# Delphi SOFC Stack Development Update

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Cell and Stack Development

Pittsburgh, PA
2009 SECA Annual Review Meeting

# Outline

- Summary Highlights
- Manufacturing progress
  - Facilities
  - Manufacturing System Design
  - Variation reduction
  - Use of engineering tools
- Gen 4 stack progress
  - Cell performance stability
  - Design status and performance projection
  - Stack development activities
- Gen 3 stack performance
  - Syngas
  - Thermal cycling
- Leveraging SECA activities
  - Truck APU
  - Vibration testing
  - NUWC

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# Summary of Year's Performance Highlights for SECA Coal Based System Stack Development

- Added 33K $ft^2$ cell development facility
- Scaled up from 105 $cm^2$ (active area) cells to 403 $cm^2$
- Fabricated > 5,000 cells and > 100 stacks of various configurations
- Completed Gen 4 stack design
- Achieved stack power density of 500 $mW/cm^2$ at 570 $mA/cm^2$, with mean cell voltage of 0.87 V
- Implemented low cost cell, interconnect, and balance of stack fabrication processes
- Achieved >100 thermal cycles on 30-cell stack

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# Delphi SOFC Development Centers

## SE Michigan

- Cell Fabrication
- Manufacturing Development
- Electrochemical Testing
- Material Characterization and Analysis
- 33K $ft^2$, added Q3 2008
- Capacity up to 8 MW in 2011

## Rochester, New York

- Stack Build and Development
- System Integration & Perform. Lab
- Reformer Development Lab
- Catalyst Durability Lab
- BOP Development

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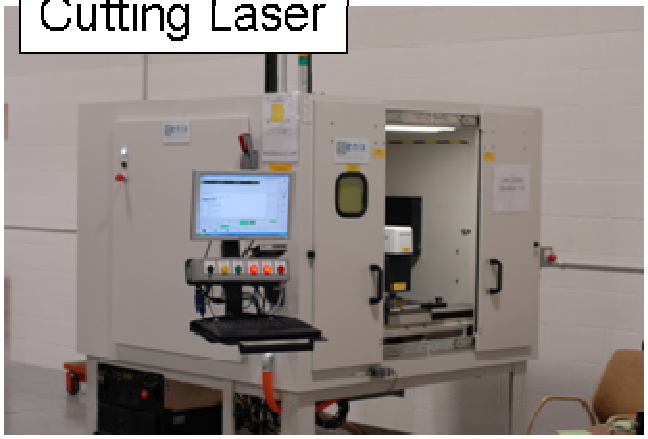
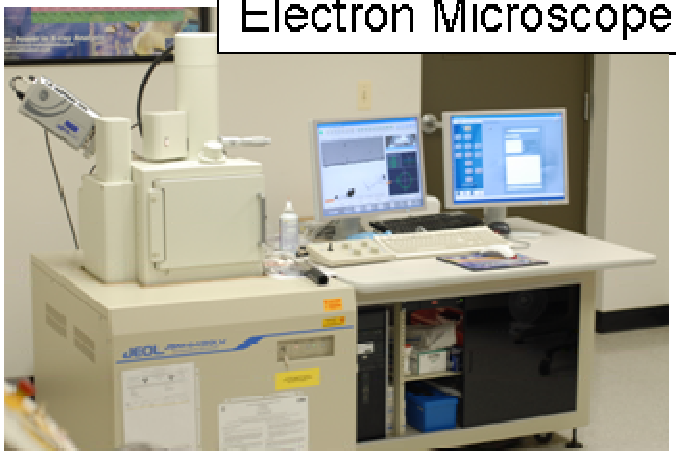
# Equipment for Cell Development and Fabrication

Cutting Laser



High Temp Kilns

Electron Microscope



Screen Printer

Laser Interferometer

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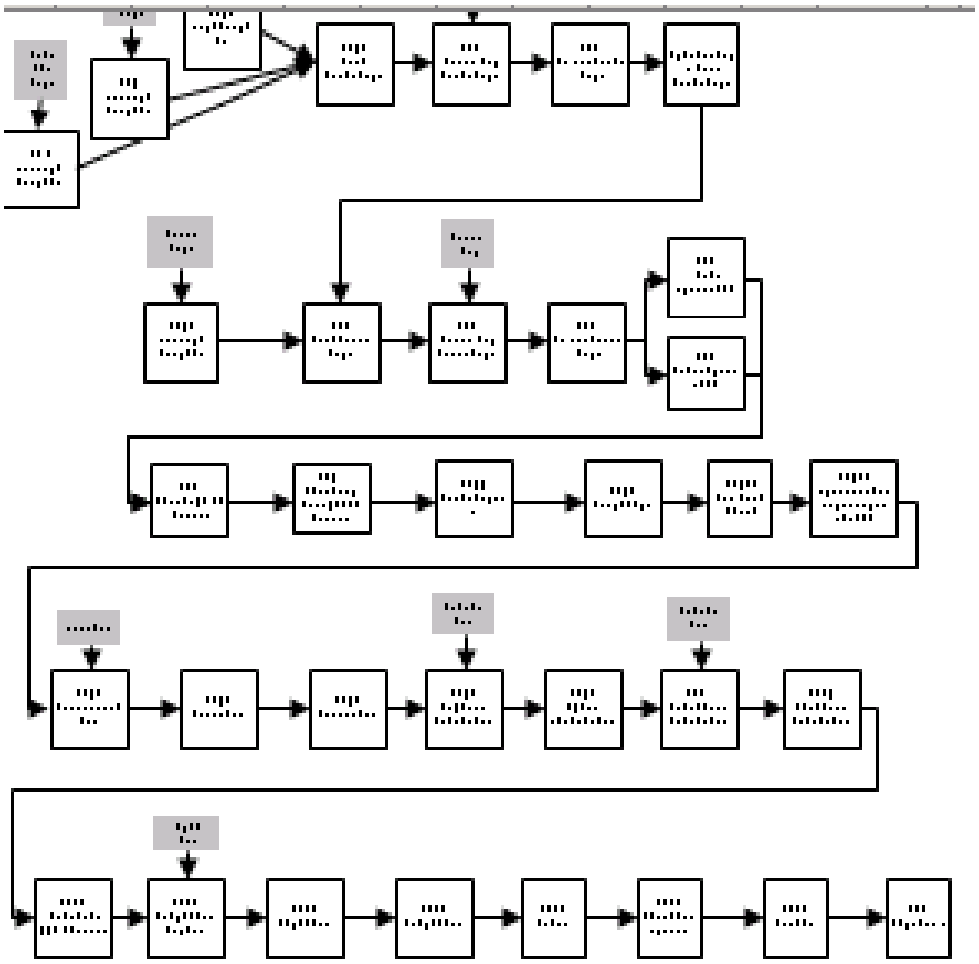
# Delphi SOFC Manufacturing Plan- Mfg System Design (MSD)



- Customer Requirements
- Project Requirements
- Detailed Mfg Sequence Chart
- Define Operator Work Content
- Balance Equipment Utilization
- Balance Operator Utilization
- Balance Material Flow

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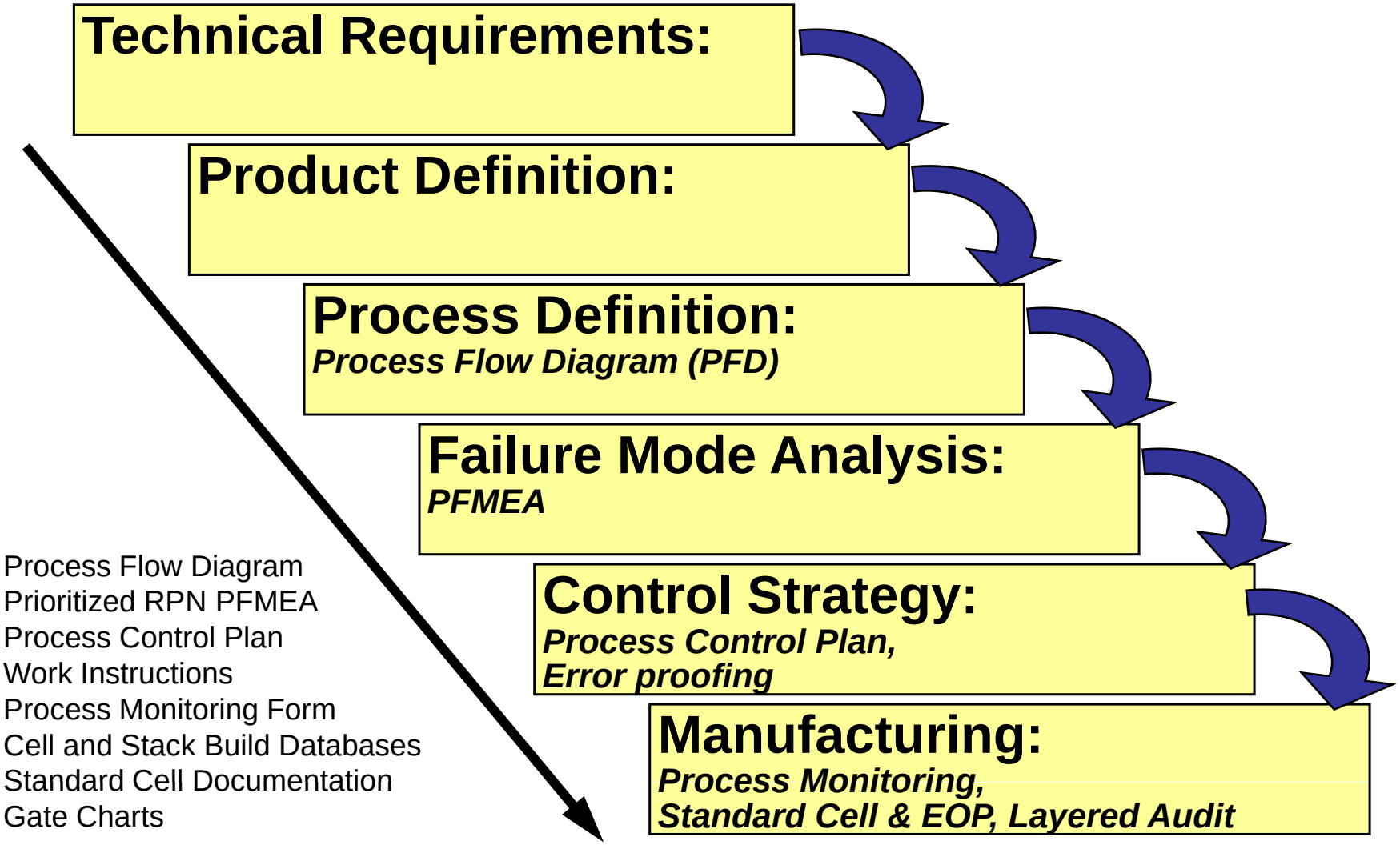
# Manufacturing System Development




Process Flow Diagram
Prioritized RPN PFMEA
Process Control Plan
Work Instructions
Process Monitoring Form
Cell and Stack Build Databases
Standard Cell Documentation
Gate Charts

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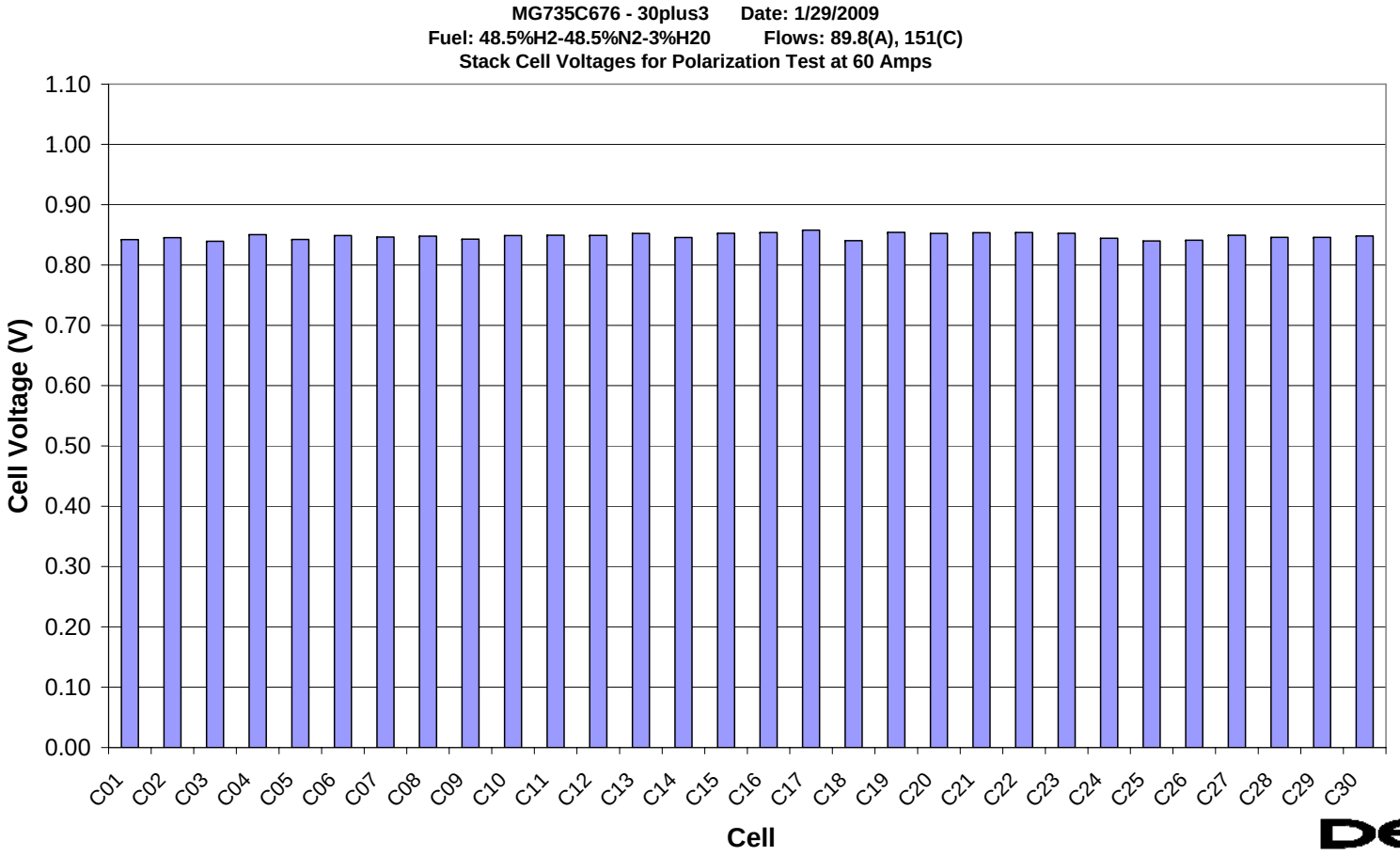
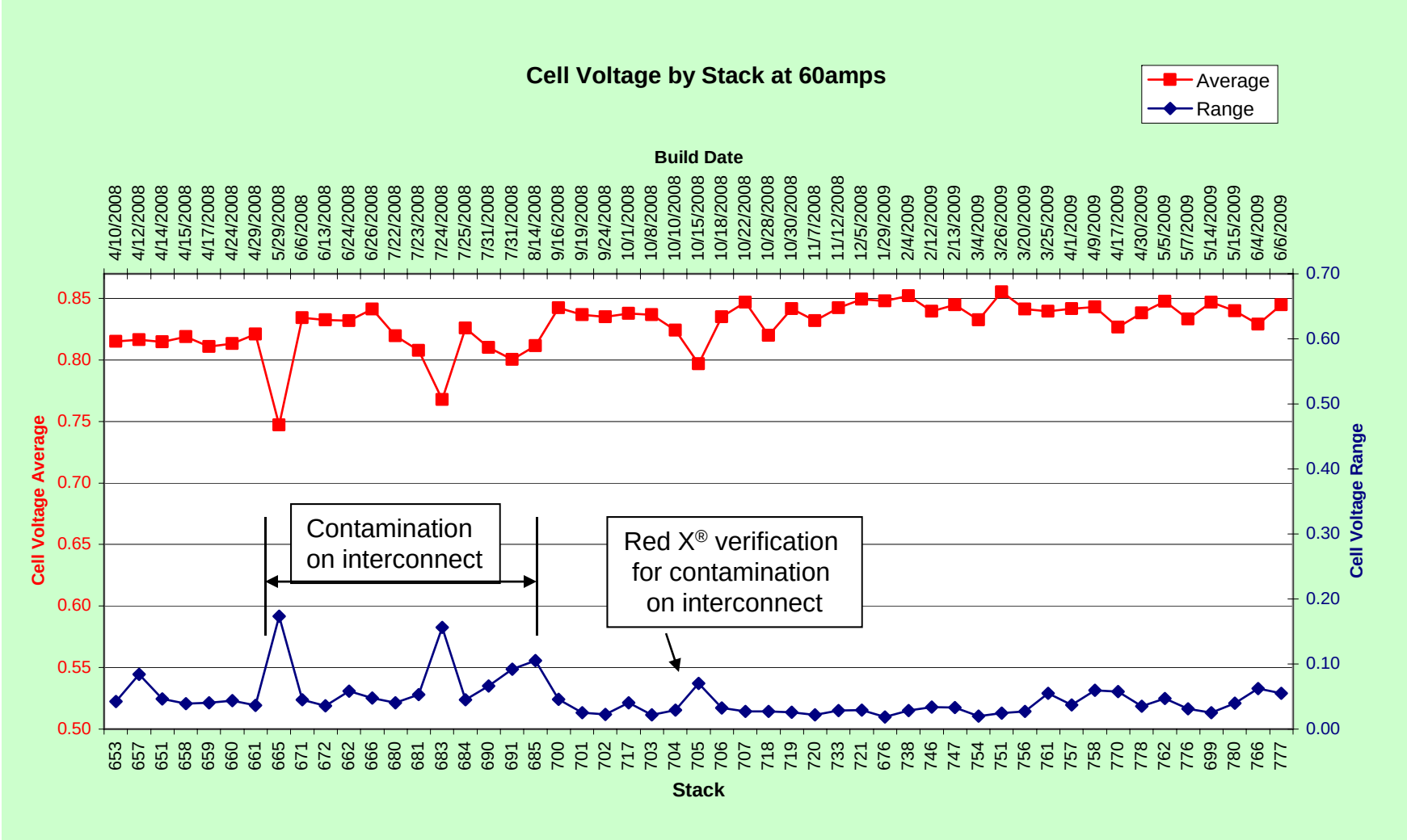
# Generation 3.2 30-Cell Stack

- Data from 30-cell Gen 3.2 stack with improved interconnect and cathode
- Very good cell to cell voltage distribution (0.02 Volts)



# Generation 3.2 30-Cell Stack Run Chart

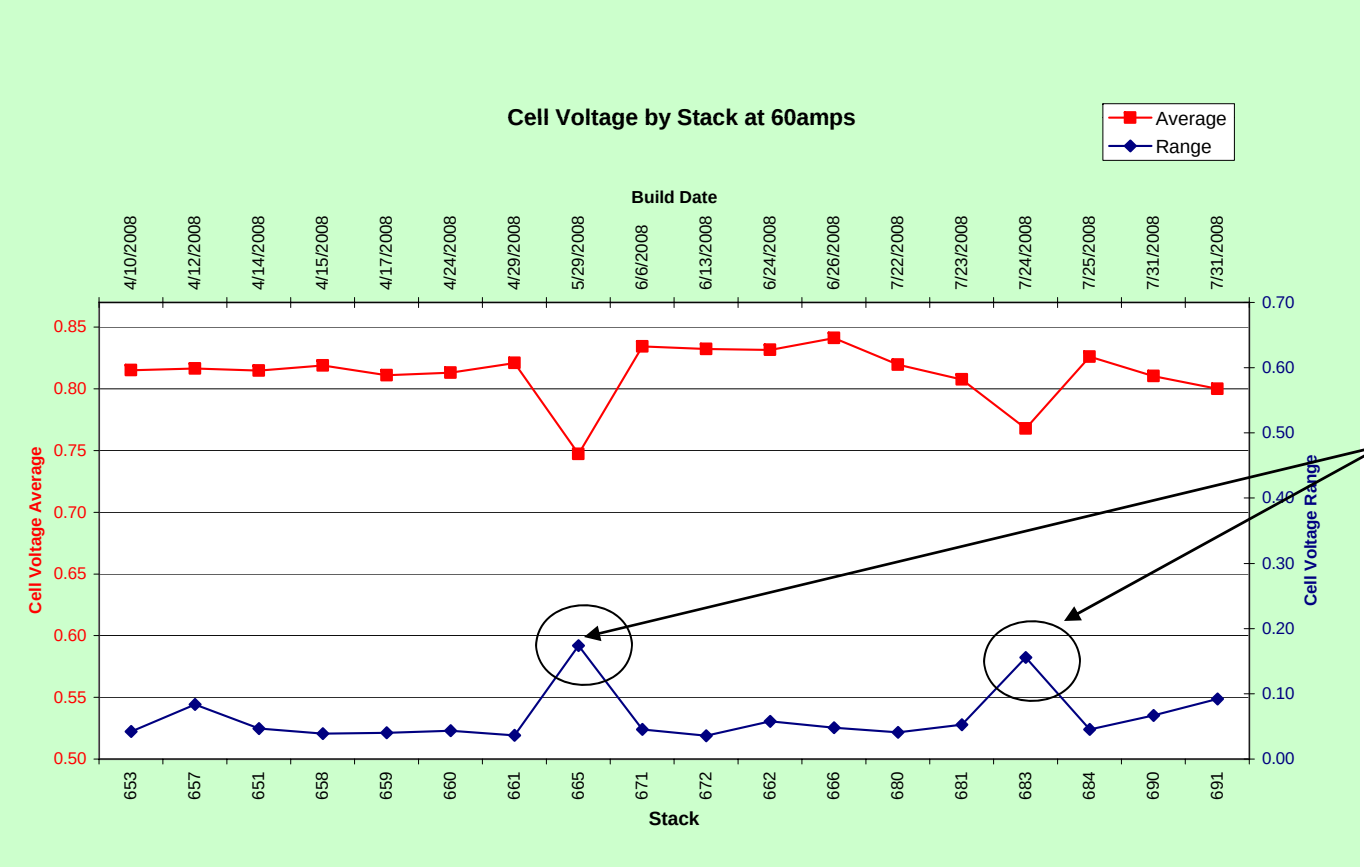
Very consistent performance in stack to stack builds



# Red X® Problem Solving Tools For Stack Issues

- Problem solving tools like Red X® are being utilized in stack manufacturing
- Lessons learned are being implemented for Gen 4 stack design and manufacturing

- Example: Find & eliminate the Red X® driving high cell voltage range




Did not meet voltage range specs

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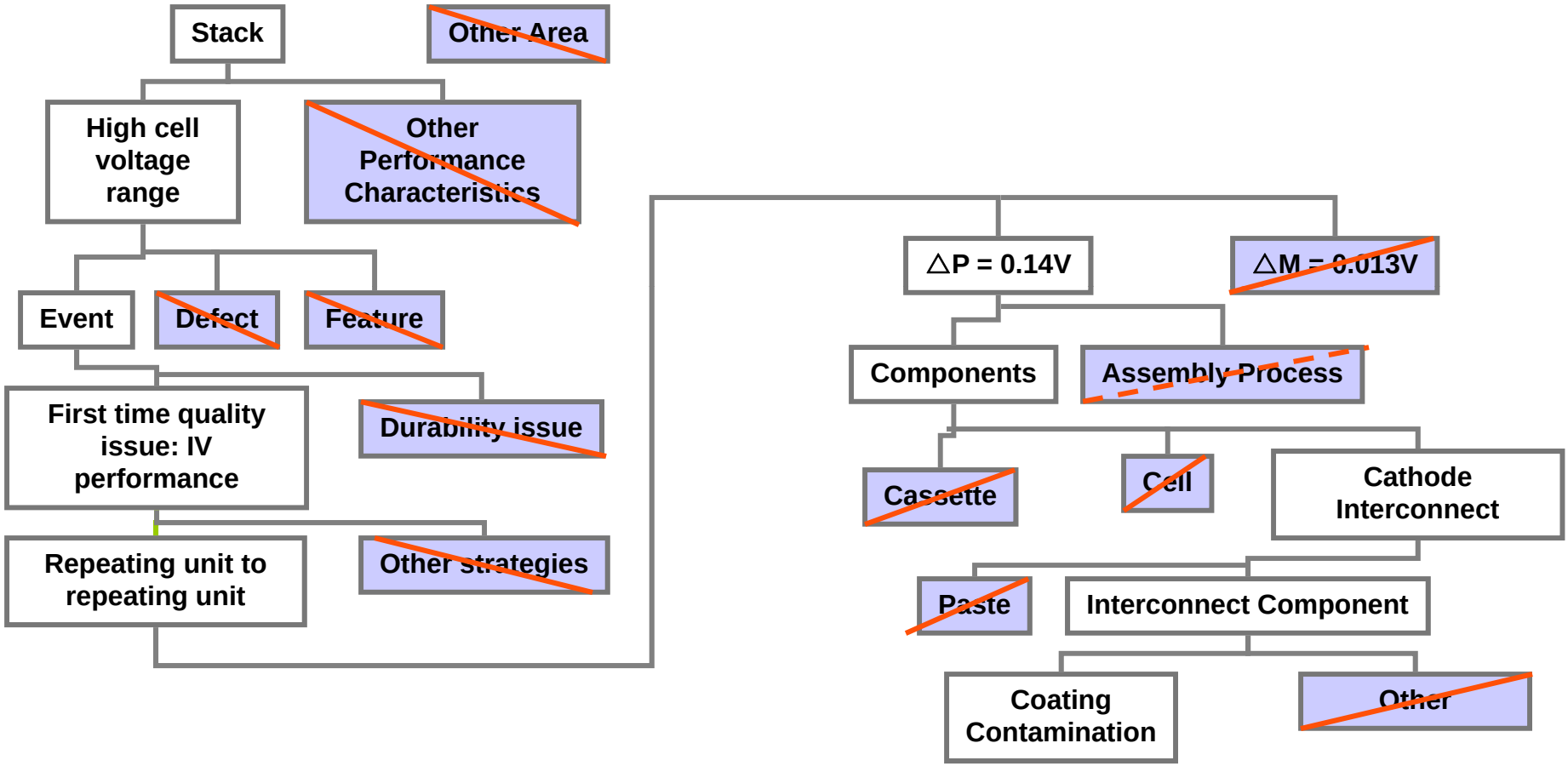
# Red X® Problem Definition Tree™




•Red X® was identified as contamination in the interconnect coating from a specific supplier

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# Optimization of Cathode Performance

- Robust Engineering tool used for performance optimization
  - Engineering optimization strategy for development of new technologies in product and process design
    - » Application of Taguchi methods for optimized performance
    - » Concentrates on identification of ideal function(s) and choosing best nominal values of design parameters for optimized performance reliability at lowest cost
  - L18 design with a “Nominal the Best” strategy was chosen for minimizing cathode polarization resistance on half cells
    - » L18 design allows for 1 control factor at 2 different levels and 7 control factors at 3 different levels
    - » Experiment results in 18 different treatment combinations
    - » Duplicates were fabricated from each treatment combination
    - » All 18 pairs were measured at two distinct noise conditions (72 runs)

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# Optimization of Cathode Performance

- Outcome of Robust Engineering Project
  - Reduced mean cathode polarization resistance by 70% compared to the standard cathode design
  - Confirmed improved electrochemical performance with button cell tests
  - Full-sized cells fabricated and to be built into stacks for evaluation

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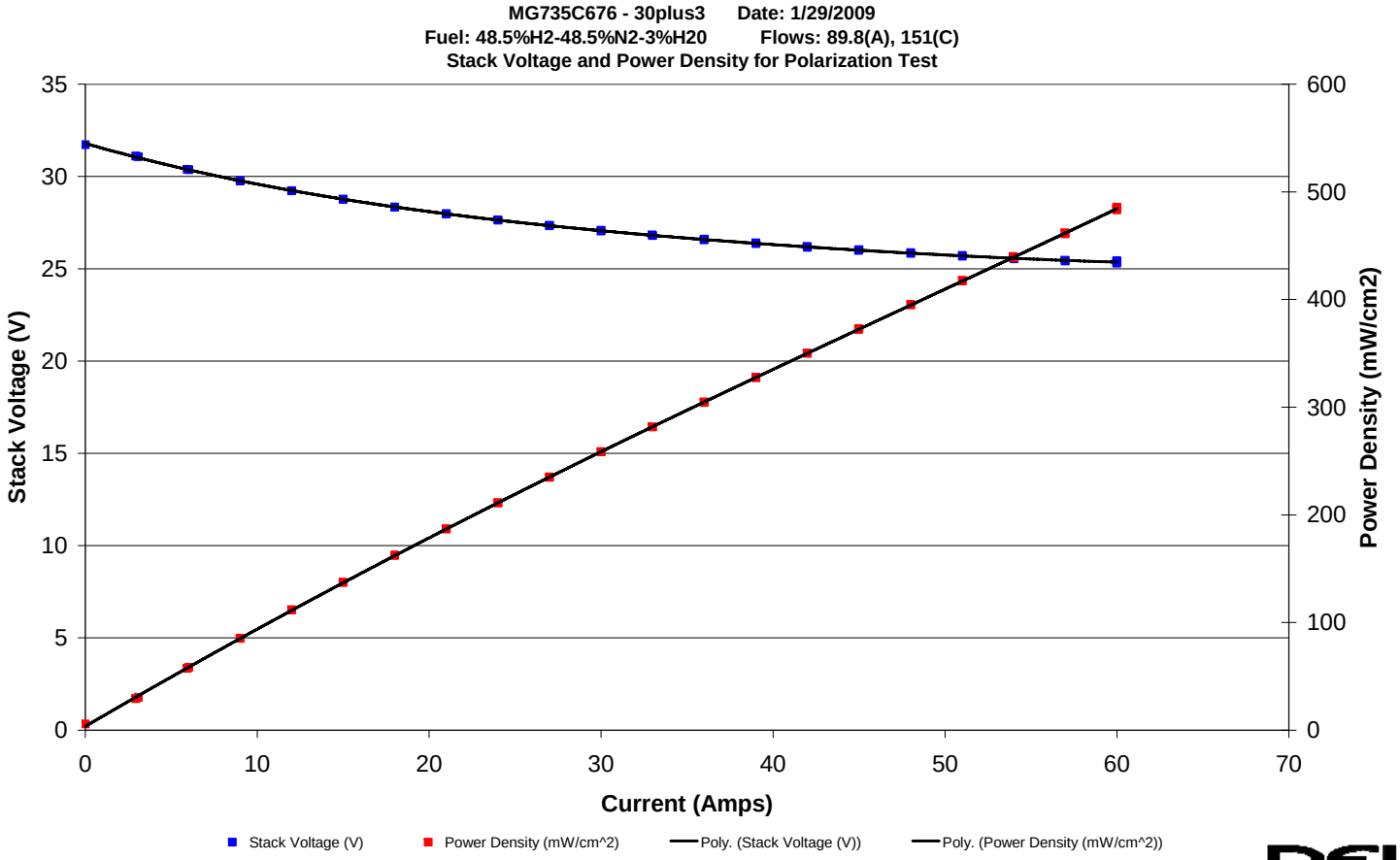
# Typical Gen 3.2 30-Cell Stack Performance

Power: 1.53 kW (486 mW/cm$^2$) @ 60A (570 mA per cm$^2$), 25.5 V (0.85V / cell avg), fuel 48.5% $H_2$ ,3% $H_2O$, rest $N_2$, 750 – 800$^o$C

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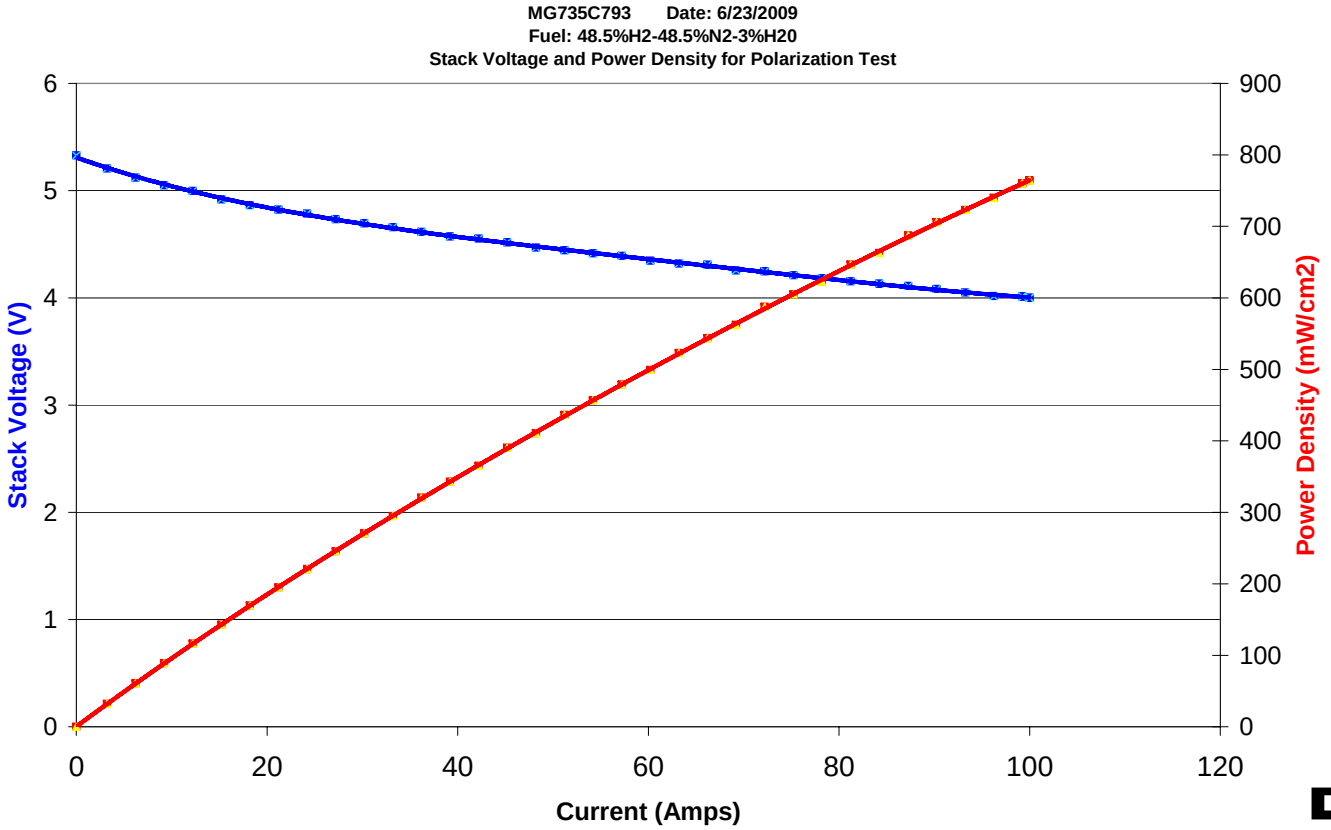
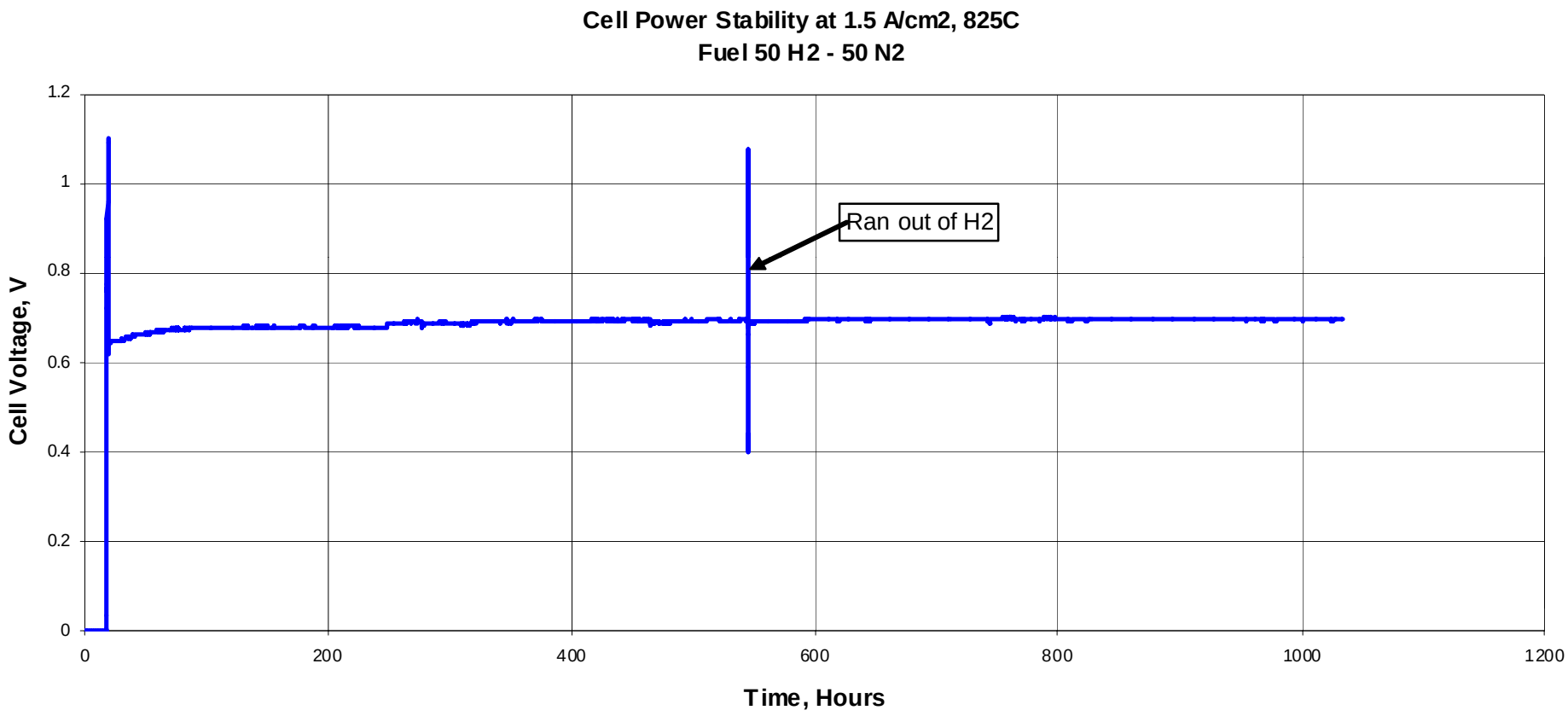
# Gen 3.2 5-Cell Stack – Maximum Power

- Data from recent 5-cell Gen 3.2 stack
- Produced 500 mW/cm$^2$ @ 60A (570 mA per cm$^2$), 0.87V / cell avg, fuel 48.5% H$^2$ ,3% $H_2O$, rest $N_2$, 750 – 800$^o$C
- Max Power density: 765 mW/cm$^2$ @ 100 Amps (952 mA per cm$^2$), 0.80V / cell avg, fuel 48.5% $H_2$, 3% $H_2O$, rest $N_2$, 750 – 825$^o$C

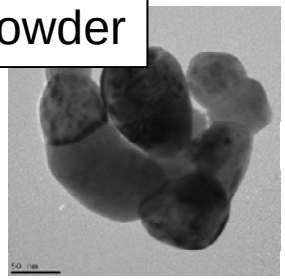


# Button Cell Accelerated Testing (at Kettering Univ.)

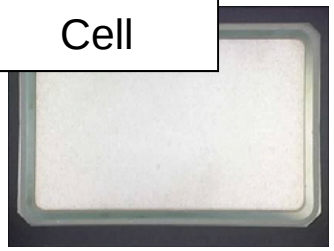


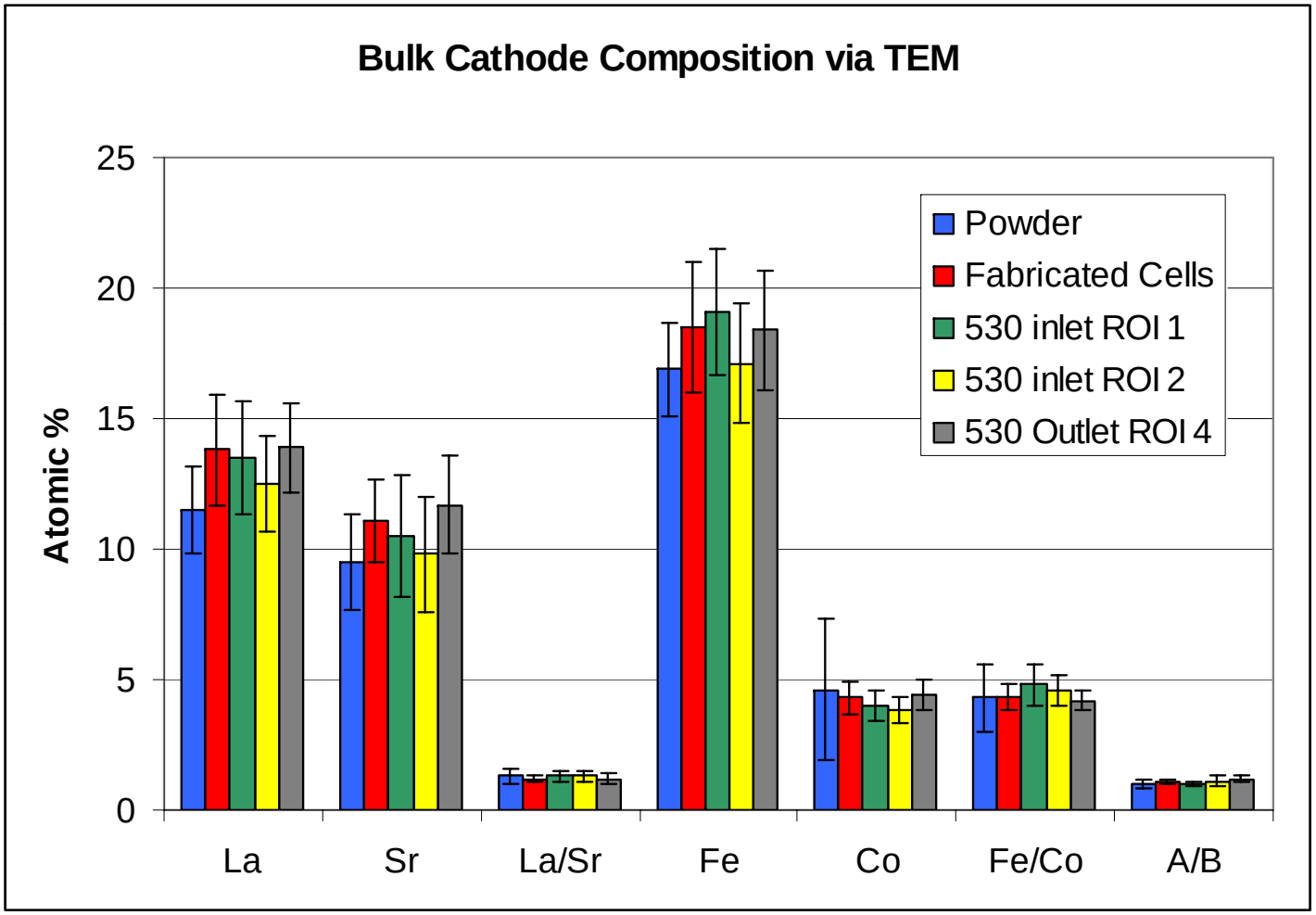
# Cathode Stability (at Carnegie Mellon University)

Powder



Fabricated Cell






5-cell stack (#530) tested 3500+ hrs at 0.8 V/cell on 28%H2 – 30%CO – 6%H2O – 2.5 ppmv S

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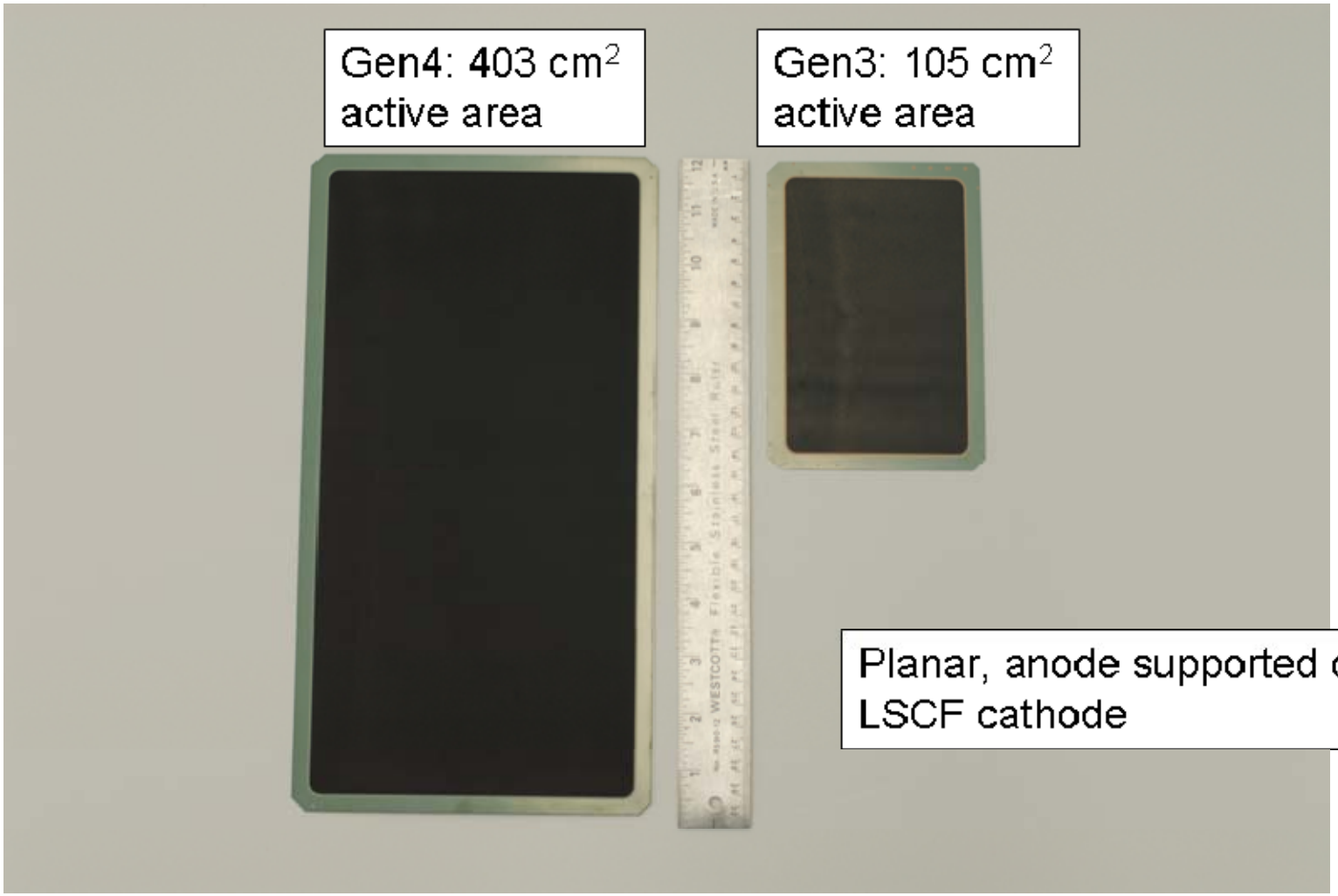
# Gen 4 Cell Development for Coal Based Systems

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# Gen 4 Stack Design for Coal Based Systems

- Delphi is developing its Generation 4 stack as the module for meeting stationary and transportation application requirements
- Key stack features are:
  - Laser welded cassette repeating unit configuration
  - Stamped metallic cassette components
  - Stamped interconnects
  - Low cost coatings
  - Low cost, conventionally processed balance of stack components

Gen 3 stack

About 4x active area of Gen3
Lower cost interconnects/coatings than Gen3
High volume production processes
5 kW core building blocks

Gen 4 stack

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# Gen 4 Stack Development  Status

- Gen 4 stack design is complete
- Design concepting completed in Q1, 2009
- Gen 4 stack components are being fabricated for stack build
- Process development and optimization ongoing to fabricate cells, cassettes, and stacks
- Pre-prototype large footprint stacks built and tested in Q4, 2008 to confirm design concept

Laser welding of SOFC parts

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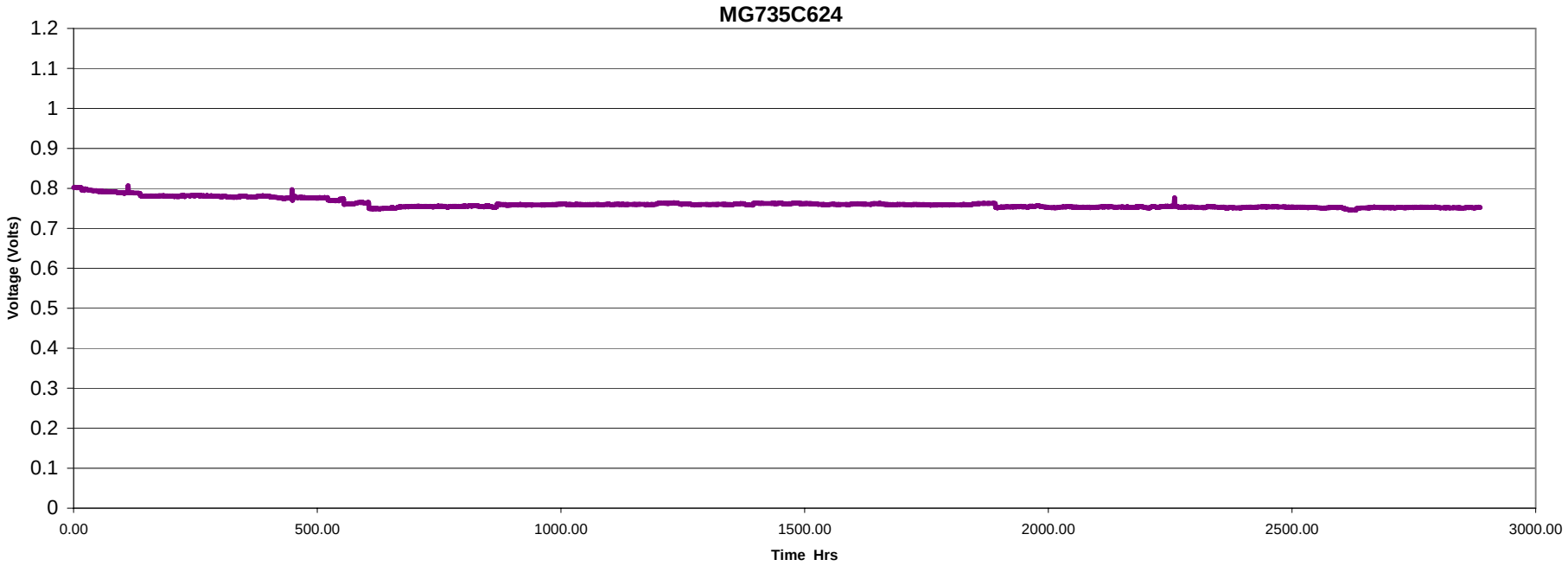
# Interconnect Development – Materials & Coatings

- Base material is ferritic stainless steel alloy
- Multiple coatings under evaluation
  - Low cost, conventionally processed coating demonstrated good stability in stack test
  - Graph shows typical repeating unit performance in a stack with coating tested for durability (Fuel = 48.5 % $H_2$, 3% $H_2O$, rest $N_2$, constant current of 570 mA per $cm^2$)
  - Further development is ongoing

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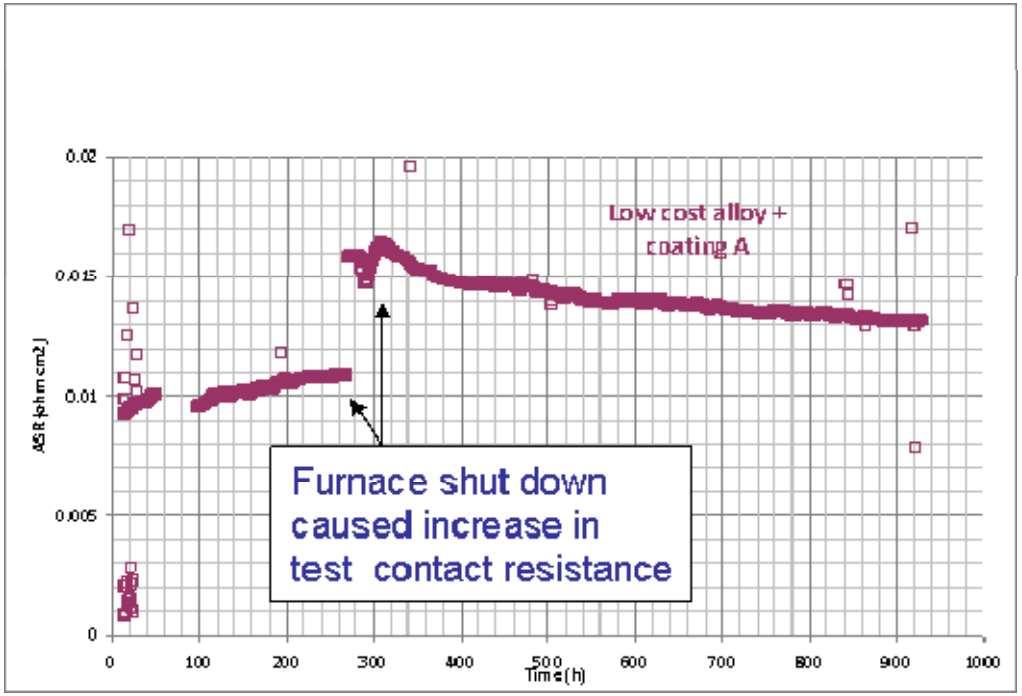
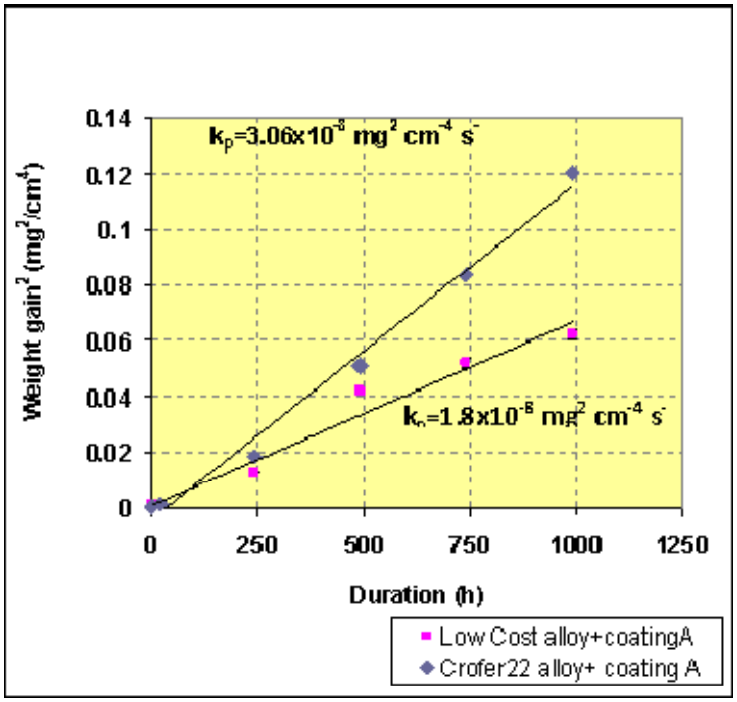
# Collaboration with UTRC

- Delphi is working with UTRC on materials and process development of base alloys and coatings
- Multiple alloys and coatings are being evaluated
- Low cost, manufacturable coating application processes are being developed

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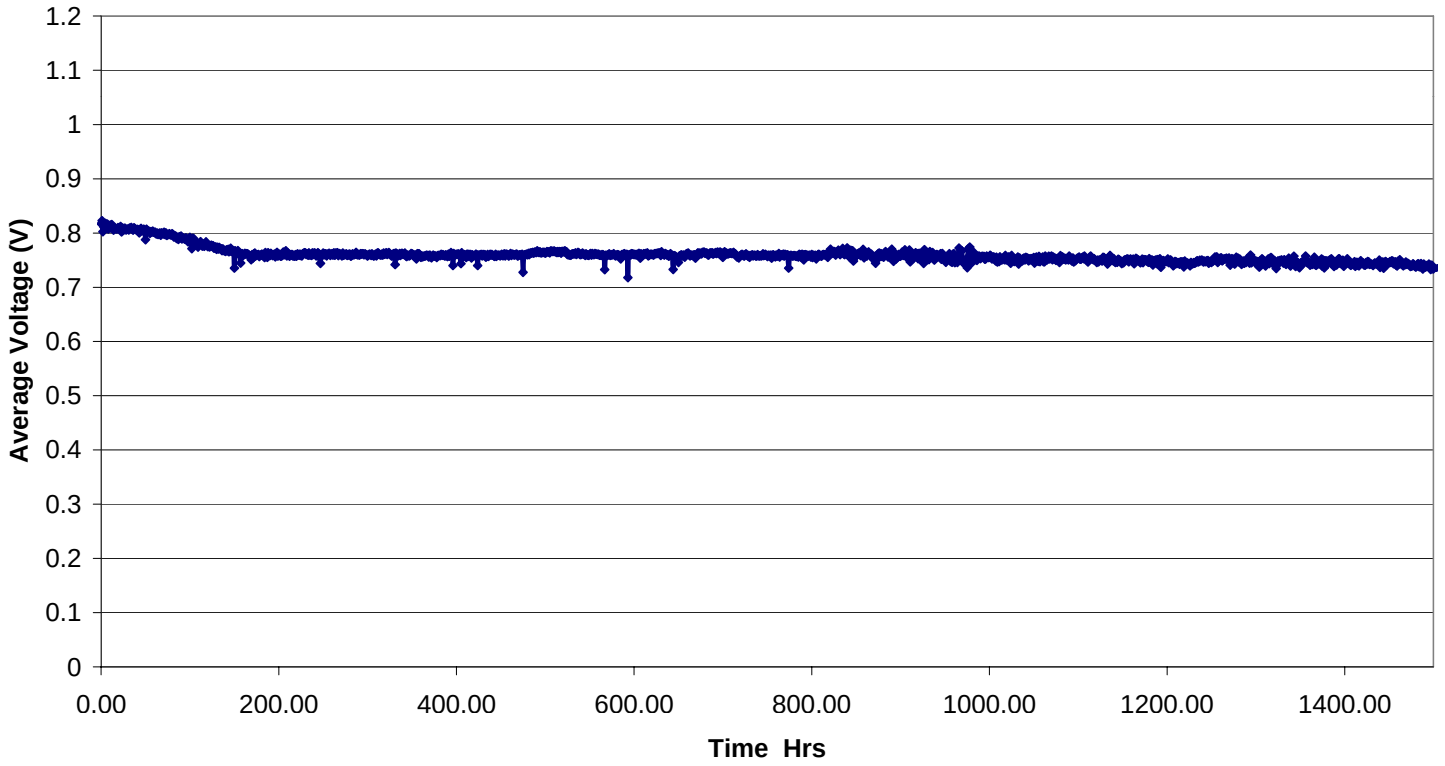
# Gen 3.2 Stack Durability with Syngas

- 10-cell Gen 3.2 stack on syngas (24%$H_2$ – 25% CO – 5% $CO_2$ – 7% $H_2O$ – Bal $N_2$) at 35 amps and 750C
- Initial voltage drop observed in the first 200 hours due to sulfur
- Minimal degradation in the last 1300 hours

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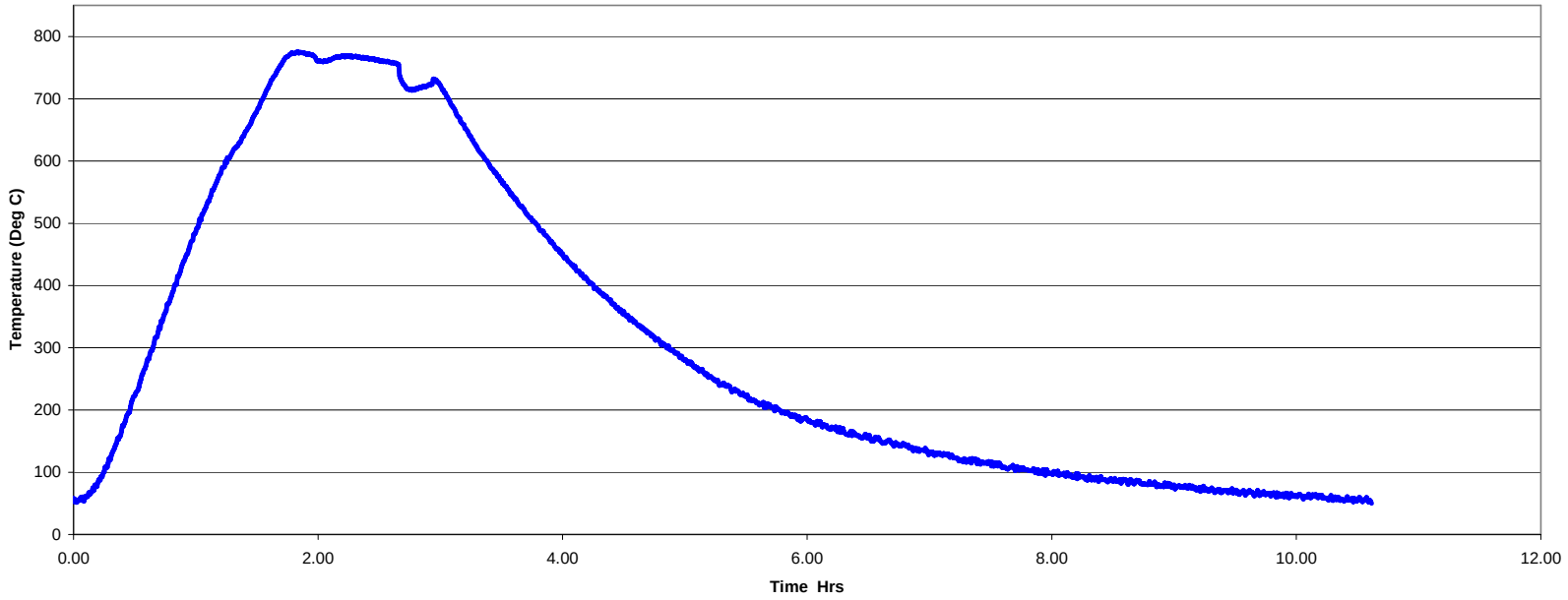
# Gen3.2 30-Cell Stack Thermal Cycling

- Gen 3.2 30-cell stack being thermal cycled
  - 10 hour cycle from 50°C to operating temperature to 50°C
  - Performance evaluated at each thermal cycle
  - Constant current load of 30 Amps at operating temperature
  - Fuel of 48.5% $H_2$, 3% $H_2O$, rest $N_2$

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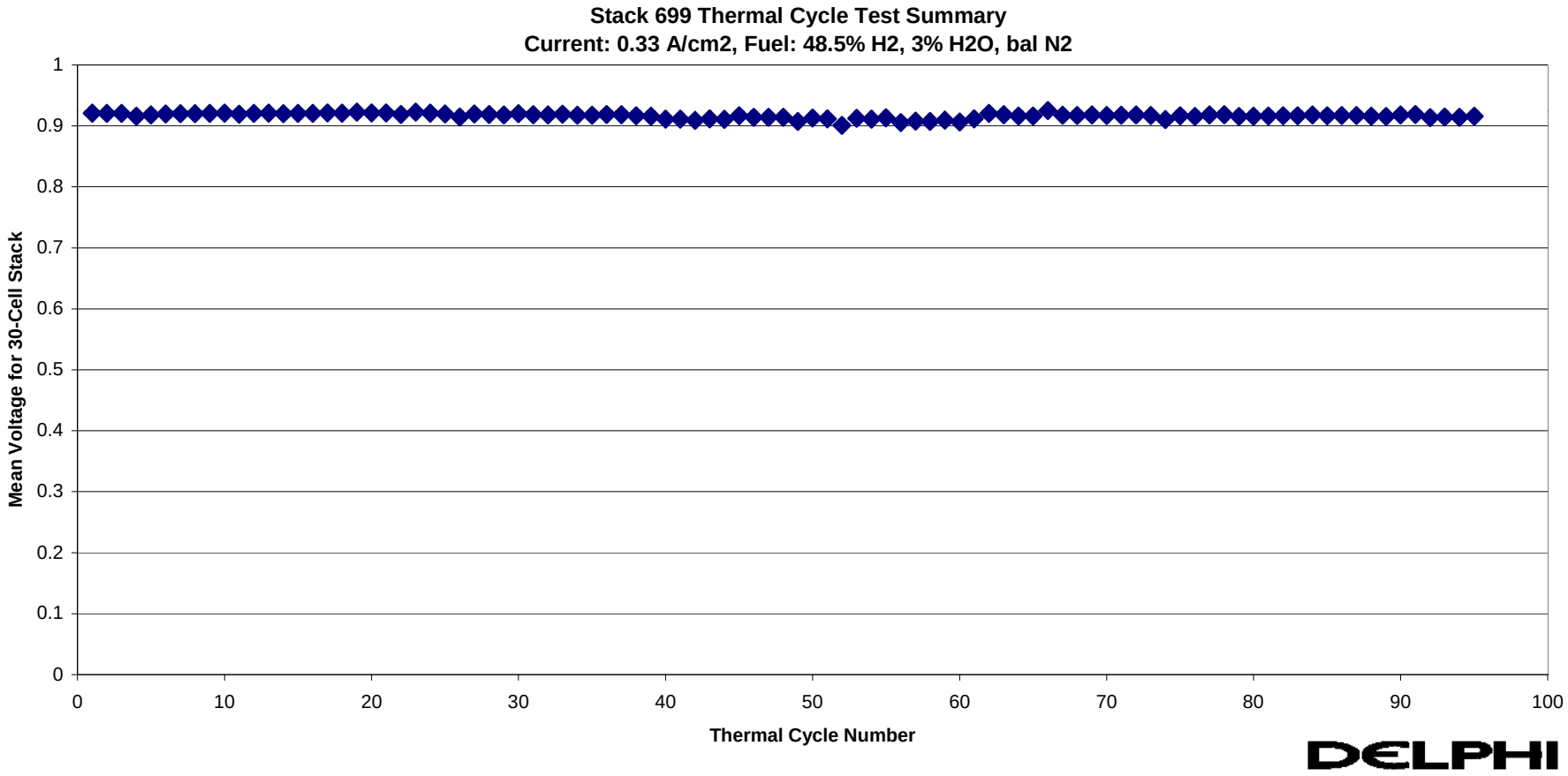
# Gen 3.2 30-Cell Stack – Thermal Cycling

- 95 full thermal cycles completed with minimal degradation (less than 0.5%)
- Test continuing to failure
- Robustness to thermal cycling allows for coal-based system shutdowns, maintenance, unplanned outages, etc.



# SOFC Market Opportunities


**Clean Coal Power Plant**

**Advanced Power Systems**

SOFC modularity and fuel flexibility allow for early market opportunities

**Commercial Power**

**Stationary Power Units**

**Residential Power**

**Stationary CHP Power Units**

**Heavy Duty Trucks**

**Auxiliary Power Units**

**Military**

**Auxiliary & Mobile Power Units**

**Recreational Vehicles**

**Auxiliary Power Units**

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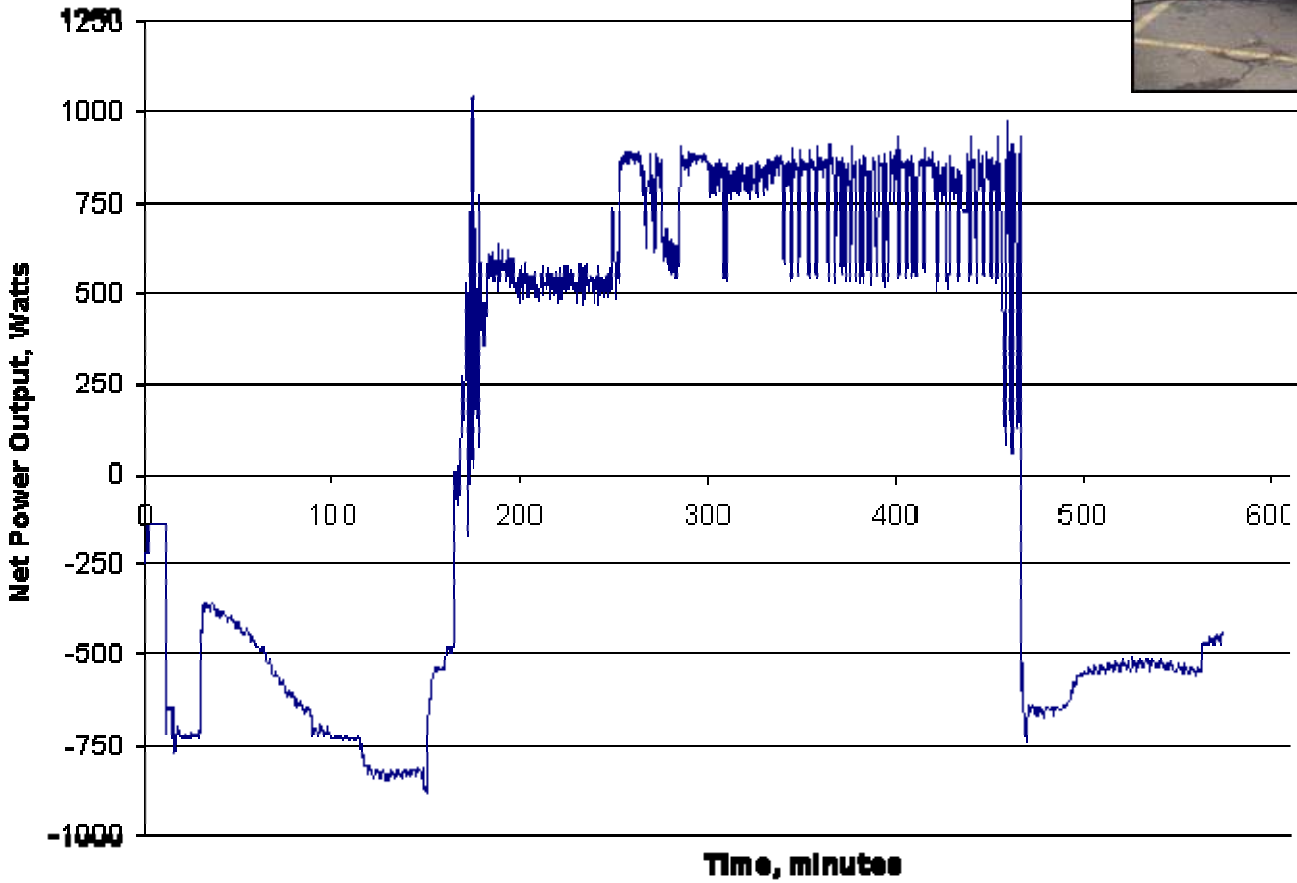
# Daimler Truck Field Demo


•System with 2 Gen 3.2 stacks provided power during period of dynamic load changes




Next Gen APU
Uses Gen 4 Stack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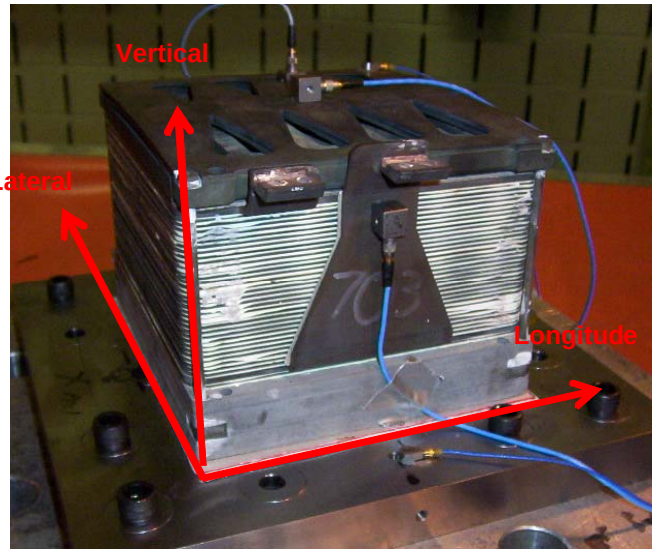
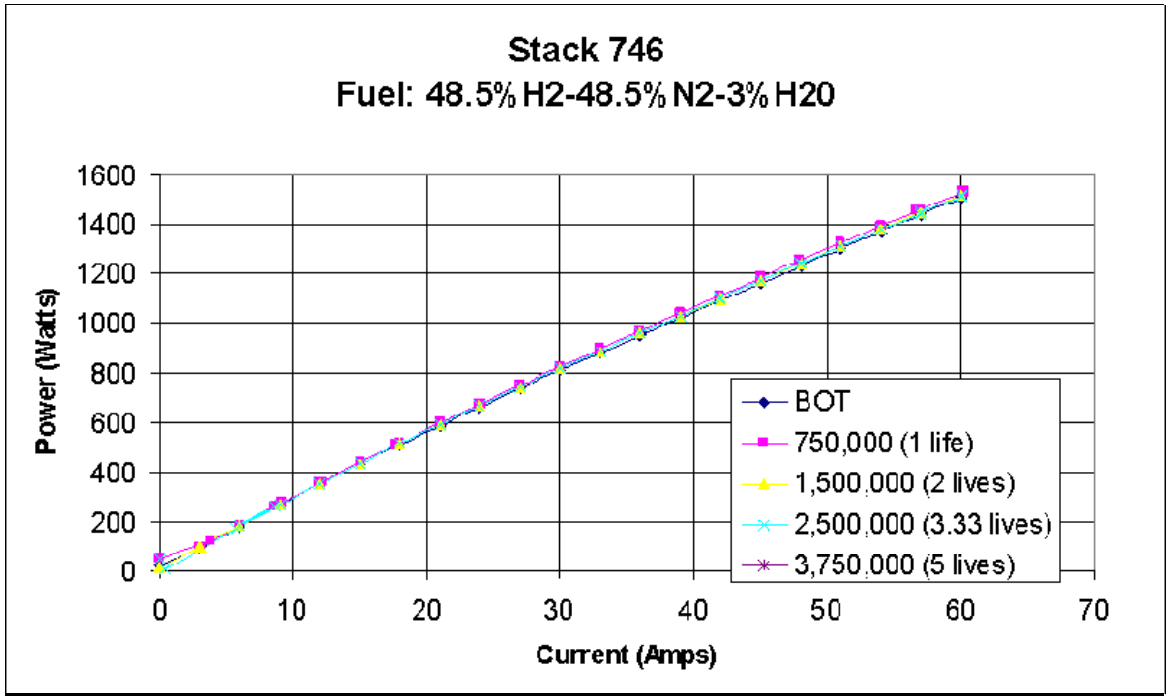
# Gen 3.2 30-Cell Stack Vibration Testing

- Test to Failure using Step Over Stress strategy to assess stack reliability
  - Mil Std 810G Method 514.6 Annex C, “Truck and Transportation Over US Highways”
  - Ambient temperature random vibration in 3 distinct axes
  - Performance evaluated after each axis of testing
- Successfully completed 3.75 million miles equiv. of vibration (5 APU lifetimes)
- Test is continuing to an additional level of stress



# Stack Testing at NUWC

- Delphi, SECA (US Dept. of Energy), and the US Navy are collaborating for SOFC technology evaluation for undersea Naval applications
- System application represents extreme conditions for SOFC environment
- A 30-cell Delphi Gen 3.2 stack was integrated with Steam Reformer, High Temp Blower, and $CO_2$ Sorbent Bed (bread board system) at NUWC
- S-8 Fuel and pure oxygen were the only reactants fed into system
- Performance achieved
  - 1 kW Power
  - 75% S-8 Fuel Utilization
  - 90% Oxygen Utilization
  - 50% Efficiency*

*** SOFC Power output / S-8 Lower Heating Value**

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# Acknowledgements




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Pacific Northwest National Laboratory
...delivering breakthrough science and technology

UTC Power
A United Technologies Company

United Technologies
Research Center

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