Plug Power DOE Topic 4B Project
1020 Air-Cooled Stack Freeze Tolerance

Project ID: FC025
Dave Hancock, Program Manager
June 9, 2010

Project Overview

Timeline

- Start: June 1, 2009
- Finish: March 31, 2011
- Progress: 40% complete

Barriers

- >25% GenDrive cost reduction with air cooled stack
- Achieve ~5000 hours and ~1500 on/off cycles with ACS
- Freeze tolerant operation with air cooled stack technology

Budget

- DOE: $2.42 million
- Cost-share: $1.26 million (34%)
- FY 2009 funding: $0.77 million
- FY 2010 funding: $1.41 million

Partners

- Plug Power – Program and GenDrive project manager
- Ballard Power Systems – 1020 air-cooled stack project manager
  - Cara Startek
- NIST Neutron Imaging Facility – Freeze failure mode diagnostics
  - Dr. Muhammad Arif

Relevance

- The mission of the hydrogen program is to reduce petroleum use, greenhouse gas emissions, and air pollution and to contribute to a more diverse and efficient energy infrastructure by enabling the widespread commercialization of hydrogen and fuel cell technologies. The program's key goals are to advance these technologies—through research, development and validation efforts—to be competitive with current technologies in cost and performance, and to reduce the institutional and market barriers to their commercialization.
- Advance the state-of-the-art for air-cooled stack technology
  - Determine stack failure modes and root causes
  - Develop baseline understanding for freeze tolerance
  - Validate mitigation strategies for failure mode root causes
  - Validate design improvements to improve freeze tolerance
- Test and evaluate air-cooled stacks and components developed for increased freeze tolerance and durability
- Evaluate failure mechanism mitigation in stack and/or system design
- Perform life-cycle cost analyses for freeze tolerance strategies
- Document and publish summary of stack freeze failure analyses

Freeze Capability Levels & Technology Status

Status of existing air cooled stack technology

Topic 4b

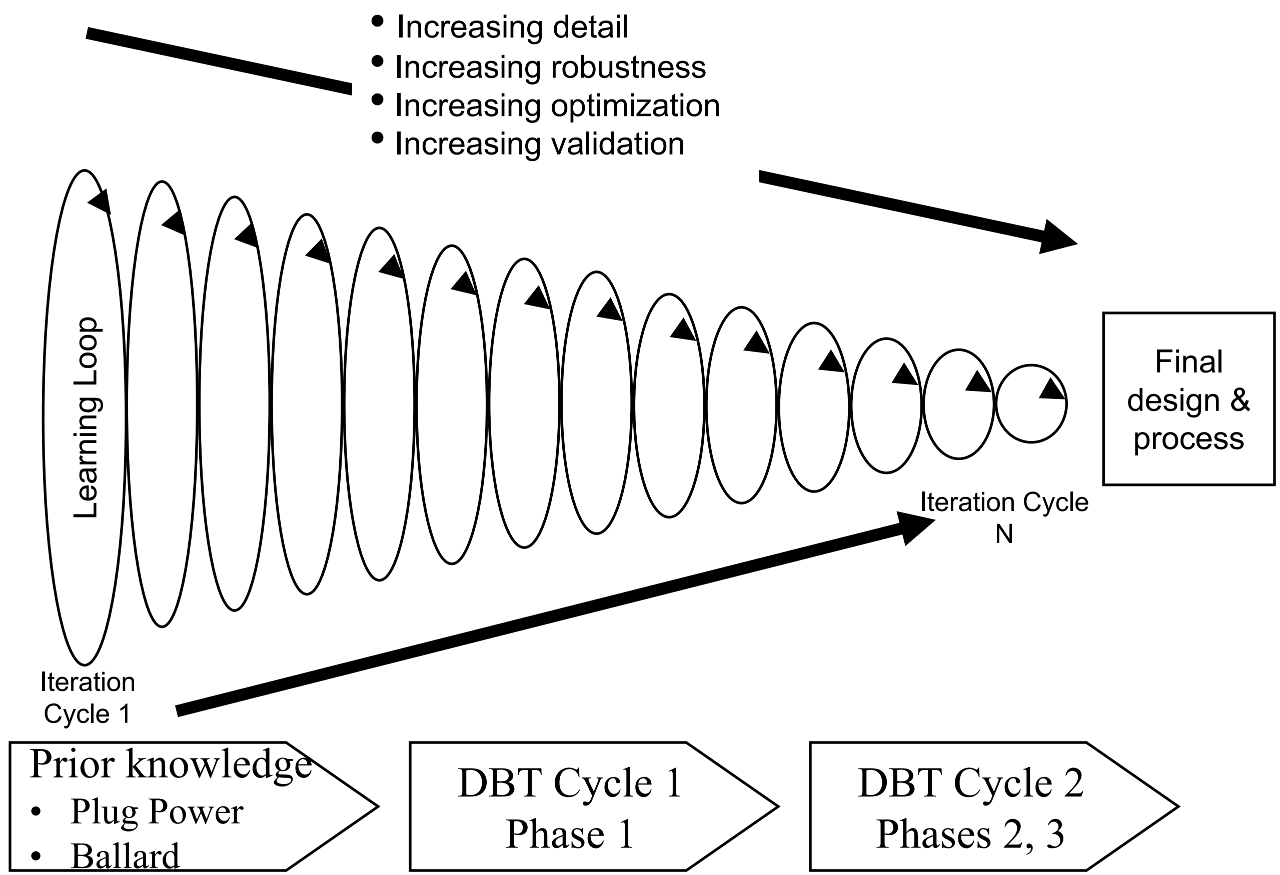
Liquid cooled GenDrive & target for air cooled GenDrive

DOE automotive target & 4b program stretch target

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 Freezable)	Freezable unit that can be restarted and returned to operation even if stored inside of a freezing environment.

Approach

- Multiple Design, Build, Test (DBT) cycles will be employed to capitalize on past knowledge and increase the learning through each iteration
  - Target trade offs between stack, system and operation for optimal durability, freeze tolerance and overall stack-system cost



Approach

GenDrive™

DBT Cycle 1

PHASE 1: Stack and Module Baseline Testing & Failure Modes ID

Task 1: Stack builds and baseline factory acceptance testing
Task 2: Test planning and test setup
Task 3: Freeze failure modes testing, diagnostics and reports

DBT Cycle 2

PHASE 2: Freeze Effect Design Mitigation Strategy

Task 4: Freeze prevention and mitigation in stack/system design

◆ **Milestone: Go/No Go Decision**

Following stack level durability testing and design mitigation strategy, PP will hold a GNG decision review with DOE to assess the value of proceeding with the balance of the SOW (metric: 25% cost reduction of existing GenDrive product)

PHASE 3: Freeze Effect Failure Mode Mitigation Testing

Task 5: Stack/system builds with freeze mitigation design changes
Task 6: Mitigation testing, diagnostics and reports

PHASE 1, 2 & 3

Task 7: Project management

Technical Accomplishments and Progress

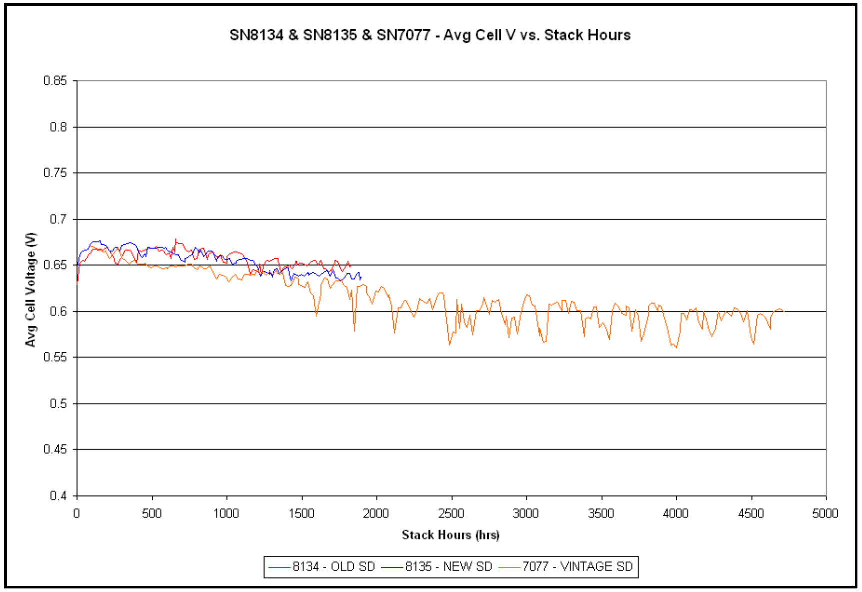
- Completed baseline testing for both liquid cooled and air cooled stack technologies at stack level (Ballard) and system level (Plug Power)
- Completed Ballard historical MK1020 ACS freeze testing data review, report in progress
- Completed stack freeze test station set-up and test plan development
- Developed system operating strategy for improved MEA durability based on collective Plug Power and Ballard Power Systems experience
- Durability testing of baseline stack in prototype system, in progress
- Accelerated stress testing of MEA concepts and components for extended durability, in progress
- Durability testing on advanced stack concepts, in progress
- Conceptual design using an air cooled stack for a motive power freezer operation application

Technical Accomplishments and Progress

Task 1.5 – GenDrive system testing air cooled stack

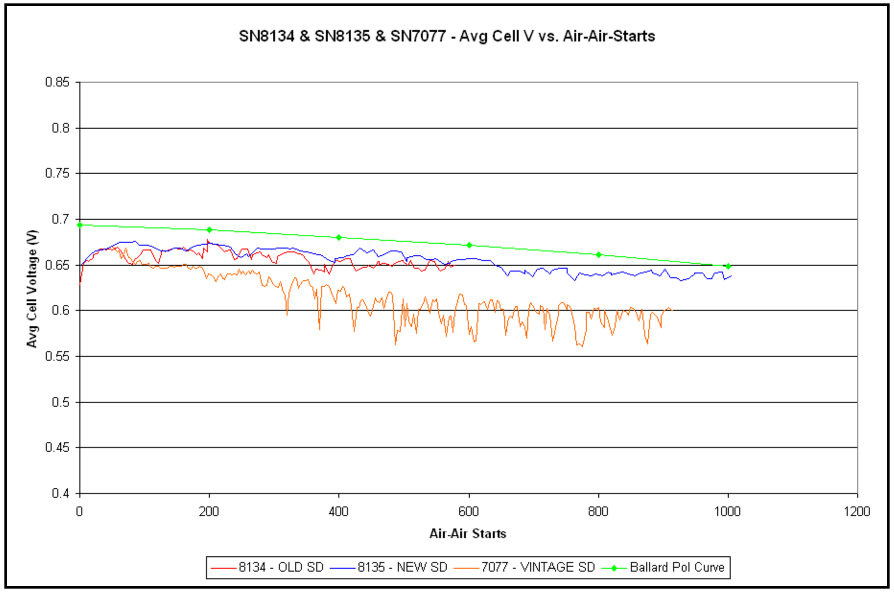
- Increased air cooled stack life and start stop cycles via successful implementation of operating strategy and system architecture strategies

Voltage Degradation as a Function of Stack Hours



80% increase in stack life; originally 2500 hour life still running at >4500 hours

Voltage Degradation as a Function of Start Stop Cycles



Stable performance with latest strategies at >1000 start/stops and still running

Technical Accomplishments and Progress

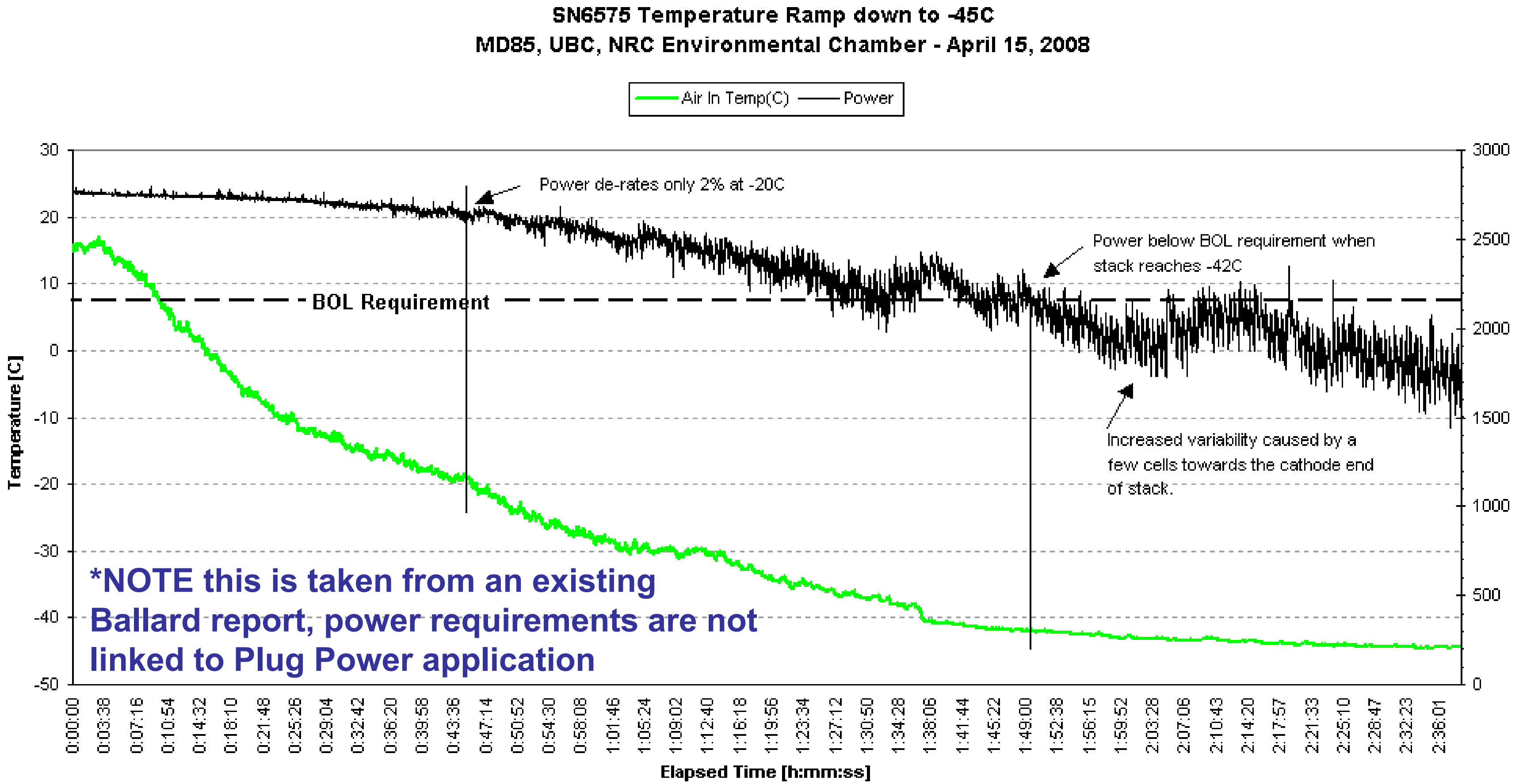
Task 2.1 - Data mining historical data to guide test strategy and limitation of stack

- Inlet temperatures down to -20°C have minimal impact on power de-rates @ 65.3A ~2%; below -20°C power de-rate is ~35%
- Low ambient temperature start-ups down to -20°C are possible but require special procedures and an impractical amount of time
  - System options that reduce the start-up time and maintain stack temperatures above 0°C will be investigated
- Stack performance is 100% recoverable as the ambient temperature increases from sub zero to nominal, freeze durability testing must be done to verify impact on degradation rates
- Below -20°C the stack can not run at low power levels (<65.3A), operating temperatures can not be maintained due to cooling systems turn-down ratio limitations
  - For materials handling applications the turn down ratio will be investigated
- The leak rate did not change during freeze testing, freeze durability testing must be done to verify impact on degradation rates

Technical Accomplishments and Progress

Task 2.1 - Data mining historical data to guide test strategy and limitation of stack

- Inlet temperatures down to -20°C have minimal impact on power de-rate ~2%; below -20°C power de-rate increases significantly

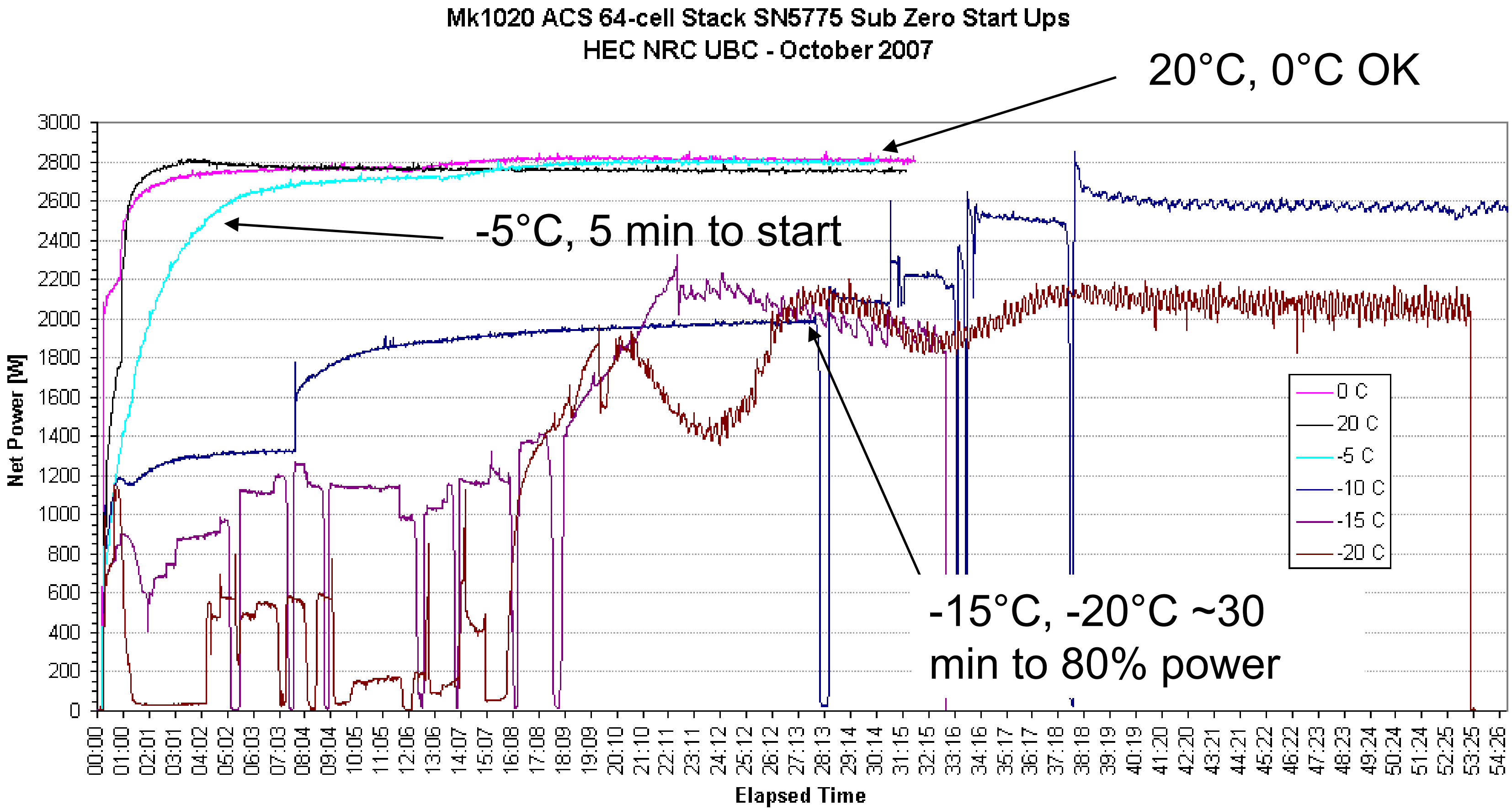


*NOTE this is taken from an existing Ballard report, power requirements are not linked to Plug Power application

Technical Accomplishments and Progress

Task 2.1 - Data mining historical data to guide test strategy and limitation of stack

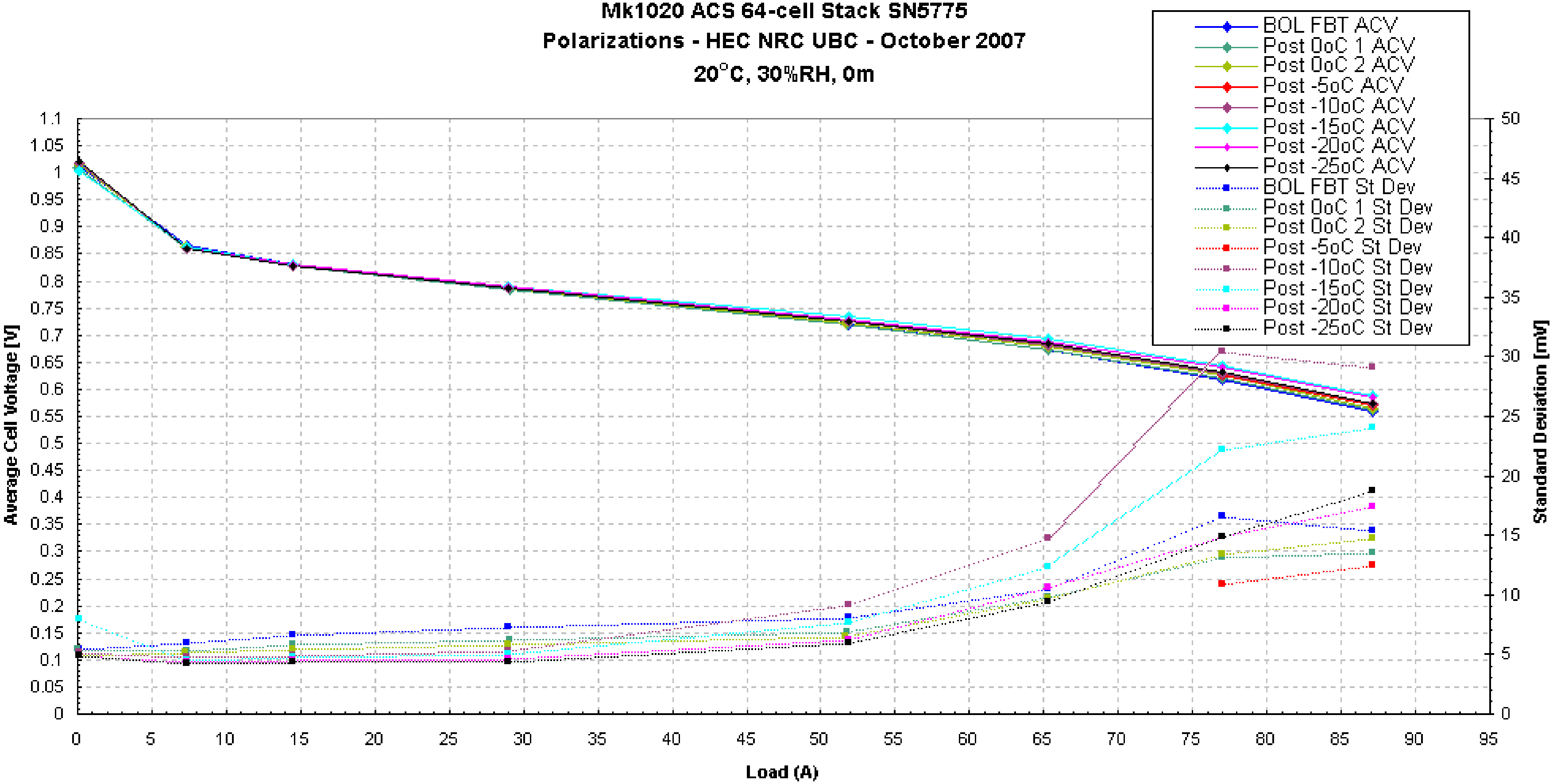
- Low ambient temperature start-ups are possible but require special techniques



Technical Accomplishments and Progress

Task 2.1 - Data mining historical data to guide test strategy and limitation of stack

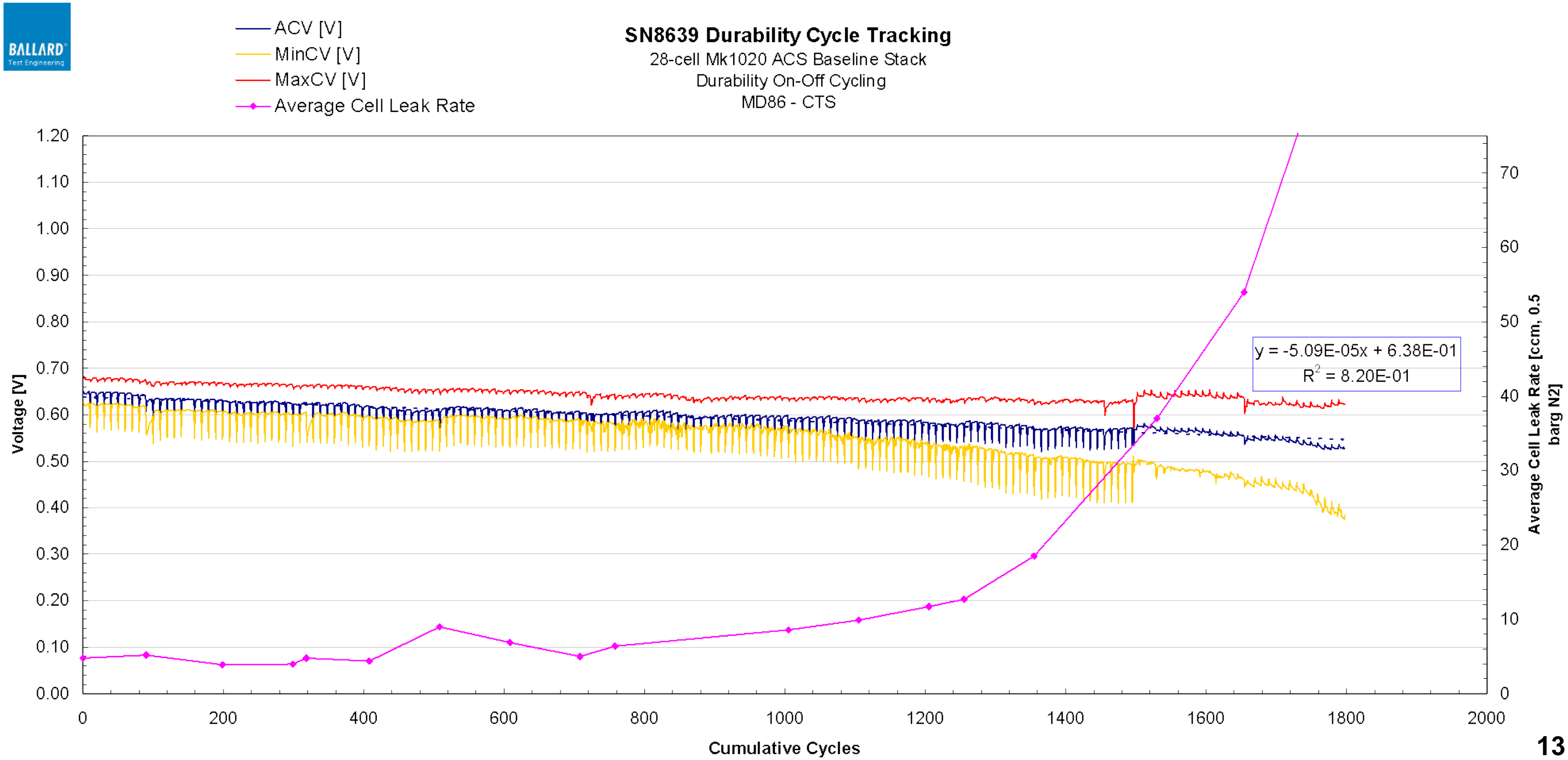
- Stack performance is recoverable as the ambient temperature increases from sub zero to nominal



Technical Accomplishments and Progress

Task 3 - Baseline testing and FA to define degradation and freeze failure modes

- Baseline test of standard performance shows a steady degradation of 50μV/cycle and the onset of internal leaks around 1200 cycles



Technical Accomplishments and Progress

Task 3 - Baseline testing and FA to define degradation and freeze failure modes

- Ballard's standard MK1020 duty cycle was used to define failures modes of standard operation (non-sub zero)
- Cells were removed from the stack every 250 cycles to capture the onset of degradation and the propagation of failures.
- Testing shows a steady degradation of 50μV/cycle and the onset of internal leaks around 1200 cycles.
  - The target for a materials handling application is about 2.5x durability of this baseline -> to be achieved with material and operation
- The MEAs from this stack will be characterized to determine failure fingerprint
  - CO stripping cyclic voltammograms (CVs), IR camera leak location, current mapping, SEM for catalyst and membrane thickness, and SEM for platinum in the membrane quantification

Collaborations

- **Partners:**
  - Ballard Power Systems (Industry): collaboration in stack design and system architecture trade off analysis for motive power applications to mitigate both catalyst and membrane degradation mechanisms as well as freeze tolerant options

- **Technology Transfer:**
  - Collaboration with Ballard Power Systems using stack and cell performance and degradation analytical models as supporting input to Plug Power system analytical models; the results are used for both stack and system sizing requirements when coupled with real application data from Plug Power customer base

Proposed Future Work

- Complete air cooled stack freeze testing and continue accelerated testing on MEA concepts for extended durability of advanced concepts, continue stack durability testing and compare to baseline
- Complete failure analysis of baseline and advanced stack concepts for durability assessment
- Build freezer operable air cooled stack subsystem and commence freeze testing using real motive power application loads and environmental conditions then perform failure analysis
- Develop mitigation strategies based on failure analysis
- Build stack/systems with mitigation design changes then perform mitigation verification testing

Summary

GenDrive™

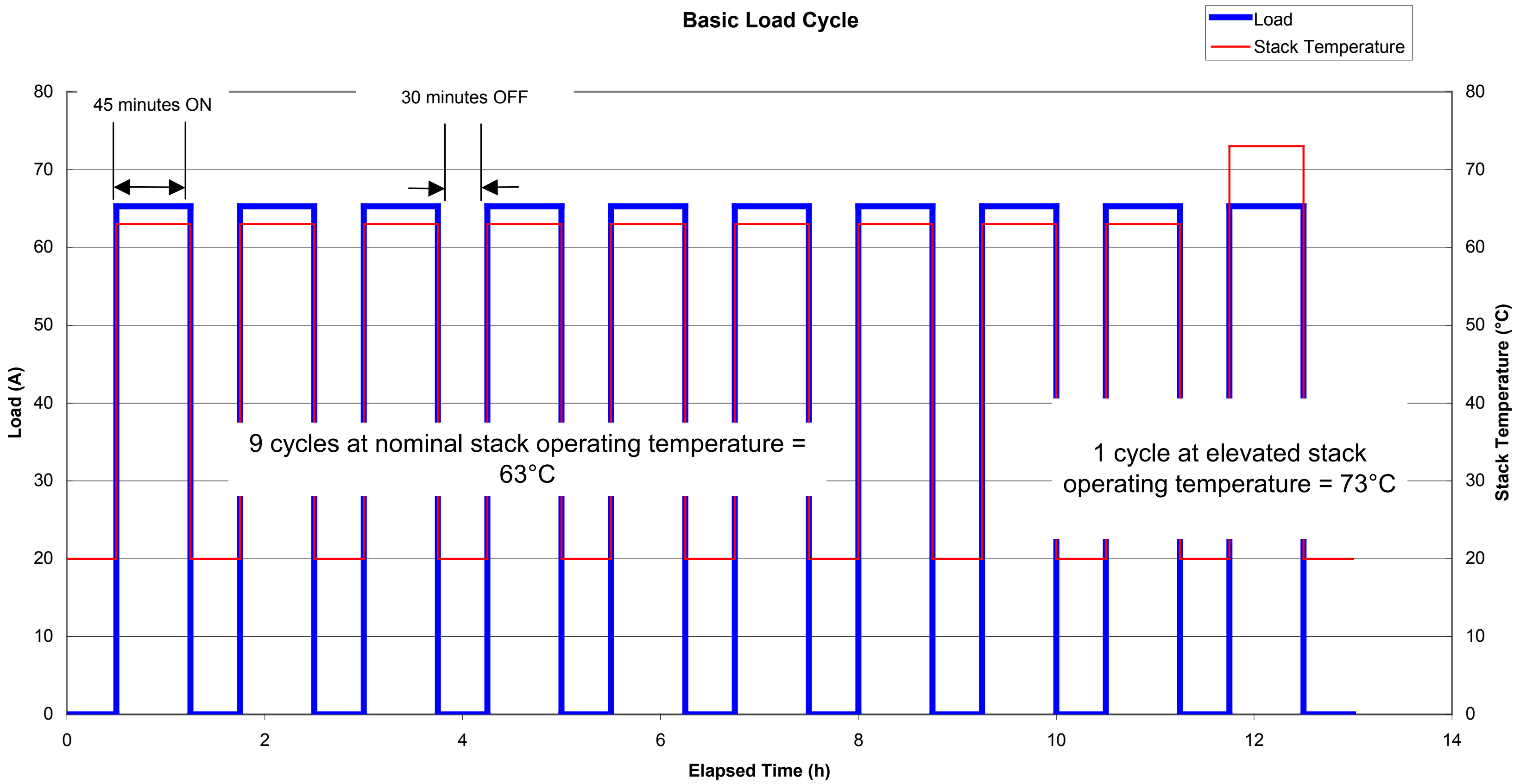
- Baseline activities are completed and freeze failure testing activities are in progress
- Freeze-start requirements are difficult to achieve at the stack level due to cost trade offs and system options will be explored
- Durability testing has not progressed far enough to verify if stack/system can meet the required lifetime

Supplemental Slides

Technical Accomplishments and Progress

Task 3 - Baseline testing and FA to define degradation and freeze failure modes

- Ballard's standard MK1020 duty cycle



GenDrive: Proven Solution for Material Handling

- Plug Power sees material handling market as path to profitability
  - Continue commercial success and traction with major customers
  - Bridge the gap to wide-scale automotive fuel-cell vehicle applications
  - Cold storage/freezer operable products
    - 20-30% of large fleet customers
    - 50-60% of total market

Class (X) All Models	Installed N.A. Base	Annual Turnover
1	266,960	32,899
2	208,211	23,067
3	206,971	21,532

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