FuelCell Energy

Versa Power Systems

Reversible Solid Oxide Electrolysis

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Product Development & Federal Programs

Electrolytic Hydrogen Production Workshop
DOE Fuel Cell Technologies Office
Hosted by:
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February 27th and 28th, 2014

Ultra-Clean, Efficient, Reliable Power

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FCE Acquires VPS

- FuelCell Energy fully acquired the shares of Versa Power Systems on December 20, 2012. Prior to this, FuelCell Energy owned approximately 39% of Versa

> ***"We view solid oxide fuel cell technology as complementary to our carbonate fuel cell product line … for future sub-megawatt power generation and storage applications.***
>
> ***By acquiring Versa, we can leverage our current … experience to accelerate the commercialization of this … technology to expand our market opportunities."***
>
> —Chip Bottone, President and CEO, FuelCell Energy, Inc.

- Following the transaction, Versa Power Systems became a wholly-owned subsidiary of FuelCell Energy

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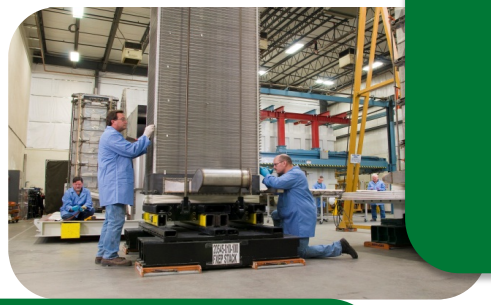
Integrated Fuel Cell Company



Design & Manufacture

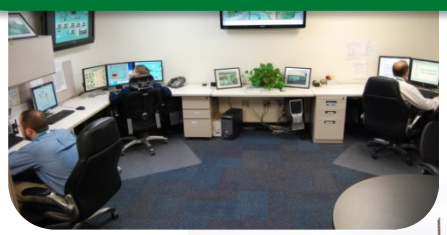
Megawatt–class power generation solutions

Services

Over 80 DFC® plants operating at more than 50 sites – 1.7 billion kWh ultra-clean power produced

Direct Sales and Sell via Partners

Installations/orders in 9 countries



Engineering / Construction

Over 300 megawatts installed and in backlog

59 MW Fuel Cell Park- on line February 19, 2014

- **59 MW fuel cell park**
  - Construction period only about one year
  - 21 power plants: 2.8 MW DFC3000®
- **Ownership**
  - 49% by electric utility KHNP
  - 21% by financial investors
  - 15% by gas company Samchully
  - 15% by POSCO Energy

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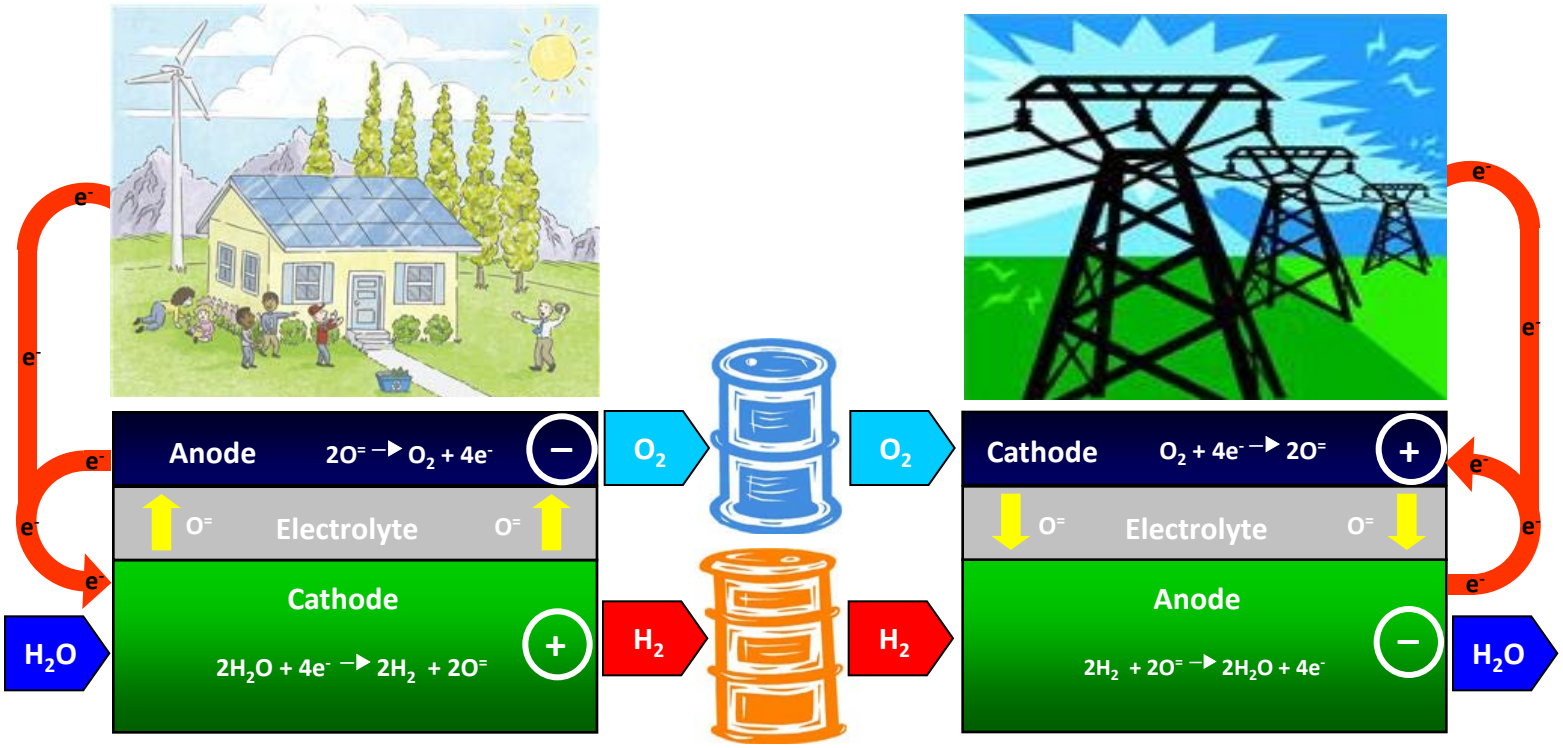
Reversible SOC Development

- Reversible Solid Oxide Cells (RSOCs) are energy conversion devices which can integrate renewable production of electricity and hydrogen when power generation (SOFC) and steam electrolysis (SOEC) are coupled in a system and have the potential of maximizing the potential of renewable (intermittent) energy

Goals

- To advance RSOC cell / stack technology in the areas of endurance and performance



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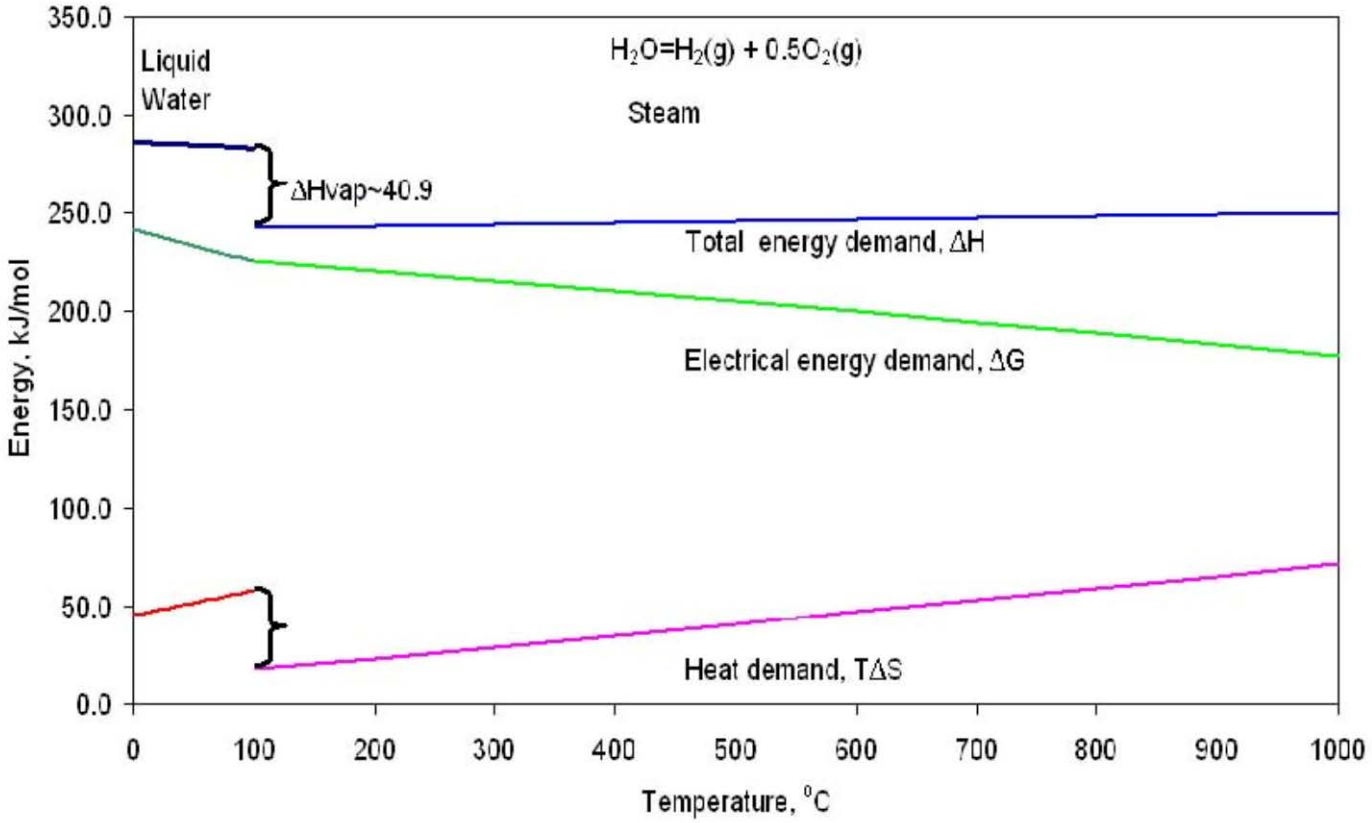
Why Solid oxide-based electrolysis development?



- At SOEC temperatures, about 20-25% less power is required per kg hydrogen delivered.

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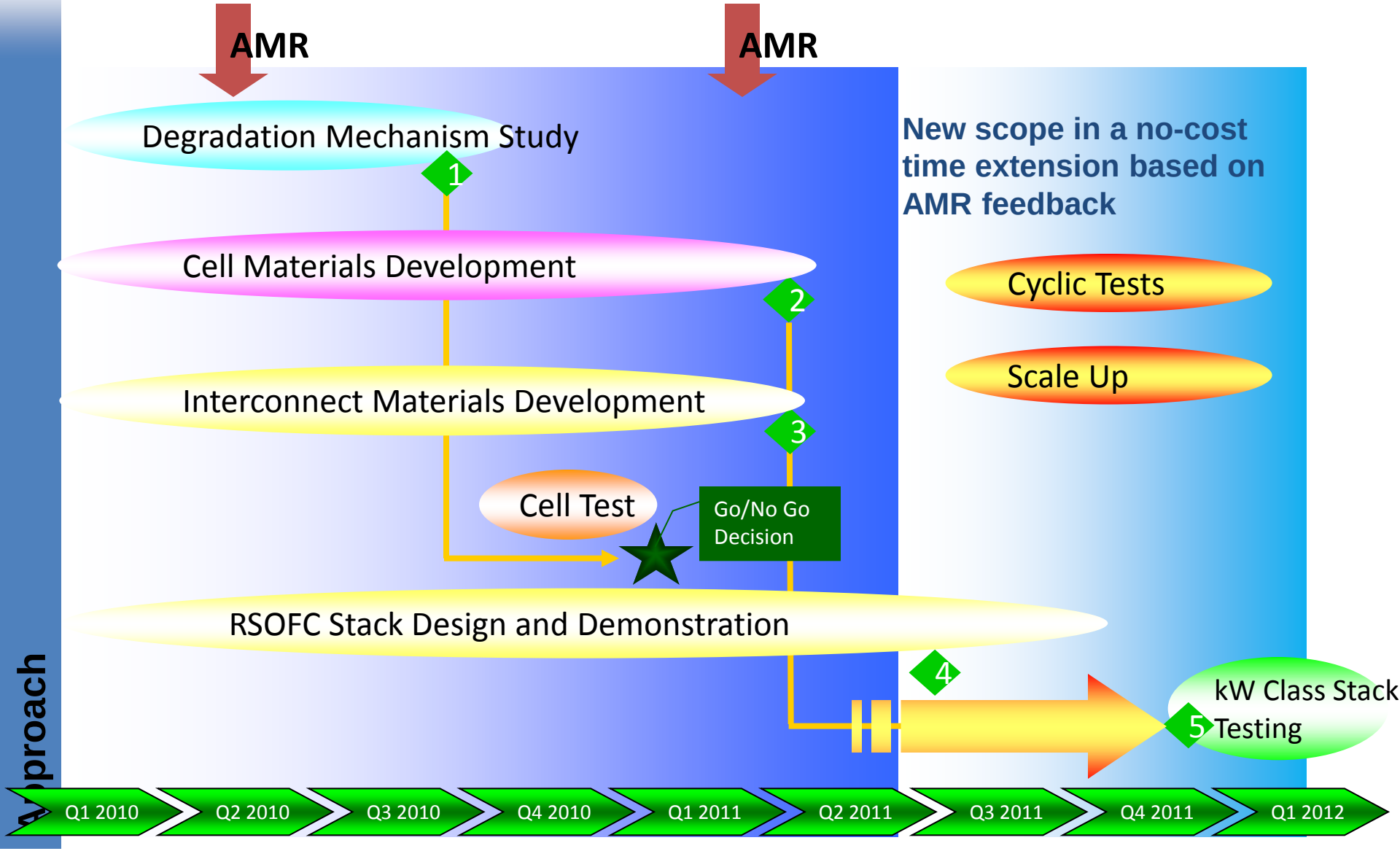
EERE Project: focused on improving degradation of SOFCEL cells and stacks



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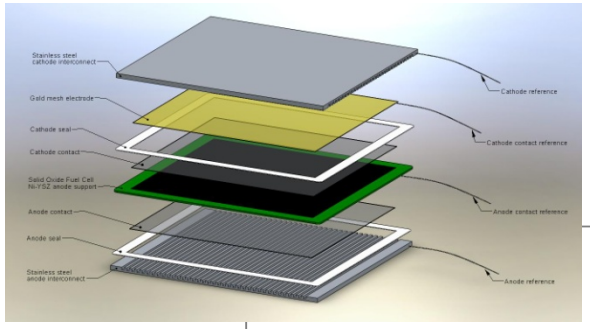
RSOC Status: Stack Repeat Unit



ASR (Ω.cm²)		
	SOEC	SOFC
800 -	0.169	0.190
750 -	0.223	0.224
700 -	0.345	0.290

50% humidity

Hydrogen/air operation

Electrolyser Mode
$H_2O \rightarrow H_2 + ½ O_2$

Fuel Cell Mode
$H_2 + ½ O_2 \rightarrow H_2O$

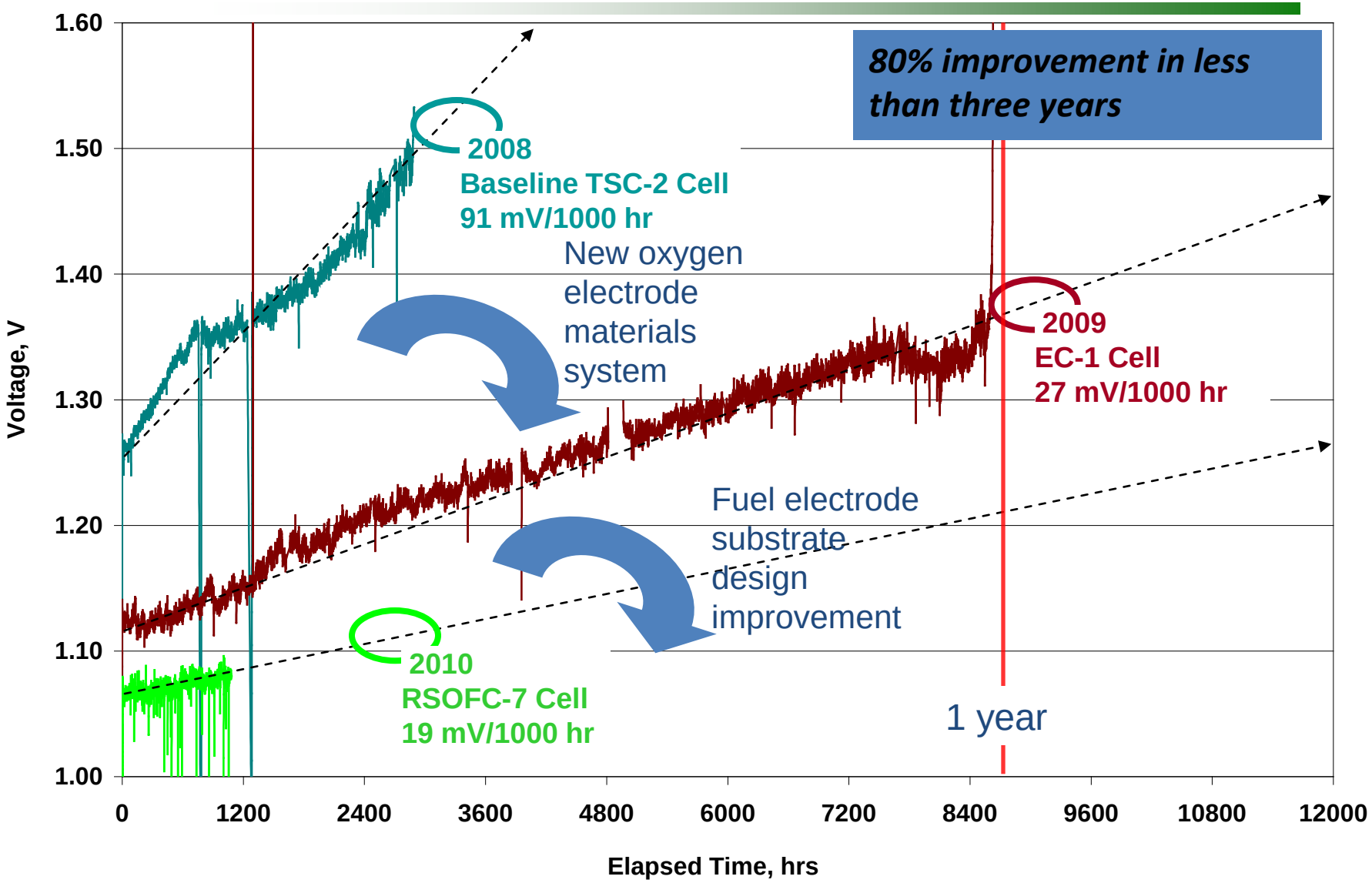
Voltage, V

1.4
1.3
1.2
1.1
1
0.9
0.8
0.7

-0.80 -0.60 -0.40 -0.20 0.00 0.20 0.40 0.60 0.80

Current Density, A/cm²

Electrolysis Endurance

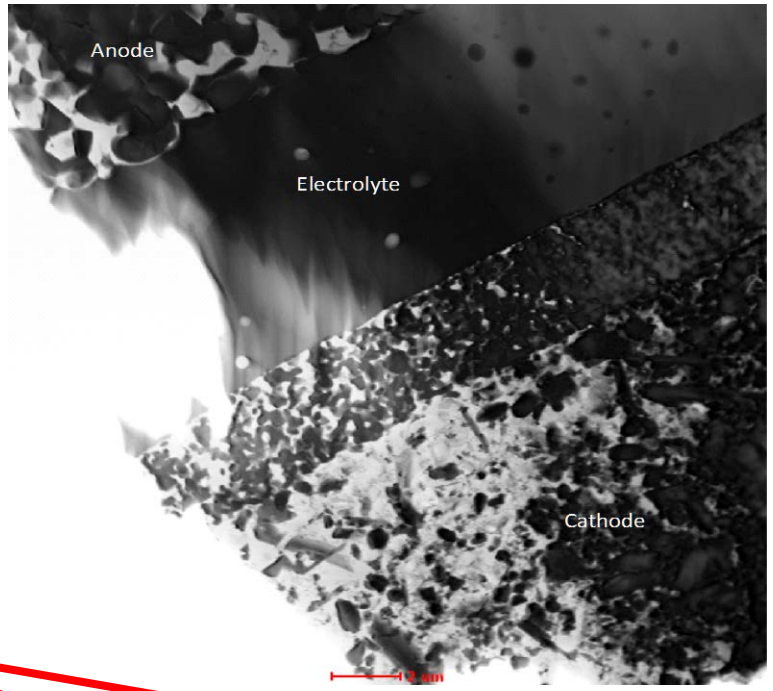


Electrolysis Degradation Status

Six cell types have passed the degradation criteria of less than 4%/1000 hours in SOEC mode

RSOFC-4 and RSOFC-7 passed both performance and degradation criteria

Cell Type	Electrolysis (SOEC) Degradation		
	mV / 1000 hrs	% / 1000 hrs	Duration (hrs)
Target	*< 50*	*< 4*	*> 1000*
TSC-2	91	7.3	2893
EC-1	27	2.2	8465
EC-2	~0	~0	2400
EC-3	72	5.8	1792
RSOFC-1	35	2.8	6472
RSOFC-2	120	9.6	1152
RSOFC-3	42	3.4	2653
RSOFC-4	24	1.9	3618
RSOFC-7	19	1.5	1005



Post Test Analysis After 8,000 Hours:

- All electrochemical functional layers fully intact, no delamination between electrodes and electrolyte
- No chemical impurities or contaminations, such as, Cr poisoning found in cathode (air electrode)
- No microstructure coarsening found

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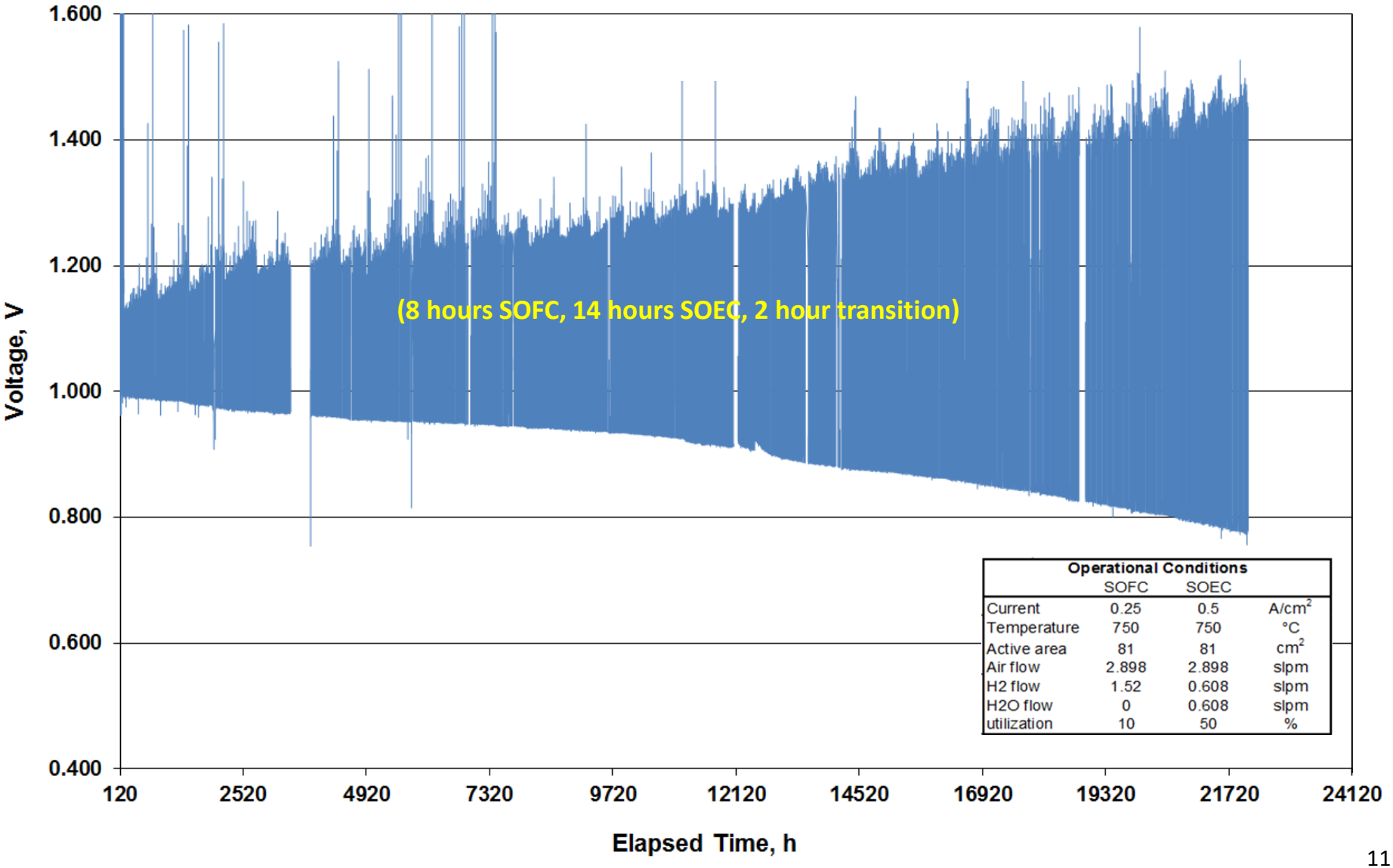
Stack Repeat Unit: Longest operating SOFCEL-Daily Cyclic Operation



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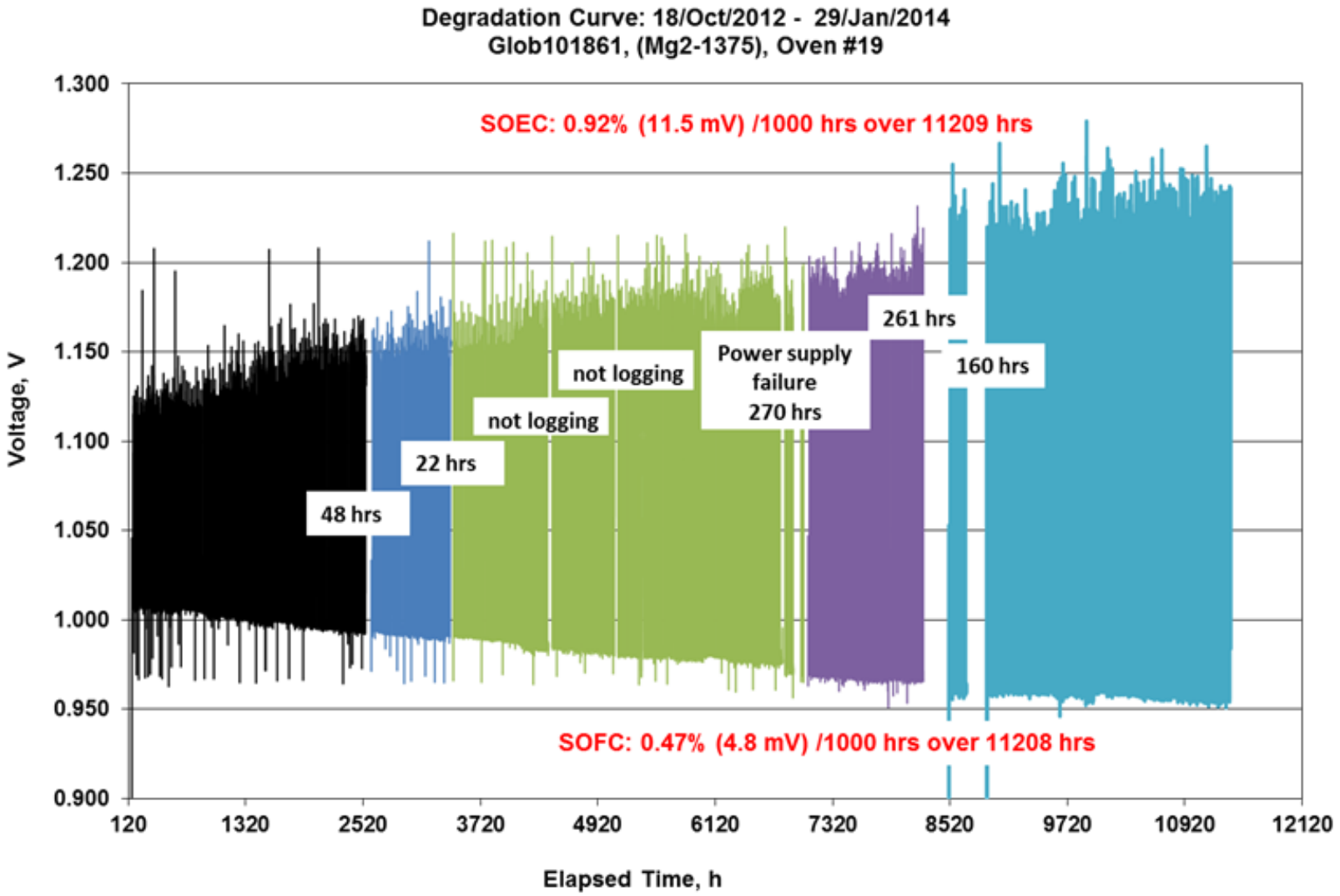
Stack Repeat Unit: SOFCEL, Status, as of January 29, 2014



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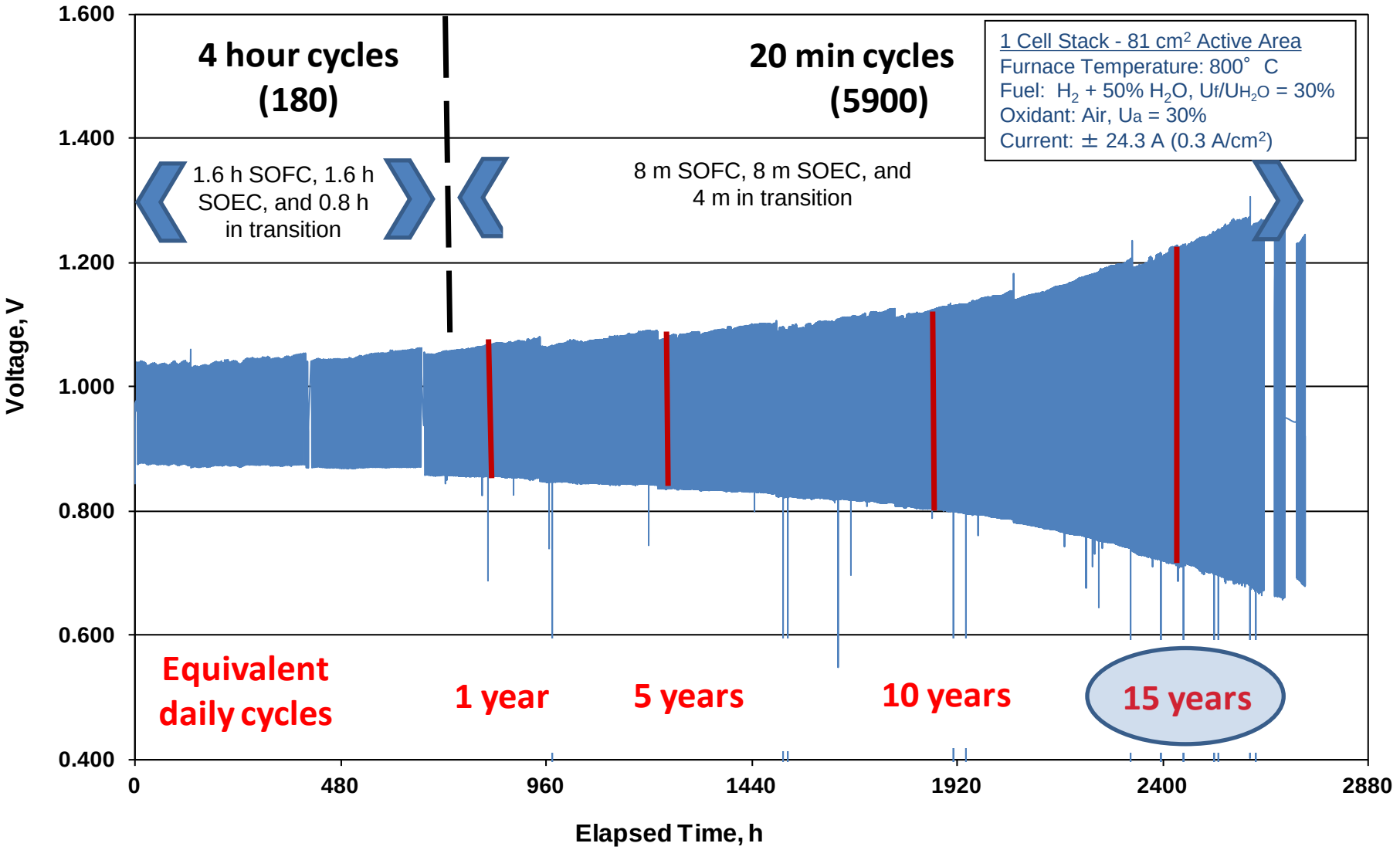
Stack Repeat Unit: Accelerated Cycling (Total 6,080 Cycles)



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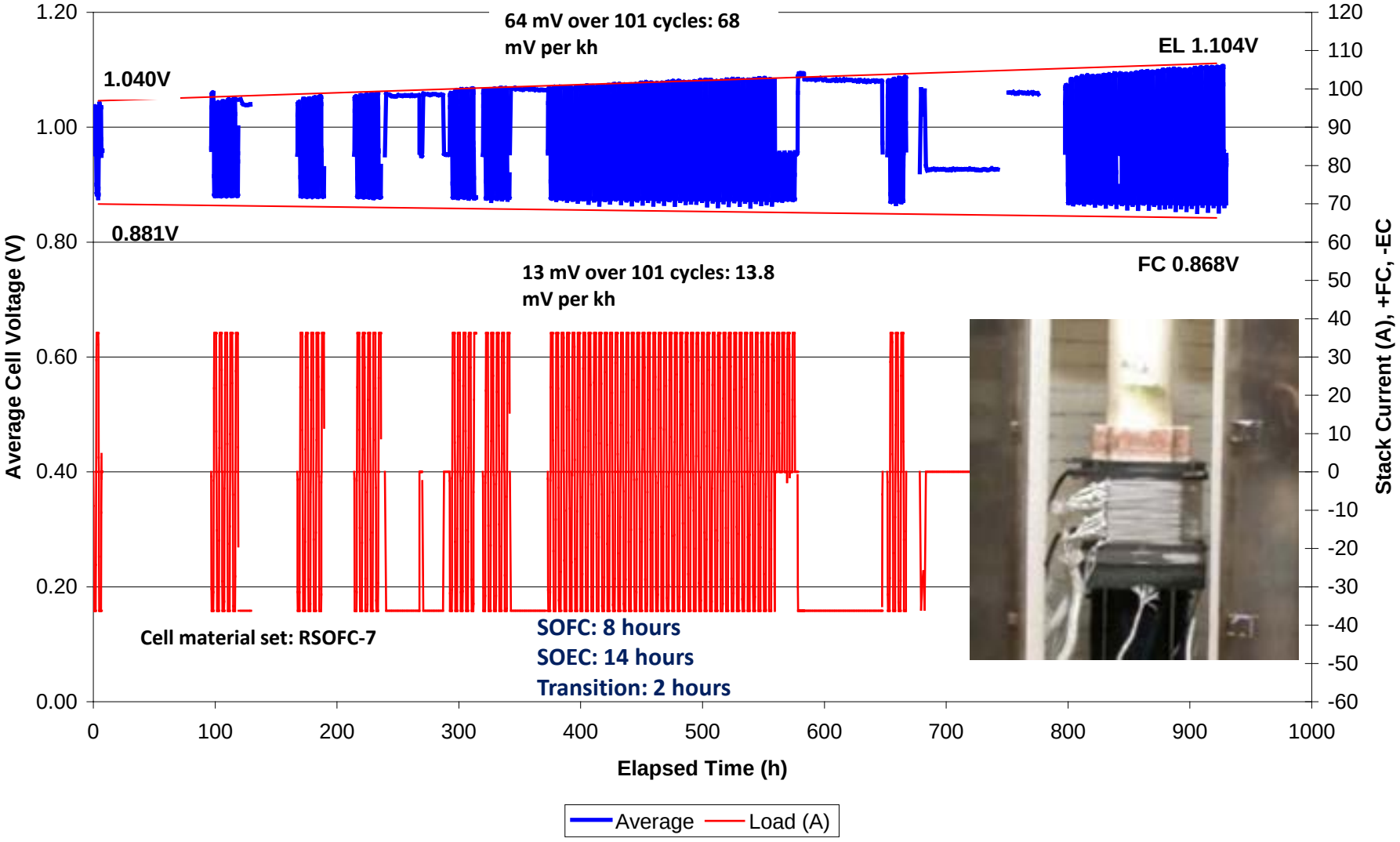
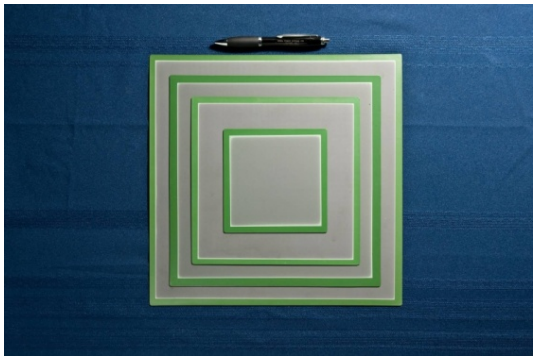
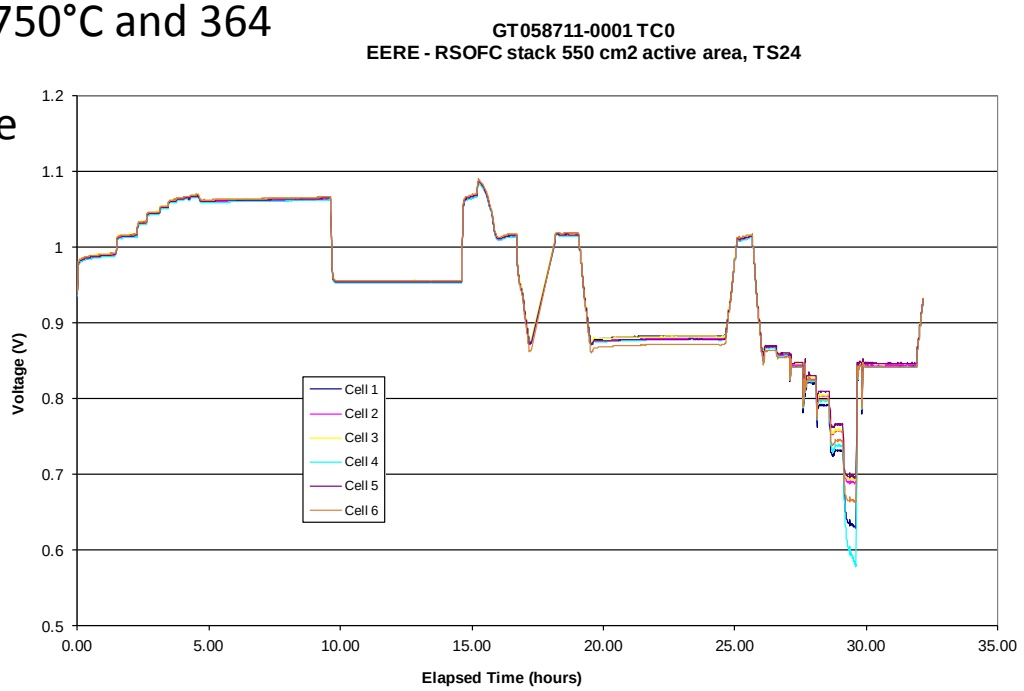
kW-Class Stack Cyclic Test: 121 cm² x 28-Cell stack, daily, SOFC, SOEC cycles



Development of a Scaled-Up kW-Class RSOFC Stack

- Leveraged SECA-- scaled up 25 by 25 cm cell (550 cm^2 active area)
- Target operating current density: 0.364 A/cm^2, 200 A load in both fuel cell and electrolysis mode
- Target operating temperature: 750°C
- The stack went through conditioning and passed the VPS standard acceptance test with one thermal cycle prior to the milestone test
- Steady state electrolysis test at 750°C and 364 mA/cm^2 (200 A)
- ~ 1kg H2 per day production rate

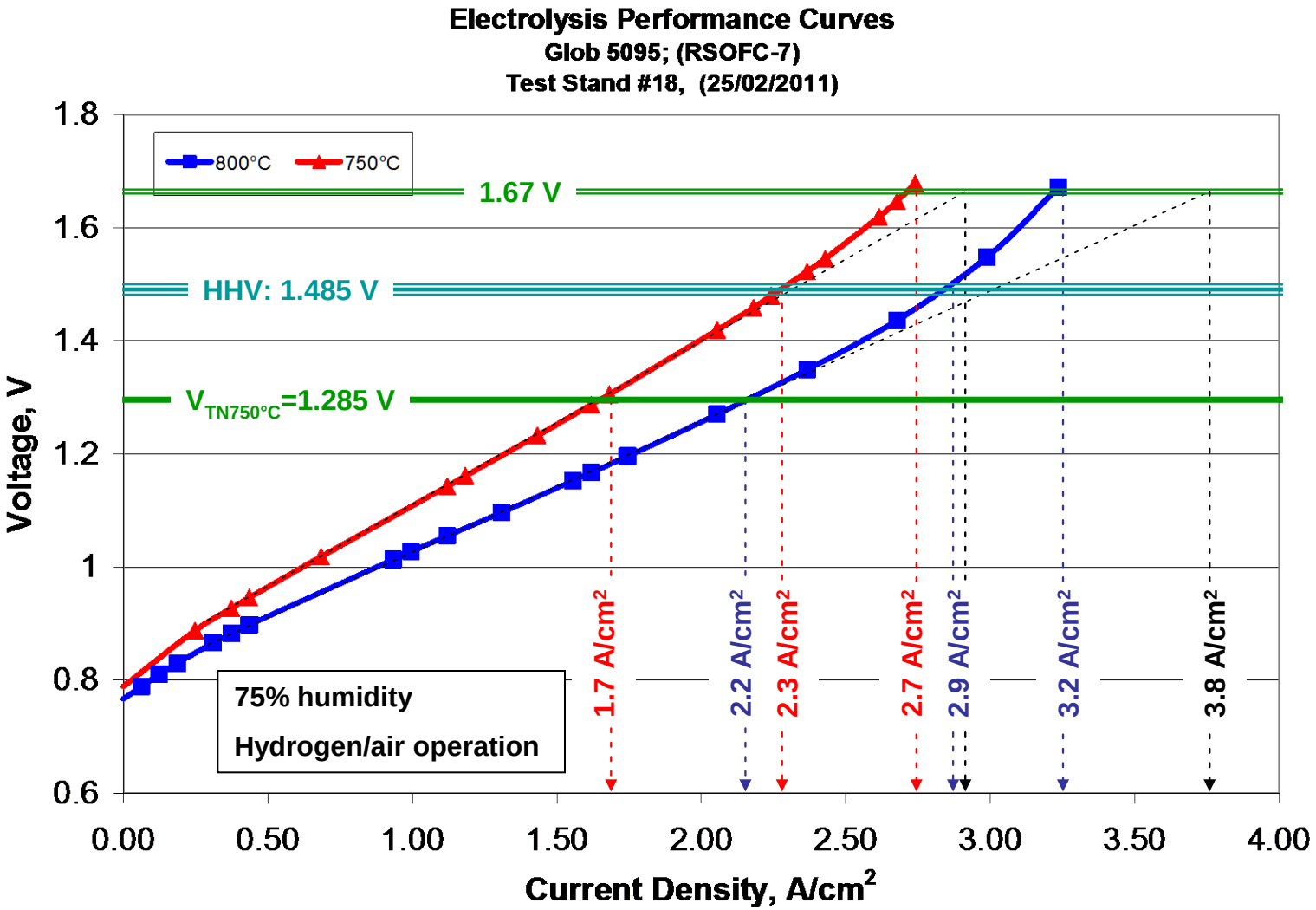




Overview: as of January 29, 2014

Metric	Status
☑ **Performance** (Area specific resistance in both SOFC and SOEC operating modes)	0.223 Ω-cm^2 in SOEC 0.224 Ω-cm^2 in SOFC
☑ **Cyclic Degradation** (Overall decay rate)	SOFC: ~0.5% per 1000 hours SOEC: <1% per 1000 hours
☑ **Current Density: Normal** **Maximum exploration**	500 mA/cm^2 3,200 mA/cm^2
☑ **Endurance- Stack Repeat Unit:**	Straight SOEL: over 8000 hours (1 year) with less than 2.5% SOFCEL: >11,000 hours cyclic operation Simulated 15 years of Cycling (6080 cycles)
☑**PreliminaryScaleup:**	• Leveraged SECA 121, and 550 cm2 platform; • A number of kW-class RSOFC stacks were built and tested; • Demonstrated kW-class stack operating in electrolysis mode with less than 3% per 1000 hours degradation rate at 750°C

RSOFC-7 Cell Performance at Ultra-high Electrolysis Current Density



High performance of RSOFC-7 can reduce hydrogen production cost and meet DOE water electrolysis efficiency (2017 target of 75%) at the same time

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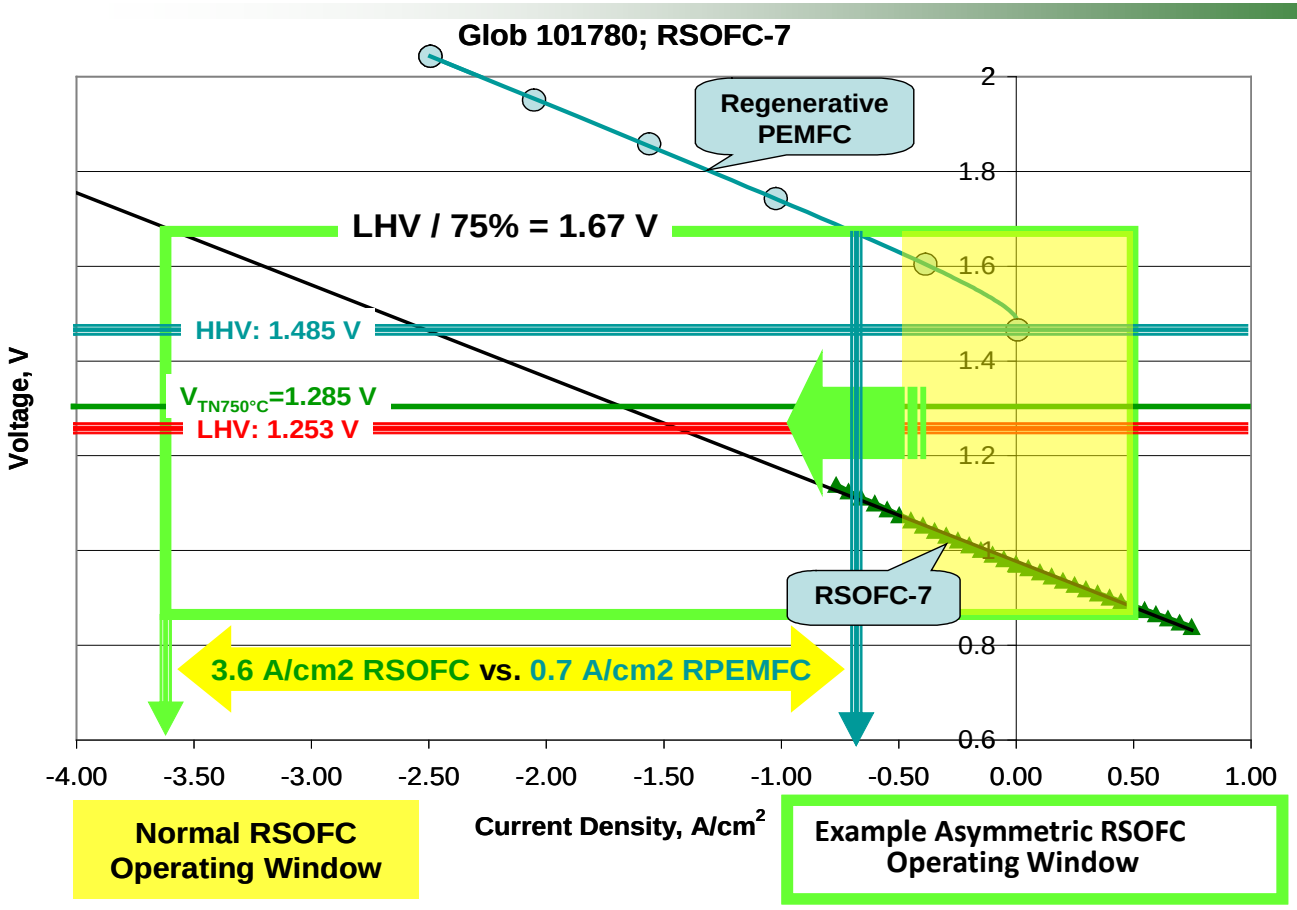
What's Next?



- In addition to the operating cost savings, high temperature SOEL or SOFCEL offers the opportunity to run at ≥ the EERE target 75% efficiency, with 2 to 5 times higher hydrogen production rate per unit electrochemical active area versus the state-of-the-art regenerative PEMFC (with the same electrical inputs)– a 2 to 5 times savings in stack module cost.

Challenges

- Techno-economic Analysis and SOEL and SOFCEL System Design
  - Tap into the strong starting point from NREL
- Materials and endurance development for ultra high current density, solid oxide-based electrolysis
- Stack Scale-up and System integration– as a function of the techno-economic direction–
  - Straight SOEL
  - SOFCEL