# Progress on the Development of Reversible SOFC Stack Technology

**Presented by: Casey Brown**

**19 April 2011**

# Versa Power Systems

- **Versa Power Systems is a developer of planar solid oxide fuel cells (SOFCs)**
- **Privately held company headquartered in Littleton, Colorado, United States**
- **SOFC development facility in Calgary, Alberta, Canada**
- **Activities in both stationary and mobile SOFC development**


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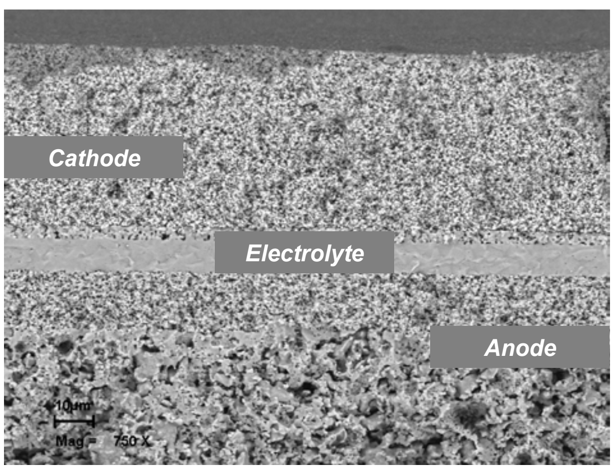
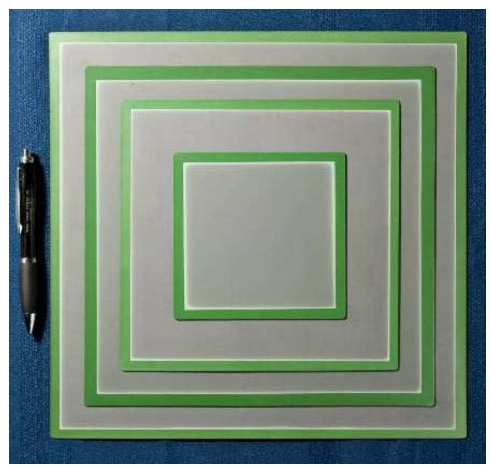
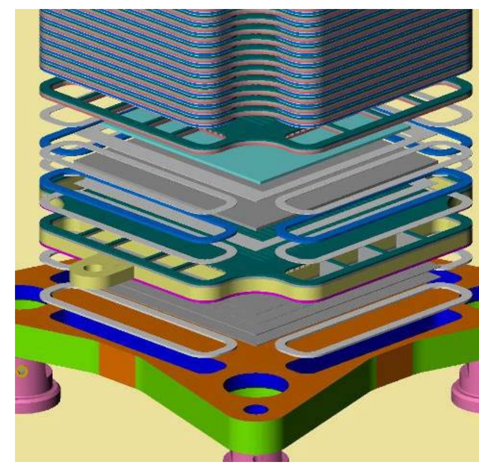
# VPS Planar SOFC Cell and Stack

- **Anode supported cells**
- **Operating temperature range of 650 C to 800°C**
- **Ferritic stainless steel sheet interconnect**
- **Cross-flow gas delivery**
- **Stack can be integrated into stack towers for various power applications**





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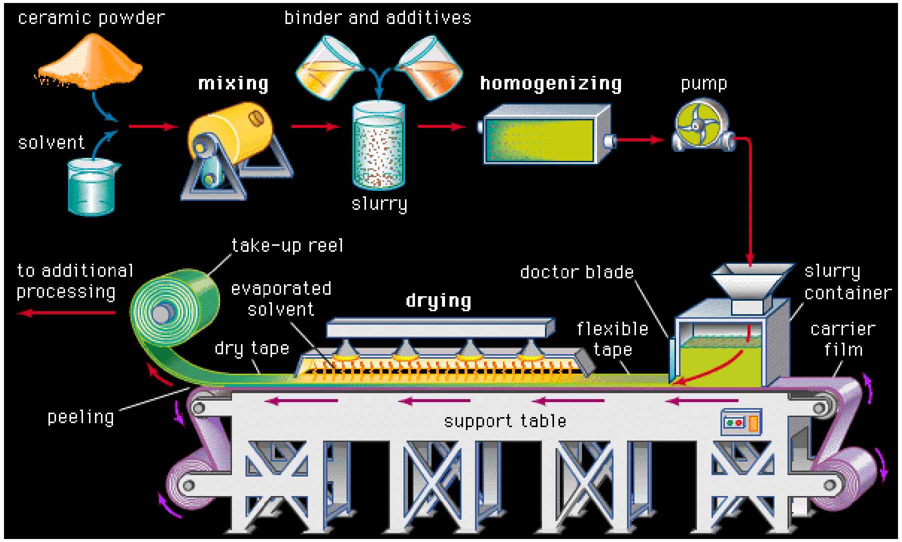
# Tape Casting

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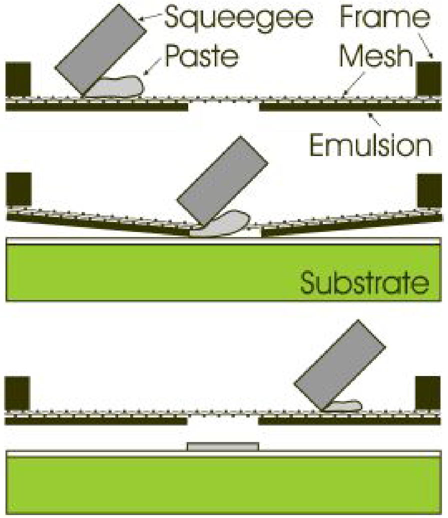
# Screen Printing

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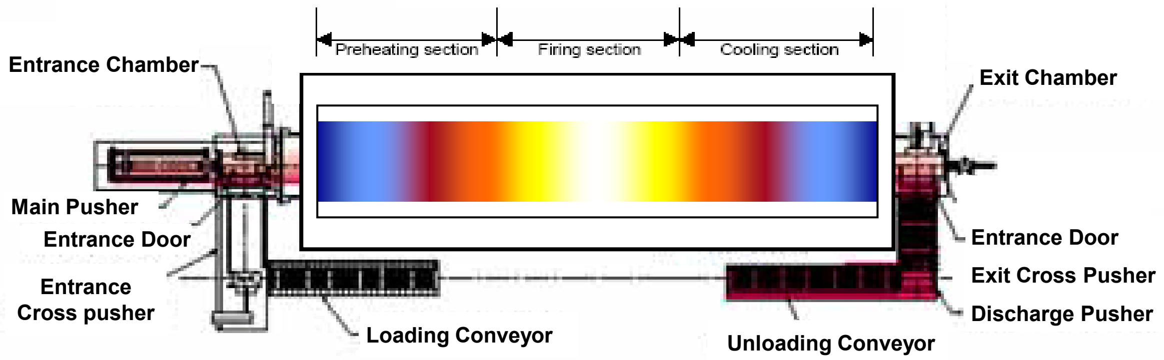
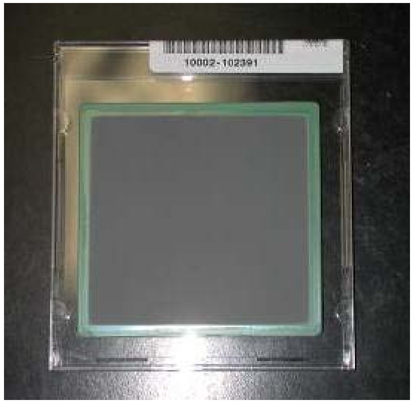
# High Temperature Co-firing



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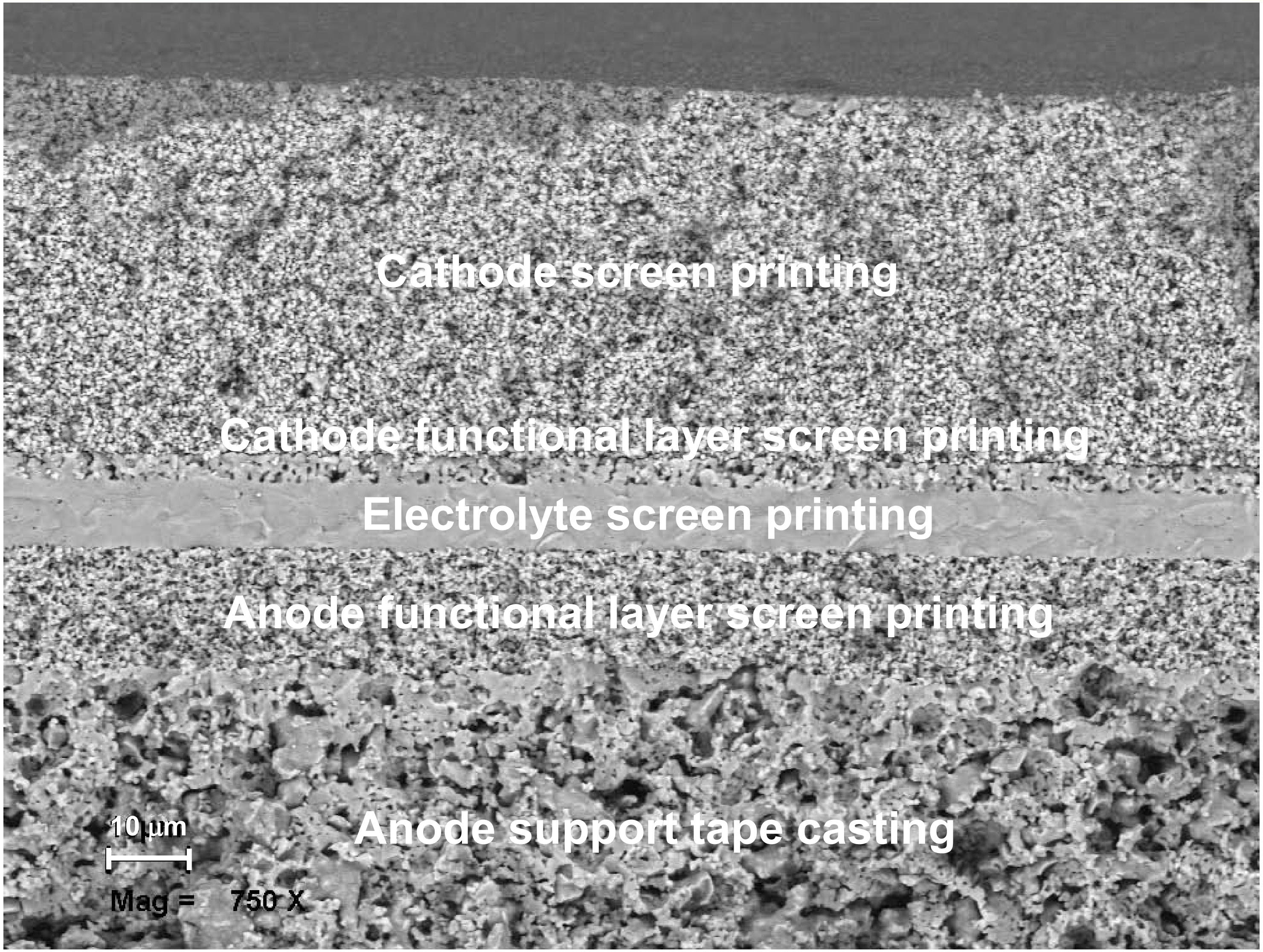
# TSC Cell Microstructure

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# VPS Processes

- **The established processes proved flexible enough to allow more than 8X increase in cell active area (121 → 1000 cm$^2$) without appreciable change in performance or yield**
- **25 x 25 cm$^2$ cells (550 cm$^2$ active area) are being used for SECA stack development**

Tape Casting

Screen Printing


Co-sintering

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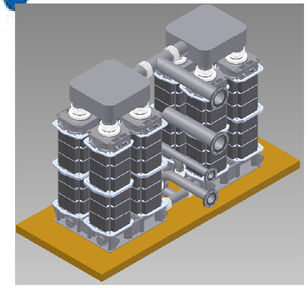
# VPS Activity Areas



- US DOE Fossil Energy SECA
  Development and supply of SOFC technology for operation on gasified coal
  - Scale-up and R&D of SOFC for Coal-Based SOFC systems
  - Large area cells and high kW stacks
- Boeing // DARPA
  Vulture II : 5 year autonomous aircraft
  - Development and delivery of high efficiency energy storage system
  - High specific power
  - Low degradation
- US DOE EERE
  Advanced Materials for RSOFC Dual Mode Operation with Low Degradation
  - Reversible SOFC materials development and demonstration
  - kW stack demonstration
- INL
  Solid Oxide Electrolysis 1-kW Stack Testing to Investigate Degradation
  - Demonstration of 1 kW electrolysis stack
- VTT (Finnish National Laboratory)
  Demonstration of 10 kW Natural Gas fired system
  - Supply of 10 kW Solid Oxide module for integration and testing with balance of plant

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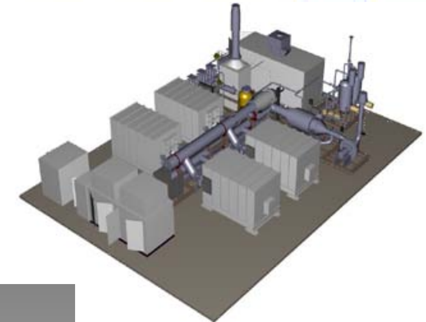
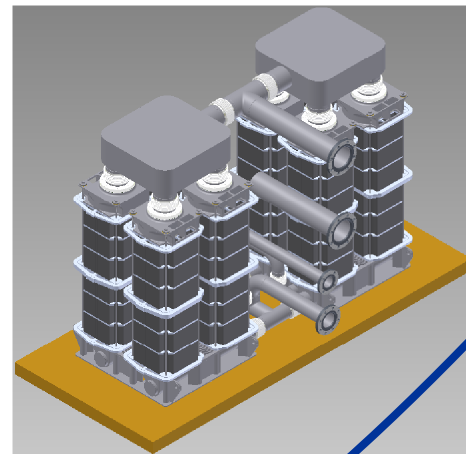
# U.S. DOE SECA Project

VPS participates in the U.S. Department of Energy's SECA program with a goal of developing large-scale SOFC power systems (project prime is FuelCell Energy)



**_SOFC Power Module_**



**_Stack Tower_**

**_10-20 kW Stack_**

**_1 kW Stack_**

- VPS responsible for core cell & stack technology
- 25 x 25 $cm^2$ cell and 20 kW (96-cell) stack block has been selected as the development platform

FuelCell Energy

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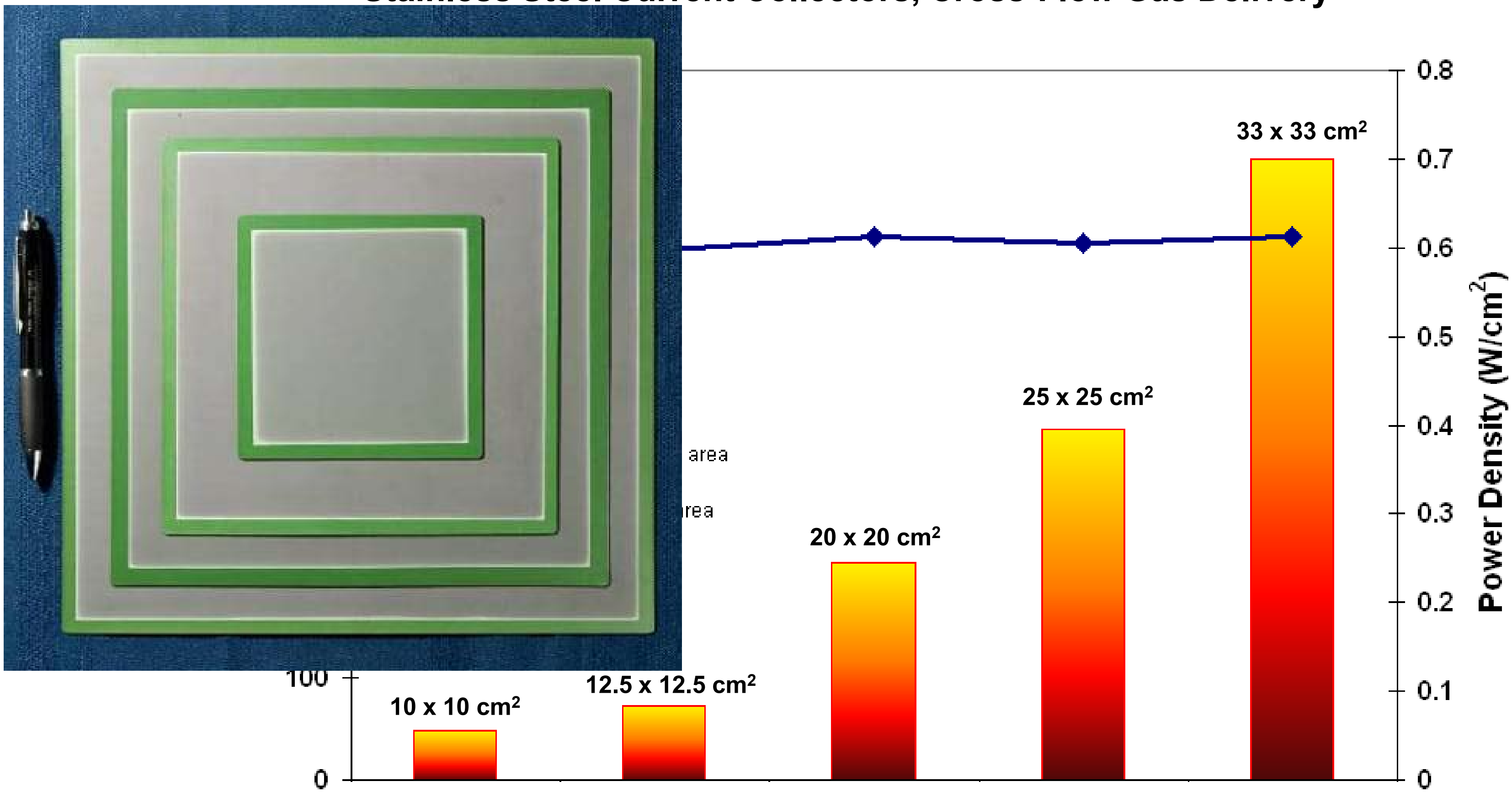
# Cell Scale-Up Status

**Stainless Steel Current Collectors, Cross-Flow Gas Delivery**




| | | | | | |
|---|---|---|---|---|---|
| Power | 49 | 72 | 214 | 346 | 612 |
| Power Density | 0.608 | 0.598 | 0.612 | 0.606 | 0.612 |

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# SECA

While not directly interested in electrolysis, the SECA program has enabled VPS to demonstrate scale up, performance and degradation improvements that could be applicable to electrolysis and energy storage systems.


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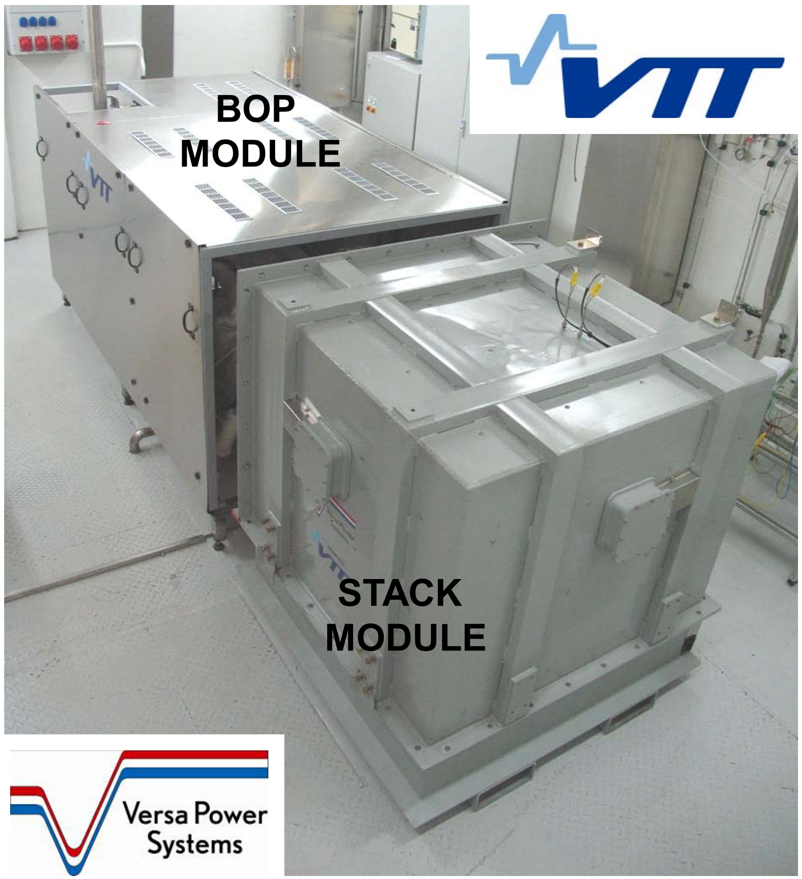
# 10 kW SOFC Demo Unit




VPS has collaborated with VTT Technical Research Centre of Finland to produce a 10 kW fully integrated SOFC system

- VTT scope: system design & BoP-module
  - BoP-components: Heat exchangers, catalytic burner, reformer, recycle loop …
  - System control
- VPS scope: stack module
  - 10 kW class SOFC stack
  - Stack and module instrumentation
  - Assembled insulated vessel

Status:

- Modules integrated, operating, and meeting targets

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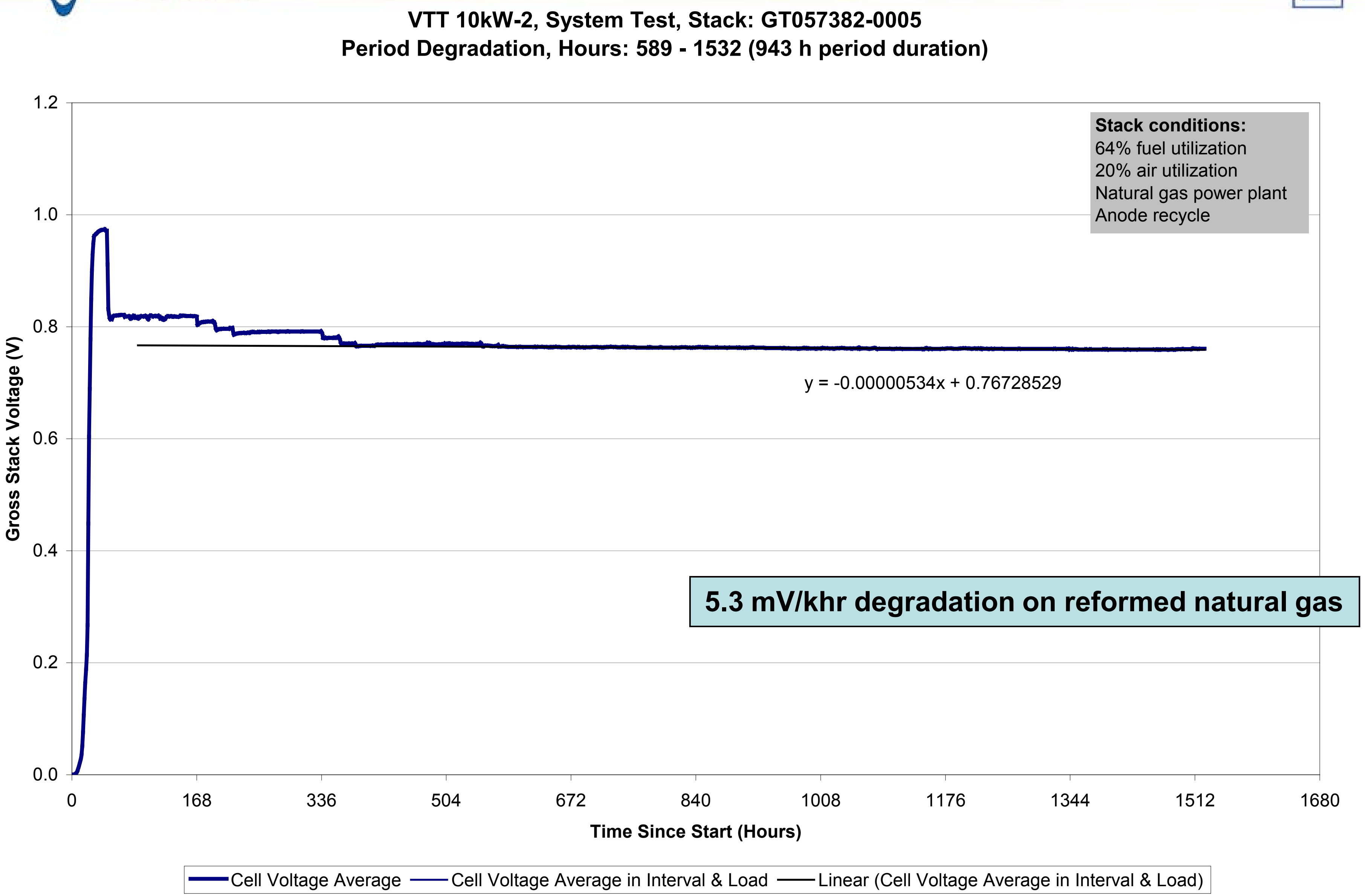
# 10 kW System Demo Unit at VTT

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# Boeing / DARPA Vulture II

General Characteristics

- Wingspan: 435 ft
- Altitude: 65000 ft
- Motors: solar/electric
- Endurance: 5 years
- Demonstrator first flight: 2014

- This is an aircraft program, not a fuel cell program. Reversible SOFC identified by Boeing as the best technology fit.
- VPS to deliver high efficiency, light weight, energy storage system

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# Single Cell Testing

Single cell testing allows controlled evaluation of new materials sets, and comparison to past results

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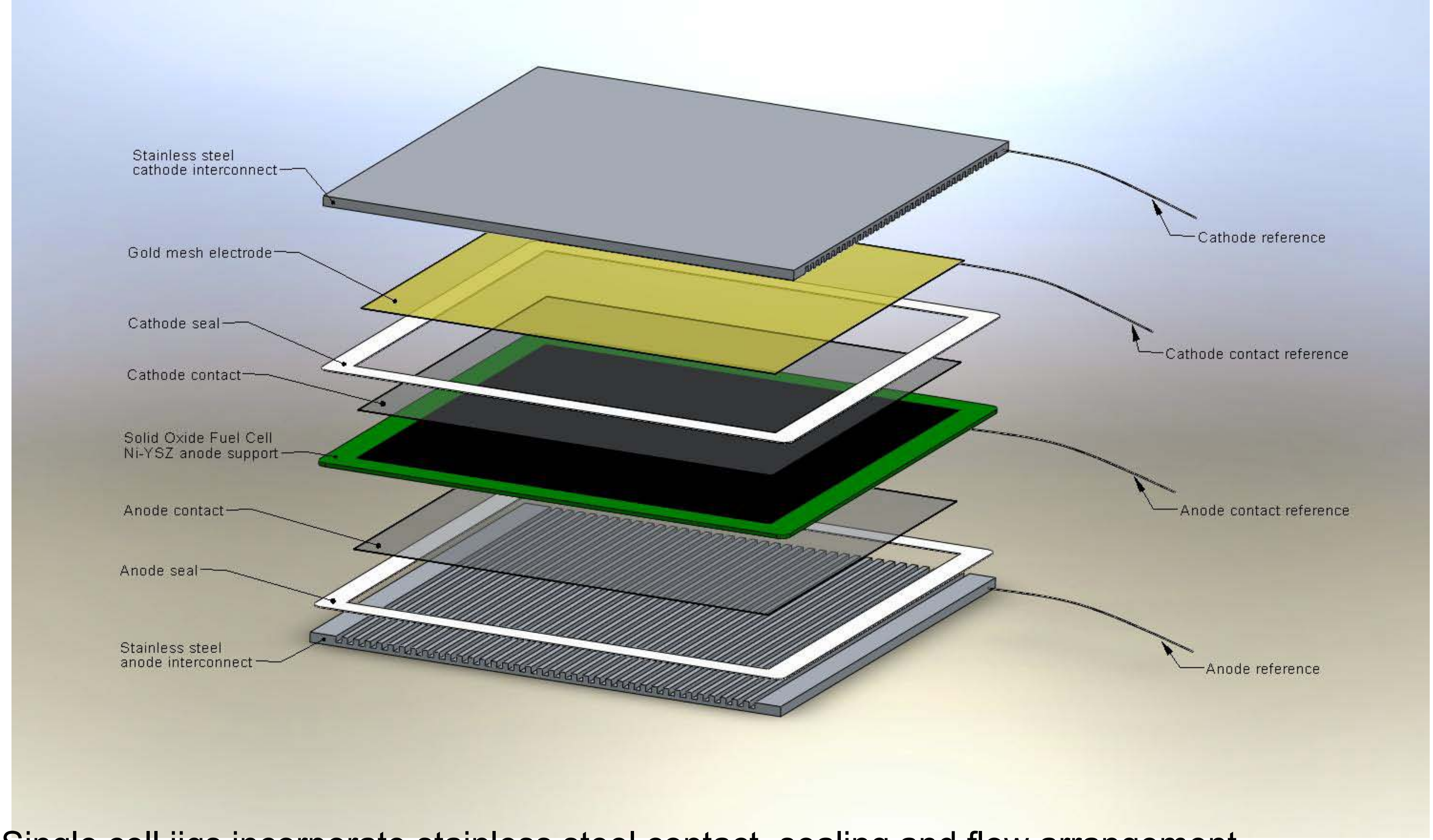
# Single Cell Testing at VPS




Single cell jigs incorporate stainless steel contact, sealing and flow arrangement representative of a stack

Degradation results include any jig degradation

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# Degradation Improvements

- 15 cell materials systems developed and tested since start of interest in electrolysis (~2008)
- 11 of these have been tested in excess of 1000 hours steady state electrolysis
- Summary of steady state results in table below
- Focus is now shifting to cyclic operation (FC/EL)

| Cell Type | ELECTROLYSIS (SOEC) Degradation mV/1000 hrs | %/1000hrs | Test time (hours) | Test No. |
|---|---|---|---|---|
| TARGET | < 50 | < 4 | 1000 | TARGET |
| TSC-2 | 91 | 7.3 | 2893 | GLOB 101670 |
| EC-1 | 27 | 2.2 | 8465 | GLOB 101695 |
| EC-2 | ~0 | ~0 | 2400 | GLOB 101706 |
| EC-3 | 72 | 5.8 | 1792 | GLOB 101728 |
| RSOFC-1 | 35 | 2.8 | 8746 | GLOB 101737 |
| RSOFC-2 | 120 | 9.6 | 1152 | GLOB 101738 |
| RSOFC-3 | 42 | 3.4 | 2653 | GLOB 101741 |
| RSOFC-4 | 24 | 1.9 | 3618 | GLOB 101744 |
| MAC-RSOFC-5 | 51 | 4.1 | 1059 | GLOB 101758 |
| RSOFC-6 | 31 | 2.5 | 689 | GLOB 101779 |
| RSOFC-7 | 18 | 1.4 | 1071 | GLOB 101780 |
| RSOFC-8 | 24 | 1.9 | 498 | GLOB 101782 |
| RSOFC-9 | 25 | 2.0 | 1002 | GLOB 101784 |

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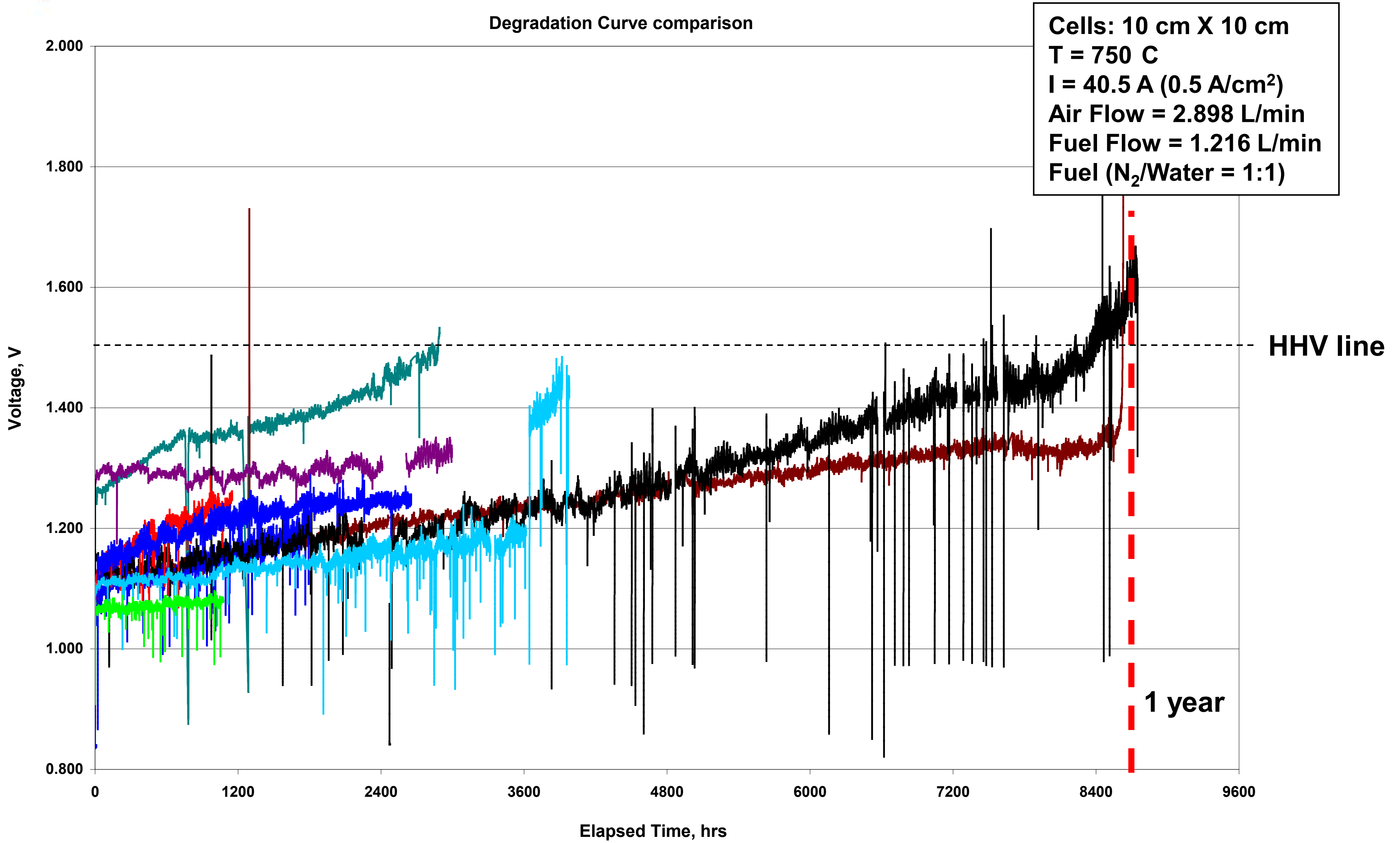
# Some Electrolysis Holds




Cells: 10 cm X 10 cm
T = 750 C
I = 40.5 A (0.5 A/cm$^2$)
Air Flow = 2.898 L/min
Fuel Flow = 1.216 L/min
Fuel ($N_2$/Water = 1:1)

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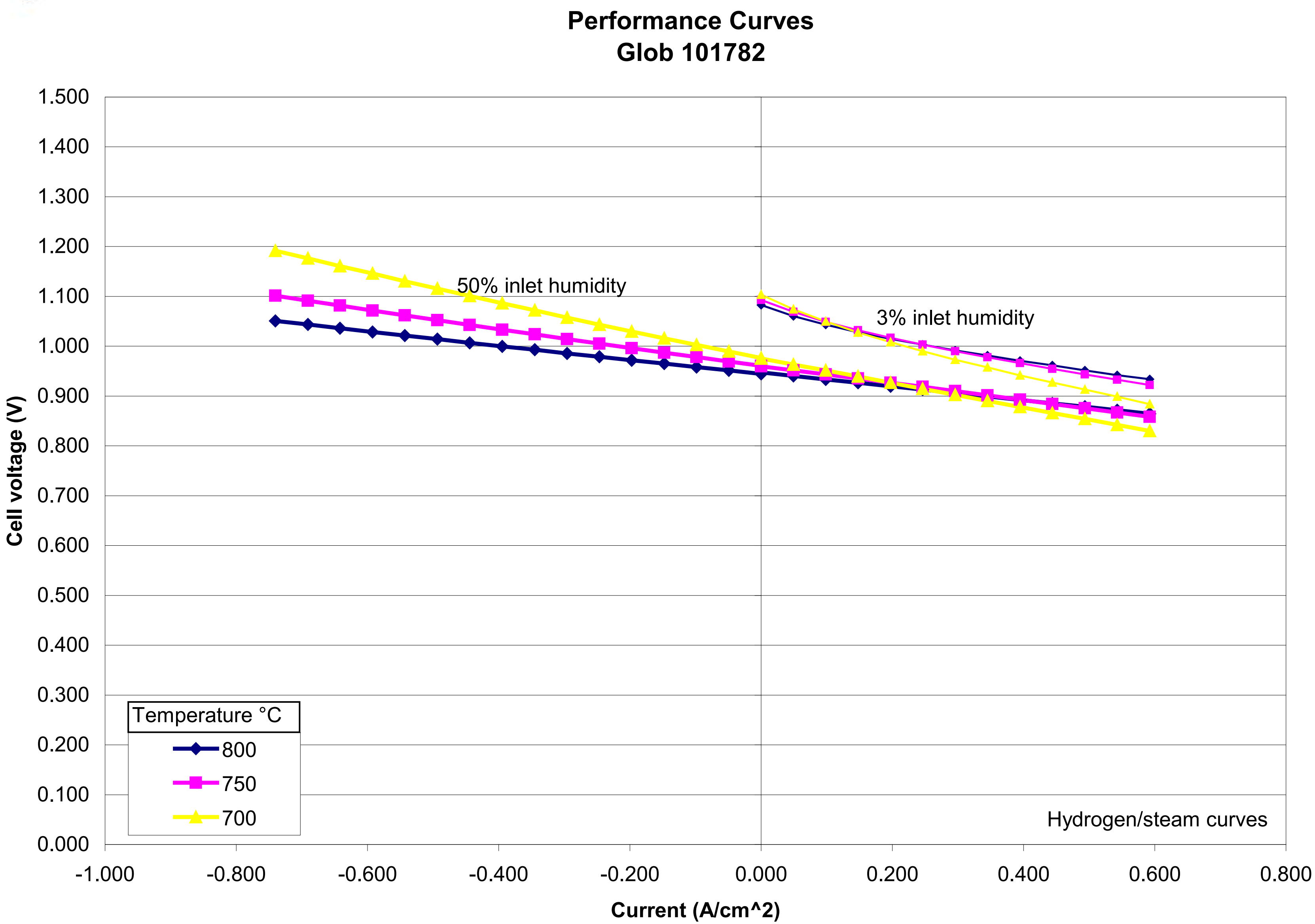
# RSOFC Cell Development

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# Stack Testing

In-stack testing demonstrates repeatability and stability of materials system in less controlled conditions than single cell

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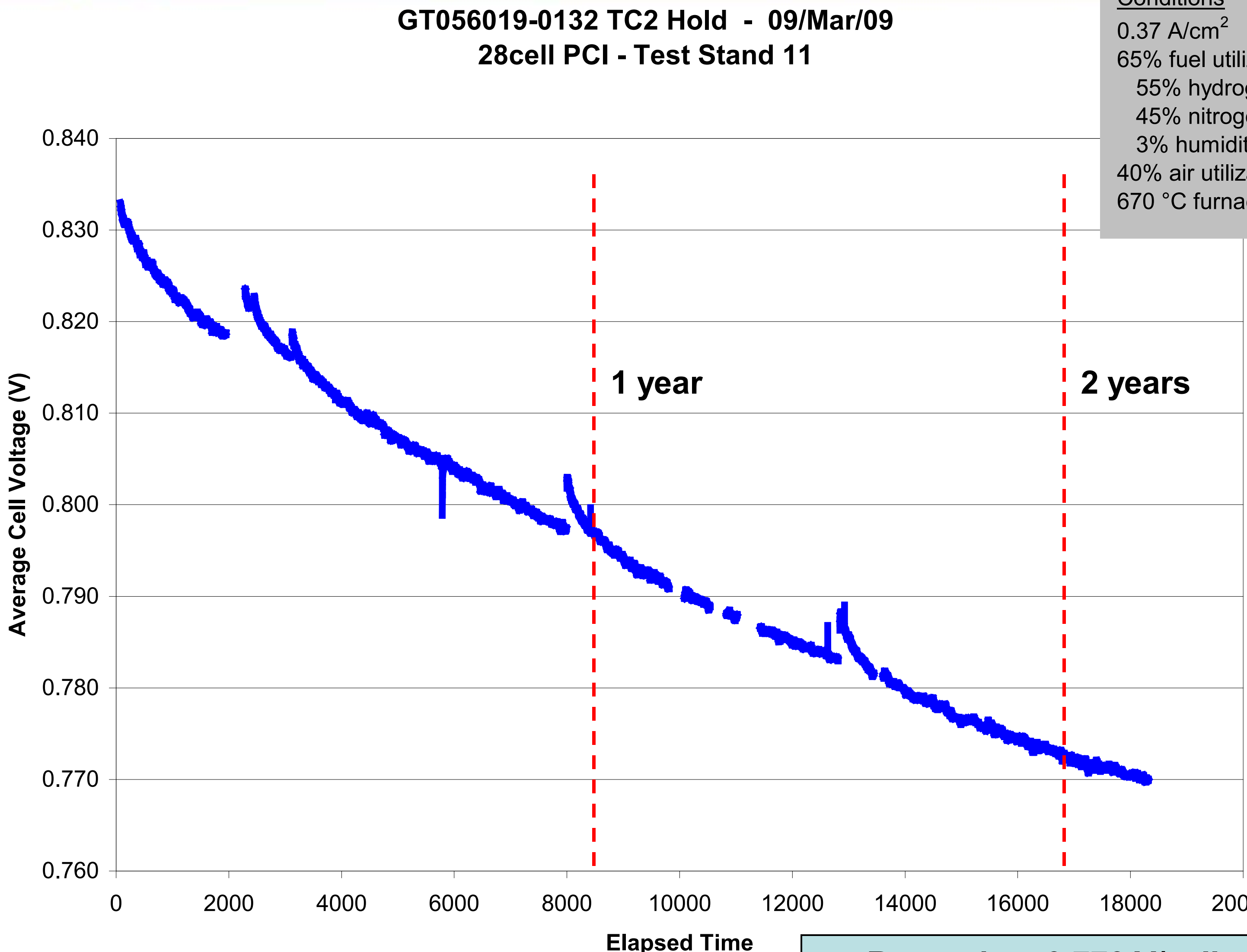
# Stack Degradation (FC)




Conditions
0.37 A/cm$^2$
65% fuel utilization
55% hydrogen (dry basis)
45% nitrogen (dry basis)
3% humidity
40% air utilization
670 °C furnace temperature

**Fuel Cell Mode Degradation: ~3.5 mV/khr**

**Better than 0.770 V/cell after 2 years**
**Projects to better than 0.7 V/cell at 4 years**

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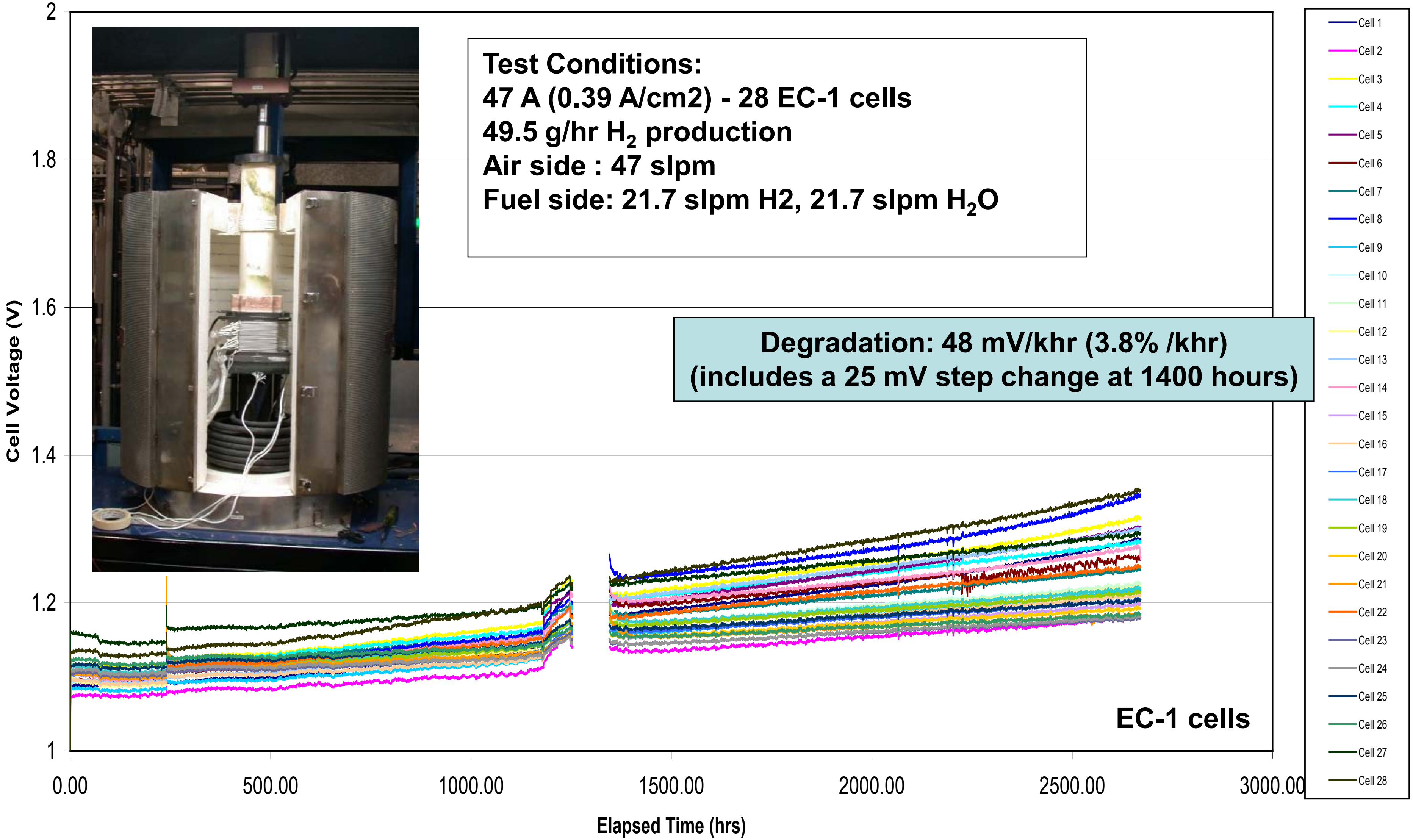
# Early Stack Degradation (EL)




IRAD

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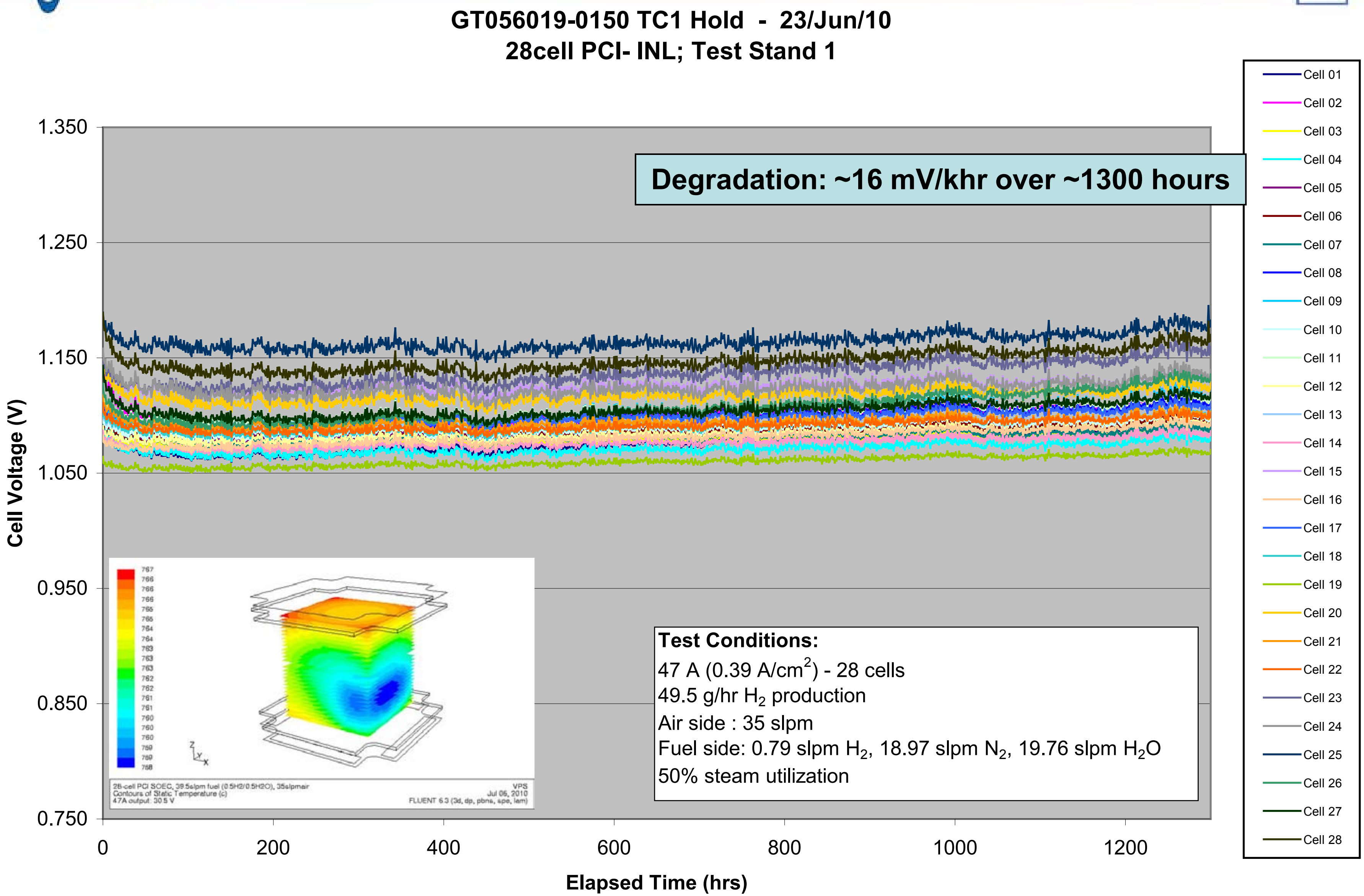
# Stack Degradation (EL)

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# Cyclic Testing
# (FC/EL cycles)

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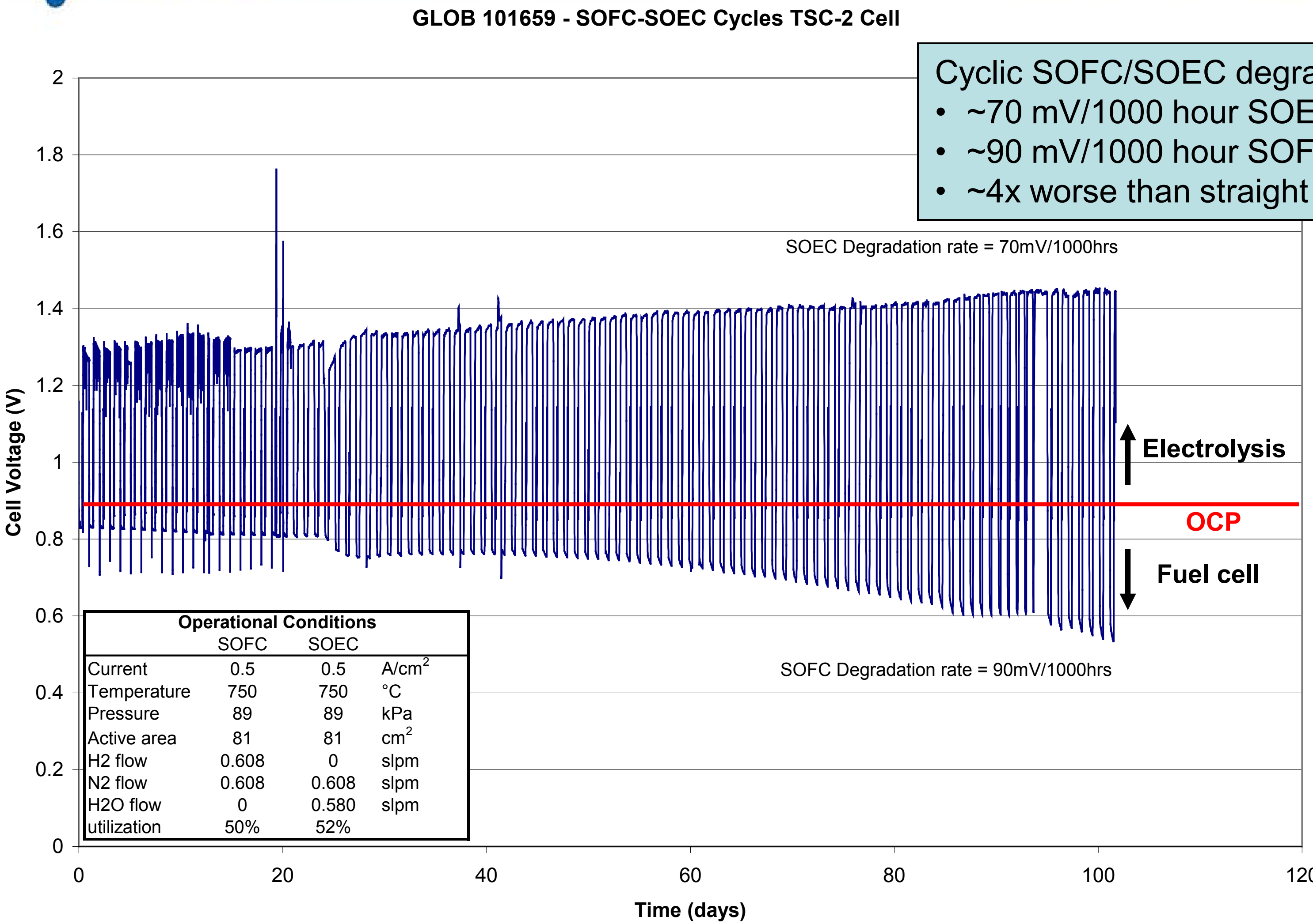
# Early TSC2 Cyclic Testing




Cyclic SOFC/SOEC degradation
- ~70 mV/1000 hour SOEC degradation
- ~90 mV/1000 hour SOFC degradation
- ~4x worse than straight SOFC

**Compare to 91 mV/khr steady state EL degradation for material system**
**-> Cyclic operation does not appear to be driving degradation**
**-> EL degradation is showing up on FC portion of cycle**

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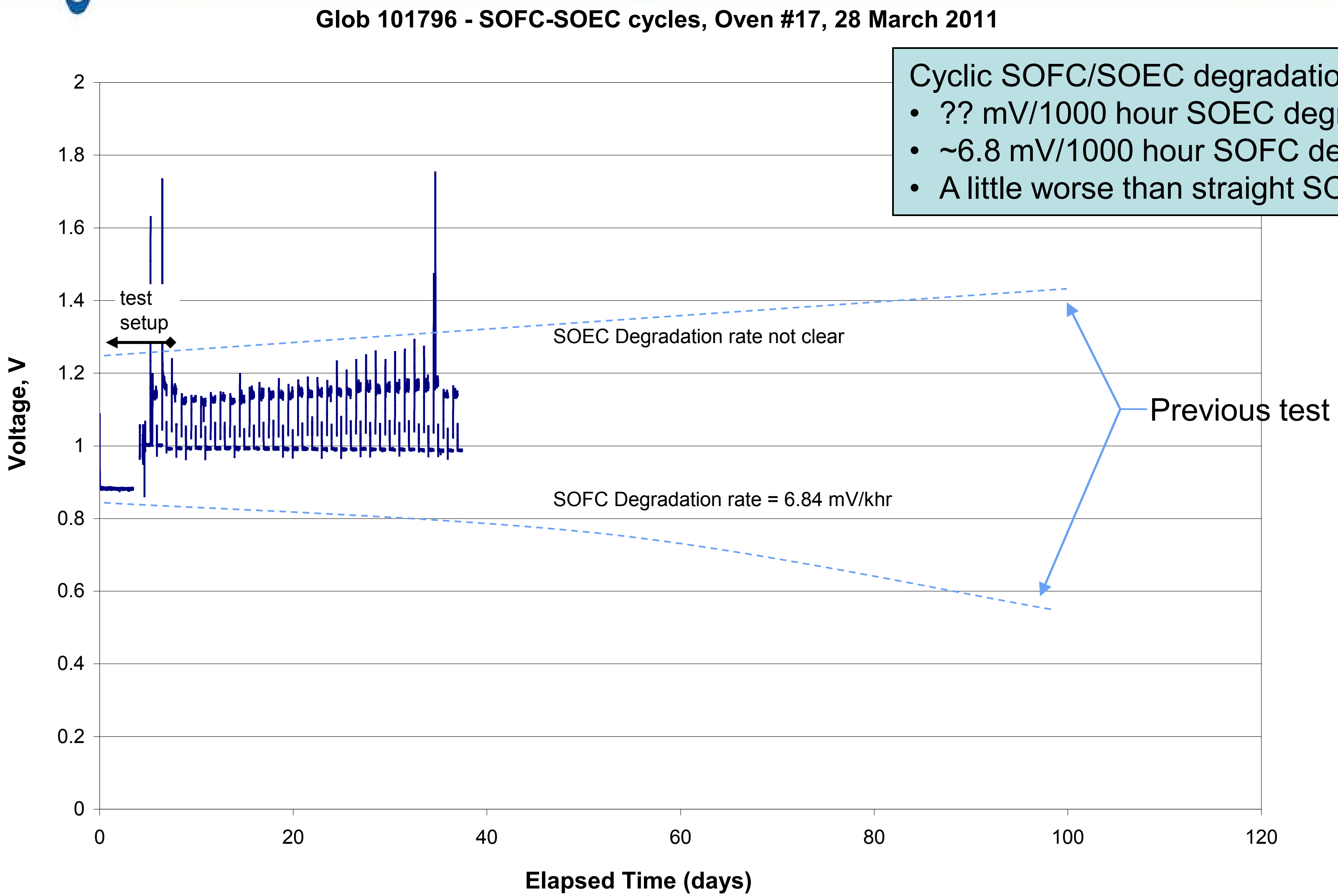
# Ongoing Single Cell Test




Cyclic SOFC/SOEC degradation

- ?? mV/1000 hour SOEC degradation
- ~6.8 mV/1000 hour SOFC degradation
- A little worse than straight SOFC

**Improved materials system delivering better than 10x improvement in cyclic impact on FC voltage**
**Uncertainty in real EL impact, more test time needed**

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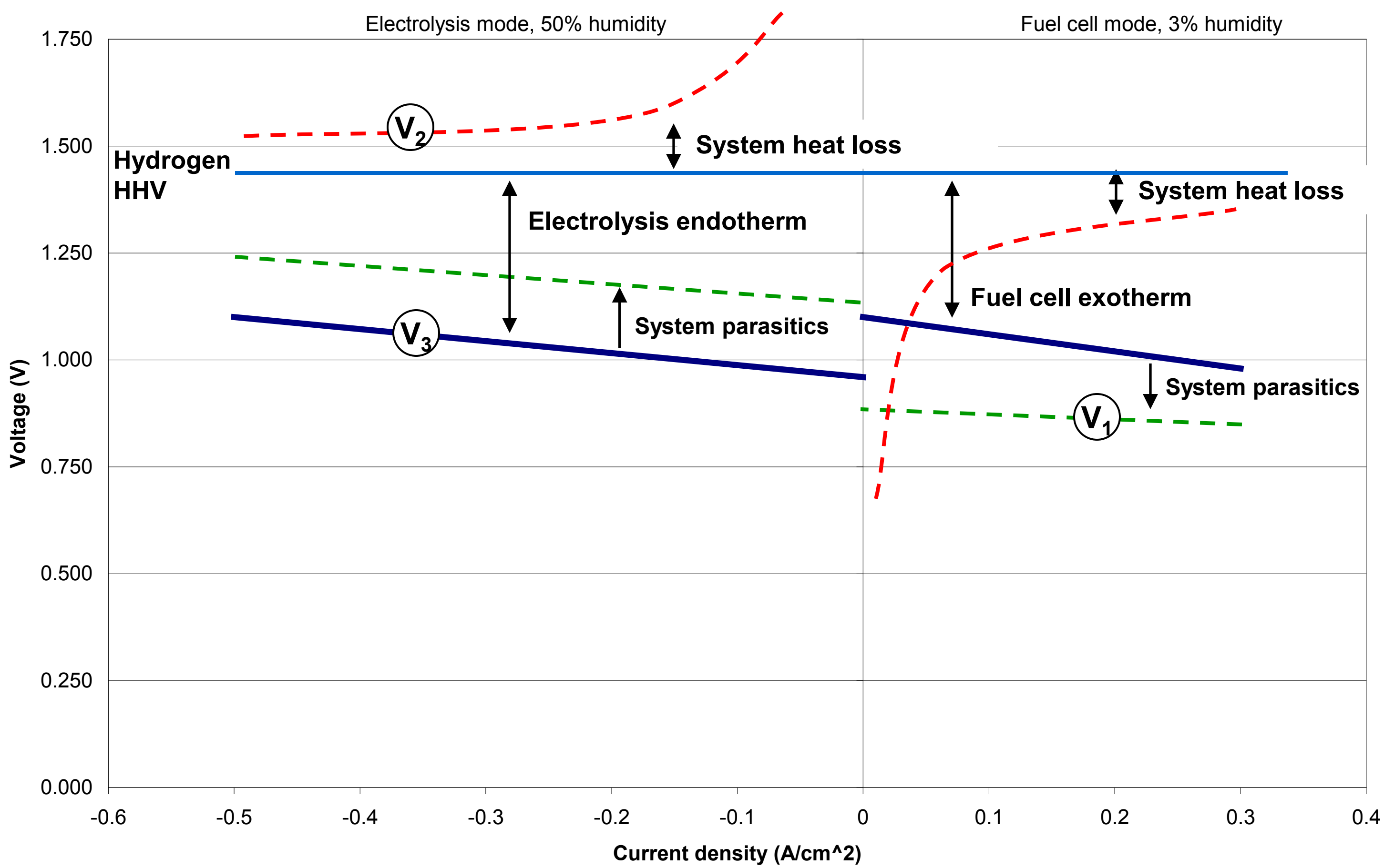
# Efficiency Review

**Reversible SOFC VI characteristics (Notional)**




Round trip (storage) efficiency = $V_1/V_2$ (e.g.: 0.900/1.560 = 58%)
Maximizing efficiency requires focus on system heat loss (EL), fuel cell performance and system parasitics (FC)

Degradation tolerance EL: $(V_2 – V_3)/dV$
e.g.: (1.560 – 1.100)/20 = 23 khrs (2.6 years)

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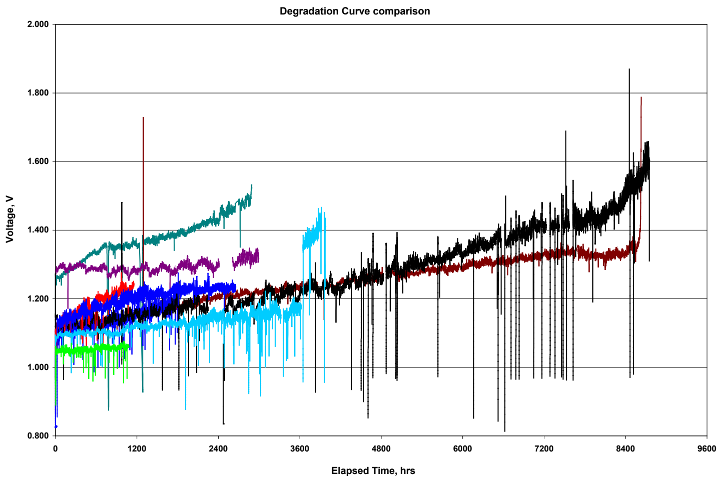
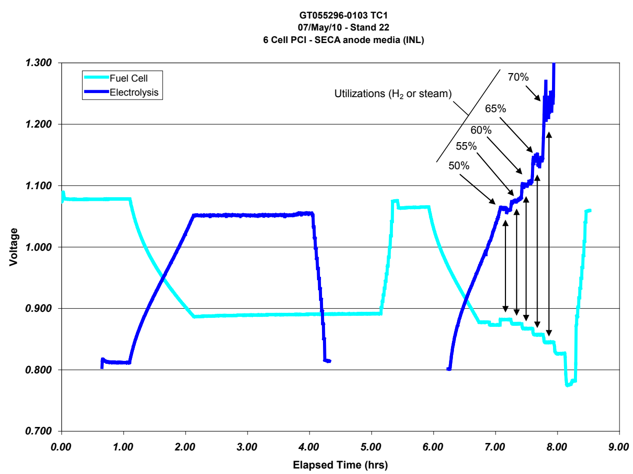
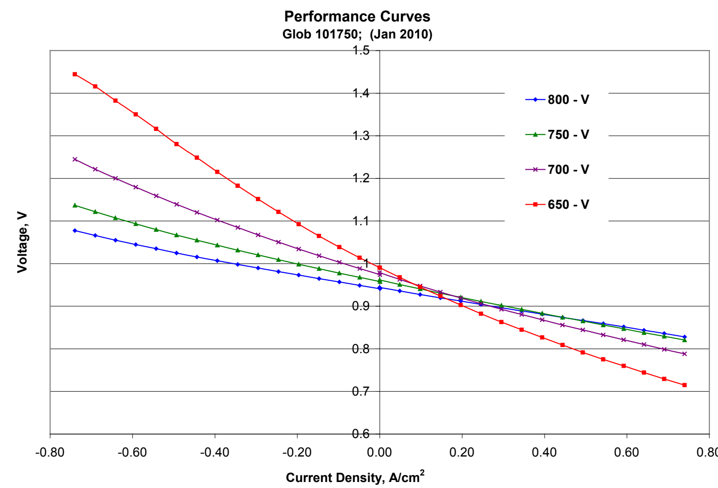
# Challenge Areas

- Compared to fuel cell history, VPS has relatively little EL experience
- Despite significant improvements, degradation remains higher in electrolysis than fuel cell
- Energy storage efficiency is strongly influenced by system design

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# Summary

1. Is this technology feasible for cost effective storage of renewable electricity?
    - A qualified ‘yes’

2. What are the materials and systems barriers to developing this technology?
    - Materials: Experience and confidence are lacking, but if demonstrated cell performance is stable and scalable, we already have 1+ year solutions. Degradation improvements always welcome
    - System: Need to understand real requirements, things like power profiles of different applications, in order to answer this. It would be nice to see demonstration systems running.
    - System: Low cost, high storage efficiency systems designs, that take advantage of SOFC potential.

3. What are the manufacturing issues that need to be addressed to be cost effective?
    - Solid oxide fuel cell: Build on SECA work, volume
    - System: ?

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# Acknowledgements

Thank you to the following funding agencies:

- US DOE Solid State Energy Conversion Alliance
- US DOE Office of Energy Efficiency and Renewable Energy Laboratory
  - FuelCell Energy (project prime)
- US DOE Idaho National Laboratory
- The Boeing Company (DARPA funded program)
- VTT Technical Research Centre of Finland
- Versa Power Systems internally funded R&D efforts

Thank you to the Versa Power Systems team

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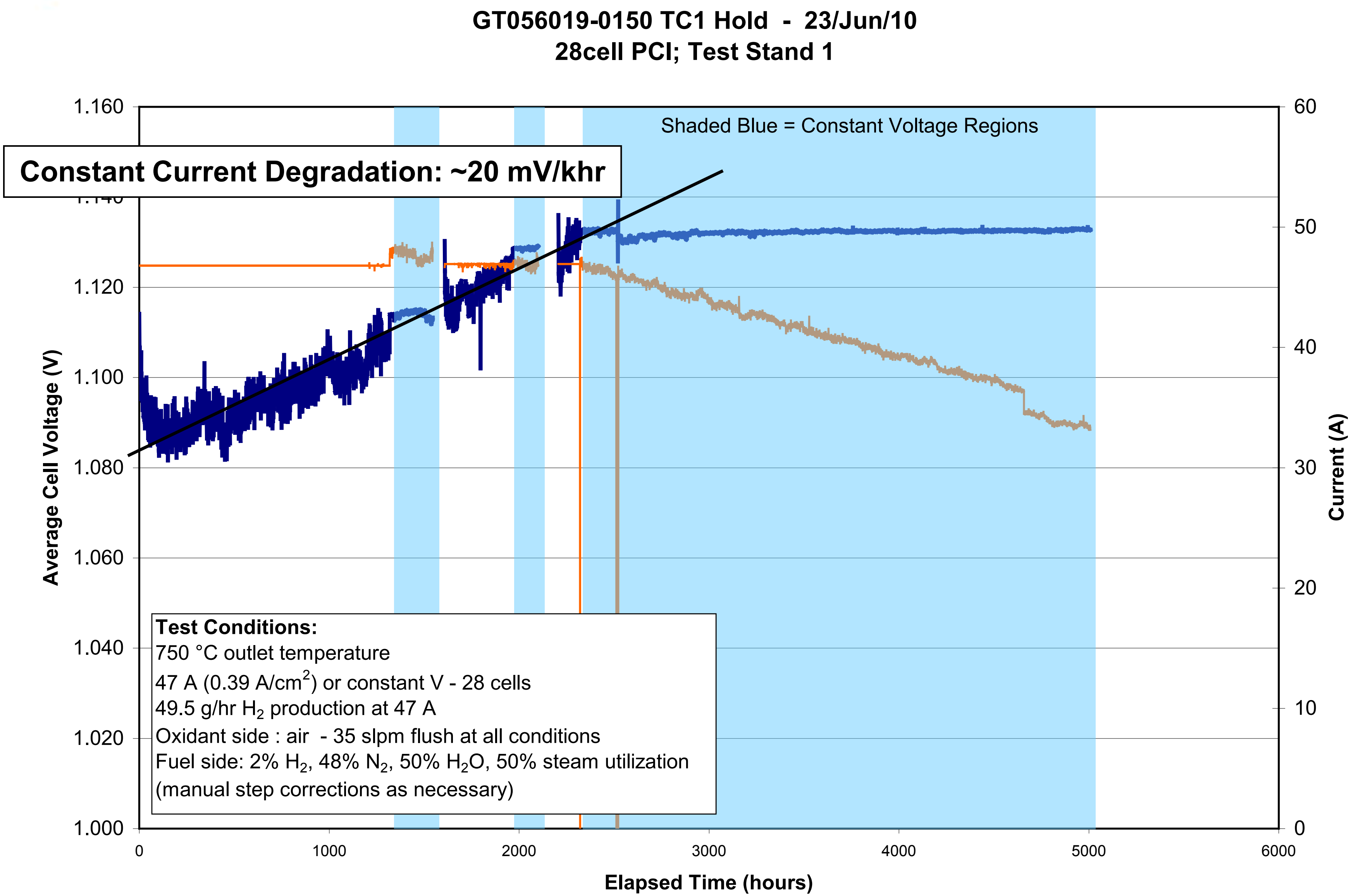
# Extra slides

# Longer Stack Data

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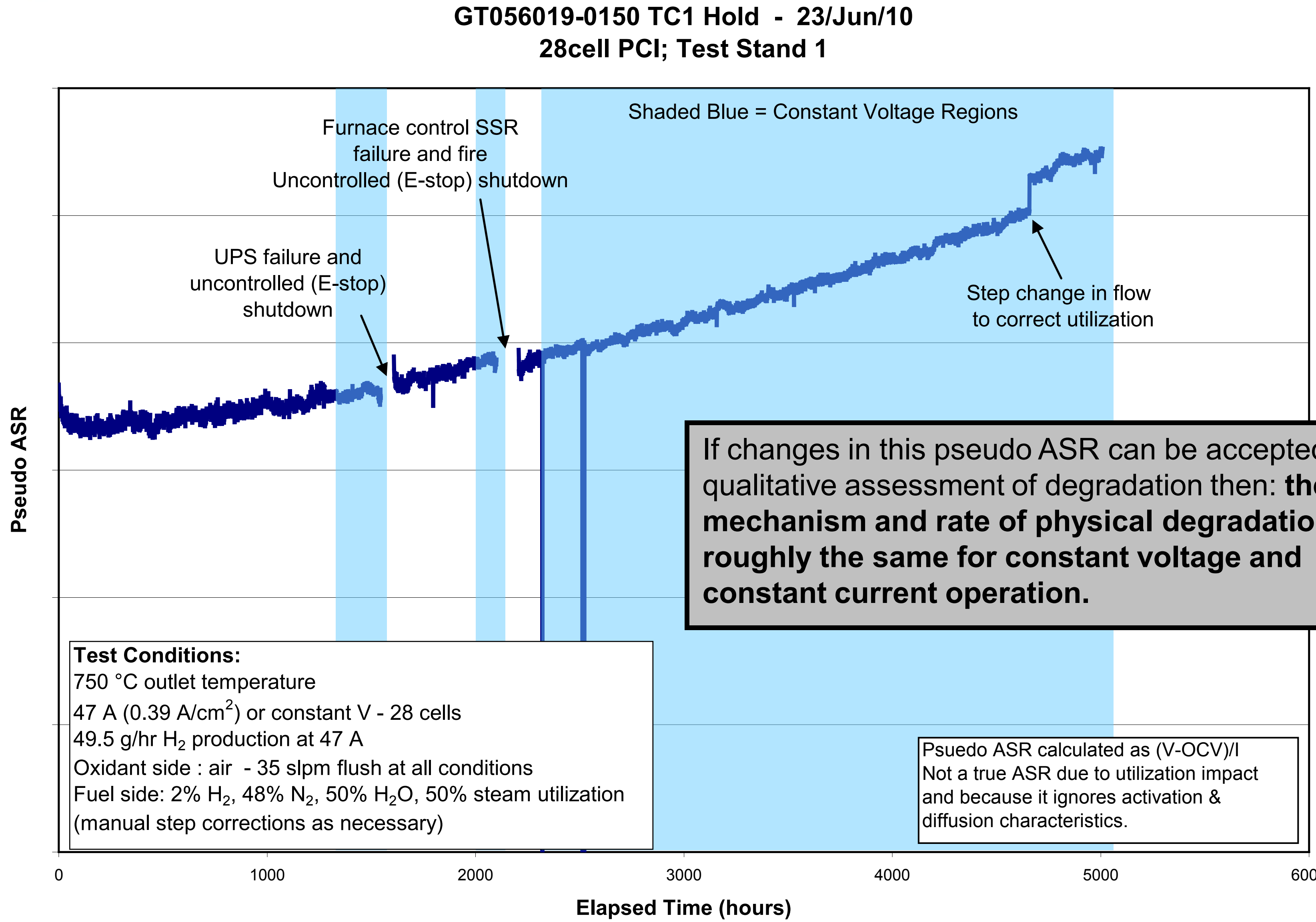
# Constant V vs I




If changes in this pseudo ASR can be accepted as a qualitative assessment of degradation then: **the mechanism and rate of physical degradation is roughly the same for constant voltage and constant current operation.**

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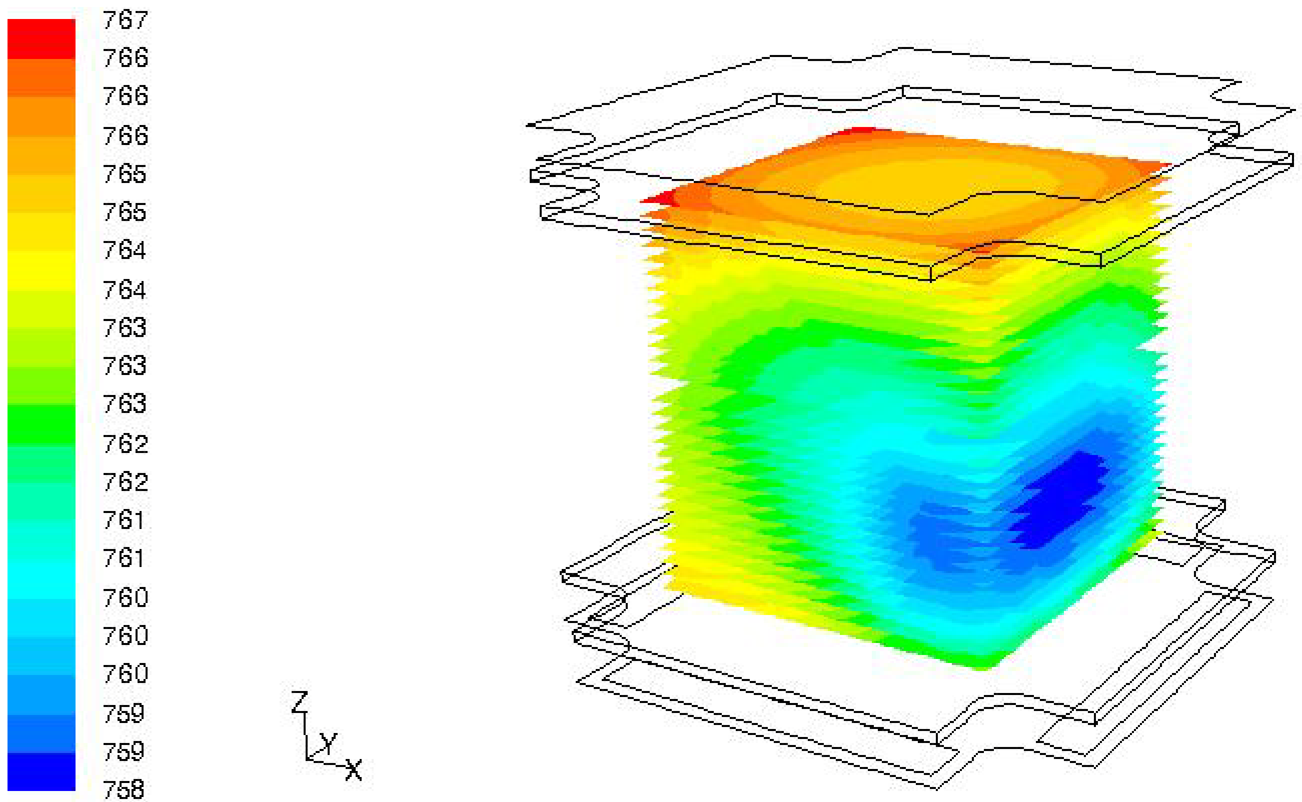
# Electrolysis Temperatures




28-cell PCI SOEC, 39.5slpm fuel (0.5H2/0.5H2O), 35slpmair
Contours of Static Temperature (c)
47A output: 30.5 V

VPS
Jul 06, 2010
FLUENT 6.3 (3d, dp, pbns, spe, lam)

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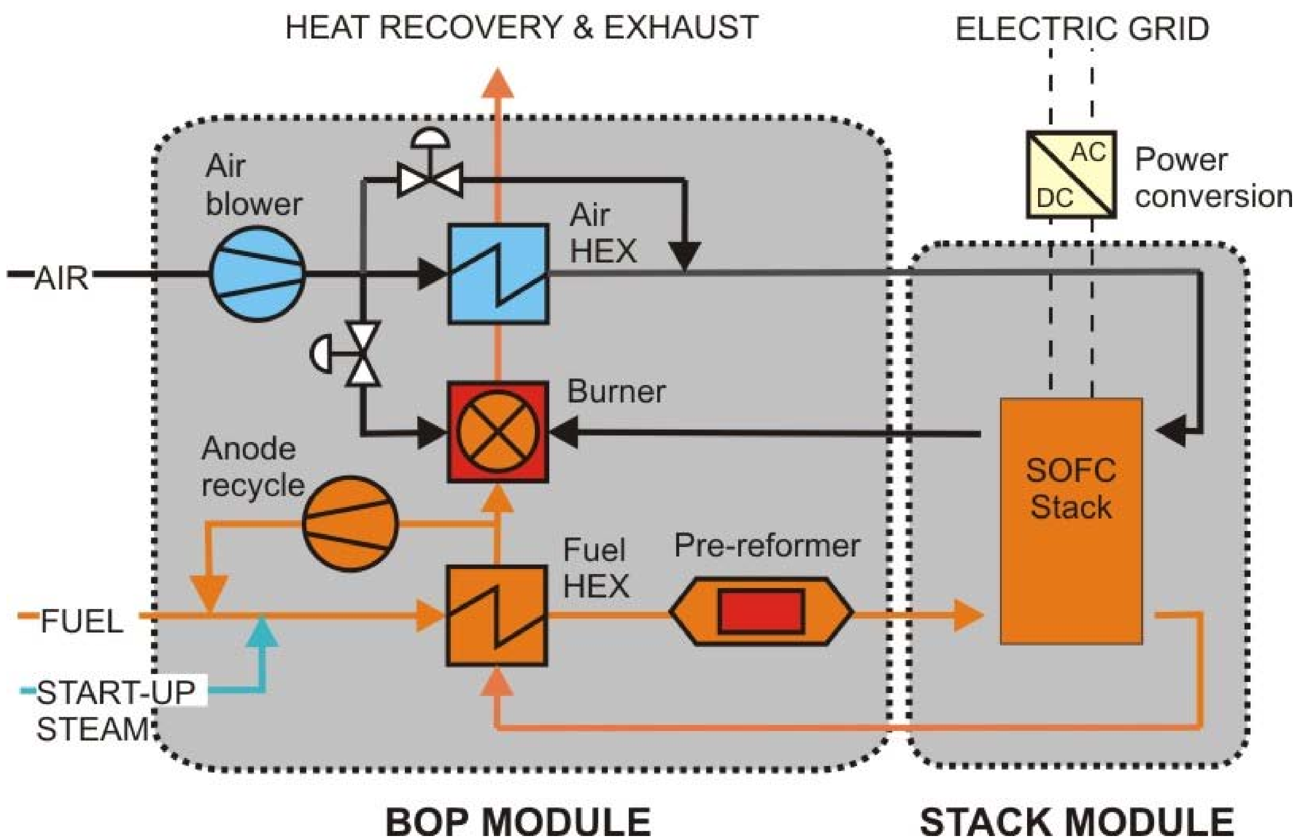
# 10 kW SOFC Demo Unit Layout

- Modular design
- Natural gas fuelled
- Warm anode recycle loop
- Air by-pass to regulate stack and afterburner temperature
- Grid connected
- Thermally self-sustained

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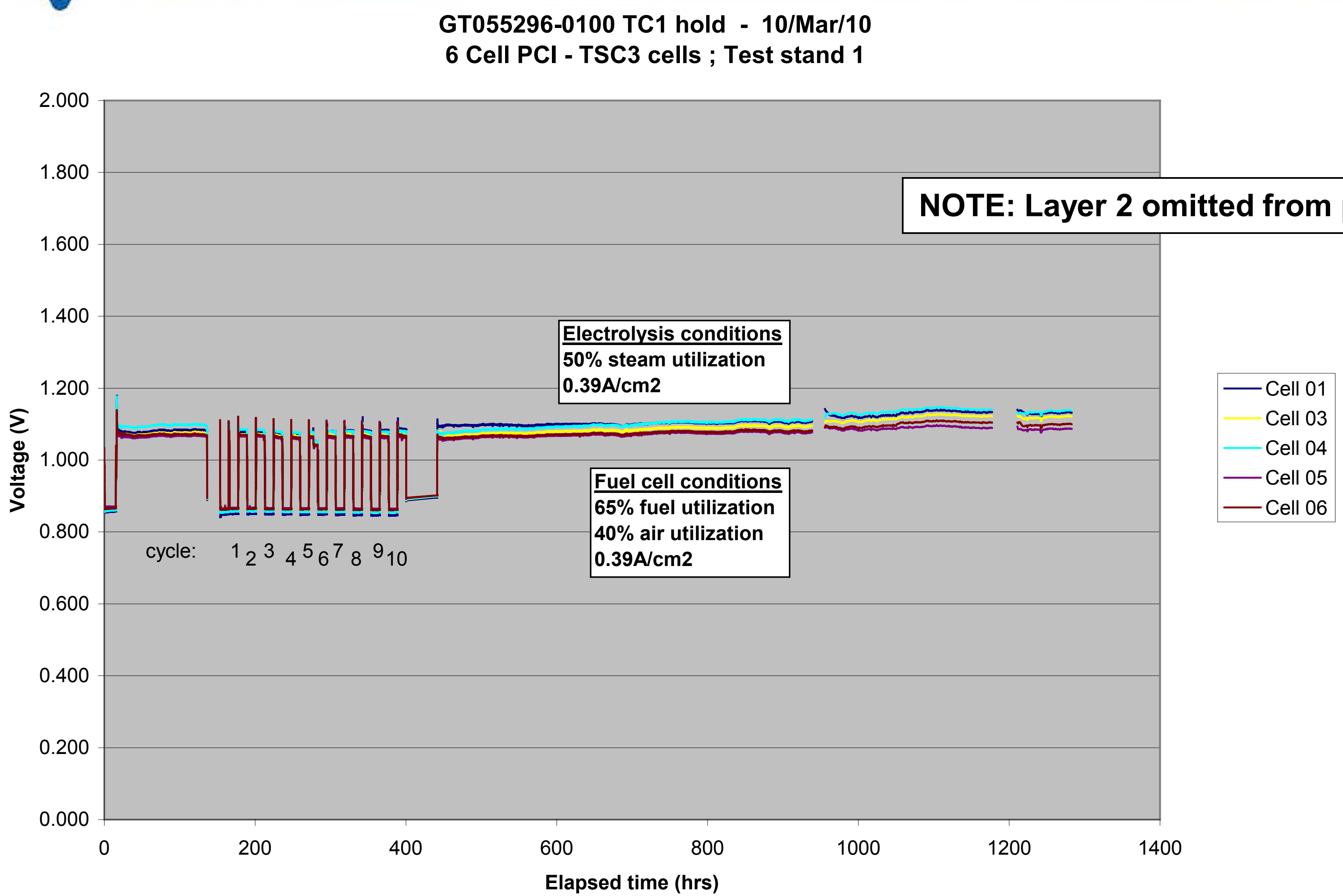
# Cyclic Testing in Stack




**In stack, steady EL degradation again dominates**

**-> Results led to concerted focus on understanding and improving steady state degradation**

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