Performance Improvements for Reversible Solid Oxide Fuel Cell Systems

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2022 SOFC Project Review Meeting

Pittsburgh, PA

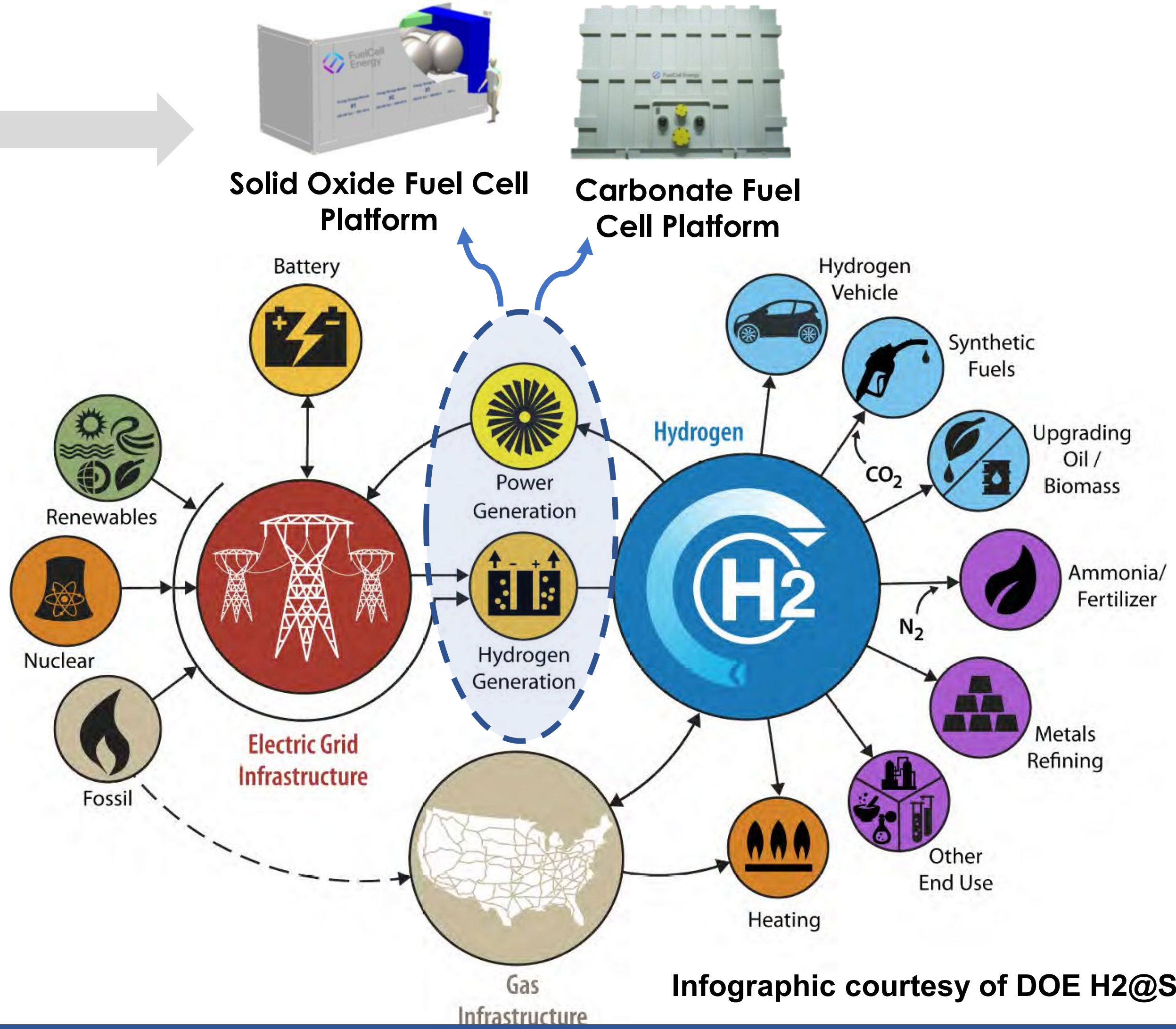
October 26, 2022

Company Overview

NASDAQ: FCEL, Operating Since 1969

A leader in decarbonizing power and producing hydrogen through proprietary fuel cell technologies:

- **Produce** low- to zero-carbon power
- **Capture** carbon and greenhouse gasses while simultaneously generating power; Negligible NO_x or SO_x emissions
- **Supply** green or blue hydrogen power
- **Store** energy from intermittent renewables by converting excess power to hydrogen – then converting hydrogen back into power when it's needed or delivering to other applications



Infographic courtesy of DOE H2@Scale

Demand for Clean, Reliable Electricity Driving Adoption of Fuel Cell Technology

FuelCell Energy

FCE Leading Technologies Providing Energy Solutions

APPLICATION	CARBONATE	SOLID OXIDE
Power gen/CHP from natural gas, biogas, or H_2 blends	✓	✓
Power generation/CHP from hydrogen fuel		✓
CO_2 capture from platform	✓	✓
CO_2 capture from external source while making power	✓	
H_2/Power/Water production from natural gas or biogas	✓	✓
High efficiency electrolysis H_2 production		✓
Energy storage		✓

TWO ADVANCED HIGH TEMPERATURE ELECTROCHEMICAL PLATFORMS ADDRESSING MULTIPLE APPLICATIONS

3

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

200 kW Power Generation System

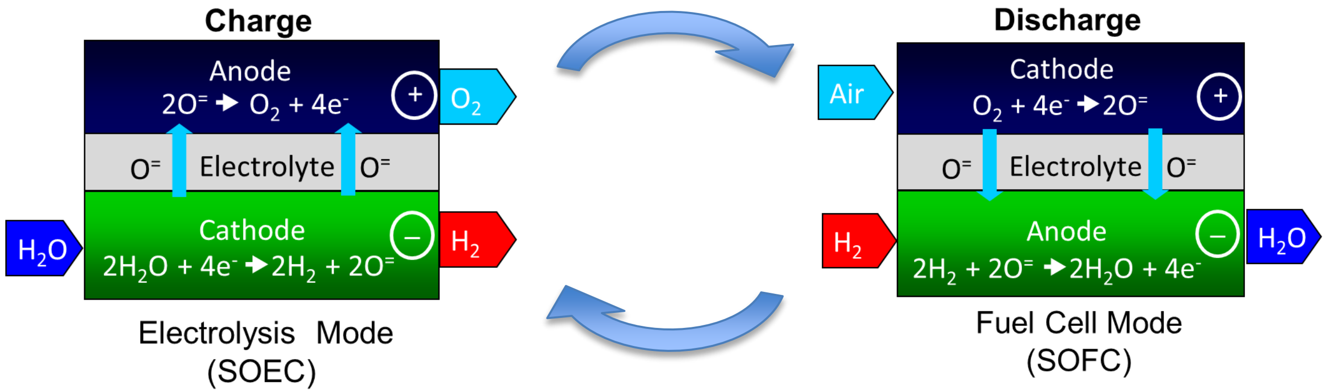
Electrolysis
600 kg/day H2 from 1.1 MW

Energy Storage System
1MW, 8MWh

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).

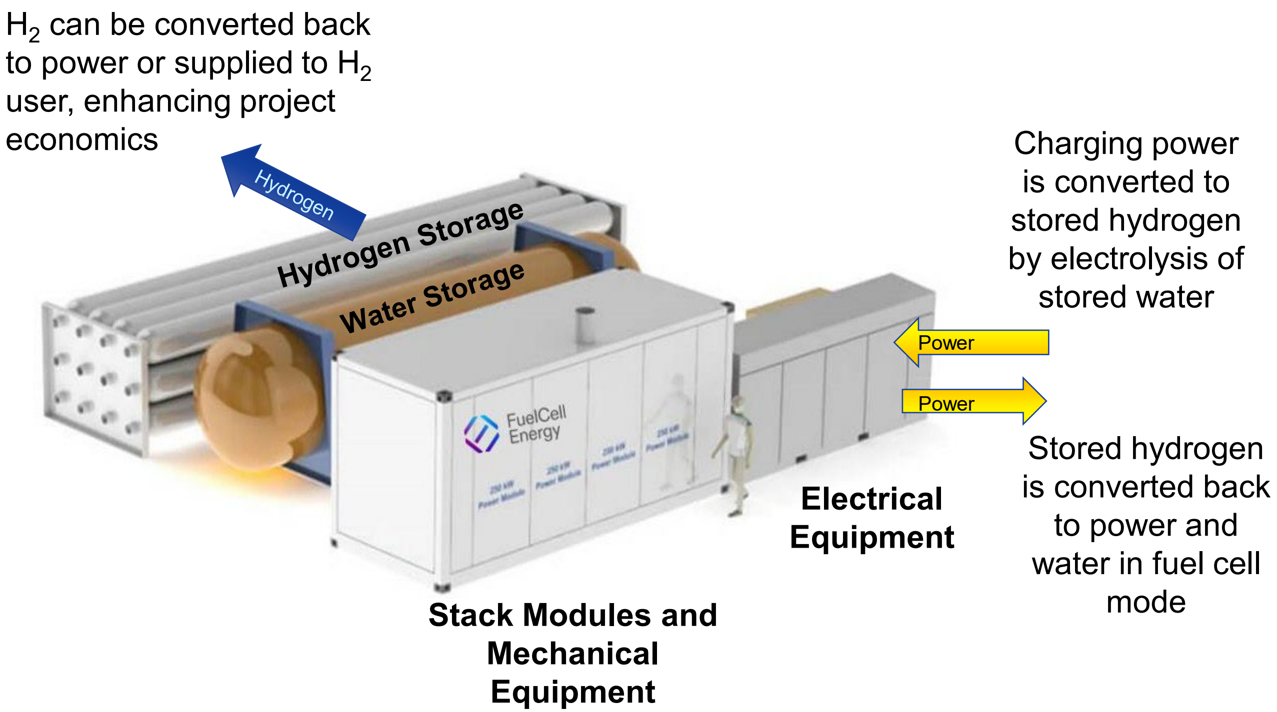
Approach



- Improve RSOFC repeat units including cell, seal, interconnects, and coatings to increase performance and reduce degradation in cyclic operation.
- Improve stack thermal management and load following capabilities by design and verification testing of specialized power electronic equipment in combination with development of advanced system control strategies.
- Demonstrate a pilot RSOFC system incorporating cell and stack improvements achieved in the project.
- Perform commercial system design and costing to validate RSOFC storage system cost of <$1000/kW at 50MW/year manufacturing level leading to H_2 production cost of $2/kg.

Solid Oxide - Hydrogen Based Long Duration Energy Storage System

- 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



- Commercial MW-scale RSOFC Cost Targets :
  - Capital Cost - Power $1000/kW
  - Capital Cost - Energy $150/kW-h
  - Levelized Cycle Cost $0.05/kWh-cycle

Cell Technology for Reversible Operation

FuelCell Energy

FuelCell Energy

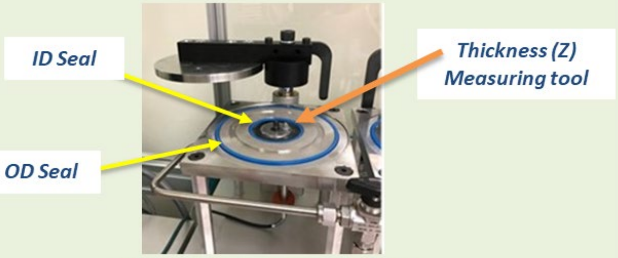
Cell Fabrication

Tape Casting

Automated Screen Printing

Co-Sintering

“ TSC 3 Process “

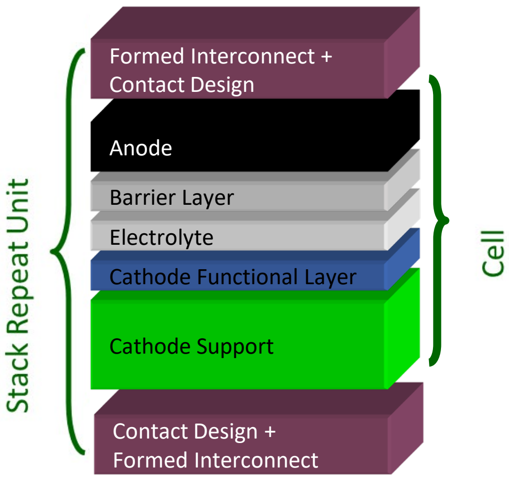


CSA Cell Leak Tester Jig with Thickness Measuring Tool

Cell QC

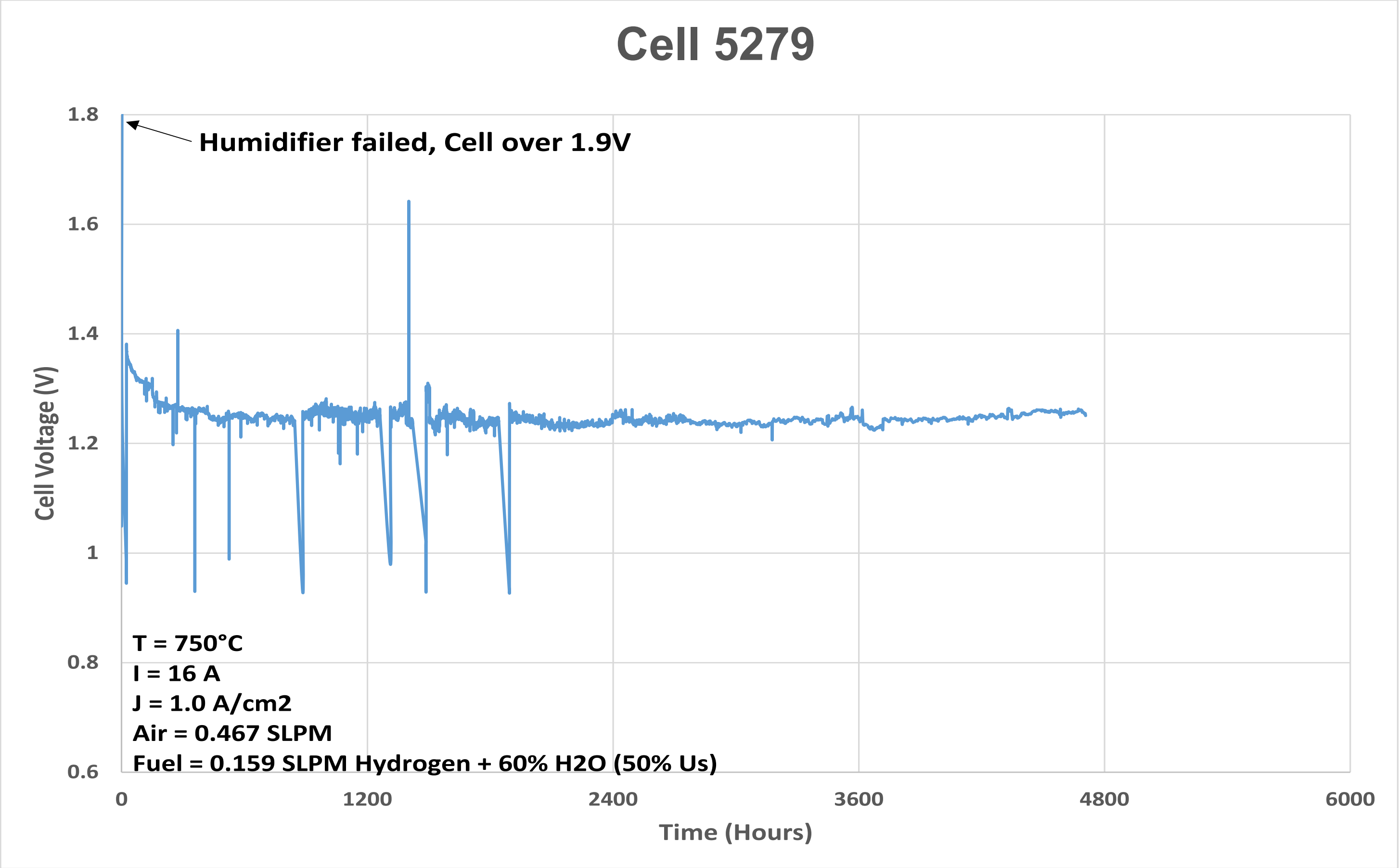
Solid Oxide Electrolysis Cell (SOEC) Constituent Layers

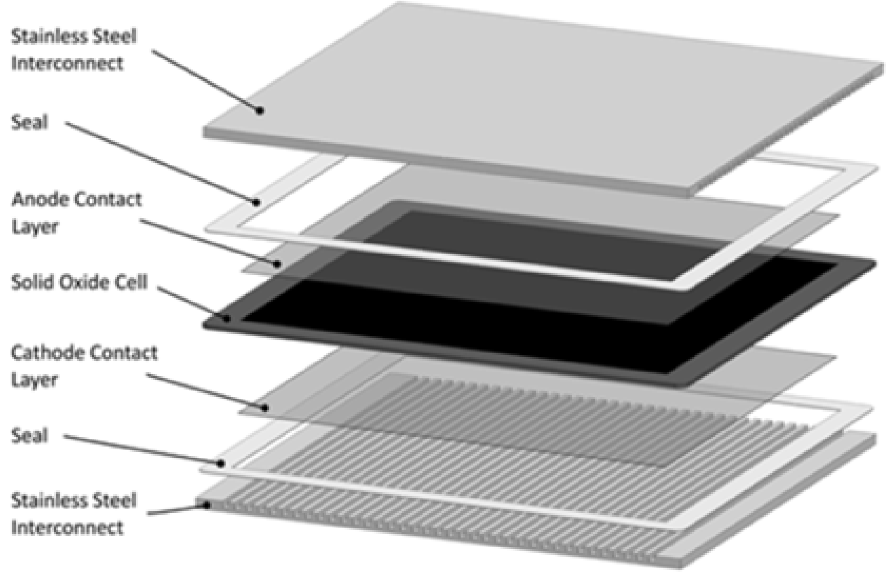
Component	Materials	Thickness	Porosity	Process
Anode	Conducting ceramic	~ 50 μm	~ 30%	Screen printing
Barrier Layer	CGO	~4 μm	<10%	Screen printing
Electrolyte	YSZ	~5 μm	< 5%	Screen printing
Cathode Functional Layer	Ni/YSZ	~8 μm	~ 40%	Screen printing
Cathode Support	Ni/YSZ	~0.3 mm	~ 40%	Tape casting



FuelCell Energy

Long-Term Stability of Cell Operation in Electrolysis Mode



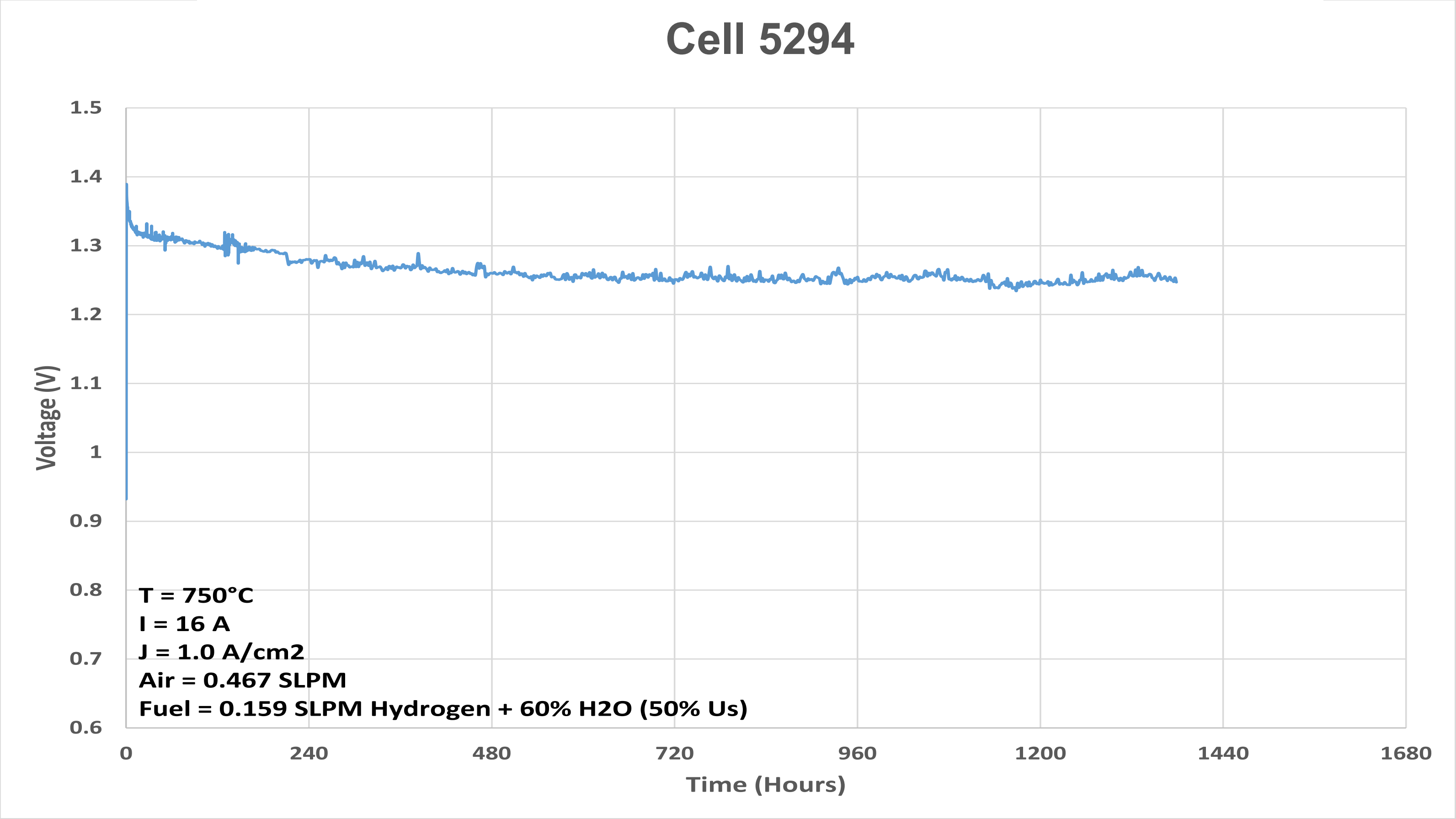


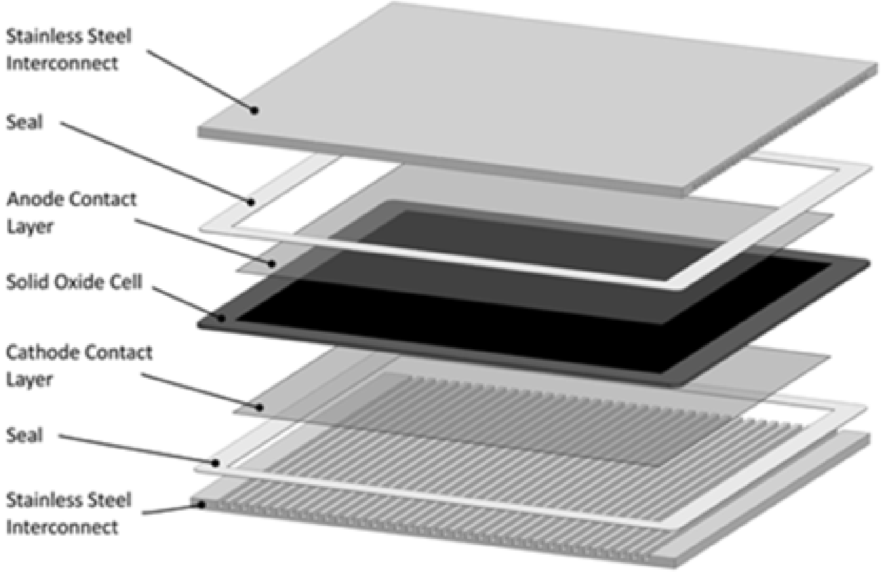
Steady State Operation in Electrolysis Mode at 1 A/cm^2

- 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

Repeat of Electrolysis Cell Test



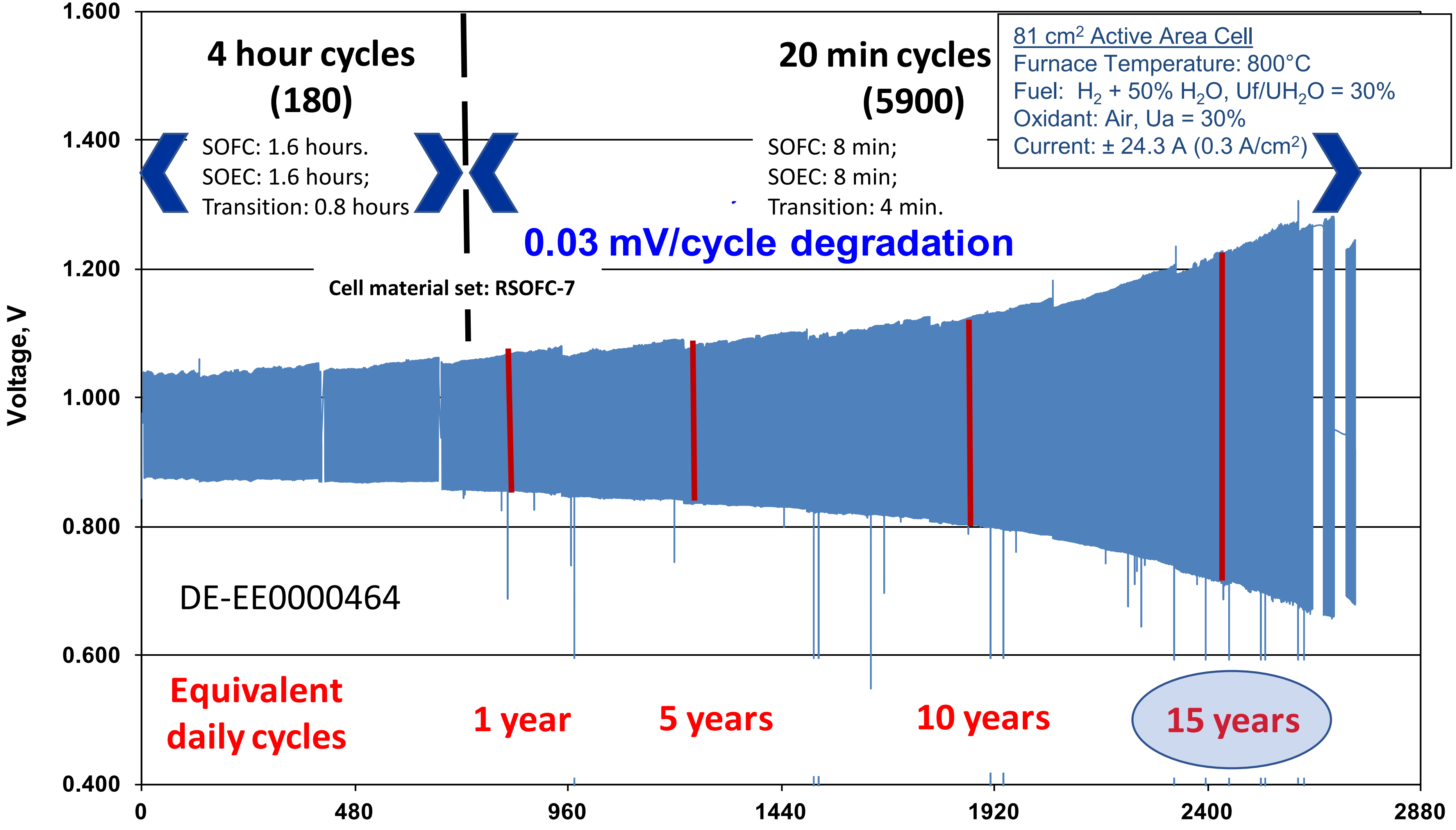


- 16 cm^2 cell configuration consisting of stack features:
- cross-flow pattern
- flow fields
- electrode contact layers
- glass seals

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

Repeat test of electrolysis cell after >1000 hours of operation showing no degradation

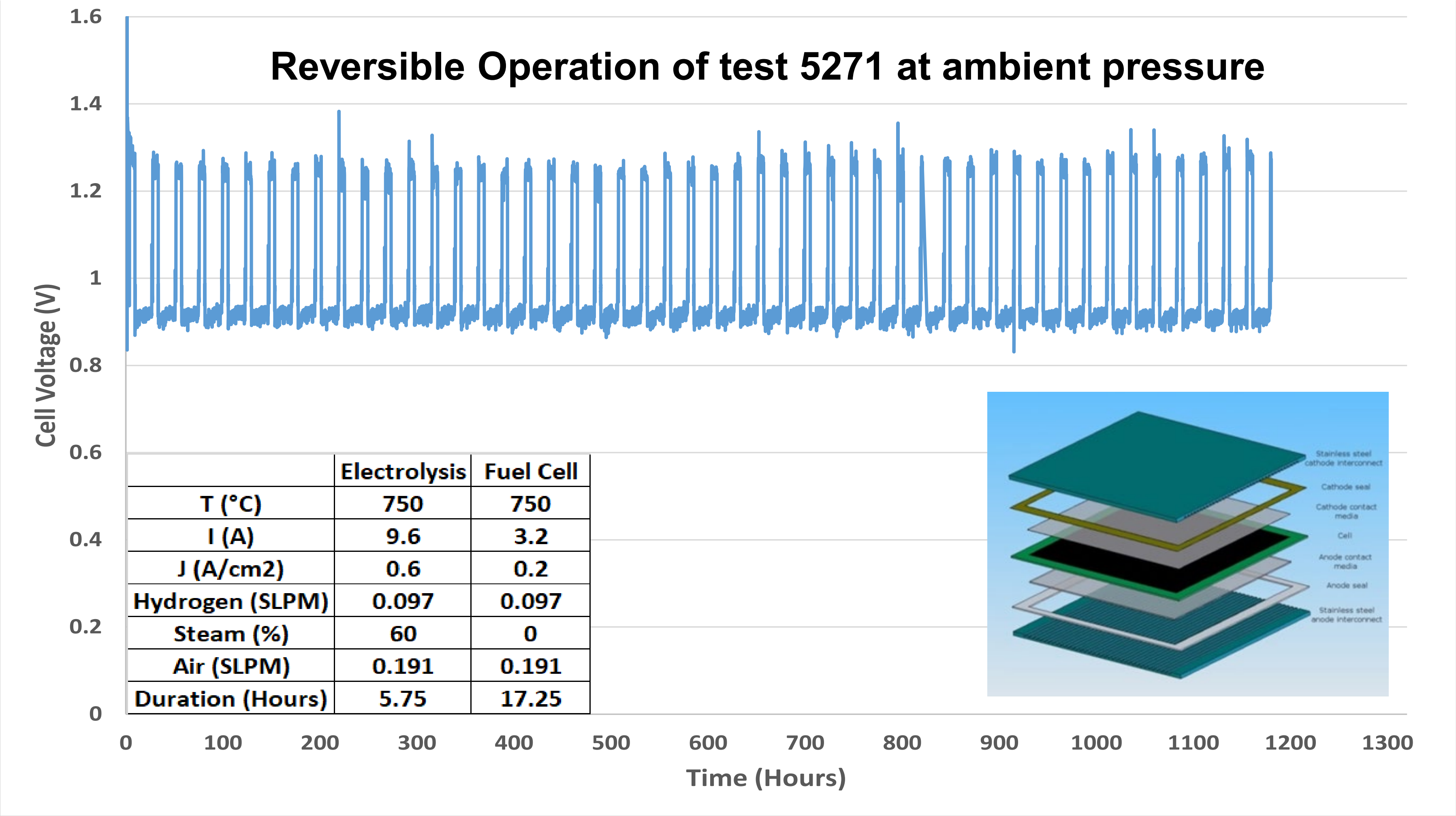
Accelerated Cycling (6,080 Cycles)



Accelerated tests representing >16 years of operation using short duration cycles

FuelCell Energy

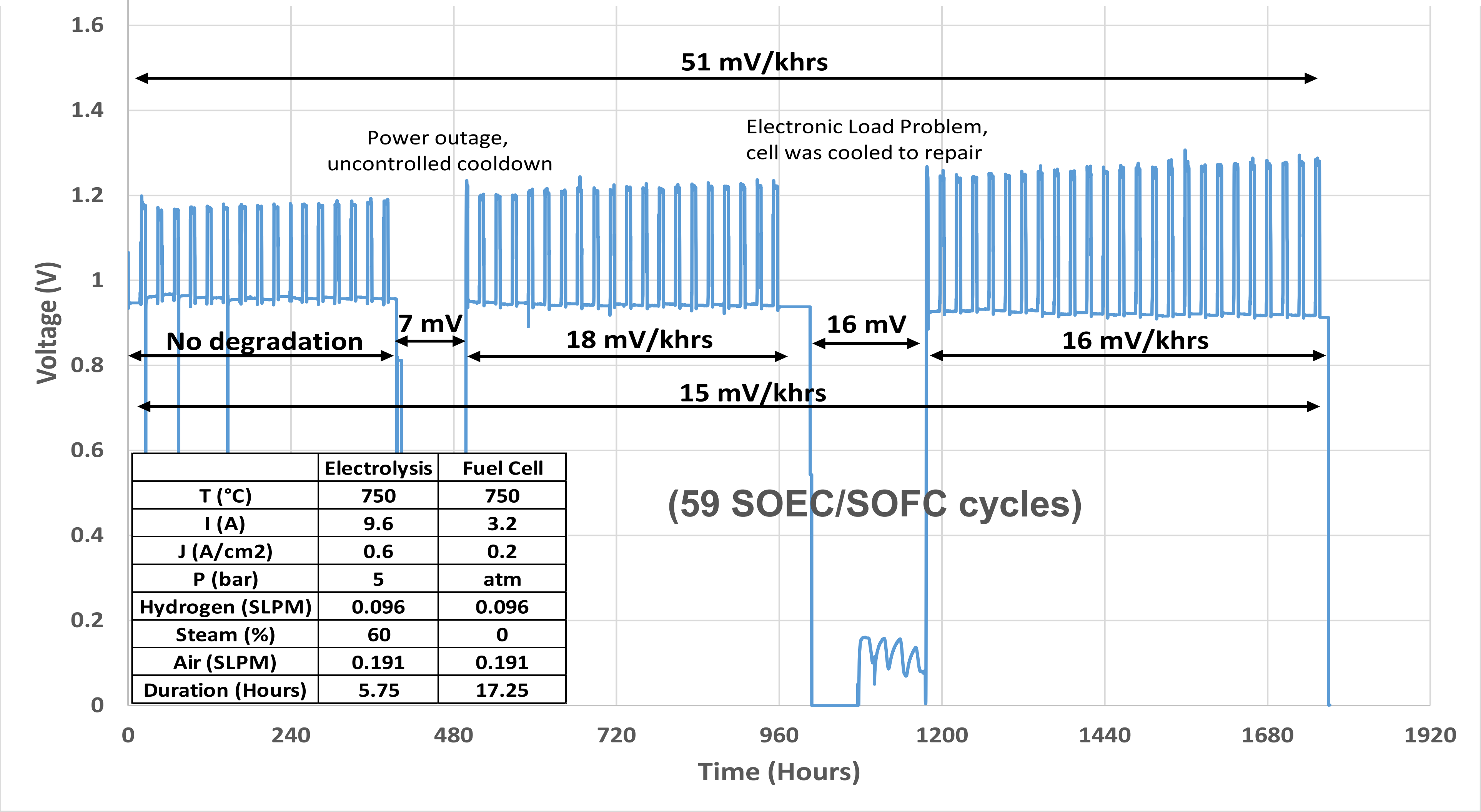
Single Cell in Reversible Operation



	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)

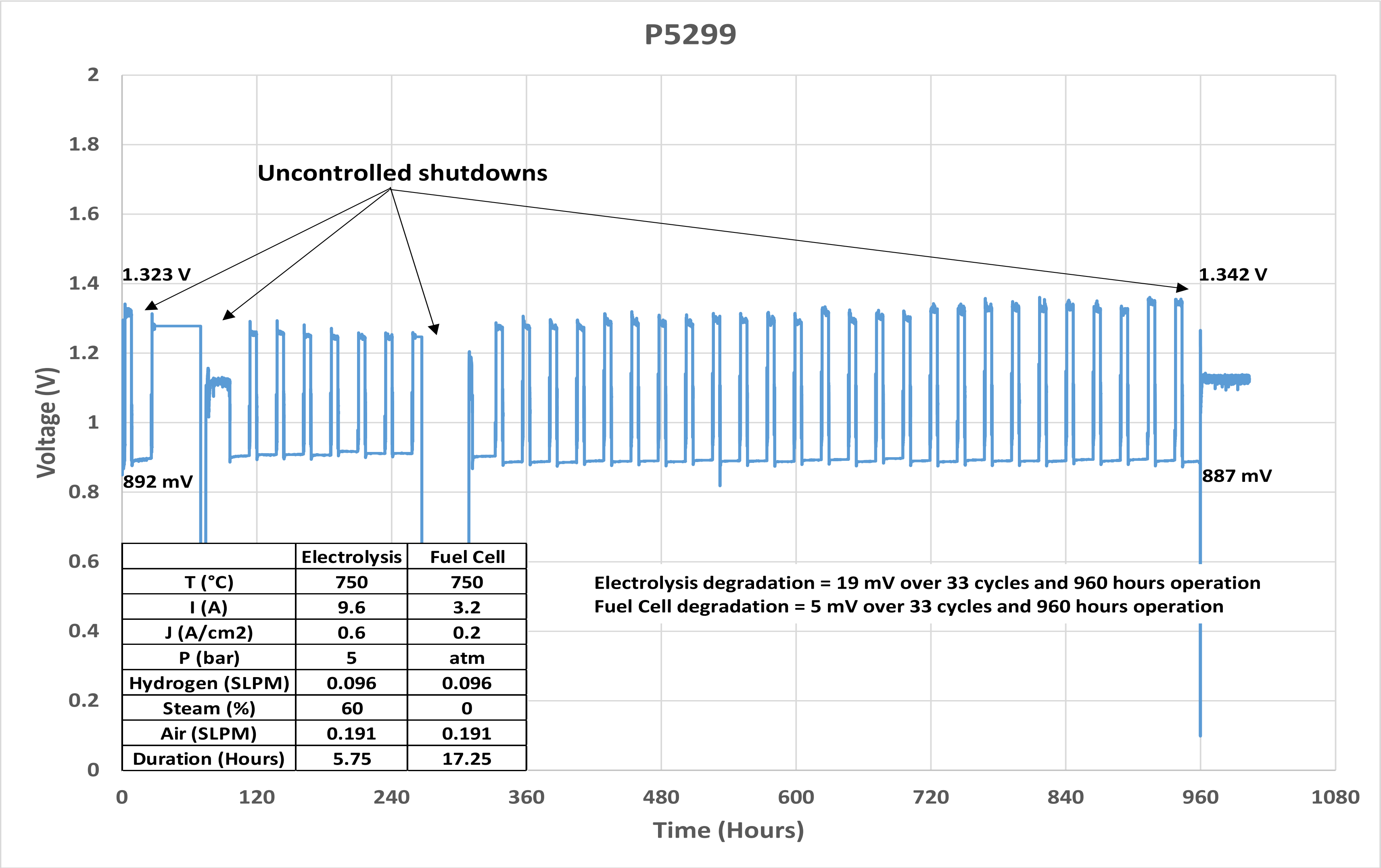
Cell P5284 Reversible Tests (Pressurized Electrolysis Mode)



	Electrolysis	Fuel Cell
T (°C)	750	750
I (A)	9.6	3.2
J (A/cm2)	0.6	0.2
P (bar)	5	atm
Hydrogen (SLPM)	0.096	0.096
Steam (%)	60	0
Air (SLPM)	0.191	0.191
Duration (Hours)	5.75	17.25

Reversible operation of 16 cm^2 P5284 cell at 5 bar for electrolysis and ambient pressure for fuel cell operation

Cell P5299 Reversible Tests (Pressurized Electrolysis Mode)



	Electrolysis	Fuel Cell
T (°C)	750	750
I (A)	9.6	3.2
J (A/cm2)	0.6	0.2
P (bar)	5	atm
Hydrogen (SLPM)	0.096	0.096
Steam (%)	60	0
Air (SLPM)	0.191	0.191
Duration (Hours)	5.75	17.25

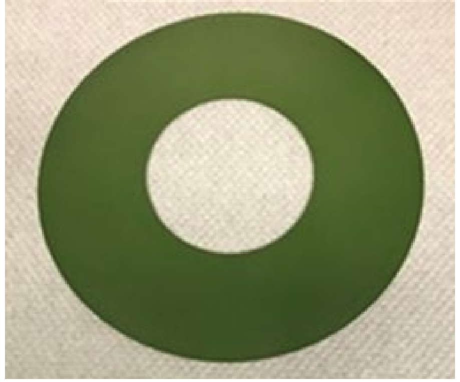
Reversible operation of 16 cm^2 P5388 cell at 5 bar for electrolysis and ambient pressure for fuel cell operation

RSOFC Stack Development

FuelCell Energy

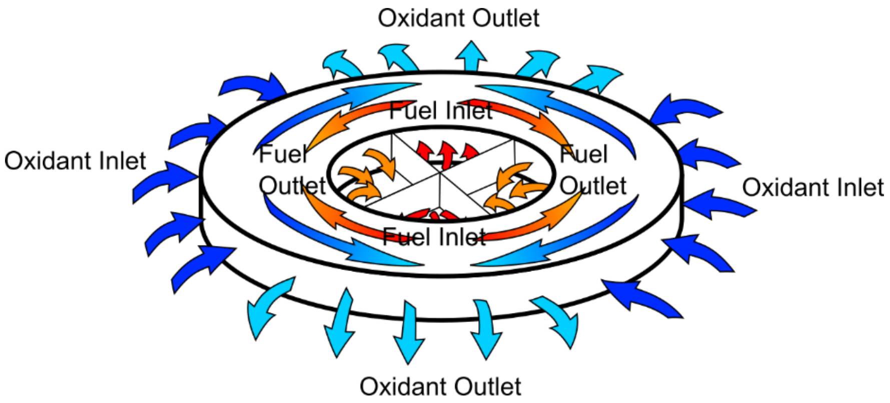
Compact SOFC Architecture (CSA) Stack Platform

FuelCell Energy



Cell
81 cm^2 active area

Standardized Stacks in three sizes



Flow Geometry

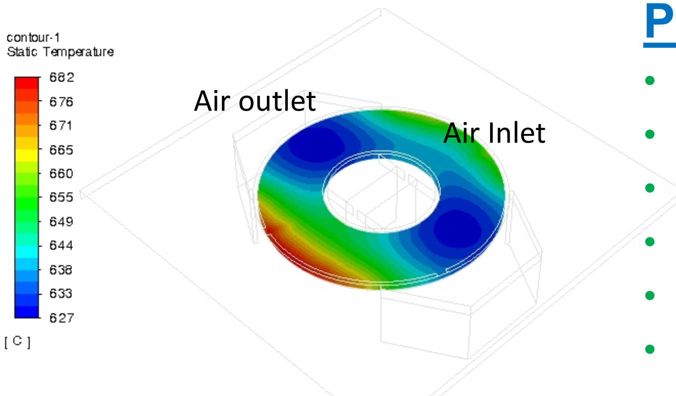
Property	Scale			Comments
	Short	Mid	Full	
Cell count	45	150	350	Nominal count
Fuel Cell Voltage, V	43	143	333	At 0.950 V/cell
Electrolysis Voltage, V	58	192	448	At 1.280 V/cell
Stack Efficiency, % LHV	74% / 100%	74% / 100%	74% / 100%	Electrochemical eff FC / EL
Power, kW	0.87 / 2.7	2.8 / 9.3	6.7 / 21.8	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

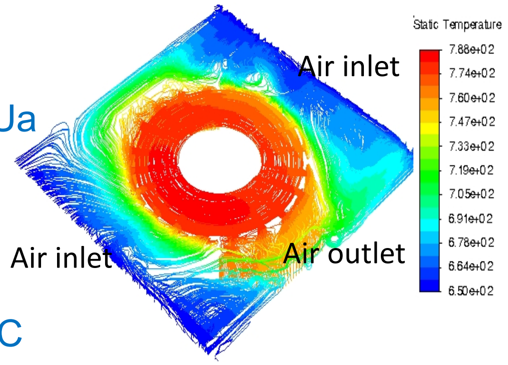
- 700 deg C inlet reactant gases
- 50%H_2, 50%H_2O steam, 60% U_{steam}, flush air
- V_{cell} average =- 1.2 volt/cell
- Stack max temperature = 661°C
- Stack min temperature = 627°C
- Stack averaged temperature = 643°C



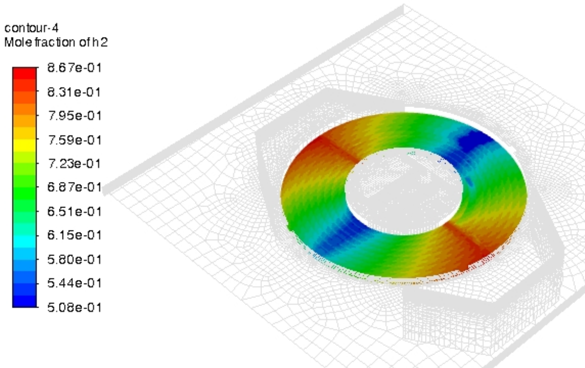
Thermal Profile

Power Mode

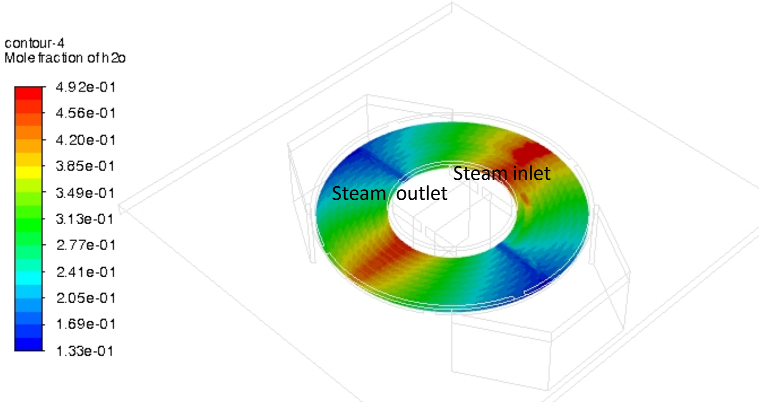
- 650 deg C inlet reactant gases
- 97%H2, 3%H2O fuel, 25% Uf, 30%Ua
- V_{cell} average =1.013 volt/cell
- Stack max temperature = 781°C
- Stack min temperature = 756°C
- Stack averaged temperature = 777°C



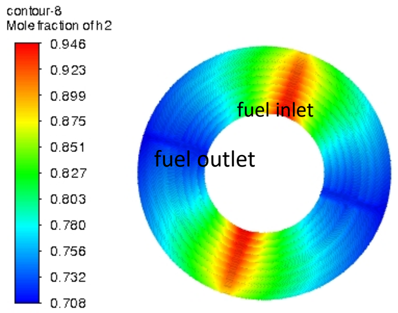
Thermal Profile



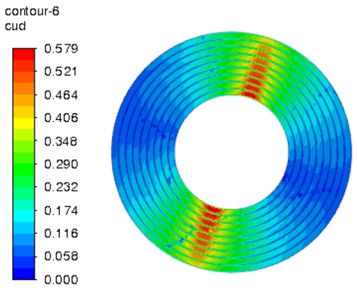
H_2 Concentration



Steam Concentration



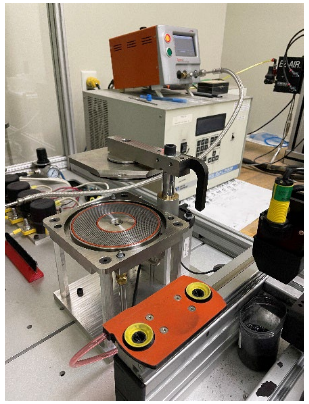
H_2 Concentration



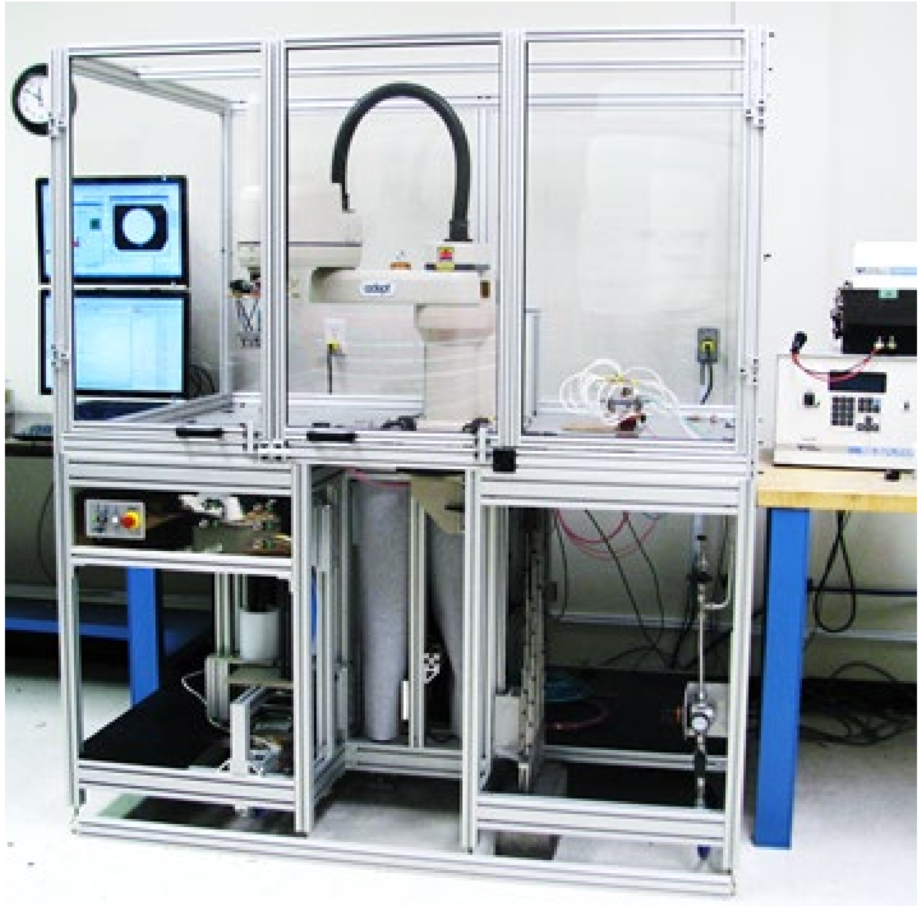
Current Density

FuelCell Energy

High Volume Manufacturing



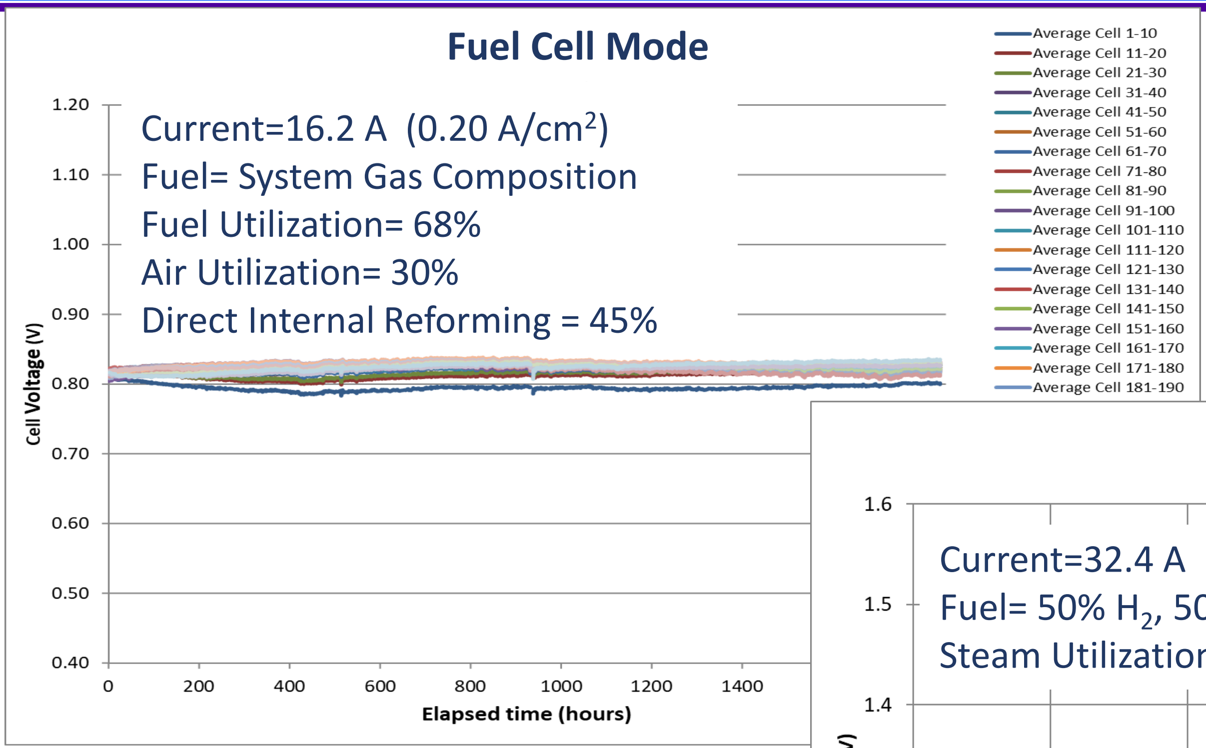
Automated screen printing, drying, cell QC, stack firing, and stack handling equipment

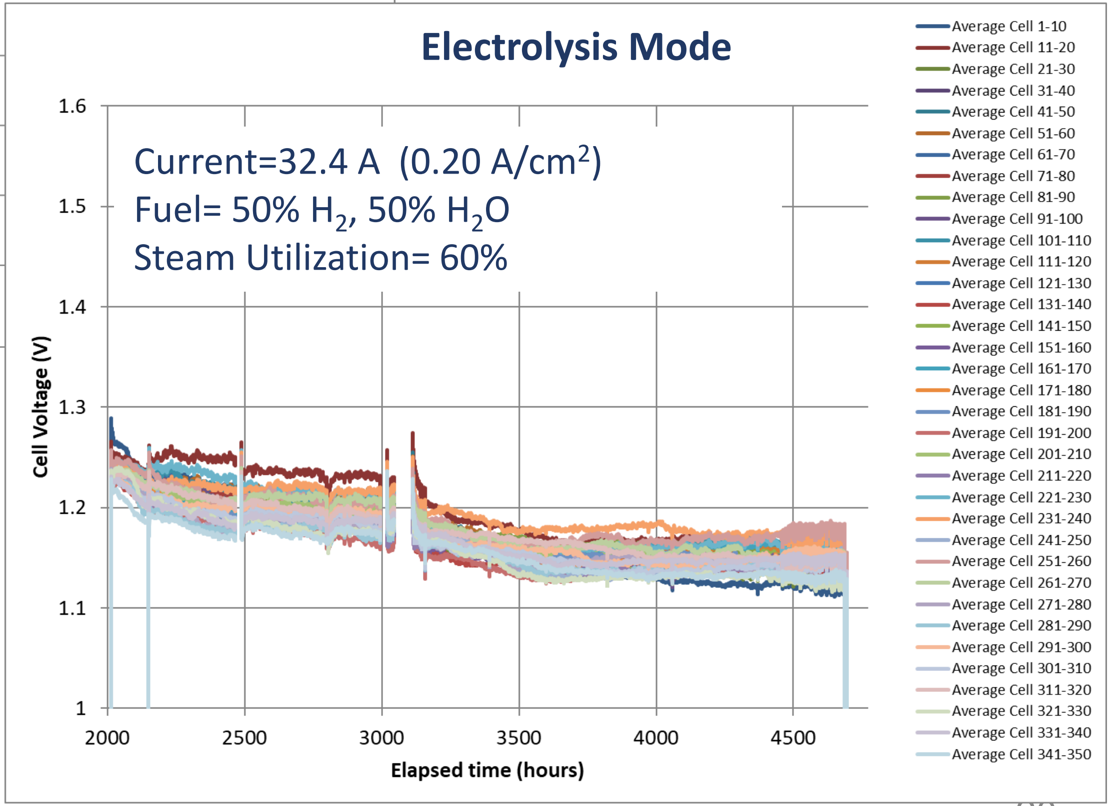


Robotic QC / Stacking Station

Expansion to 1 MW/year CSA Stack Production

Recent Full Height Stack Test

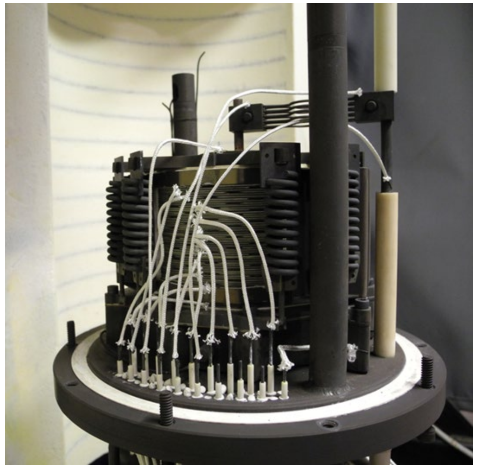




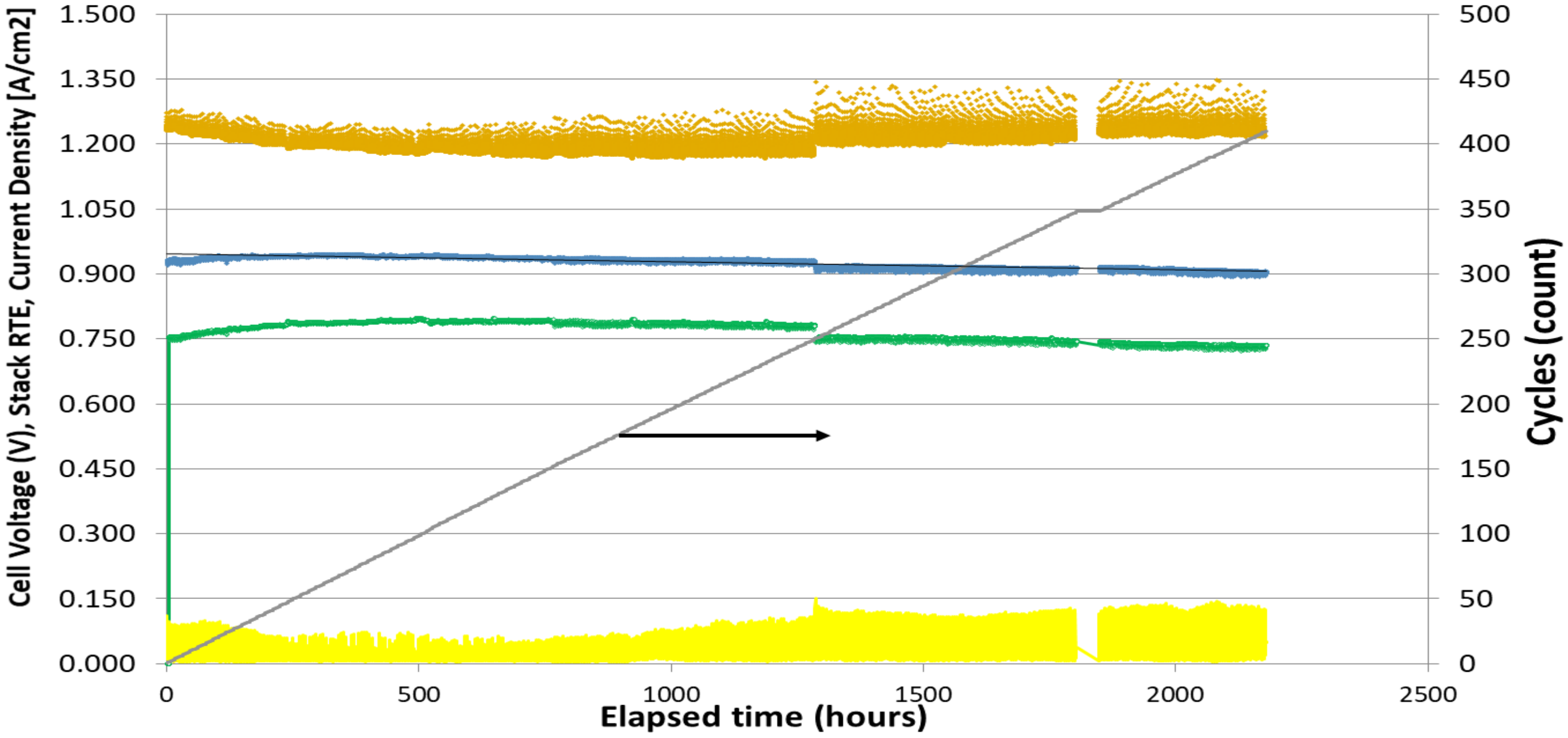
GT060081-0004

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

50-Cell CSA Stack Test Results



50-cell CSA stack (DE-EE0008847)



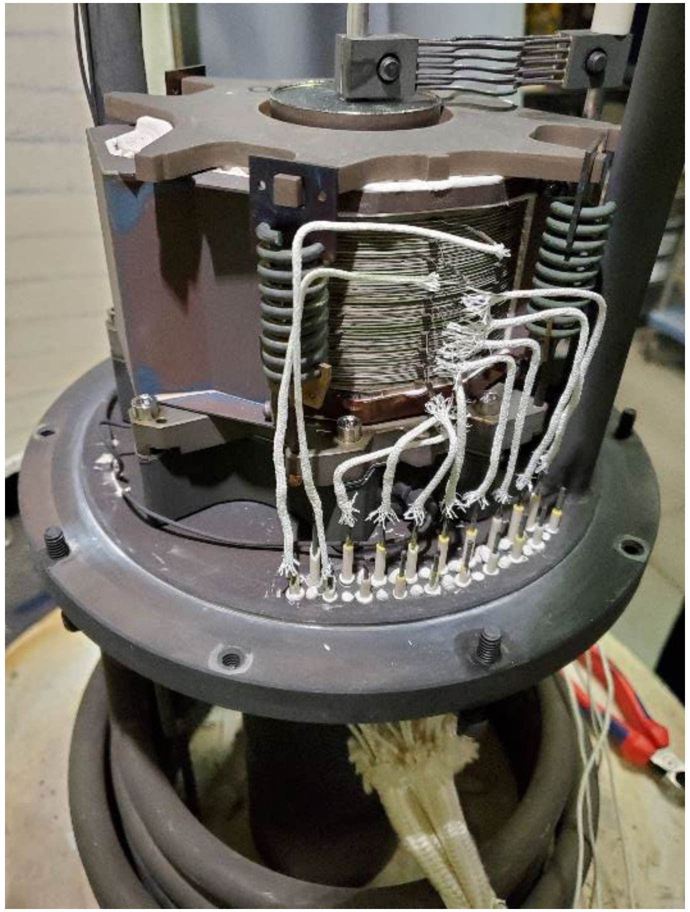
Test Parameters

	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
H2/Steam Concentrations	~100%/0% (approx.)	22%/78%

- Completed 410 cycles overall in >2180 hours of operation
- Achieved a peak stack Round Trip Efficiency (RTE) of 80%

New 45-Cell Stack Fabrication

- 45 cell RSOFC stack GT060248-0032

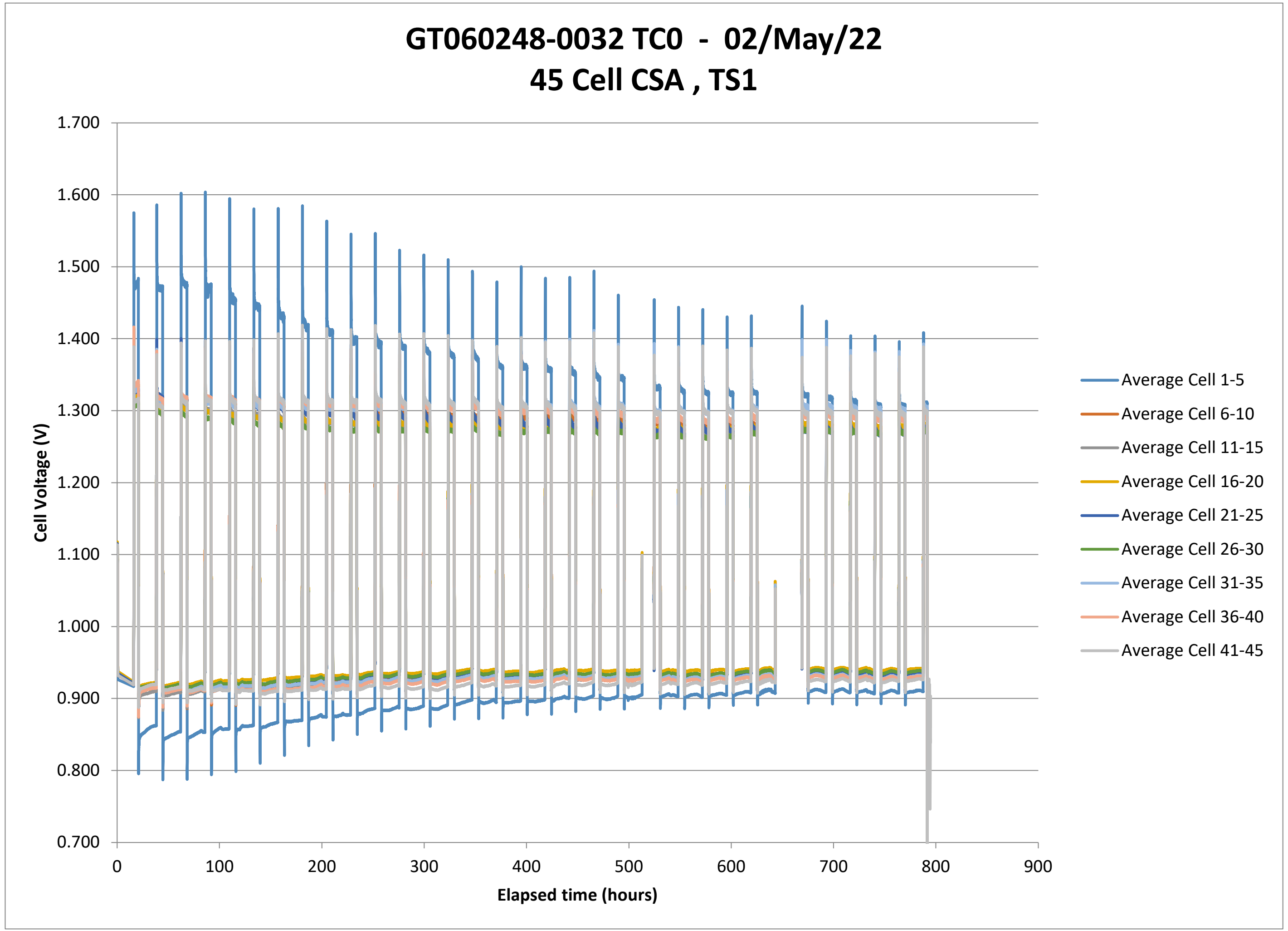


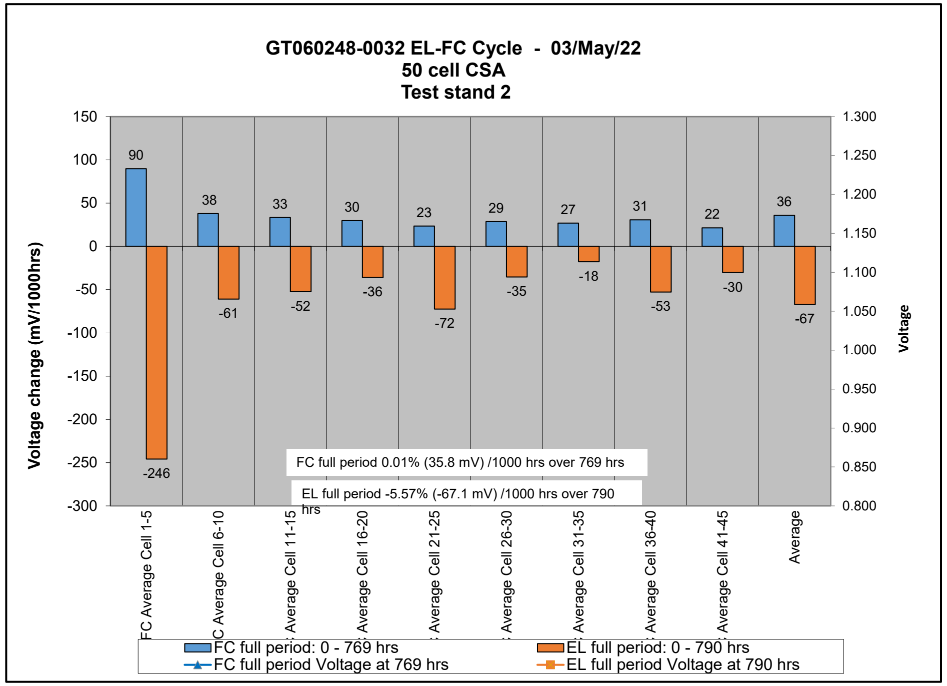
Cyclic Operating Conditions

	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

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

RSOFC Pilot System Demonstration

FuelCell Energy

Pilot System Demonstration

- FCE has built and operated a brass-board >4 kgH_2/day SOEC system under a DOE/EERE project (DE-EE0007646)
- The pilot unit has the key balance-of-plant equipment similar to a commercial plant and is utilized to study the performance of SOEC stacks

Parameter	Value
Cell Voltage	1.285 V/cell
Current Density	Up to 1 A/cm^2
Operating Temperature	700-750°C
Operating Pressure	Up to 8.6 Bara (60 PSIG)
Flush Gas Inlet	Air
Flush Exhaust Composition	60% N_2, 40% O_2
Inlet Composition	50% H_2, 50% Steam
Steam Utilization, stack	60%
Steam Utilization, system	88%

Nominal system operating conditions selected to achieve project objectives for efficiency with acceptable stack life

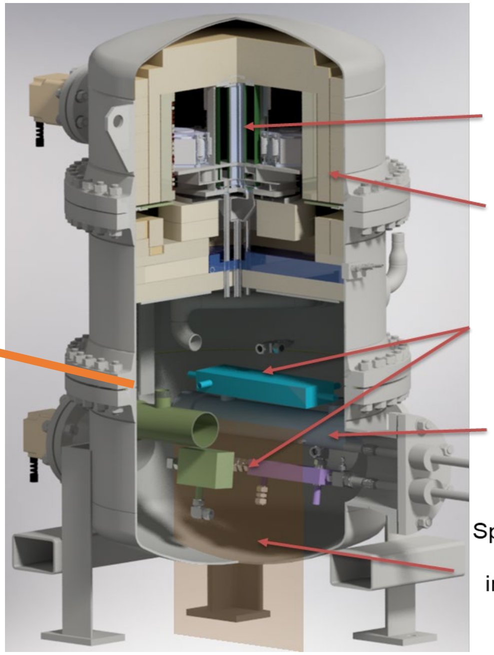
System Parameter	Performance
Stack Electrical Eff (HHV)[1]	115.2%
System Electrical Eff (HHV)[1]	107.4%
System Total Eff (HHV)[1]	92.2%
Electricity Consumption [2]	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption[1]	42.7 kWh/kg

[1] Based on 98% rectifier efficiency, other BoP efficiency also included (motor efficiency, etc)

[2] Total electrical consumption includes stack, BoP, and high temperature thermal input

Pilot System Demonstration Key Features

SOEC Electrolyzer System



SOEC Electrolyzer Module

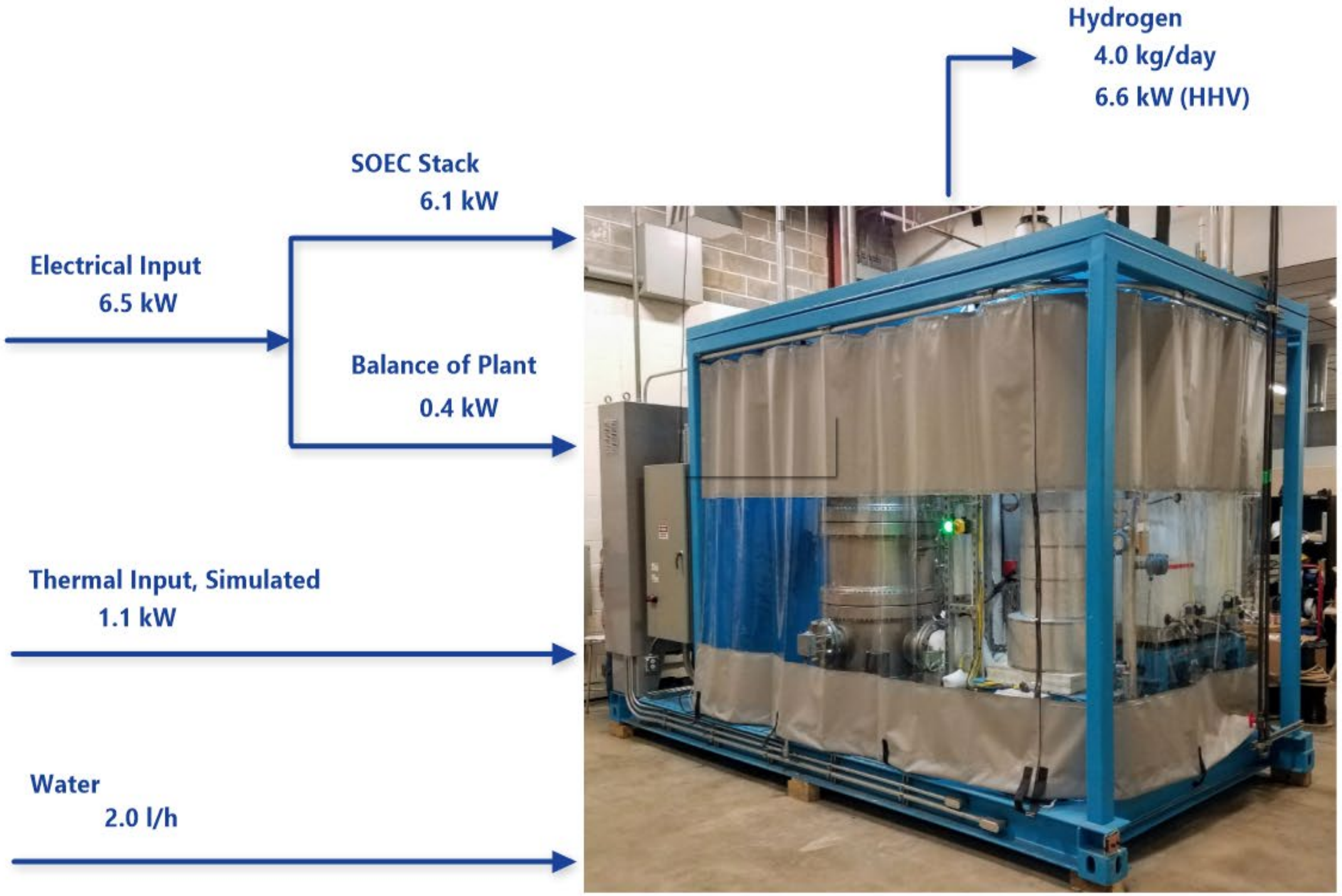
Mid Size CSA Stack

Stack Module Assembled

- SOEC Electrolyzer Module:
  - 125 psig (8.6 barg) max design pressure
  - Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
  - Enclosure 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

FuelCell Energy

4kg H_2/day Pilot System Performance (DE-EE0007646)



System Performance Parameter	Value
Stack Electrical Efficiency (HHV)	110.2 %
System Electrical Efficiency (HHV)	100.7 %
System Total Efficiency (HHV)	86.4 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.6 kWh/kg

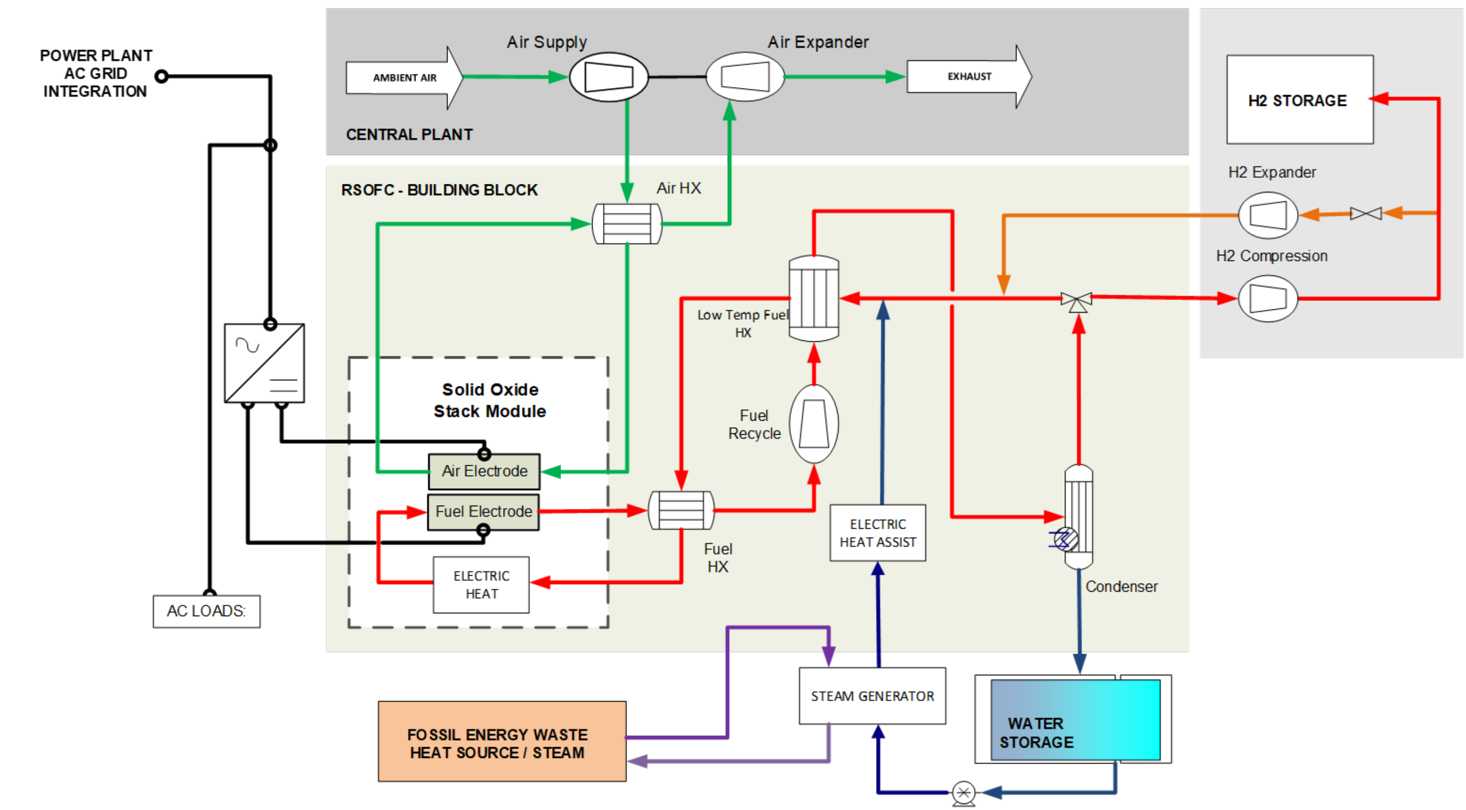
Solid Oxide Electrolysis Pilot System Demonstrated High Efficiency for H_2 Production

SOEC Pilot System Upgrade to RSOFC Operation

- The existing Solid Oxide Electrolysis Pilot System has been upgraded to RSOFC energy storage operation with capacity of up to 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

FuelCell Energy

RSOFC System Performance Targets

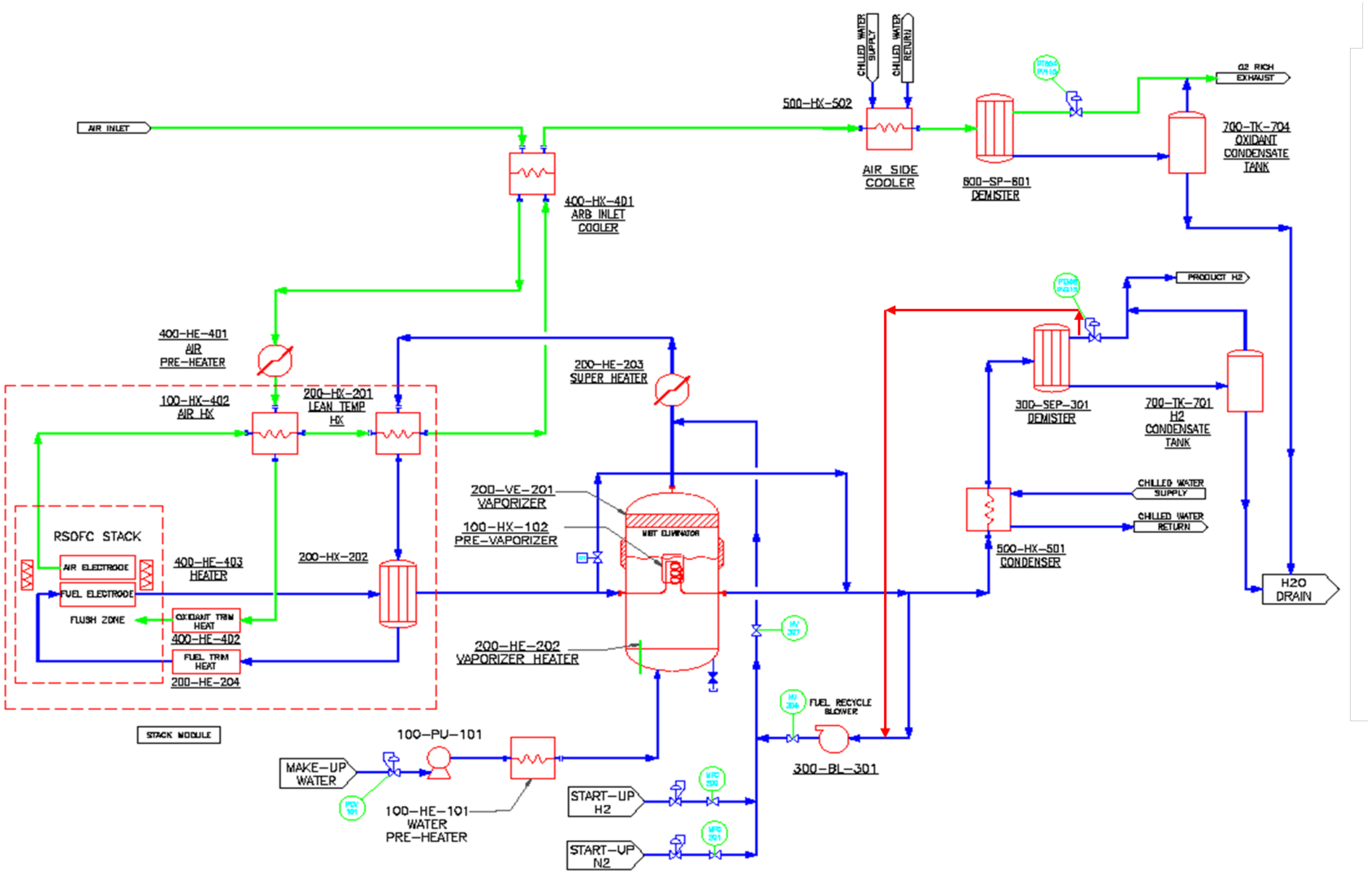


Charge Mode (SOEC) - with Thermal Input					
AC In	4,388	kW	Water Flow	1022	kg/h
Voltage	1,250	mV/cell	Air Flow	842	kg/h
Current density	670	mA/cm^2	H2 Produced	114	kg/h
Charge Duration	**6**	**h**	H2 Produced	686	kg
AC Energy In	26,328	kW-h	Water Consumed	6129	kg
Thermal Energy In	2,675	kW-h	HHV Eff. Elec Only	102.6	%
H2 Energy Out - HHV	27,014	kW-h	HHV Eff. Elec+Therm	93.1	%

Discharge Mode (SOFC)					
H2 Flow	38	kg/h	Net AC Power	1,016	kW
Air Flow	2,000	kg/h	Voltage	1,012	mV/cell
H2O Produced	341	kg/h	Current density	221	mA/cm^2
Discharge Duration	**18**	**h**	Water Produced	6129	kg
H2 Energy In - HHV	27,014	kW-h	Water Consumed	686	kg
AC Energy Out	18,297	kW-h	HHV Eff. Elec Only	67.7	%
			RTE	69.5	%

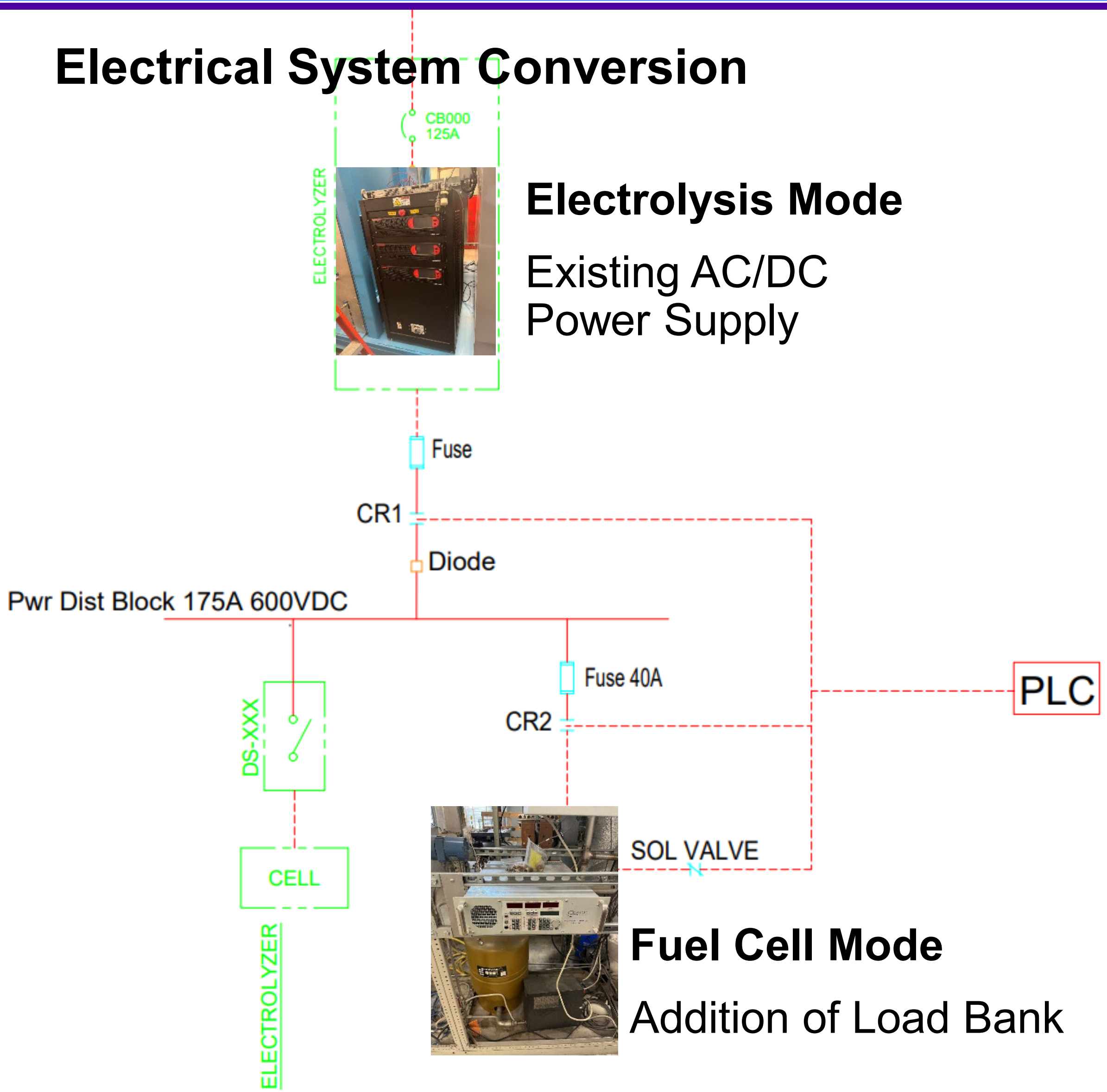
Updated Pilot Demonstration System Process Flow Diagram (PFD)

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



Electrical Equipment Upgrade

Electrical System Conversion

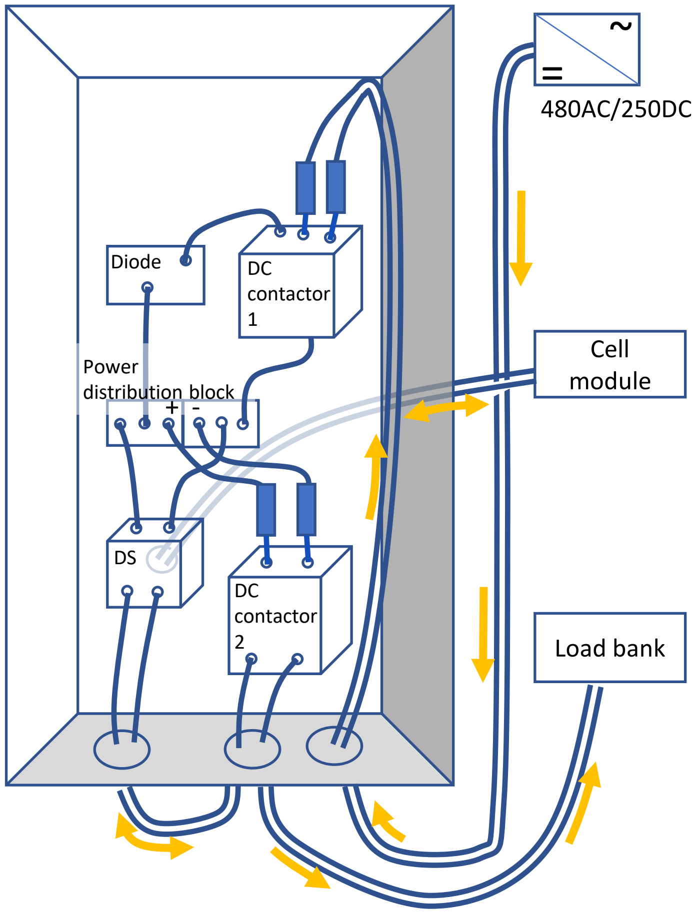


Electrolysis Mode

Existing AC/DC Power Supply

Fuel Cell Mode

Addition of Load Bank

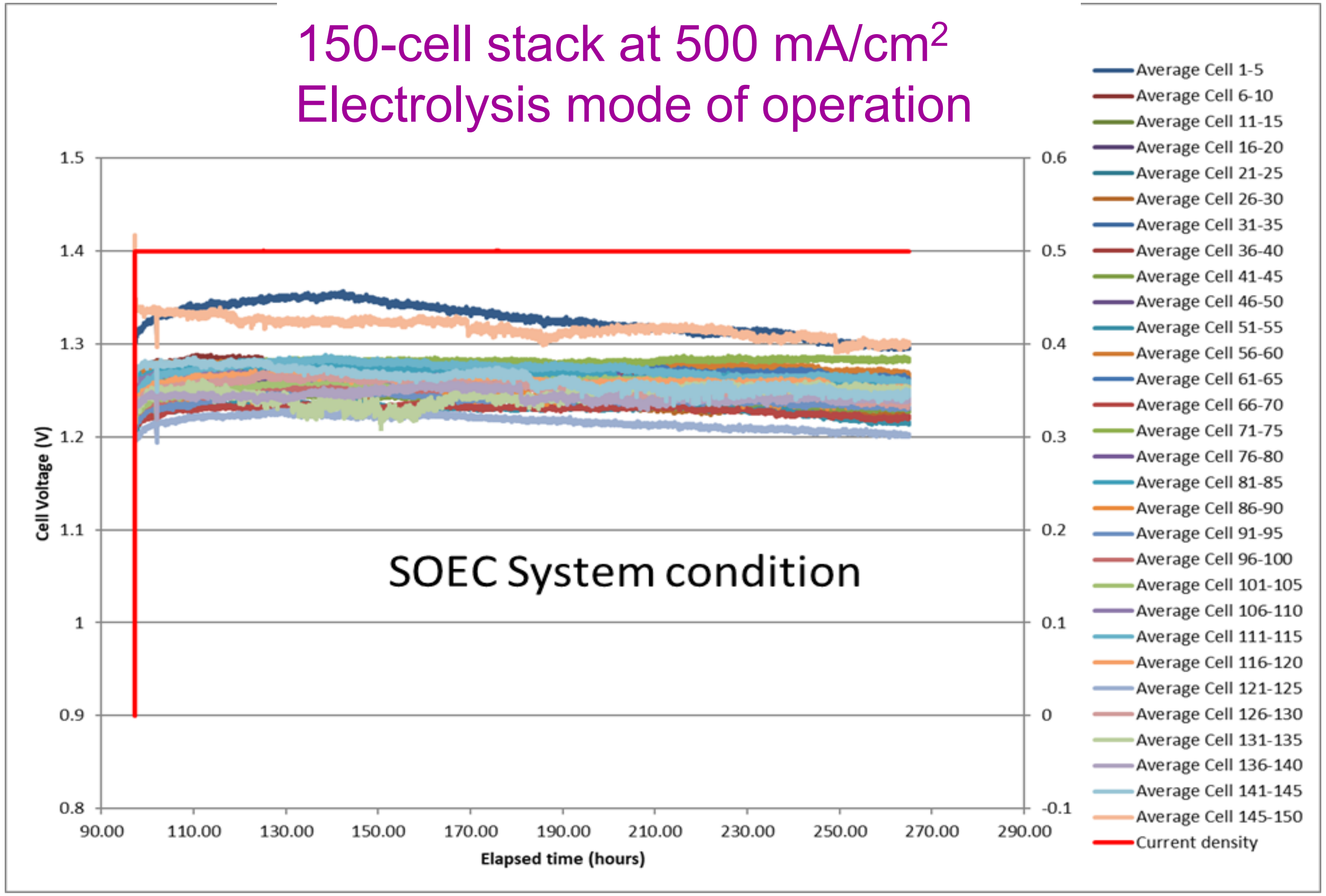


Electric Panel Modification

150-Cell Stack for RSOFC System Demonstration

150-cell stack (GT60247-0005)

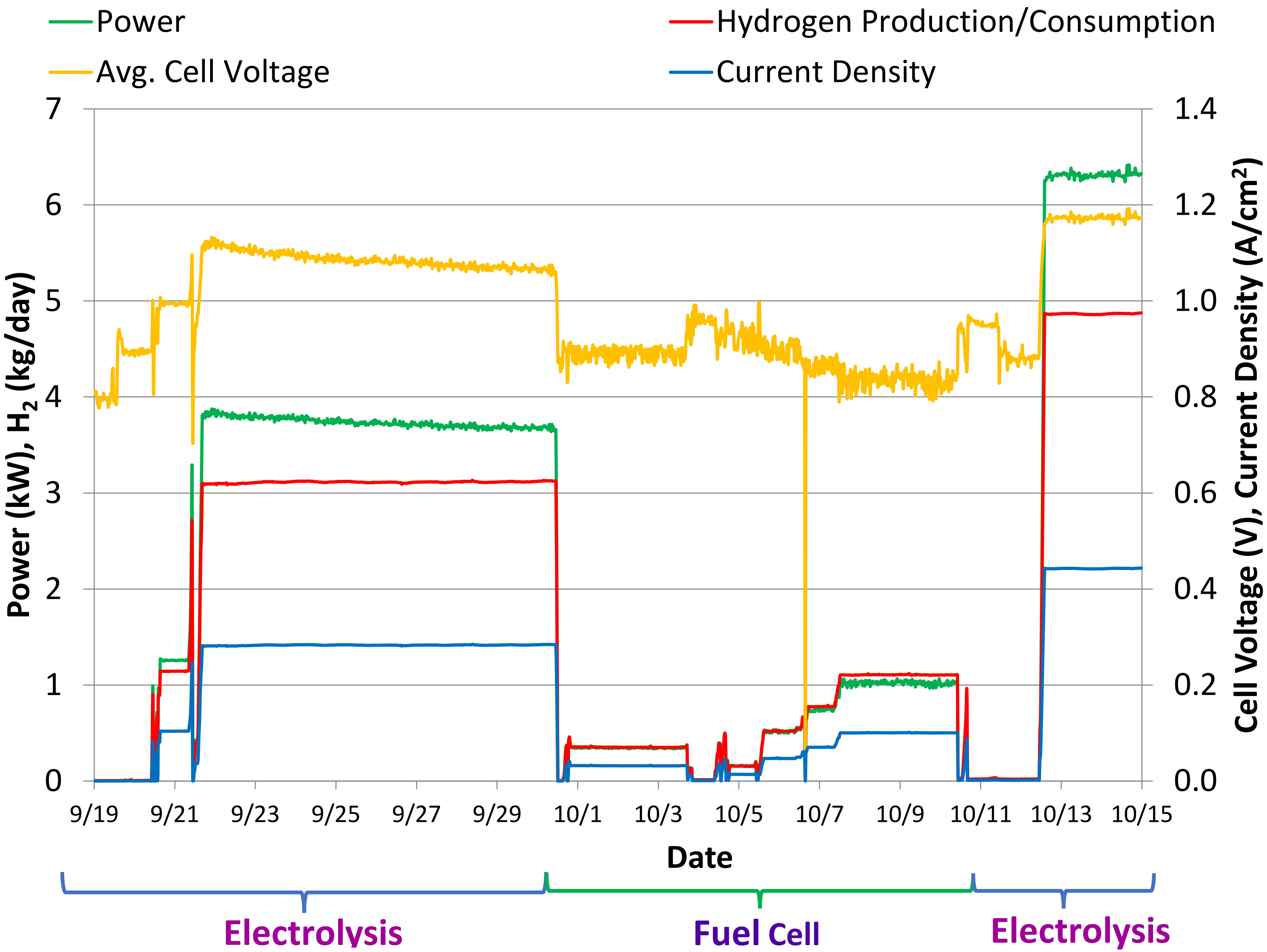
- 150-cell stack was tested in electrolysis mode in the Pilot RSOEC System



- 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%

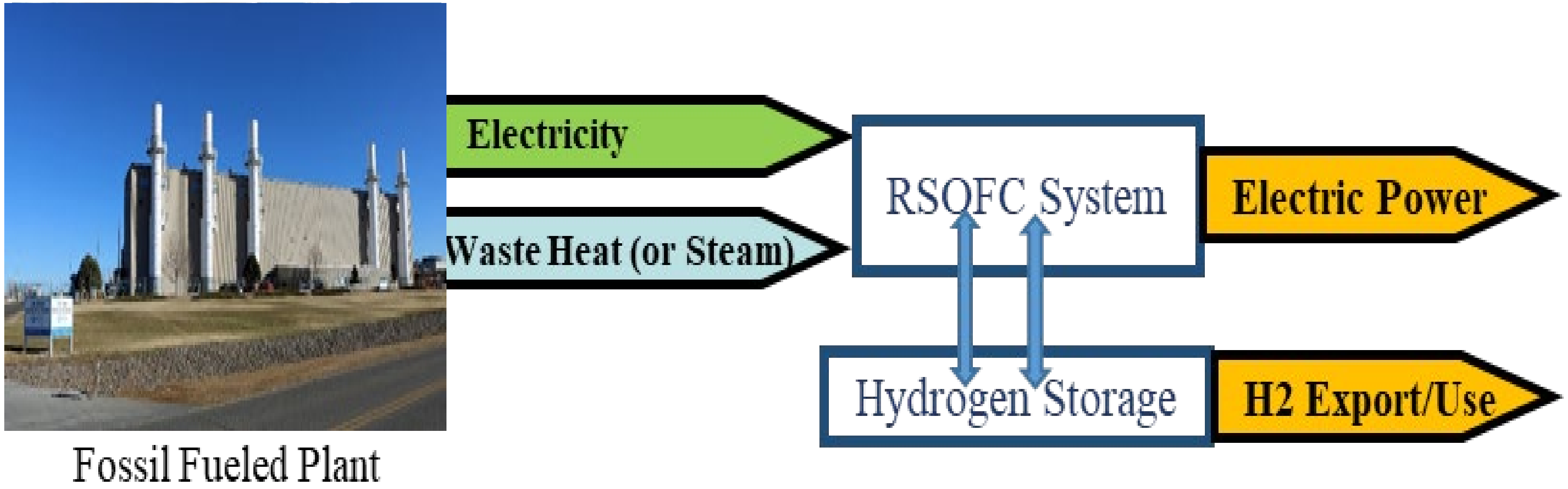
FuelCell Energy

Preliminary Pilot System Commissioning Tests



Technoeconomic Analysis

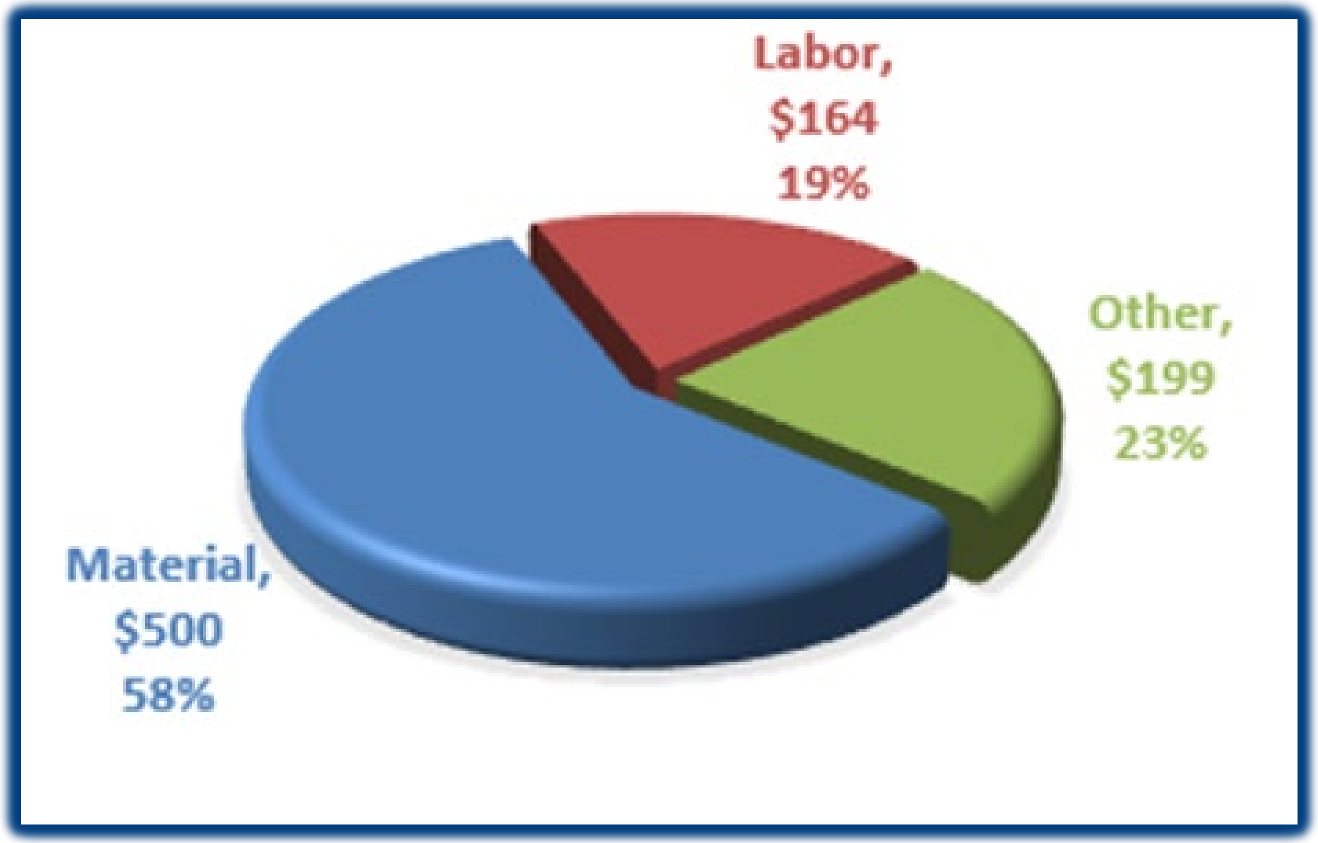
RSOFC Integrated with Fossil Fueled Powerplants



- RSOFC energy storage systems for integration with fossil fueled Electricity Generating Units (EGUs) was investigated (DE-FE0032032)
  - Increased operating flexibility and profitability as well as life extension of the EGU capital assets through energy storage and/or H_2 generation

Giga Factory Stack Cost Breakdown

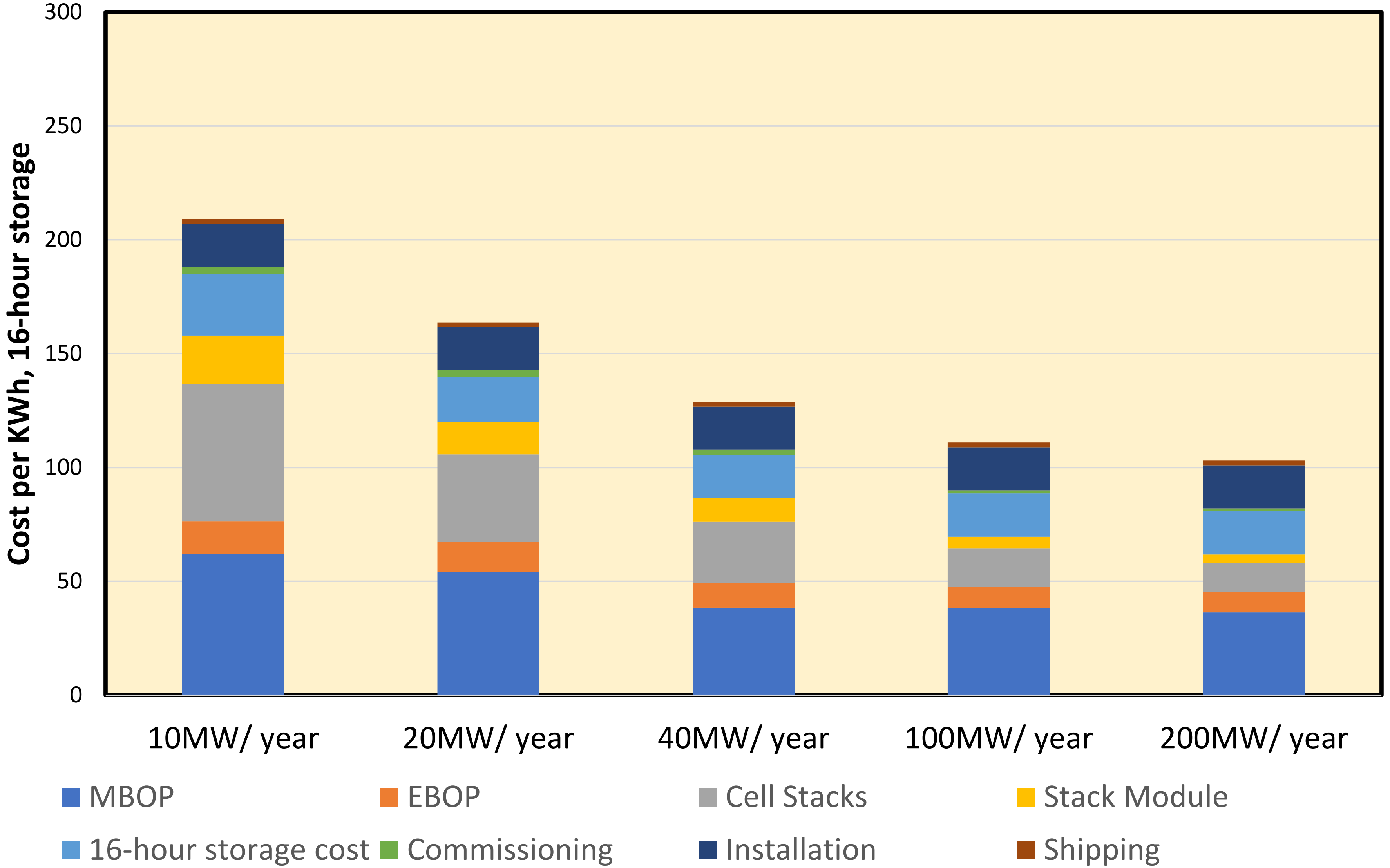
Yr2019 CSA-SOFC Stack Factory Cost Estimate for 1 GW Stacks per Year



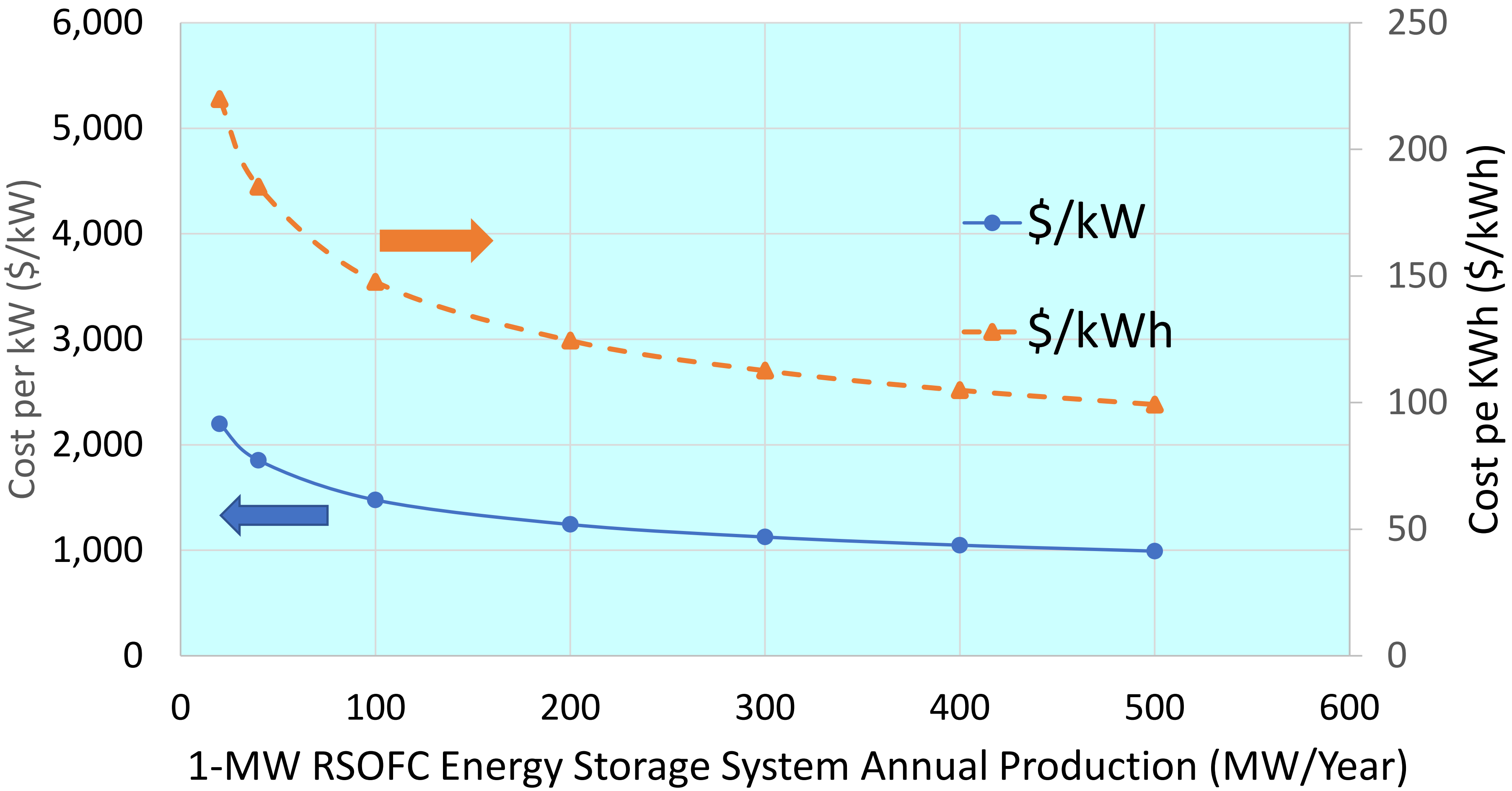
$ 863 / stack (~$130/kWdc output) at 160,000 stacks/year

FuelCell Energy

RSOFC Cost vs Production Volume



Cost of Commercial Units Per KWhr



Wrap-up

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

Acknowledgement:
Support and Management under DOE/NETL Projects DE-FE0031974 & DE-FE0032032

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Our purpose:

Enable the world to be empowered by clean energy