Air Cooled Stack Freeze Tolerance

Project ID: FC025
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May 12, 2011

Overview

Timeline

- Start: November 15, 2009
- Finish: November 15, 2011
- Progress: 70% complete

Budget

- Total: $3.68M
  - **DOE: $2.42M**
  - **Plug Power: $1.26M (34%)**
- FY 2010 funding: $0.97M
- FY 2011 funding: $0.55M

Barriers

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

Partners

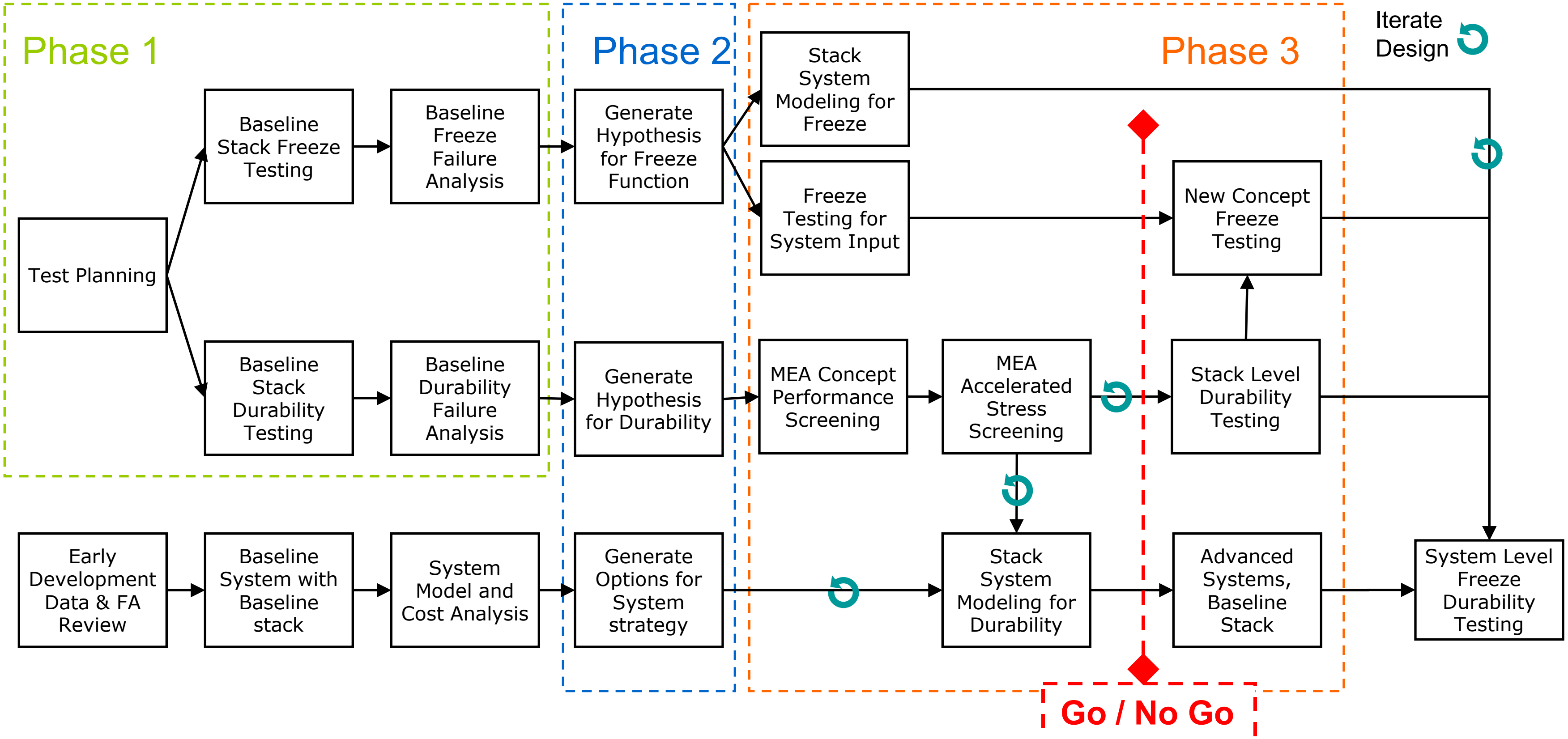
- Plug Power
- Ballard Power Systems
  - Cara Startek

Project Objective Relevance

- Evaluate and develop the stack and system together to meet durability, cost, performance and freeze tolerance requirements
  - Trade-off stack and system attributes to achieve the best function and cost
- Develop understanding around integrating air cooled stack technology into a dynamic materials handling system (frequent start-up cycles)
  - Every start-up of an air-cooled stack is an air-sir start; every freeze start is an air-air start; understanding start-stop durability is key for freeze capable stack-system
- Test and evaluate air-cooled stacks and system compatible operation developed for increased freeze tolerance and durability
  - Determine key failure modes and root causes
  - Develop baseline understanding for freeze tolerance
  - Validate mitigation strategies
- Evaluate failure mechanism mitigation at MEA, stack and system level
- Perform life-cycle cost analyses for freeze tolerance strategies
- Document and publish summary of freeze failure analysis

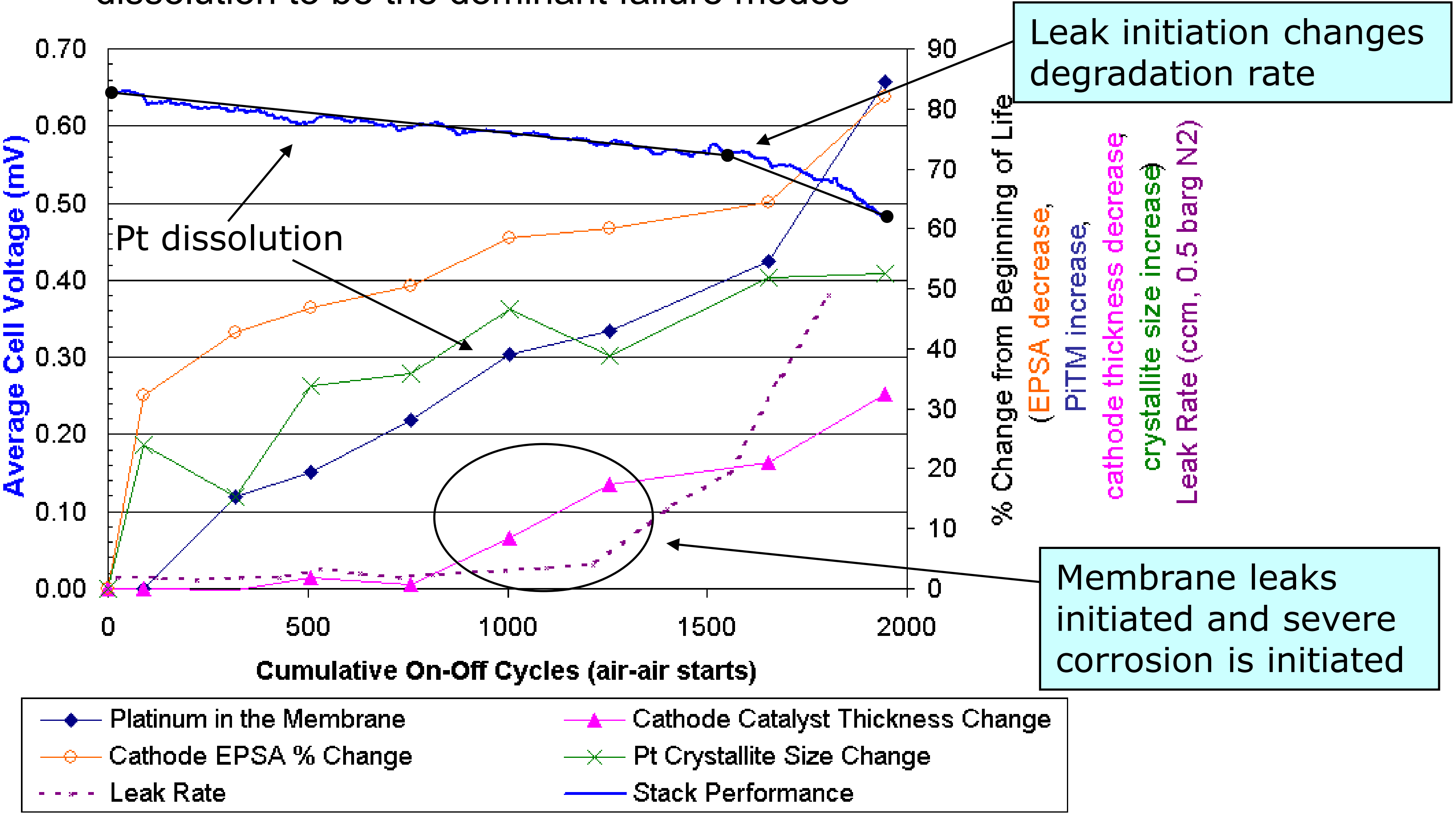
Approach

- Use understanding of market needs, system requirements, stack-system limitations, historical data, models and small scale testing to develop stack/system operating strategies to achieve required freeze function and durability
- Build stacks/system with mitigation strategies
- Test stack/system for against requirements and perform failure analysis



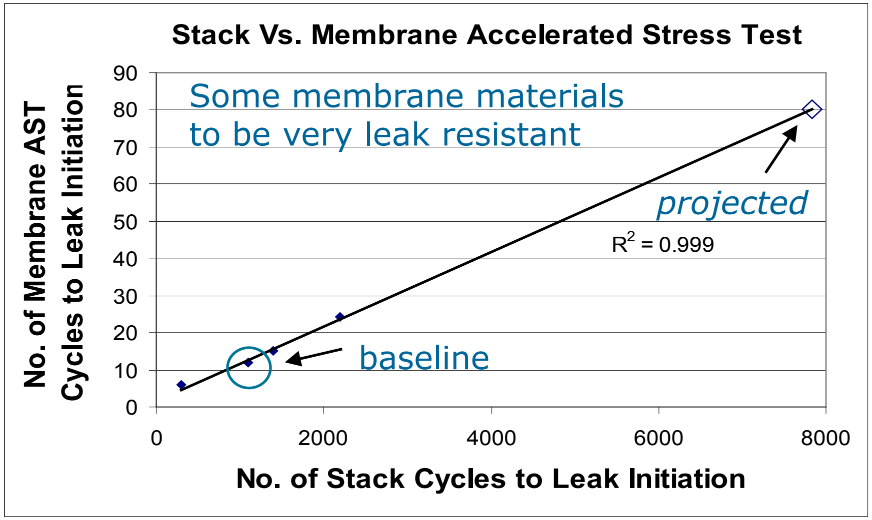
Define Baseline Stack Degradation Modes

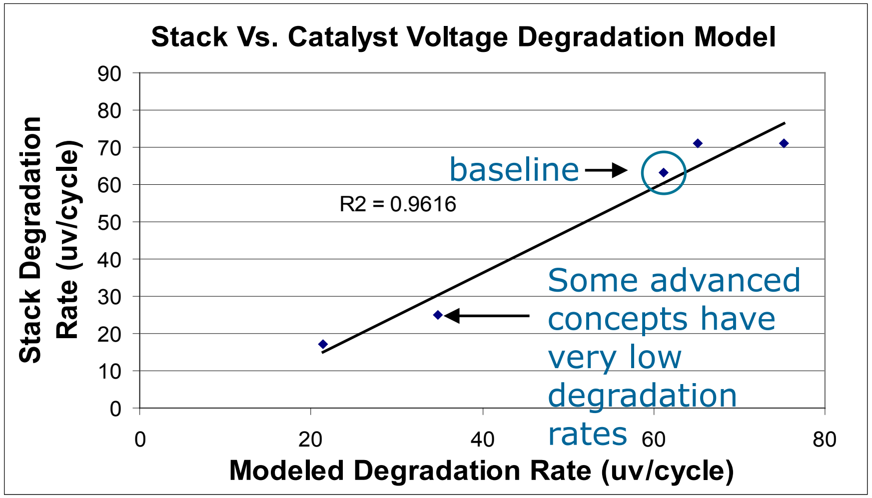
- Failure analysis identified membrane leaks causing corrosion and platinum dissolution to be the dominant failure modes



Screening with ASTs & Stack Durability Models

- Guided by failure analysis results, seek components that offer improved resistance to leaks, corrosion and platinum dissolution
- Membrane AST and time to leak initiation during stack durability testing follow linear trend
- Semi-empirical voltage degradation model exhibits a linear trend with stack level durability testing
  - Model based on corrosion/dissolution ASTs and steady state degradation rates





Advanced Concept Stack Durability Testing

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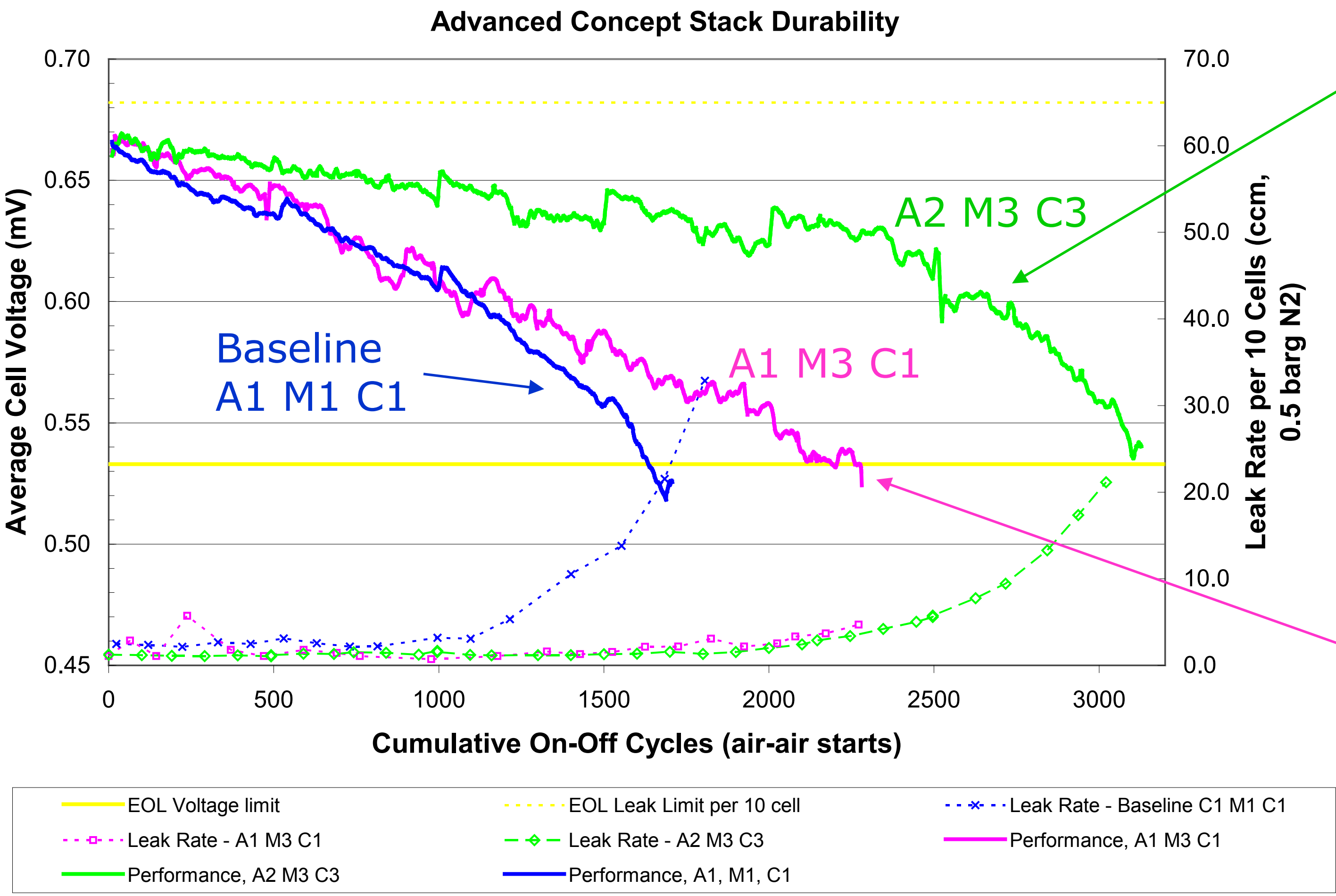
- Advanced MEA concepts selected based on small-scale screening and models meet the cascaded stack durability requirement of 2500 cycles

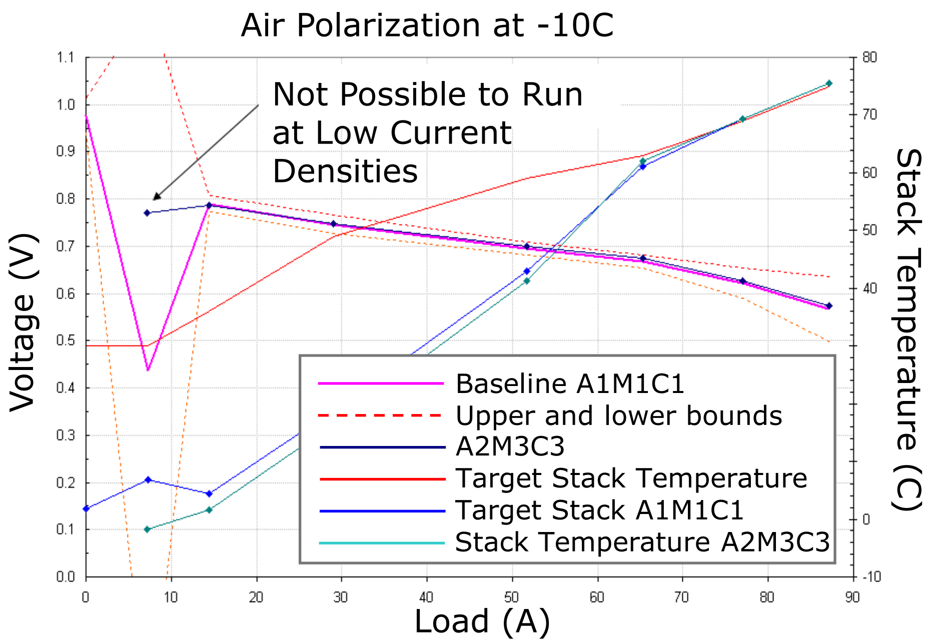


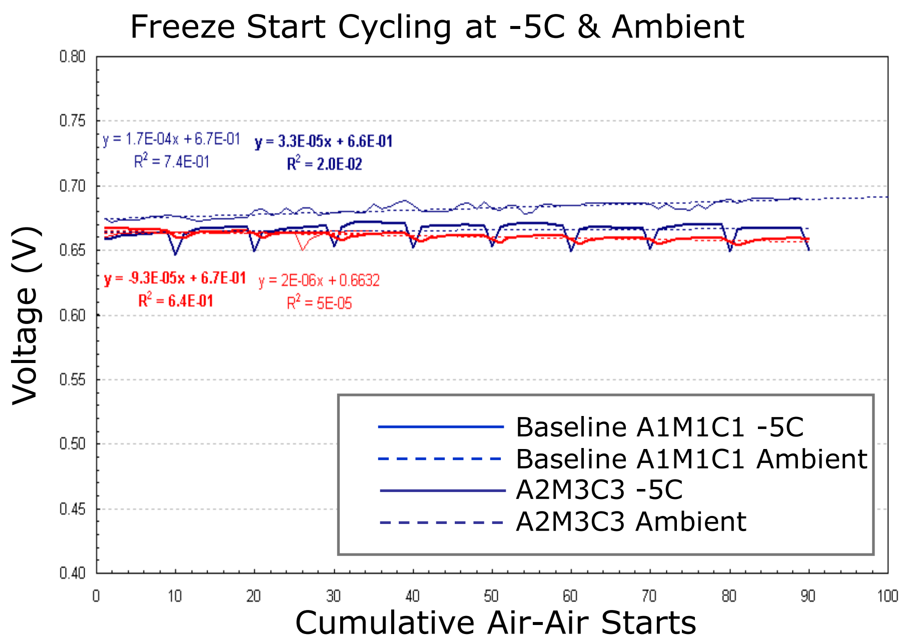
Improvement from extending time to membrane leak initiation and reducing platinum dissolution

Improvement from extending time to membrane leak initiation

Air-Cooled Stack Freeze Test Results

- ACS has functional limitations in environments below -10°C
  - Excessive stack cooling and low ambient RH are main causes
  - Below -10°C start-up resulted in variability and catalyst damage
  - Due to membrane resistance and ice accumulation in the catalyst layer
- Freeze durability cycling @ -5°C shows no change in degradation rate compared to ambient cycling
  - Recommendation: explore system modifications to keep stack temperature above -10°C





Stack-System Freeze Modeling

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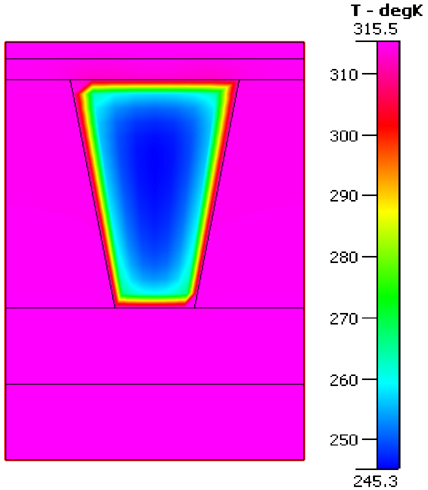
- Cathode air recirculation is feasible as a means of maintaining stack temperatures above -10°C
  - Air temperature increase versus oxygen consumption for 100% recirculation is not an issue
  - At peak power stack can heat up in less than 30 seconds
- CFD model shows air flow rate turn down decreases with use of air inlet heaters
  - CFD model combines fluid flow and heat transfer in a single air channel geometry for simplicity

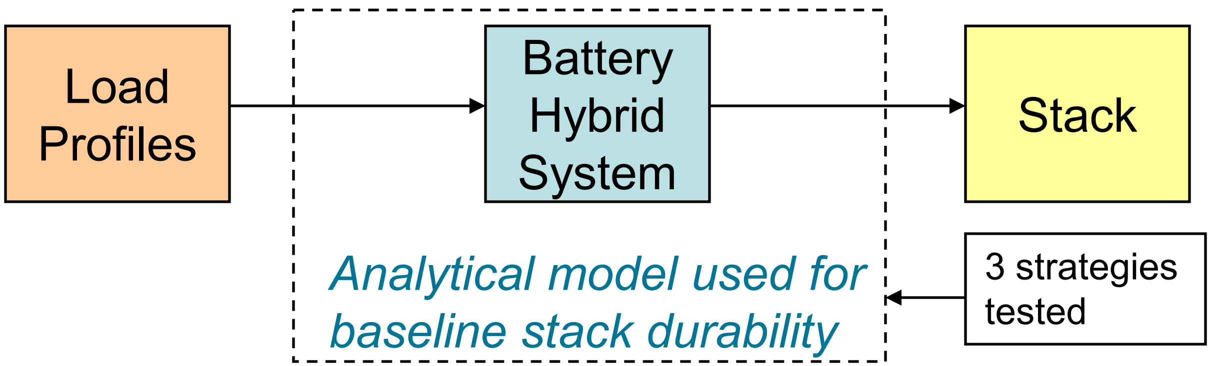


	Units	Nominal Conditions	Sub-zero No Heater	-30°C Ambient Conditions + Heater
Cathode/Air Inlet Temperature	°C	20	-30	-10
Fan Turn Down Ratio*	-	6	22 →	15
Heat Required to Heat Air from -30°C to Required Inlet Temp	W	345	0	52

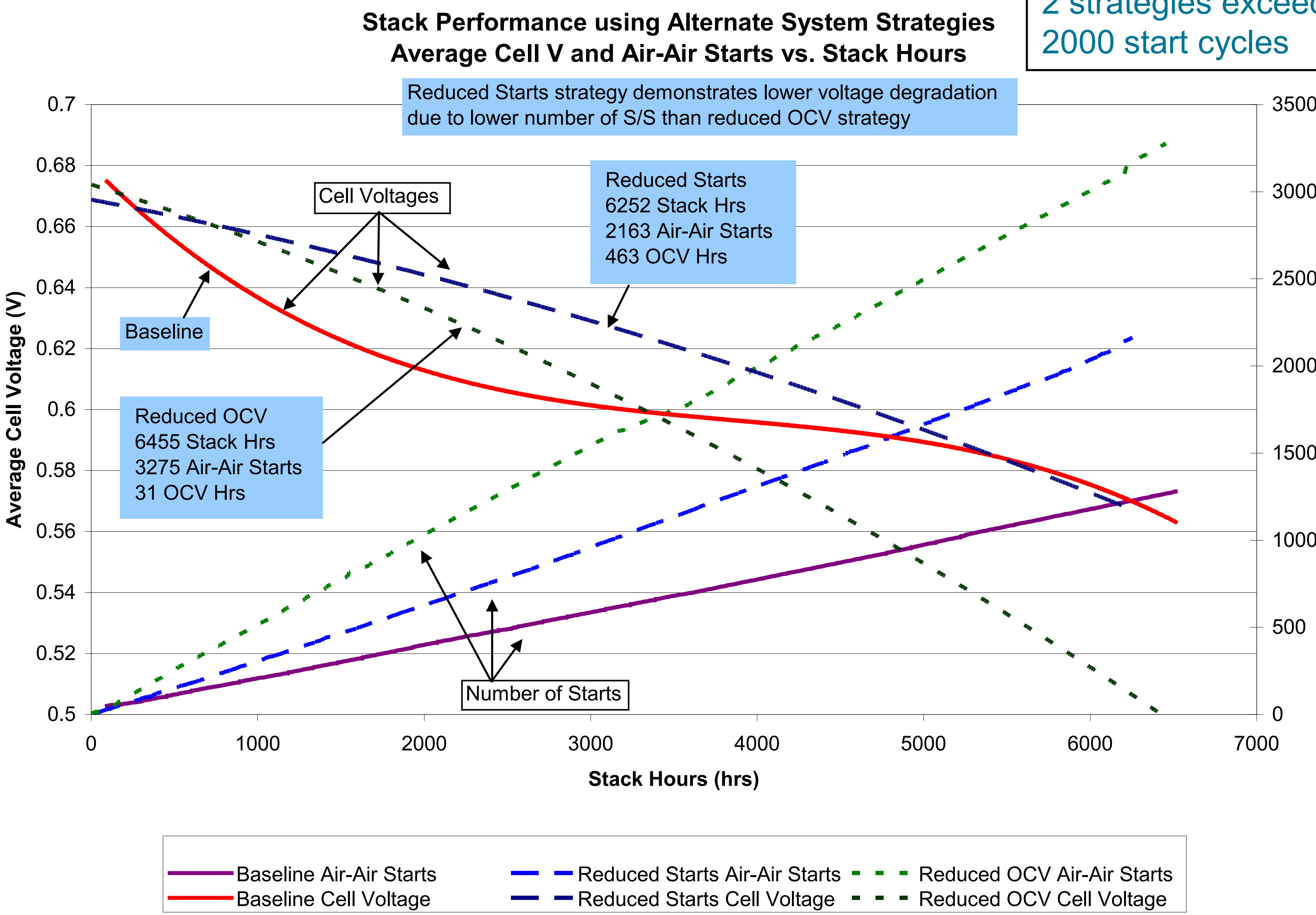
* Calculated from 51.7 A flow at 20C to 7.8 A flow at required inlet temperature

System Operating Strategy Development

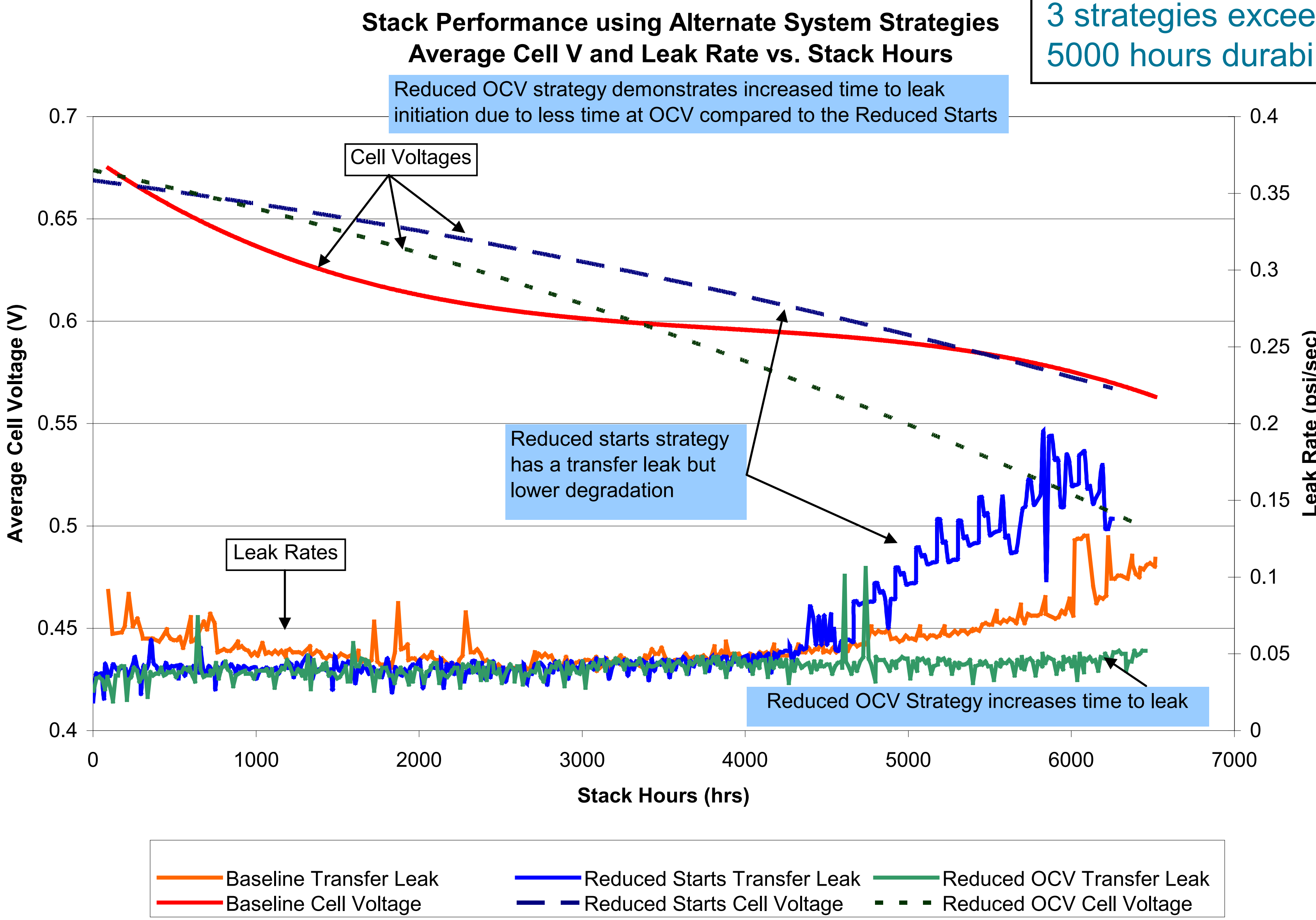
- Development of an analytical system model to evaluate performance and durability of a Fuel Cell / Battery Hybrid System
- Collaboration with Ballard to understand stack stressors and failure modes then develop system operating strategies to mitigate stressors
  - Air-Air Starts degrade the catalyst and cause voltage degradation
  - Time at OCV degrades the membrane and causes transfer leaks
  - High currents and stack temperatures stress the membrane
  - Mixed potentials (at start-up and shutdown) degrade the catalyst
- Baseline stack testing with customer load profiles; system model used to generate the stack operation, durability data w/o expense of a system



2 strategies exceed 2000 start cycles

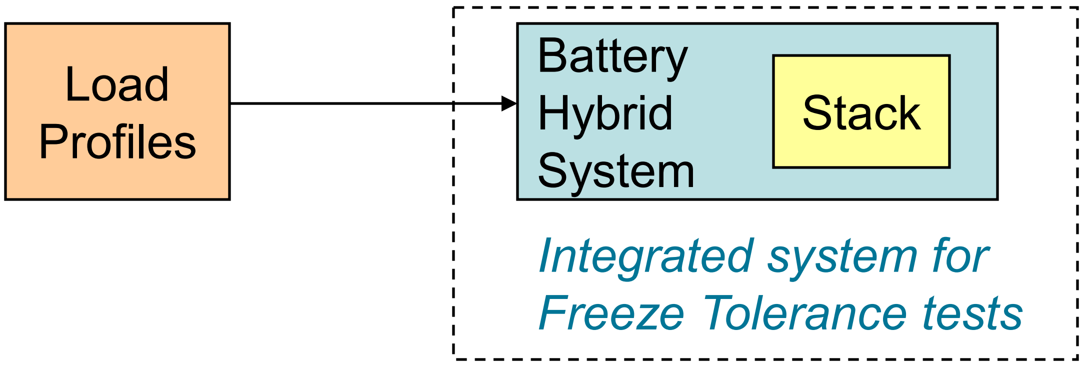


3 strategies exceed 5000 hours durability

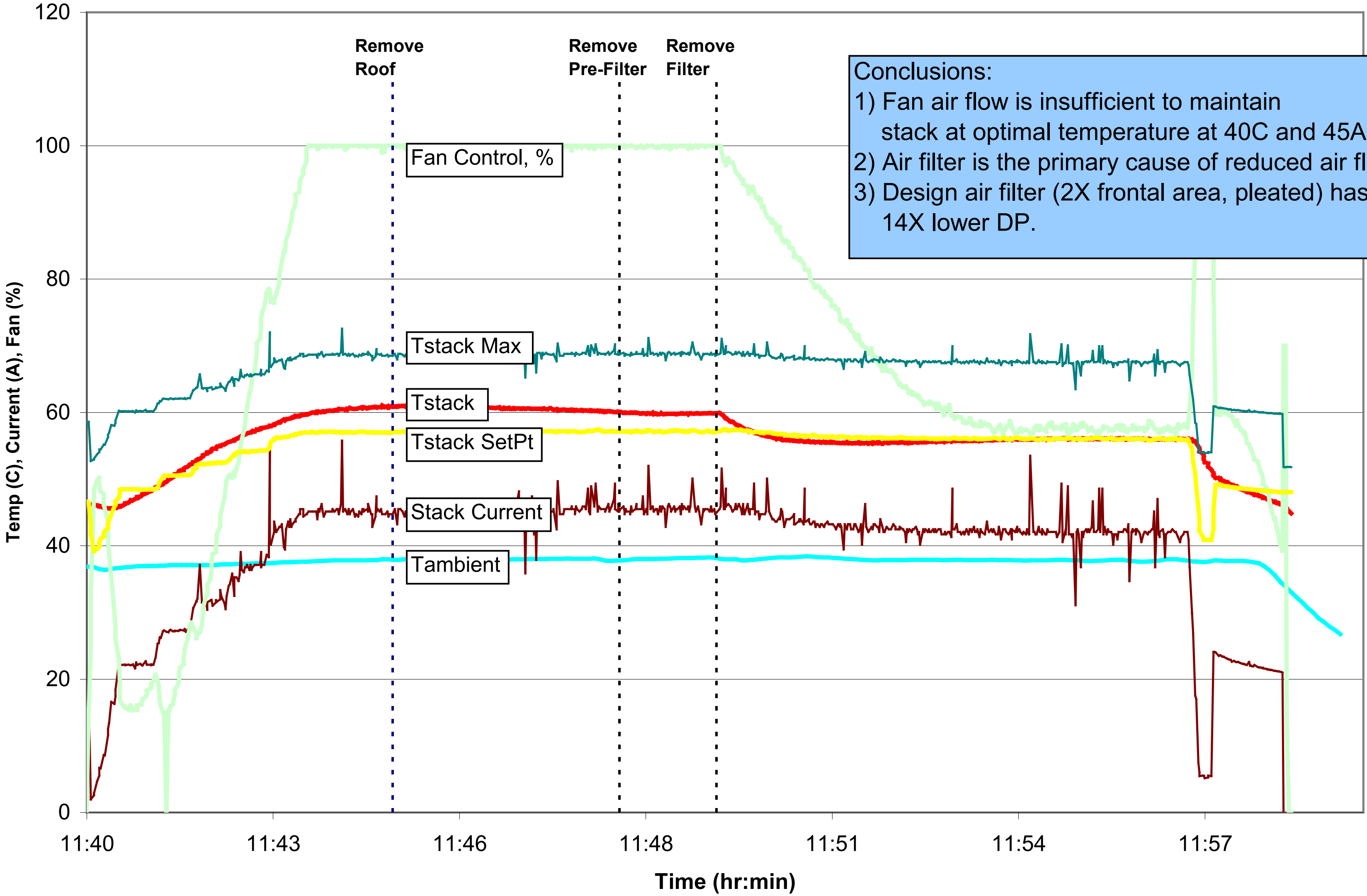


System Freeze Tolerance Testing

- Fully functional system used for Freeze Tolerance Tests
- System Integration of Air Cooled Stack (ACS)
  - Electrical energy storage
  - Thermal management
  - Hydrogen storage
  - System controls development for hybrid operation with system operating strategies from baseline test results
  - Designed for ambient temperature range from -30°C to $+40^{\circ}$C
  - Fan, heater and air recirculation used to control stack temperature
- Integrated system testing performed in Plug Power environmental testing chamber



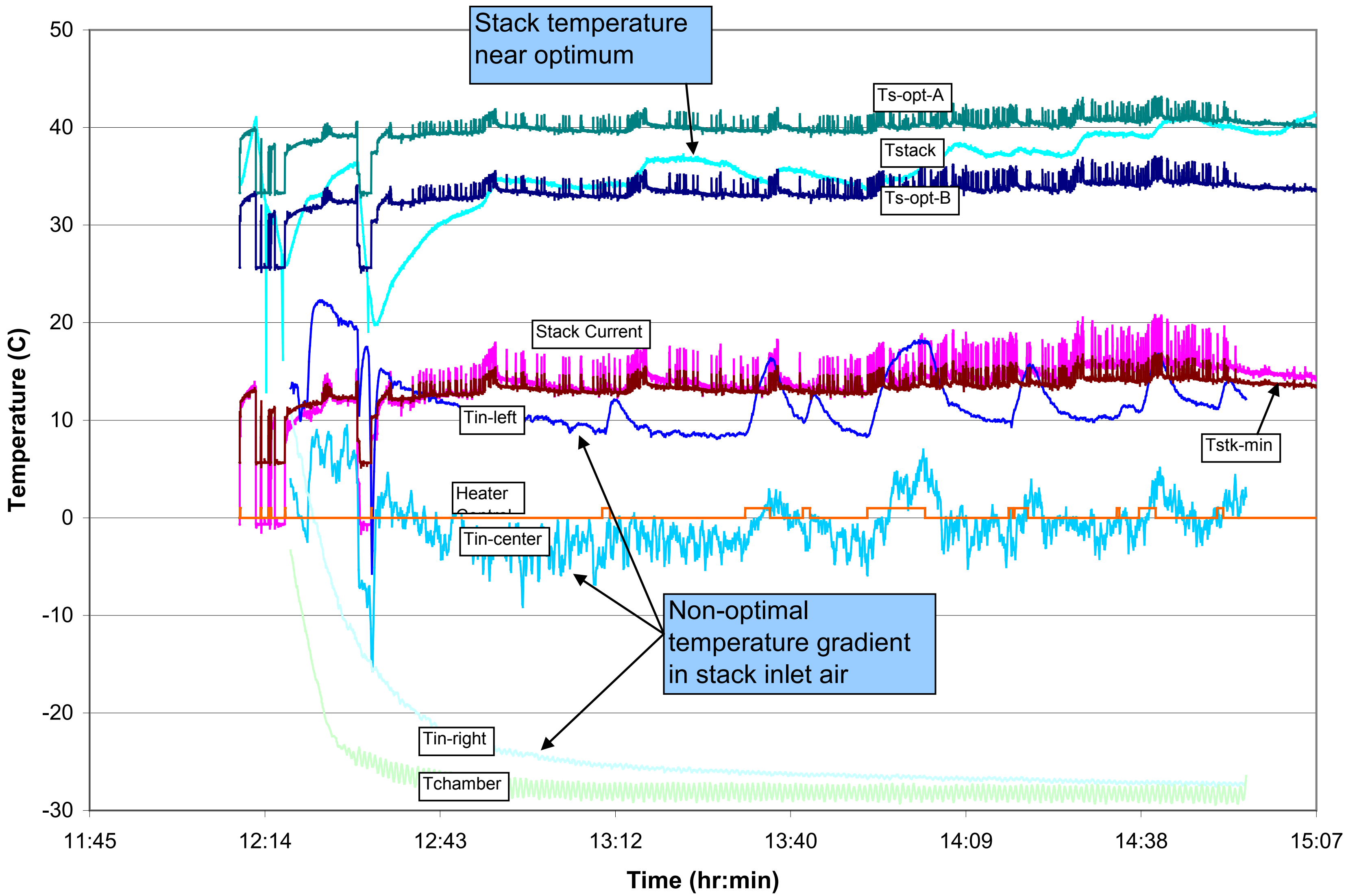
Test Results - ACS Proto System at +40C Ambient



Conclusions:

1) Fan air flow is insufficient to maintain stack at optimal temperature at 40C and 45A
2) Air filter is the primary cause of reduced air flow
3) Design air filter (2X frontal area, pleated) has 14X lower DP.

Test Results - ACS Proto System at -30C Ambient

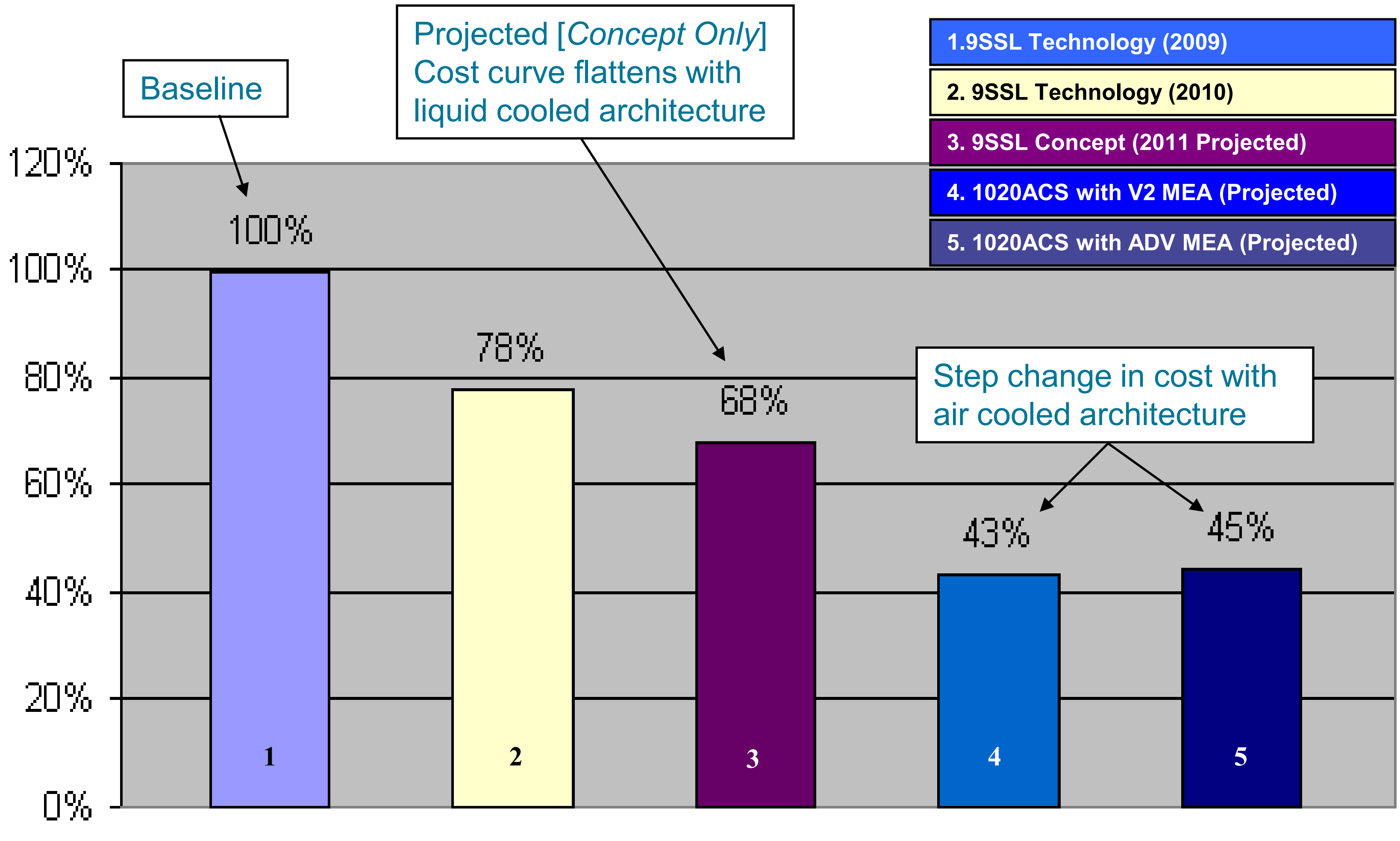


Project Go / No Go Metric Overview

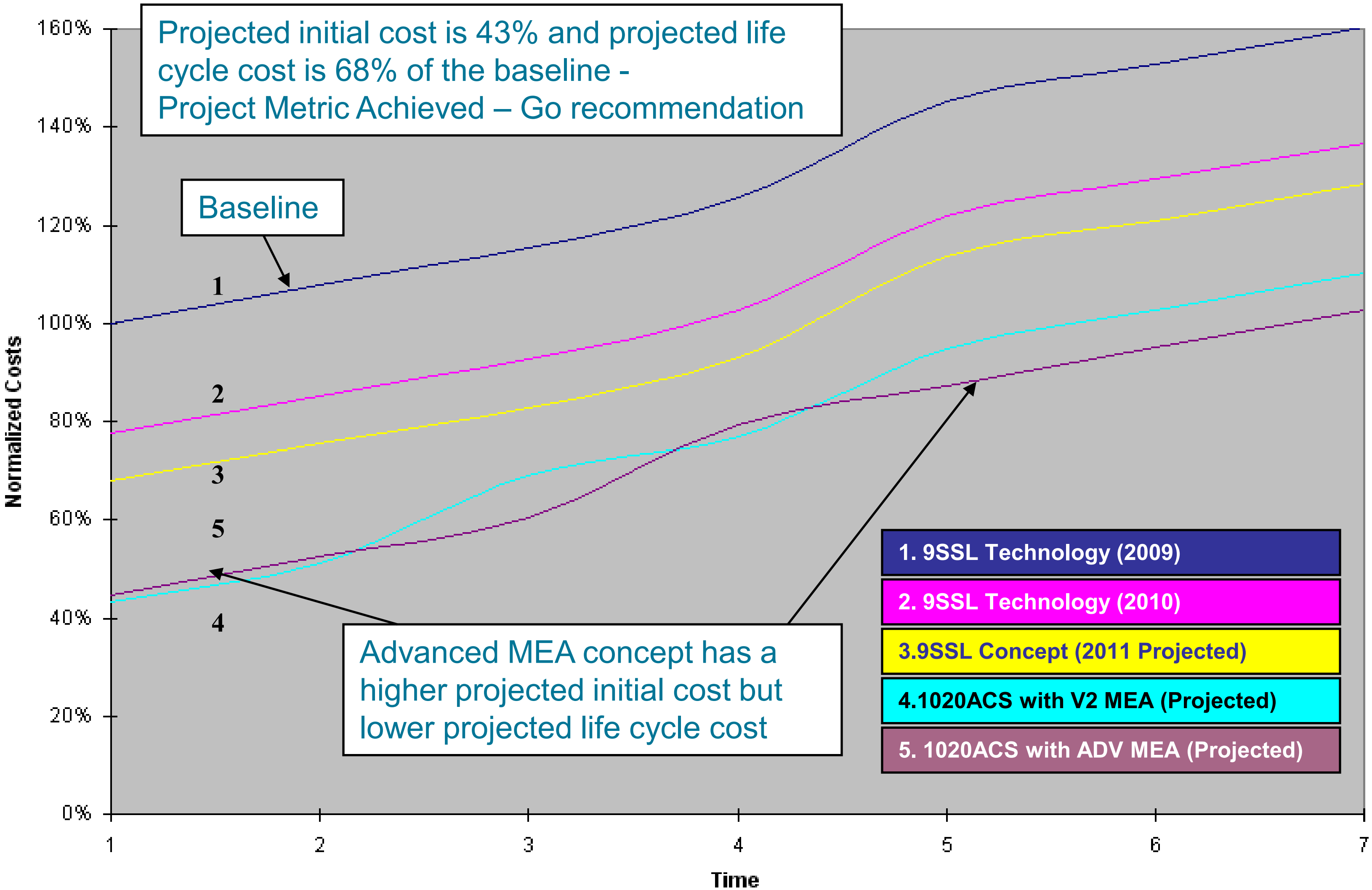
- Go / No Go Metric: GenDrive™ product cost reduction of 25% or greater using an air cooled fuel cell stack (ACS) when compared to 2009 end of year GenDrive™ with a liquid cooled fuel cell stack (9SSL)
  - Inherent to product cost is that the ACS solution must meet minimum performance and durability requirements; specifically 5000 hour durability and sustained operation at -30C ambient
- Both the initial product cost and the product life cycle cost with liquid cooled and air cooled fuel cell stack technology were evaluated
  - Product life cycle cost includes the initial cost, maintenance costs and operating costs
- Product and life cycle costs shown normalized to the baseline product (2009 end of year GenDrive™)

Go / No Go Review held with DOE in December 2010 with recommendation to continue project

Projected Initial Product Cost (Normalized)

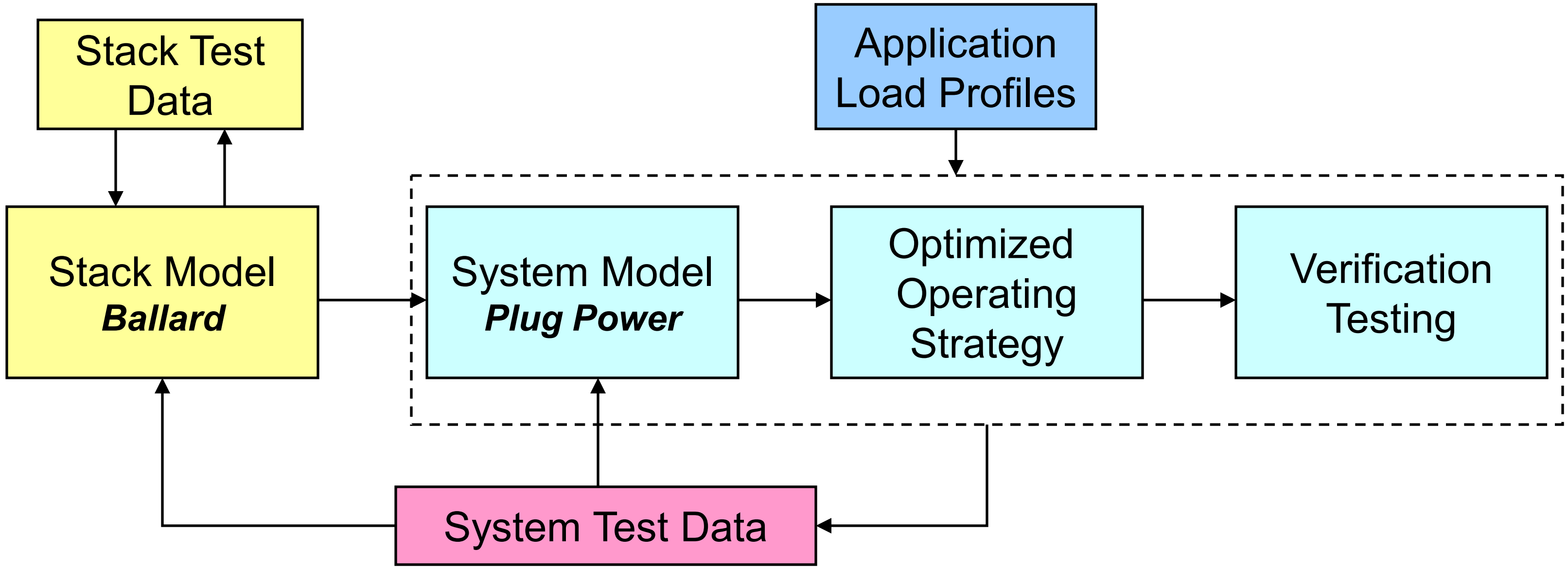


Projected Product Life Cycle Cost (Normalized)



Collaboration

- Modeling and operating strategy collaboration with Ballard Power Systems (subcontract partner)
- Stack model from Ballard / System model from Plug Power
- Models used with actual load profiles to optimize operating strategies to meet performance, efficiency, and durability requirements
- Test data, including degradation rates and failure analysis results, are fed back to improve the model capability



Issues Identified and Future Work

Issue	Proposed Mitigations	Next Steps
ACS durability	- Improve control strategy	- Use analytical system model to optimize operating strategy
Stack temperature at +40C ambient	- Larger pleated filter - Filtration space claim	- Develop low pressure drop particulate and chemical filter
Inlet air temperature gradient	- Heater location - Air recirculation ducting - Ambient air inlet ducting	- Use CFD modeling to optimize air flow and minimize stack inlet air temperature gradients
Moisture condensing and freezing	- Heater location - Air recirculation ducting - Ambient air inlet ducting	- Use CFD modeling to optimize air flow and minimize stack inlet air temperature gradients

Address all issues, build test systems with design mitigations and re-perform tests to verify performance

Summary

- 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 and OCV time
- Sustained operation at -30C possible with system mitigation strategies employed but additional development needed to address temperature gradients and condensing
- Product cost and life cycle cost analysis demonstrates significant lower cost utilizing ACS technology for material handling order picker applications

Technical Back-Up Slides

Feasibility of Air Recirculation

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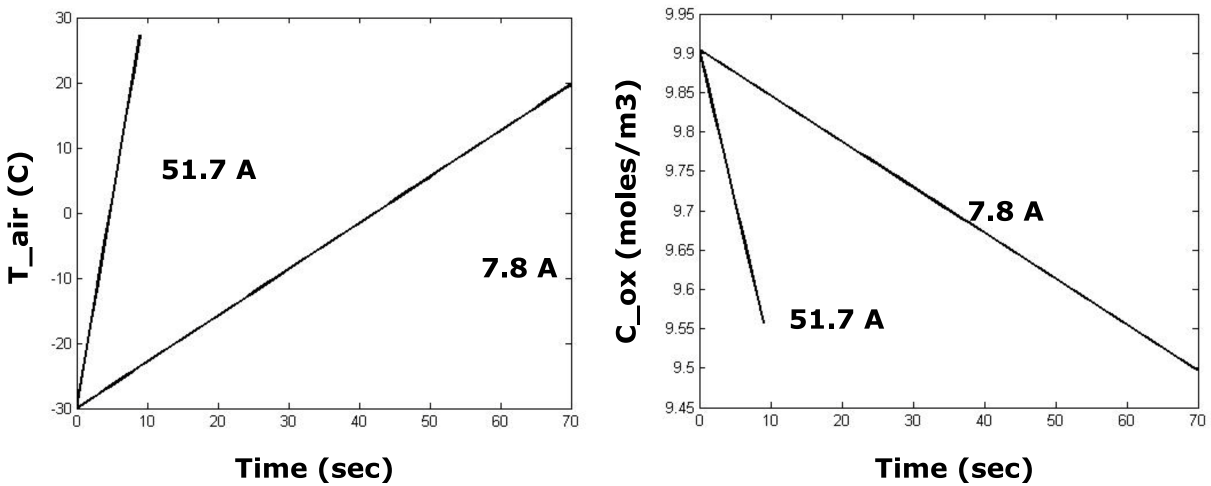
- Modeled air temperature increase versus oxygen consumption for 100% recirculation



- Results show a recirculation concept is feasible, the decrease in O2 concentration is small

Baseline Stack Freeze Results

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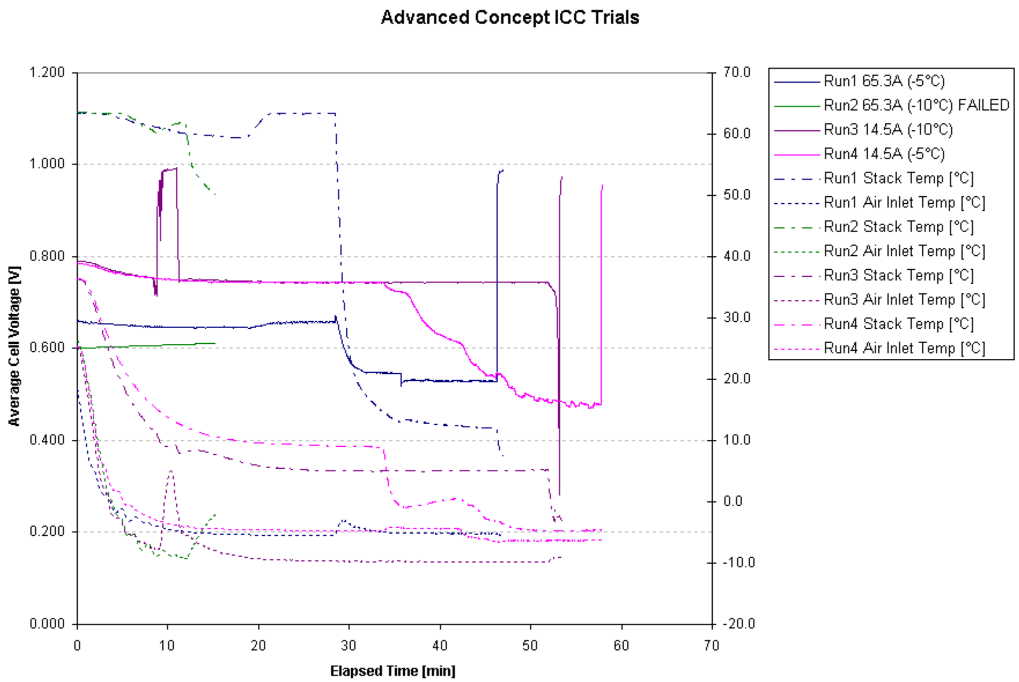
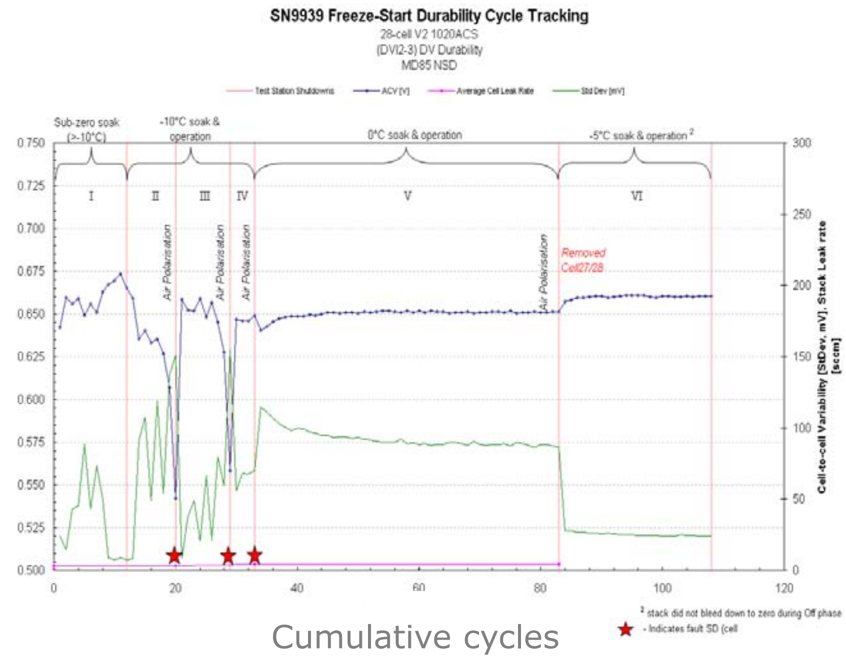
- ACS does not function well in sub-zero conditions due to excessive cooling of the stack
- 110 freeze-start cycles completed, start up variability was an issue
  - Mainly end cells that are colder
- Isothermal constant current testing shows limitations from ice build up when stack is below -10°C





Freeze Failure Analysis Results

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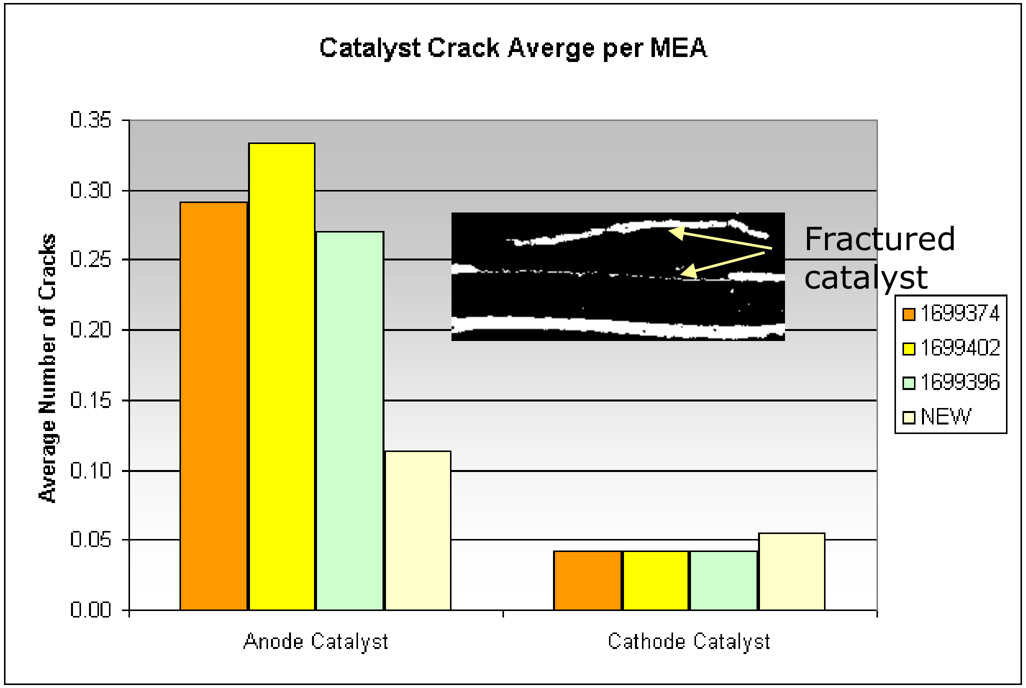
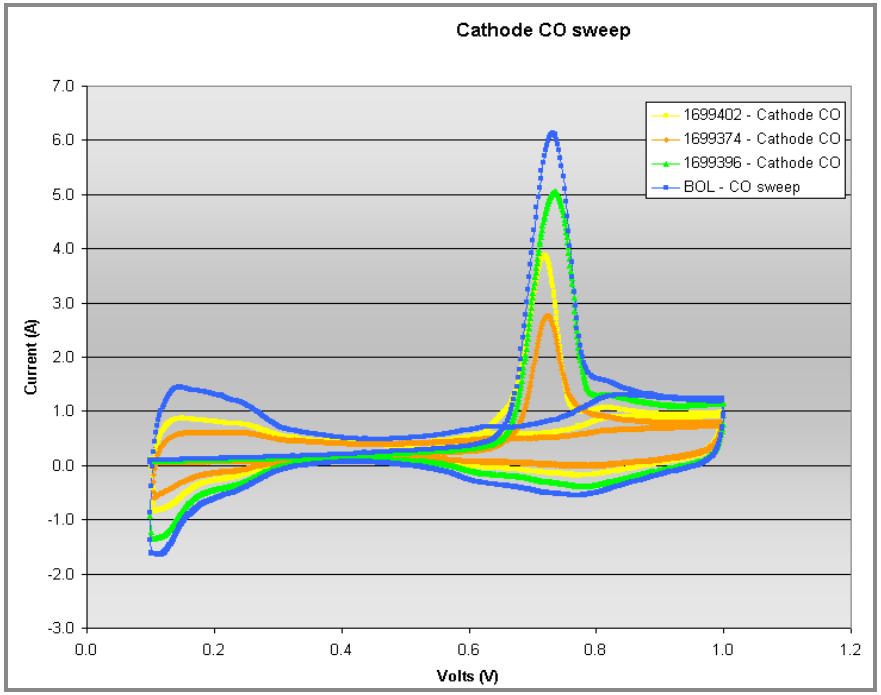
- Membrane thickness, anode catalyst thickness and cathode catalyst cracks not affected by freeze-start
- Increase in anode cracks evident in all MEAs
- End cells showed reduced EPSA





ACS Test Results, Low Ambient T (-15C)