FuelCell Energy

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


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## 2023 FECM/NETL SPRING R&D PROJECT REVIEW MEETING

## Pittsburgh, PA

## April 18, 2023

# FuelCell Energy overview

Demand for clean, reliable electricity driving adoption of fuel cell technology

### Headquarters
### Danbury, CT

- Corporate Headquarters
- Research labs
- Engineering design
- Global Service center

### Manufacturing
### Torrington, CT

- Cell & Stack fabrication, Module assembly
- 167,000 sq. ft.

### Other facilities
### Taufkirchen, Germany

- Final assembly for SubMW carbonate stack modules
- Carbonate SubMW power plant sales and service
- Sales and service for carbonate MW scale platforms made in US

### Calgary, Canada

- Solid oxide R&D for power generation, electrolysis, and energy storage
- Solid oxide cell and stack manufacturing

### Global customers

### Company Highlights[1]

| | | | |
|---|---|---|---|
| **HQ** Danbury, Connecticut | **>500** Employees | **95** Platforms in commercial operation[2] | **3** Continents |
| **FCEL** Listing: NASDAQ | **>220 MW** Capacity in field | **>13** Million MWh's generated with patented technology | |

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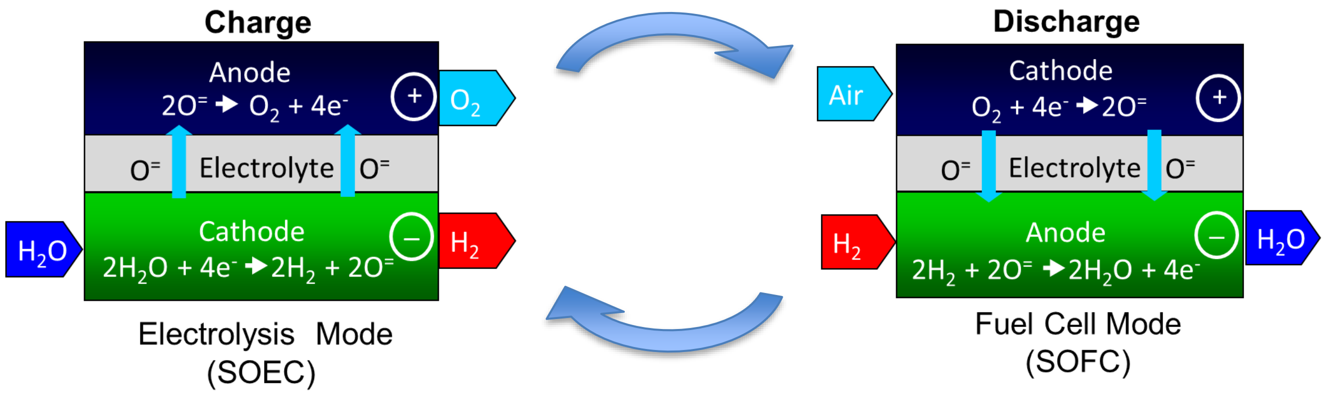
[1]As of the year ended October 31, 2022.
[2]Note that certain sites have multiple platforms. As an example, our 14.9 MW Bridgeport project site has five 2.8MW platforms. As of 10/31/22, there were 33 sites with the Company's carbonate fuel cell platforms..

# DE-FE31974 Project Objectives

- The overarching goal of the project is to advance the high efficiency and low-cost 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.
- The objectives of the project include cell performance improvements, stack durability, and optimization of 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).



# Solid oxide - hydrogen based long duration energy storage system

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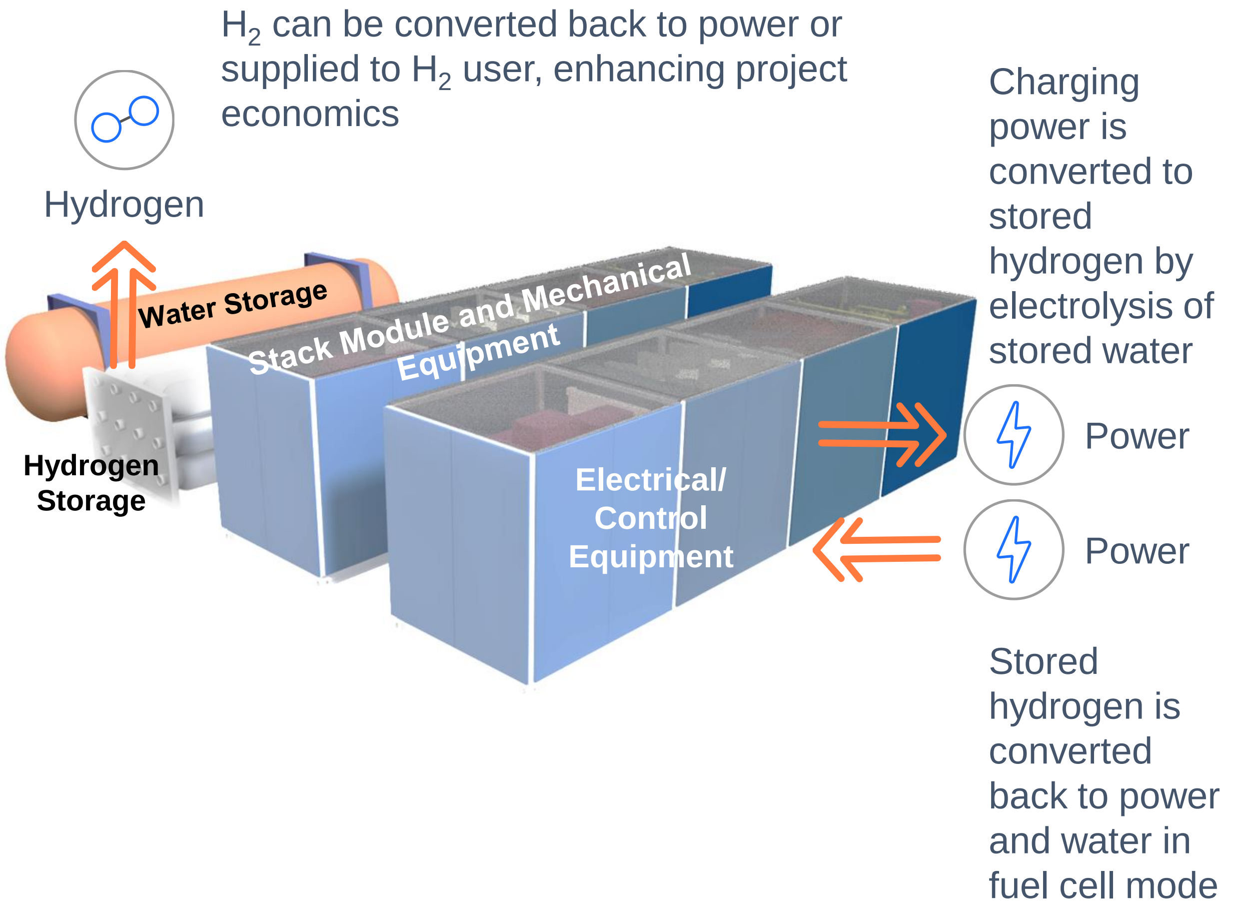
- Hydrogen during charge cycle can be used to provide power during discharge cycle or can be exported to hydrogen user
- Waste heat from other sources can be utilized to reduce electric power consumption
- Expected round trip efficiency of ~70%
- The storage reactant is water, which is regenerated during power generation discharge – does not depend on limited quantities of lithium or cobalt
- Discharge duration is added by adding inexpensive hydrogen and water storage – so cost of storage capacity reduces significantly with longer duration
- Geological storage of hydrogen can provide weekly or seasonal storage



# Solid Oxide Technology Applications

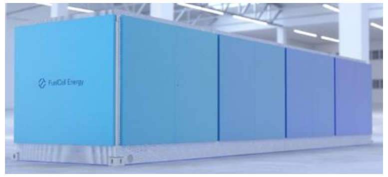
Manufacturing

**Solid oxide stack is a common platform**

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

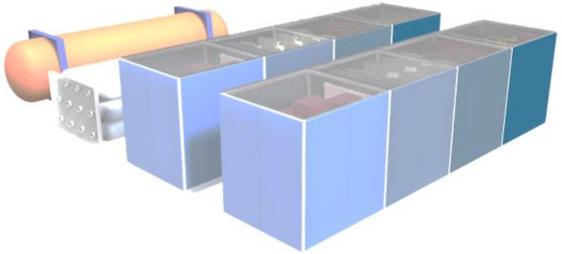
**Electrolysis**
- Producing hydrogen from steam with power input

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



*250 kW Power Generation System*

*Electrolysis*
*600 kg/day H2 from 1.1 MW*



*Energy Storage System*
*1MW, 8MWh*

# Cell Technology for Reversible Operation

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# Cell Fabrication

Tape Casting

Automated Screen Printing

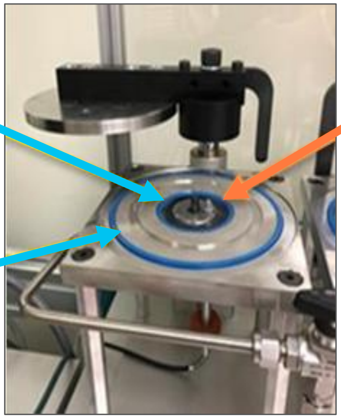
Co-Sintering

"TSC 3 Process"

Cell QC

ID seal

Old seal



Thickness (Z) measuring tool

CSA cell leak tester jig with thickness measuring tool

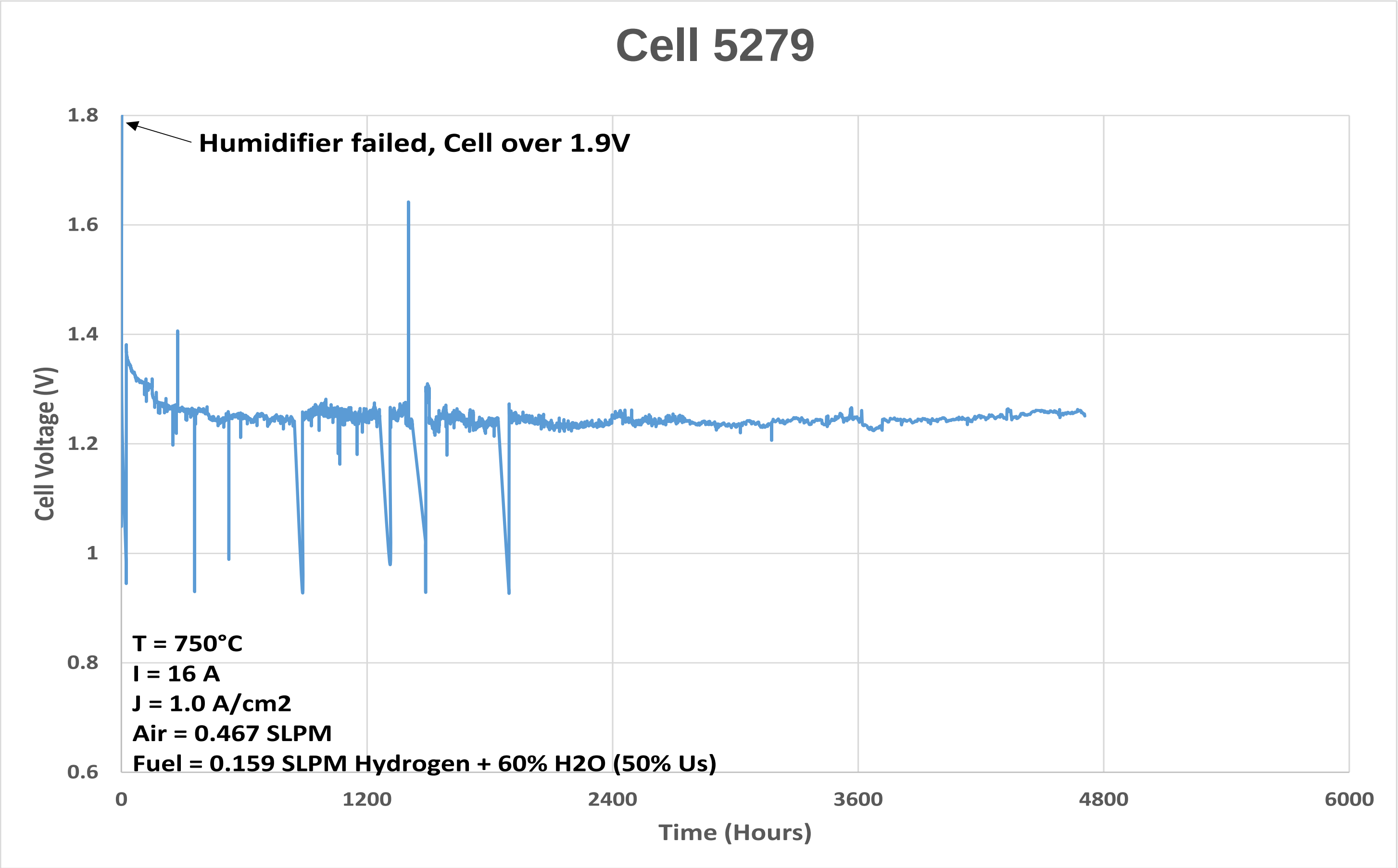
Solid Oxide Cell (SOFC) Constituent Layers

| 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 |

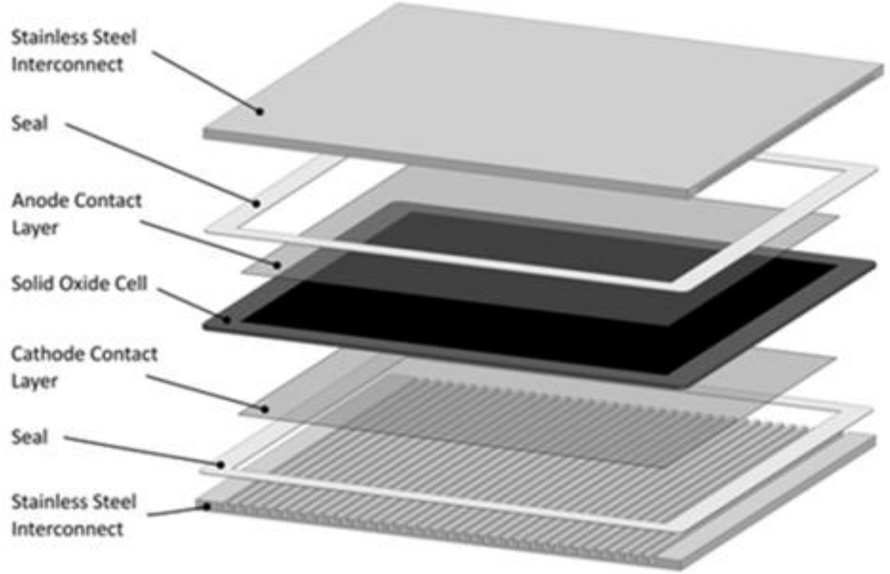
Stack repeat unit:

- 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



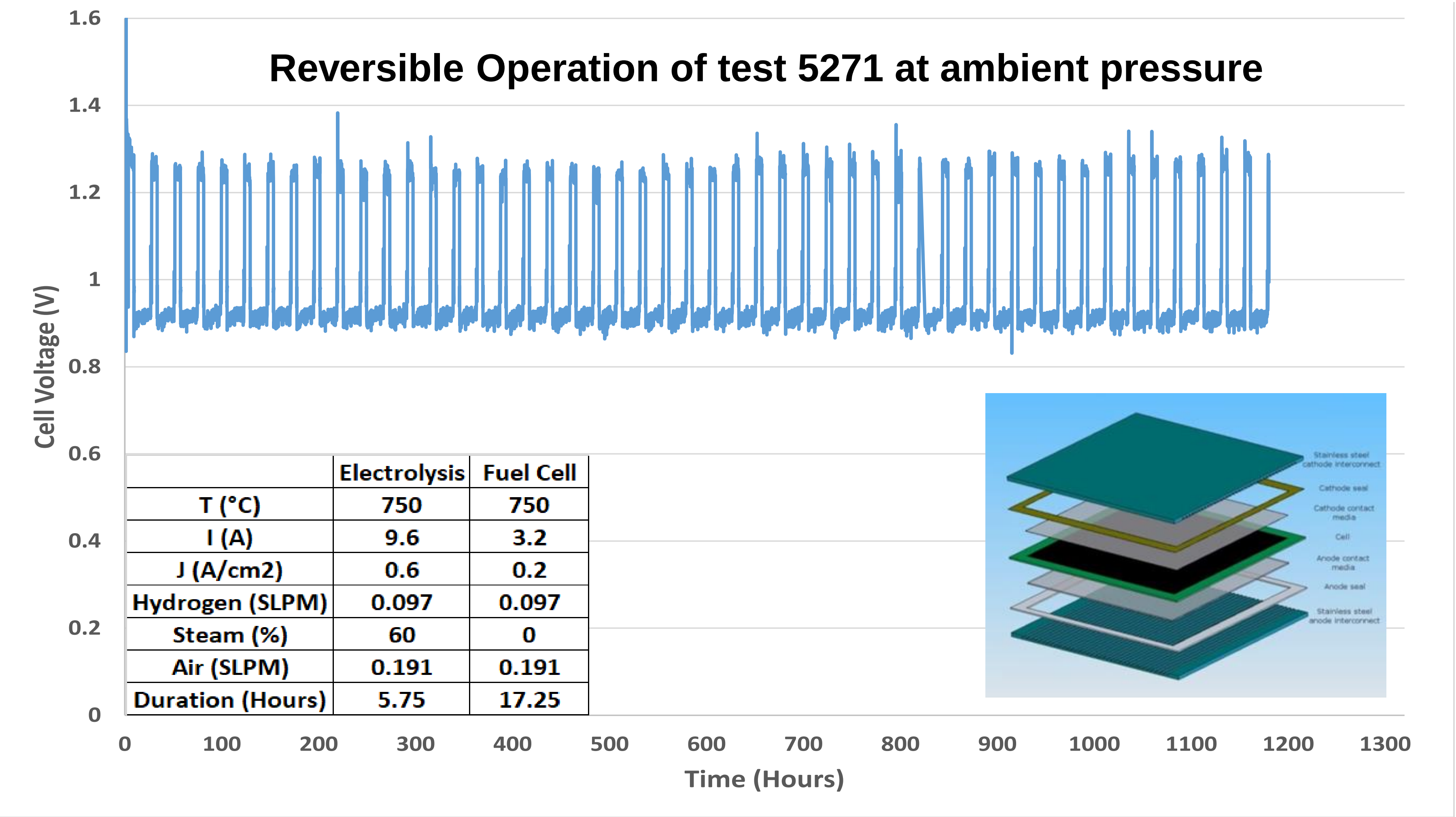

**Steady State Operation in Electrolysis Mode at 1 A/cm$^2$**




- 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**

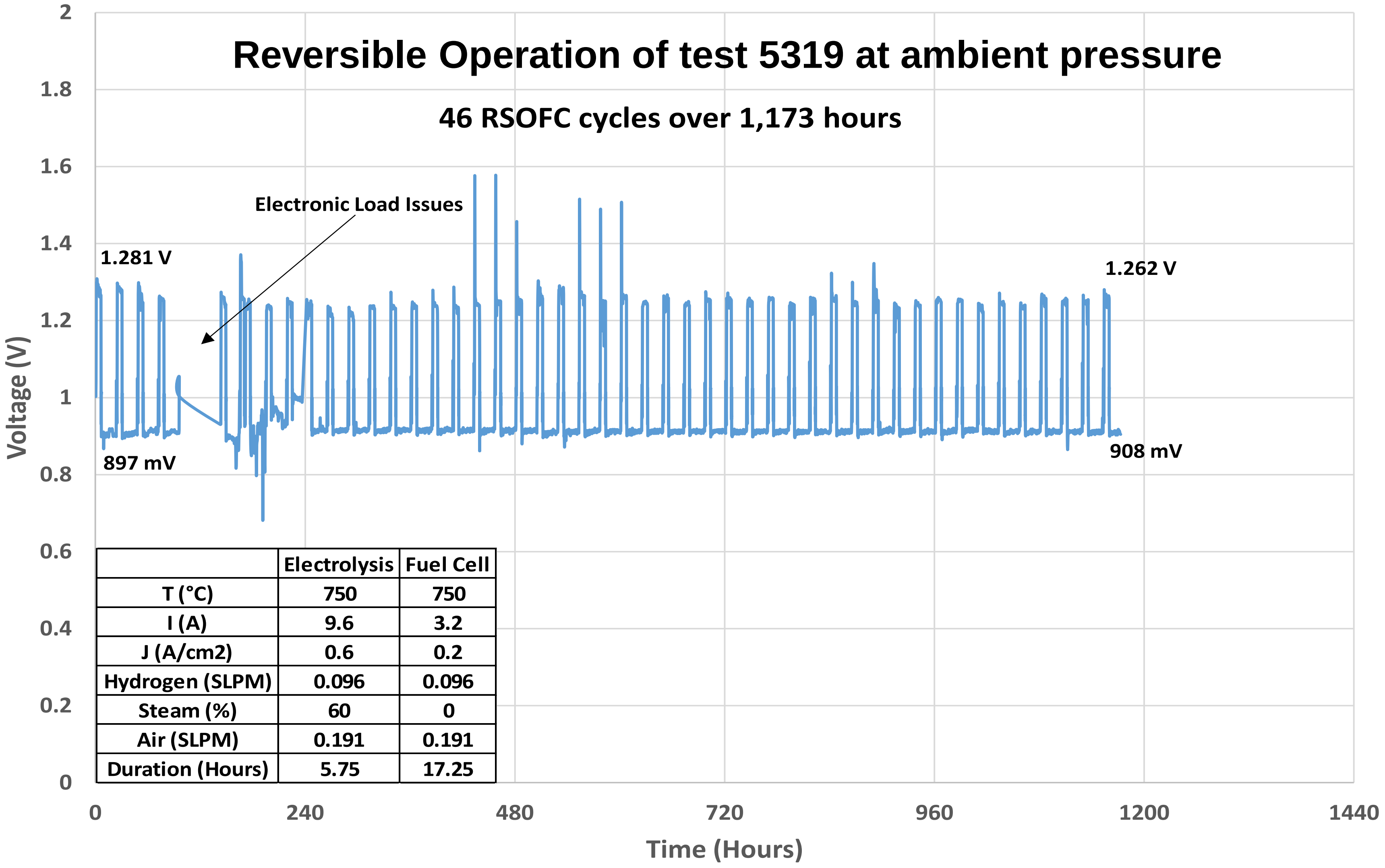
# Cell 5271 in Reversible Operation




| | 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 |

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

# Cell 5319 in Reversible Operation




| | Electrolysis | Fuel Cell |
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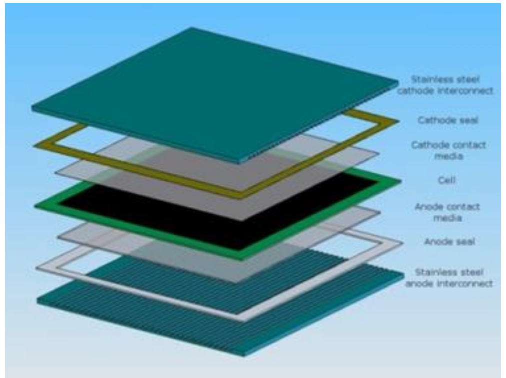


**1,000-hour technology stack testing in RSOFC mode with 46 cycles showing ≤ 10 mV/khr degradation**

# RSOFC Stack Development

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# Compact SOFC Architecture (CSA) Stack Platform

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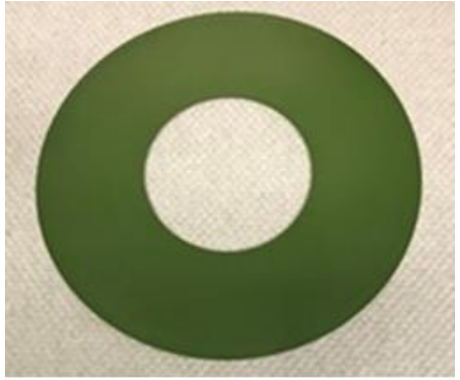
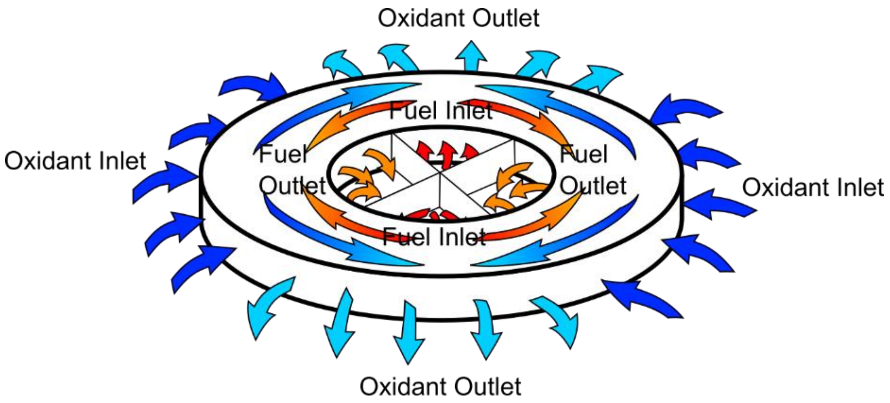


Cell
81 $cm^2$ active area

Standardized Stacks in three sizes




Flow Geometry

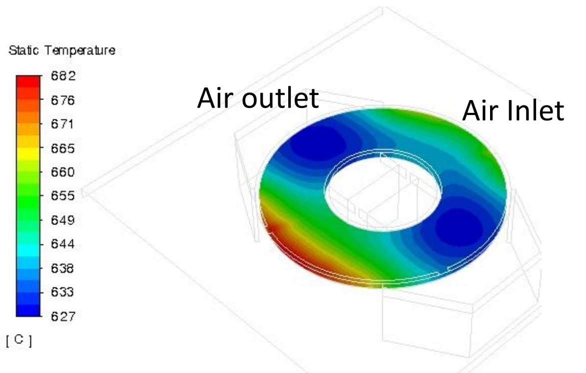
| Property | Scale | | | Comments |
|---|---|---|---|---|
| | Short | Mid | Full | |
| **Cell count** | 45 | 150 | 350 | Nominal count |
| **Fuel Cell Voltage, V** | 43 | 143 | 333 | At 0.950 V/cell |
| **Electrolysis Voltage, V** | 58 | 192 | 448 | At 1.280 V/cell |
| **Stack Efficiency, % LHV** | 74% / 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**

# RSOFC Modeling

## Electrolysis Mode

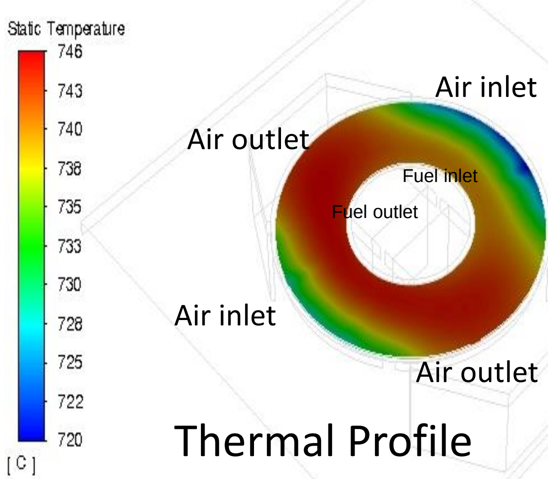
- 700 deg C inlet reactant gases
- 50%$H_2$, 50%$H_2O$ steam, 60% $U_{steam}$, flush air
- $V_{cell}$ average =- 1.2 volt/cell
- Stack max temperature = 661°C
- Stack min temperature = 627°C
- Stack averaged temperature = 643°C



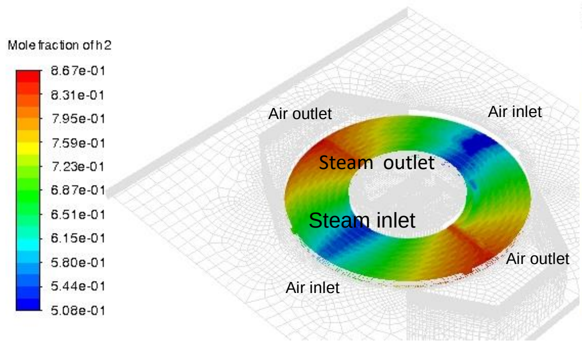

Thermal Profile

## Power Mode

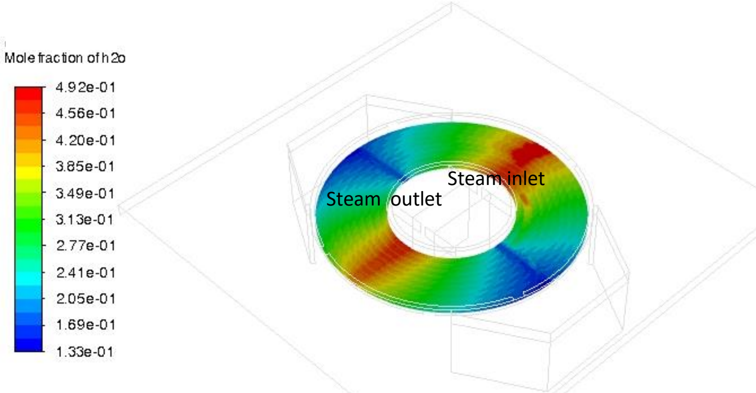
- 650 deg C inlet reactant gases
- 97%H2, 3%H2O fuel, 25% Uf, 15%Ua
- $V_{cell}$ average =1.022 volt/cell
- Stack max temperature = 745°C
- Stack min temperature = 727°C
- Stack averaged temperature = 740°C



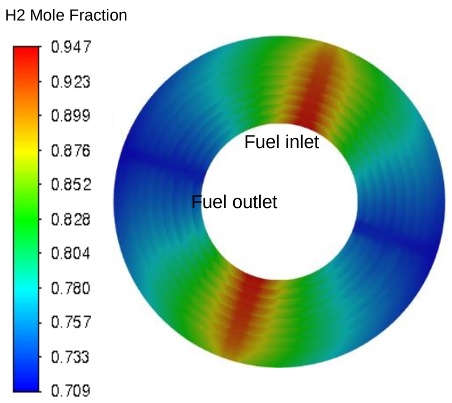

Thermal Profile



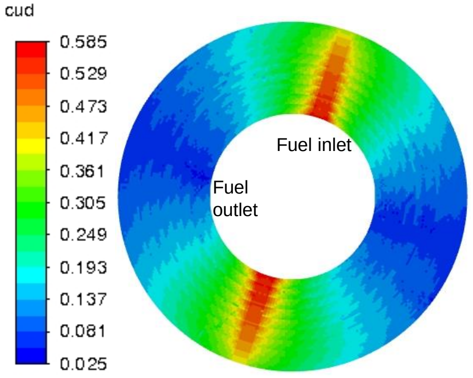

$H_2$ Concentration




Steam Concentration




$H_2$ Concentration




Current Density

CFD analysis is used to study the concentration and thermal profile of the stack in charge/discharge modes of operation

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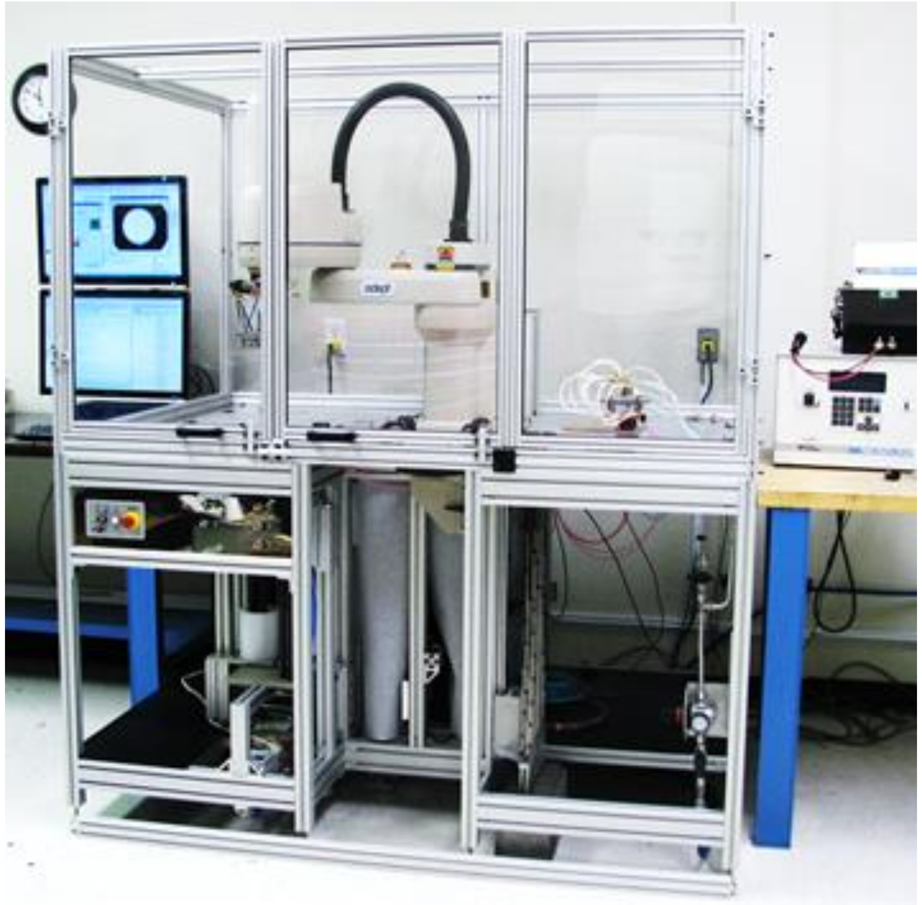
# High Volume Manufacturing

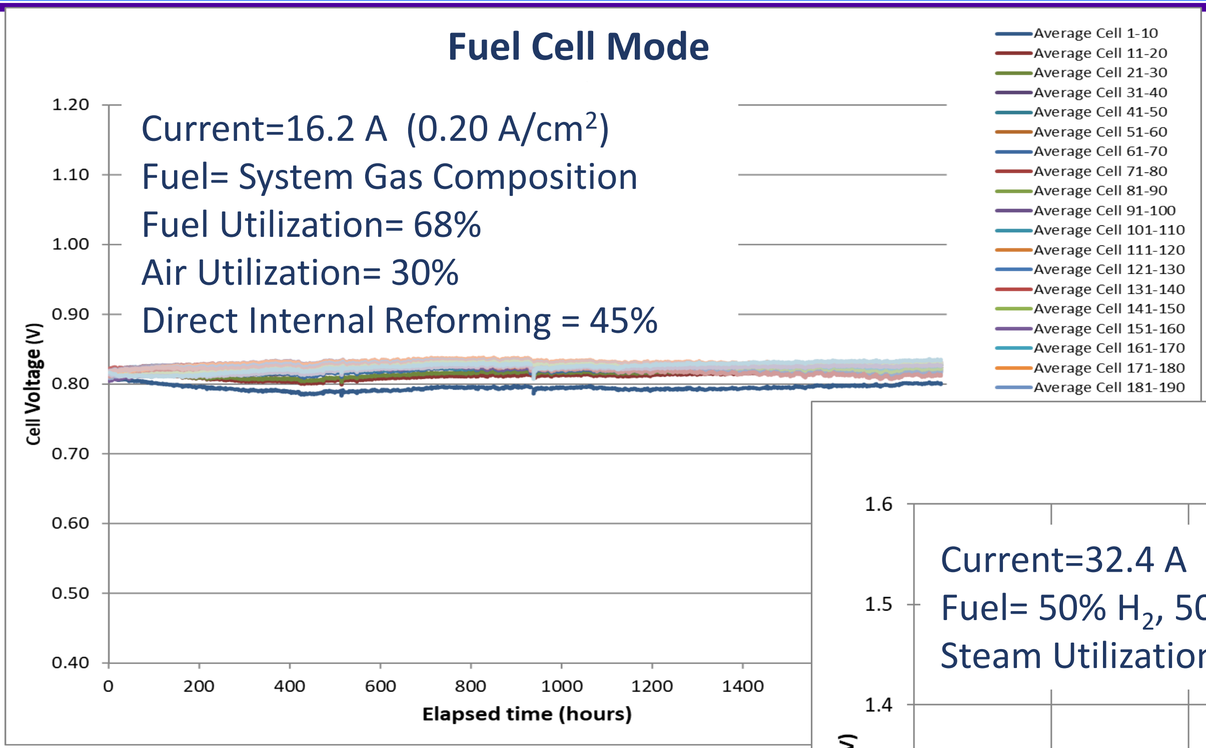

**Automated screen printing, drying, cell QC, stack firing, and stack handling equipment**

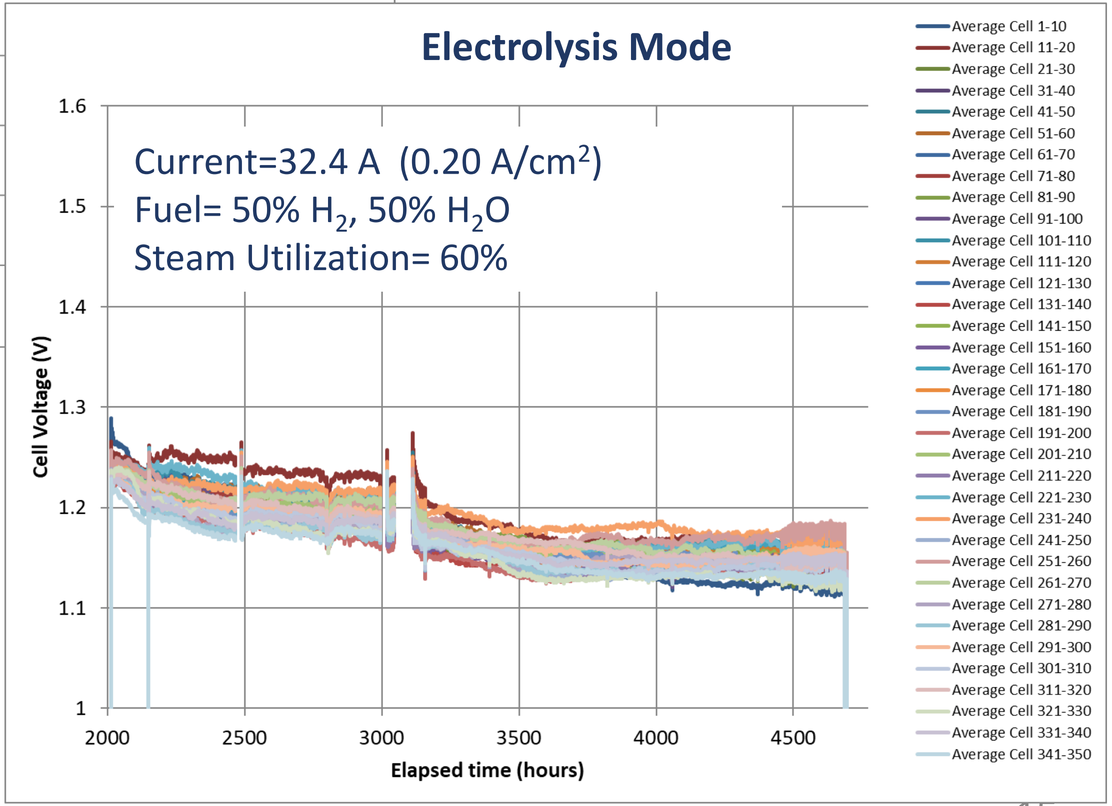


**Robotic QC / Stacking Station**

**Expansion to 1 MW/year CSA Stack Production**

Recent Full Height Stack Test



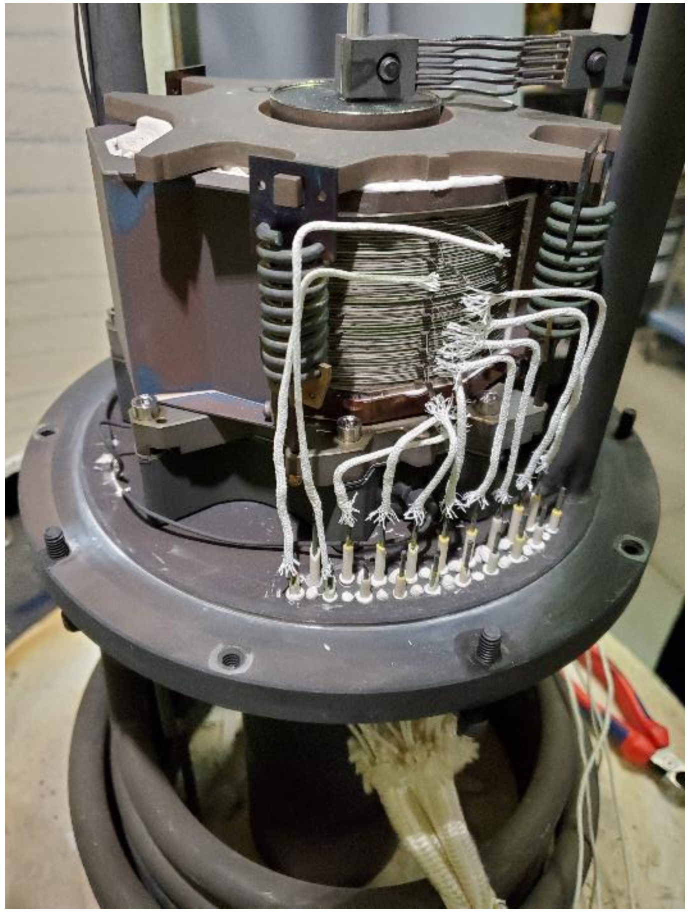




## GT060081-0004

- Completed over 1800 hours of fuel cell operation on reformate followed by >2,500 additional hours of electrolysis operation

# New 45-Cell Stack Fabrication

- 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

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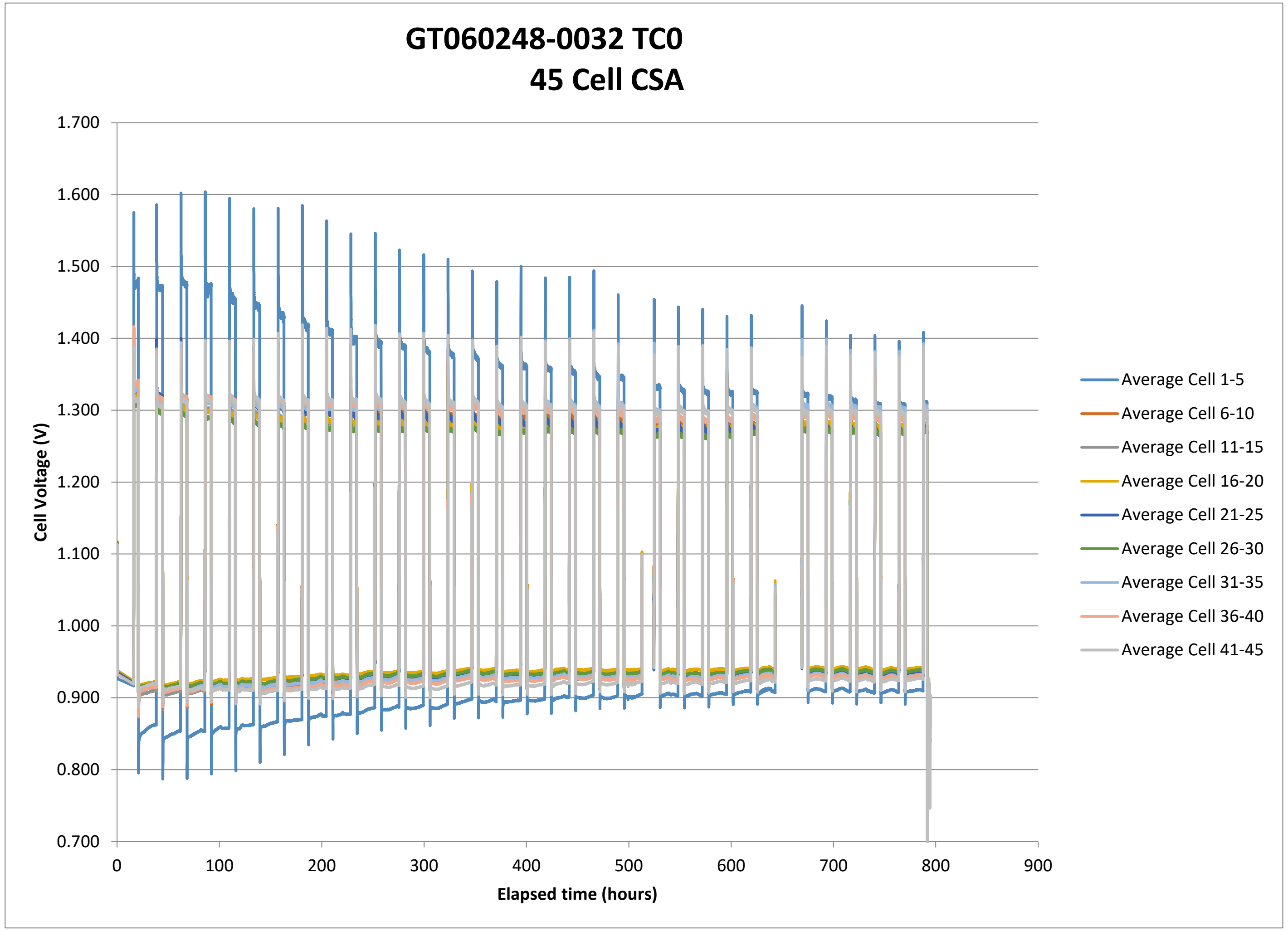
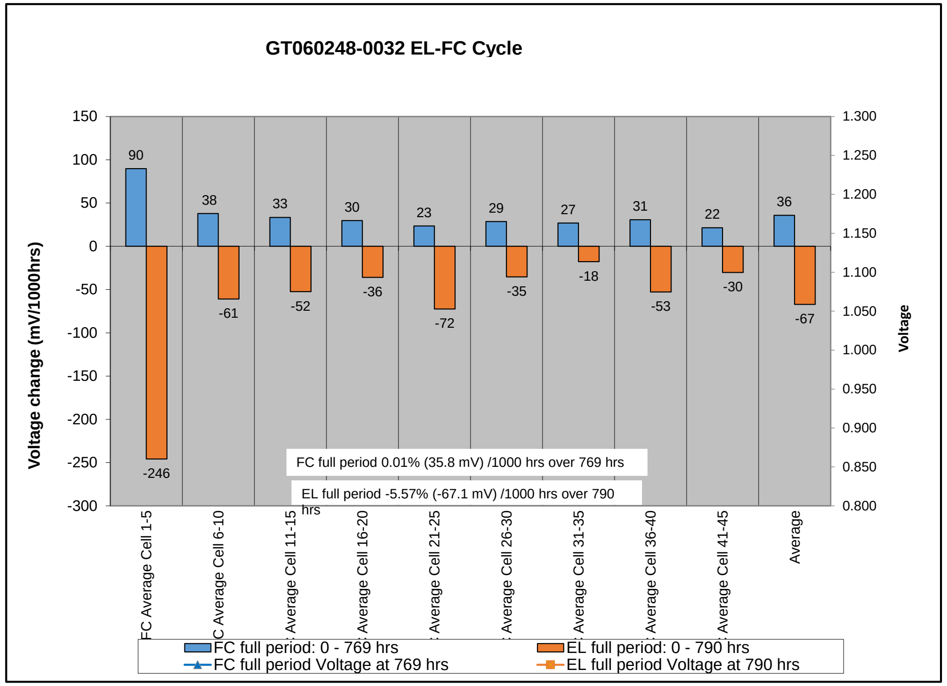
# 45-Cell CSA Stack Tests




## Summary of Results

- 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
- Two test stand related interruptions without significant impact on performance
- Internal short ended test after 800 hours

# RSOFC Pilot System Demonstration

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# Energy Storage Demonstration System

Recently, FCE's Solid Oxide Electrolysis (SOEC) pilot system was 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

Vent hood

Vaporizer

Power and controls cabinet

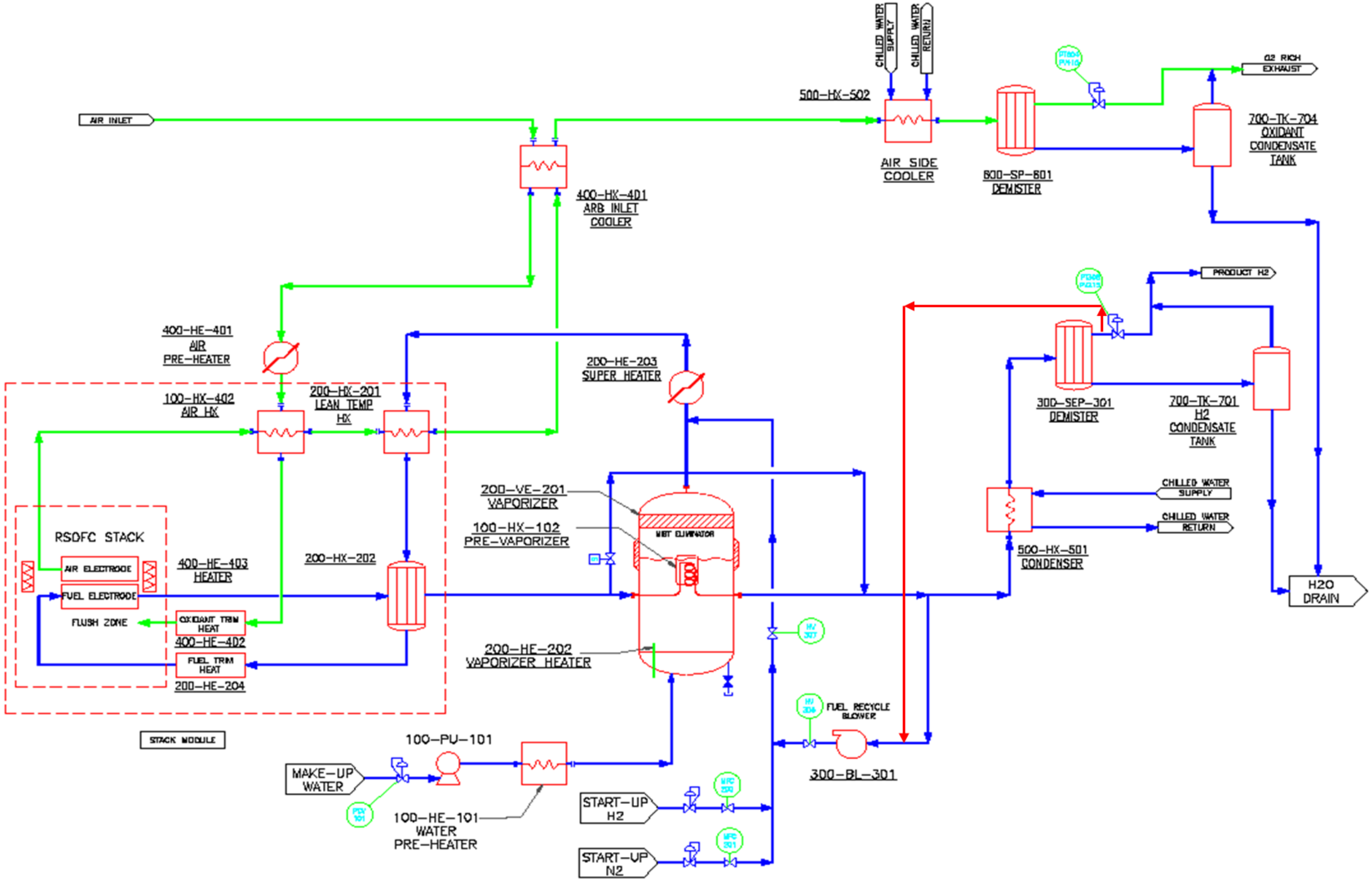
SOEC Electrolyzer Module

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

Fuel Cell Mode Load Bank

# Updated Pilot Demonstration System Process Flow Diagram (PFD)

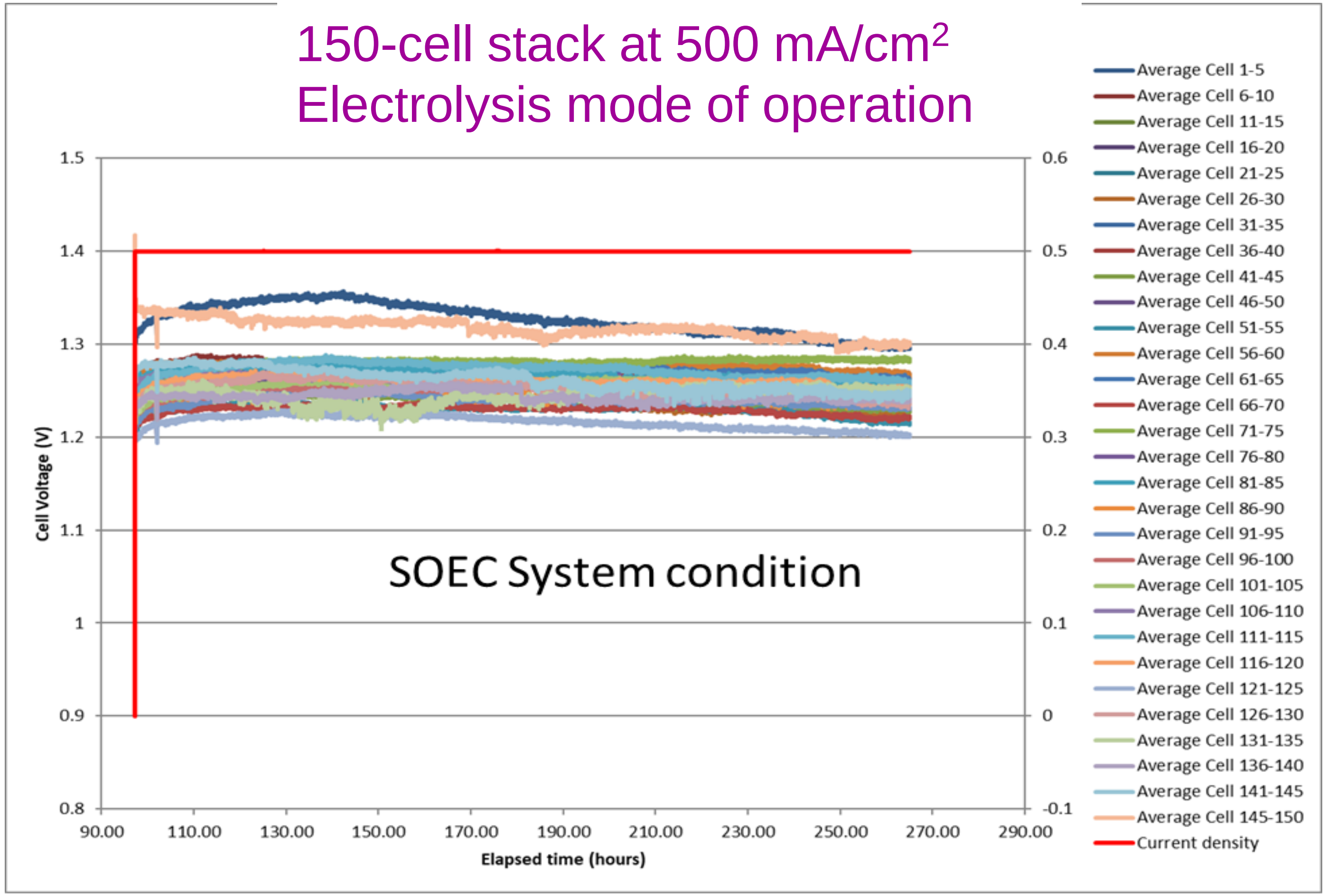
- Process Flow Sheet was completed
- Computer Simulation of the system was completed:
  - Steady-State Mass & Energy Balances using ChemCad simulation software



# 150-Cell Stack for RSOFC System Demonstration

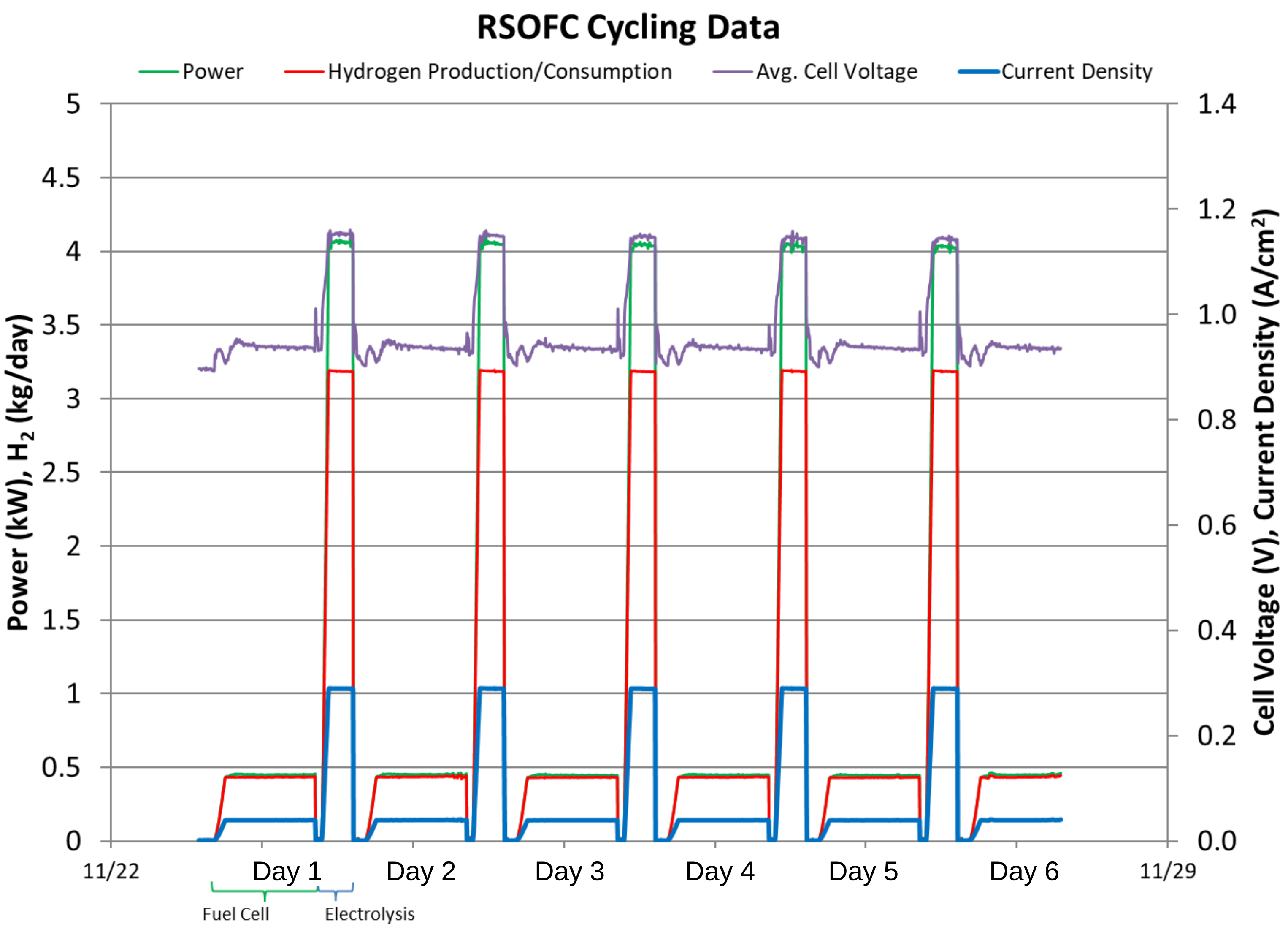
**150-cell stack (GT60247-0005)**

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



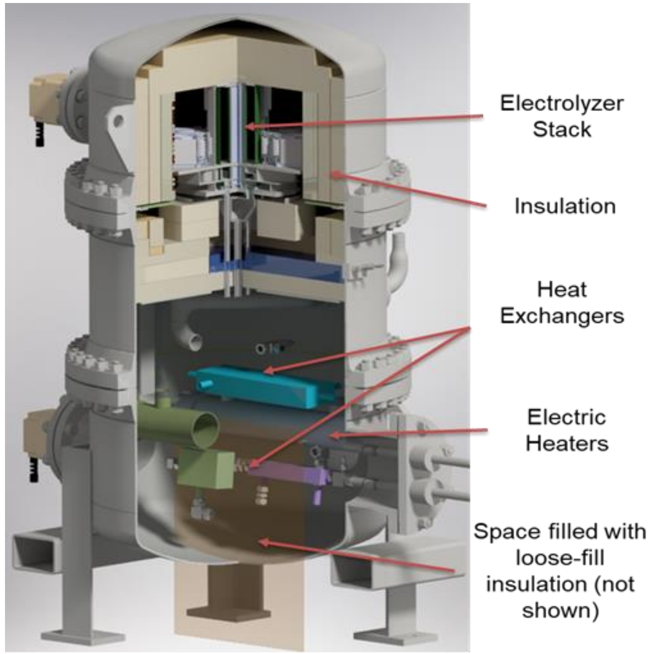

- Furnace: 627 C
- Fuel: 50% $H_2O$ , 50% $H_2$ @ 76.05 SLPM $H_2$
- Air: 150 SLPM @ 40.5 A -- 76.05 SLPM $H_2O$
- Usteam = 60.0%

# RSOFC Pilot System Commissioning Tests
# DE-EE0008847




Daily Charge/Discharge Cycles

# RSOFC Pilot System Upgrade



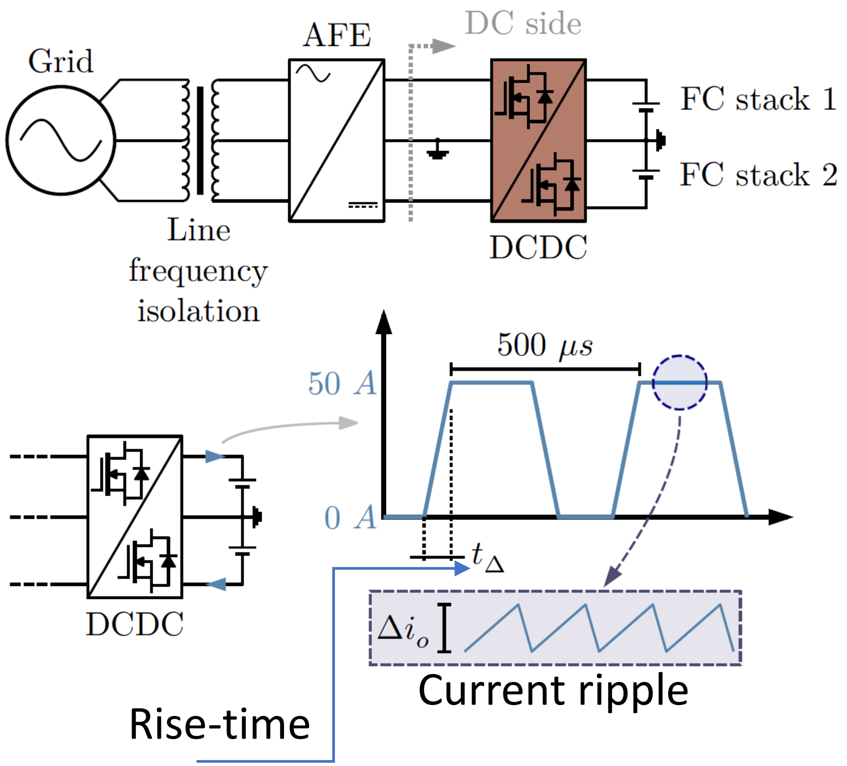

Internal view of RSOFC Module


RSOFC Energy Storage Pilot System

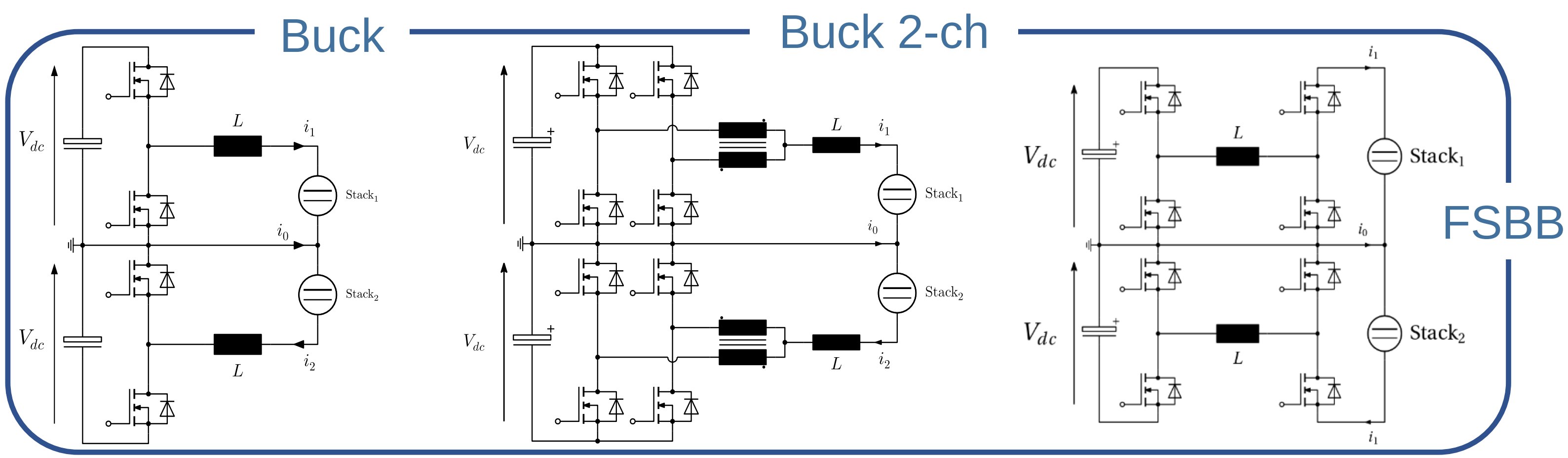
- The RSOFC Pilot System will be further upgraded to a capacity of 6 kW discharge and 32 kW charge.
  - Planned development of an advanced power conversion system including a robust algorithm for enhanced stack thermal management and transient load response, resulting in longer stack life and durability

# Development of Power Electronics

- Center of Power Electronics System (CPES) at Virginia Tech is developing Bidirectional DC-DC Converter for RSOFC applications:
  - Current work is focused on development of a topology to minimize current response rise-time and ripples




## Analyzed topologies



# Technoeconomic Analysis

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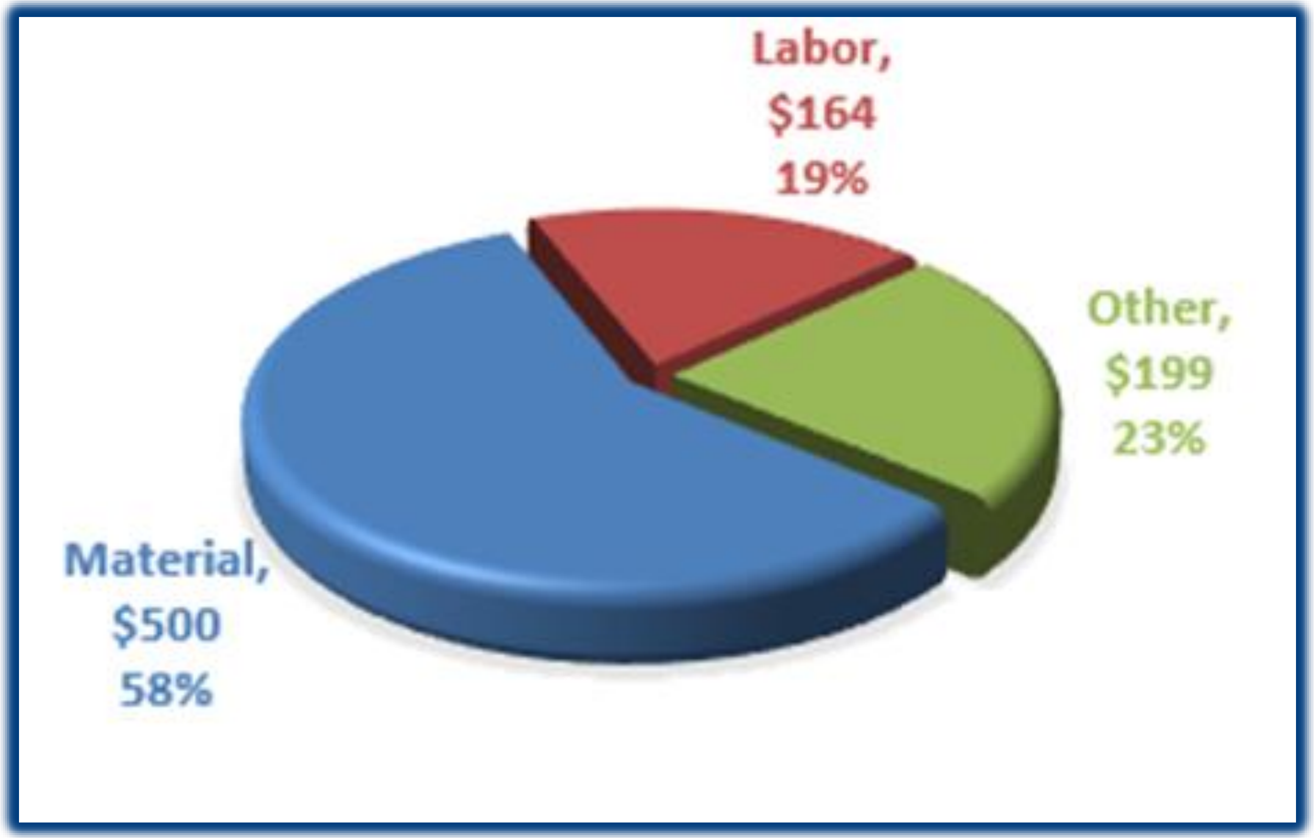
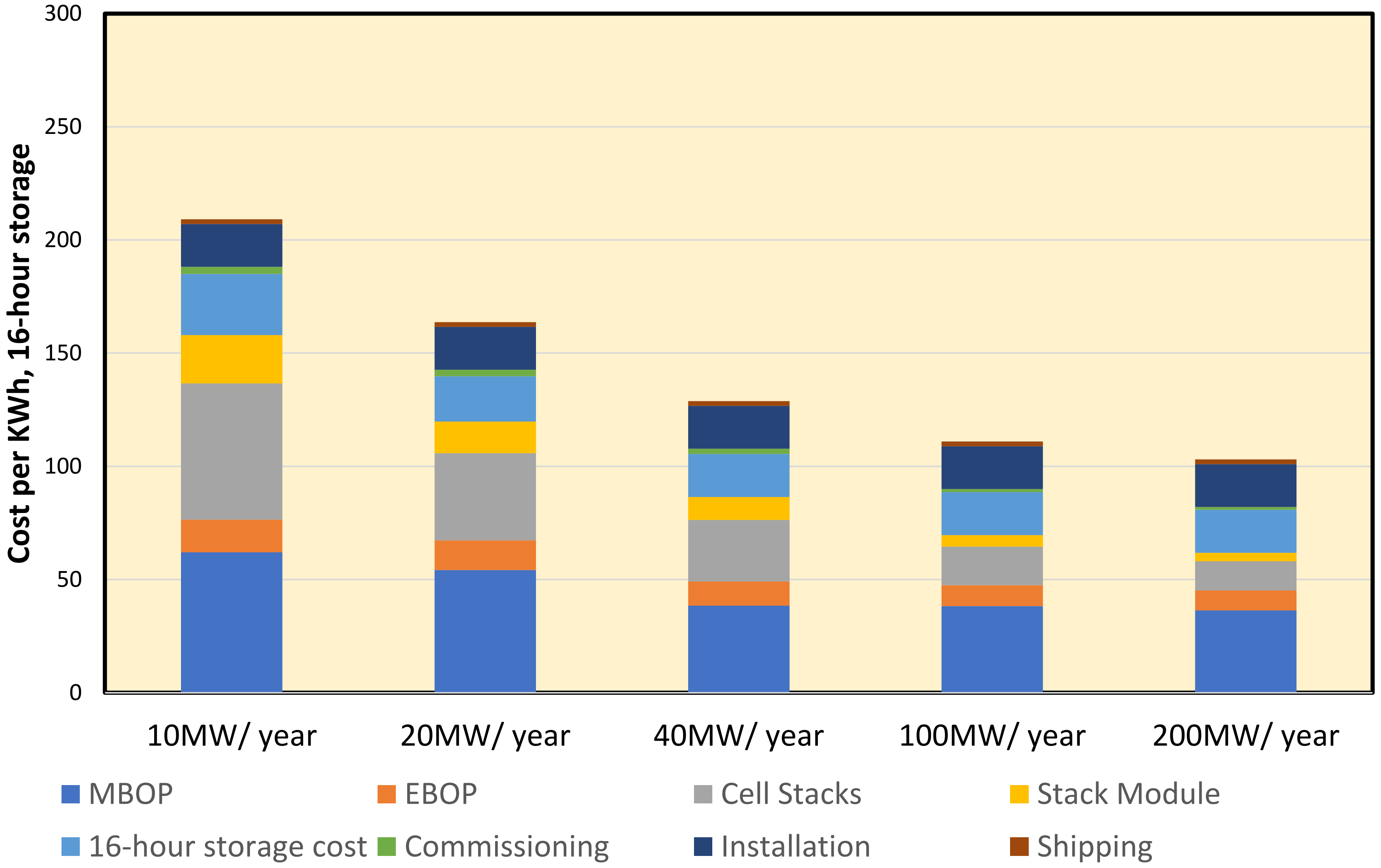
# Giga Factory Stack Cost Breakdown

## Yr2019 CSA-SOFC Stack Factory Cost Estimate for 1 GW Stacks per Year

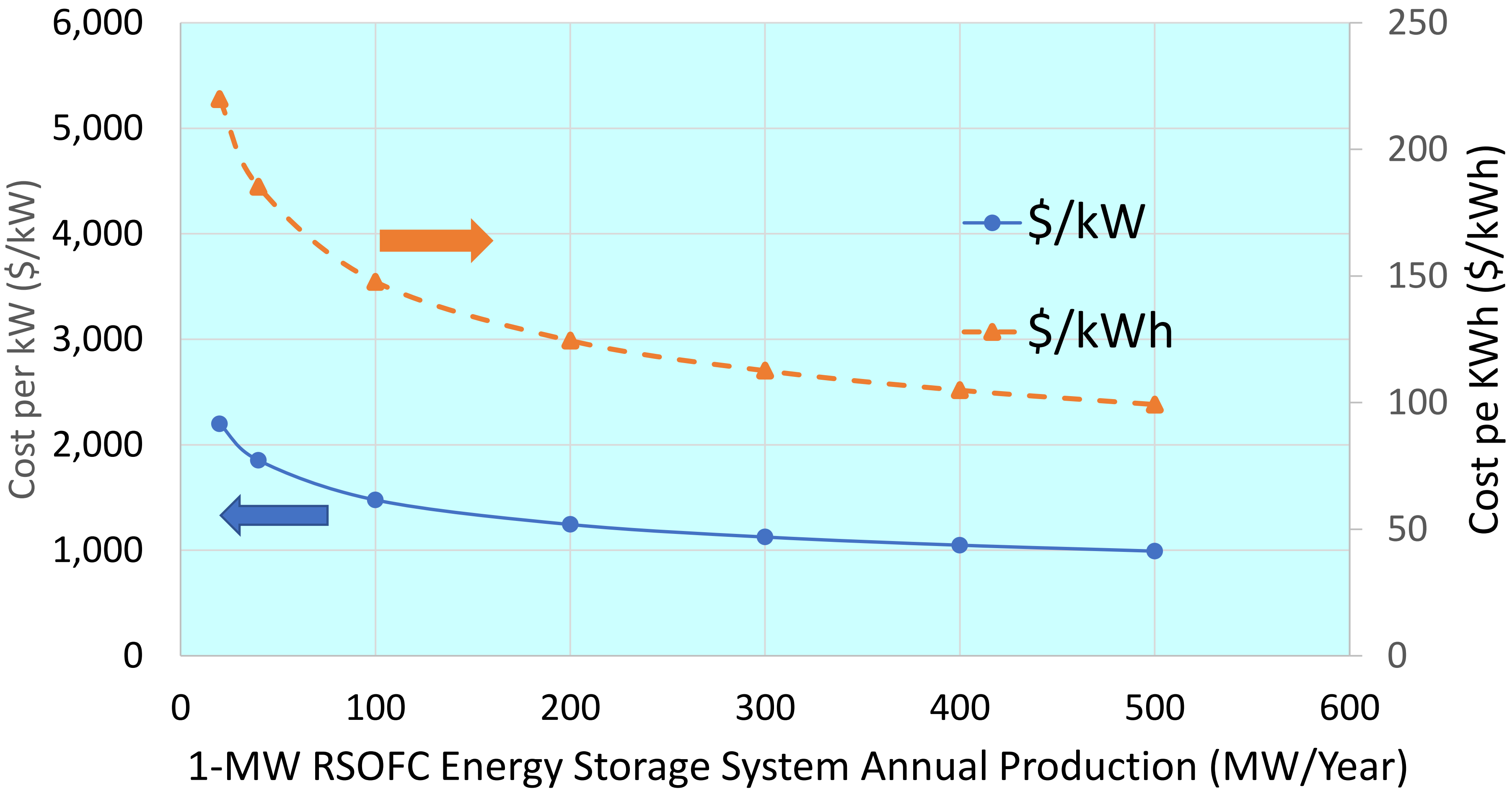



**$ 863 / stack (~$130/kWdc output) at 160,000 stacks/year**

# RSOFC Cost vs Production Volume



# Cost of Commercial Units Per KWhr



# Wrap-up

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# Future Plan

- Develop Pilot RSOFC System design
  - Finalize System Commissioning
  - Perform case studies at operating conditions of interest
  - Perform parametric analysis to maximize round trip efficiency
- Perform Pilot System upgrade
  - Develop control algorithms
  - Incorporate hardware upgrades
- Conduct RSOFC system demonstration tests

# Thank You

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Dr. Shailesh Vora
Dr. Patcharin (Rin) Burke
Sarah K. Michalik

Our purpose:

**Enable the world to be empowered by clean energy**