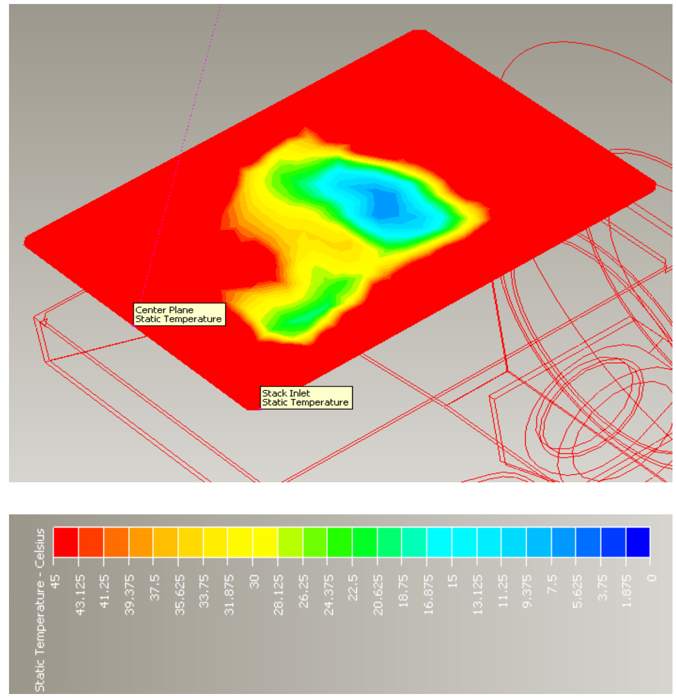


Figure 39: CFD Air Temperature Profile at stack inlet – air duct refinements

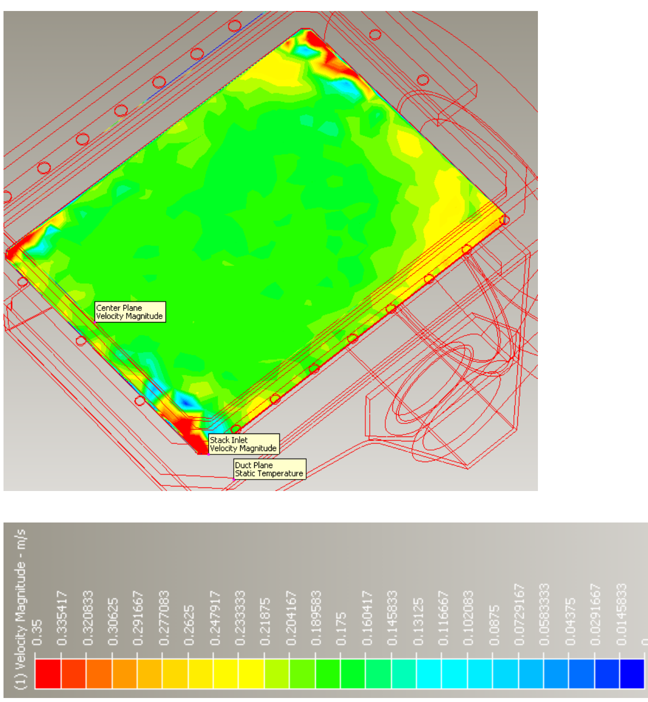


Figure 40: CFD Air Velocity Profile at stack inlet – initial duct modeling

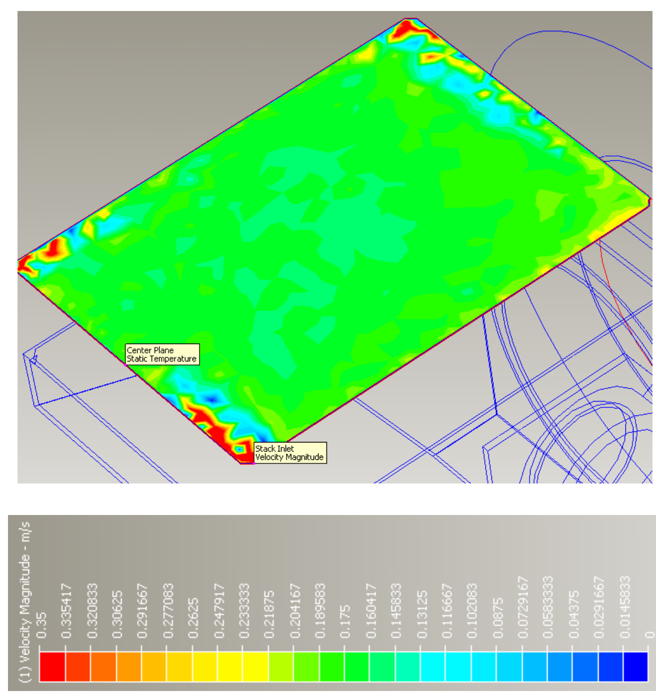
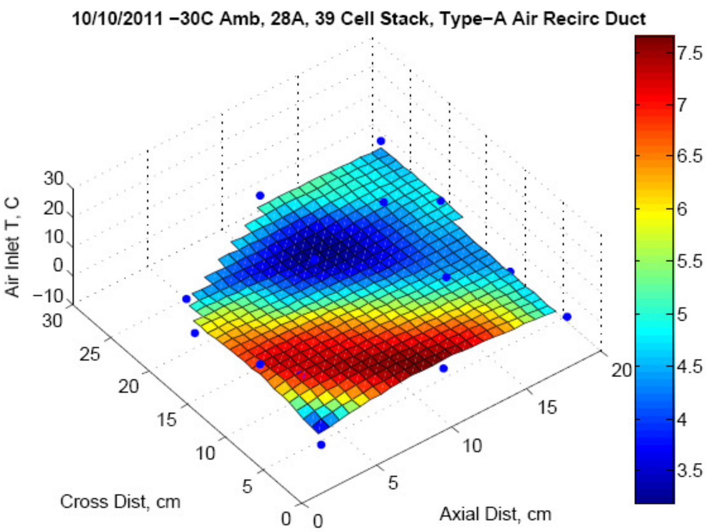


Figure 41: CFD Air Velocity Profile at stack inlet – air duct refinements

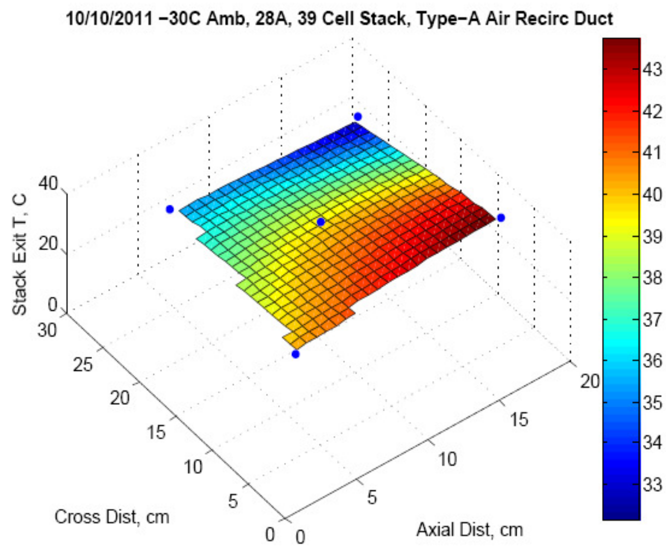
The proposed air recirculation solution to maintain the target stack inlet temperatures was tested at the module level to verify the CFD model results. The strategies developed using CFD were so successful that the use of additional heaters was not required. Additionally, the refinements made in the air recirculation eliminated the condensing and freezing that was observed during the initial tests. Test results for air inlet temperature profile and the stack temperature profile (measured at the stack air exit) are shown below for the worst case -30^{o}C ambient temperature. Figures 42 and 43 illustrate the profiles at medium stack load [30 amps] while Figures 44 and 45 illustrate the profiles at a low stack load [11 amps].



3.5 to 7.5C inlet air T

Figure 42:

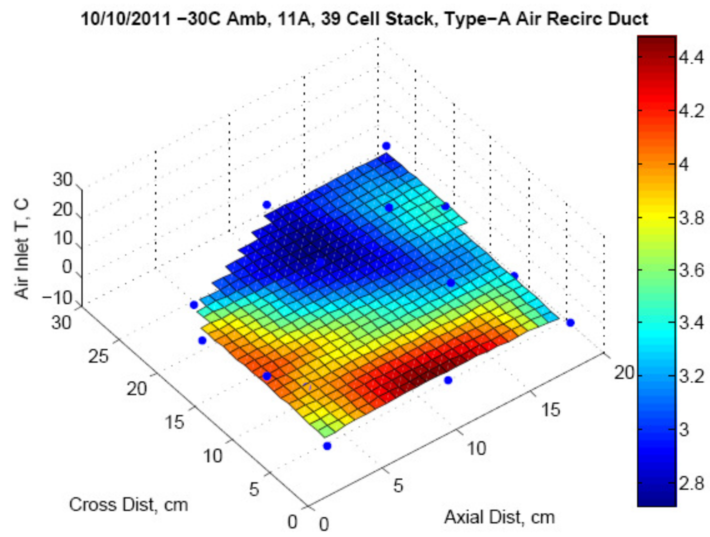
Stack Inlet Air Temperature Profile at medium stack load [30 amps] and -30^{o}C ambient temperature



33 to 43C stack T

Figure 43:

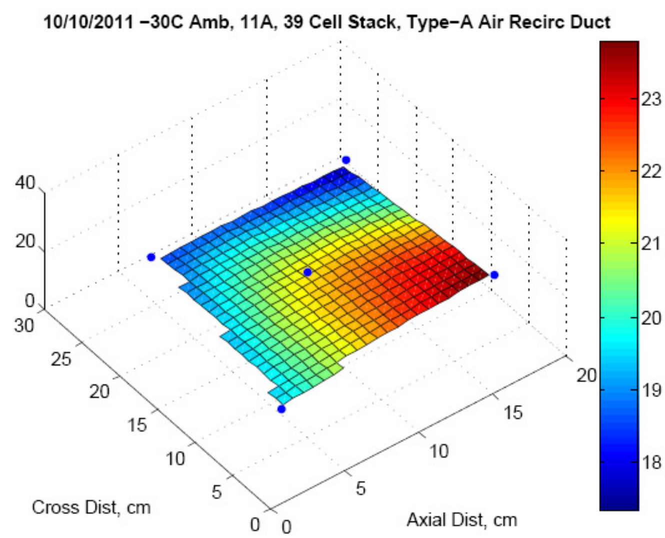
Stack Exit Temperature Profile at medium stack load [30 amps] and -30^{o}C ambient temperature



3 to 4.5C inlet air T

Figure 44:

Stack Inlet Air Temperature Profile at low stack load [11 amps] and -30°C ambient temperature



18 to 23C stack T

Figure 45:

Stack Exit Temperature Profile at low stack load [11 amps] and -30°C ambient temperature

Design Mitigation Summary

The final system design mitigation strategies are summarized below and compared to the proposed mitigations from the Go / No Go Review.

Issue	Proposed Mitigations	Actual Mitigation
ACS durability	- Improve control strategy	-Manage system startup controls and stack idle time to minimize AA starts → 46% reduction -Perform periodic cathode air starves to minimize catalyst oxide layer growth -Manage mixed potentials in cells on shutdown to minimize carbon corrosion damage
Stack temperature at +40C ambient	- Larger pleated filter - Filtration space claim	Low pressure drop particulate and chemical filter developed for the available space claim; fan is able to maintain target stacks temperatures at +40C ambient temperature
Inlet air temperature gradient	- Heater location - Air recirculation ducting - Ambient air inlet ducting	CFD modeling used to optimize air flow and minimize stack inlet air temperature gradients without the use of a heater – Final systems built with new inlet and air recirculation ducting; see test results
Moisture condensing and freezing	- Heater location - Air recirculation ducting - Ambient air inlet ducting	CFD modeling used to optimize air flow and minimize stack inlet air temperature gradients – No condensing or freezing observed during final low ambient temperature testing

System Build with Mitigation Strategies

Following the design mitigation phase, a new system was constructed with all the mitigations in place. A partially completed system is shown in Figure 46 below and a complete system instrumented for testing is shown in Figure 47.

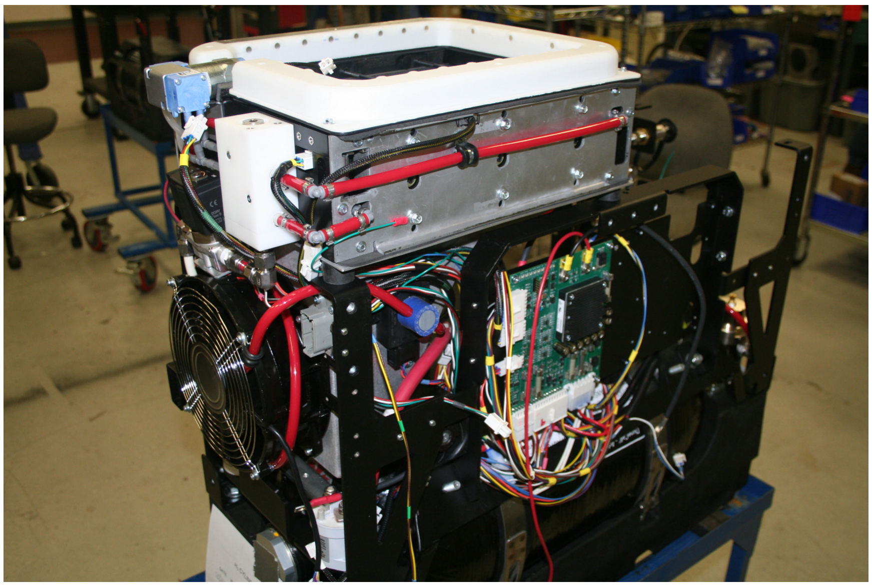


Figure 46: System Build using an Air Cooled Stack

Figure 47: New system shown in Plug Power environmental testing chamber

System Testing with Mitigation Strategies Employed

Final system verification testing at a low ambient temperature of -30°C was performed in the environmental testing chamber at Plug Power; reference Figure 48 below. The system was operated at both high and low loads over an 8 hour period. 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.

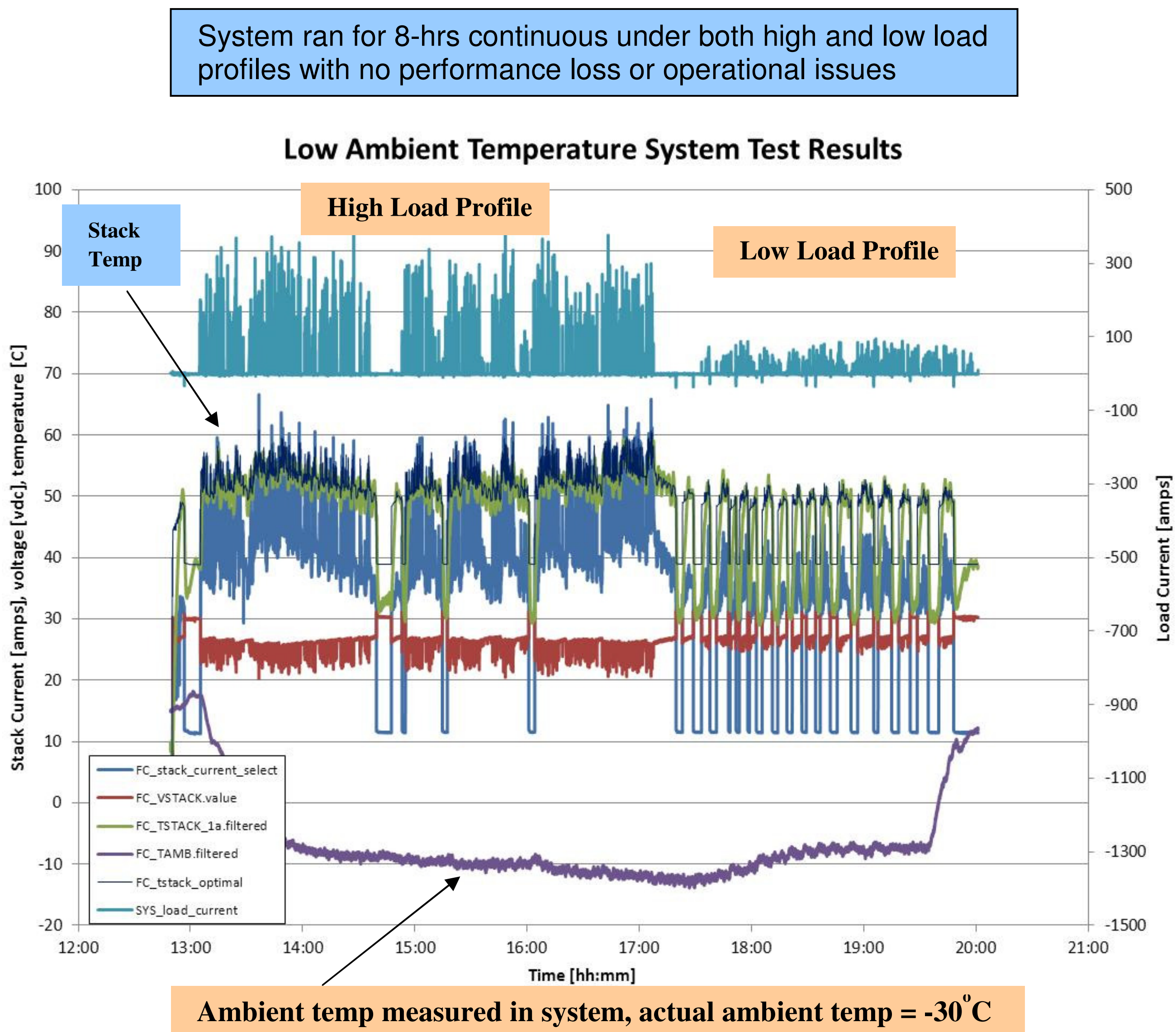


Figure 48: System Test Results from -30°C ambient temperature testing

Conclusions

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 5000 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, reduced 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 significant 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. The primary project conclusions are as follows:

- Dominant ACS failure modes are catalyst dissolution and cathode carbon corrosion during air-air starts
- Two MEA designs show reduced degradation in lab testing, new materials mitigate dissolution, corrosion and membrane leaks
- AST's and models can be used to define system operating strategies to extend lifetime by targeting main failure modes
- ACS stack not capable of a significant numbers of consecutive freeze start-ups from below -10°C
- Stack thermal model identified inlet heaters and cathode recirculation as options to keep stack above -10°C
- Minimal degradation seen from freeze start-ups from -10°C
- Freeze capable stack technology more expensive than freeze prevention at system level
- 5000 hour durability target met with system operating strategies 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

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.

5 TECHNOLOGY TRANSFER

This DOE project funding accelerated the development activities required to determine if the air cooled stack technology could be used in a material handling application that requires operation in -30°C ambient temperature environments. Stack durability and freeze mitigation strategies developed during this project proved the technology could meet the performance requirements. A cost analysis demonstrated a meaningful change in both initial cost and product life cycle cost using air cooled stack technology when compared to the Plug Power incumbent liquid cooled solution for material handling order picking applications.

In October 2011, Plug Power announced its next generation order picker commercial product based largely on the technology developed over the course of this 2 year project with the DOE. Additionally, Plug Power filed 3 patent applications for concepts that extend stack life and allow an air cooled stack to function in a -30°C ambient temperature environment. DOE support helped to accelerate solving the technical challenges associated with using air cooled technology in a material handling freezer environment. Plug Power began shipping these units in the 4th quarter of 2011.