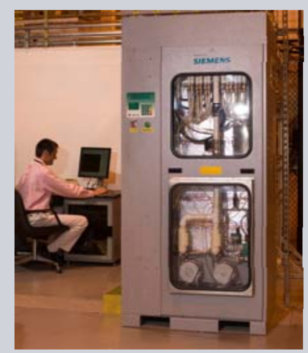
# Siemens Energy

11th Annual SECA Workshop
Pittsburgh, PA
July 27, 2010

**Joseph Pierre**
**Siemens Energy**
**Fossil Power Generation**
**Stationary Fuel Cells**

# The world is changing –
# Siemens has answers to these burning questions

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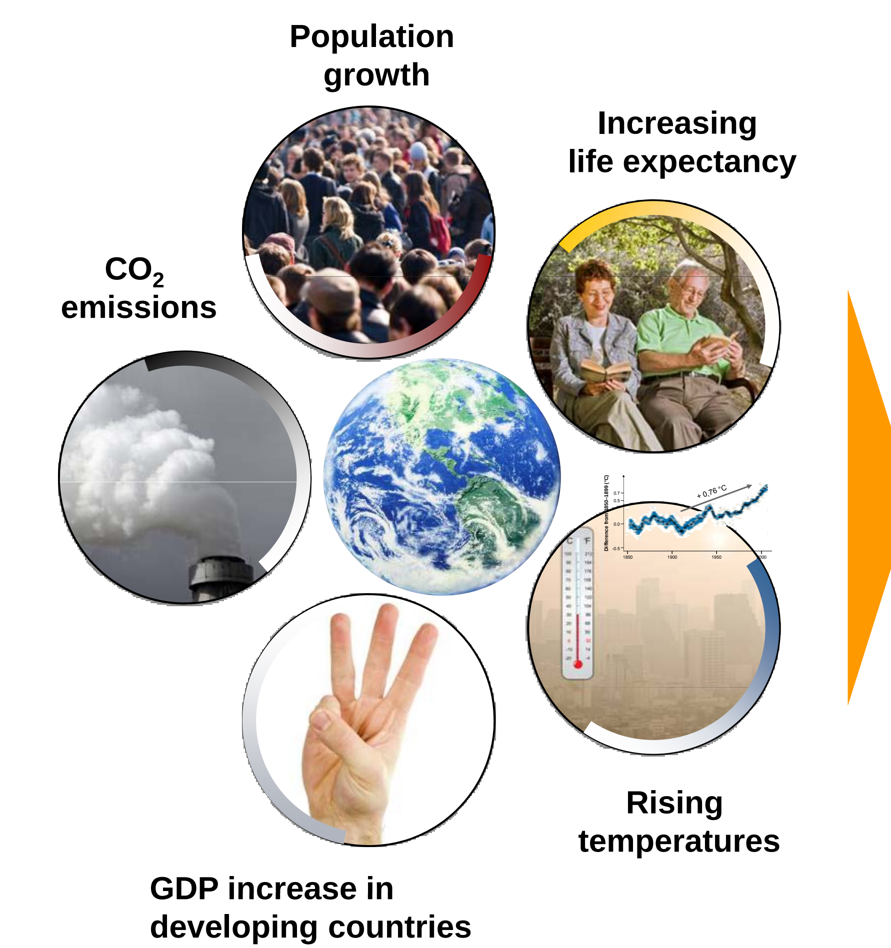


Source: Siemens

## Industry

**We solve the challenges of a booming population**

## Healthcare

**We supply better and affordable healthcare**

## Energy

**We lower $CO_2$ emissions with our energy solutions**

# Answers provided by 15 Divisions in three Sectors

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| Sectors | Divisions | Former Groups |
|---|---|---|
| Industry   | ■ Industry Automation<br>■ Drive Technologies<br>■ Building Technologies<br>■ Osram<br>■ Industry Solutions<br>■ Mobility | ■ Automation and Drives (A&D)<br>■ Industrial Solutions and Services (I&S)<br>■ Siemens Building Technologies (SBT)<br>■ Osram<br>■ Transportation Systems (TS) |
| Energy   | ■ Oil & Gas<br>■ Fossil Power Generation<br>■ Renewable Energy<br>■ Energy Service<br>■ Power Transmission<br>■ Power Distribution | ■ Power Generation (PG)<br>■ Power Transmission and Distribution (PTD)<br>■ Industrial Solutions and Services (I&S OGM) |
| Healthcare   | ■ Imaging & IT<br>■ Workflow & Solutions<br>■ Diagnostics | ■ Medical Solutions (Med) |

# Siemens Energy Sector –
# Answers for energy supply

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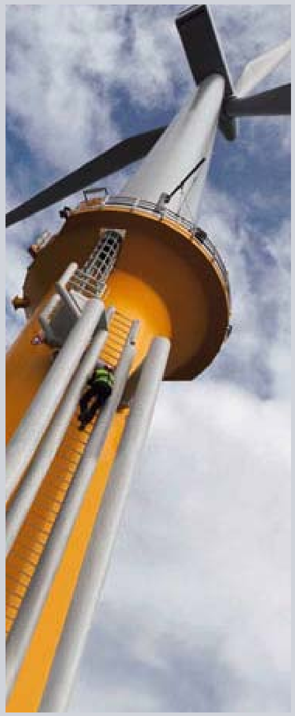
## Energy products and solutions – in 6 Divisions

**Oil & Gas**

**Fossil Power Generation**

**Renewable Energy**



**Energy Service**

**Power Transmission**

**Power Distribution**

# Fossil Power Generation Division – Organizational structure

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**Fossil Power Generation**

**CEO Dr. Michael Suess**

Division

| Products (E F PR) | Energy Solutions (E F ES) | Instrumentation & Electrical (E F IE) | Business Segment | Business Units |
|---|---|---|---|---|
| ▪ Steam Turbines<br>▪ Generators<br>▪ Gas Turbines<br>▪ Sales<br>▪ System Integration<br>▪ Feeder Plants | ▪ Power Plant Solutions, Europe, CIS<br>▪ Power Plant Solutions, Near Middle East, Africa, Asia-Pacific<br>▪ Power Plant Solutions Americas<br>▪ Steam Power Plant Solutions<br>▪ Project Site Execution<br>▪ Module & Project Engineering | ▪ Northern Europe, CIS, Germany<br>▪ Southern Europe, Africa, Middle East, West Asia<br>▪ Region Americas, Asia-Pacific, Australia, Spain, Portugal<br>▪ Intergroup Business and Operational I&C NPPs<br>▪ Product Management | **New Technologies (E F NT)**<br>▪ Fuel Gasification<br>▪ Stationary Fuel Cells<br>▪ Carbon Capture and Storage<br><br>**Nuclear Power, Conventional Island (E F NP)** | Segments |
| Nr. 2 | Nr. 2 | Nr. 1 | | Market position |

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# New Technologies Business Segment (E F NT)

## Portfolio

- Fuel gasification
  – Gasifier
  – Technology licenses
  – Gasifier island solutions for IGCC, production of chemical products from coal („Coal-to-Chemicals“)
- Stationary fuel cells
- New technologies for carbon capture

## Strategy

- Expansion of the gasifier component business
- Development and marketing of other CCS components
  (Carbon Capture and Storage)
- Development of IGCC-integrated concept solutions





# Welcome to SFC Headquarters


George Westinghouse Science and Technology Park

# SFC Technology has demonstrated Best-in-Class performance


**Developed over 25 fully integrated SOFC power generating systems, including the world's first pressurized hybrid demonstration unit**

# Acknowledgement

This material is based upon work supported by the Department of Energy under Award Numbers DE-FC26-05NT42613

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# DOE SECA Coal-based System Program

**Program Objectives**

**Phase I**

| | |
|---|---|
| ▪ Conceptual design and feasibility analysis of baseline design and Proof-of-Concept **(**POC) system | 3Q2008 ✓ |
| ▪ Verify Delta-8 performance via cell and stack tests | 3Q2008 ✓ |
| ▪ Initiate and complete 5,000 hrs Delta8 R0 stack test | 1Q2009 ✓ |

**Phase II**

| | |
|---|---|
| ▪ Detailed design, performance, and cost analysis of baseline design | 3Q2010 ✓ |
| ▪ Initiate and complete 1,500 hrs of operation Delta8 R1 Stack Test | 3Q2010 |

**Phase III**

| | |
|---|---|
| ▪ Initiate and complete 5,000 hrs operation of Delta8 "MWe-class" module | 3Q2012 |
| ▪ Initiate and complete 25,000 hrs operation of MWe-scale POC System | 3Q2015 |
| ▪ Corroborate performance and cost of 100 MWe baseline design | 3Q2015 |

**A Multi-Year, Multi-Phase DOE Program**

- Phase I – 3 years: $26M
- Phase II – 2 years: $17M
- Phase III – 5 years: $33M

**The ultimate goal of DOE program beyond Phase III: Coal syngas fueled, >100 MWe class fuel cell central station efficiency >50%, with 90% $CO_2$ isolation at $400/kWe (excluding $CO_2$ sequestration and gasification systems)**

# DOE SECA Coal-based System Program
# Phase II Key Activities

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- Baseline Systems Analysis
- Cell and Module Development
- POCD8R1 Stack Test

## Significant Results

- Identified an alternate high(er) efficiency cycle concept
- Increased power density between 800-1000C on cylindrical cells through material and process improvements
- Showed voltage stability of the power-enhanced cells at 900$^{o}$ and 1000$^{o}$C
- Demonstrated stability of the power-enhanced cells through 10 thermal cycles
- Transfer power enhancement technology to Delta8 cells
- Initiated testing of a power-enhanced Delta8 cell
- Continued HPD test with an excellent voltage stability
- Completed construction and initiated validation of Pressurized Test Facility
- Initiated POCD8R1 Stack Test

# Baseline System Analysis

## Goals

Must Operate on Coal Synthesis Gas

Must Use a Fuel Cell

$CO_2$ Capture ≥ 90%

Efficiency ≥50% (Net AC/Coal HHV)

Power System Capacity >100 MWe

Cost ≤ $600/Max kWe (End Phase 1 Concept Design)

## Objectives

Baseline System Performance and Cost Estimate Updates

Baseline System Performance Analysis

Confirm the Proffered Baseline System Concept

Baseline System(s) Definition and Analysis

Baseline System Cost Analysis

Factory Cost Report

## Technical Challenges

Cell performance confirmation

Efficiency targets

Handling inerts in the alternate high efficiency cycle concept

Water management

## Accomplishments

Continued evaluation of alternate higher efficiency concept

Validated performance and cost of the Baseline System

# Pressurized Cell Testing

## Goals:

Validate the existing test facility against existing pressurized cell test data.

Obtain performance data on the Delta8 cell configuration under pressurized conditions

## Technical Challenges:

Fuel distribution within the test article

High temperature leak rate

Fuel bypass

## Objectives:

Design improved Delta8 pressurized test articles

Procure and assemble tubular test articles to validate test rig

Upgrade existing test facility

Conduct testing and obtain performance data at elevated pressures

Conduct post test analysis

## Activities:

Assembly of tubular cell test article completed

Installation of tubular test article into test facility completed

Facility modifications and shakedown underway

## Pressurized Cell & Stack Test
## Tubular Cell Test 1213 – Heater Assembly

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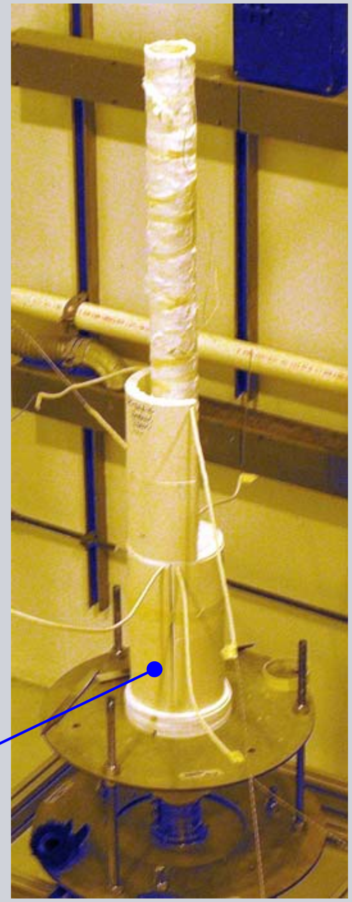
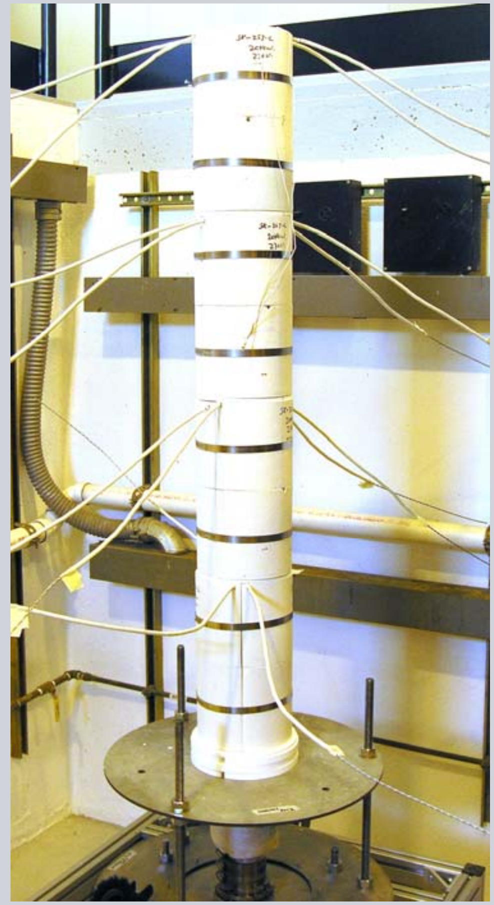
**Test article**

Clam-Shell heaters



**1 ½ clam shell heaters installed**



**All (4) clam shell heaters installed**

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# Pressurized Cell & Stack Test
# Tubular Cell Test 1213 – Insulation Wrap


**Before final insulation**

**Insulation complete**

**Covered with Aluminum sheeting**

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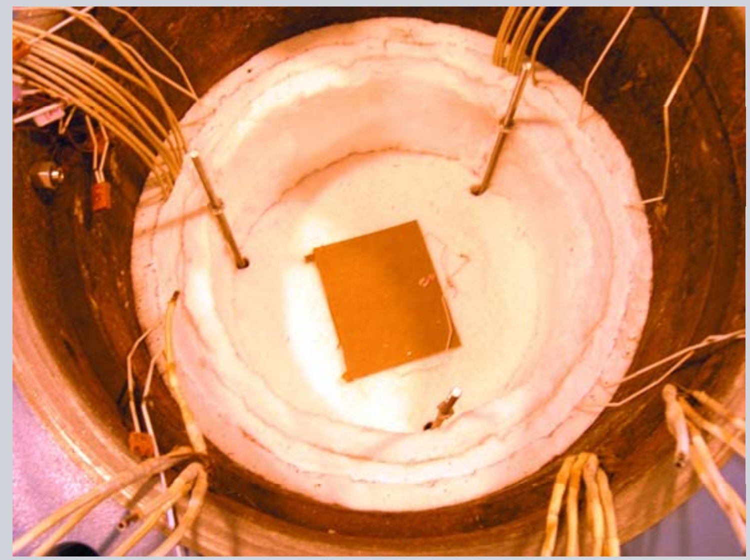
# Pressurized Cell & Stack Test
# Tubular Cell Test 1213 – Installation in Test Rig

Article installed in pressure vessel with final insulation wraps

Article lowered into the pressure vessel

# Cell Development

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## Goals

- Achieve cost and performance requirements utilizing HPD Delta8 seal-less planar cell design
- Manufacture Cells and Bundles for Proof-of Concept tests

## Objectives

- Develop process conditions for the manufacturing of the air electrodes for the Delta8 one meter active length cells which improve quality and lower cost
- Develop process conditions for the application of electrolyte, fuel electrode, and interconnection utilizing PS which improve quality and lower cost
- Develop high quality, low cost process for the bundling of Delta8 cells
- Development lower operating temperature cell

## Technical Challenges

- Dimensional control (side bow and taper) of Delta8 cell
- Elimination of air electrode flaws
- Elimination of closed end cracks
- Ability to achieve high yield with Delta8 cell
- Ability to spray electrolyte at high feed rates in carousel design
- Demonstrate ability to implement additive into a manufacturing friendly process

## Activities/Accomplishments

- Dimensional control of air electrode
- Reduction of Air Electrode Flaws
- Elimination of closed end cracks
- Application of electrolyte at commercially viable conditions
- Cell and Bundle Development and Manufacturing
- Demonstrate stable high performance of power-enhanced cells
- Evaluation and definition of manufacturing process for power enhanced cells

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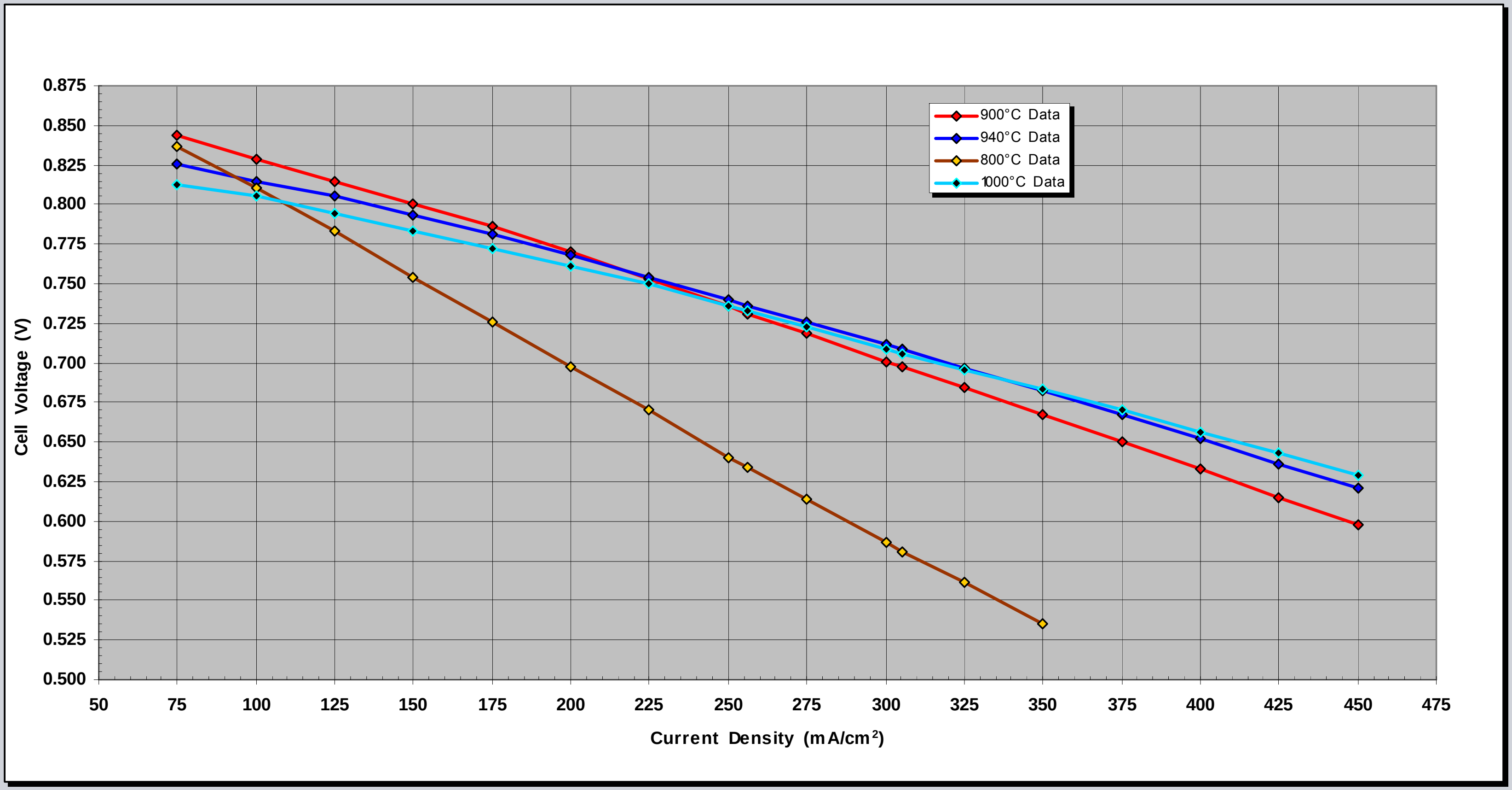
# Performance of Power Enhanced Cylindrical Cell




**Enhanced power at all temperatures**

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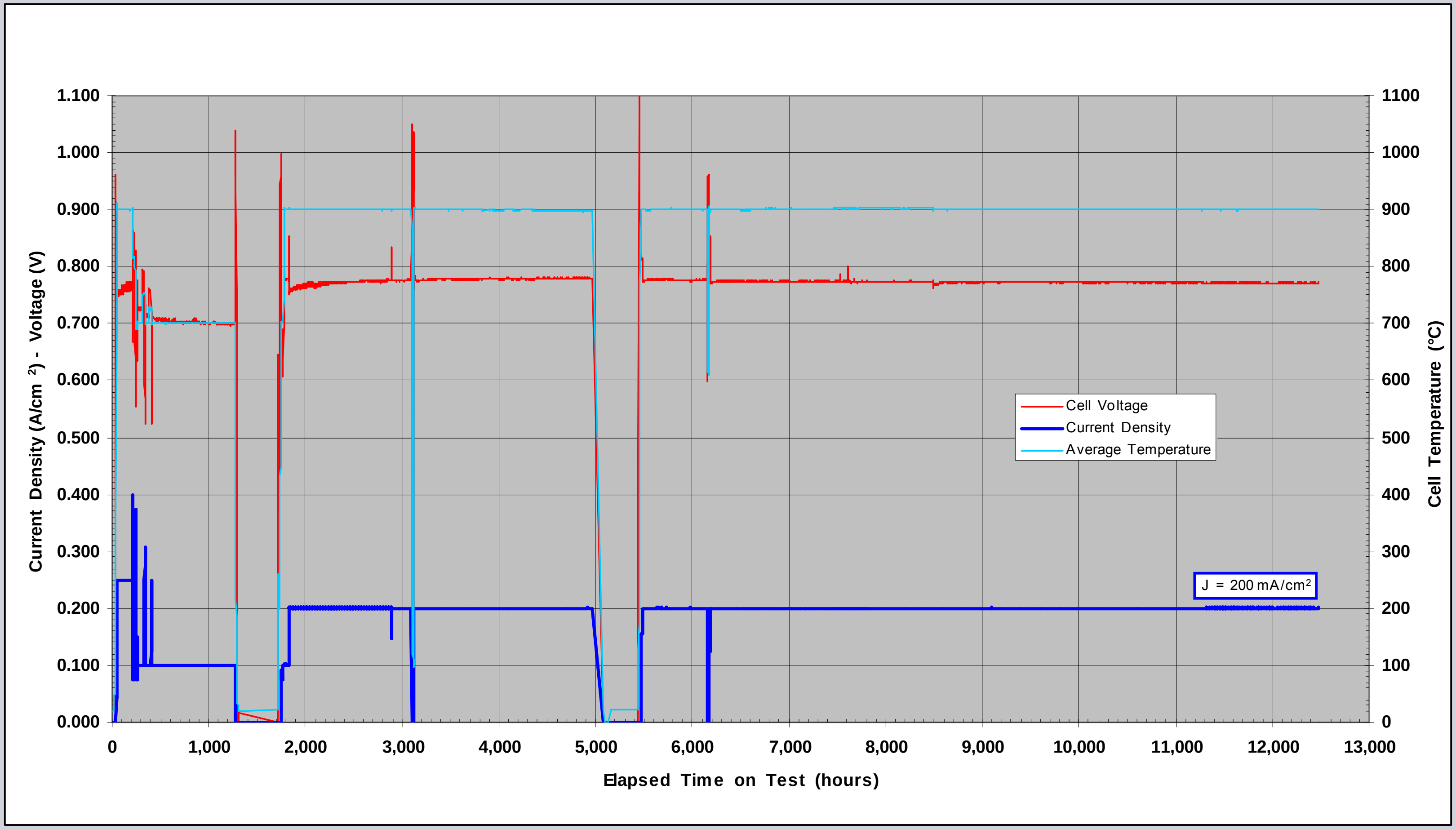
# Voltage Stability of Power Enhanced Cylindrical Cell




**Excellent Voltage Stability … Test continues…**

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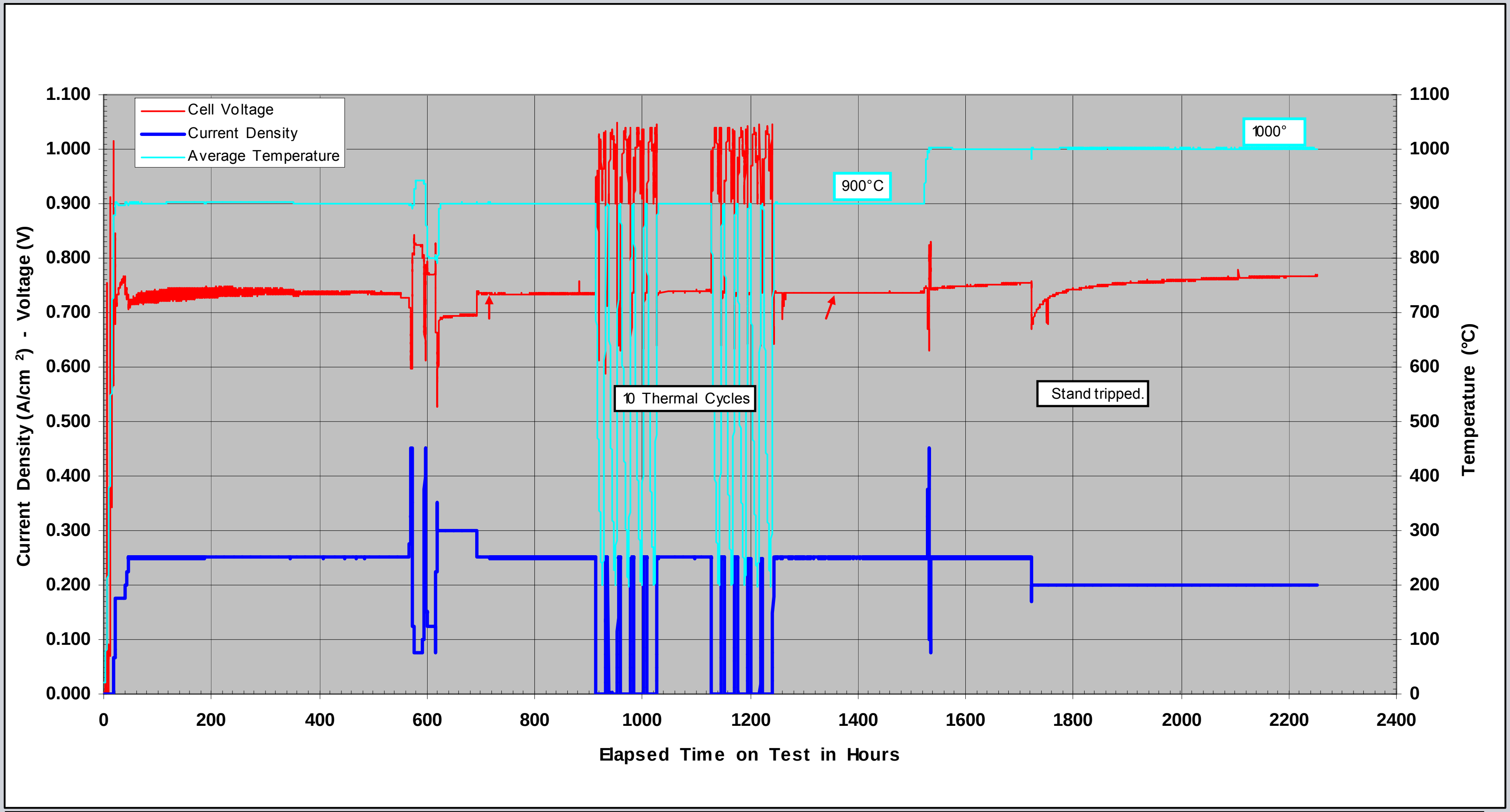
# Cell Thermal Stability – Cylindrical Cells




**Cell went through 10 thermal cycles without losing voltage and was very stable at 1000C. Test continues…**

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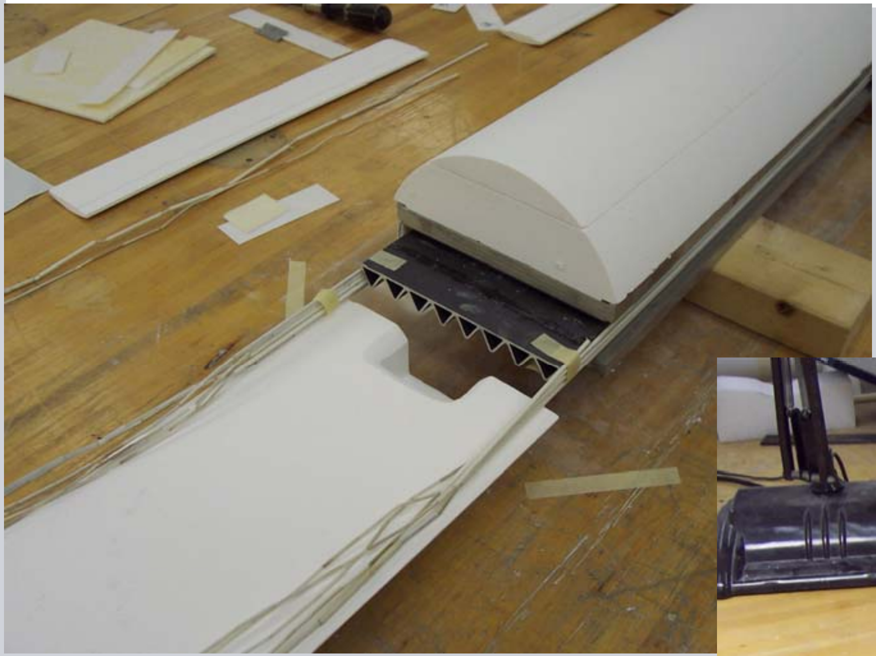
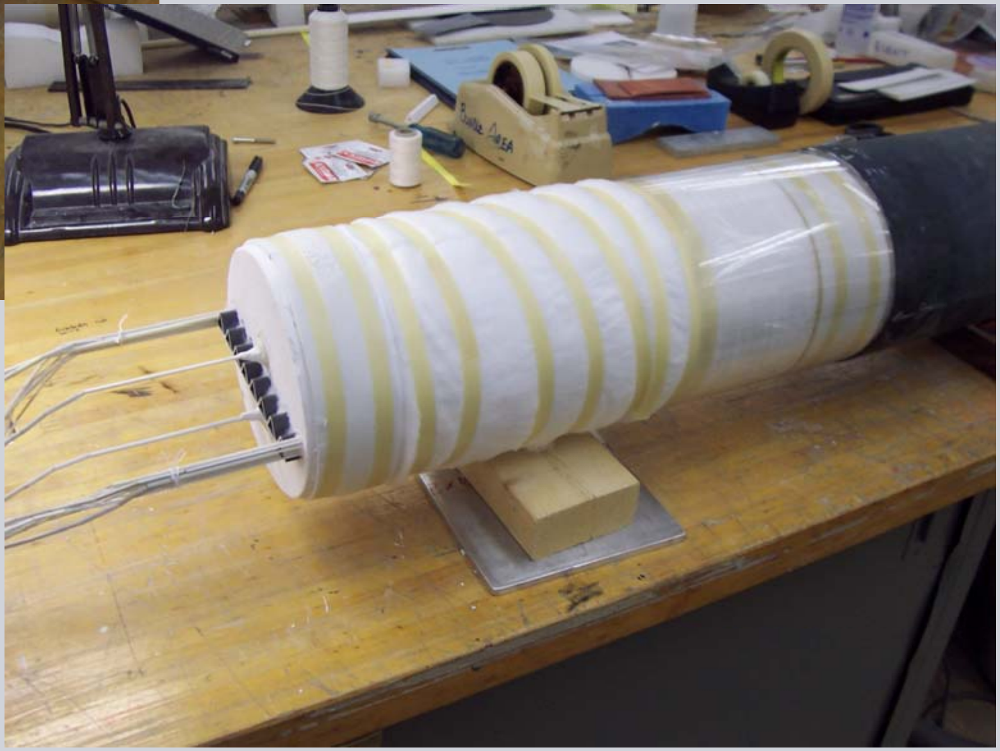
## Delta8 Cell Assembly





# Delta8 Cell Performance Curve-Voltage vs. Current Density

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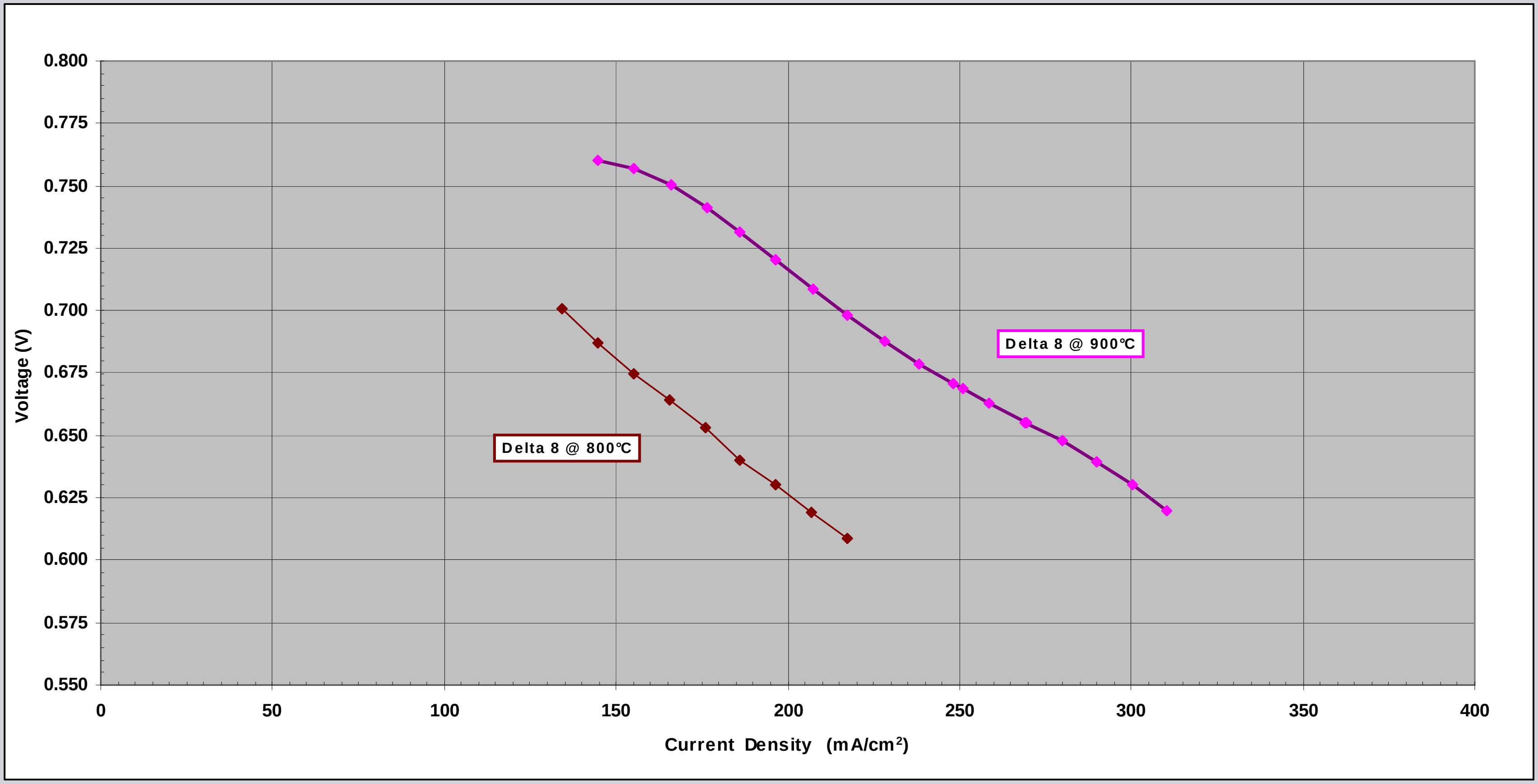


**Cell assembly process needs to be improved to lower fuel by pass**

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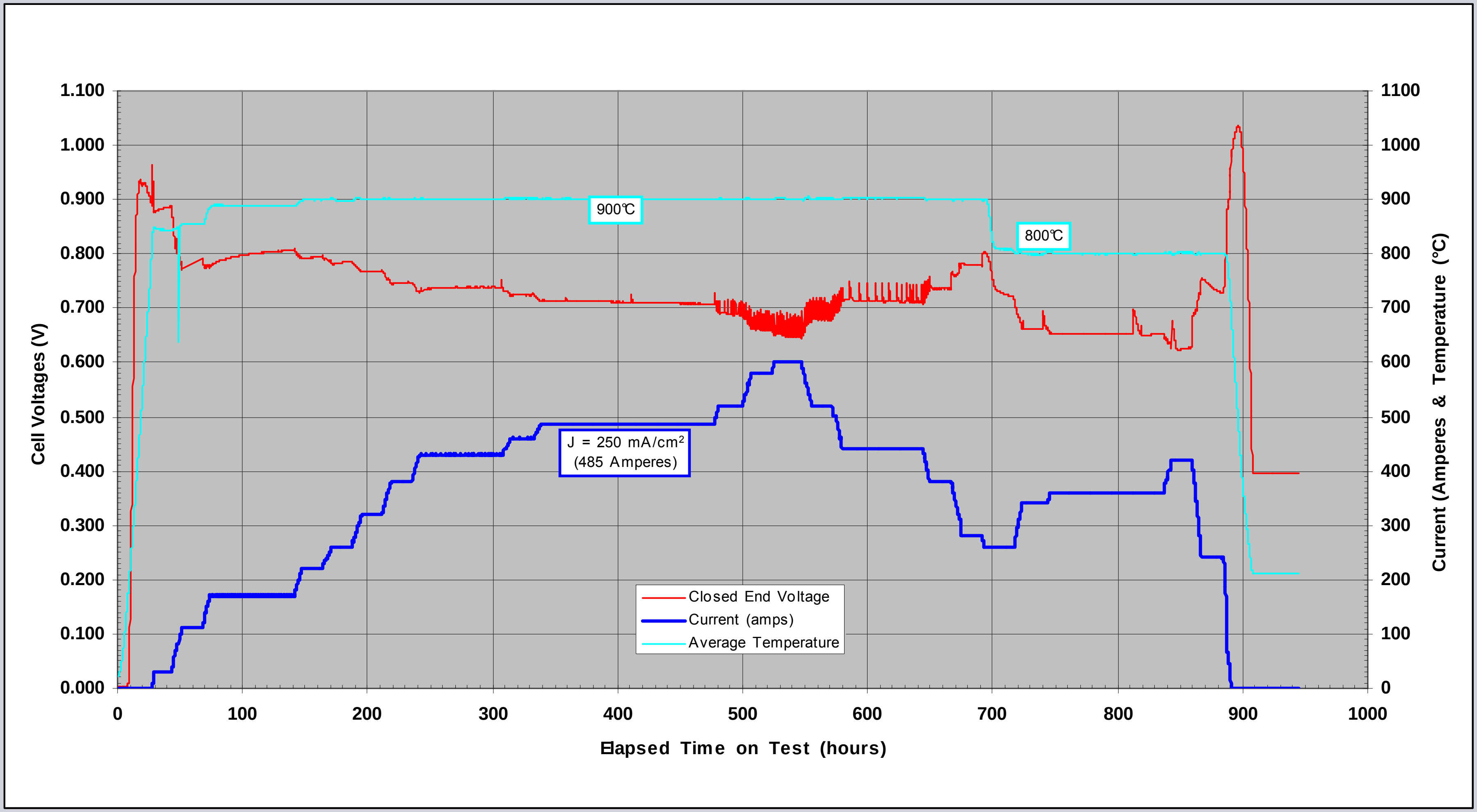
# Delta8 Cell Life Time Plot



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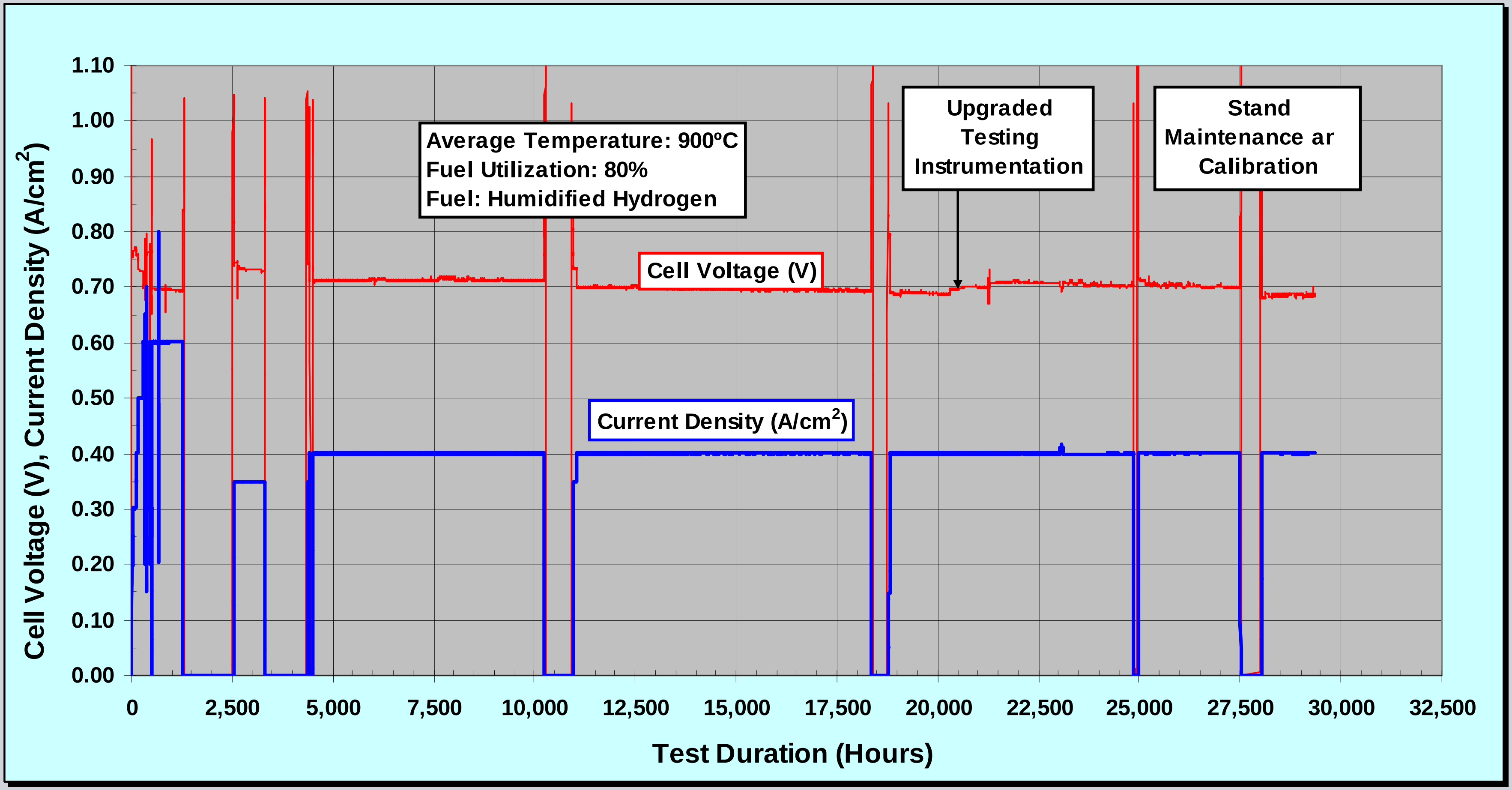
# HPD Voltage Stability



# POCD8R1 Stack Test

## Goals

- Deliver a ≥ 25 kWe SOFC stack incorporating Delta8 cells
- Initiate End-of-Phase II Stack Test
- Achieve 1,500 hrs operating time prior to End-of-Phase II
- Satisfy performance requirements as specified in the Minimum Requirements Document

## Technical Challenges (D&B)

- Cell Production / Bundle Assembly
  - Cell production yield
  - Cell/bundle dimensional tolerances
  - Bundle assembly and sintering
- Back-up for critical contractor
- Delta8 cell and bundle integrity

## Objectives (D&B)

| | (FY) |
|---|---|
| Complete R1 module design | 3Q09 |
| Complete R1 module assembly | 2Q10 |
| Cells and bundle manufacturing | 4Q09 |
| Complete R1 BOP design | 3Q09 |
| Complete R1 BOP assembly | 4Q09 |
| Complete R1 test article assembly and installation | 2Q10 |
| Initiate stack test | 2Q10 |

## Activities/Accomplishments

- Integrating BOP with test article
- Validating control system software
- Assembling external recirculation loop
- Identify and qualify backup machining contractor

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# POCD8R1 Stack Test

## Goals

- Initiate End-of-Phase II SECA Stack Test
- Achieve 1,500 hrs operating time prior to End-of-Phase II
- Satisfy performance requirements as specified in the Minimum Requirements Document

## Technical Challenges

- Fuel side heating
- Anode stream recirculator
- New stack architecture (IBA)
- One meter Delta8 cells

## Objectives

- System startup 03/01 ✓
- Begin Load to NOC 03/07 ✓
- Initiate cell conditioning 03/21 ✓
- Peak power test 04/06
- VJ curves at NOC 04/25
- Initiate Stability Test 04/25
- Initiate system shutdown 06/25
- Stack test completed 06/27
- Complete Root Cause Investigation 06/15 ✓

## Activities/Accomplishments

- Initiated stack test
- Heatup completed
- Introduction of NHmix and Hydrogen
- Achieved current loading >300 amps
- Disassembly/Root Cause Investigation completed

## POCD8R1 Stack Test Summary

- Second generator to test Delta 8 cells
  - First, POCD8R0, operated for 5300 hours with max DC power of 9.8 kW
  - Stack was damaged due to failure of the control system hard drive
- Began operation in March 2010
  - Operated for 400 hours
  - Loaded to 11.1 kW stack DC power
- Design successfully demonstrated many advanced features:
  - Integral Bundle Assembly (IBA)
  - Cast ceramic components
  - Fuel side heating
  - Fuel recirculator
- Several cells failed during an air transient at 400 hours
  - Stack failed during loading (311 amps at failure vs 818 amps at NOC)
  - Stack was damaged early in heatup by intermittent electrical shorts caused by carbon formation
  - Stack contained more organic binders than previous generators

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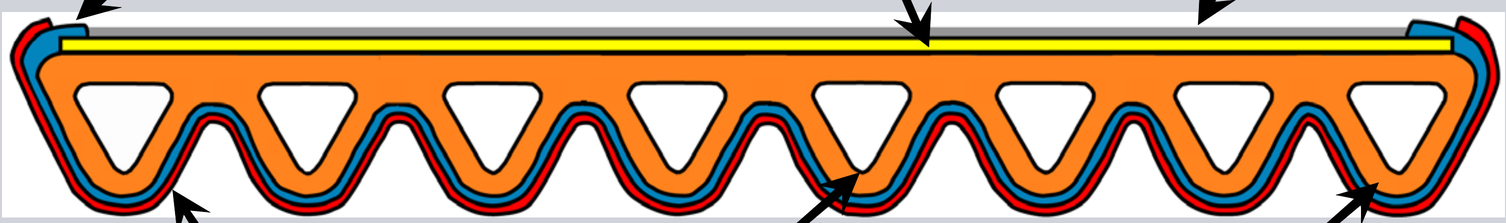
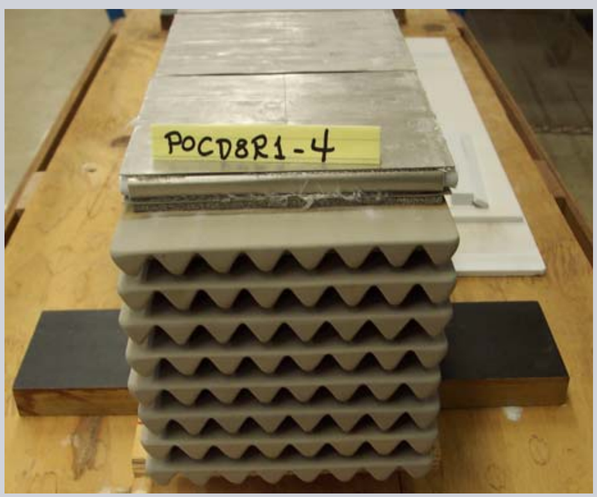
# Delta 8 Cell




| Delta 8 Cell Materials | |
|---|---|
| **Component** | **Material** |
| Cathode (Air Electrode) | Doped lanthanum manganite |
| Electrolyte | Scandia stabilized zirconium oxide |
| Interconnection | Doped lanthanum chromite |
| Anode (Fuel Electrode) | Nickel – zirconium oxide cermet |
| Plating | Nickel |
| | |

# POCD8R1 Stack Test – Delta8 Bundle (8 cell)




# POCD8R1 Stack Test - IBA & Bundle Row Assembly

Up-righting finished IBA

Up-righted IBA

Row Assembly

## POCD8R1 Stack Test - Bundle Rows

Bundle rows installed in the stack assembly fixture

# POCD8R1 Stack Test
# Stack Assembly

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Stack being installed into container

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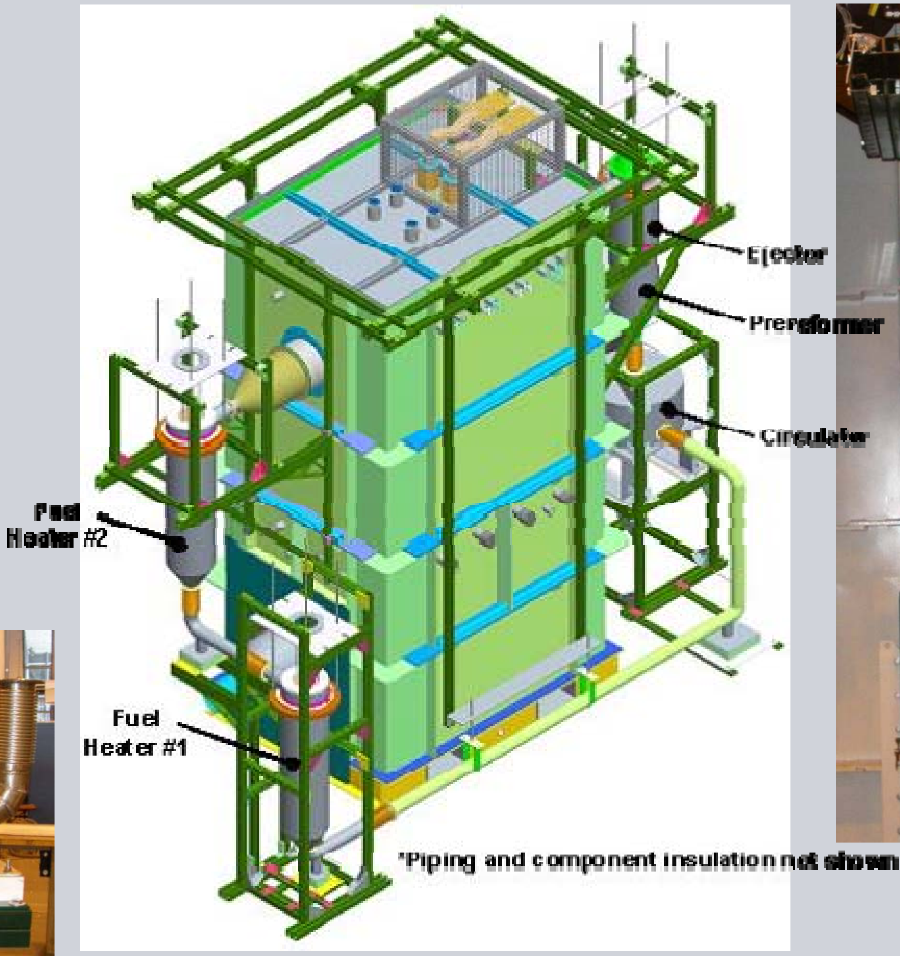
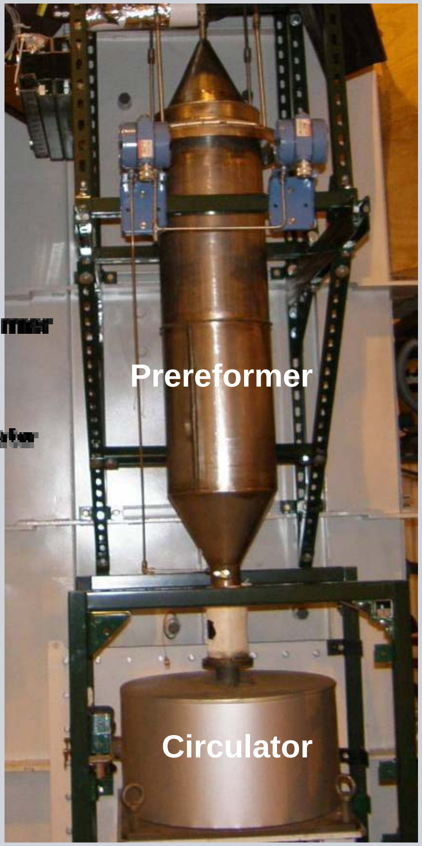
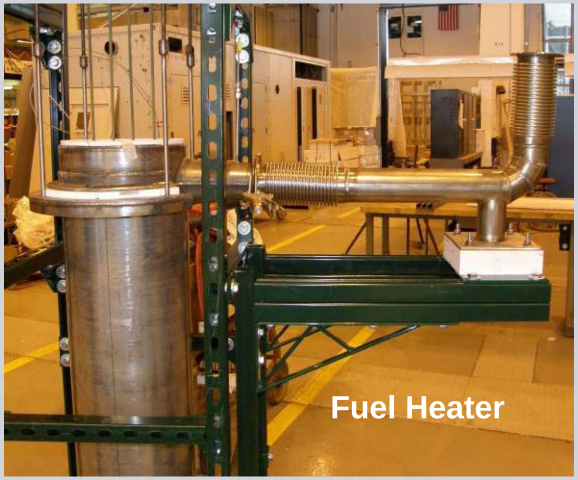
## POCD8R1 Generator and Recirculation Loop

Advanced features:

- Integral Bundle Assembly (IBA)
- Cast ceramic components
- Fuel side heating
- Fuel circulator



## POCD8R1 Test Facility

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# POCD8R1 Instrumentation and Control

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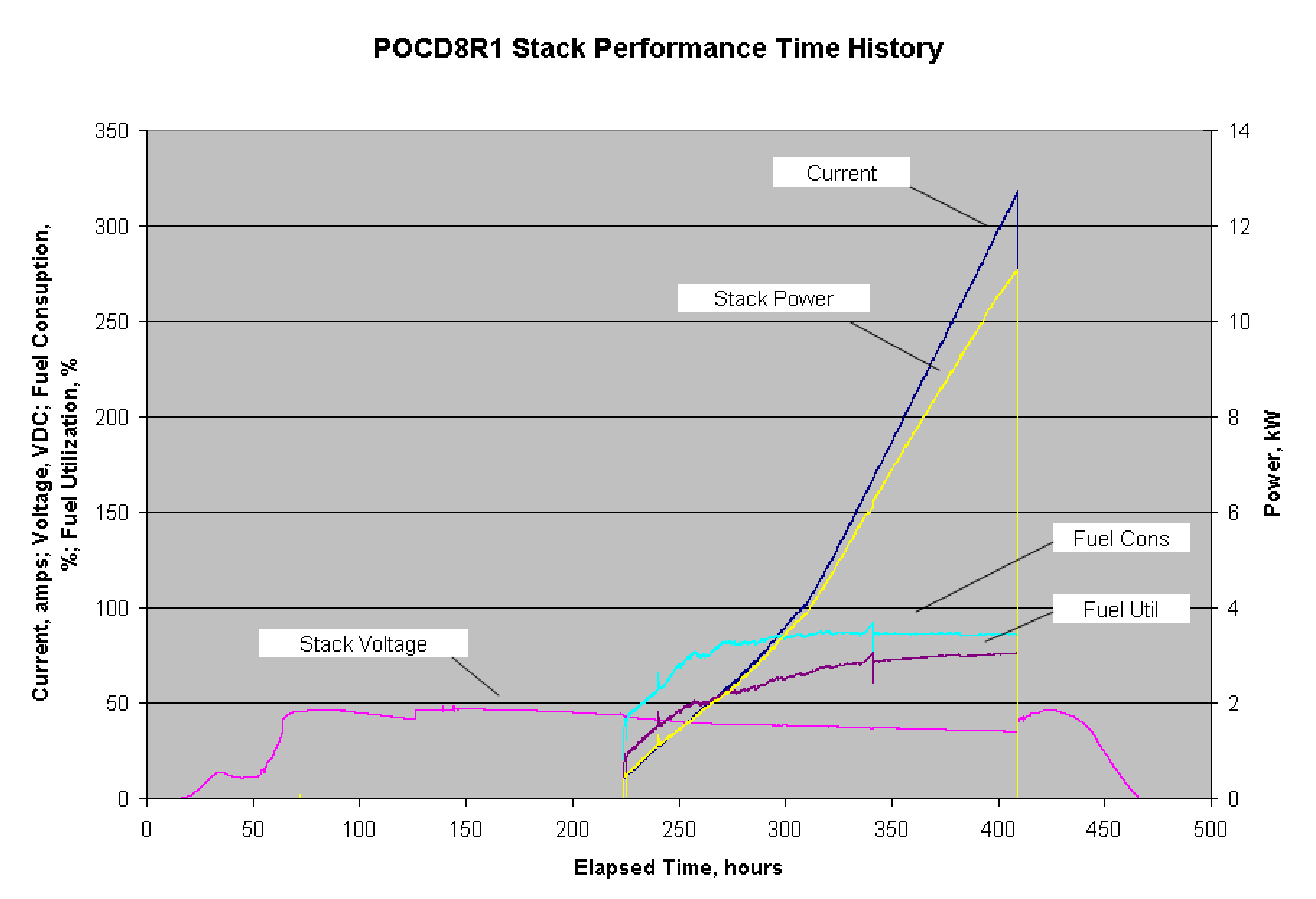
# POCD8R1 Operation



# POCD8R1 Stack Test
# Root Cause Analysis

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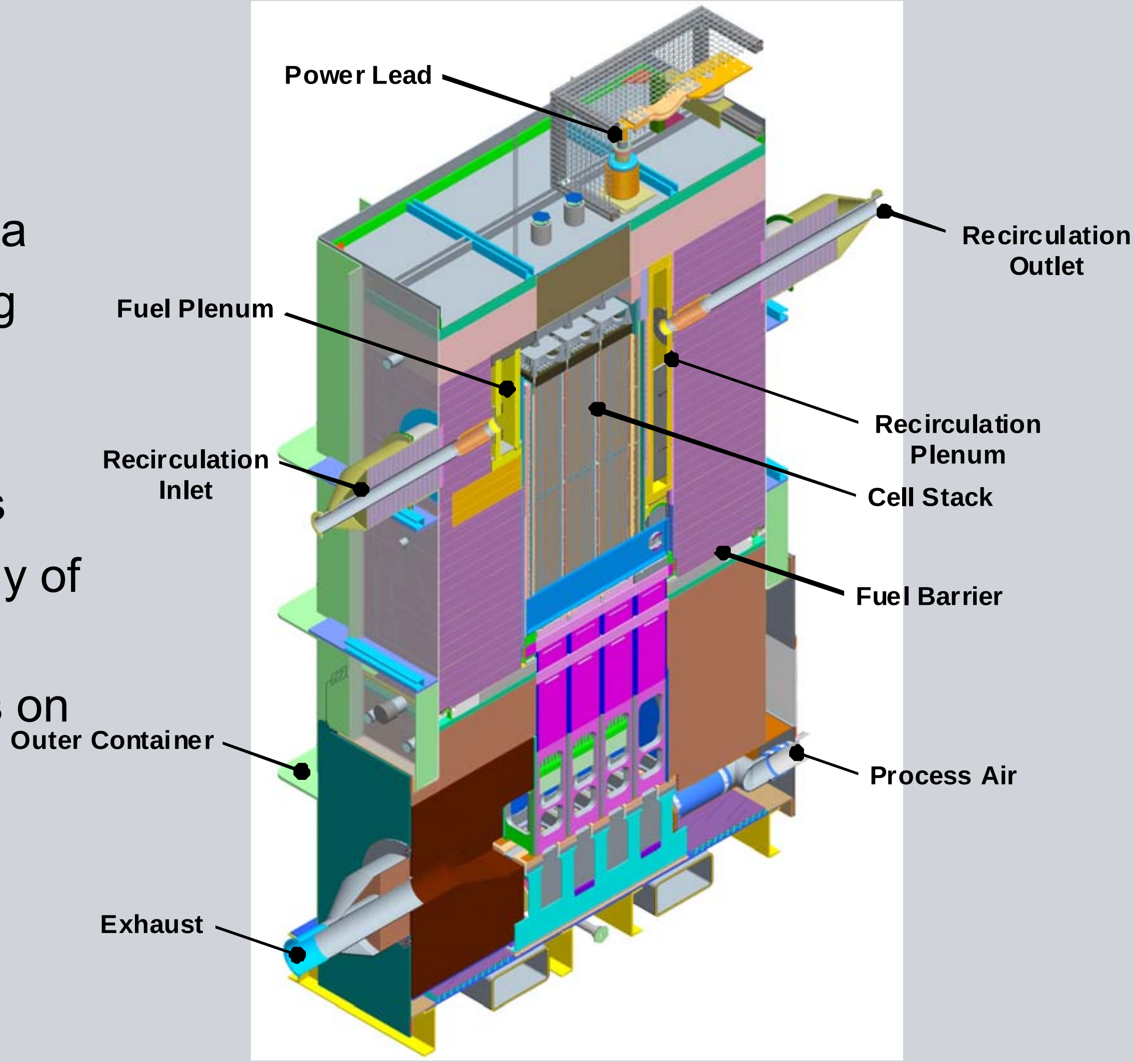
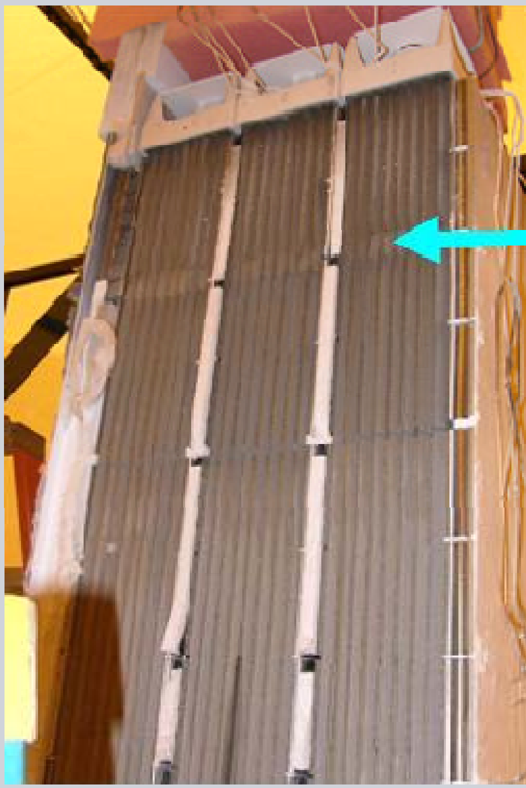
## Root Cause Analysis Process

- Review stack voltage data
- Review stack temperature data
- Review fuel cell manufacturing history
- Review operating procedure
- Review thermal stress models
- Carefully examine disassembly of test article
- Perform fractography analysis on broken fuel cell
- 58 observations
- 12 failure mechanisms
- 31 recommendations
- Path forward defined



## In-stack Carbon



Carbon on Saffil Felt

Damaged Bundle Row

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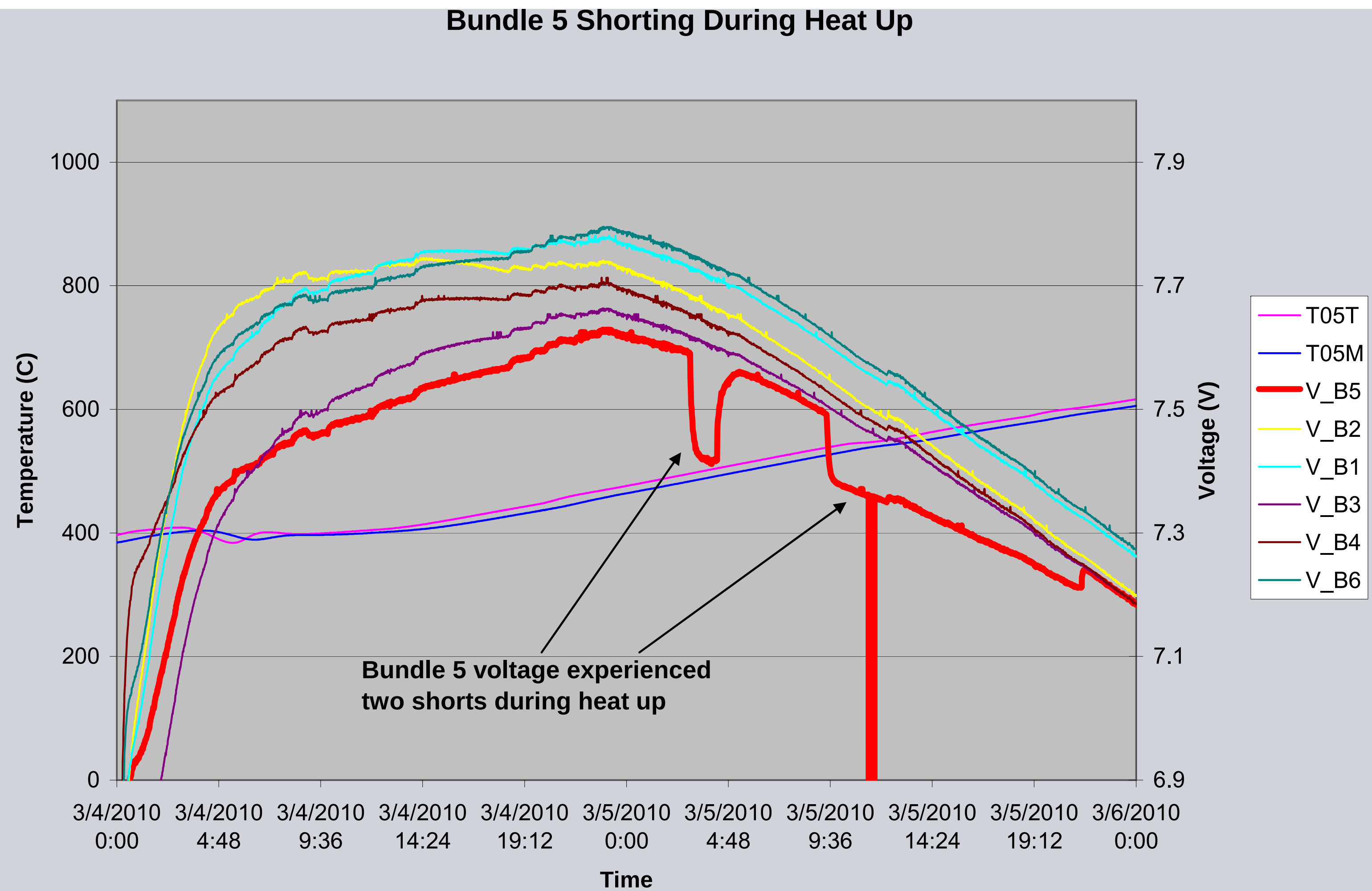
# POCD8R1 Stack Test Root Cause Investigation




**Bundle 5 shorting at low temperature may have led to tight closed end fuel cell cracks**

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# Acknowledgements


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- Joe Stoffa, Program Manager
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- Travis Shultz

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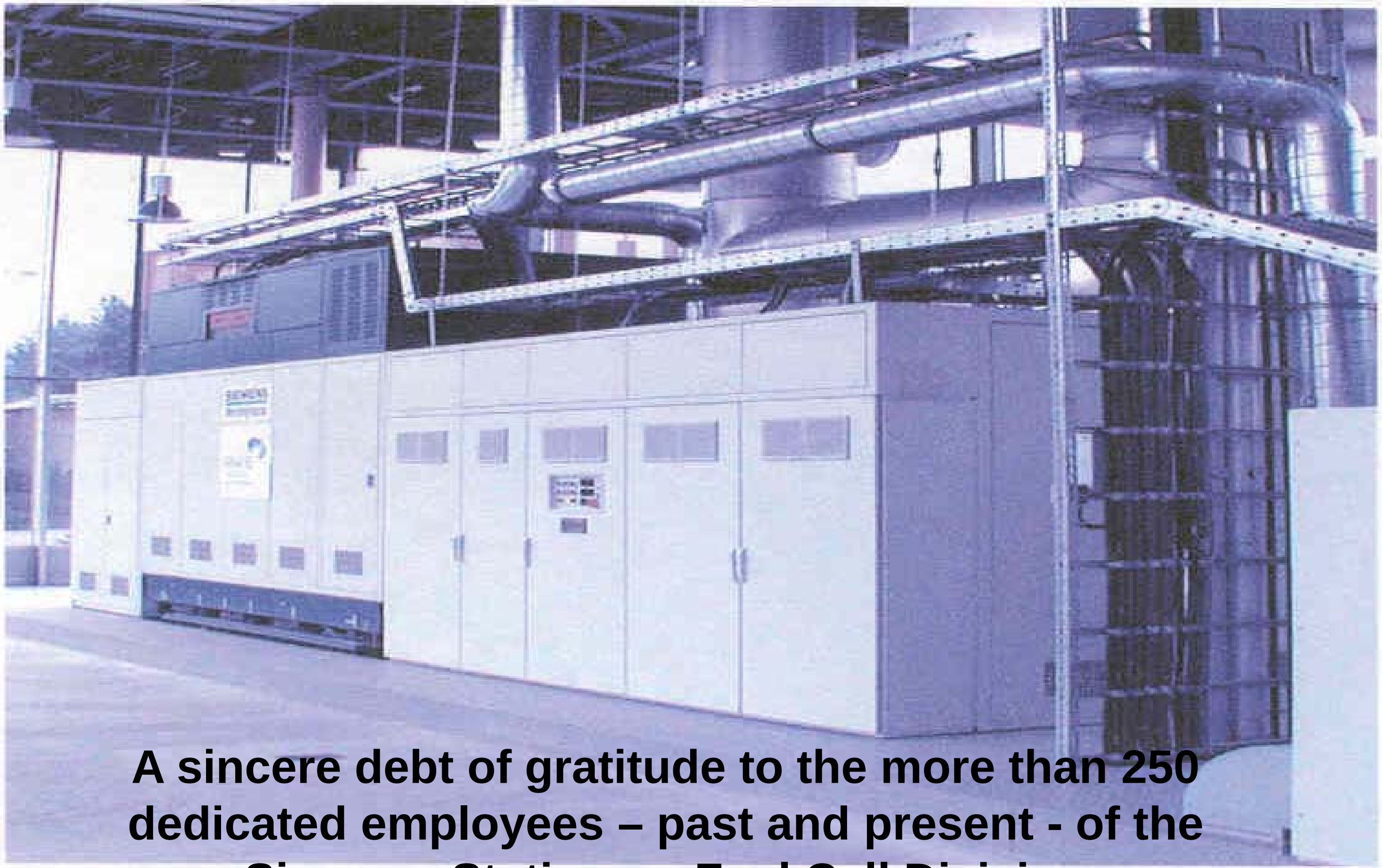

**A sincere debt of gratitude to the more than 250 dedicated employees – past and present - of the Siemens Stationary Fuel Cell Division**