Performance Improvements for Reversible Solid Oxide Fuel Cell Systems

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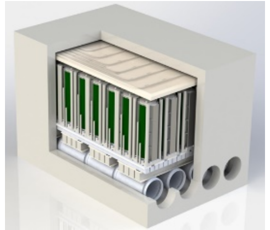
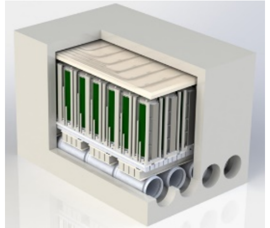
Solid Oxide Applications

SOFC Stack
7 kW DC Power Generation
36 kW DC / 25 kg H_2/day electrolysis
350 cells, 17” height

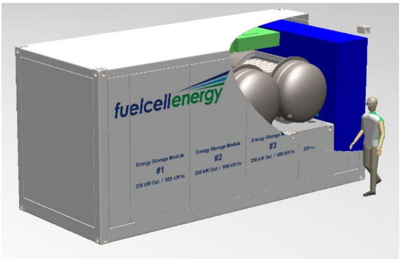


Power Generation Stack Module – Only runs in power generation mode on natural gas fuel

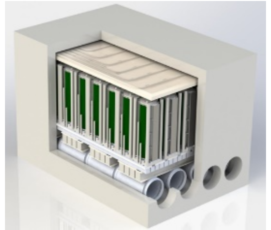
Power Generation System



Electrolysis Stack Module – Produces hydrogen from steam with power input



Electrolysis
4,000 kg/day H2 from 7.3MW



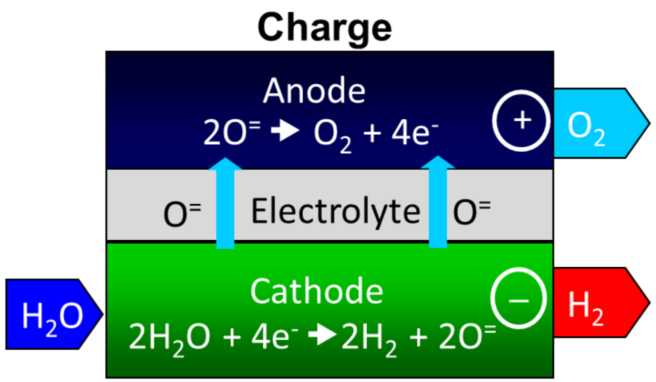
Energy Storage Stack Module – Alternates between power generation on hydrogen fuel and electrolysis producing hydrogen from water

Energy Storage System
1MW, 10 MWh

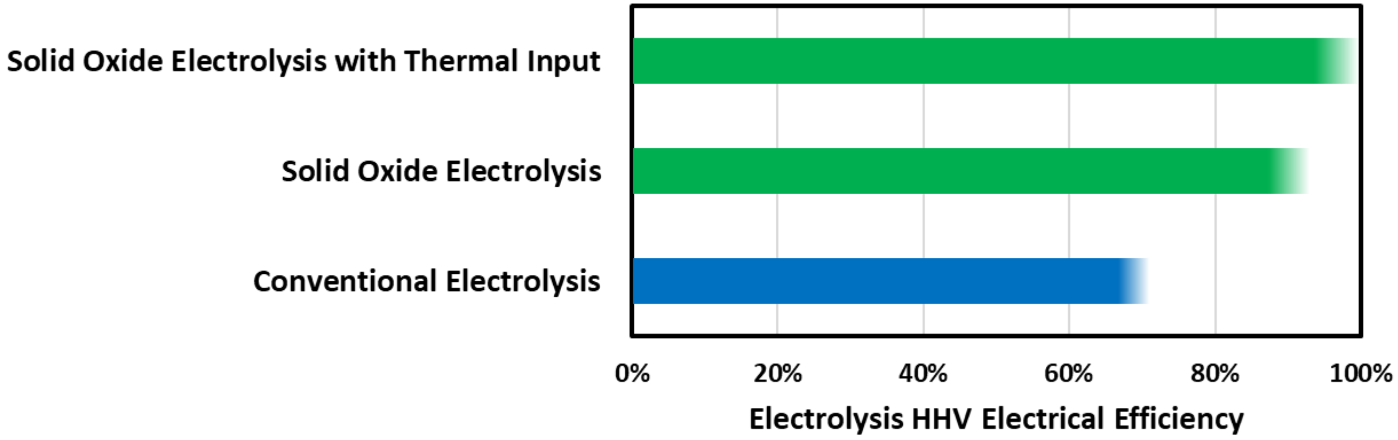
Versatile platform with multiple commercialization paths

Solid Oxide Electrolysis

- Comparison to the conventional low temperature electrolysis:
  - **High current density, low weight stacks** = lower stack cost needed for given hydrogen production rate
  - **Low electrolysis voltage** = less power needed for given electrolysis rate: **Higher Electrical Efficiency**
  - Lower stack hardware requirement and lower power requirement = **30 to 50% lower cost per kg for hydrogen depending on power cost**
- Solid Oxide Electrolysis Cells (SOEC) are **more than 100% electrically efficient (HHV Basis)** and can use thermal energy input to maintain temperature
  - Provides opportunities for **waste heat utilization in hydrogen production**
  - Allows high round trip energy efficiency in **energy storage systems** with thermal energy storage



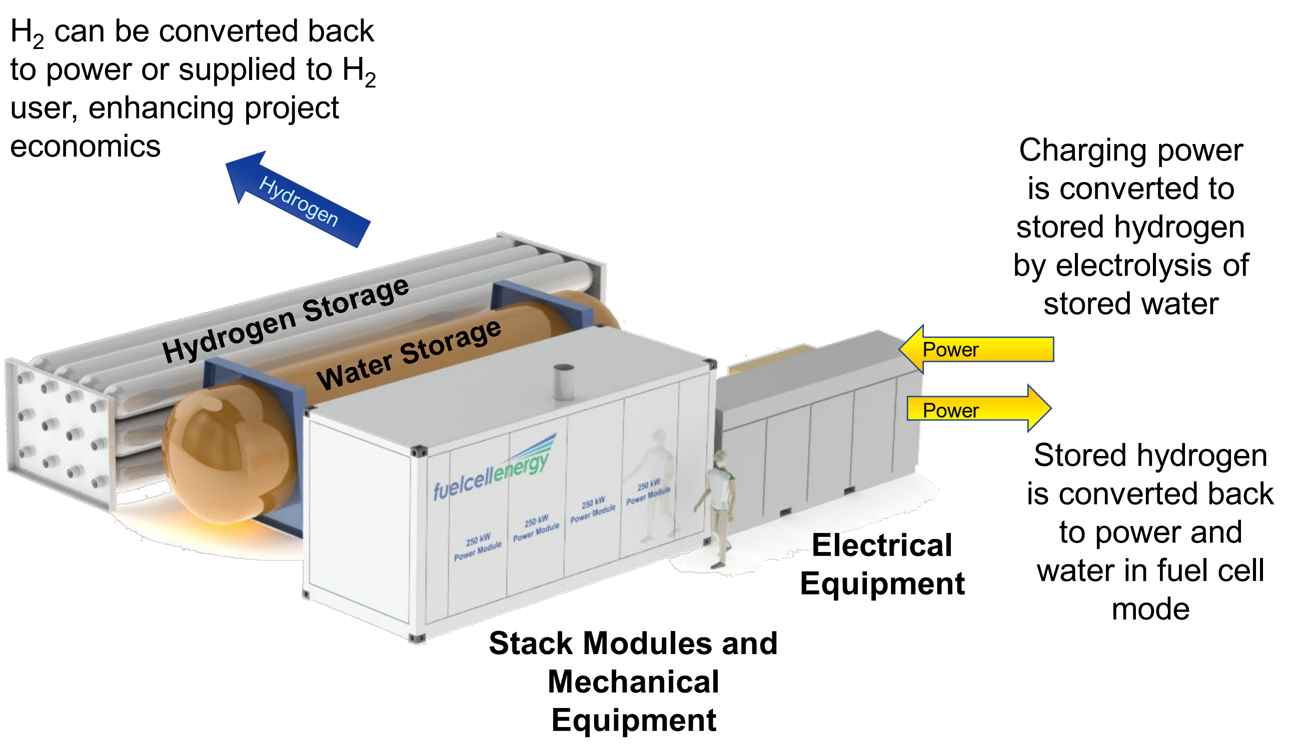
Electrolysis Mode



High hydrogen production electrical efficiency can be increased further with use of waste heat

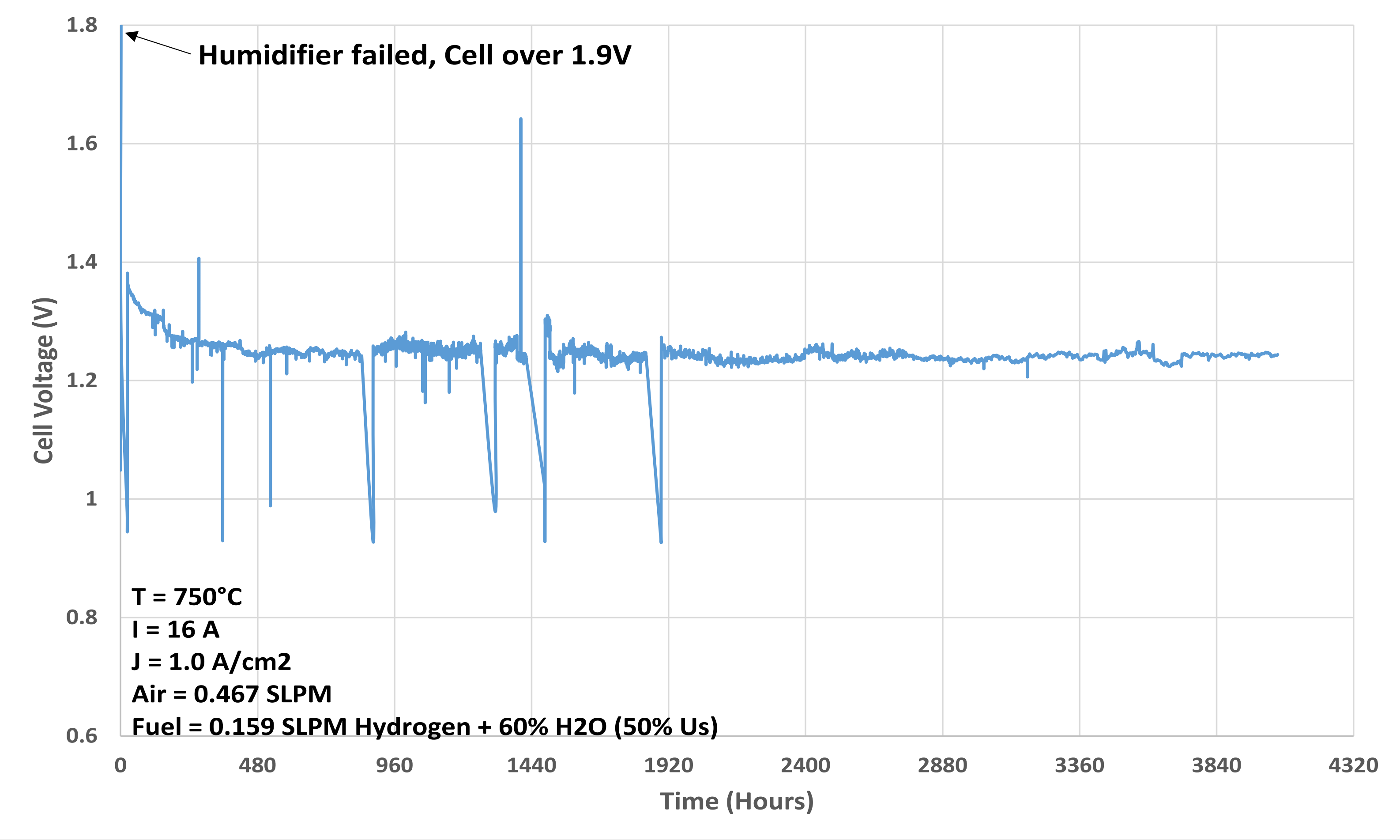
Solid Oxide - Hydrogen Based Long Duration Energy Storage System

- Hydrogen during charge cycle can be used to provide power during discharge cycle or can be exported to hydrogen user
- Expected round trip efficiency of ~70%
- Geological storage of hydrogen can provide weekly or seasonal storage
- 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
- Waste heat from Electric Generating Units can be utilized to produce excess hydrogen
  - A newly selected project with EPRI as part of the team will focus on pre-feed engineering of a 10 MWhr energy storage unit for application in a fossil-fueled power plant with an option to produce excess hydrogen for export

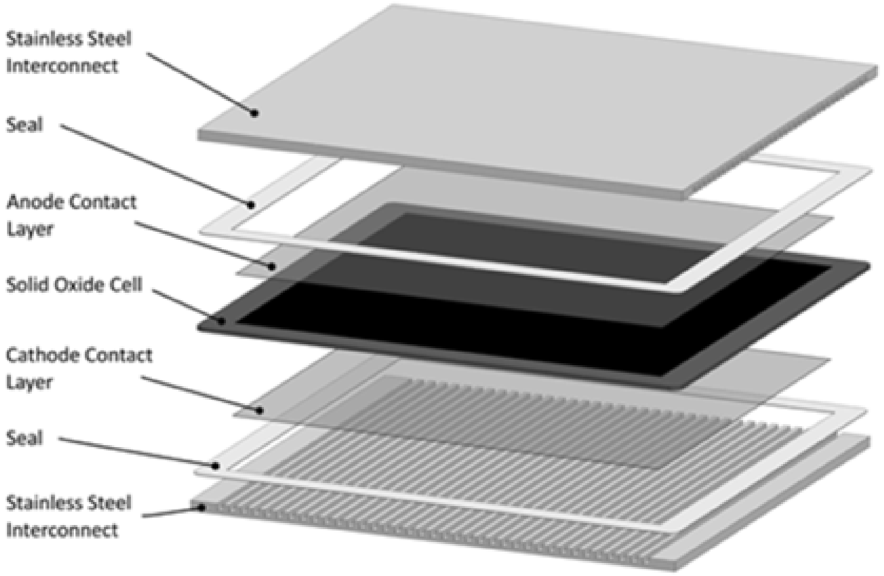


- Commercial MW-scale RSOFC Cost Targets :
  - Capital Cost - Power $1000/kW
  - Capital Cost - Energy $150/kW-h
  - Levelized Cycle Cost $0.05/kWh-cycle

Long-Term Stability of Cell Operation in Electrolysis Mode



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

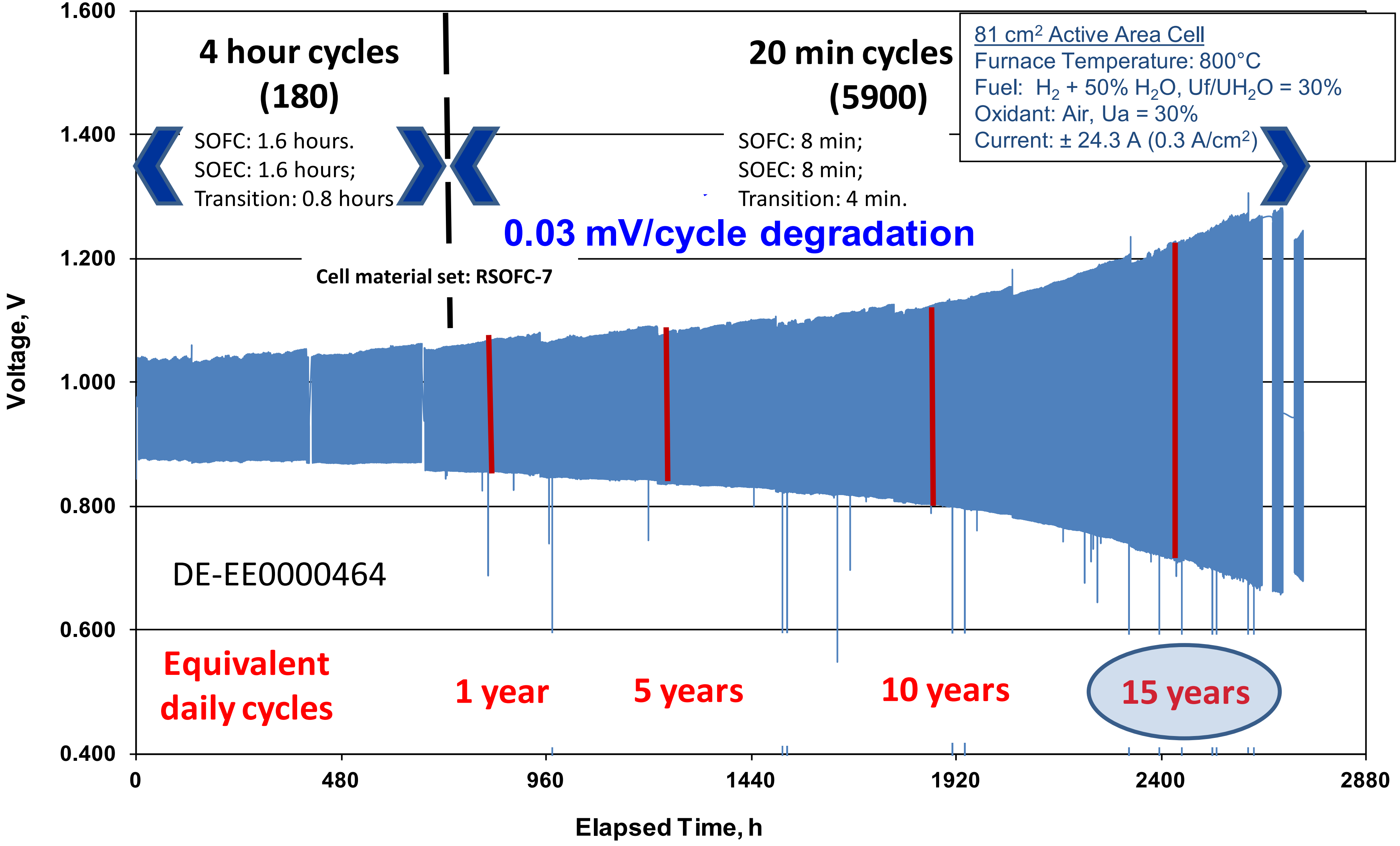


16 cm^2 cell configuration consisting of stack features:

- cross-flow pattern
- flow fields
- electrode contact layers
- glass seals

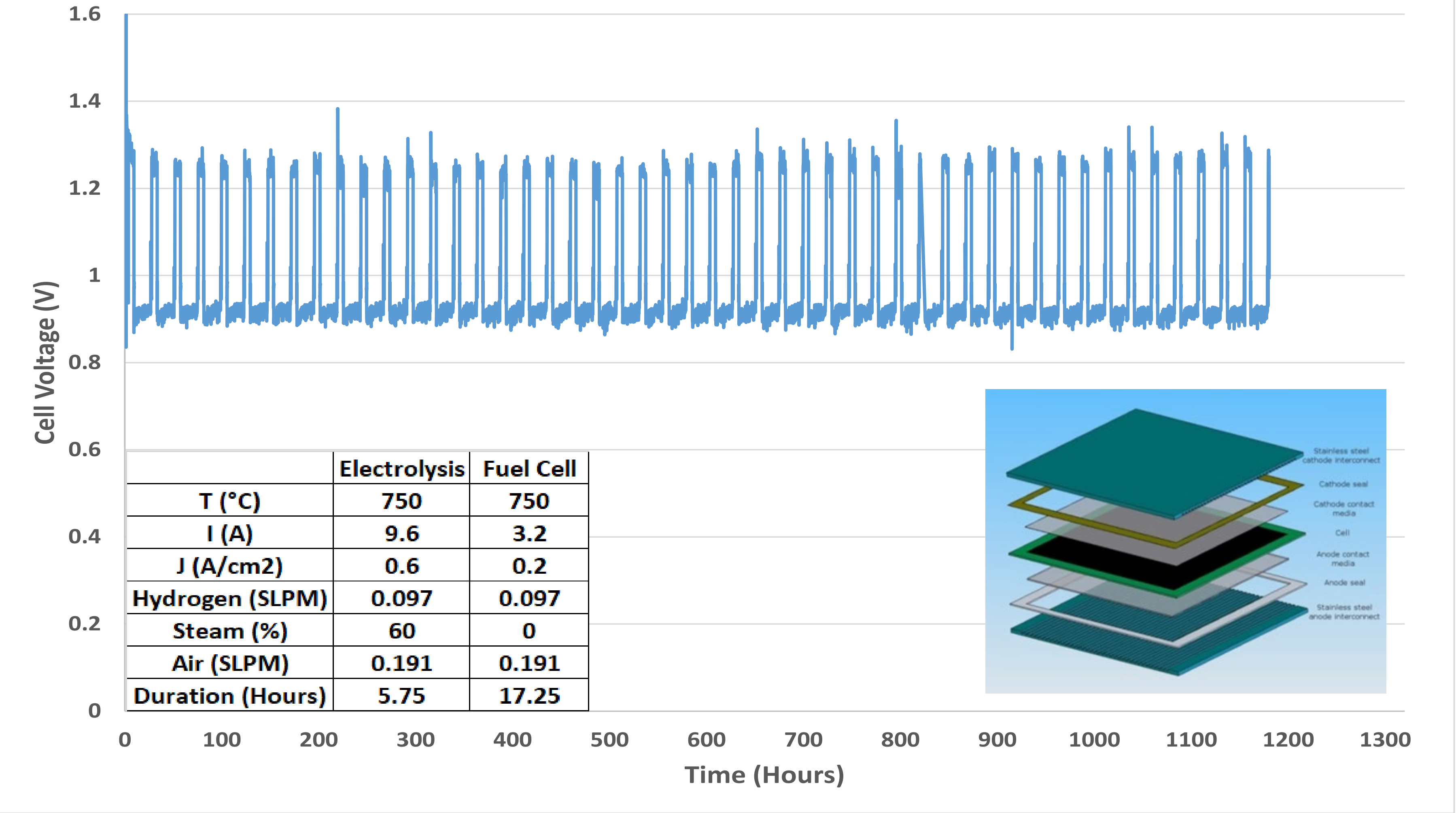
Negligible cell degradation after the initial stabilization period

Accelerated Cycling (6,080 Cycles)



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

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 cm² cell at ambient pressure (46 SOEC/SOFC cycles over 1,104 hours)

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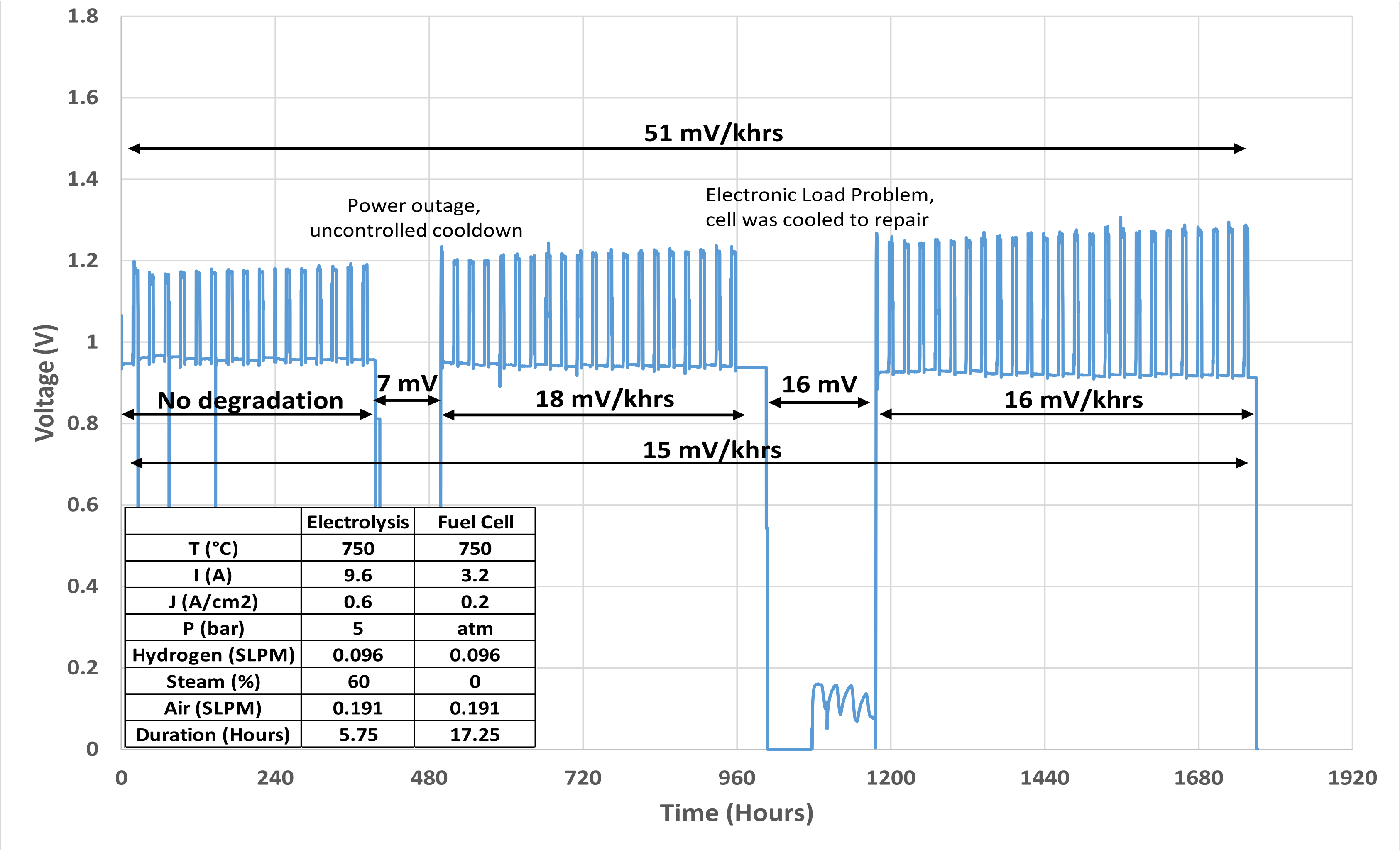
Single Cell in Reversible Operation (Pressurized Electrolysis Mode)



	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 a 16 cm^2 cell at 5 bar for electrolysis and ambient pressure for fuel cell operation (59 SOEC/SOFC cycles)

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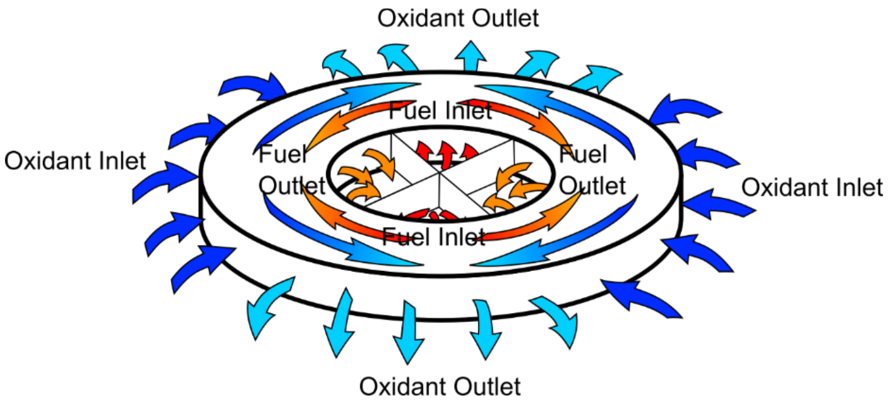
Compact SOFC Architecture (CSA) Stack Platform

Cell with active area of 81 cm^2

Standardized Stacks in three sizes

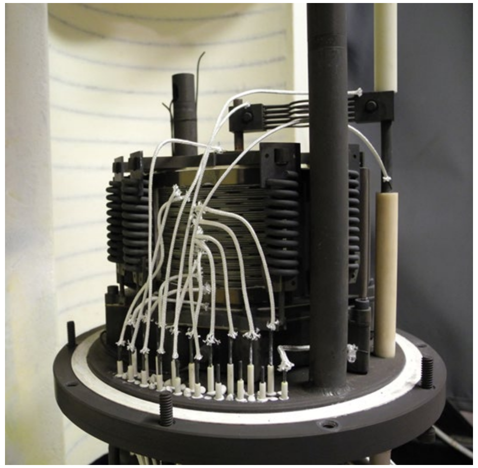


Flow Geometry

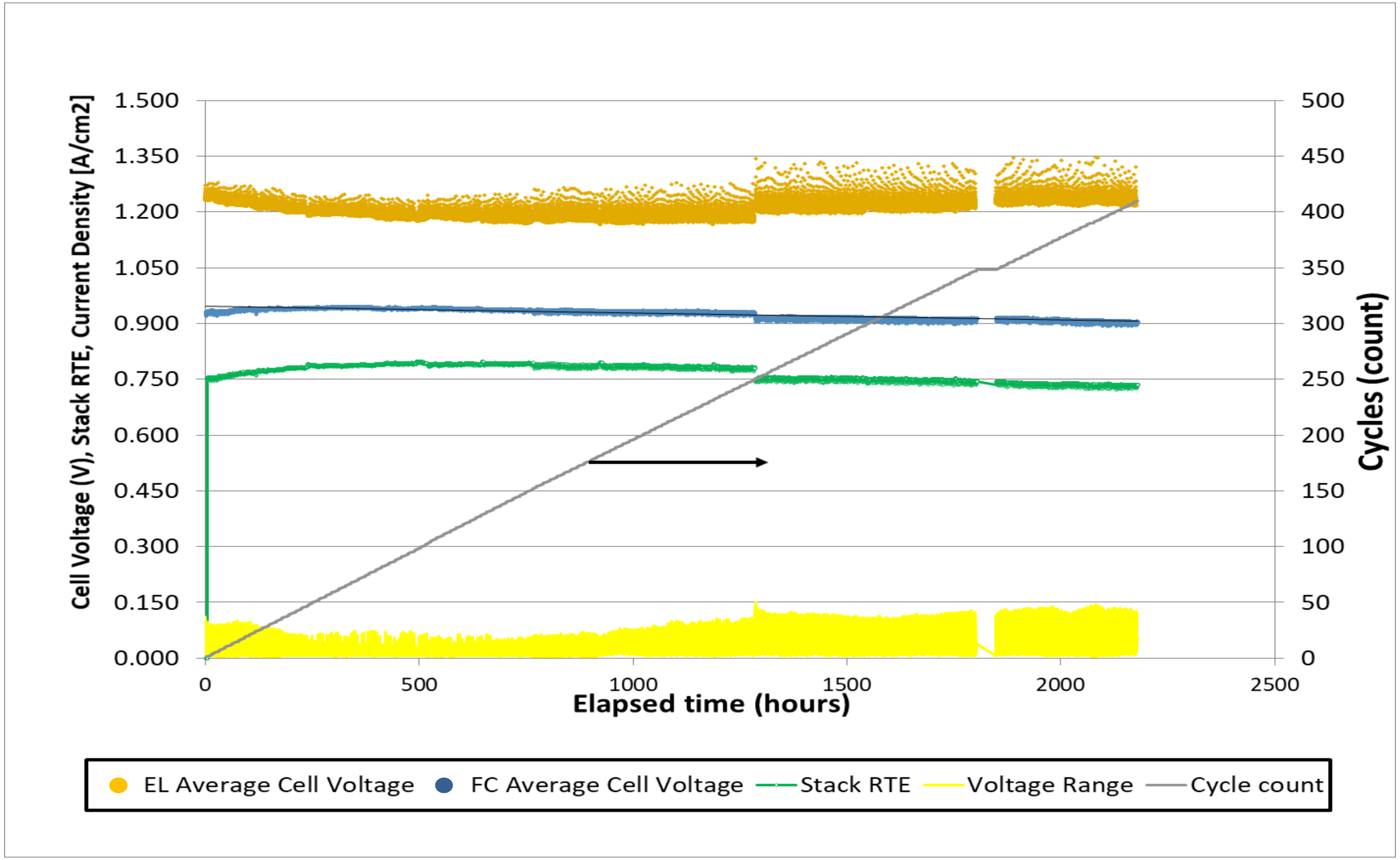
Property	Scale			Comments
	Short	Mid	Full	
Cell count	45	150	350	Nominal count
Fuel Cell Voltage, V	43	143	333	At 0.950 V/cell
Electrolysis Voltage, V	58	192	448	At 1.280 V/cell
Stack Efficiency, % LHV	74% / 100%	74% / 100%	74% / 100%	Electrochemical eff FC / EL
Power, kW	0.87 / 2.7	2.8 / 9.3	6.7 / 21.8	At 0.25 / -0.6 A/cm^2
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

50-Cell CSA Stack Test Results (DE-EE0008847)



50-cell CSA stack



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

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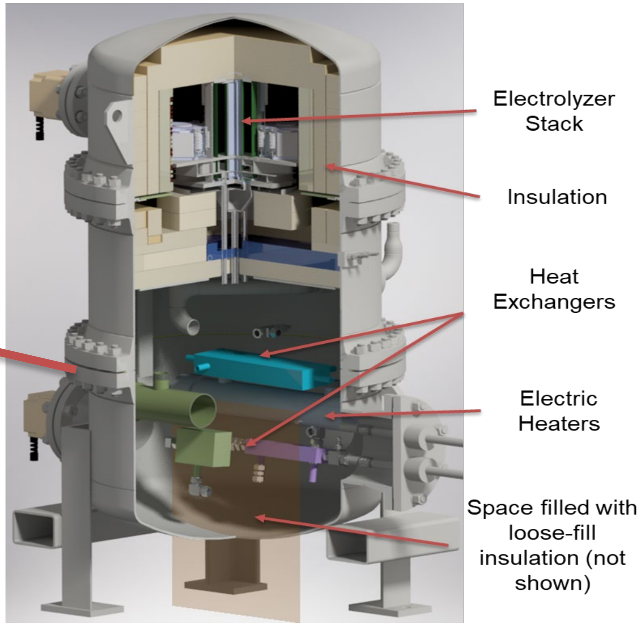
Electrolysis Demonstration Unit (DE-EE0007646)

Power and Controls Cabinet

Vaporizer

SOEC Electrolyzer System



SOEC Electrolyzer Module

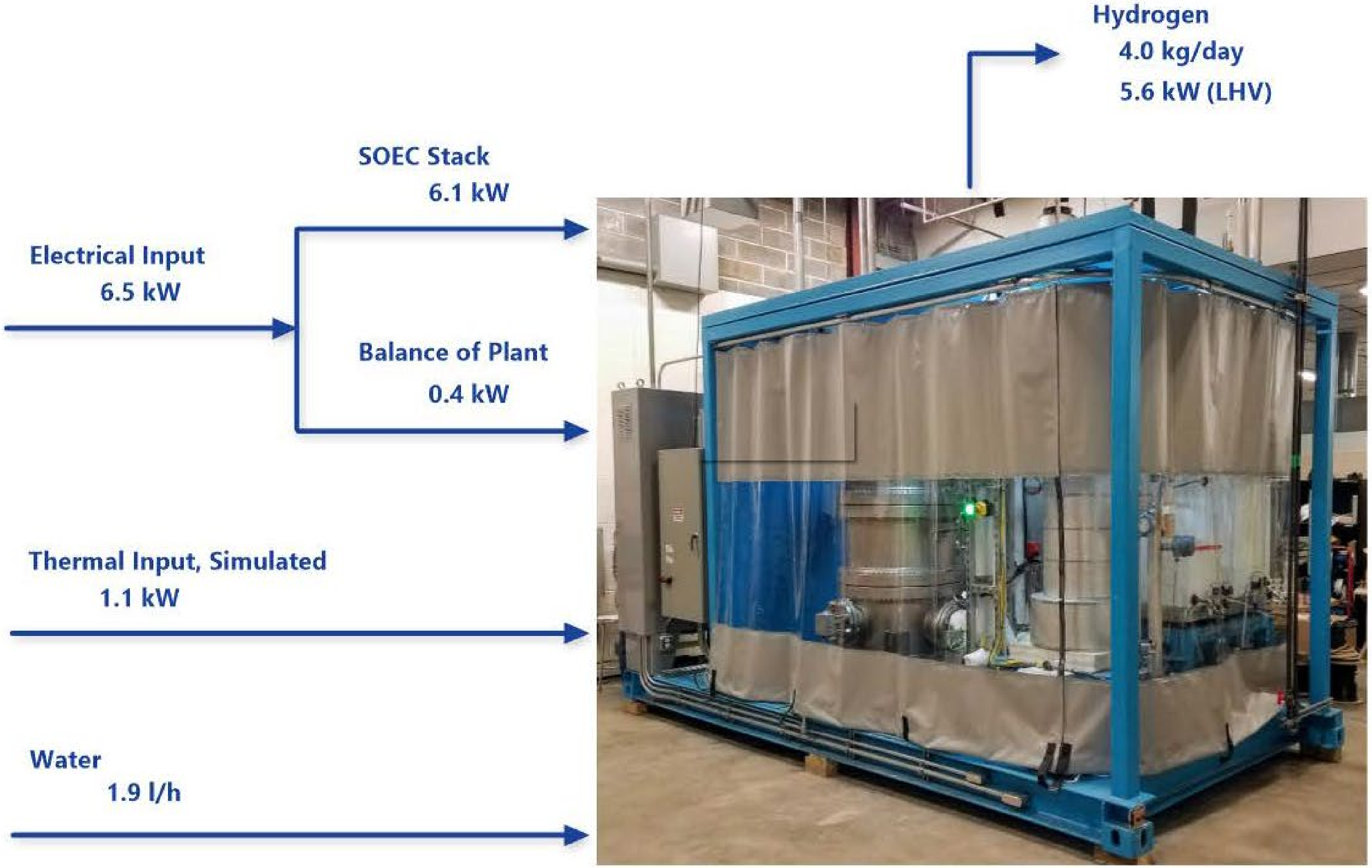
Mid Size CSA Stack

Stack Module Assembled

SOEC Stack Module:

- 125 psig (8.6 barg) 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

4kg H2/day Pilot System Performance



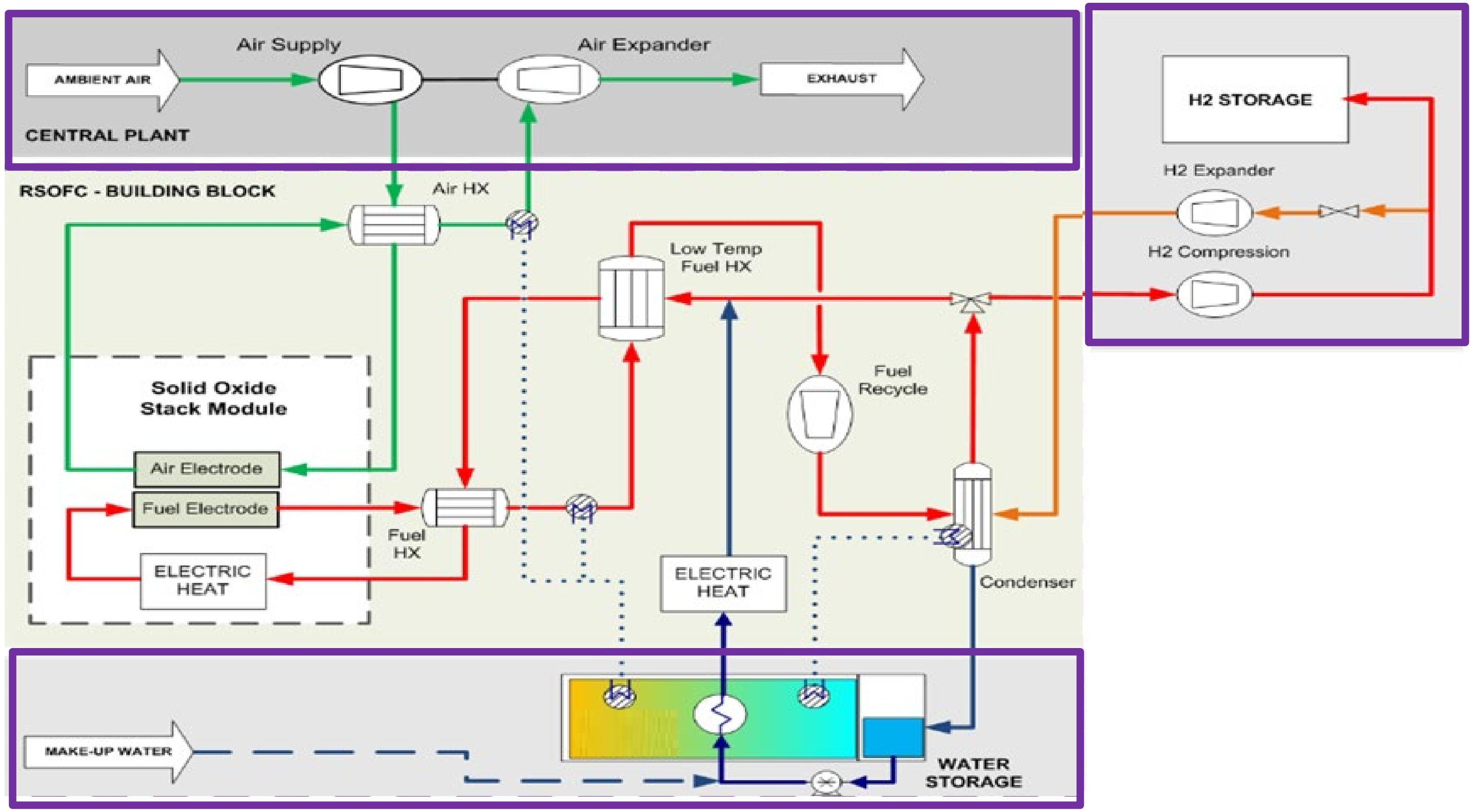
System Performance Parameter	Value
Stack Electrical Efficiency (LHV)	93.1 %
System Electrical Efficiency (LHV)	85.1 %
System Total Efficiency (LHV)	73.0 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.7 kWh/kg

Solid Oxide Electrolysis Pilot System Demonstrated High Efficiency for H_2 Production

RSOFC System Prototype

- Under the newly awarded project from DOE (FE/NETL), DE-FE0031974, the existing Solid Oxide Electrolysis system will be 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

SOEC Pilot System Upgrade to RSOFC Operation



System upgrade includes the following additions (gray shaded areas):

- Water Storage
- H_2 and air compression/expansion equipment
- H_2 Storage
- Incorporation of advanced power conversion technologies

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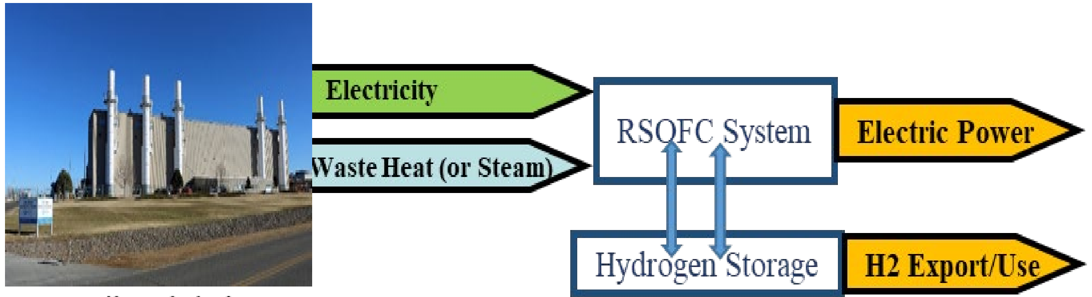
Development of RSOFC Energy Storage Systems (DE-FE0032032)

- Develop reversible solid oxide fuel cell (RSOFC) energy storage systems for integration with fossil fueled Electricity Generating Units (EGUs)
- Increase operating flexibility and profitability as well as life extension of the EGU capital assets through energy storage and/or H2 generation
- Validate high efficiency and low-cost H2 production from RSFOC using electricity and waste heat from fossil fueled EGUs
- Develop conceptual design of a site-specific >10MWh RSOFC energy storage demonstration system and determine its cost and performance



Fossil Fueled Plant

System Performance Characteristics

Electrolysis Mode (Charge)				Fuel Cell Mode (Discharge)		
H2 Production	76.8	kg/hr		H2 Consumption	38.4	kg/hr
Air Flow	33,023	SLPM		Air Flow	67,739	SLPM
Water Intake	11.4	SLPM		RSOFC Stack Power Production	1023	kWdc
RSOFC Stack Power Demand	2577	kWdc		Ney Electric Power Output	948	kWac
Net Electric Power Intake	2662	kWac		System Efficiency (Discharge)	76	%
System Efficiency (Charge)	92	%				
Round Trip Efficiency	**70**	**%**				

RSOFC Demonstration Team

Energy Storage System
1MW, 10 MWh

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FuelCell Energy, Inc. (FCE)
RSOFC System Developer

EPRI

Electric Power Research Institute
Technology-to-Market

AECOM

Technoeconomic

TRI-STATE

Tri-State G&T
Demonstration Site Host

J.M. Shafer Generating Station
Demonstration Site

J.M. Shafer Generating Station, Fort Lupton, CO

Thank You

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