FuelCell Energy

Performance Improvements for Reversible Solid Oxide Fuel Cell Systems (FE0031974)

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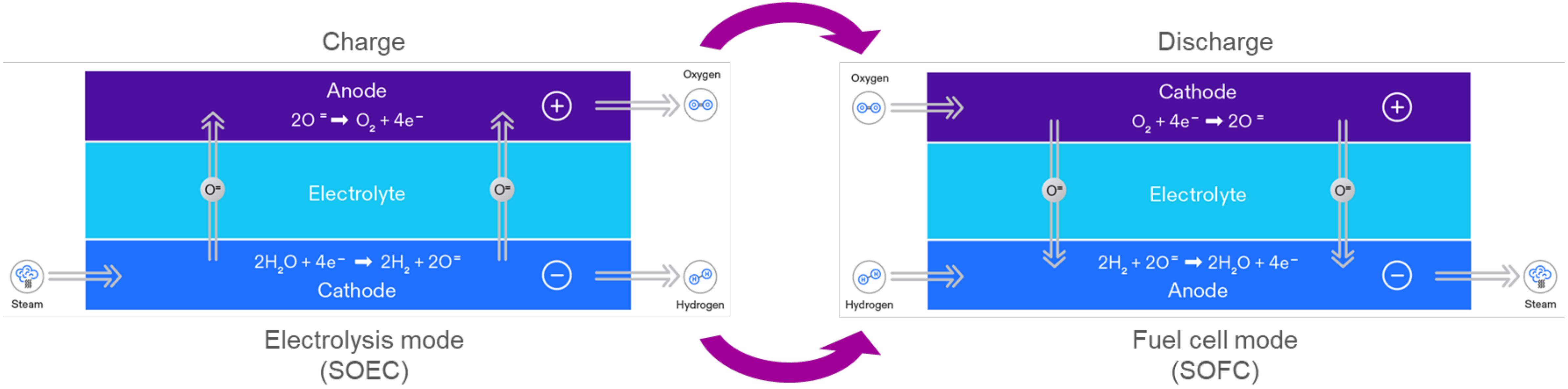
Objectives

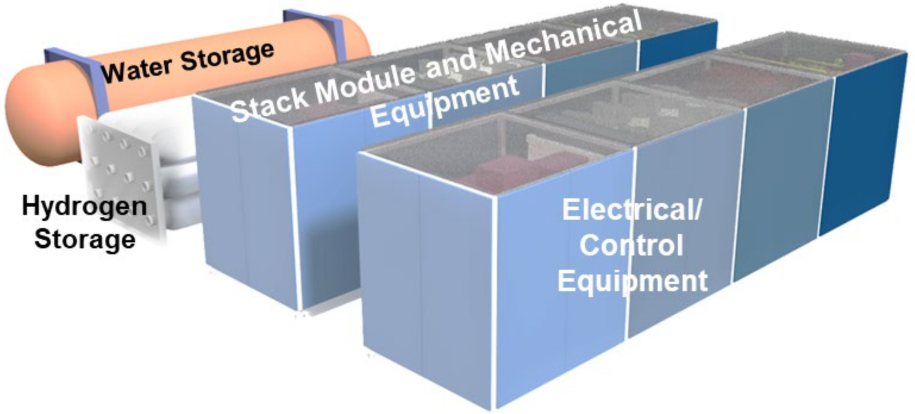
- Advance Reversible Solid Oxide Fuel Cell (RSOFC) technologies for hybrid operation of water electrolysis as well as power generation, suitable for energy storage combined with capabilities for hydrogen production
- Achieve cell performance improvements, stack durability, and high system efficiency, resulting in the design of a MW-scale energy storage system with no carbon footprint and an anticipated storage system cost of <$1000/kW at 50MW/year manufacturing level, leading to hydrogen production cost of <$2/kg H_2 (at $30/MWh electricity price)

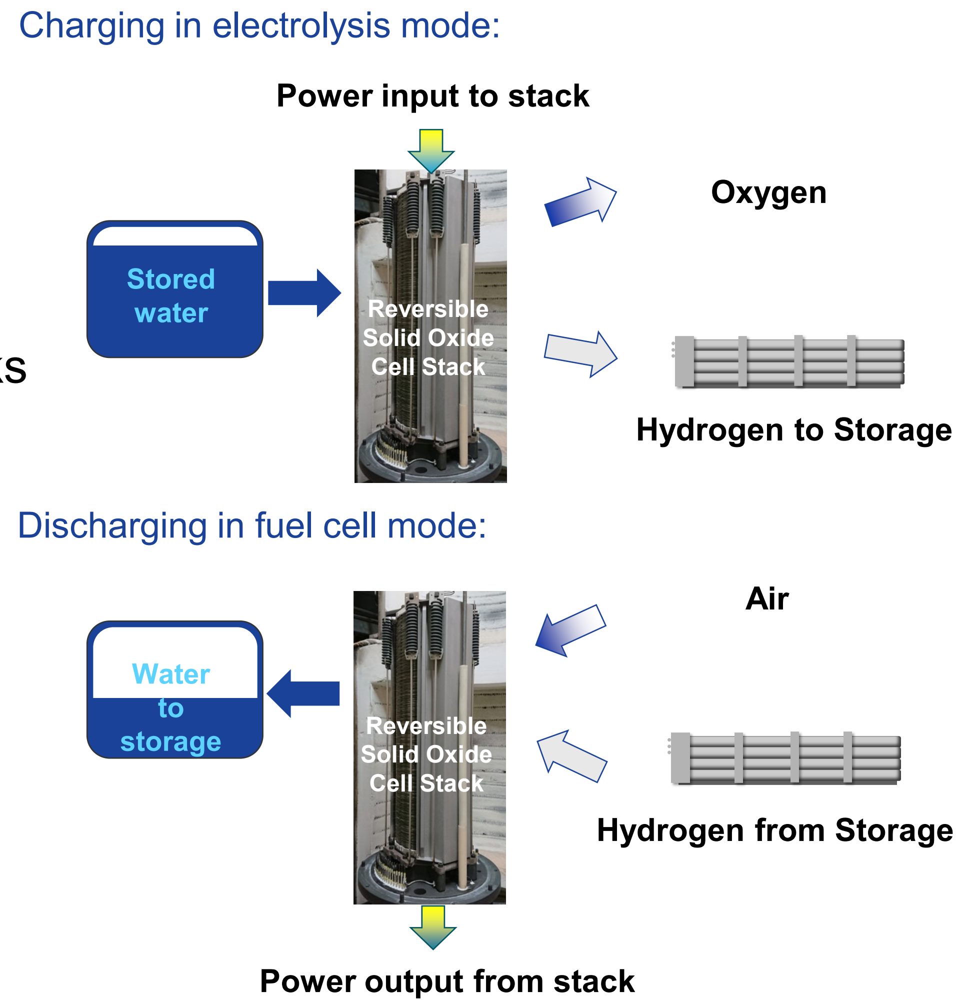


- During charge, hydrogen is produced and stored using electric power
- During discharge, stored hydrogen and oxygen from air are used to produce electricity

Solid Oxide Hydrogen Based Energy Storage

- RSOFC benefits:
  - Inexpensive water is the only reactant – added as an initial fill and regenerated with each discharge cycle
  - Long duration achieved by adding low-cost hydrogen and water storage capacity, without the need to add more stacks
  - Excess hydrogen can be produced and sold directly to costumers for additional revenue
  - Geological storage of hydrogen can be used to provide weekly or seasonal storage





With water as the only stored reactant, hydrogen-based storage has significant advantages for long duration storage

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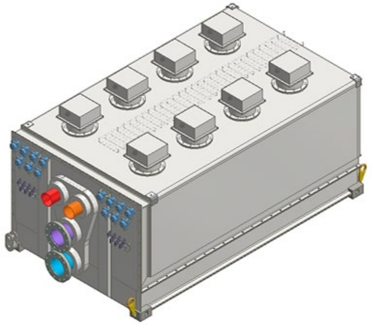
Solid Oxide Technology Applications

Manufacturing

Solid oxide stack is a common platform



48-stack module

Fuel Cell

- Power generation using a wide range of fuels, including natural gas, biofuels and hydrogen

250 kW Power Generation System

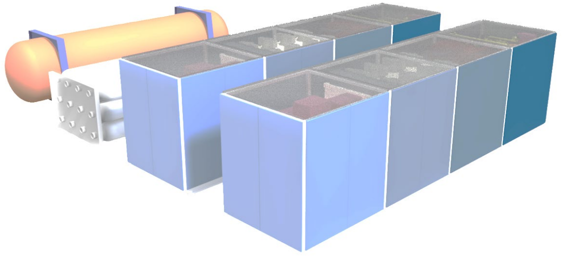
Electrolysis

- Producing hydrogen from steam with power input

Electrolysis
600 kg/day H2 from 1.1 MW

Energy Storage

- Alternating between power generation and electrolysis to produce hydrogen from water



Energy Storage System
1MW, 8MWh

Cell Technology for Reversible Operation

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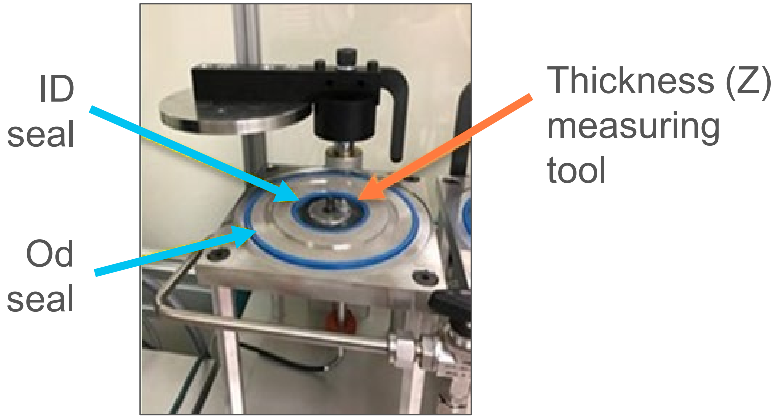
Cell Fabrication

Cell QC

Tape Casting — Automated Screen Printing — Co-Sintering

"TSC 3 Process"



CSA cell leak tester jig with thickness measuring tool

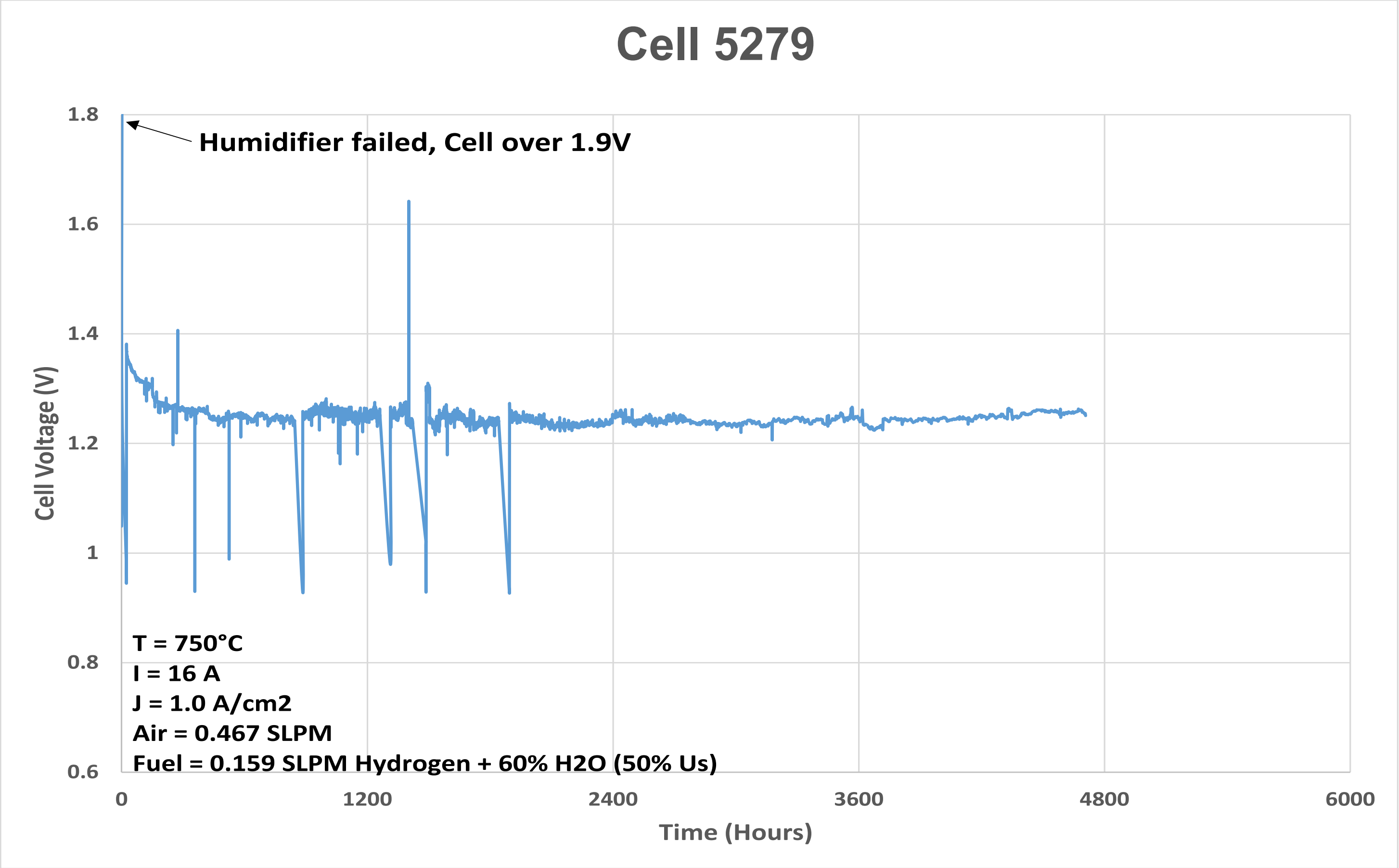
Solid Oxide Cell (SOFC) Constituent Layers

Component	Materials	Thickness	Porosity	Process
Cathode	Conducting ceramic	~ 50 µm	~ 30%	Screen printing
Barrier layer	CGO	~4 µm	<10%	Screen printing
Electrolyte	YSZ	~5 µm	< 5%	Screen printing
Anode functional layer	Ni/YSZ	~8 µm	~ 40%	Screen printing
Anode support	Ni/YSZ	~0.3 mm	~ 40%	Tape casting

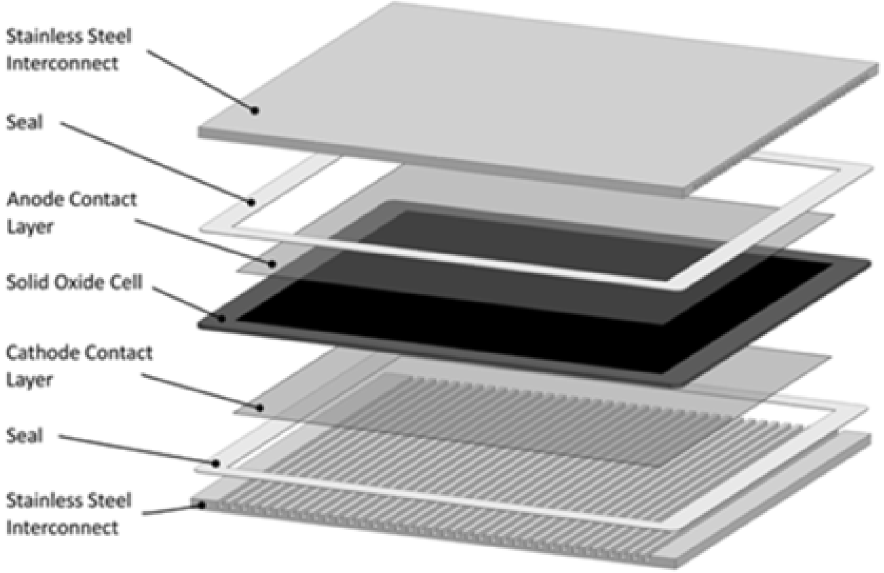
Stack repeat unit:

- Contact Design + Formed Interconnect
- Cell:
  - Cathode
  - Barrier layer
  - Electrolyte
  - Anode Substrate (fuel electrode)
- Contact Design + Formed Interconnect

Long-Term Stability of Cell Operation in Electrolysis Mode



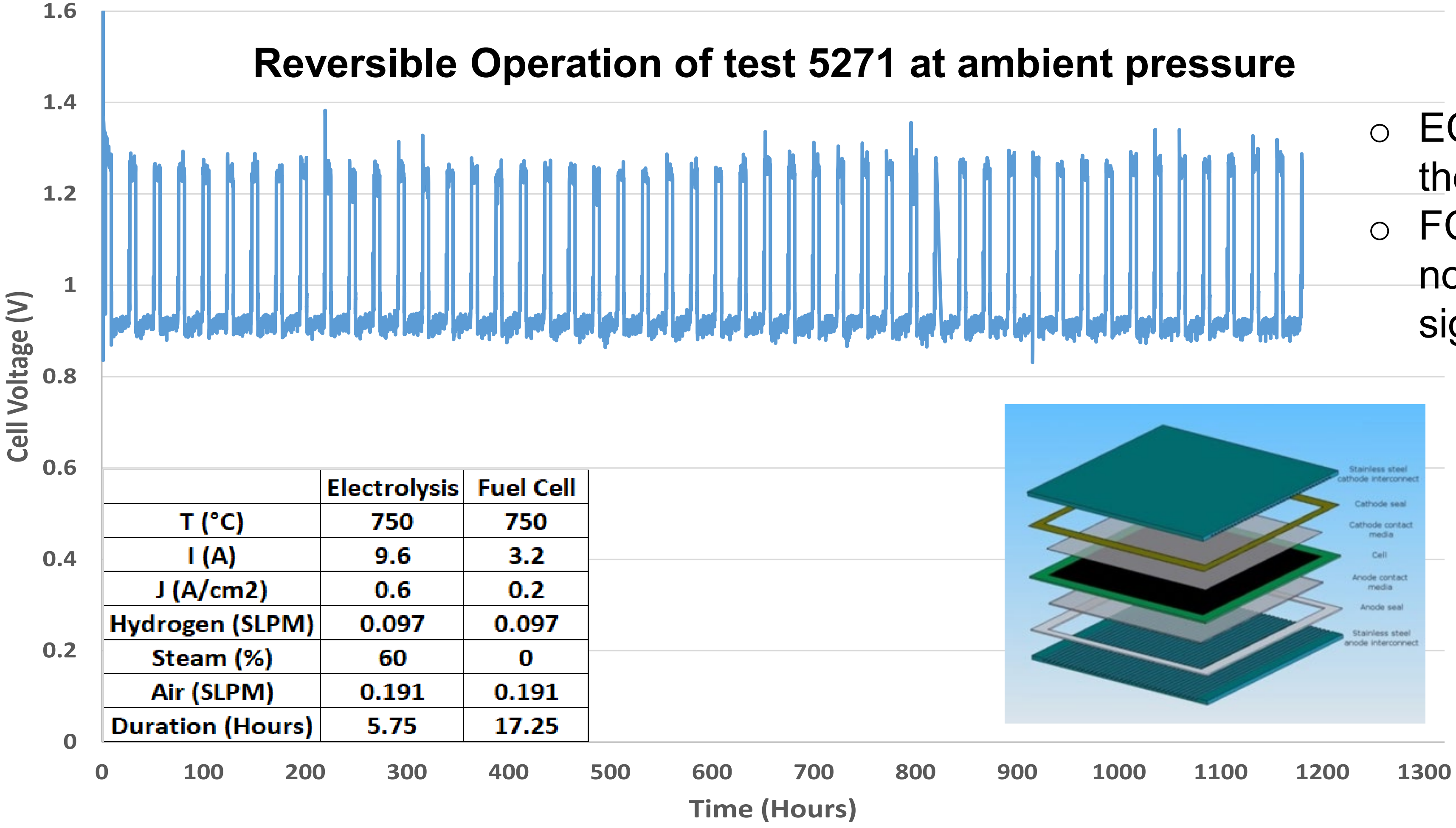
Steady State Operation in Electrolysis Mode at 1 A/cm^2



- 16 cm^2 cell configuration consisting of stack features:
- cross-flow pattern
- flow fields
- electrode contact layers
- glass seals

Negligible cell degradation observed after >6 months of operation

Cell 5271 in Reversible Operation

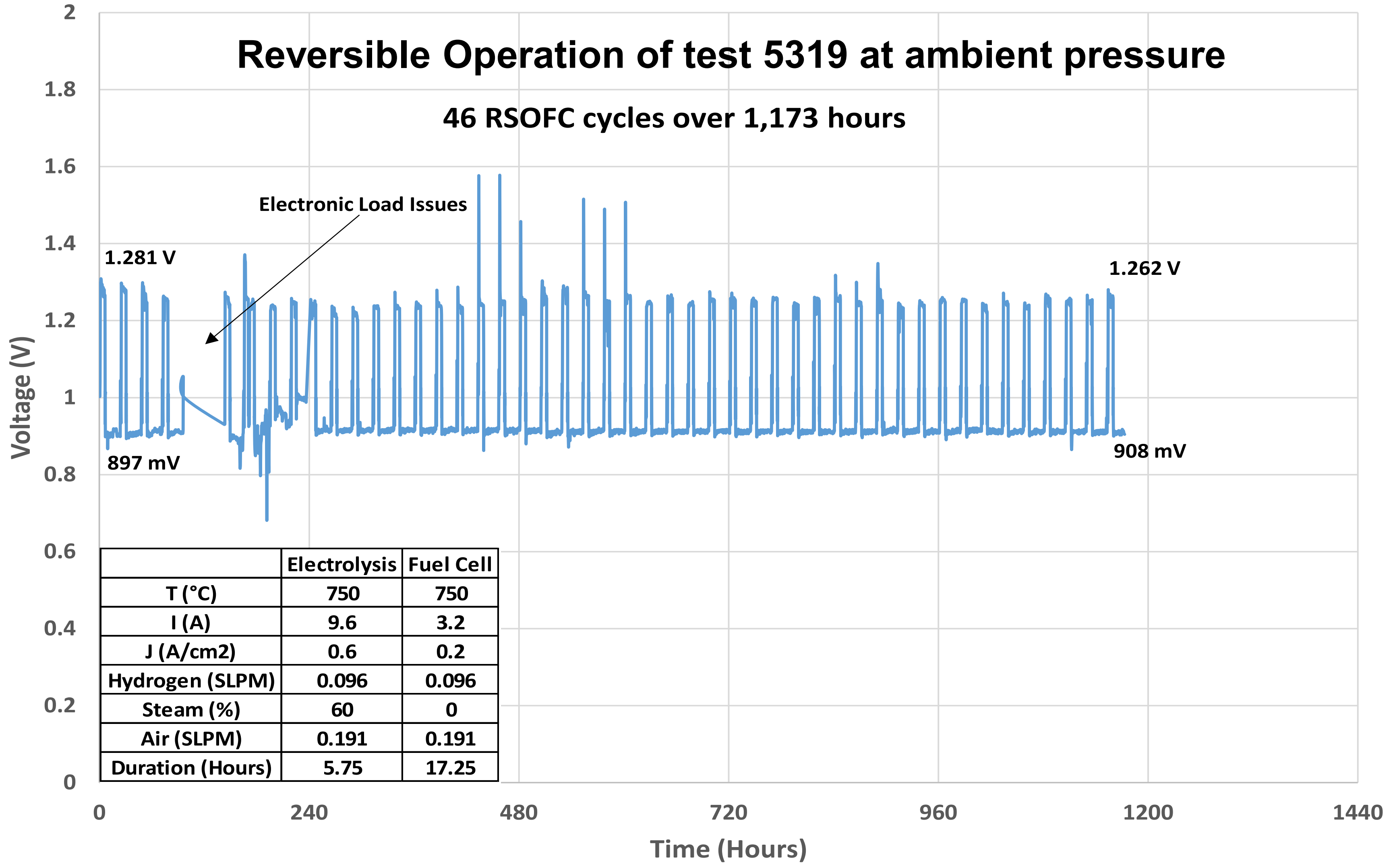


	Electrolysis	Fuel Cell
T (°C)	750	750
I (A)	9.6	3.2
J (A/cm2)	0.6	0.2
Hydrogen (SLPM)	0.097	0.097
Steam (%)	60	0
Air (SLPM)	0.191	0.191
Duration (Hours)	5.75	17.25

- EC Voltage below thermoneutral
- FC Voltage did not changed significantly

Reversible operation of a 16 cm^2 cell at ambient pressure (46 SOEC/SOFC cycles over 1,104 hours)

Cell 5319 in Reversible Operation



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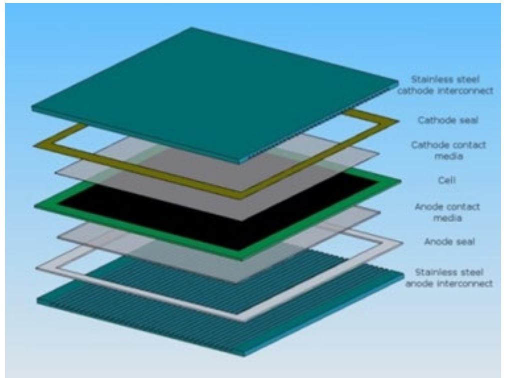

1,000-hour technology stack testing in RSOFC mode with 46 cycles showing ≤ 10 mV/khr degradation

RSOFC Stack Development

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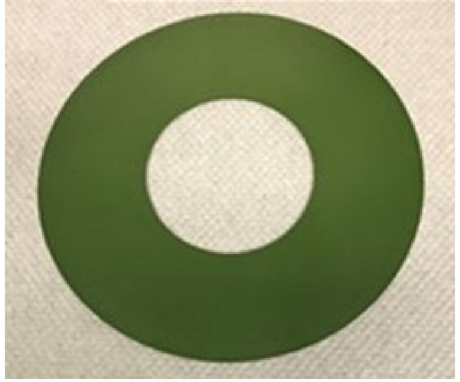
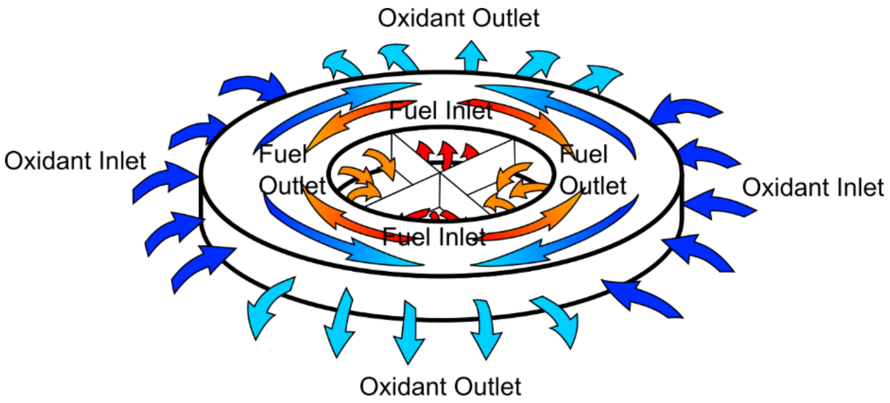
Compact SOFC Architecture (CSA) Stack Platform



Cell
81 cm^2 active area

Standardized Stacks in three sizes



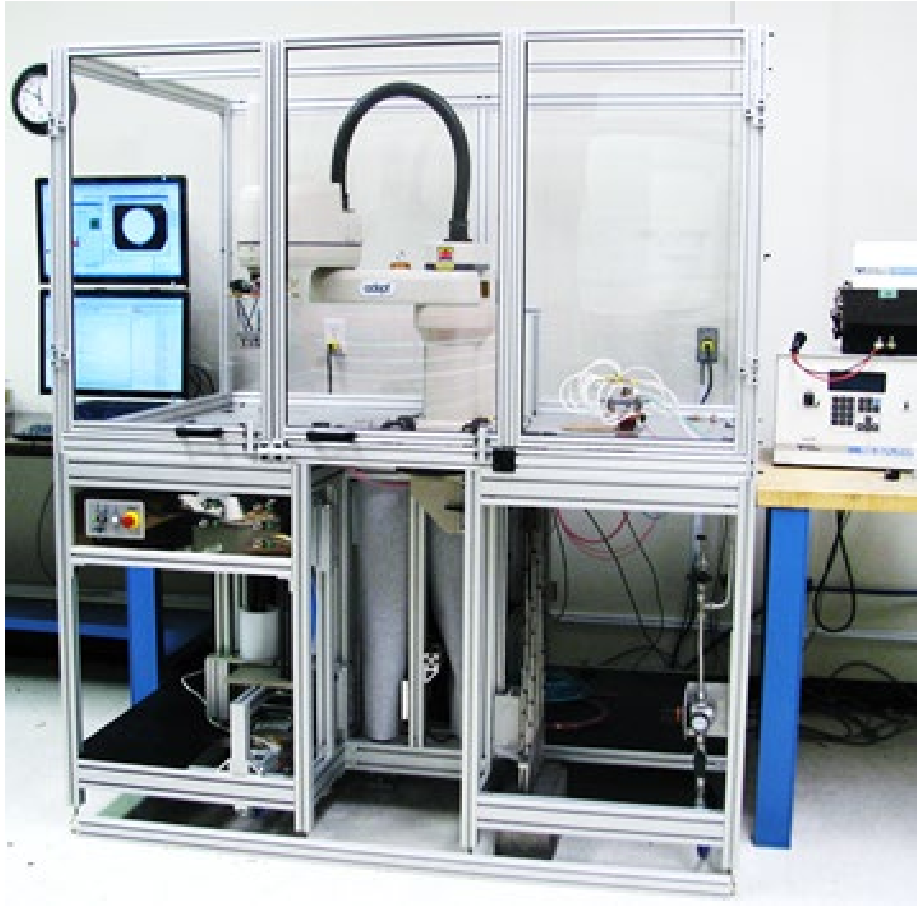
Flow Geometry

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 / 2.7	2.8 / 9.3	6.7 / 21.8	At 0.25 / 0.6 A/cm^2 (FC / EL)
H2 production, kg/day	2	6.6	15	At 0.6 A/cm^2
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	

Operating conditions shown are representative of energy storage applications

High Volume Manufacturing

Automated screen printing, drying, cell QC, stack firing, and stack handling equipment

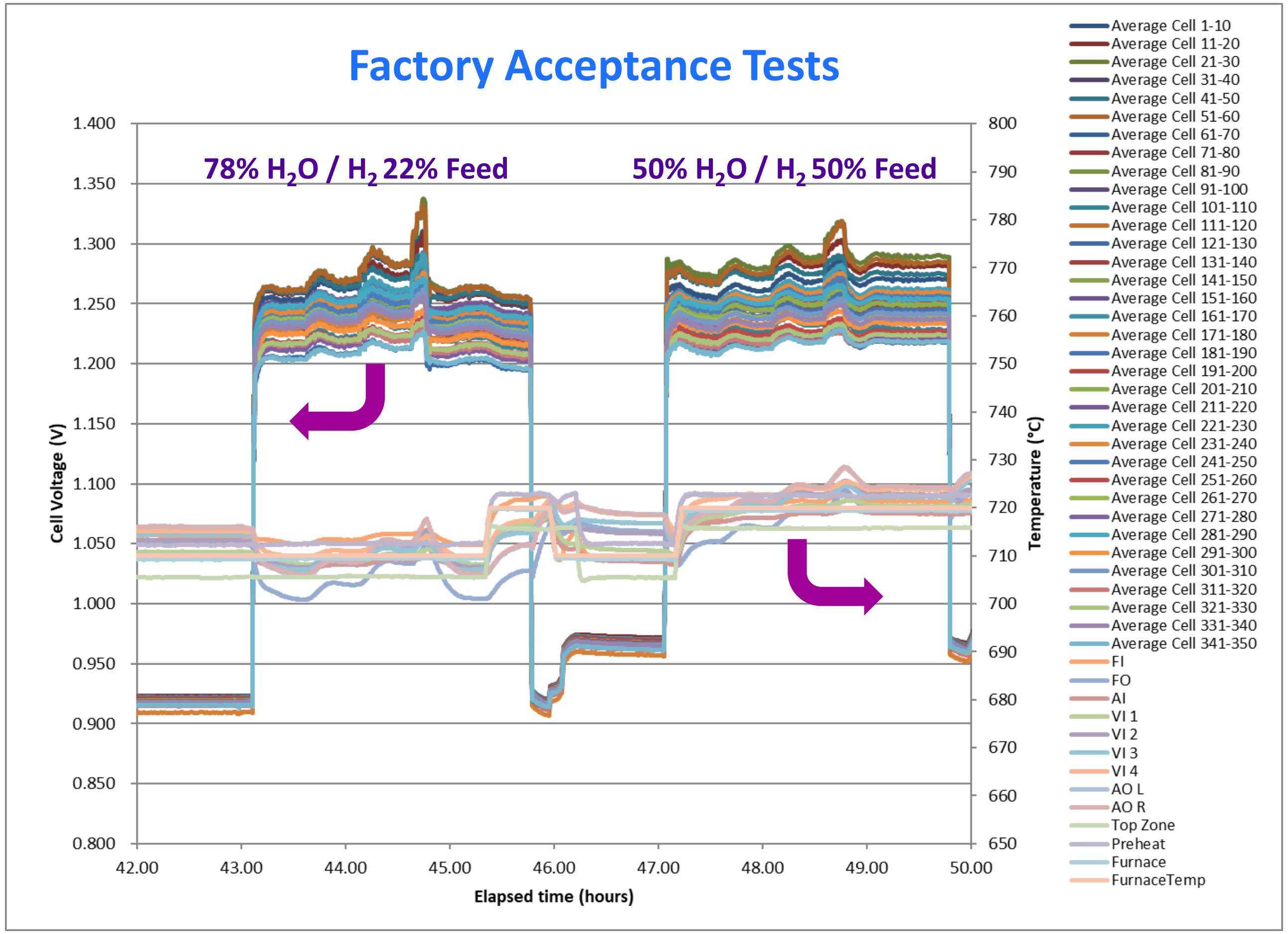


Robotic QC / Stacking Station

Expansion to 4 MW/year CSA Stack Production

Stack Fabrication and Factory Acceptance Testing

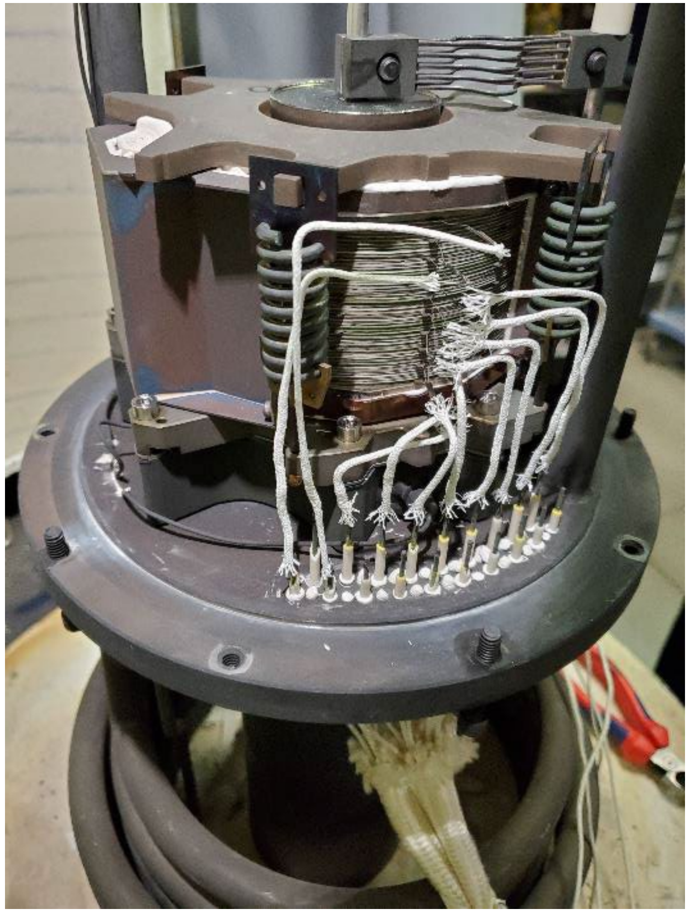
Assembled stack (350 cells) prior to performance testing



- Near thermoneutral voltage (1.285 V/cell) at 0.4 mA/cm^2
  - Overall stack temperature differentials < 10°C

45-Cell Stack Tests

- 45 cell RSOFC stack GT060248-0032

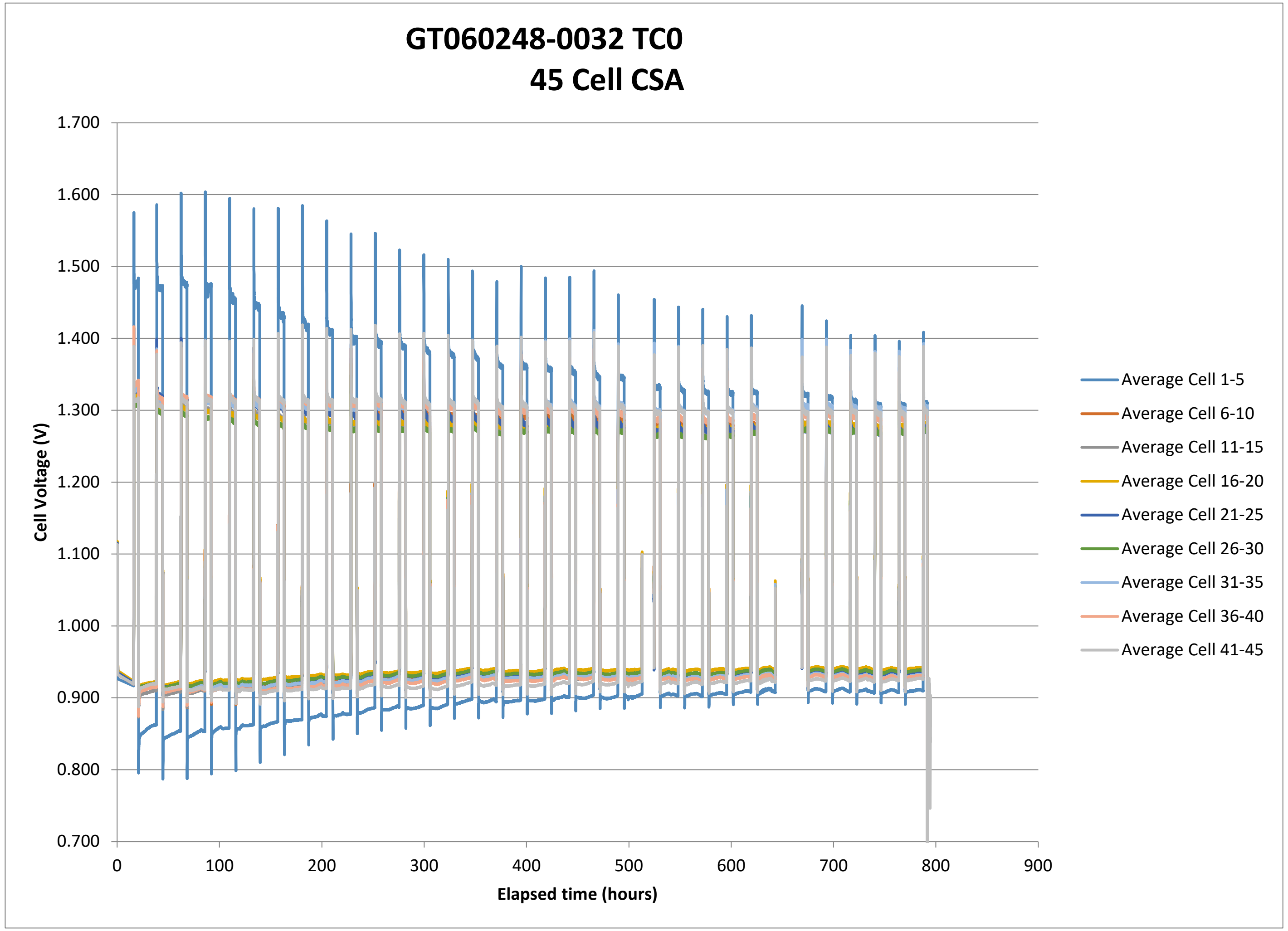


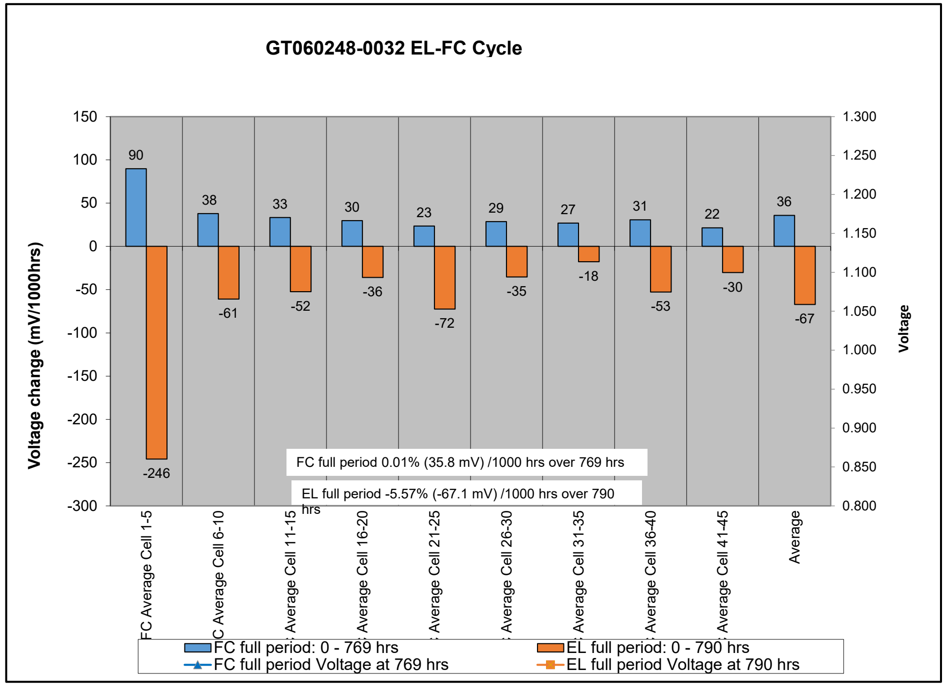
Cyclic Operating Conditions

	Fuel Cell (Discharge)	Electrolysis (Charge)
Current density	0.2 A/cm^2	0.6 A/cm^2
Time on load	17.25 hours	5.75 hours
Utilizations	25% H_2, 30% Air	50% steam
H2/Steam Concentrations	100%/0% (approx.)	22%/78%

1 hour transition times resulting in total cycle time of 24 hours

45-Cell CSA Stack Tests





Summary of Results

- Overall duration of load test after 800 hours
- Two test stand related interruptions without significant impact on performance
- Completed 31 24-hour cycles of reversible operation
- Improving fuel cell as well as electrolysis performances over the course of the test, no degradation observed in the test

RSOFC Pilot System Demonstration

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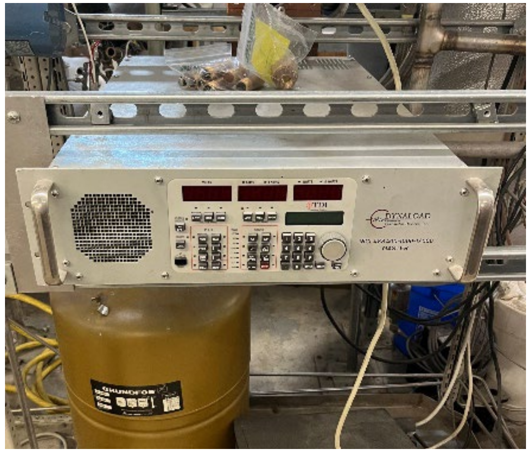
Energy Storage Demonstration System

FCE's Solid Oxide Electrolysis (SOEC) pilot system has been upgraded to RSOFC Energy Storage prototype system for reversible demonstration of ~15 kW charge and ~3 kW discharge cycles under EERE project DE-EE0008847

- Upgrade mainly consisted of:
  - Process: Piping & Instrumentation Diagram (P&ID), equipment installation, safety analysis, control philosophy
  - Electrical: power supply/load bank integration, instrumentation, control software and hardware

H2/Steam Recycle Blower from Mohawk Innovative Technology (MTI)



Fuel Cell Mode Load Bank

Vent hood

Vaporizer

Power and controls cabinet

SOEC Electrolyzer Module

150-Cell Stack for RSOFC System Demonstration

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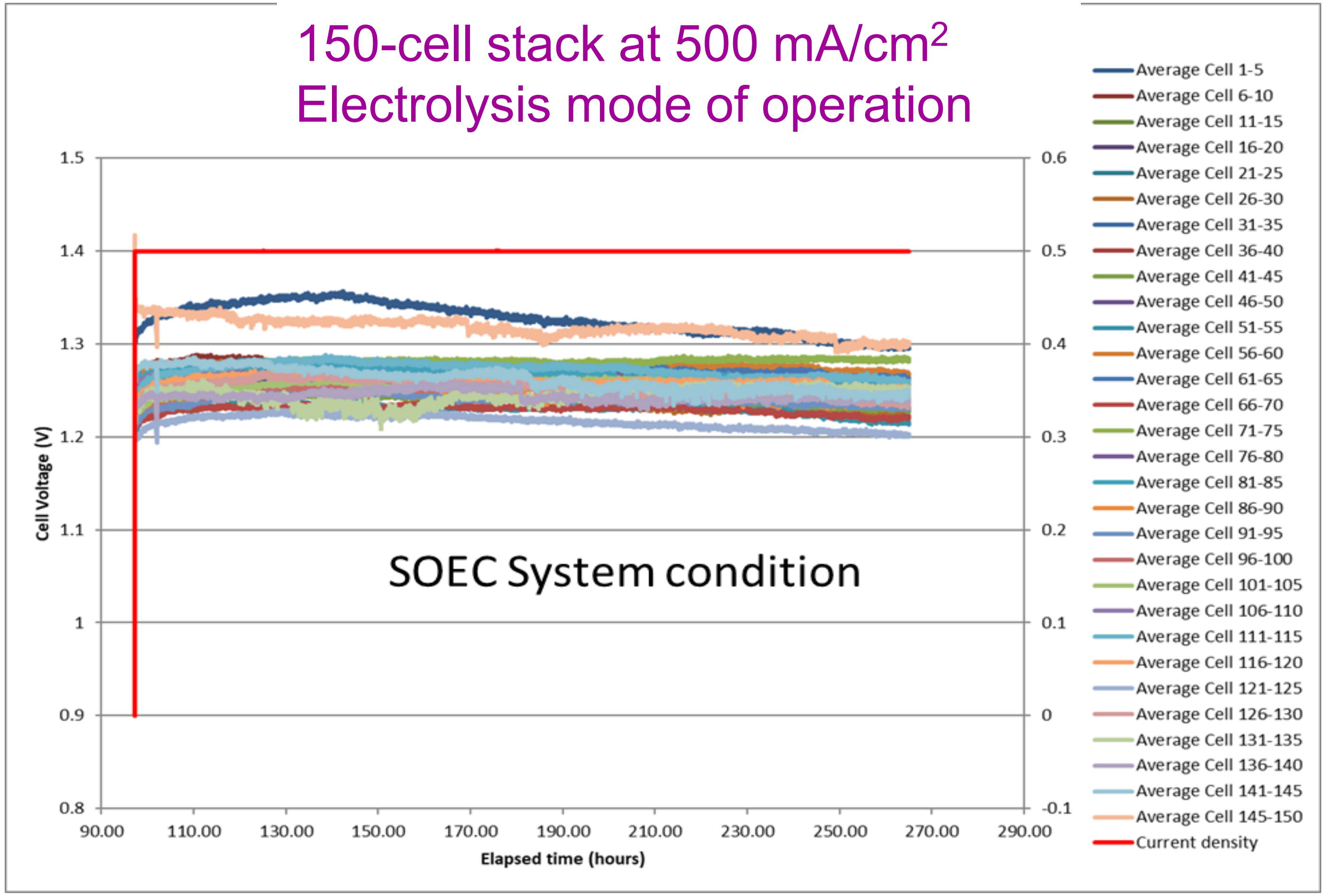
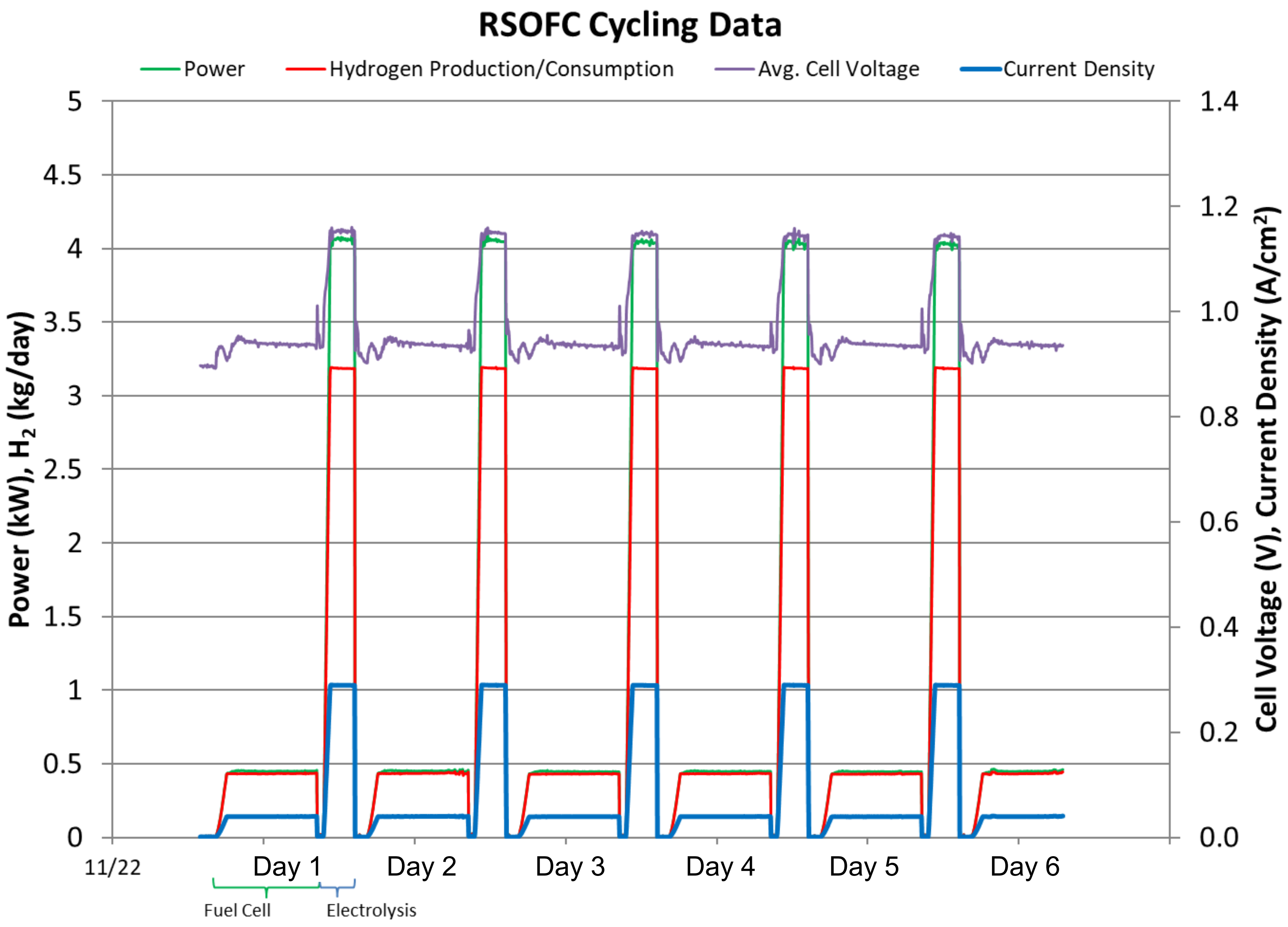
150-cell stack (GT60247-0005)

- 150-cell stack was tested in electrolysis mode in the Pilot RSOEC System



- Furnace: 627 C
- Fuel: 50% H_2O , 50% H_2 @ 76.05 SLPM H_2
- Air: 150 SLPM @ 40.5 A -- 76.05 SLPM H_2O
- Usteam = 60.0%

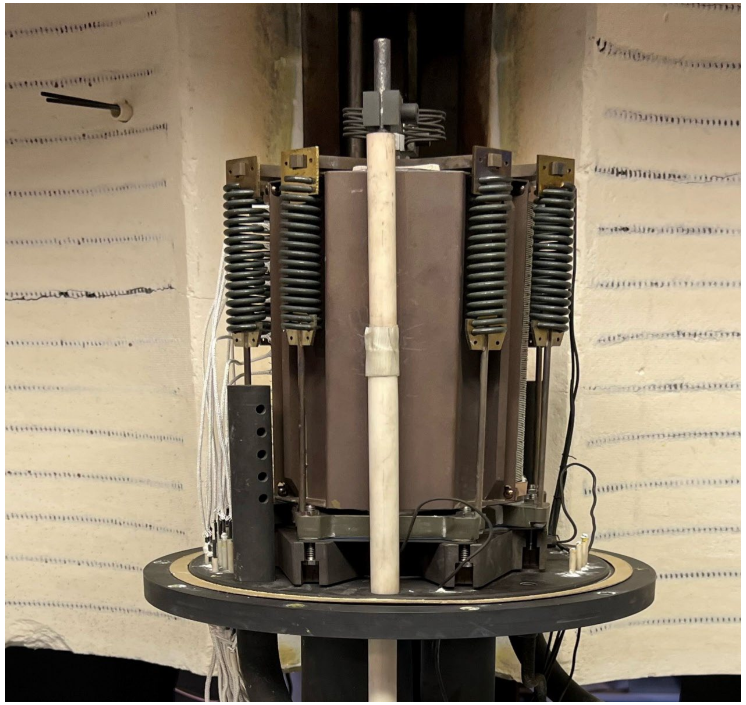
Reversible Operation & Cycling



Daily Charge/Discharge Cycles

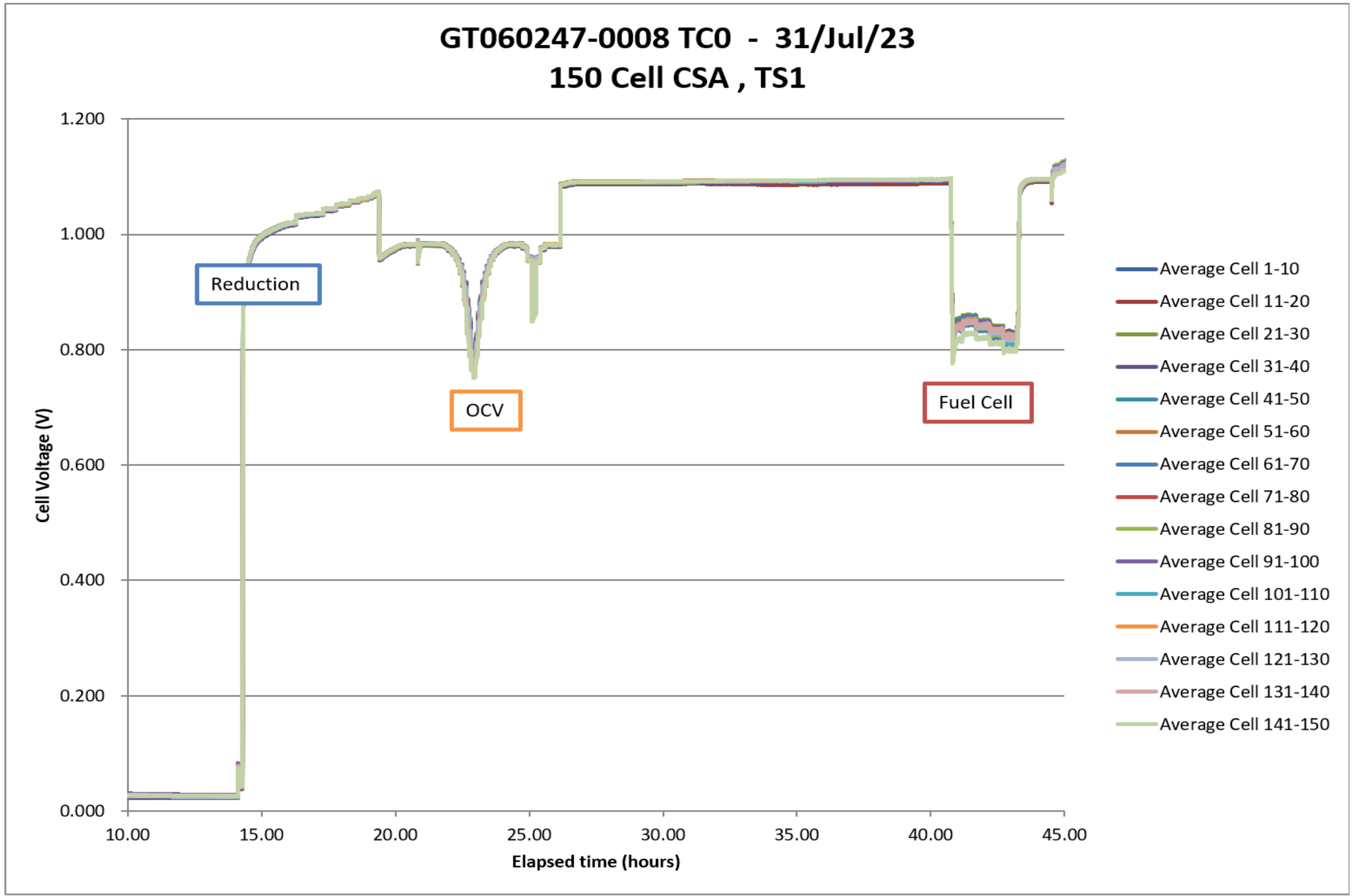
Results of 150-cell stack (GT60247-0005) cycling tests (DOE Contract DE-EE0008847)

New 150-Cell Stack for RSOFC System Demonstration



150-cell stack (GT60247-0008)

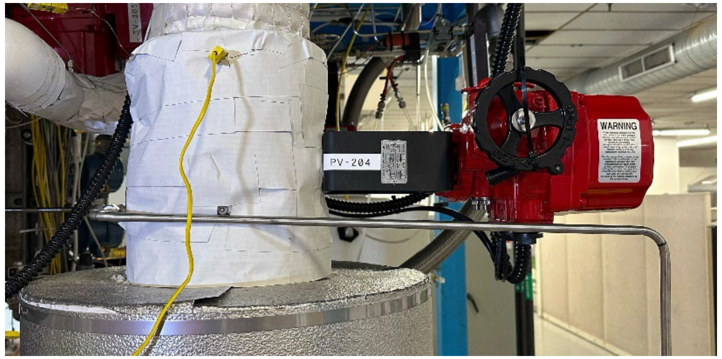
In 2023 a new stack was fabricated and conditioned for system testing



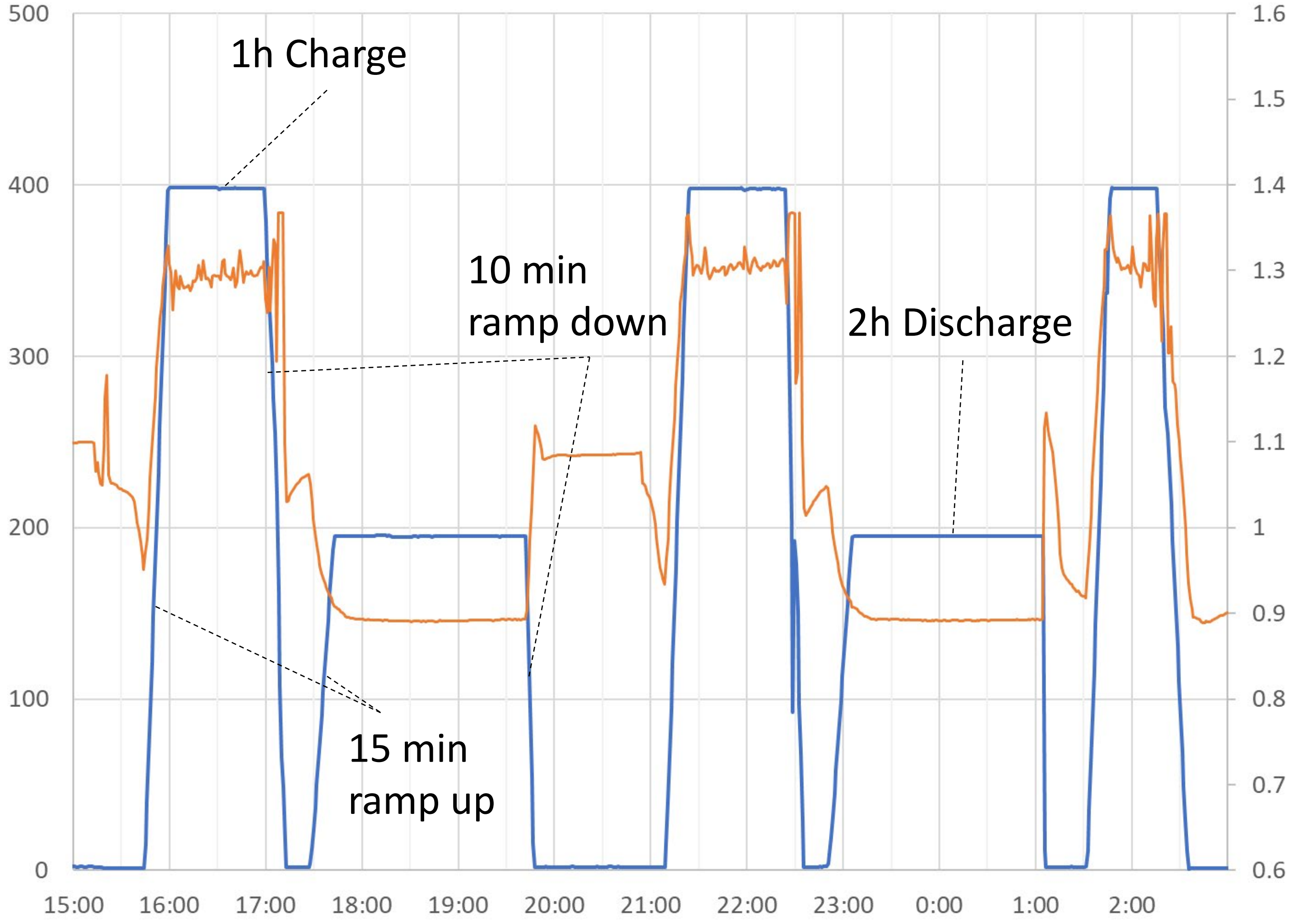
System Dynamic Improvements

(DOE Contract DE-EE0008847)

- Installed a vaporizer pressure control valve

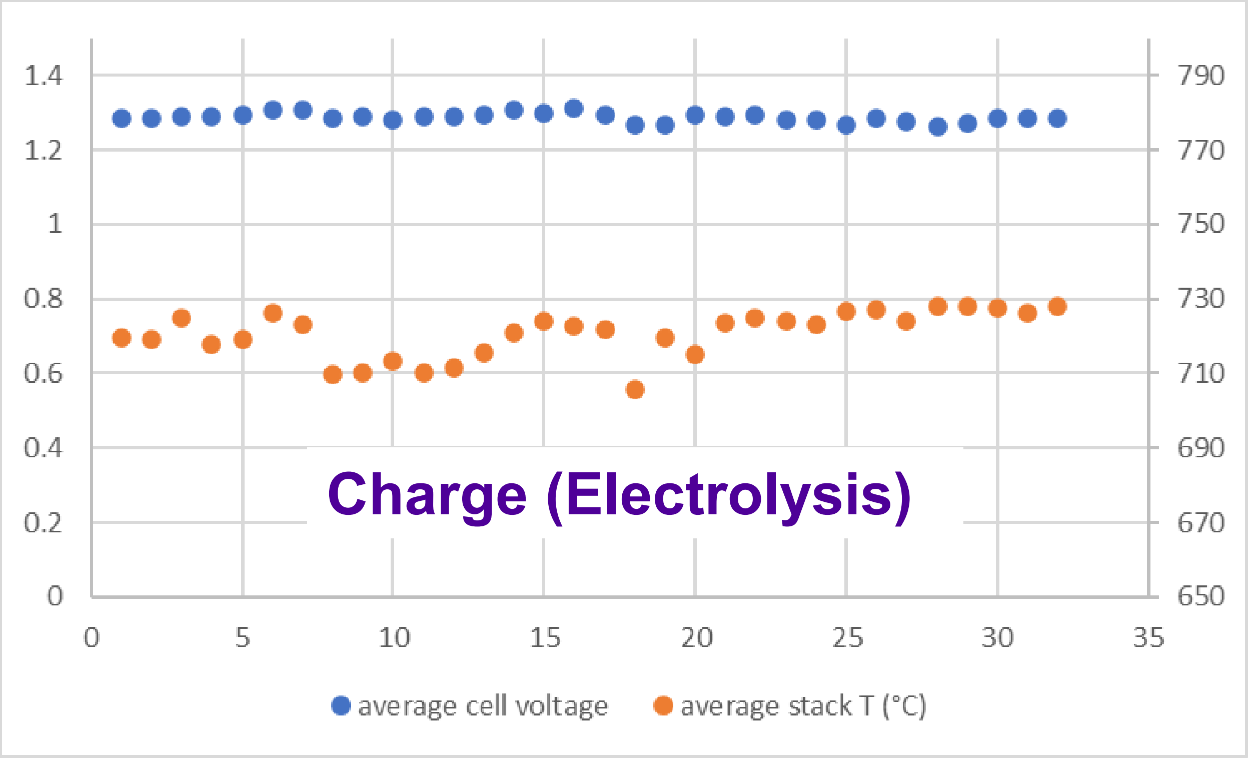


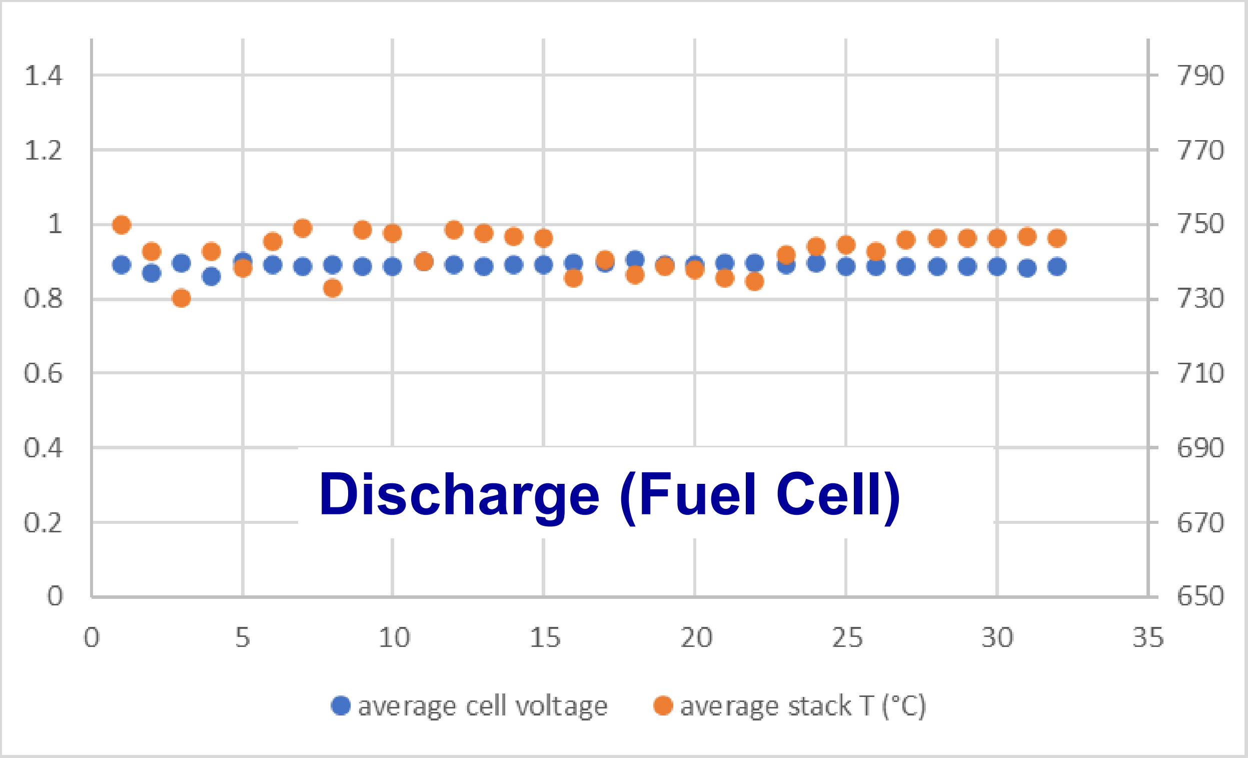
- Installed proportional (instead of shutoff) valves on fuel recycling lines for charge and discharge modes, resulting in smoother transitions
- Implemented process control strategies to accelerate roundtrip transitions between charge and discharge



Cycling Tests of GT60247-0008

(DOE Contract DE-EE0008847)

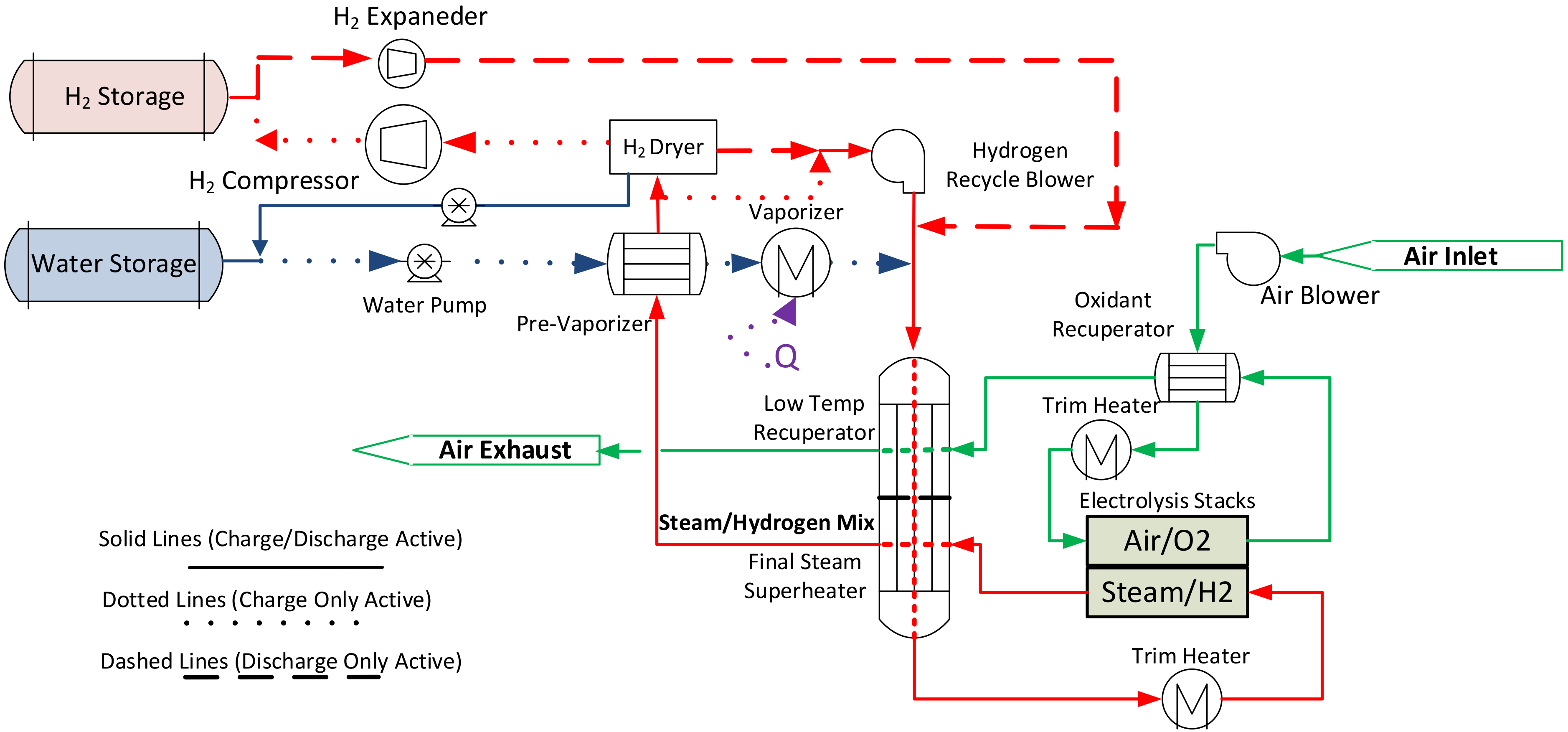




- No significant stack performance degradation has been observed after completion of 32 cycles
- Overall system performance will be analyzed after planned 100 cycles of charge/discharge
  - Targeted goal is to verify less than 0.5% round trip efficiency (RTE) degradation per 100 cycles

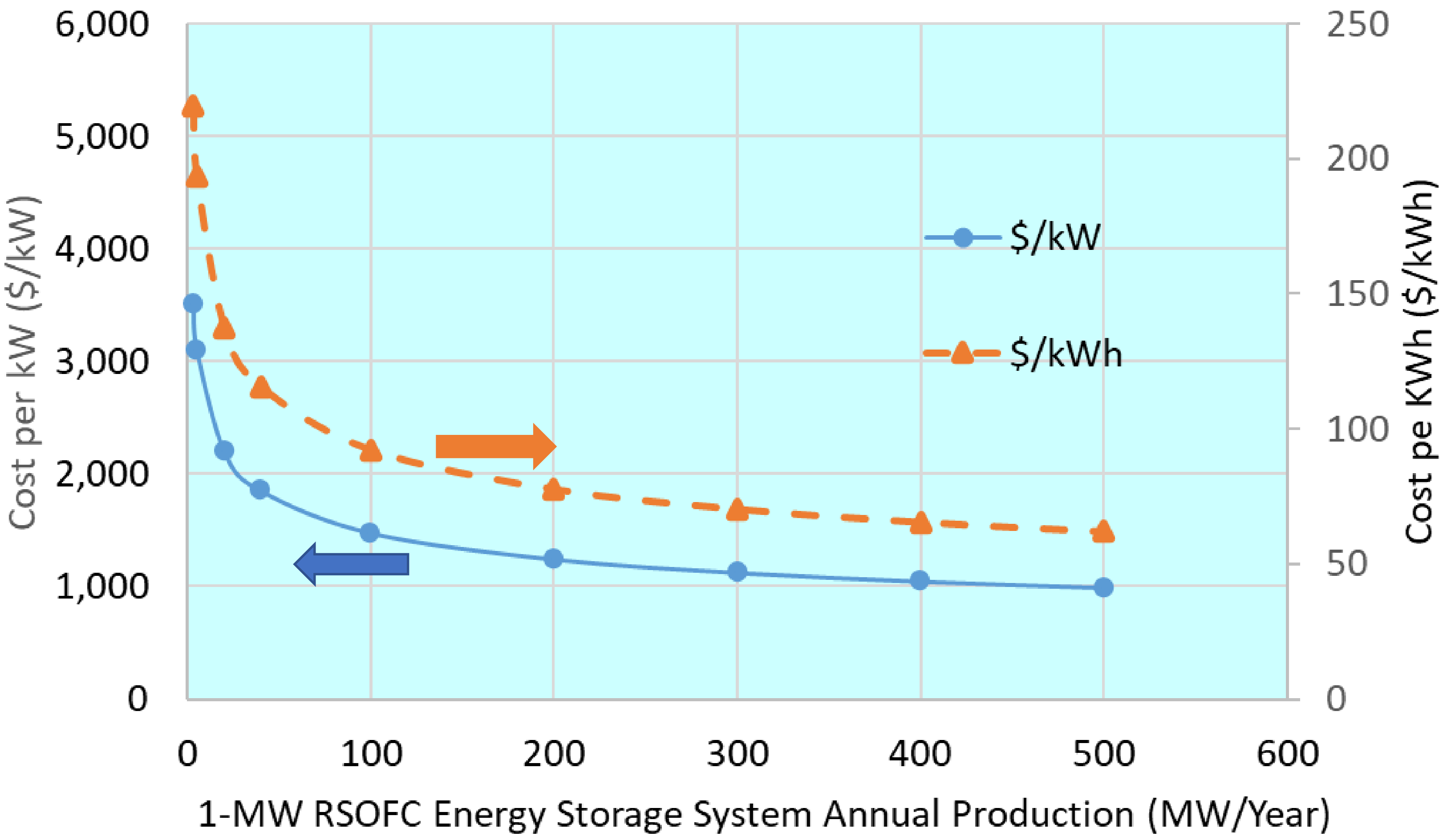
Technoeconomic Analysis

8 MWhr RSOFC System Simplified Flow Diagram



Charge (Electrolysis)		Discharge (Power)	
Stack Power In, kW	1258	Stack Power Out, kW	292
Parasitic Power, kW	101	Parasitic Power, kW	-10
Net Power In, kW	1359	Net Power Out, kW	302
Charge Period, h	6	Discharge Period, h	18
H2 Stored, kg	204	H2 Consumed, kg	204
Electrolysis Efficiency, % LHV	84.2	Power Generation Efficiency, % LHV	80
Round Trip Efficiency , %		**67.4**	

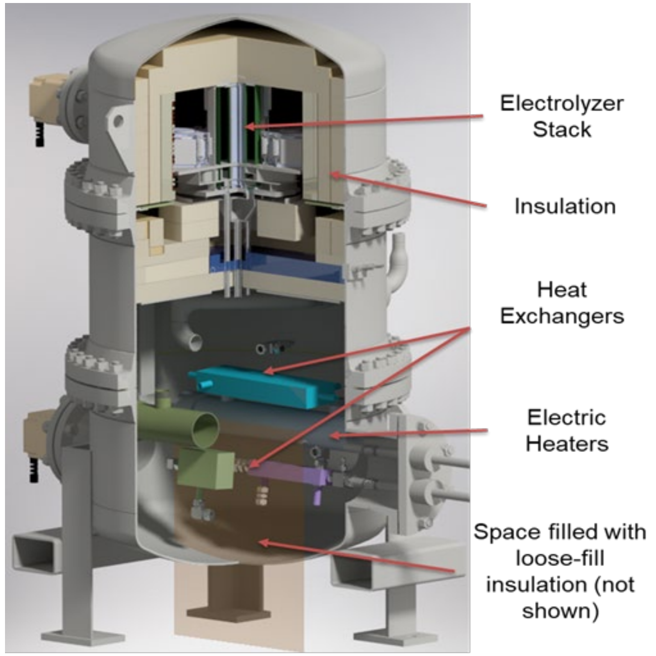
RSOFC Cost of Commercial Units



Cost of energy storage < 100 $/kWh is projected at annual production of >200 units of 1 MW systems

Wrap-up

Future RSOFC Pilot System Upgrade



Internal view of RSOFC Module

RSOFC Energy Storage Pilot System

- The RSOFC Pilot System will be further upgraded to a capacity of 6 kW discharge and 32 kW charge.
  - Planned development of an advanced power conversion system including a robust algorithm for enhanced stack thermal management and transient load response, resulting in longer stack life and durability

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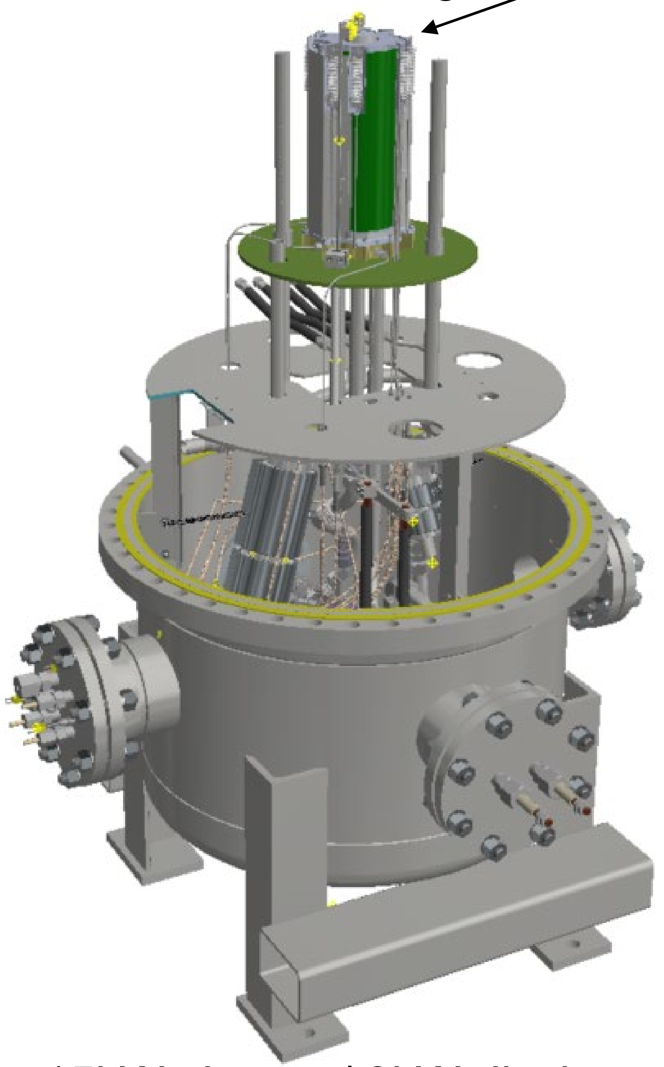
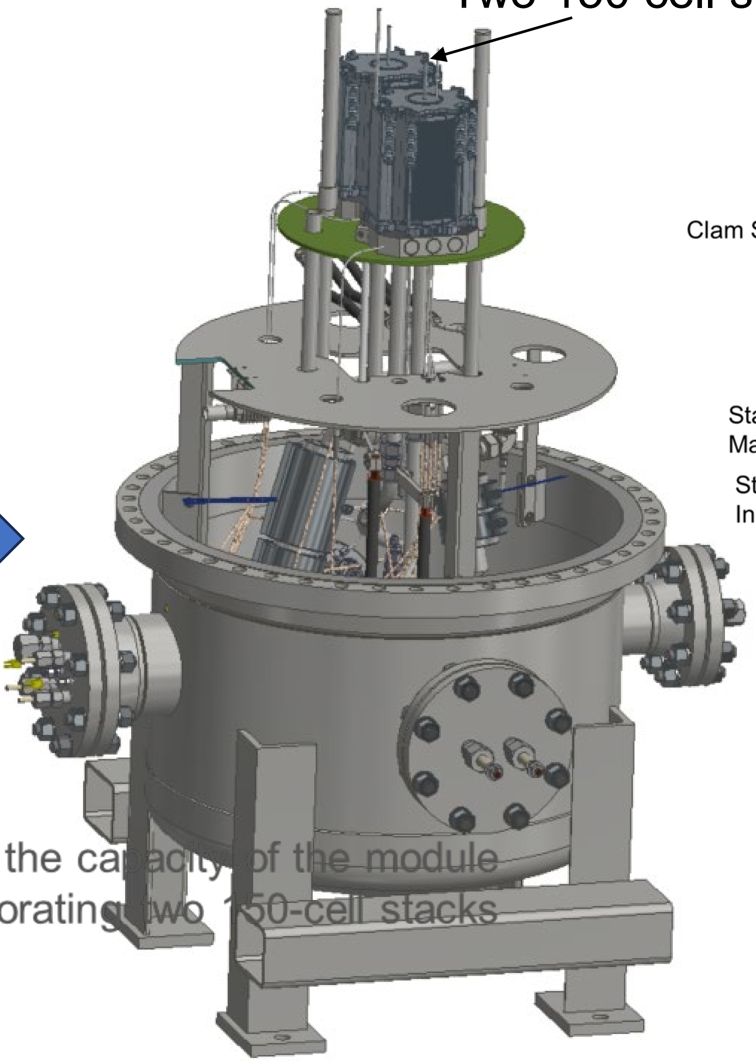
Stack Module Upgrade

Single 150 cell stack

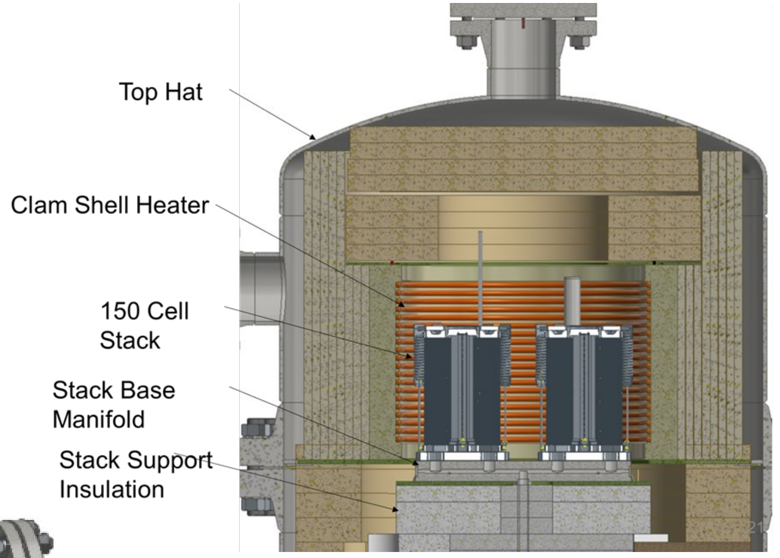


15kW charge / 3kW discharge

Two 150 cell stacks



32kW charge / 6kW discharge



- Doubling the capacity of the module by incorporating two 150-cell stacks in series

CPES Research Laboratories

- FCE is working with Center of Power Electronics System (CPES) at Virginia Tech to develop a bidirectional DC-DC Converter for RSOFC application

Center for Power Electronics Systems, Virginia Tech (VT)

Blacksburg, VA

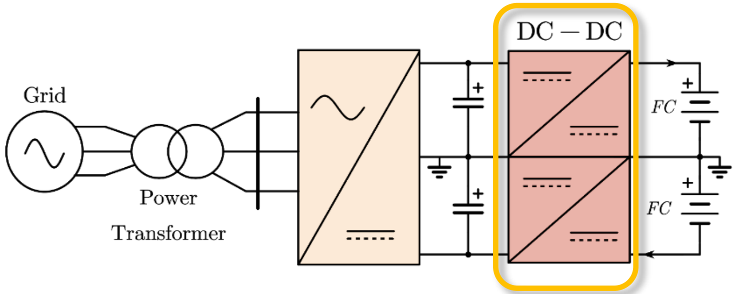
Arlington, VA (Washington, D.C. Area)

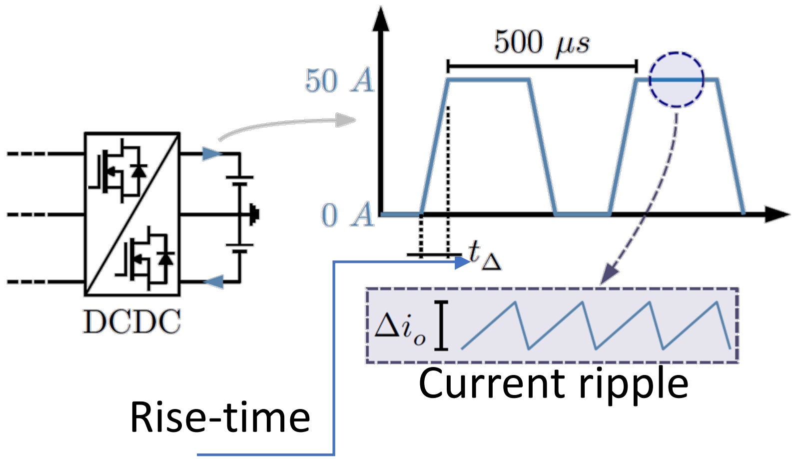
- New packaging & integration lab in Arlington, VA (January 2022)
- Electrical power lab expansion in Arlington, VA (Nov. 2023)

VT CPES Center for Power Electronics Systems

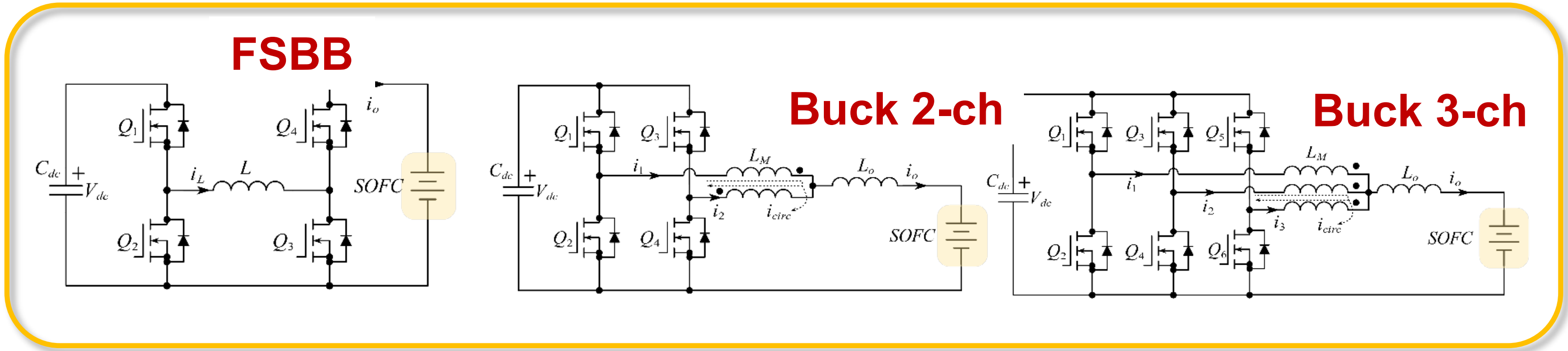
Optimization of DC-to-DC Conversion Topologies

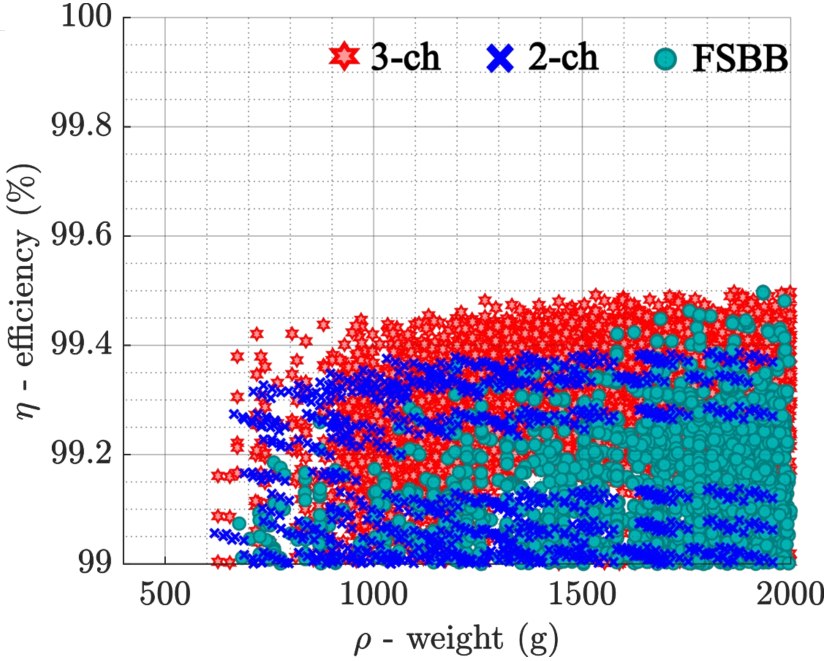
- Focused on development of a topology to minimize current response rise-time and ripples





Analyzed topologies

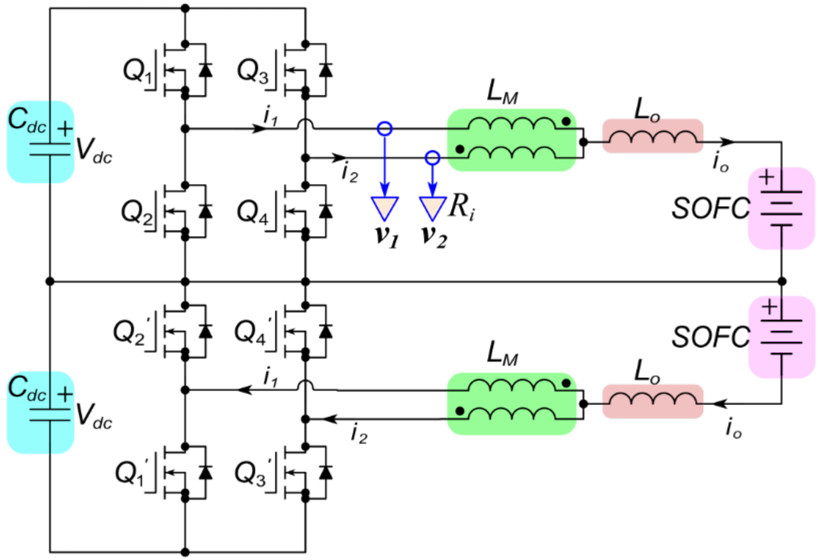


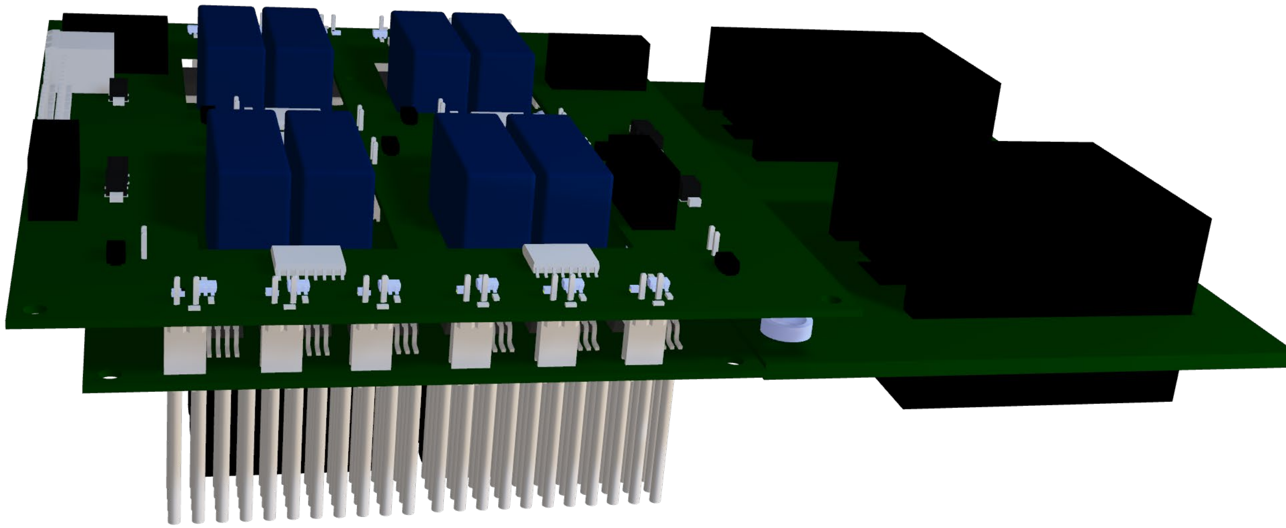


- **FSBB (Four-Switch Buck-Boost):** high filter inductor limiting load current ripple at low frequency
- **2-ch:** better performance compared FSBB but limited by commercial cores
- **3-ch:** best performance among candidate topologies but complex

Selection of Bidirectional DC-DC Converters

- Both charging and discharging cycles of the solid oxide fuel cell are considered in the optimization of the power board
  - Ensuring that all components meet the requirements for both operating modes, for example, SiC MOSFET selection and paralleling arrangements
- The two-channel buck dc-dc converter has a superior weight and loss performance in addition to minimized coupled inductor complexity
- ➢ The converter design is near completion and the construction and demonstration of the prototype will follow





Future Work

- Pilot RSOFC system upgrade
  - Install hydrogen compression and storage equipment
  - Incorporate VT-developed power electronics hardware
  - Develop and implement advanced power control software algorithms
- Conduct RSOFC system demonstration tests
  - Complete 100-cycle tests of a second 150-cell technology stack to identify operating condition parameters in each mode of charge/discharge which would optimize performance and reduce degradation
  - Plan for future tests of dual mid-size stacks configuration to checkout the advance power control software
  - Perform parametric analysis to maximize round trip efficiency

- Existing in-house hydrogen storage tanks rated at 300 psi
- Inspection to be followed hydrostatic testing (to ensure suitability for intended service)

Thank You

Acknowledgement:
Support and Management under DOE Project:
<u>**DE-FE0031974**</u>
Dr. Patcharin (Rin) Burke
Mr. John P. Homer

Our purpose:
Enable the world to be empowered by clean energy