

High Efficiency Reversible Solid Oxide System



FuelCell Energy

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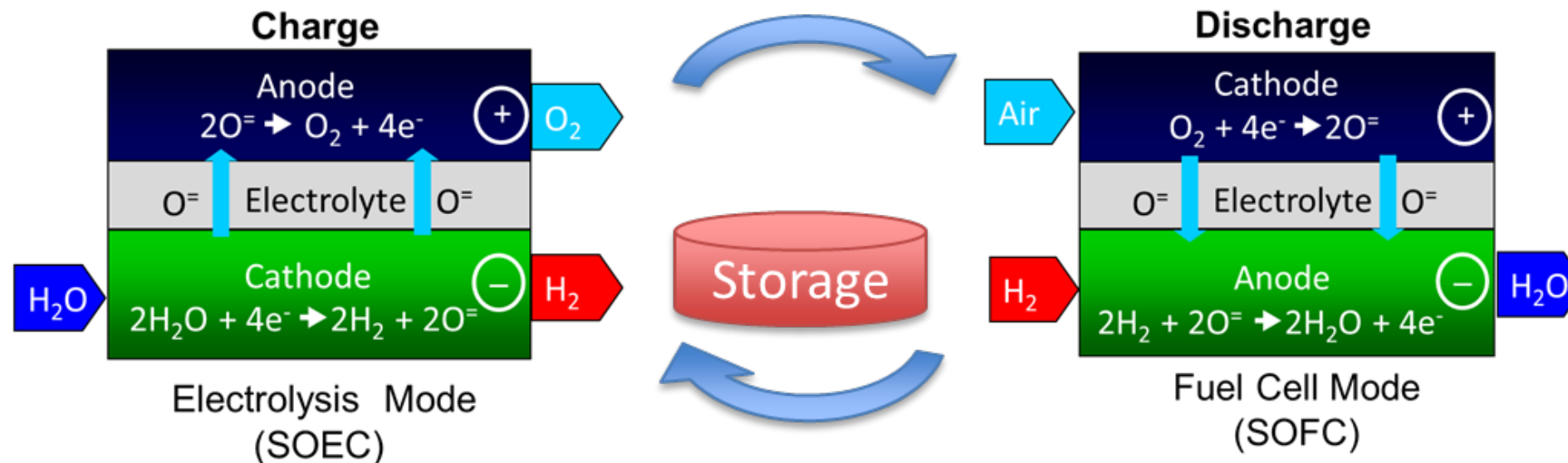
June 6-8, 2022

**DOE Hydrogen Program
2022 Annual Merit Review and Peer Evaluation Meeting**

Project ID# FC330

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- Develop an energy storage technology based on Reversible Solid Oxide Fuel Cell (RSOFC) system capable of round-trip efficiency of 70% and projected energy cost of less than \$100/kWh



Timeline

- Project Start Date: 10/01/2019
- Budget Period 1 End Date: 05/31/2022
- Project End Date: 05/31/2023

Budget

- Total Project Budget: \$2,500,000
 - Total Federal Share: \$2,000,000
 - Total Recipient Share: \$500,000
 - Total DOE Funds Spent*: \$542,451
 - Total Cost Share Funds Spent*: \$135,613
- * As of 3/31/2022

Barrier

- Key barriers addressed in the project are:
 - F. Capital Cost
 - G. System Efficiency and Electricity Cost
 - J. Renewable Electricity Generation Integration

Partner

- FuelCell Energy (FCE) – Project Lead
- Versa Power Systems (VPS)

Project objectives relate to the Hydrogen Production subprogram area of Hydrogen and Fuel Cell Technologies Office (HFTO) by addressing the barriers identified: cost, performance and demonstration of the technology

Project Objectives:

- Validate RSOFC stack performance of less than 0.5% round trip efficiency (RTE) degradation per 100 cycles of testing
- Identify operating conditions that maximize the potential of the RSOFC stack towards meeting RTE performance and degradation goals
- Demonstrate that better than 50% RTE (equivalent to >60% RTE when extrapolated to a large system) and 5%/1000-cycles RTE degradation are achievable via testing of a subscale integrated prototype system
- Establish the plans for transformation of RSOFC technology from laboratory to commercial products
- Verify that the stretch-goals of 70% RTE and cost of <\$1000/kW resulting in energy cost of <\$100/kWhr are achievable for commercial products

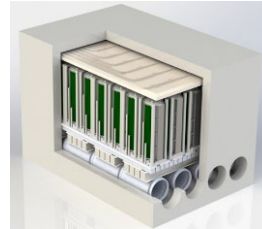
Project approach is focused on development of RSOFC systems achieving RTE, cost and operability goals

- Develop storage system design and Identify operating conditions that maximize the potential of the RSOFC stack and materials technology in meeting RTE performance and degradation goals
- Perform RSOFC stack testing to validate system-identified operating conditions (such as stack pressure of up to 10 bar) and to verify less than 5%/1000 cycles RTE degradation over 100 cycles between fuel cell and electrolysis operating modes
- Build and test a thermally self-sustaining RSOFC demonstration system, rated at 3 kWe output and 15 kWe input, and verify >50% RTE (equivalent to >60% RTE in larger systems) and degradation of less than 5%/1000 cycles RTE degradation
- Develop Technology-to-Market (T2M) plan including commercialization strategies and product specifications by organizing an industry committee consisting of utilities and potential users
- Perform Techno-Economic Analysis (TEA) for RSOFC commercial products using system simulation modeling and components costing to determine the cost of the plant per kW and cost of energy storage per kWhr of power discharge

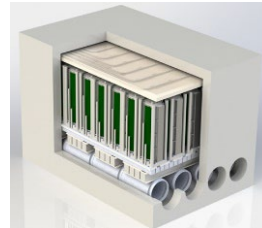
Milestone #	Subtask Title	Project Milestones	Completion Date	Percent Complete	Progress Notes
M1	Stack Development and Testing	Complete technology stack degradation characterization over 50 fuel cell-electrolyzer cycles targeting operating conditions that will provide $\leq 5\%$ RTE degradation/100 cycles	Q2	100	
GN1	Stack Development and Testing	Demonstrate $< 5\%$ round trip efficiency degradation per 1000 cycles over 100 cycles between fuel cell and electrolysis operating modes for a reversible SOFC 45-cell stack operating at constant fuel cell current density $> 200 \text{ mA/cm}^2$ and voltage $> 0.85 \text{ V/cell}$ and electrolysis current density of $> 500 \text{ mA/cm}^2$ and voltage $< 1.3 \text{ V/cell}$ in each cycle of > 20 minutes)	Q4	100	
M3	Stack Manufacturing for System Test	Complete stack manufacturing and qualification testing meeting acceptance criteria and system requirements including minimum open circuit voltage ($> 1.0 \text{ V/cell}$), high fuel cell fuel utilization voltage ($> 0.80 \text{ V/cell}$) for all individual cell blocks within the stack	Q10	25	
M4	Demonstration System Design	Issue preliminary process design for the RSOFC system and identify target stack operating conditions for technology stack characterization testing	Q4	100	
M5	Demonstration System Design	Demonstration RSOFC system design complete, incorporating the thermal storage system and stack qualification requirements issued to achieve 70% system RTE	Q7	40	
M6	Demonstration System Fabrication	RSOFC prototype system fabrication and commissioning complete	Q9		
M7	Demonstration System Test	Demonstrate high efficiency thermal storage sub-system with $> 80\%$ storage efficiency after 12 hours storage (useful heat extracted/heat stored)	Q11		
M8	Demonstration System Test	Demonstrate a complete, pressurized $\sim 3 \text{ kW}$ fuel cell/ $\sim 15 \text{ kW}$ electrolysis unitized RSOFC system with less than 5% round trip efficiency degradation per 1000 cycles over 100 fuel cell-electrolysis cycles, with a demonstrated RTE $> 50\%$, reaching $> 60\%$ when extrapolated to a large system	Q12		
M9	Industry Committee Input and Requirements	Use preliminary input from the industry committee to define system operating targets, including duty cycle, for the RSOFC system demonstration.	Q8		
M10	Industry Committee Input and Requirements	Identify customer operation points (including duty cycles) of interest. Demonstrate system model RTE $\geq 70\%$ at customer relevant conditions and load cycles	Q11		
M11	RSOFC Large Scale System Techno-Economic Analysis	Report system TEA with $< \$1000 / \text{kW}$ and $< \$100 / \text{kWh}$ capital costs, targeting $< 0.1 \text{ \$ / kWh-cycle}$ and validating $\geq 70\%$ RTE system design	Q12		



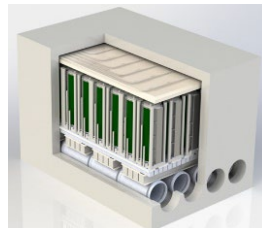
SOFC Stack



Power Generation Stack Module –
Only runs in power generation
mode on natural gas fuel



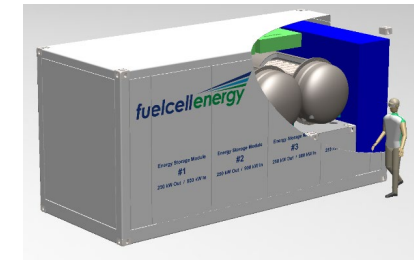
Electrolysis Stack Module – Produces
hydrogen from steam with power input



Energy Storage Stack Module – Alternates
between power generation on hydrogen fuel and
electrolysis producing hydrogen from water



**Power Generation
System**



Electrolysis
4,000 kg/day H₂ from 7.3MW

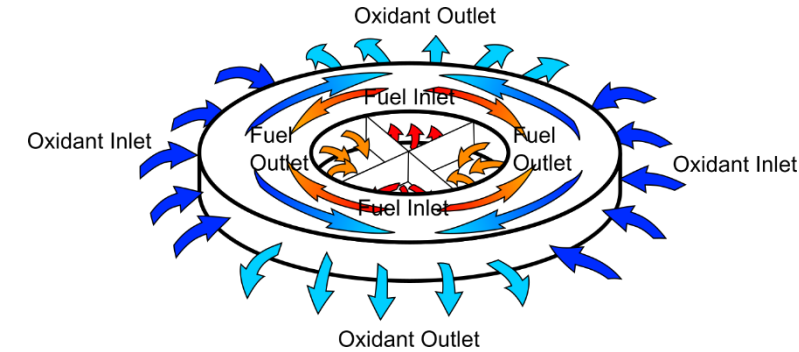


Energy Storage System
1MW, 8MWh



Cell with active area of 81 cm²

Stack size for system demonstration

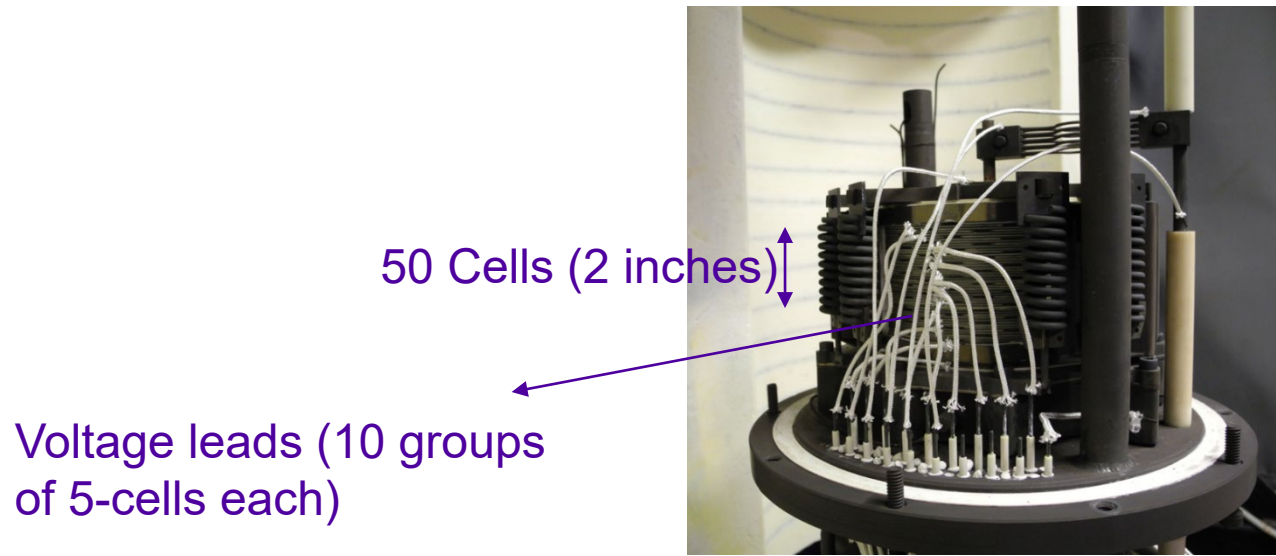


Flow Geometry

Property	Scale			Comments
	Short	Mid	Full	
Cell count	45	150	350	Nominal count
Fuel Cell Voltage, V	43	143	333	At 0.950 V/cell
Electrolysis Voltage, V	58	192	448	At 1.280 V/cell
Stack Efficiency, % LHV	74% / 100%	74% / 100%	74% / 100%	Electrochemical eff FC / EL
Power, kW	0.87 / 1.6	2.8 / 5.4	6.7 / 12.7	At 0.25 / -0.35 A/cm ²
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	

Conditions selected to emphasise storage efficiency

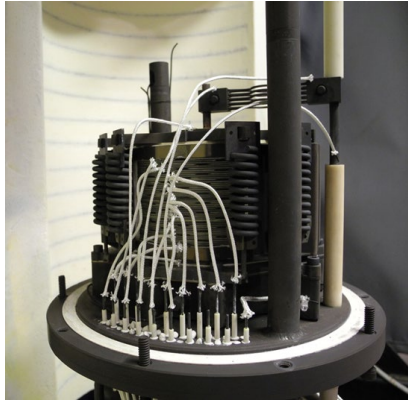
- A 50-cell stack was fabricated for testing in the project



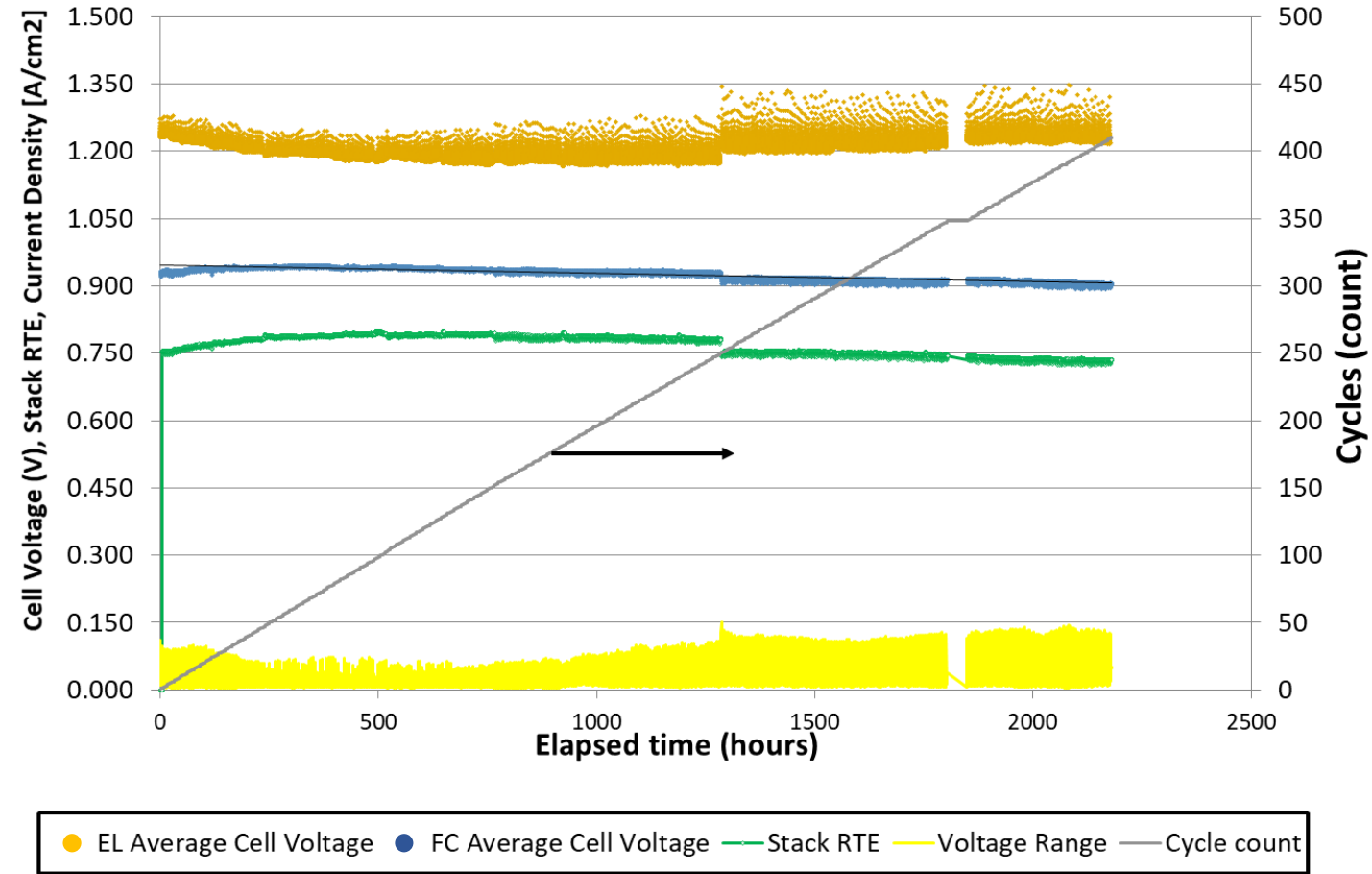
Cyclic Operating Conditions

	Fuel Cell (Discharge)	Electrolysis (Charge)
Current density	0.2 A/cm ²	0.6 A/cm ²
Time on load	3 hours*	1 hour*
Utilizations	25% H ₂ , 30% Air	50% steam
H ₂ /Steam Concentrations	100%/0% (approx.)	22%/78%

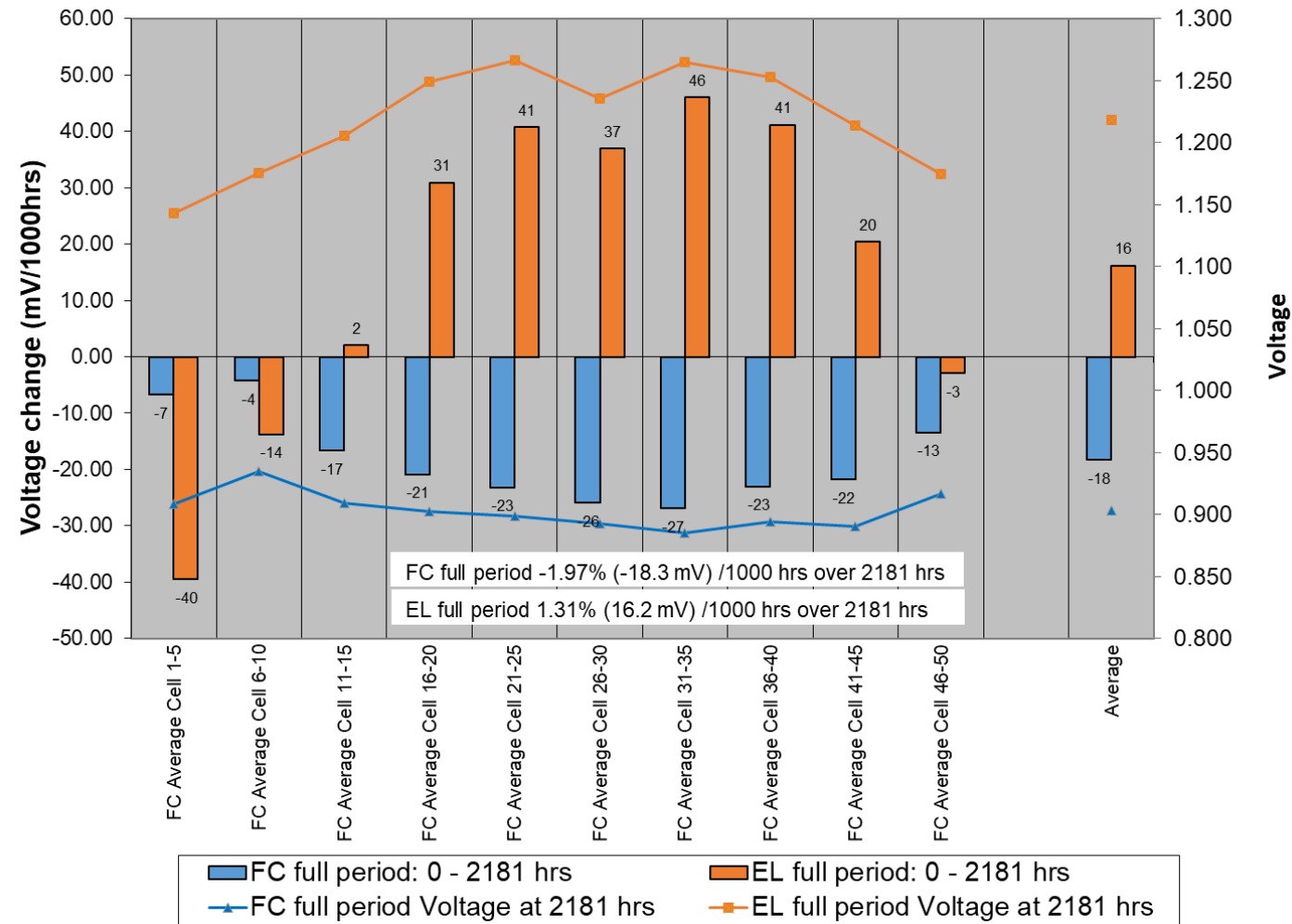
* 30 minutes transition times resulting in total cycle time of 5 hours



50-cell CSA stack



- Completed 410 cycles overall in >2180 hours of operation
- Achieved a peak stack RTE of 80%



- Overall degradation (linear fit)
- Fuel Cell Operation: 18 mV/khr (1.97%/khr) – End voltage: 0.903 V/cell average
- Electrolysis Operation: 16 mV/khr (1.31%/khr) – End Voltage: 1.218 V/cell average

Milestone 1.1.1 (Q2)

- Completed technology stack degradation characterization over 50 fuel cell-electrolyzer cycles targeting operating conditions that provided $\leq 5\%$ RTE degradation/100 cycles

Characteristic	Requirement	Achieved	
# cycles	50	410	✓
Operating conditions	Representative	Representative	✓

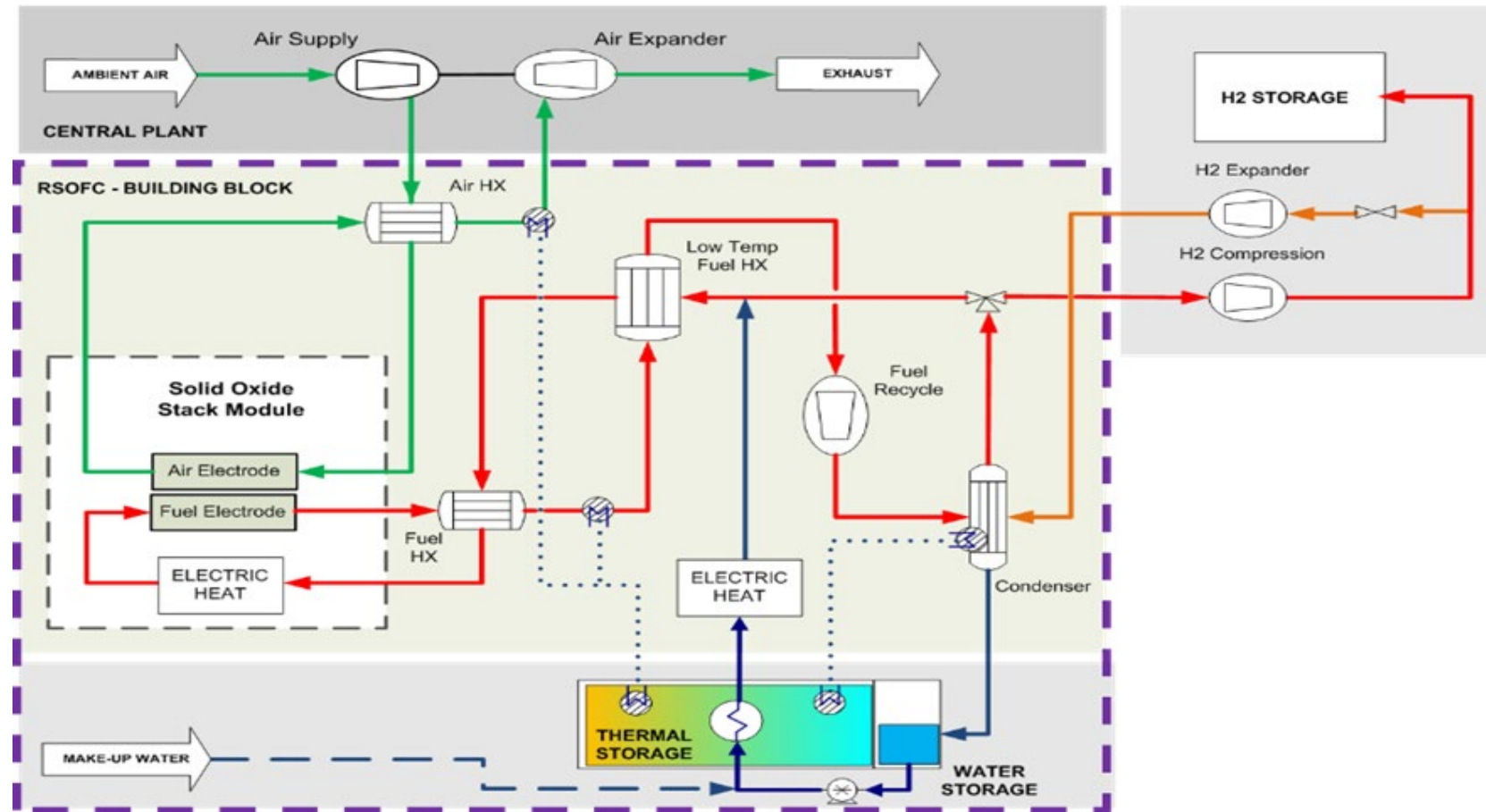
Go/No-Go 1.1.2 (Q4)

- Demonstrated $< 5\%$ round trip efficiency degradation per 1000 cycles over 100 cycles between fuel cell and electrolysis operating modes for a reversible SOFC 50-cell stack operating at constant fuel cell current density $> 200 \text{ mA/cm}^2$ and voltage $> 0.85 \text{ V/cell}$ and electrolysis current density of $> 500 \text{ mA/cm}^2$ and voltage $< 1.3 \text{ V/cell}$ in each cycle of > 20 minutes

Characteristic	Requirement	Achieved	
# cycles	100+	410	✓
Fuel cell current	$> 0.2 \text{ A/cm}^2$	0.2 A/cm^2	✓
Fuel cell voltage	$> 0.85 \text{ V/cell}$	0.903 V/cell ending	✓
Electrolysis current	$> 0.5 \text{ A/cm}^2$	0.6 A/cm^2	✓
Electrolysis voltage	$< 1.3 \text{ V/cell}$	1.218 V/cell	✓
Cycle duration	> 20 minutes	> 5 hours	✓
Degradation	$< 5\%$ / 1000 cycles over 100 cycles	$< 5\%$ / 1000 cycles over 410 cycles	✓

- Size: ~3 kWe FC / ~15 kWe EC
- Basis: Modification of existing 20 kg/day High Temperature Steam Electrolysis (HTSE) pilot system developed under Modular SOEC System project (DE-EE0007646)
- Addition of Thermal Energy Storage (TES) subsystem
- Develop operating strategies to achieve efficiency and degradation targets
- Detailed design:
 - Process (Piping & Instrumentation Diagrams (P&ID), equipment specs, HAZOP safety analysis, controls)
 - Mechanical (pressurized stack module, equipment integration, solid modelling)
 - Electrical (power supply/load bank integration, instrumentation and control hardware)
- Metrics
 - $\geq 50\%$ RTE (extrapolated to 60% for larger systems via heat and mass balance models)
 - $\leq 5\%$ round trip efficiency degradation per 1000 cycles, over 100 cycles
 - Demonstrate TES with $>80\%$ heat recovery after 12 hours (useful heat extracted/heat stored)



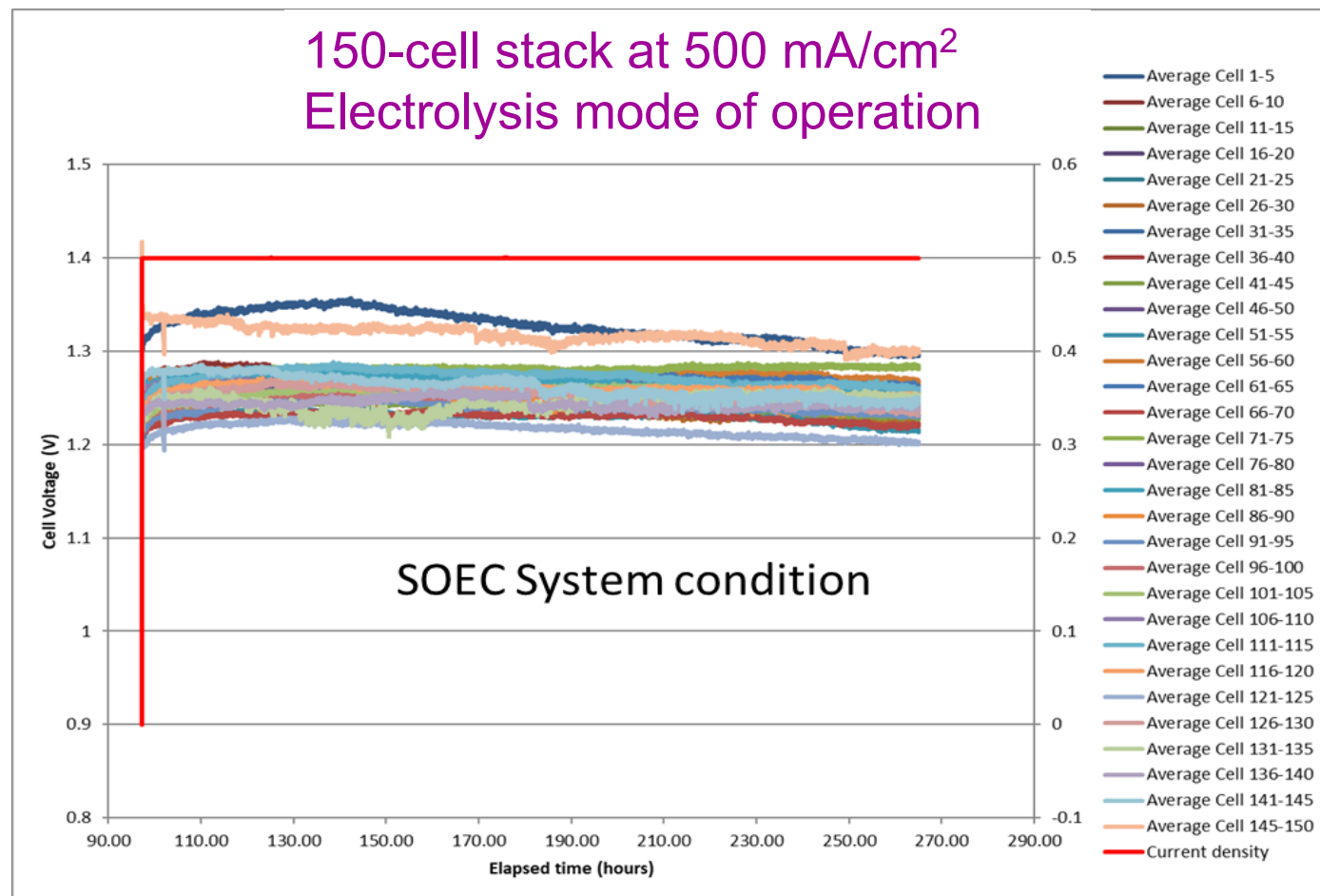


- Process Flow Sheet was completed
- Computer Simulation of the system was completed:
 - Steady-State Mass & Energy Balances using ChemCad simulation software



150-cell stack (GT60247-0005)

- 150-cell stack was fabricated and conditioned for further testing in the Pilot RSOEC System



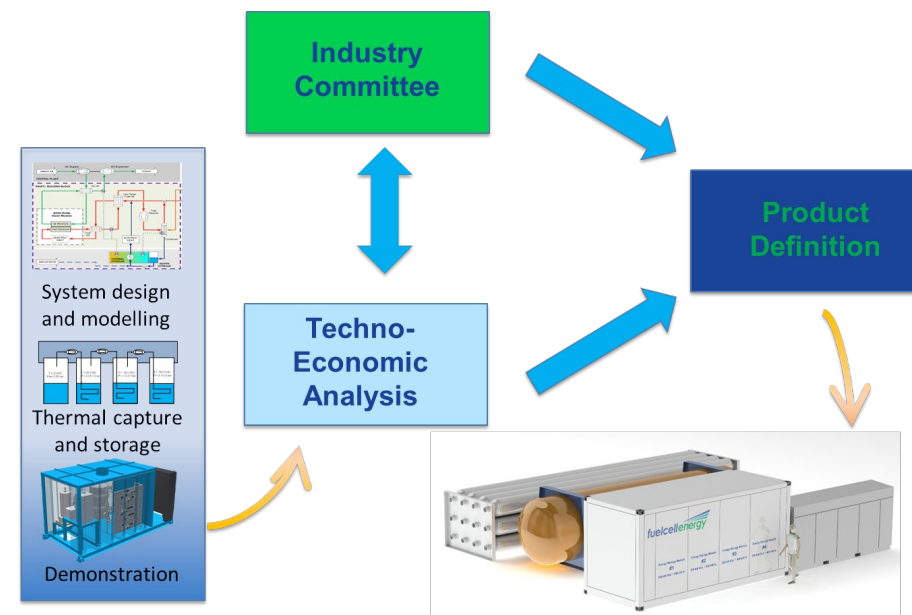
- Furnace: 627 C
- Fuel: 50% H₂O , 50% H₂ @ 76.05 SLPM H₂
- Air: 150 SLPM @ 40.5 A -- 76.05 SLPM H₂O
- Usteam = 60.0%

- This project was not reviewed last year

An Advisory Board is being formed to provide guidance for product definition and specifications; and to oversee the development of the energy storage RSOFC systems

- List of potential industry committee members:

- Exelon
- EPRI
- Linde
- National Resource Defense Council (NRDC)
- National Rural Electric Coop Association (NRECA)
- TriState G&T
- Southern Company
- Xcel



- Identify preliminary committee input for storage requirements
- Define system operating conditions and characteristics (size, cycle duration, etc.)
 - CHEMCAD model will be developed based on this input

- Improvements in the cyclability of RSOFC stacks
 - Refinement in stack thermo-mechanical design for maintaining good electrical contact between electrode and interconnect during the cyclic operation
- System demonstration:
 - Efficient thermal storage design
 - Reduction in degradation of RSOFC performance
 - Achieving RTE targets >50% in a 3 kW (discharge) demonstration system
- Techno-economic targets:
 - System cost of <\$1000/kW resulting in energy cost of <\$100/kWhr

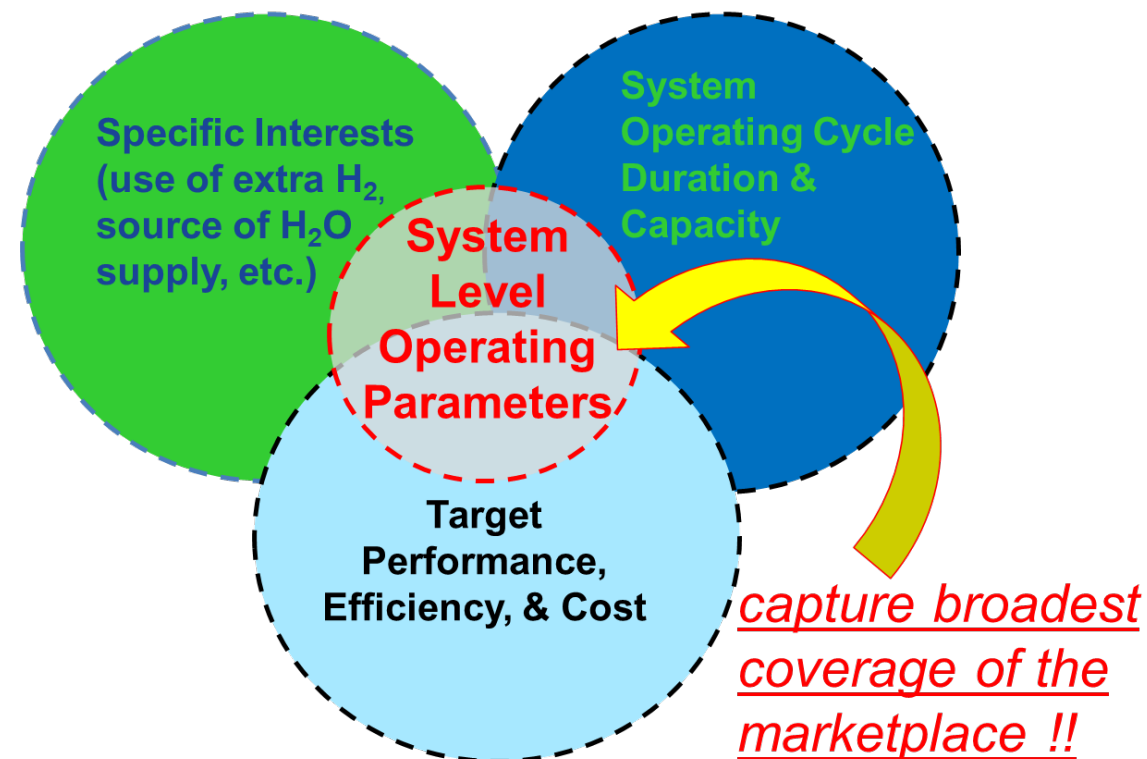
- Test a 150-cell technology stack in the Pilot SOEC System to optimize operating condition parameters in each mode of charge/discharge to optimize performance and reduce degradation:
- Complete fabrication of the equipment needed to upgrade the Pilot SOEC System for cyclic operation (charge/discharge)
 - Power electronics
 - Heat exchangers
- Complete revamp of the Pilot SOEC System for demonstration of 3kW (discharge) energy storage in Budget Period 2
- Perform Techno-economic Analysis
 - RSOFC product configuration
 - Stack and system cost at high volume production
 - Operating and maintenance costs

Any proposed future work is subject to change based on funding levels

- Built and tested a 50-cell SOEC stack subject to 410 charge/discharge cycles for >2000 hours
 - Verified voltage degradation rates of <2%/khr for electrolysis (charge) and fuel cell (discharge) modes of operation
 - Achieved peak round trip efficiency of 80% and overall RTE degradation of <5% per 1000 cycles
- Completed thermodynamic analysis of energy storage system and flowsheet design
- Initiated formation of prospective members of an Advisory Board for product characterization

Technical Backup and Additional Information

- A concurrent Project from DOE (FE/NETL), DE-FE0031974, expands the market potential for the RSOFC energy storage to fossil fuel power plants with an option for additional production of hydrogen
 - Concept design of 10MWhr SOEC energy storage at a fossil plant
- FCE is developing a 250 kW / 150 kg/day hydrogen production SOEC system under an EERE project (DE-EE0009290). The unit will be demonstrated at Idaho National Lab (INL) next year using hardware-in-the-loop simulation of a nuclear power plant operation
 - System will demonstrate high efficiency :
 - i. Without thermal input (electrically generated steam), 92% (HHV) efficiency
 - ii. With free steam, nearing 100% (HHV) efficiency



Product Development Process

This project will contribute to achievement of the following DOE High Temperature Reversible Fuel Cell Targets:

Characteristic	Units	2030 Targets	Project Results
Cell Performance/ Roundtrip Electric Efficiency	%	85	80
Cell Durability/Degradation Rate (RTE)	%/1000 hrs	0.25	1
System Roundtrip Efficiency (includes thermal energy input)	%	60	tbd
Levelized Cost of Storage	\$/kWh	0.2014	tbd
System Capital Cost by Power	\$/kW	1,800	tbd
System Capital Cost by Energy ¹⁴	\$/kWh	250	tbd

- SOFC Cell fabrication process has evolved from laboratory to pilot-production in 2001



Tape Casting

Anode Tape



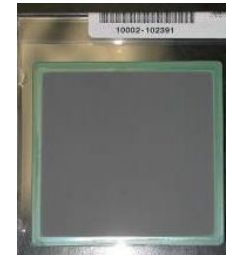
Screen Printing

Unfired Cell

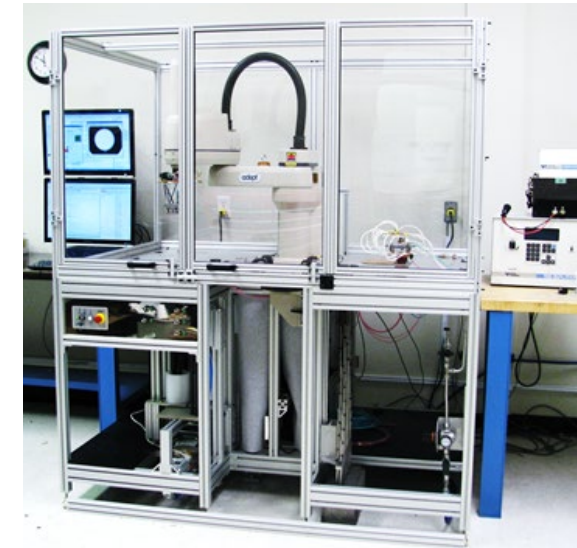


Co-sintering

Fired Cell

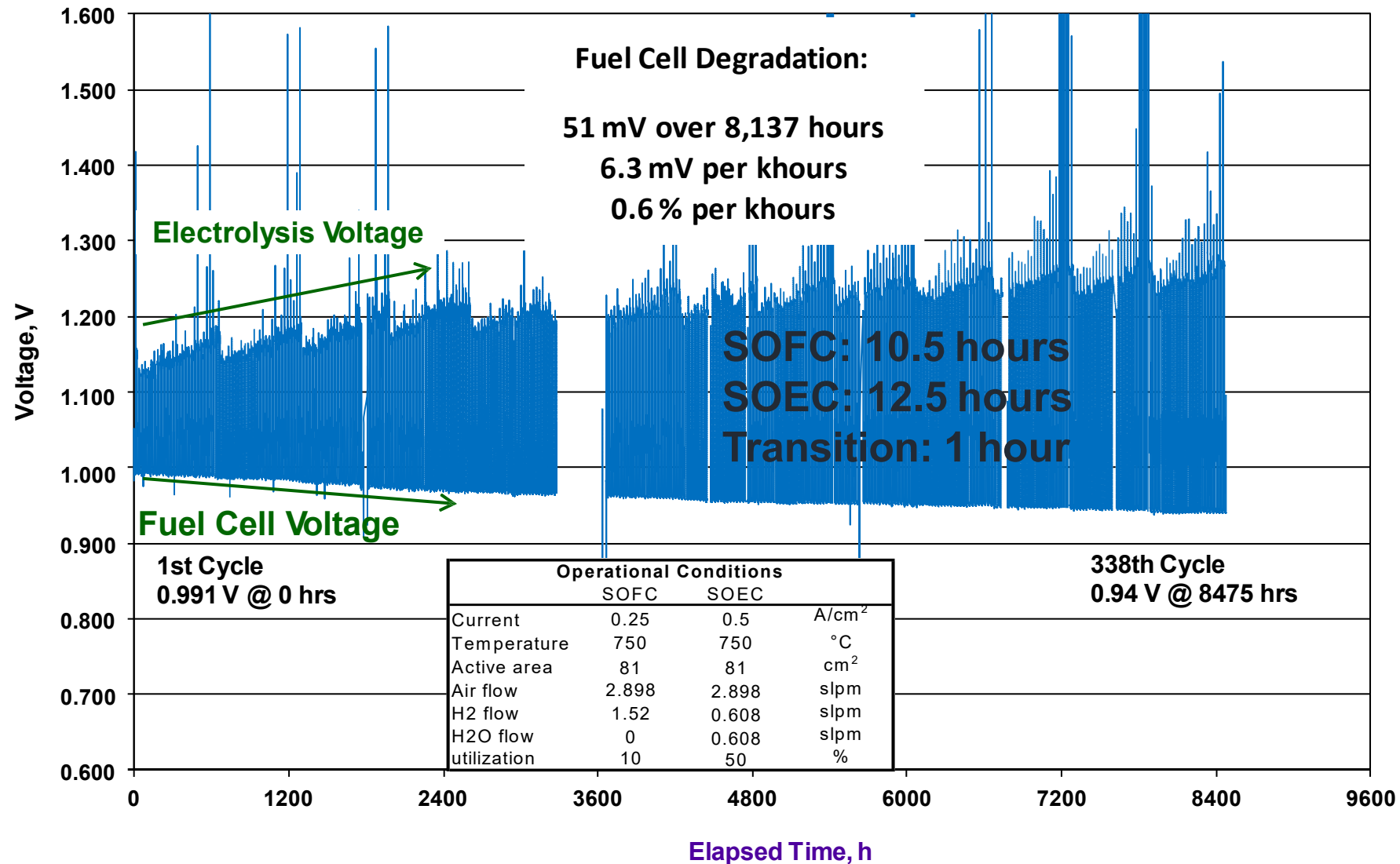


Automated Screen Printing

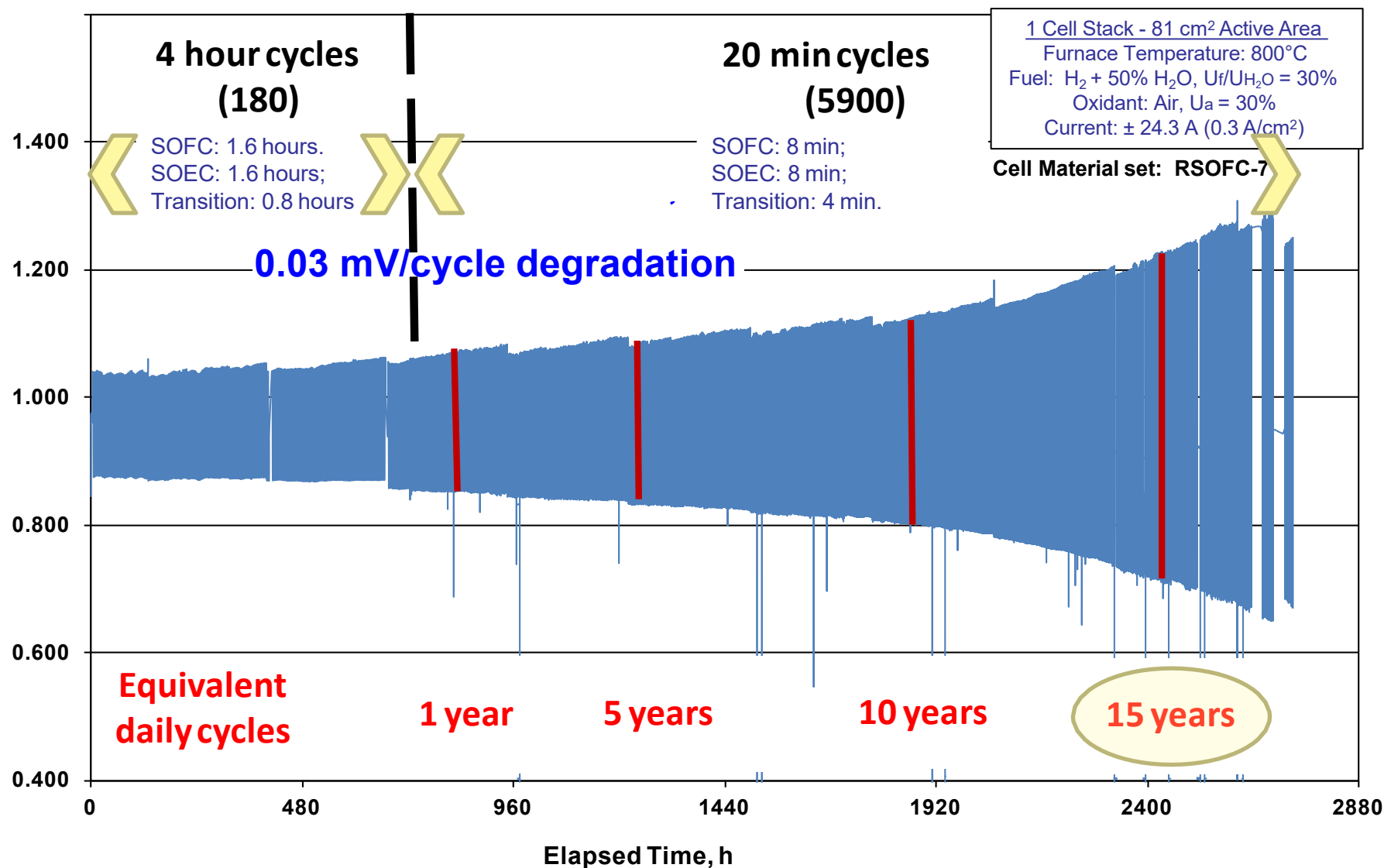


Automated QC / Stack Assembly

“TSC” SOFC fabrication process is flexible & scalable to high volume and low-cost production



Simulated RSOFC Operating Profile – 24hr daily cycle



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

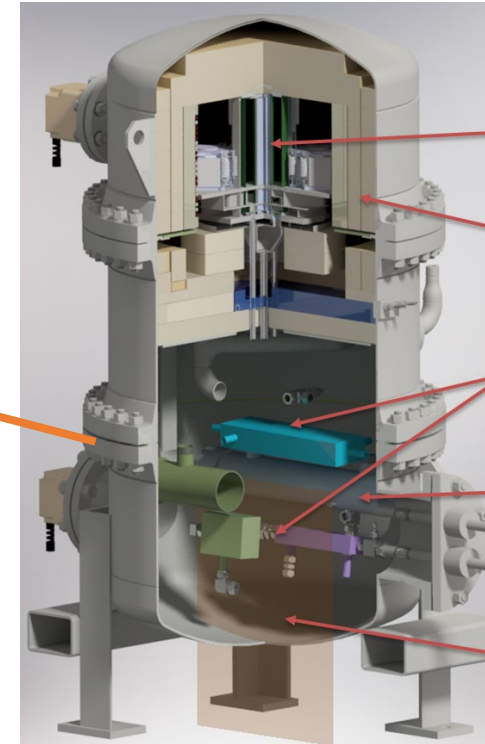


Vaporizer

Power and Controls Cabinet

SOEC Electrolyzer System

System Parameter	Performance
Stack Electrical Eff (HHV)	115.2%
System Electrical Eff (HHV)	107.4%
System Total Eff (HHV)	92.2%
Electricity Consumption	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption	42.7 kWh/kg



SOEC Electrolyzer Module

Electrolyzer Stack

Insulation

Heat Exchangers

Electric Heaters

Space filled with loose-fill insulation (not shown)



Mid Size CSA Stack



Stack Module Assembled

Stack Module:

- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- Vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature