Advanced Materials for RSOFC Dual Mode Operation with Low Degradation

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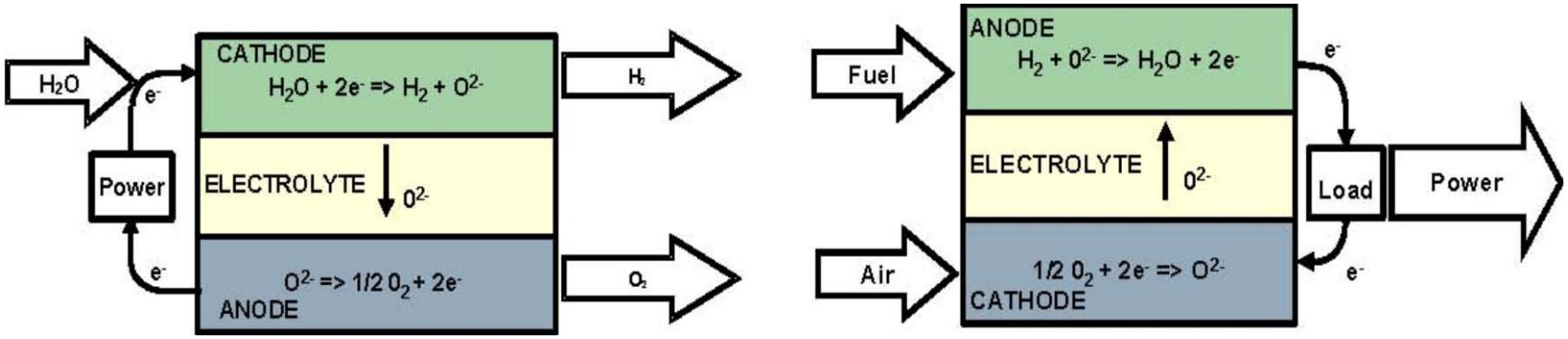
Versa Power Systems Inc.
2011 DOE Hydrogen Program Review
May 12, 2011
Washington, DC

Project ID: FC042

Overview

- Timeline
  - Start: September 2009
  - End: August 2011
  - 80% complete (ahead of schedule)
- Barriers
  - A. Durability
  - B: Cost
  - C. Performance
- Budget
  - $1,994,618 total project
    - $1,595,694 DOE share
    - $398,924 VPS share
  - $76,857 in FY10
  - $518,837 in FY11
- Partners
  - Boeing
  - Idaho National Laboratory (INL)

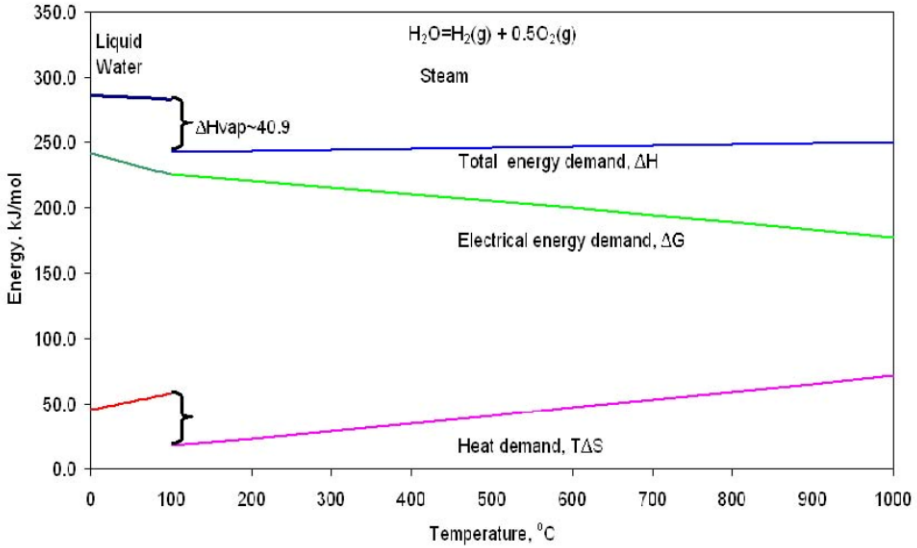
Project Background



Relevance

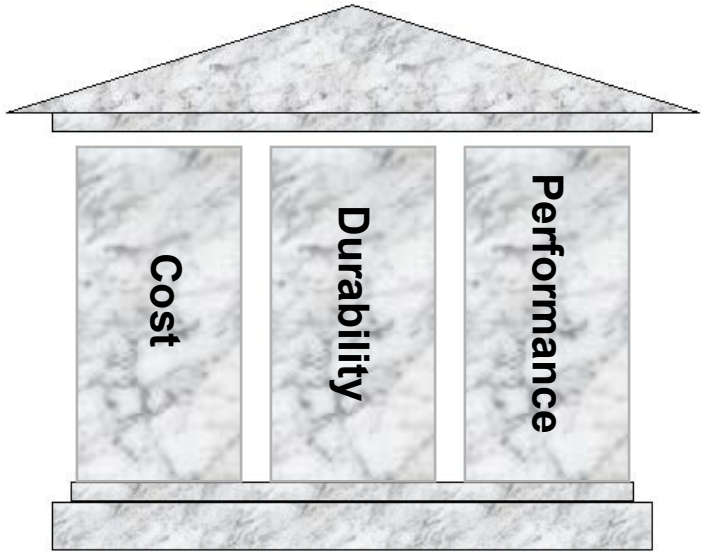
- Reversible Solid Oxide Fuel Cells (RSOFCs) are energy conversion devices: they are capable of operating in both power generation mode (SOFC) and electrolysis mode (SOEC)

- RSOFC can integrate renewable production of electricity and hydrogen when power generation and steam electrolysis are coupled in a system, which can turn intermittent solar and wind energy into “firm power”



Project Objectives

- To advance RSOFC stack technology in the areas of endurance and performance through RSOFC materials development and reversible stack design
- To meet the following performance targets in a kW-class RSOFC stack demonstration:
  - RSOFC dual mode operation of 1500 hours with more than ten SOFC/SOEC transitions
    - Performance (C), Durability (A)
  - Operating current density of more than 300 mA/cm^2 in both SOFC and SOEC modes
    - Cost (B), Performance (C)
  - Overall decay rate of less than 4% per 1000 hours of operation
    - Durability (A), Cost (B)



Relevance

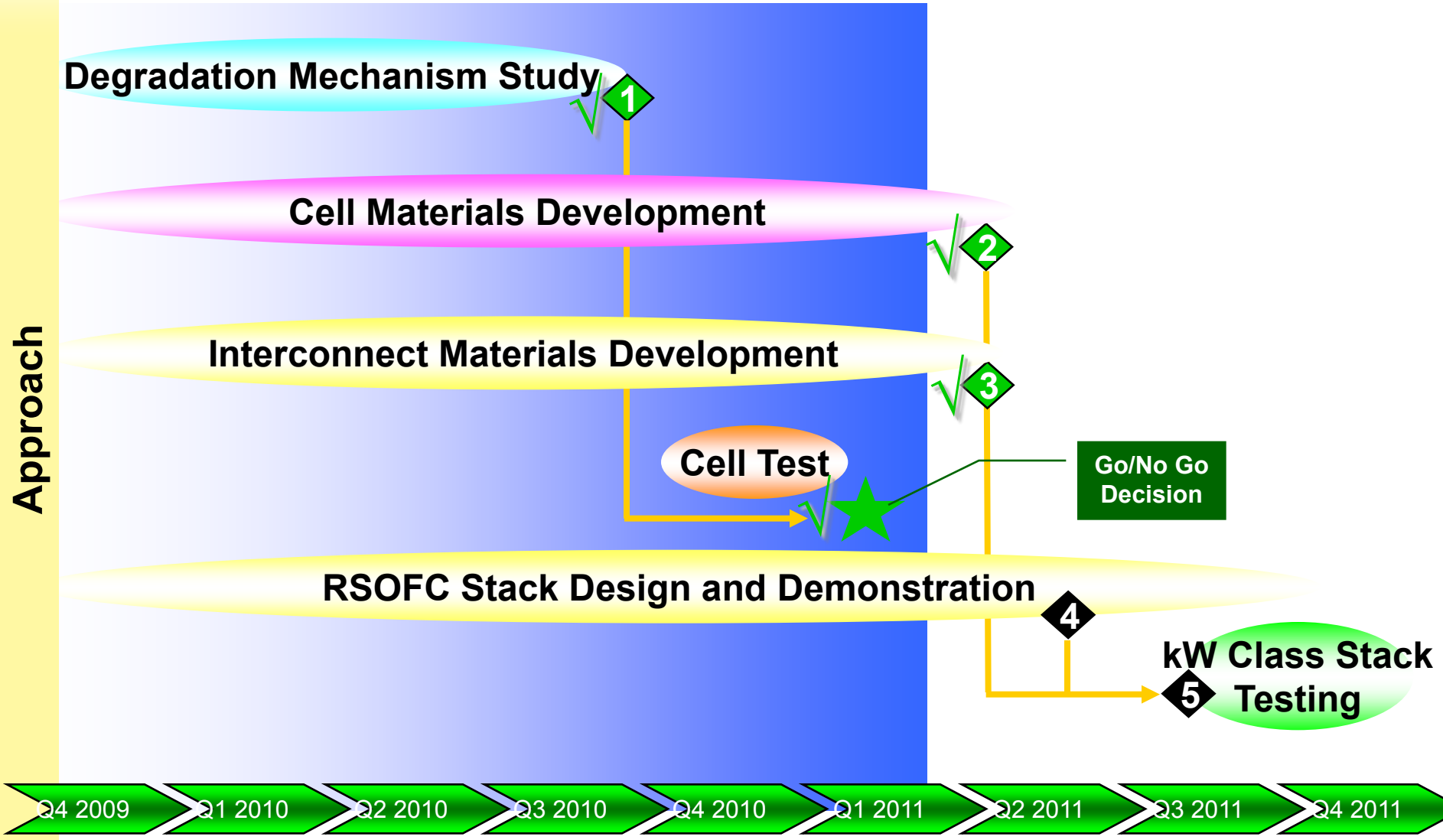
How Objectives Address Barriers

Relevance

	Hurdle	Targets
Endurance	**Performance decay in SOEC mode is too high for RSOFC system development** ▶ Materials system is not stable at SOEC operating mode with a decay rate more than 20% per 1000 hours ▶ Performance decay during transient between SOEC and SOFC is high	**Reducing decay to under 4% per 1000 hours for both SOFC and SOEC** ▶ ***Met endurance target in a 1000 hour single cell test (month 15)*** ▶ Meet endurance target in a 1500 hours kW-class stack (month 24) ▶ Demonstrate transient capability with more than 10 FC/EC transients
Performance	**Performance in SOEC mode is not sufficient for viable RSOFC system development** ▶ ASR is more than 1.0 Ω-cm^2 at 750 C and below in SOEC mode	**Improve performance at 750 C in SOEC mode by reducing ASR to less than 0.3 Ω-cm^2** ▶ ***Met performance technical target in a single cell test (month 15)*** ▶ Operate kW-class RSOFC stack at more than 300 mA/cm^2

Project Timeline, Milestones, Decision Points

Approach



Decision Points and Milestones

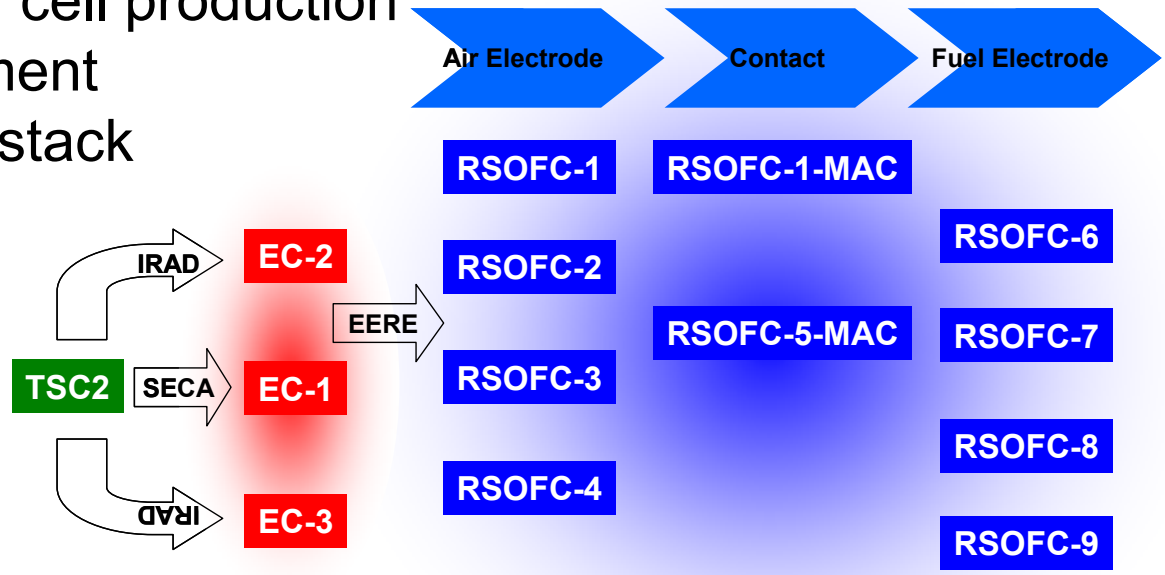
Approach

- In February 2011, the second budget period effort was approved based on 1000 hour single cell test relative to the following performance and endurance metrics:
  - RSOFC area specific resistance of less than 0.3 Ω-cm^2 in both SOFC and SOEC operating modes
  - Operating current density of more than 300 mA/cm^2 in both SOFC and SOEC modes
  - Overall decay rate of less than 4% per 1000 hours of operation
- Five technical milestones will be tracked and measured throughout the project
  1. Task 1: Completion of degradation mechanisms study of baseline cells (4th quarter)
  2. Task 2: Completion of RSOFC cell materials selection (6th quarter)
  3. Task 3: Completion of RSOFC interconnect materials selection (6th quarter)
  4. Task 4: Completion of RSOFC stack design (7th quarter)
  5. Task 4: Starting end of the project RSOFC stack metrics test (8th quarter)

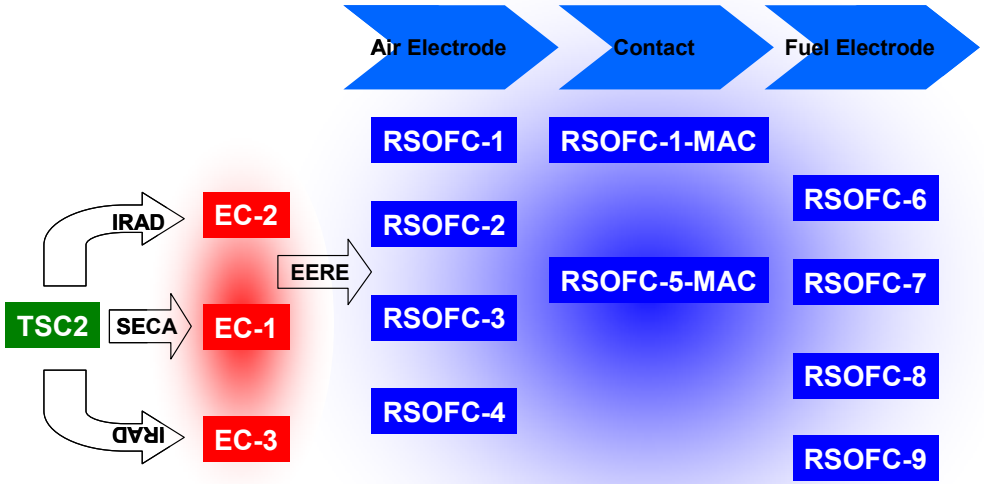
RSOFC Development Path

Approach

- Building on VPS' strong SOFC cell and stack baseline
- Leveraging cell and stack advancements from the DOE SECA SOFC project
- Addressing RSOFC degradation mechanisms in SOEC mode with innovative cell and stack repeat unit configurations
- Conducting parallel materials development activities and integrating them with cell production technology development
- Completing RSOFC stack and process designs to address durability, performance, and cost in both SOFC and SOEC operating modes



RSOFC Cell Performance Development Status

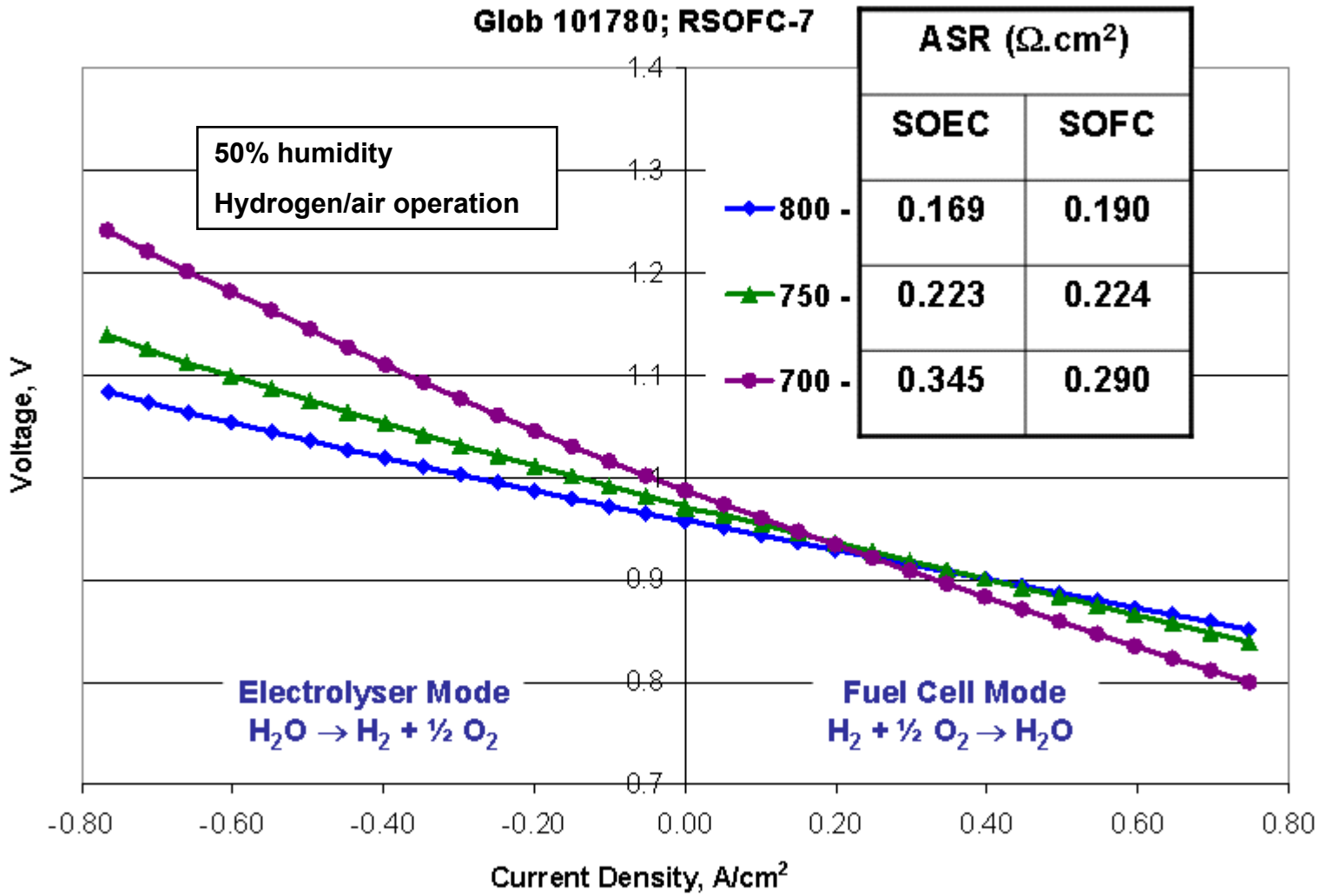


Cell Type	SOEC ASR (mΩ-cm²)	SOFC ASR (mΩ-cm²)
TSC-2	375	180
EC-1	366	281
EC-2	362	393
EC-3	278	251
RSOFC-1	308	245
RSOFC-1-MAC	251	245
RSOFC-2	285	295
RSOFC-3	386	283
RSOFC-4	268	238
RSOFC-5-MAC	341	253
RSOFC-6	271	242
RSOFC-7	223	224
RSOFC-8	194	223
RSOFC-9	230	219

- Fuel Cell (SOFC) ASR at 3% humidity and 750°C
- Electrolysis (SOEC) ASR at 50% humidity and 750°C

8 cell types passed the performance criteria of ASR less than 300 mΩ-cm² in both SOFC and SOEC modes at 750 C

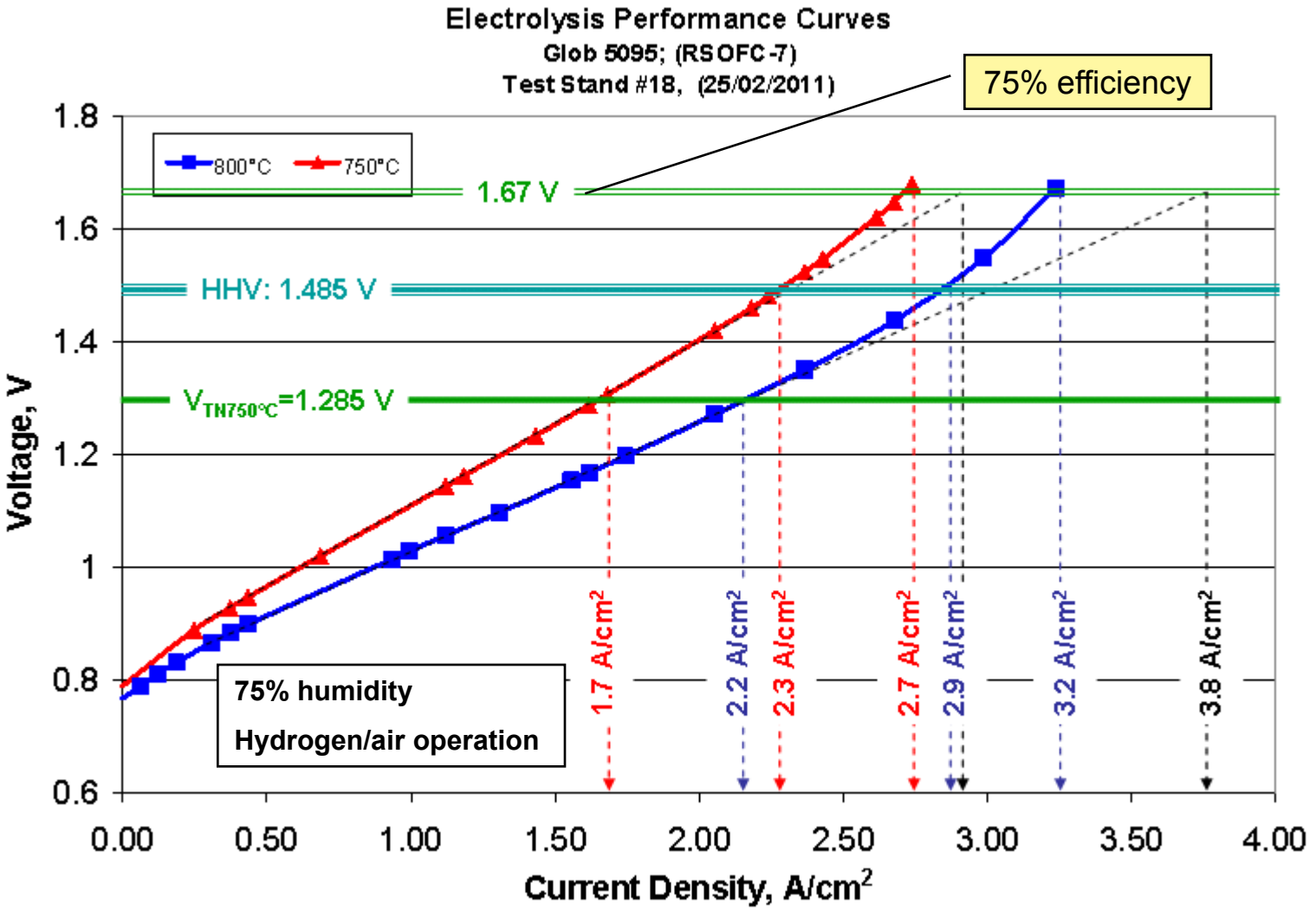
RSOFC-7 Cell Performance



ASR (Ω.cm²)	
SOEC	SOFC
0.169	0.190
0.223	0.224
0.345	0.290

High performance of RSOFC-7 can reduce hydrogen production cost in SOEC mode and improve efficiency in SOFC mode

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

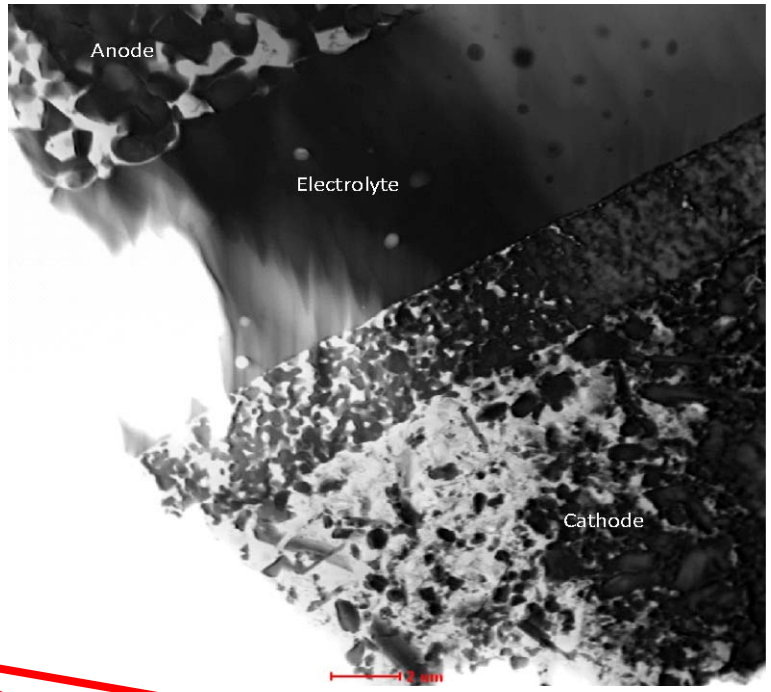


High performance of RSOFC-7 can reduce hydrogen production cost and meet DOE water electrolysis efficiency 2017 target of 75% at the same time

Electrolysis Degradation: Status

- 6 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

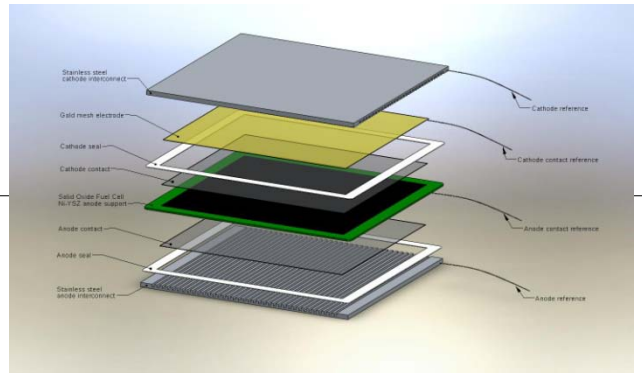


Post Test Analysis After 8000 Hours:

- 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

Steady-State Electrolysis Test of a RSOFC-7 Cell

Degradation Curve
Glob 101780; (M1A2-1325), Oven #17, Oct. 29, 2010



Cell: 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)

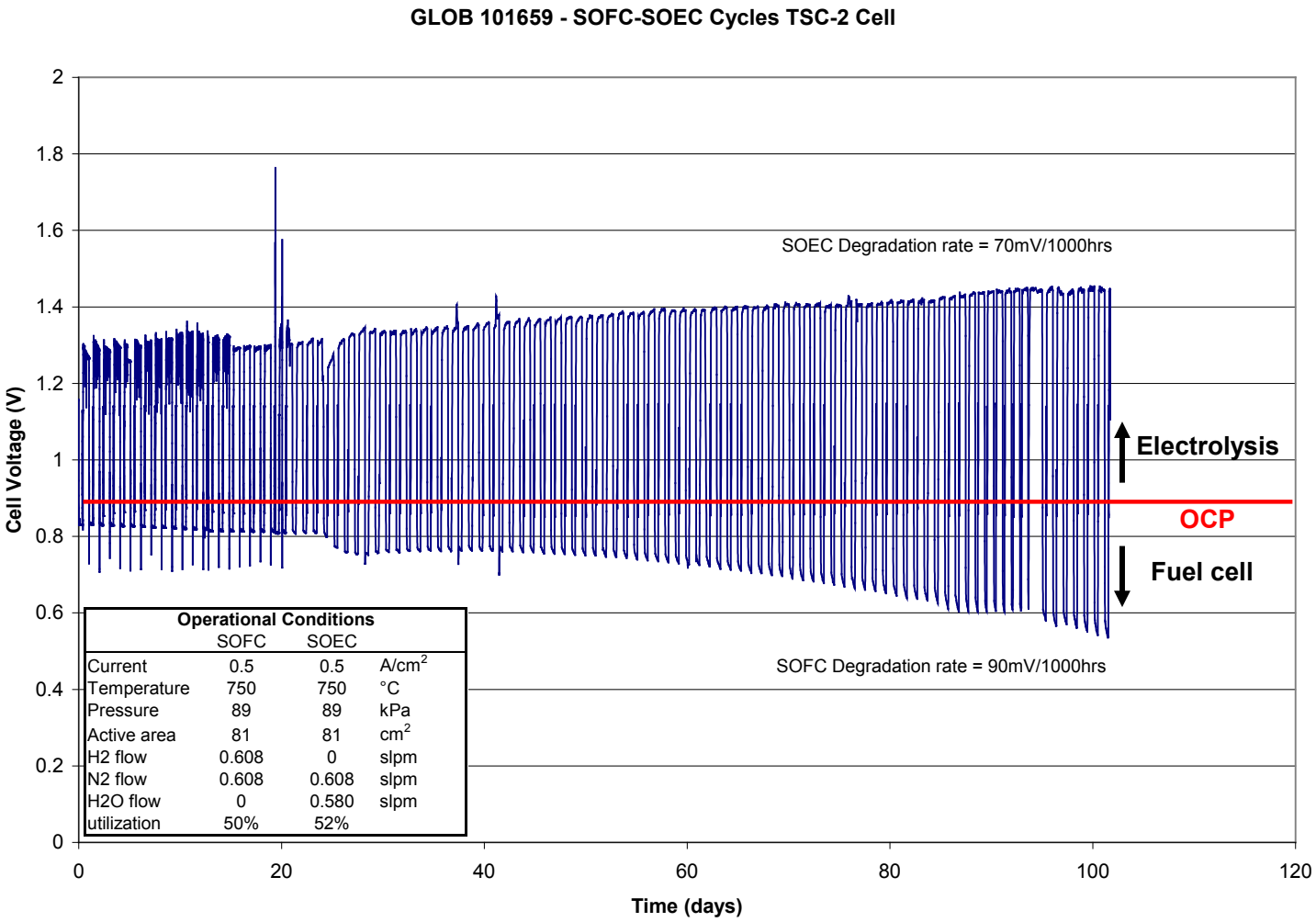
19 mV over 1005 hrs
18.9 mV or 1.5% / 1000 hrs

Demonstrated electrolysis mode degradation of ~1.5% per 1000 hours for the Go/No-Go Decision Test

Summary of Go/No-Go Decision Points

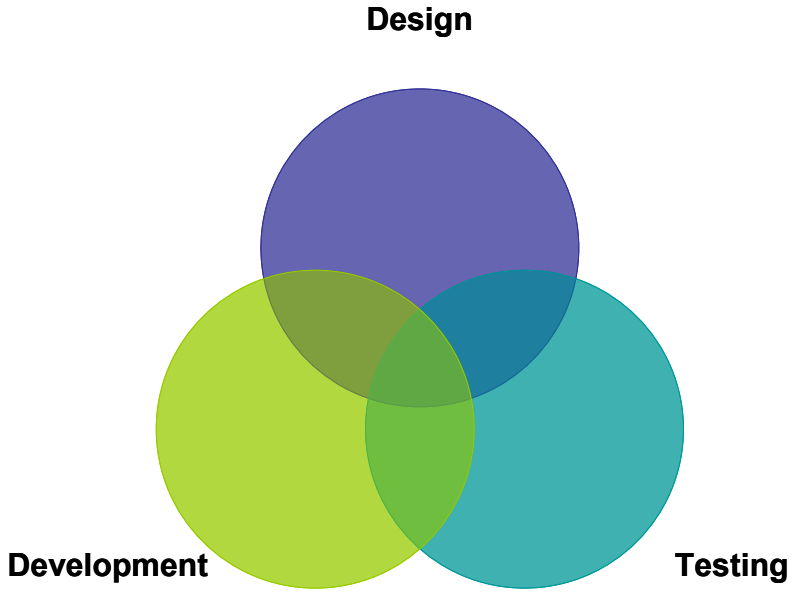
Metric	Target	Status
☑ **Performance** (Area specific resistance in both SOFC and SOEC operating modes)	**< 0.3 Ω-cm²**	**0.223 Ω-cm² in SOEC** **0.224 Ω-cm² in SOFC**
☑ **Degradation** (Overall decay rate)	**< 4% per 1000 hours**	**~1.5% per 1000 hours**
☑ **Operating Duration**	**> 1000 hours**	**1005 hours** (as of Go/No-Go Decision)
☑ **Operating Current Density**	**> 300 mA/cm²**	**500 mA/cm²**

Single Cell Electrolysis/Fuel Cell Cycling Test

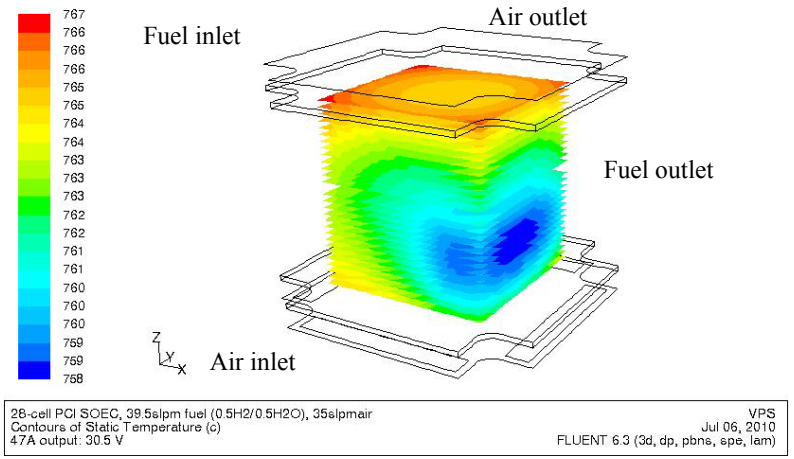


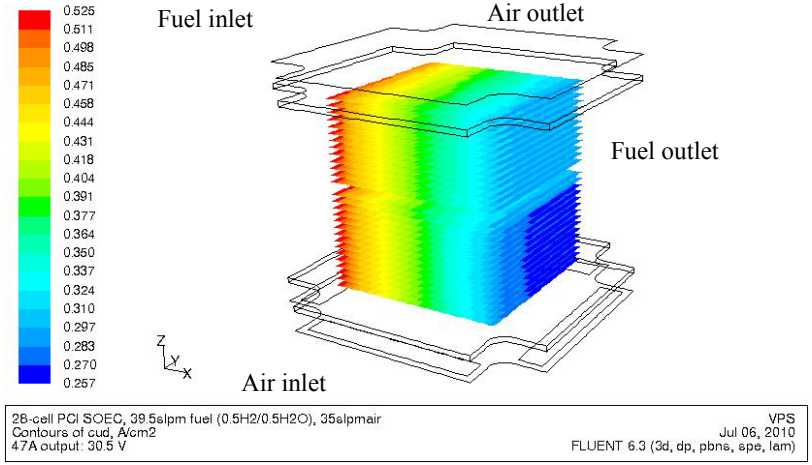
Demonstrated 100 electrolysis/fuel cell mode cycles

SOEC Stack Design and Development

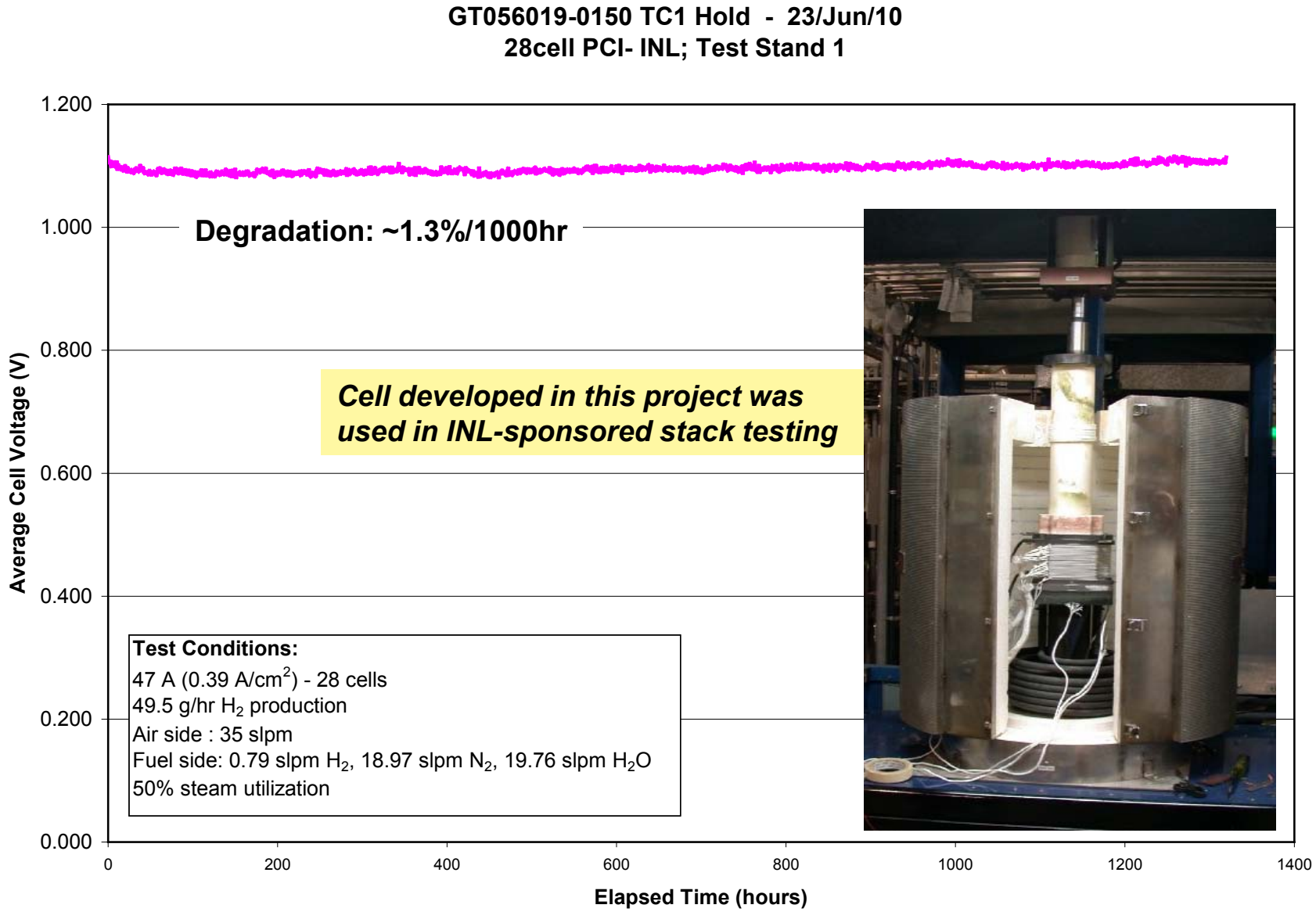


- Developed fully integrated CFD model for RSOFC stack
- Excellent stack thermal profile at SOEC operating mode
- Investigated local current density and chemical species concentration in SOEC operating conditions
- Electrolysis kinetics yet to be verified and calibrated in stack testing





kW-Class Stack Testing for INL



Collaborations

- Boeing
  - Collaborated on and funded initial RSOFC development work through both Boeing and DARPA funded efforts
  - DARPA Vulture Phase 2 project was started October 2011
    - RSOFC stack integration into full reversible system
    - Stack design and development for reduced cost and weight
- INL
  - Eventual integration of SOEC technology for hydrogen production with Next Generation High Temperature Nuclear Reactor
  - Demonstrated suitability of VPS SOEC technology for this application at the kW-class stack level

Proposed Future Work

- FY2011
  - Complete the final project metric test with a kW-class RSOFC stack
  - Complete the additional cell development scope of advancing performance and degradation beyond the original project target

- *Potential Additional Scope for FY2011:*
  - Complete RSOFC system economic study
  - Explore the option of developing larger (up to 20 kW) stack for RSOFC operation
  - Explore the option of developing a RSOFC system integrated with renewable energy sources, such as solar and wind

Versa Power Systems

Summary

Relevance	▶ RSOFC can integrate renewable production of electricity and hydrogen when power generation and steam electrolysis are coupled in a system, which can turn intermittent solar and wind energy into “firm power”
Approach	▶ Developing high performance and low degradation RSOFC cell and stack technology is critical for the reversible SOFC/SOEC system
Technical Progress	▶ 11 types of RSOFC cells were developed in the project. Two types of cells (RSOFC-4 and RSOFC-7) exceeded both performance and degradation criteria ▶ A steady-state single cell test of RSOFC-7 has run in electrolysis with a degradation rate of about 1.5% per 1000 hours ▶ A baseline 28-cell stack (kW-class) test has run in electrolysis for over 1000 hours at about 1.3% per 1000 hours degradation rate
Collaboration	▶ Boeing/DARPA, SECA, and INL
Proposed Future Research	▶ In addition to executing the original project scope, additional development activities are under consideration to accelerate RSOFC technology development for integrating with renewable energy sources, such as solar and wind.