Air Cooled Stack Freeze Tolerance

Project ID: FC025

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Today's Fuel Cells for proven, reliable power.

Overview

Timeline

- Start: June 1, 2009
- Finish: November 15, 2011
- Progress: ***Complete***

Budget

- Total Project Funding: $3.679M
  - **DOE Share: $2.423M**
  - **Plug Power Share: $1.256M (34%)**
- FY 2009 Funding: $0.900M
- FY 2010 Funding: $0.975M
- FY 2011 Funding: $0.548M

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 Objectives / Relevance

- This project addresses critical barriers to fuel cell commercialization by developing a low ***cost*** fuel cell stack and system with 5000 hour ***durability*** and -30^{o}C capable ***performance*** for the near term material handling market
  - Stack and system developed together to meet cost, durability, and freeze tolerance performance requirements
  - No specific DOE technical targets established for material handling application at the time of this project
  - The primary technical target established for this project is based on the cost Go / No Go metric
  - Inherent to the cost metric requirement are minimum performance and durability requirements
  - 2011 project activities focused on validating the 5000 hour durability on next generation MEA designs and validating design mitigation strategies to improve freeze tolerance performance at -30^{o}C ambient temperature
  - Specific project targets and results are presented on the following slide as related to DOE barriers

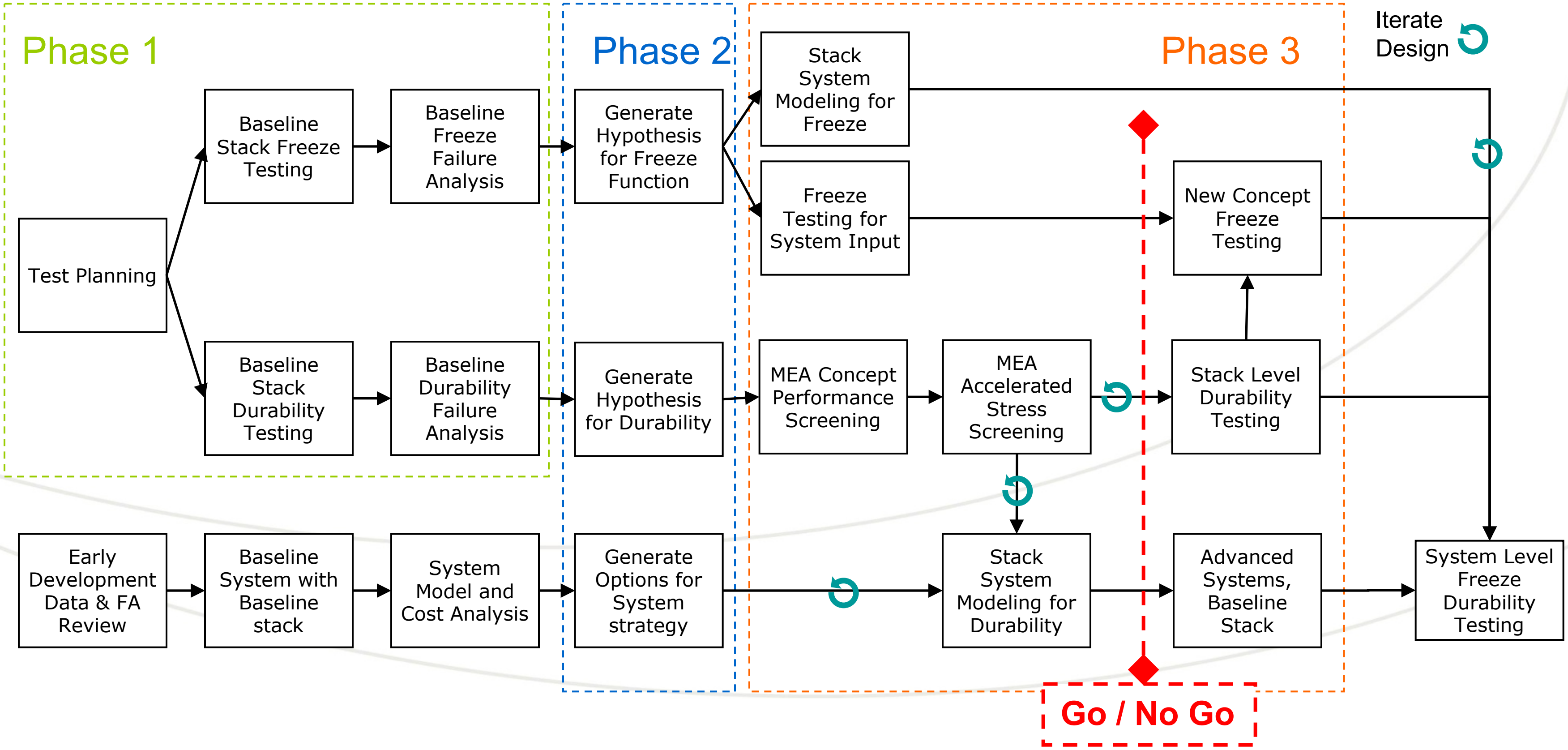
Relevance

Project Targets

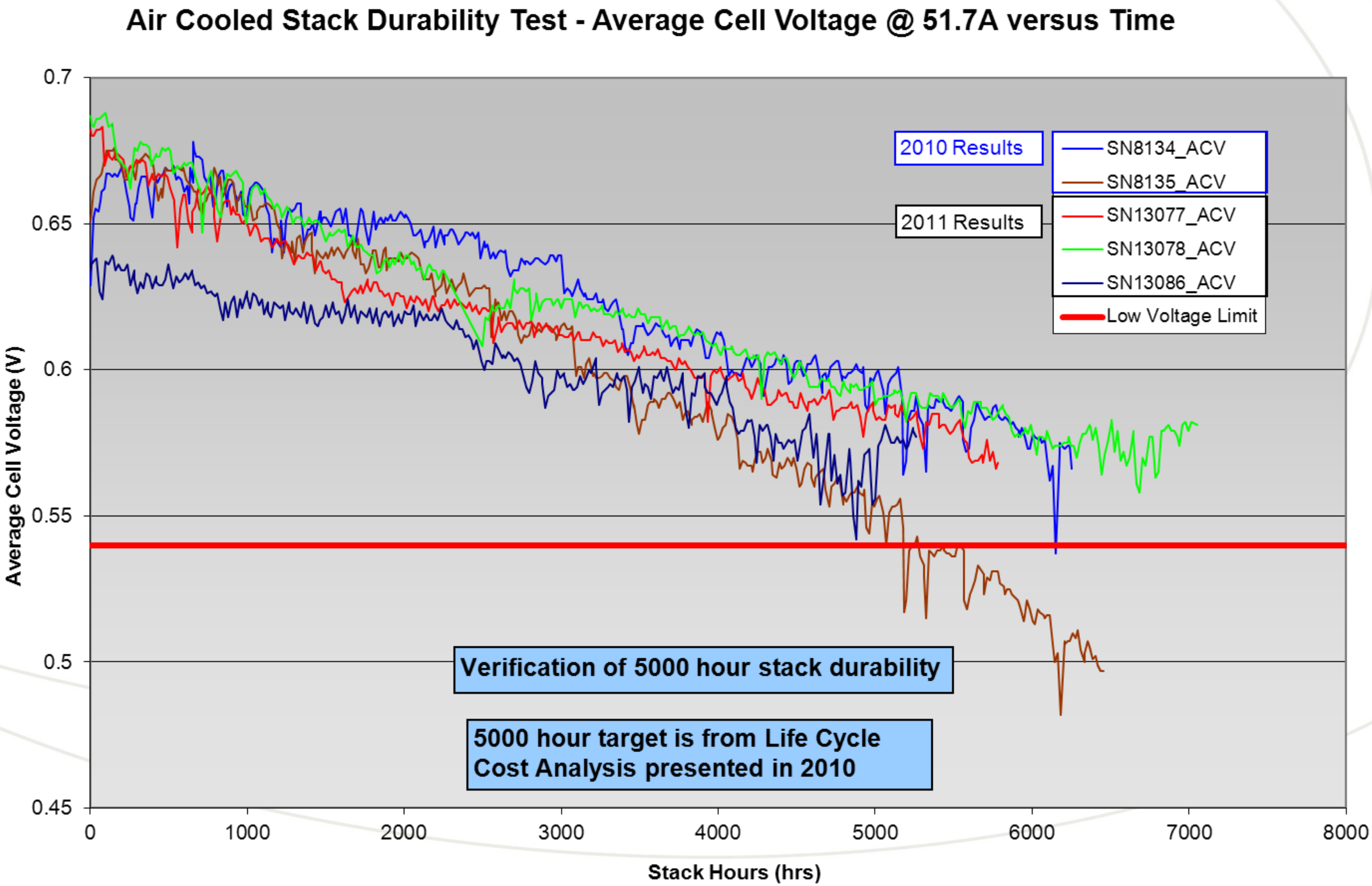
Characteristic *(DOE Barrier)*	Project Target	Project Results
Cost	≥ 25% cost reduction compared to liquid cooled stack solution [while simultaneously meeting the durability and performance targets]	Projected 57% initial product cost reduction and projected 32% product life cycle cost reduction
Durability	5000 hour stack life with >0.54 volts/cell at 51.7 amps	Validated 5000 hour durability on 6 air cooled fuel cell stacks [average durability 5700 hours]
Performance	Sustained operation in -30^{o}C ambient temperature with stack inlet air temperature >0^{o}C and stack temperature gradient <10^{o}C	Designed and validated sustained operation at -30^{o}C ambient temperature; stack inlet temperature >2^{o}C and stack temperature gradient <6^{o}C

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

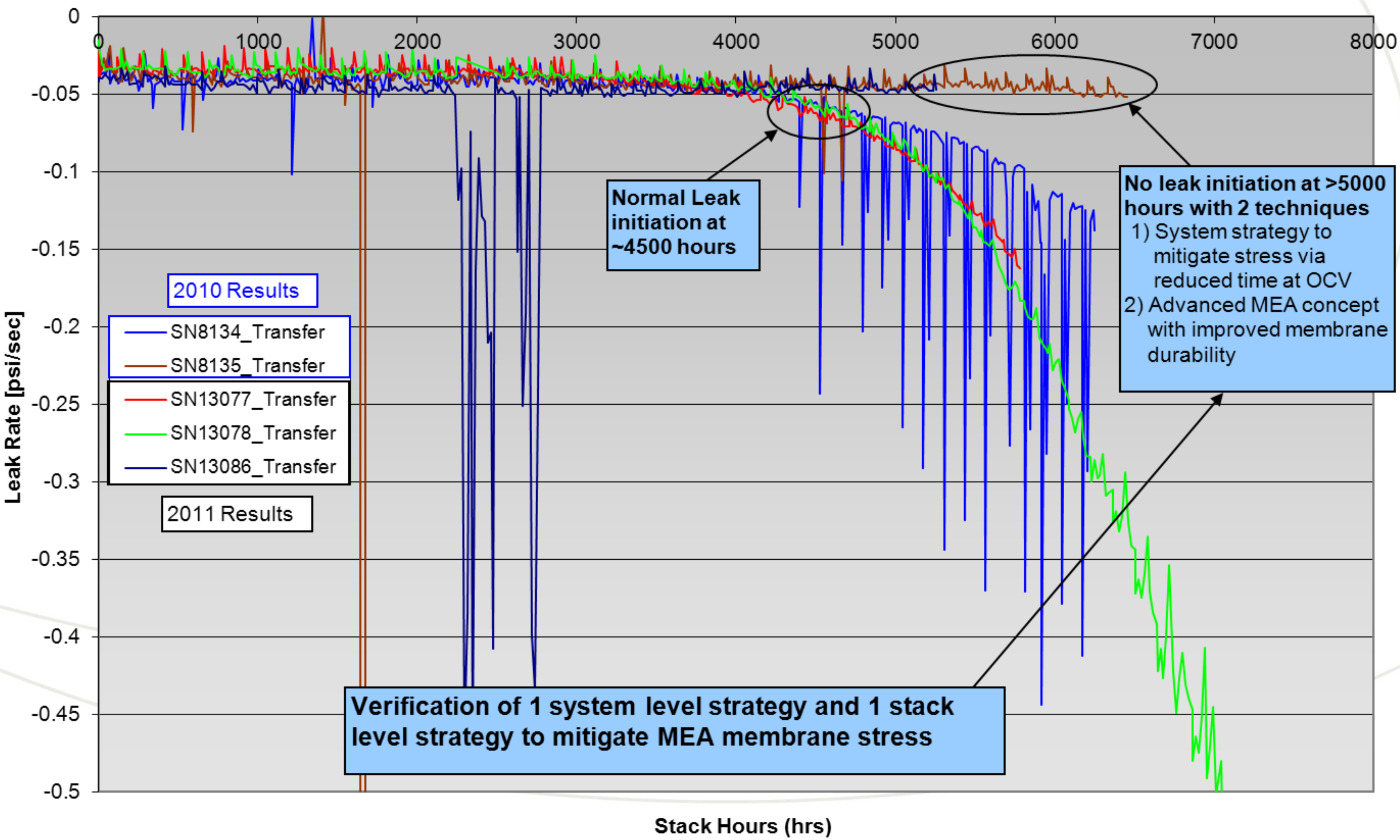


Technical Accomplishments and Progress

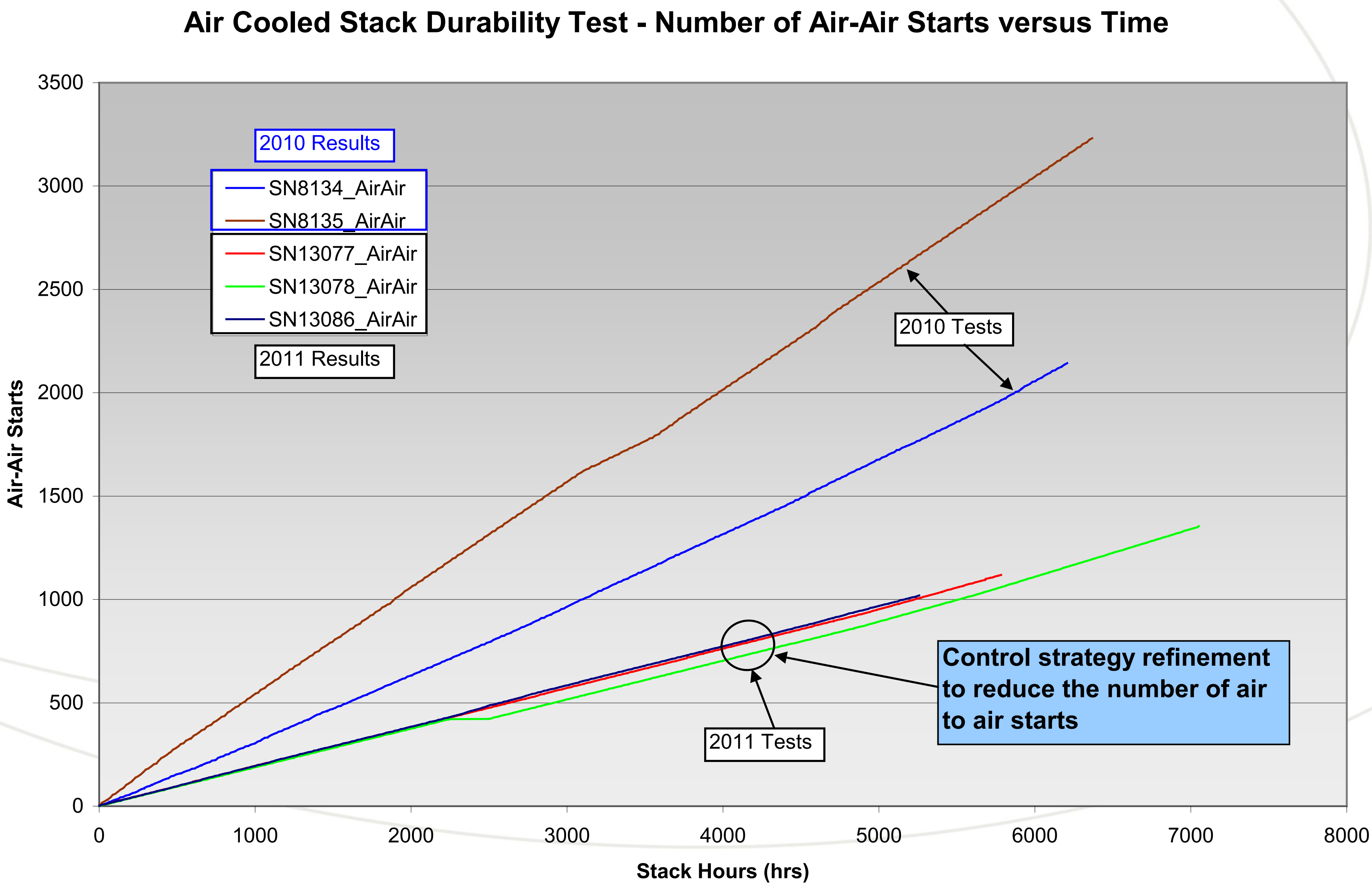


Technical Accomplishments and Progress

Air Cooled Stack Durability Test - Transfer Leak Rate versus Time



Technical Accomplishments and Progress



Stack Durability Test Summary

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 2010
SN8135	36	V1	6456	3275	-27.1	-15.0	No	Finished 2010
SN13077	36	V2	5785	1119	-16.8	-12.0	Yes	Finished 2011
SN13078	36	V2	7054	1354	-15.6	-12.3	Yes	Finished 2011
SN13086	36	V2-A	5261	1019	-13.3	-6.9	No	Finished 2011

MEA Version Description

- V1 – baseline (original) Ballard Air Cooled Stack MEA
- V2 – baseline MEA with improvements to cathode catalyst to mitigate corrosion
- V2-A – V2 MEA with improvement to membrane to mitigate transfer leak

Technical Accomplishments and Progress

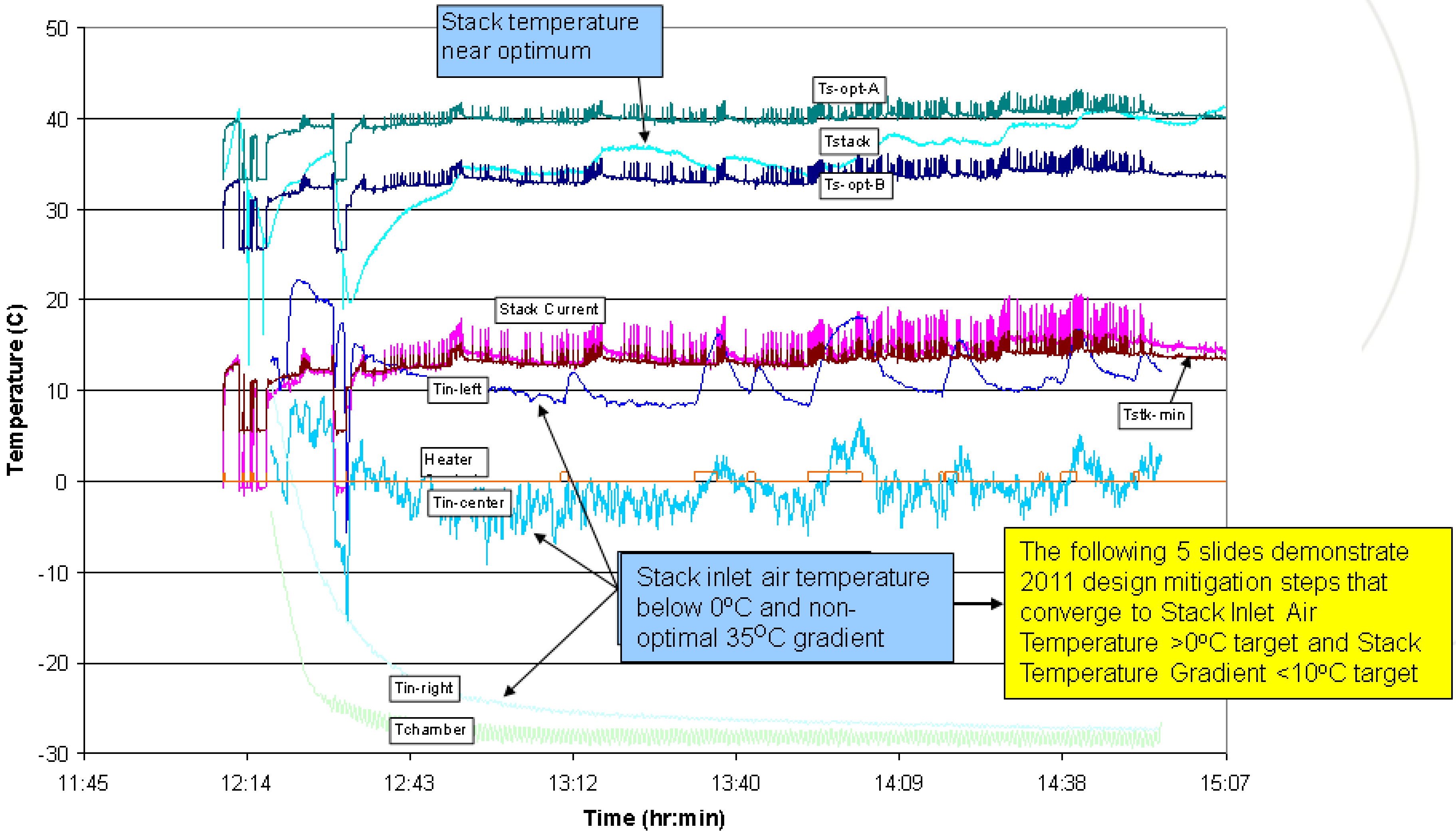
Mitigation Activities

Project effort in 2011 focused on design mitigation activities to address issues found in prior project phases

Issue from Phase 3 tests	Proposed Mitigations - 2010 Go / No Go	Actual Mitigation - 2011
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

Technical Accomplishments and Progress – from 2010 shown for comparison (to following 5 slides)

Original Test Results at -30°C Ambient - 2010



Technical Accomplishments and Progress

Air Recirculation CFD Model for -30°C Ambient - initial duct modeling

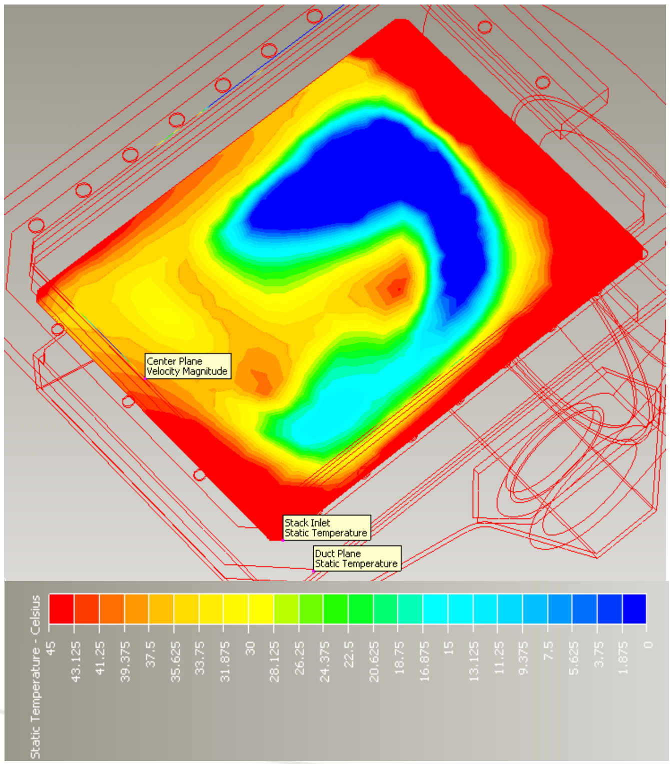


Figure 1: Air Temperature Profile at stack inlet – initial duct modeling

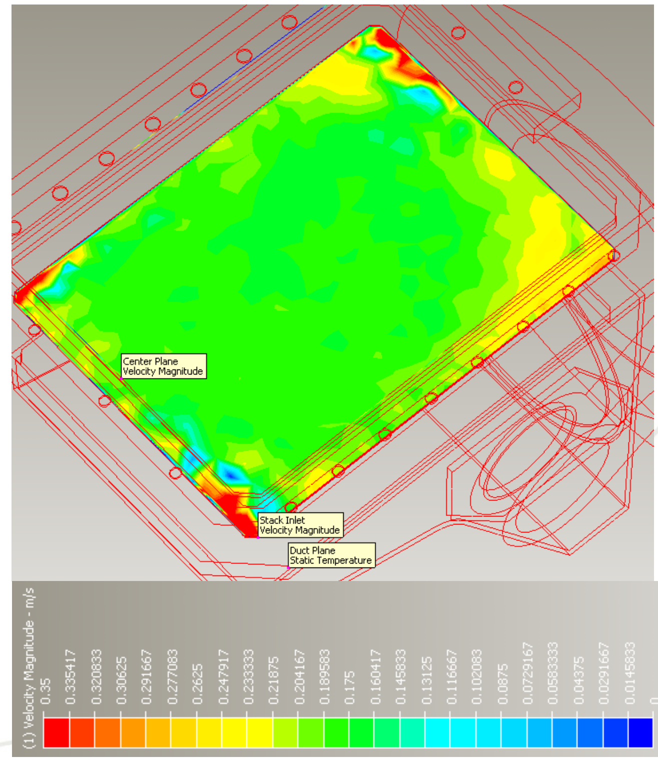


Figure 2: Air Velocity Profile at stack inlet – initial duct modeling

Initial concept had 25% variance in velocity profile and 45°C temperature variation

Technical Accomplishments and Progress

Air Recirculation CFD Model for -30°C Ambient - refined duct modeling

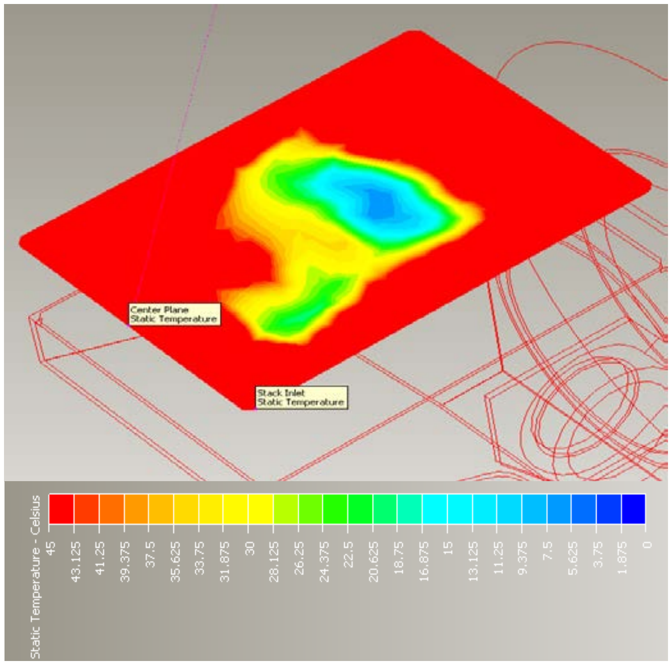


Figure 3: Air Temperature Profile at stack inlet – air duct refinements

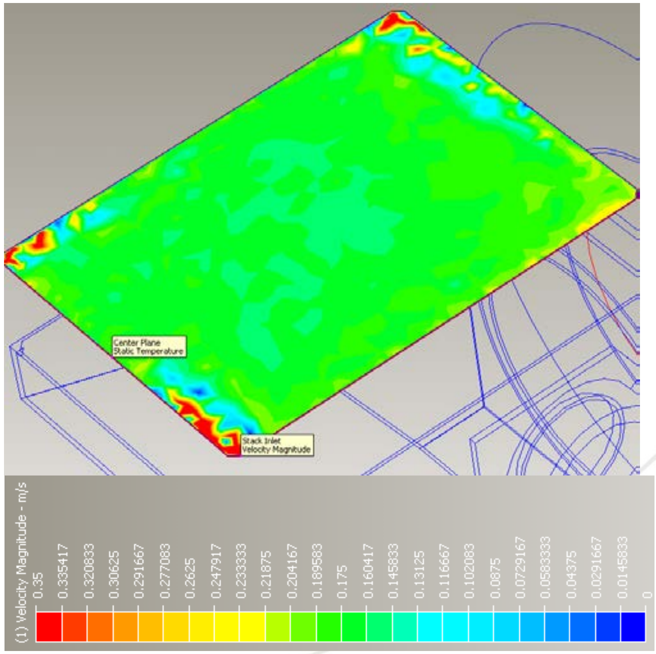
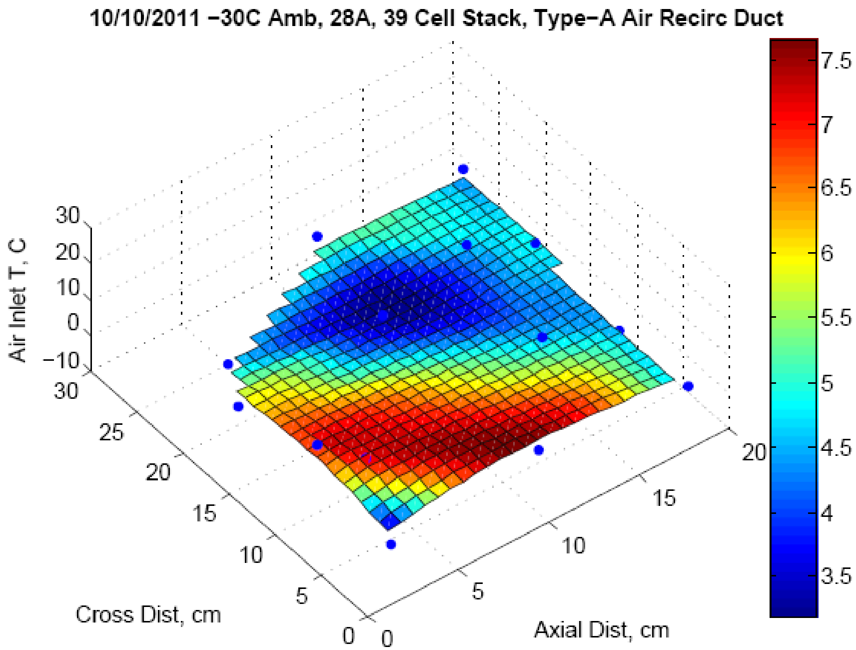


Figure 4: Air Velocity Profile at stack inlet – air duct refinements

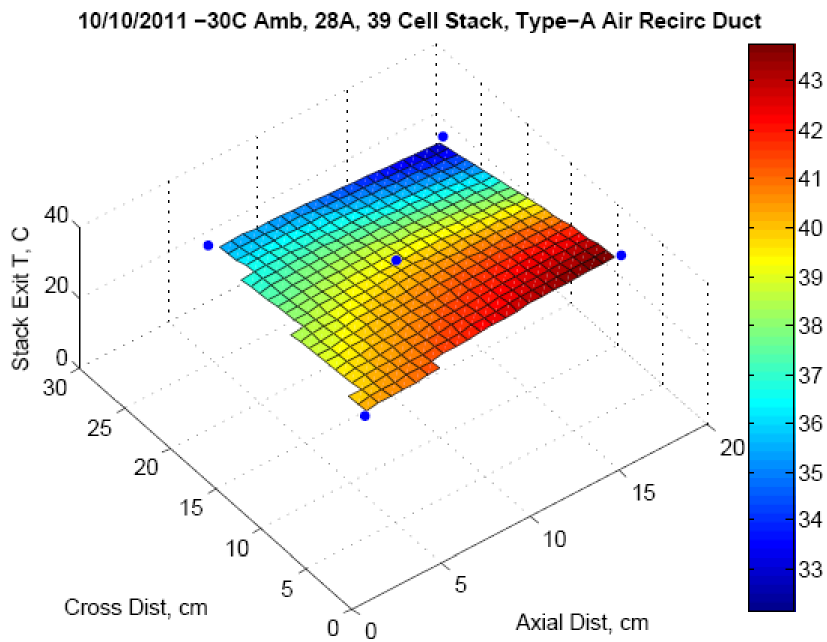
Refined concept 15% variance in velocity profile and 20°C temperature variation

Air Recirculation Test Results at -30°C Ambient Temperature - Instrumented Stack Module, Medium Power Condition

Inlet Air Temperature above 0°C target and Stack Temperature within 10°C gradient target



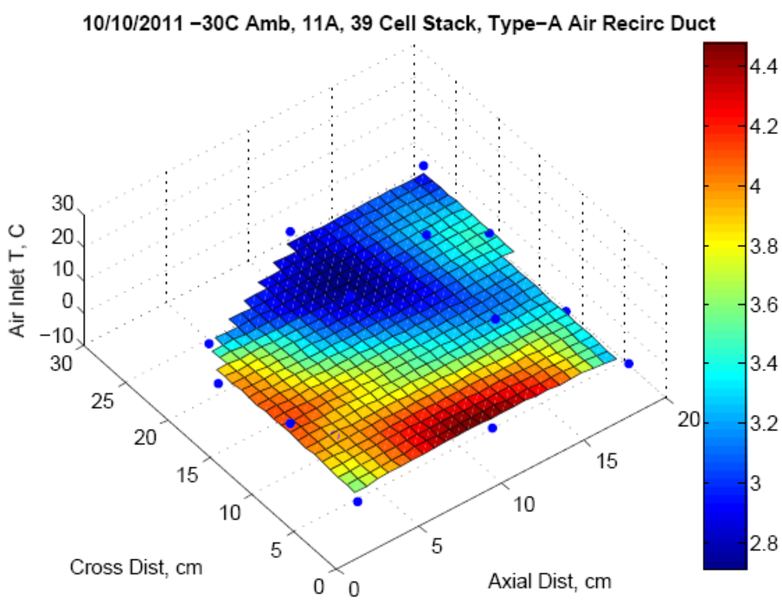
3.5 to 7.5C inlet air T



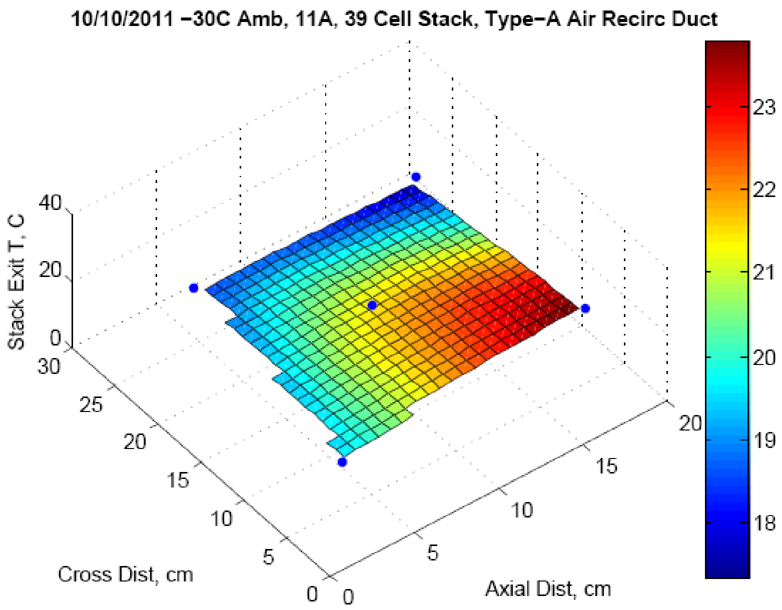
33 to 43C stack T

Air Recirculation Test Results at -30°C Ambient Temperature - Instrumented Stack Module, Idle Condition (worst case)

Inlet Air Temperature above 0°C target and Stack Temperature within 10°C gradient target



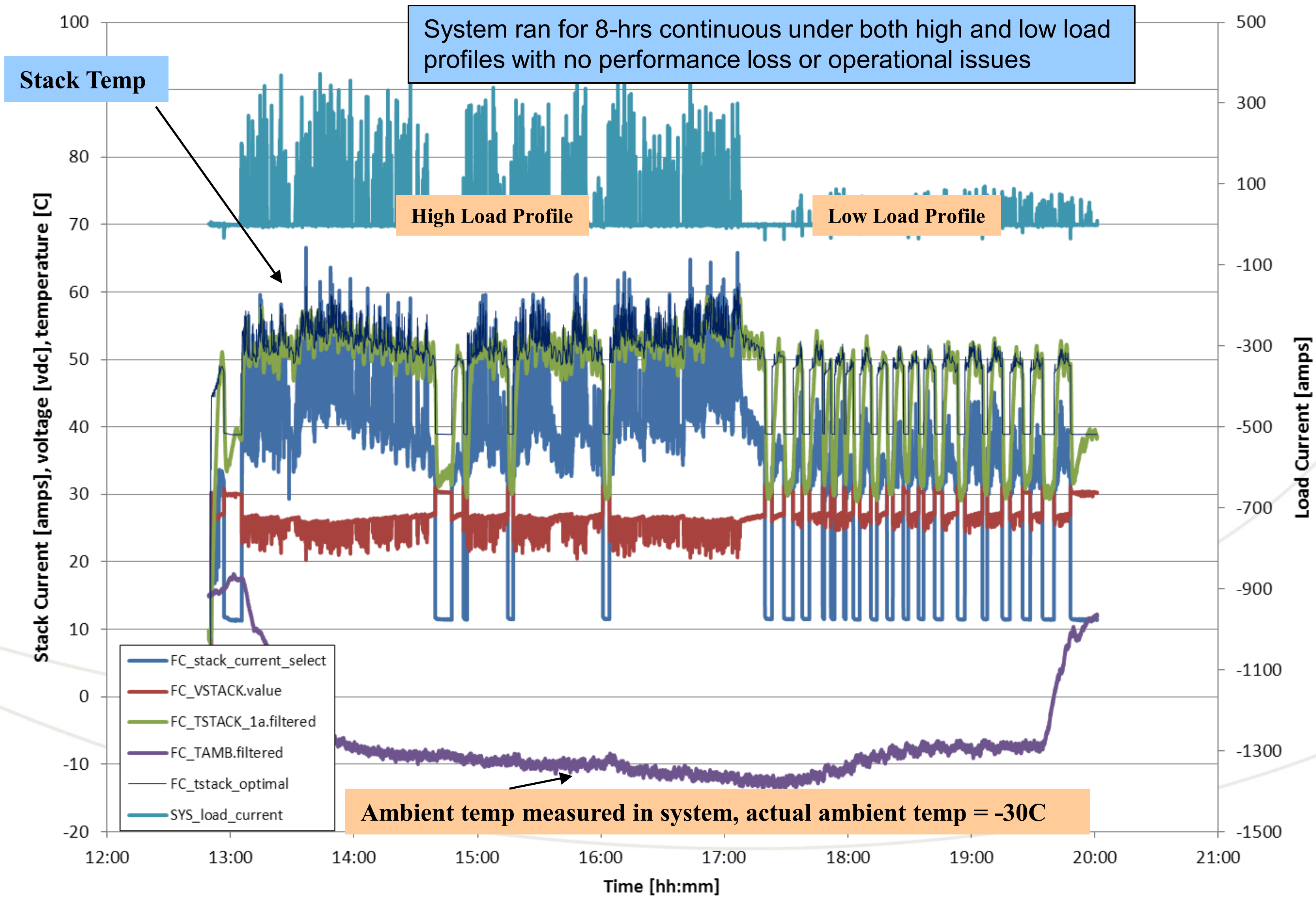
3 to 4.5C inlet air T



18 to 23C stack T

Technical Accomplishments and Progress

Low Ambient Temperature System Test Results

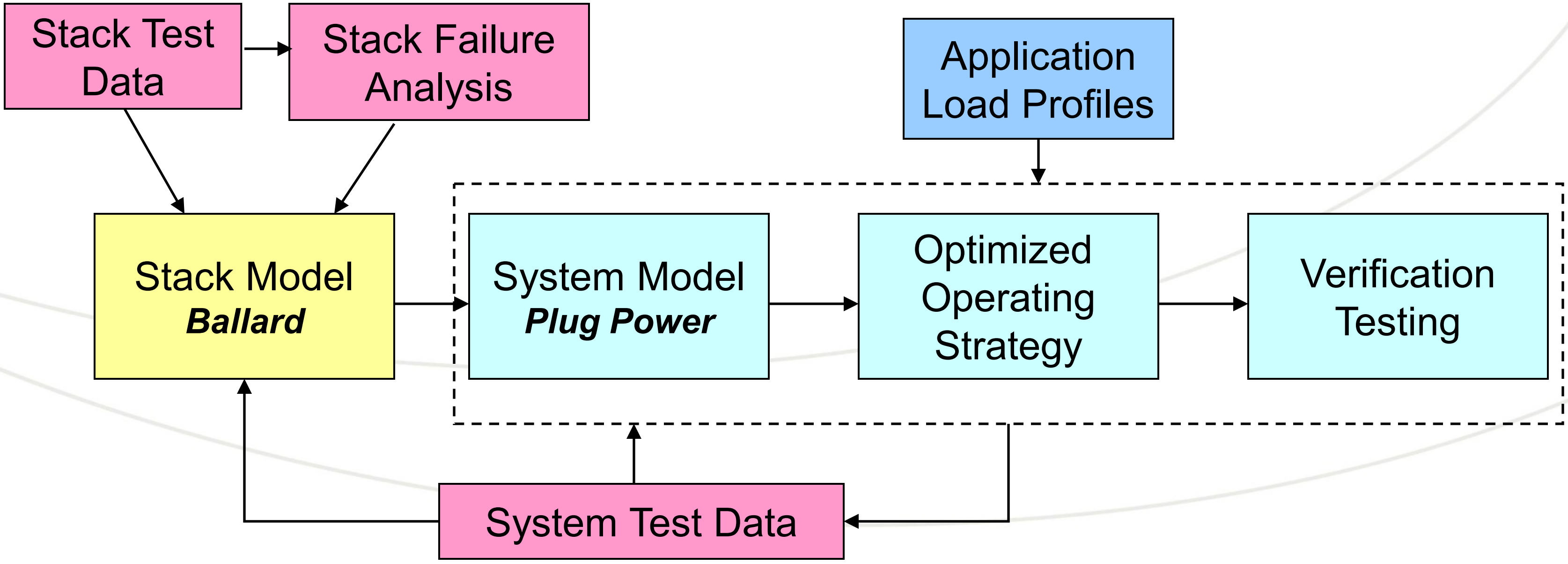


Next Generation Order Picker from Plug Power

- Announced in October 2011 and based on the technology developed over the course of this 2 year project with the DOE
- Shipped over 100 units to at least 4 customers in Q4 2011 and have received positive customer feedback
- Units can operate in a freezer environment; operating range -30^{o}C to +40^{o}C

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



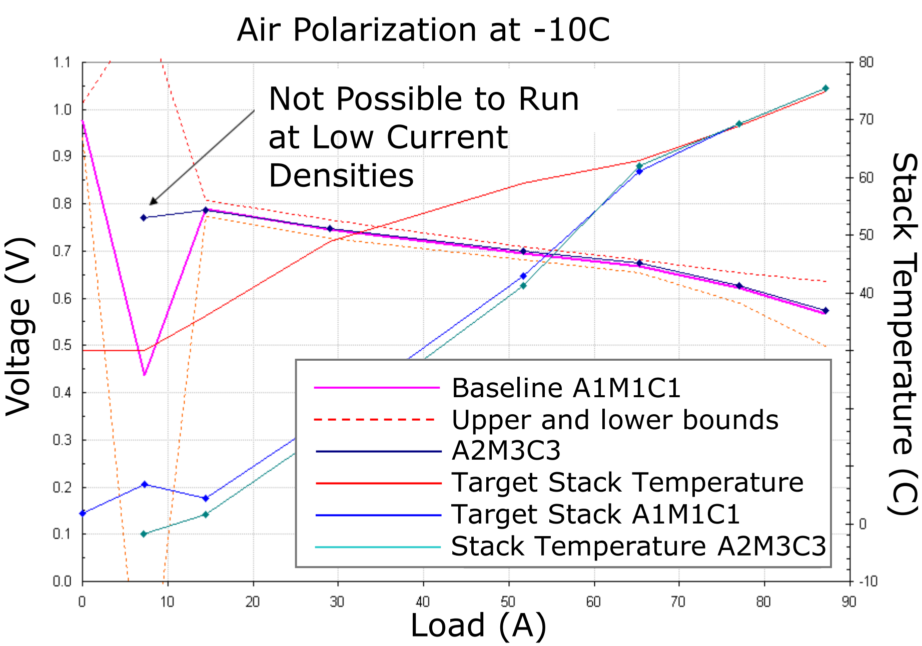
Summary

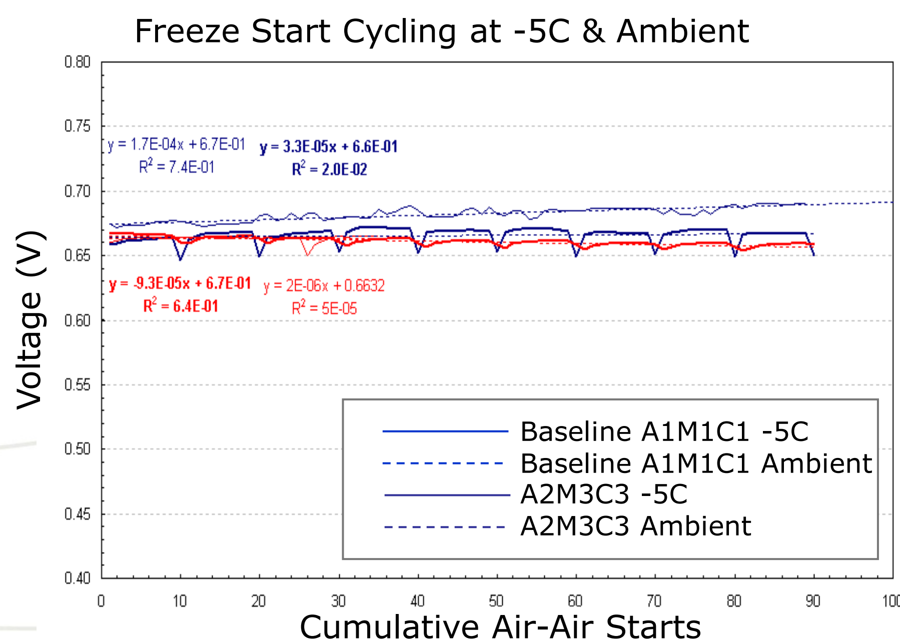
- Dominant failure modes related to catalyst and membrane degradation
  - Dissolution and carbon corrosion during air-air starts, membrane degradation during OCV
  - Two MEA designs show reduced degradation in lab testing, new materials mitigate dissolution, corrosion and membrane leaks
- 5000 hour durability target met using operating strategies to reduce stressors
  - 5000 hour durability target: >0.54 volts/cell at 51.7 amps current draw
  - Mitigate failure modes related to air-air starts and OCV time with both MEA improvements and system operating strategies
  - AST's and models used to define system operating strategies for extended lifetime
- Freeze tolerance designed into the FC system, capable of -30°C operation
  - Freeze capable stack technology more expensive than freeze prevention at system level
  - Minimal degradation seen from freeze start-ups from -10°C, below -10°C the stack had issues with consecutive freeze start-ups
  - Stack thermal model identified inlet heaters and cathode recirculation as design mitigations
  - CFD modeling used to minimize the inlet air temperature gradient and eliminate freezing of recirculation air as observed in the original tests
  - Sustained operation at -30°C possible with system mitigation strategies employed
- Projected initial product cost reduced by 57% and life cycle cost reduced by 32% utilizing ACS technology for material handling order picker applications by compared to the incumbent liquid cooled stack solution

Technical Back-Up Slides

Air-Cooled Stack Freeze Test Results

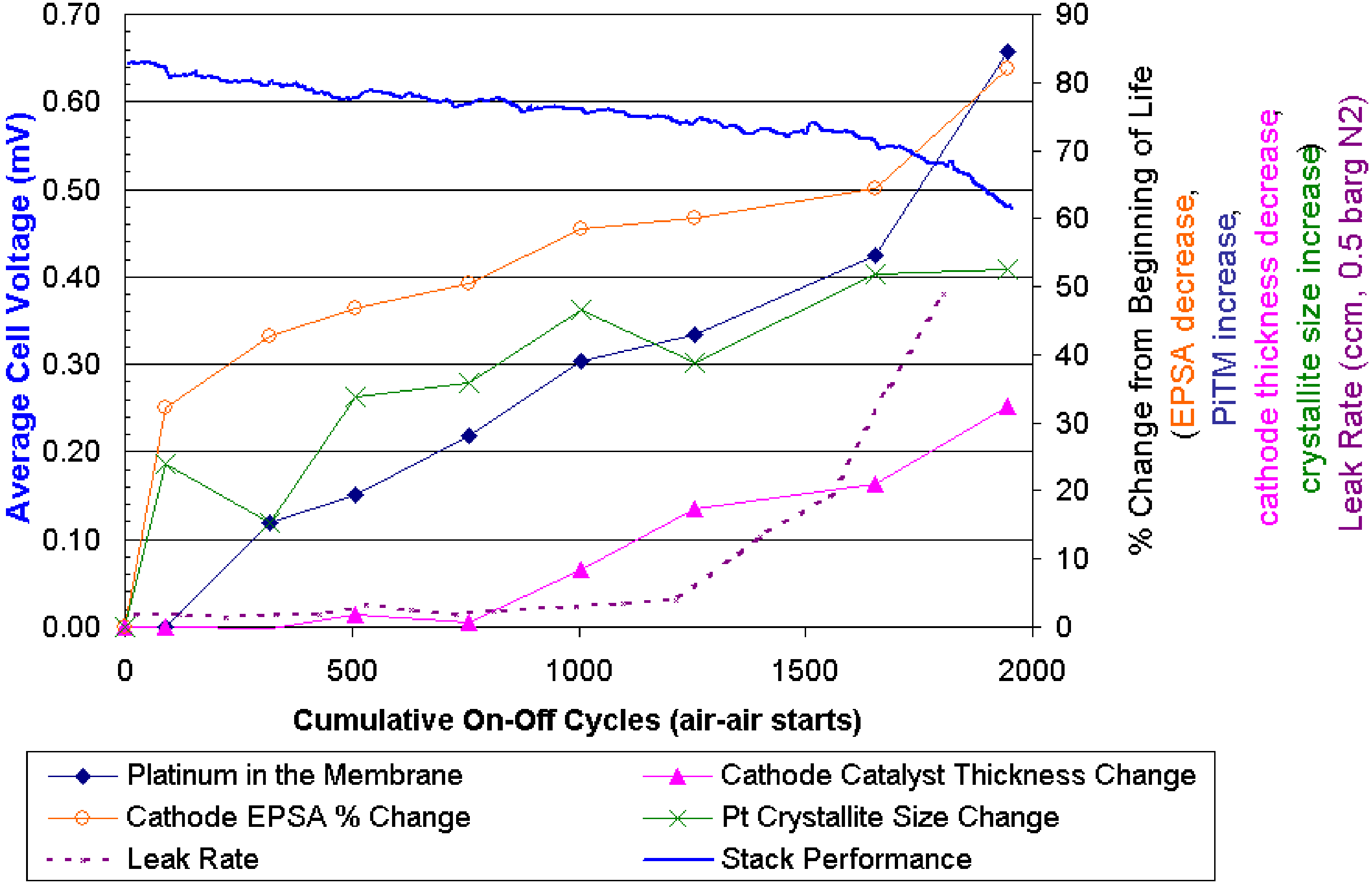
- ACS has functional limitations in environments below -10°C
  - Excessive stack cooling and low ambient RH are main causes
  - Below -10°C start-up resulted in variability and catalyst damage
  - Due to membrane resistance and ice accumulation in the catalyst layer
- Freeze durability cycling @ -5°C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





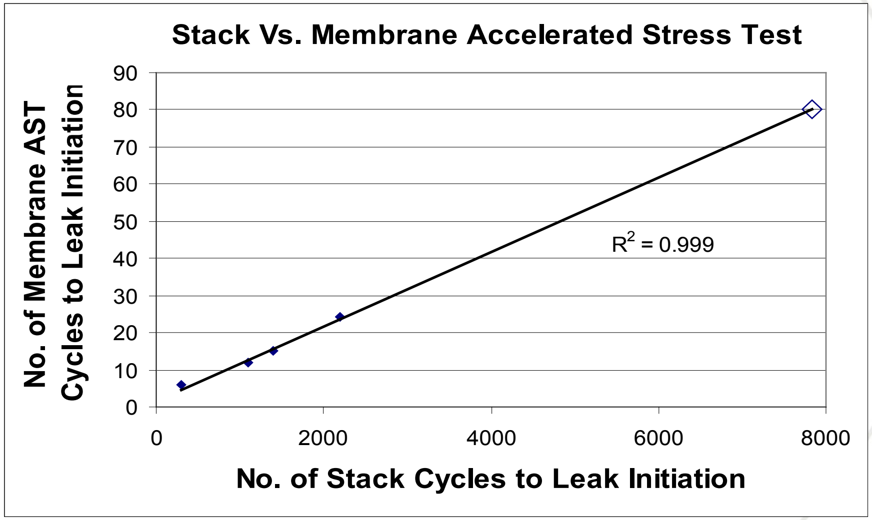
Define Baseline Stack Degradation Modes

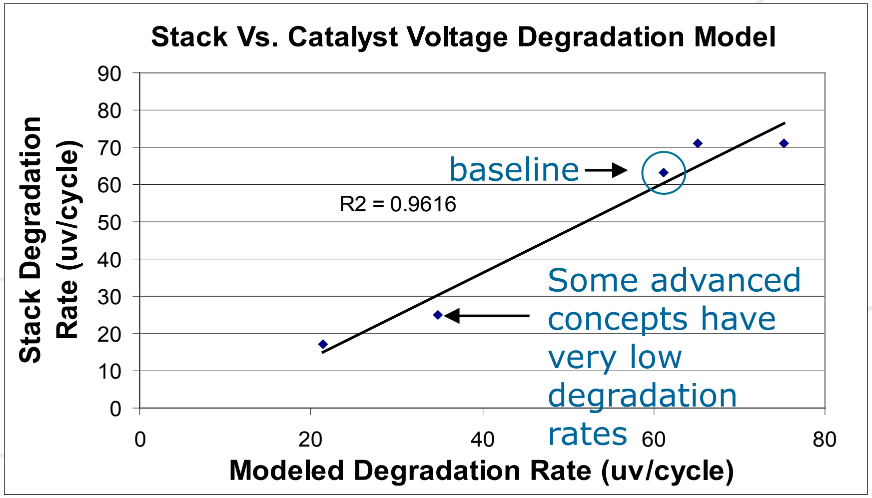
Failure analysis identified membrane leaks causing corrosion and platinum dissolution to be the dominant failure modes



Screening with ASTs & Stack Durability Models

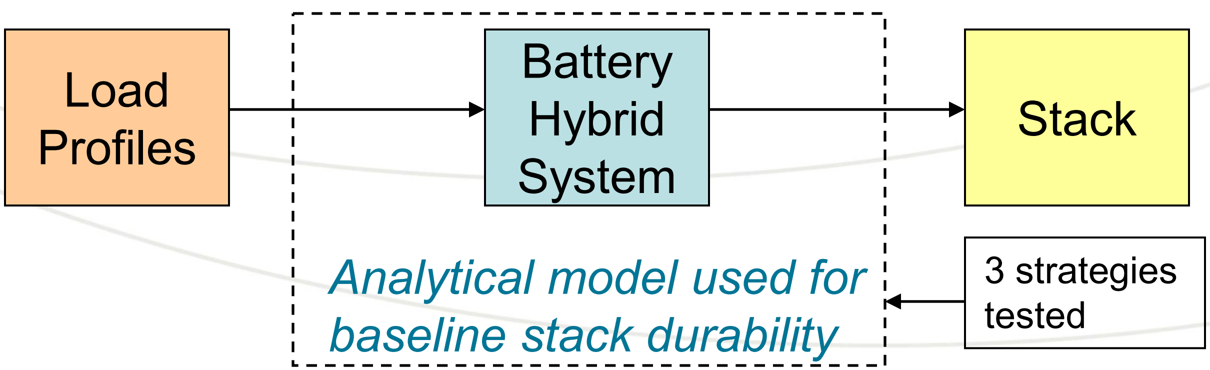
- Guided by failure analysis results, seek components that offer improved resistance to leaks, corrosion and platinum dissolution
- Membrane AST and time to leak initiation during stack durability testing follow linear trend
- Semi-empirical voltage degradation model exhibits a linear trend with stack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



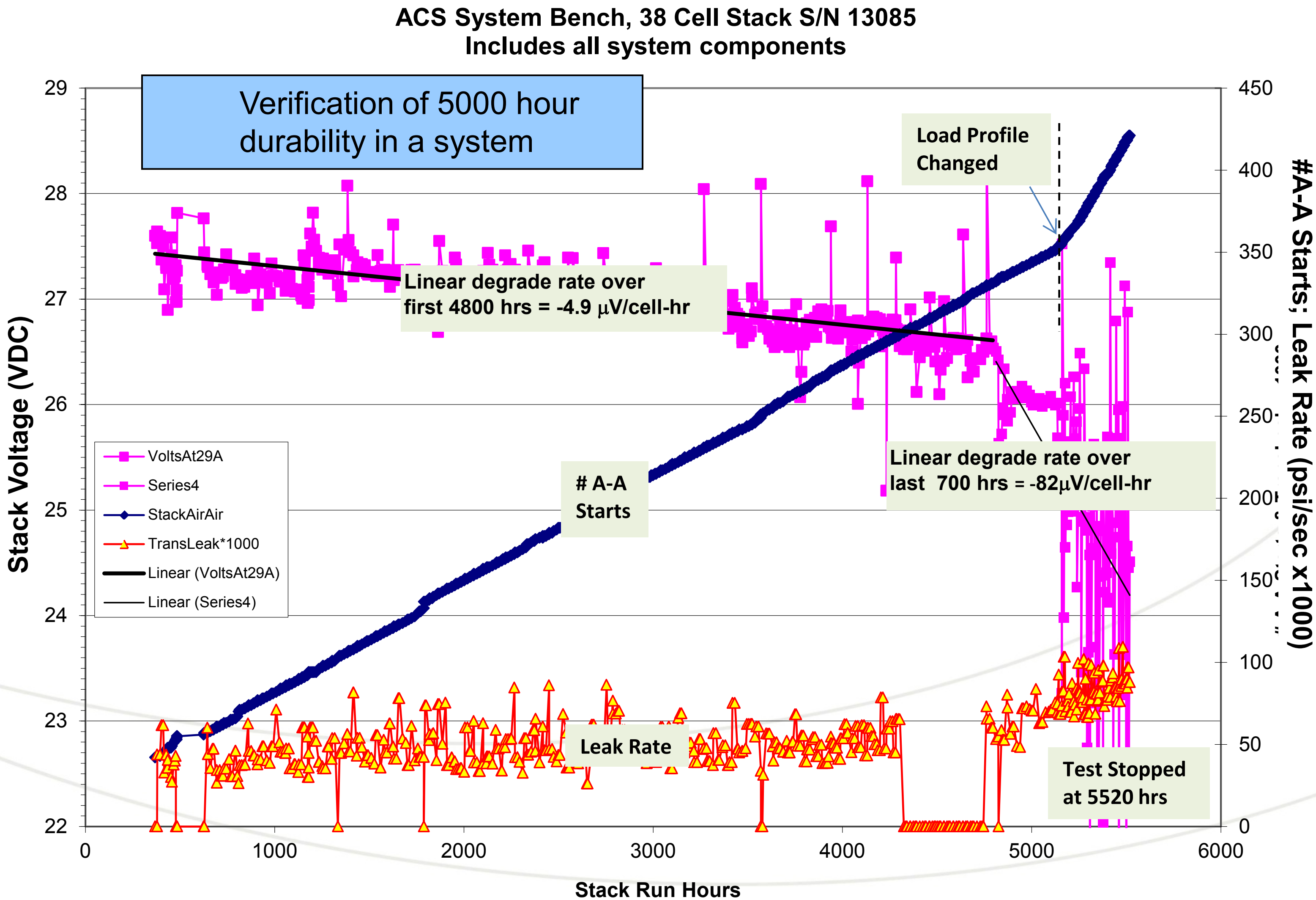


System Operating Strategy Development

- 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



System Bench Test Results



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