Progress in SOFC Technology Development at FuelCell Energy

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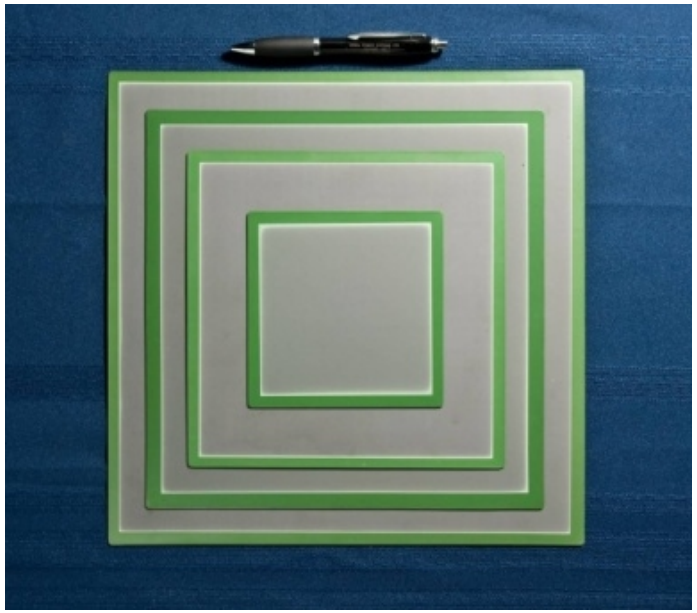
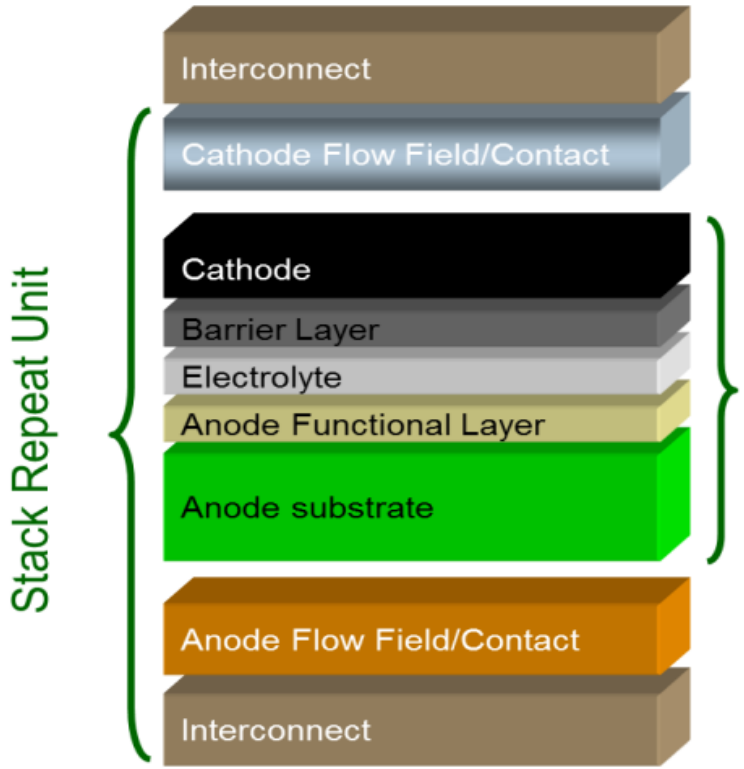
2021 SOFC Project Review Meeting
November 16, 2021

Solid Oxide Fuel Cell Technology Overview

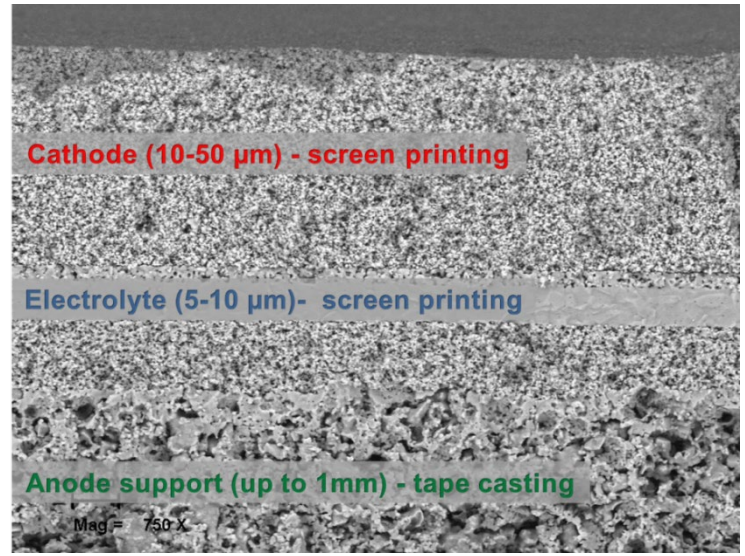


Anode-Supported Solid Oxide Fuel Cell

- Cell scale up to 1000 cm^2 active area



Solid Oxide Fuel Cell Structure



Component	Materials	Thickness	Porosity	Process
Anode	Ni/YSZ	~0.3 mm	~ 40%	Tape casting
Electrolyte	YSZ	5 - 10 µm	< 5%	Screen printing
Cathode	Conducting ceramic	10 - 50 µm	~ 30%	Screen printing

Solid Oxide Manufacturing Highlights

Manufacturing processes scalable to high volume at low cost

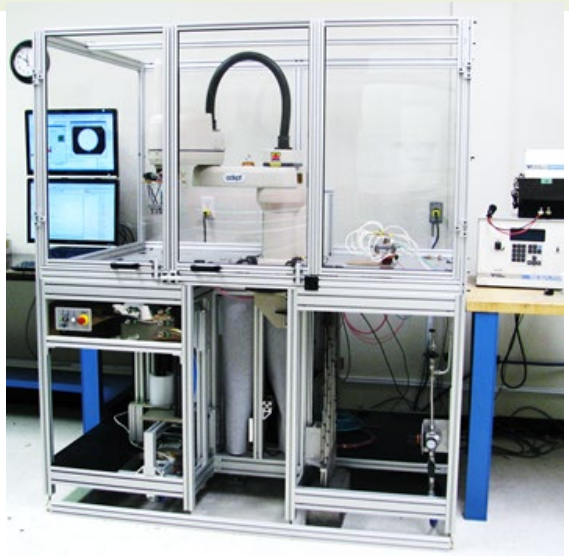
Tape Casting

Automated Screen Printing

Sintering

" TSC 3 Process "

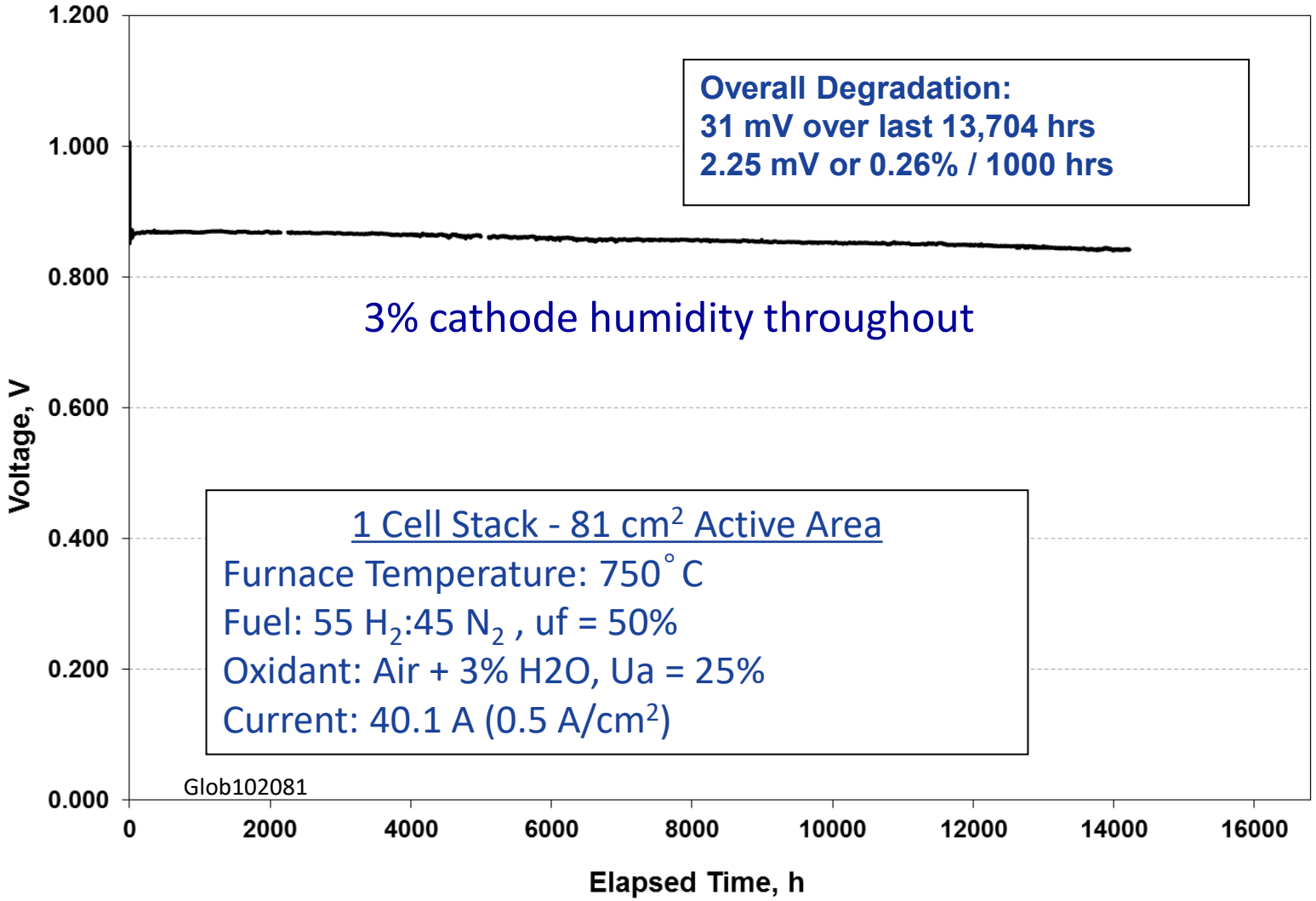
- 32,000 ft^2 facility engaged in R&D, cell/stack production and factory testing

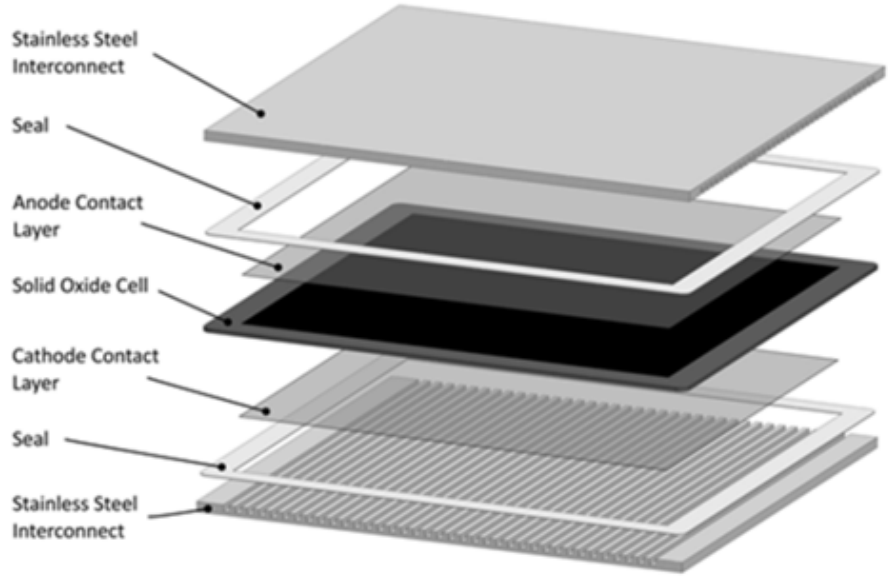


Automated QC / Stacking

Conditioning & Test Infrastructure

Long-term Performance

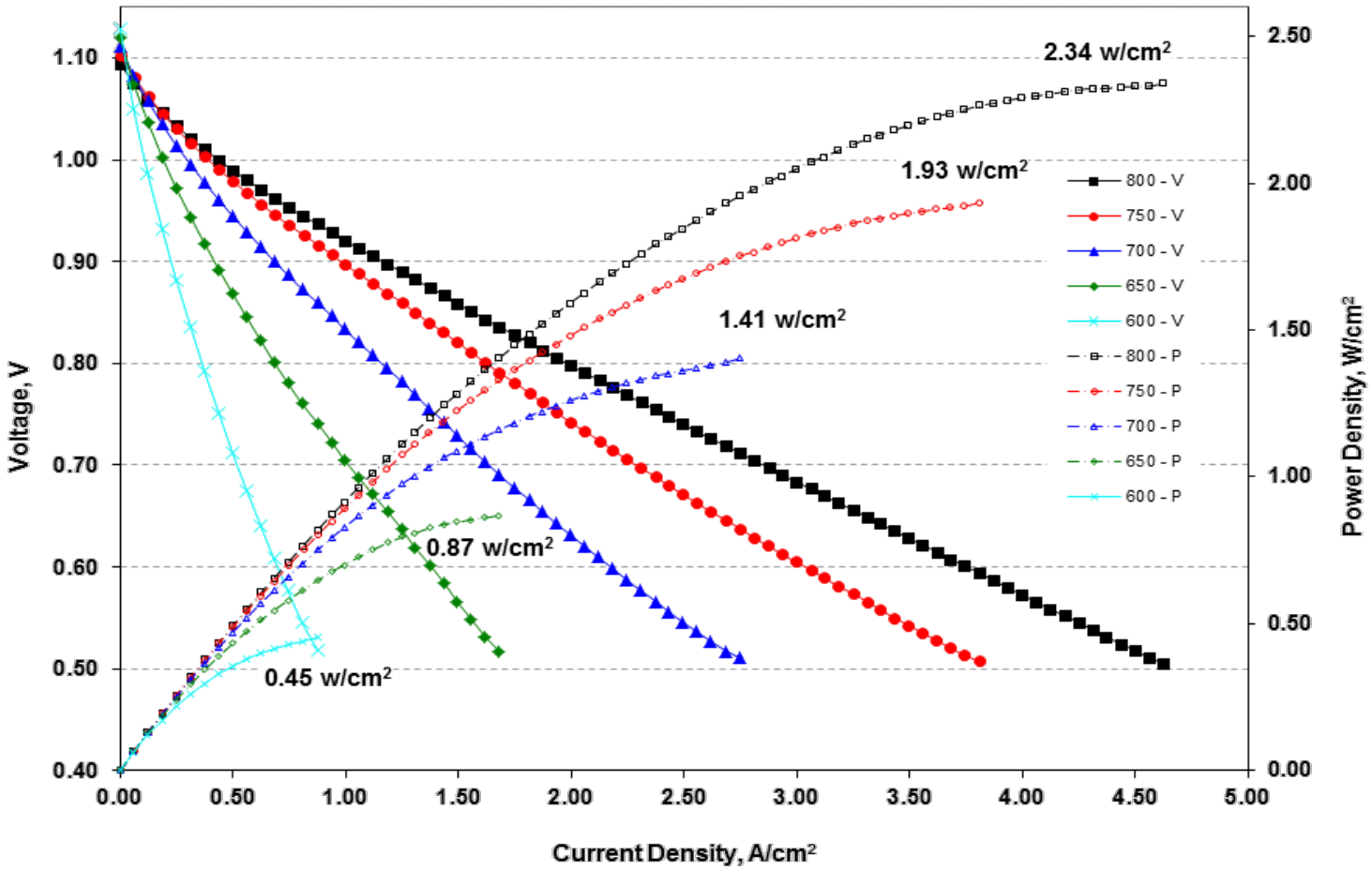


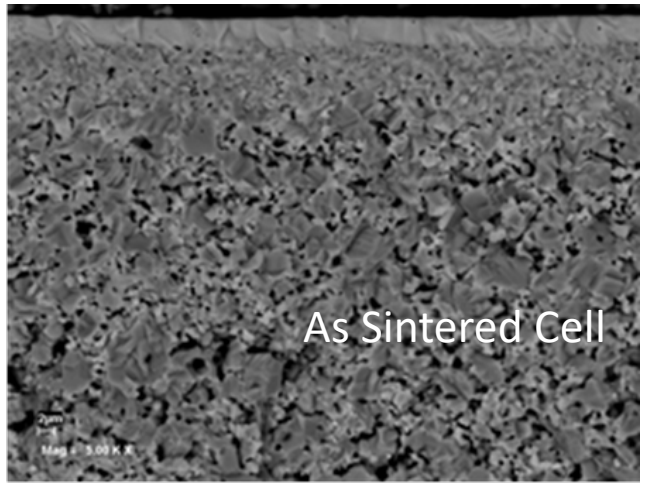


- Single cell configuration consisting of stack features: cross-flow pattern, stack flow fields, electrode contact layers and seals

Verified long-term cell endurance after >1.5 years of operation with 3% cathode air humidity resulting in 0.26%/1000h performance degradation

Recent Thin Cell Performance

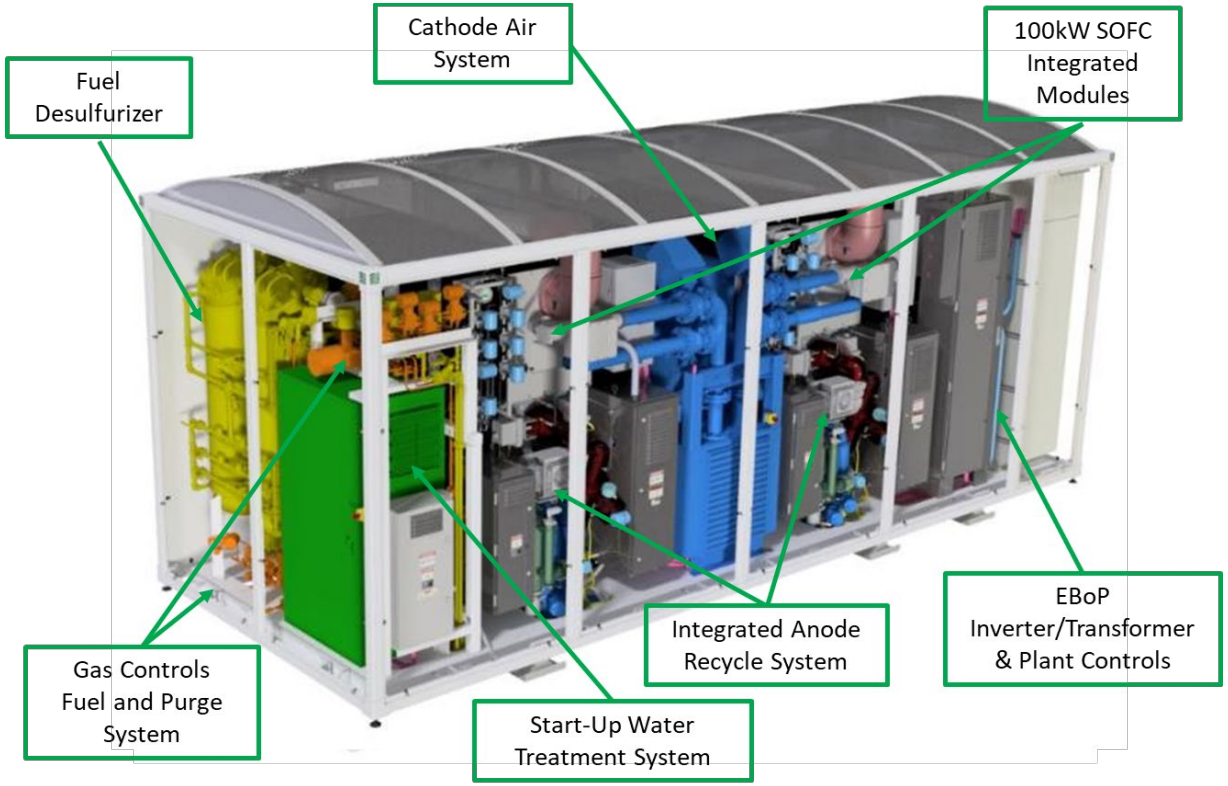


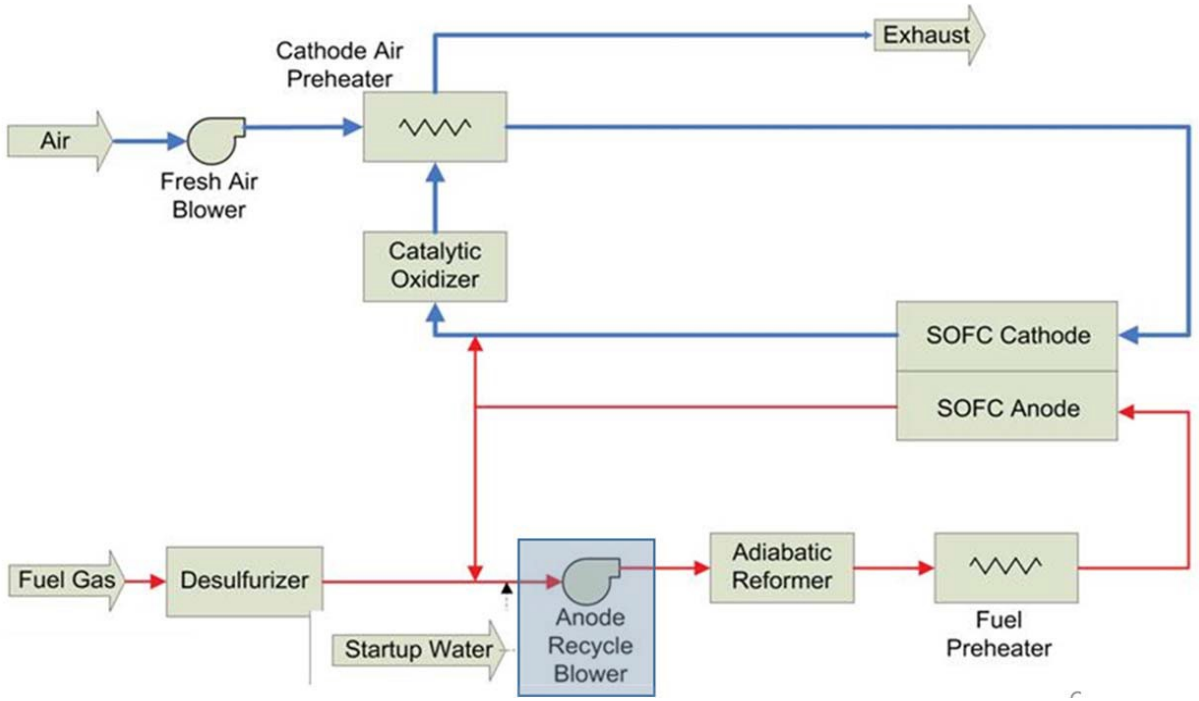


- Performance of cell at high fuel utilization is strongly dependent on anode thickness and structure

Recent 300 µ anode development has further improved cell performance (2.34 W/cm² at 4.7 A/cm2)

200kW SOFC Power System Overview

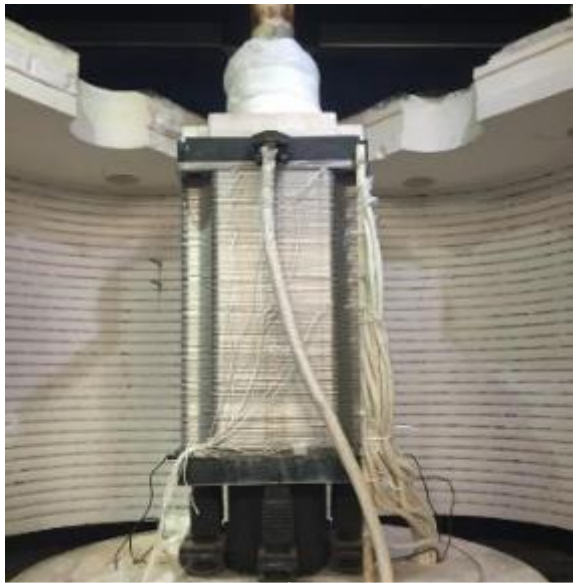




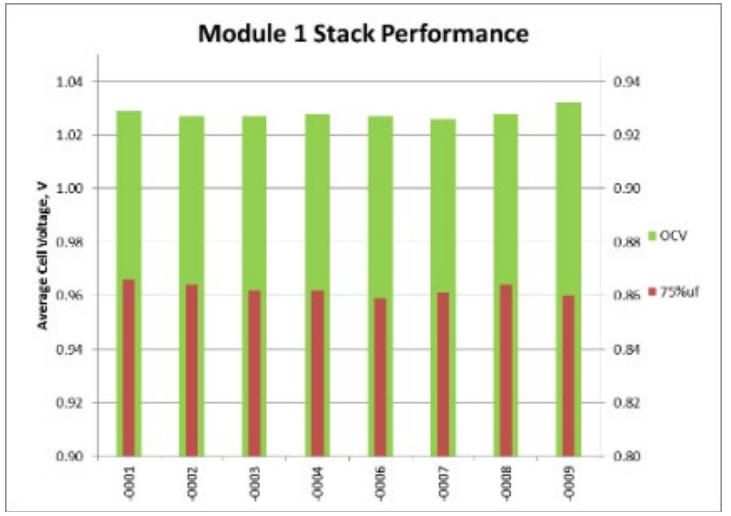
- Includes (2) 100kW SOFC stack modules designed to operate independently
- Factory assembled & shipped to site

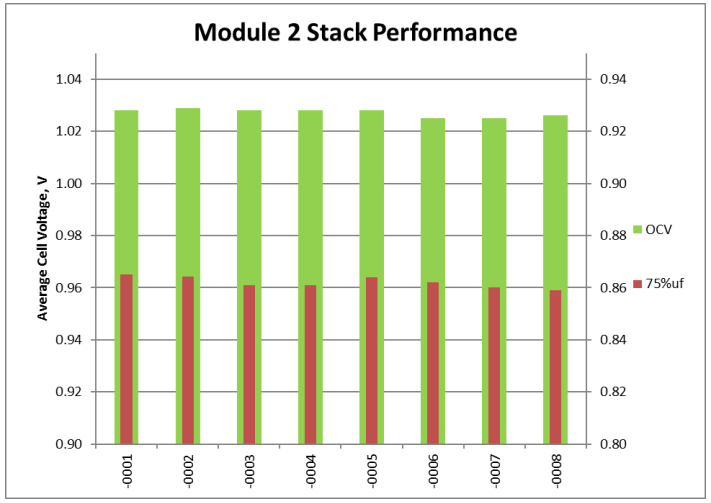
- 200 kW System Process Flow Diagram

100kW Module Design & Fabrication



Cell Size	25 x 25 cm^2
Active Area	550 cm^2
Number of Cells	120





- Excellent stack to stack performance reproducibility

100 kW modules include 4 towers each consisting of 2 legacy stacks (8 stacks per module)

200 kW System Operation Highlights

- Field Tests at Clearway Energy Center, Pittsburgh, PA

- Factory Tests at Danbury, CT

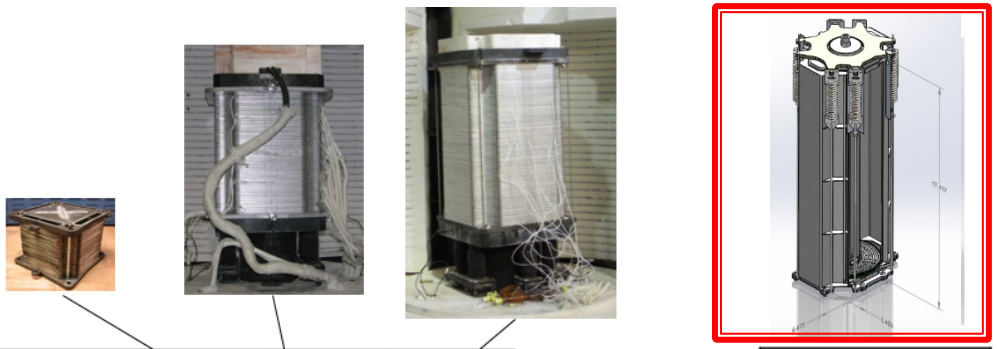
Highlight of Factory Tests + Clearway Site 4/9/2019 – 10/14/2020	
Total Hours Net AC Generated	5895 hours
Total Net Energy Output from System	299,458 kW-h
Gross DC Efficiency Achieved	56% (LHV NG)

Compact Solid Oxide Architecture (CSA) Stack

- Thinned components (cell + interconnect) to minimize stack material content (~0.5 kW/kg)
- Simplified unit cell with fewer components
- Designed for automated assembly
- Thermal and flow design to control temperature variations in module

Number of Cells	350
Active Area	81 cm^2
Power @ 0.25 W/cm^2	7 kW
Seal Technology	Crystallized glass

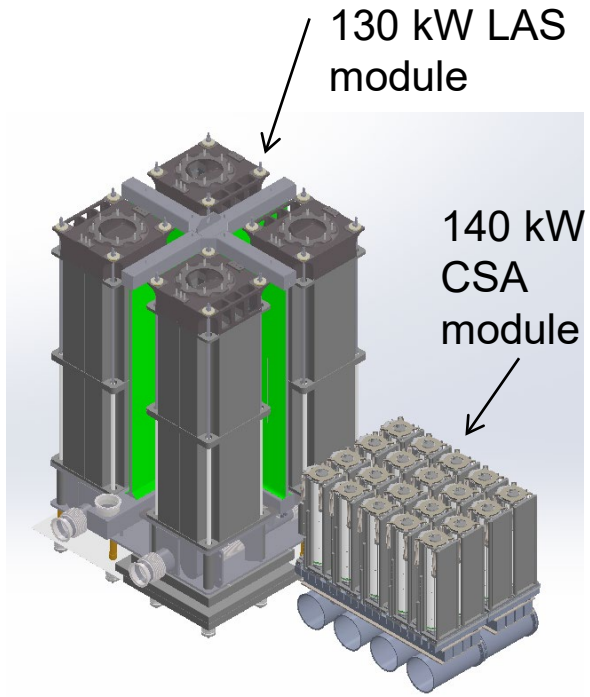
CSA offers low material content stack for commercialization



	Baseline PCI 390 mA/cm²	96 cell Wartsila 360 mA/cm²	120 cell coal based 290 mA/cm²	350 cell CSA Stack At 290 mA/cm²
Gross Power (W)	1100	14900	16200	7000
Stack voltage (Vdc)	24	75	101	295
Weight (kg)	17.3	185	213	15
Power to Weight Ratio (W/kg)	64	80	76	467
Approx. envelope (L)	5.3	69	88	9
Power to Volume Ratio (W/L)	207	215	185	778

6 X

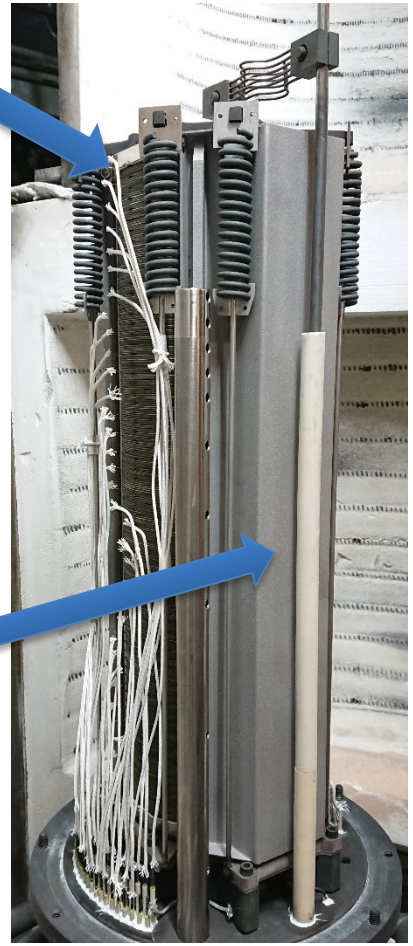
4 X



CSA Stack Overview

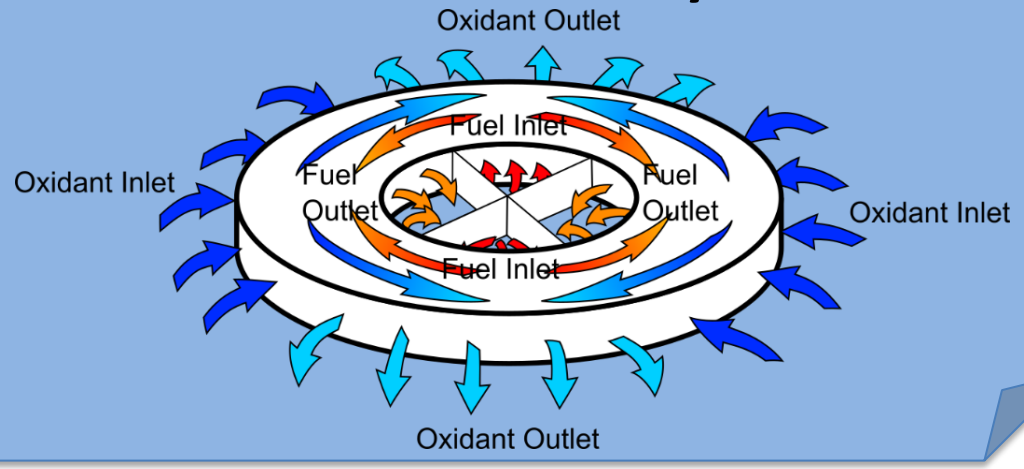
Integrated compression

Oxidant outlet manifold

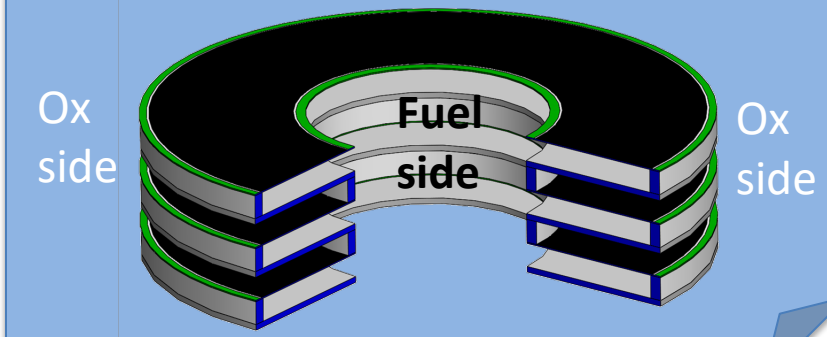


350 cells - 17” tall
10 kW (pressurized)

Flow Geometry



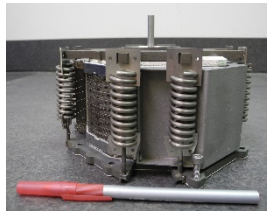
Underlying Structure



Flexible structure offers compliance and robustness

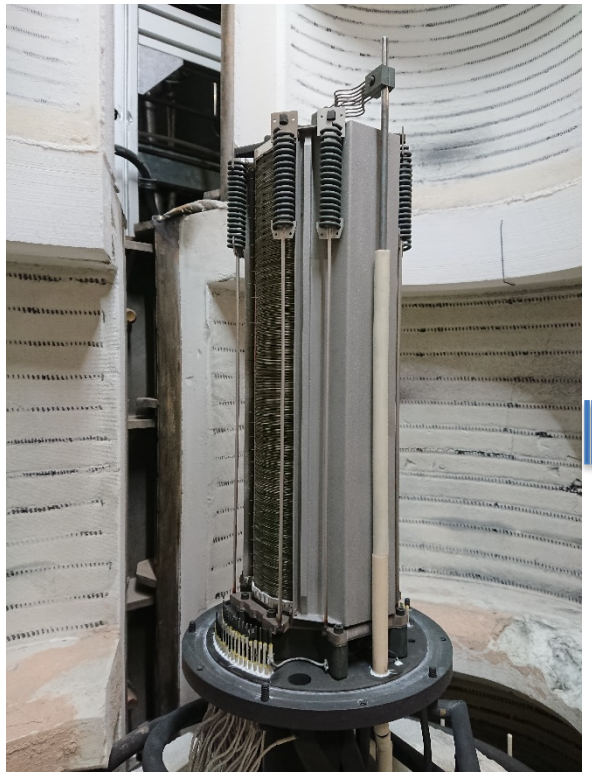
CSA Platform

Property	CSA Stack Scale			Comments
	Short	Mid	Full	
Cell count	45	150	350	
Fuel cell voltage, V	38	128	298	At 0.85 V/cell
Stack power, kW	0.9	3.0	7.0	At 0.29 A/cm^2
Stack power, kW	1.2	4.1	9.6	At 0.40 A/cm^2 Pressurized 4 bar
Height, mm	91	211	440	

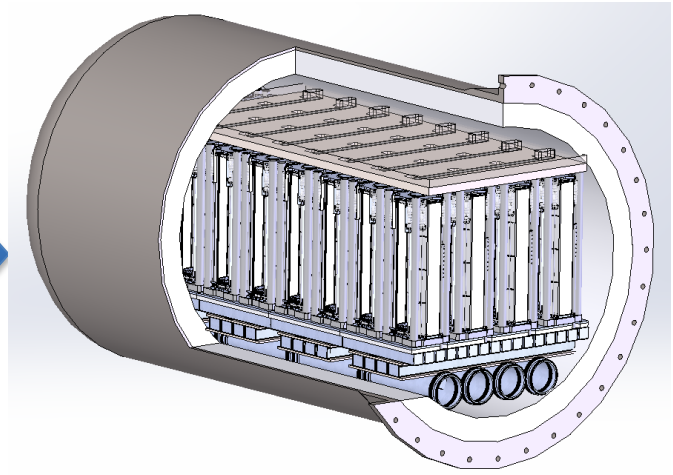


Short

Mid Size



Full Size

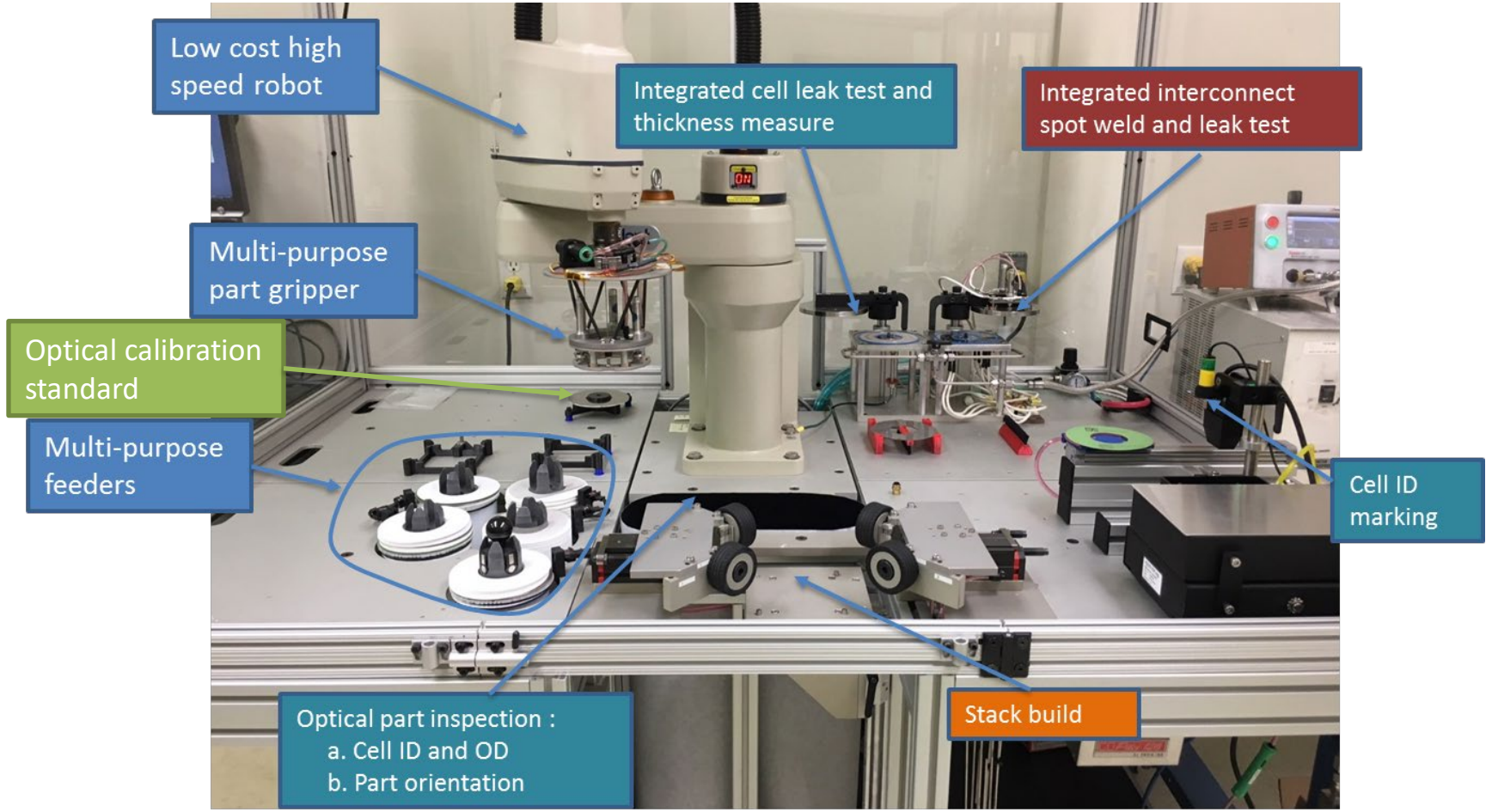


Stack Module

Next generation CSA stacks utilizing advanced thin and lightweight cell structures

Automated Integrated Stacking & QC Station

Automated part handling, automated QC, and automated assembly are aided by the CSA small lightweight parts resulting in lower cost of stack manufacturing at higher quality than hand assembly



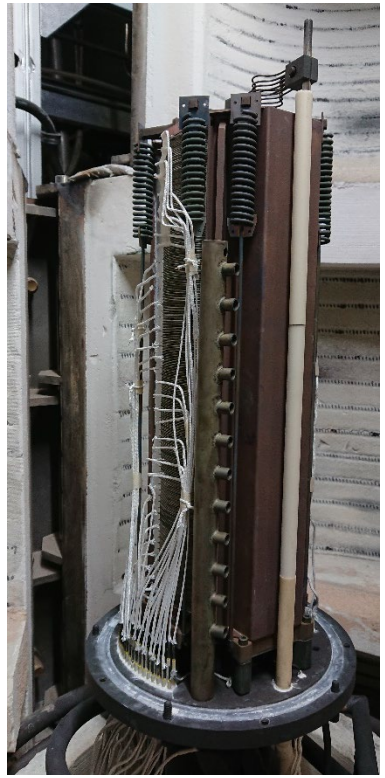
Robotic work cell for:

(a) Cell QC - measure / leak test
(>3 MW/shift/year throughput)

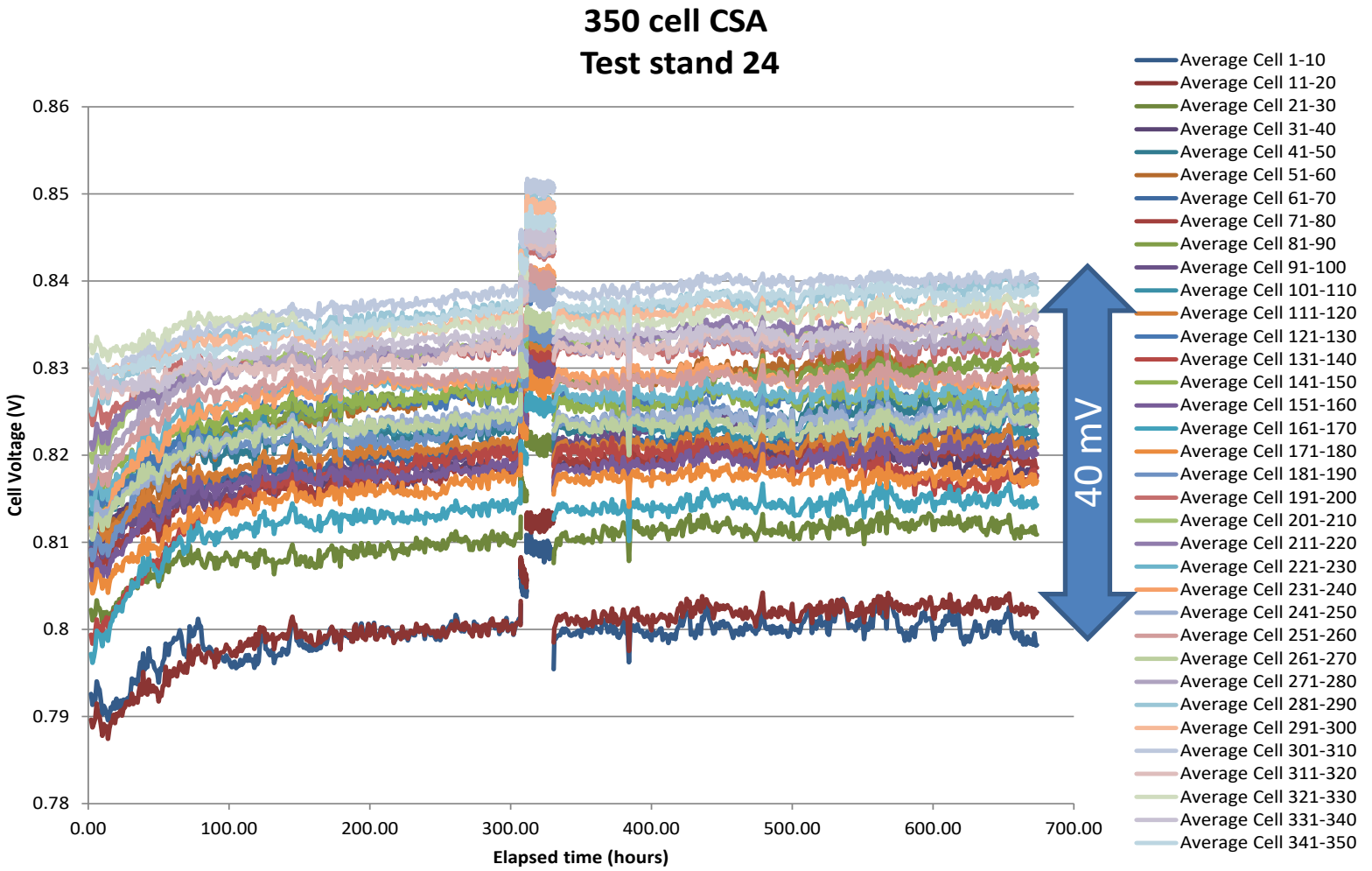
(b) Interconnect sub-assembly / QC
(> 3 MW/shift/year throughput)

(c) Stack build
(> 10 MW/shift/year throughput)

Full Height Stack Test



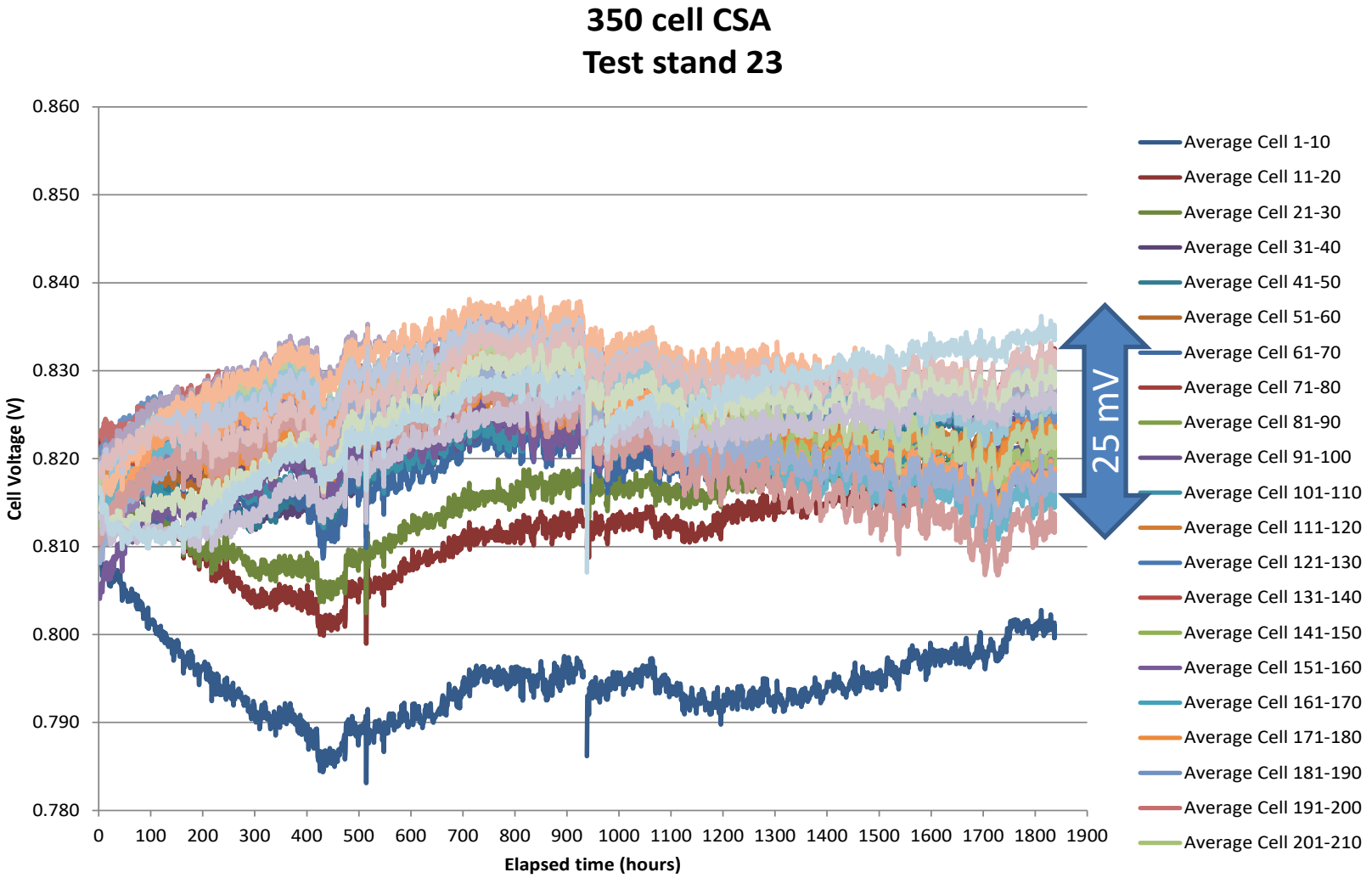
GT060081-0002



- Initial operation showed no degradation with a narrow band of voltage distribution (~40 mV for 350 cells)
- Stable operation for 674 hours when test stand failed and damaged stack due to no flows to the stack while the load kept on drawing current

Repeat of Full Height Stack Test

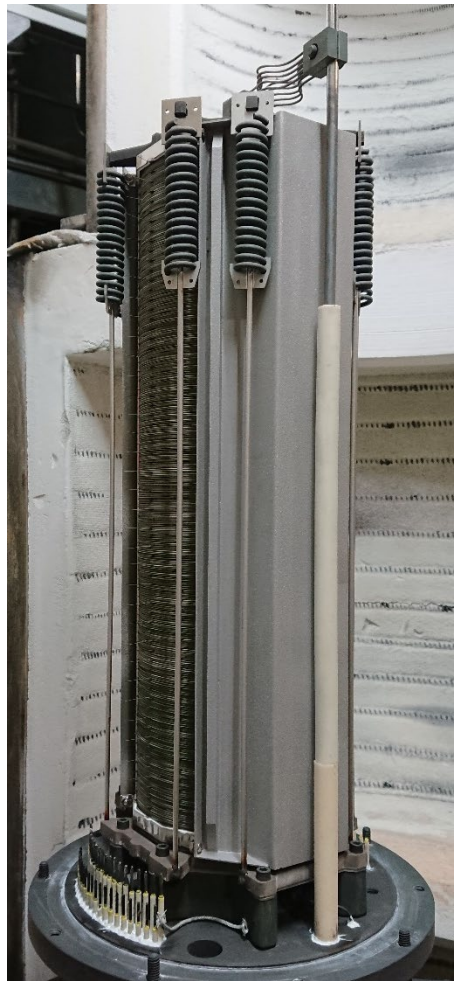
GT060081-0004



- Completed over 1800 hours of fuel cell operation on reformate with good voltage stability and tight voltage spread (except cells group of 251-260)

CSA Stack Cost Update @1 GWe/yr Production

- CSA Stack Factory Cost was updated from its last estimate in 2019 (DE-FE0026093) including the following major modifications:
  - Cost sensitivity analysis of different parts containing nickel (part thickness and porosity) for high volume costing
  - Updating cost of re-designed non-repeat parts (NRP) including top and bottom end plates and air manifolds
  - Advances in manufacturing automation
  - Cost trade-off analysis for Manganese-Cobalt Oxide (MCO) coating processes (in-situ versus ex-situ)
  - Update of cost parameters subject to Inflation



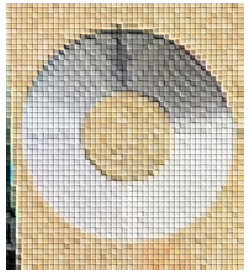
Cost Contributions Included:

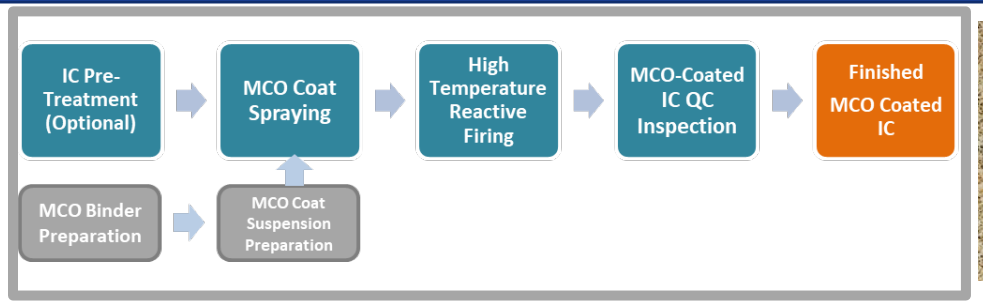
- Procured Parts
- Commodity Materials
- Direct Fabrication Labor
- Direct Assembly Labor
- Indirect Labor
- Utilities
- Capital Recovery
- Equipment Maintenance
- Consumables
- Equipment Commission and Test
- Overhead & Building

Excluded:

- R&D, sales and marketing, G&A, warranty expenses and taxes

GWe/y Production Costing for Manganese-Cobalt Oxide Spinel (MCO) Coating





In-Situ IC Fabrication

- Raw Coil → • PVD Co-Coating
- Co-Coated Coil → • IC Forming & Cutting
- Co-Coated IC → • Stack Assembly
- Thin MCO Coated IC → • MCO forms in-situ during Operation

- Protective MCO interconnect coating is needed to prevent Cr-poisoning
- Costing approach is to bring both in-situ and ex-situ coating processes into GW factory to assist feasibility against current cost basis
  - compare costs of labor, materials & capital
- Compare thin sub-micron in-situ against 5 micron ex-situ coating

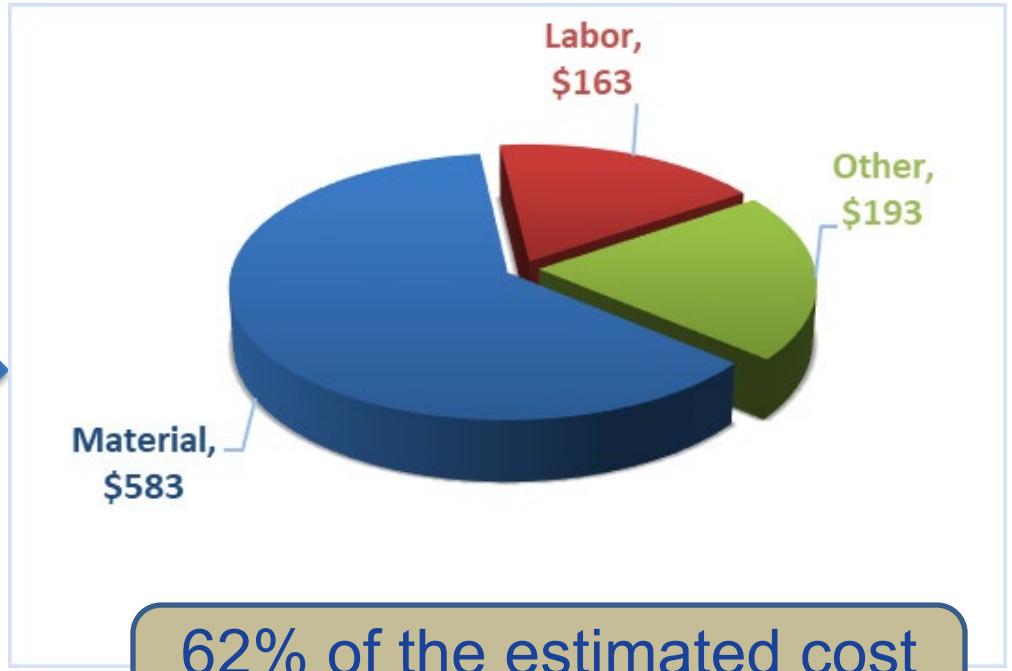
Ex-Situ IC Fabrication

- Sheet Metal → • IC Forming
- IC → • MCO Coating
- Porous MCO Coated IC → • Densification – Reduction at 800 C
- Dense MCO Coated IC → • Stack Assembly

CSA Stack Cost Distribution

Yr2011 CSA-SOFC Stack Factory Cost Estimate for 1 GW Stacks per Year

$ 940 / stack
at
160,000 stacks/year



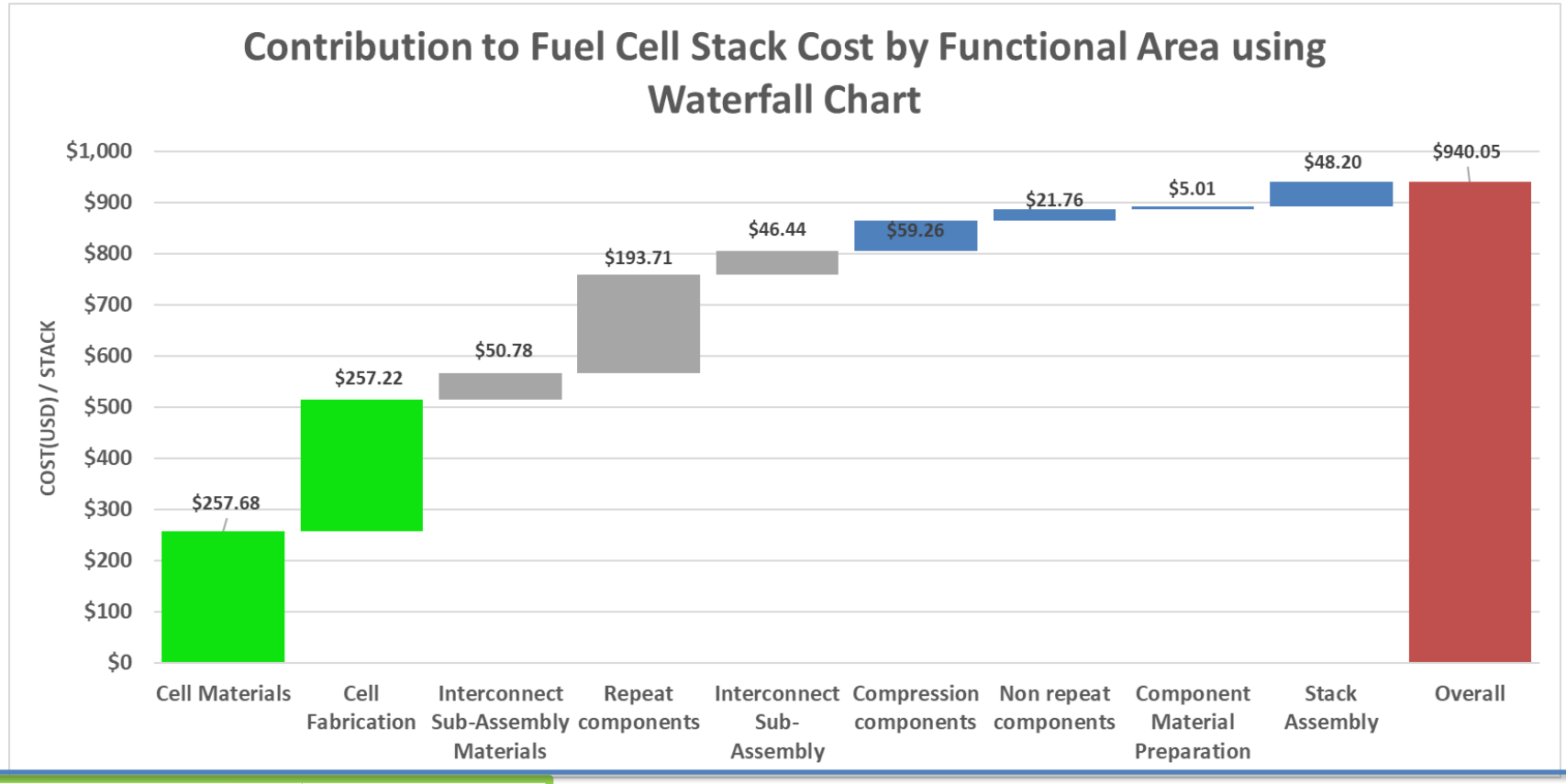
62% of the estimated cost is due to material

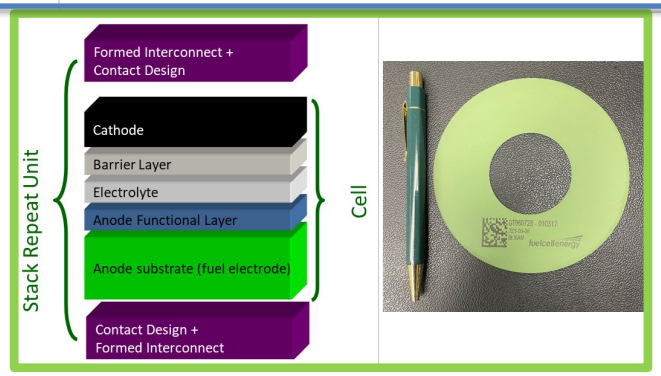
- SOFC @ 300 mW/cm^2 = $111 $/kWe out (gross stack DC)
- = $116 $/kWe out (gross stack AC)*

< $225 / kWe AC DOE cost target

* Assuming 96% DC to AC power conversion efficiency

Factory Cost Estimate – Waterfall Chart



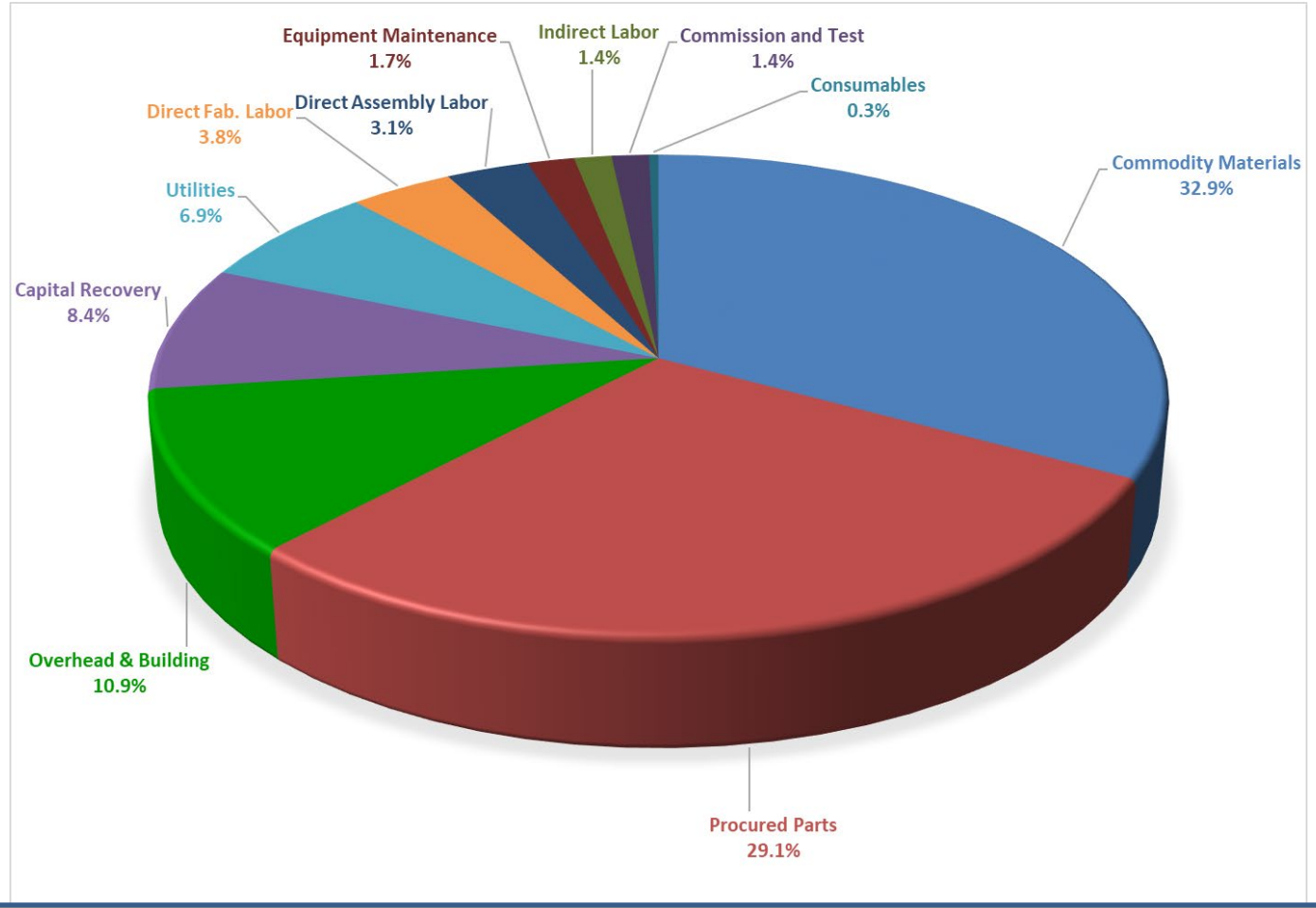


Top 3 cost contributors by **Functional Area** are:

1) Cell Materials
2) Cell Fabrications
3) Repeat Components

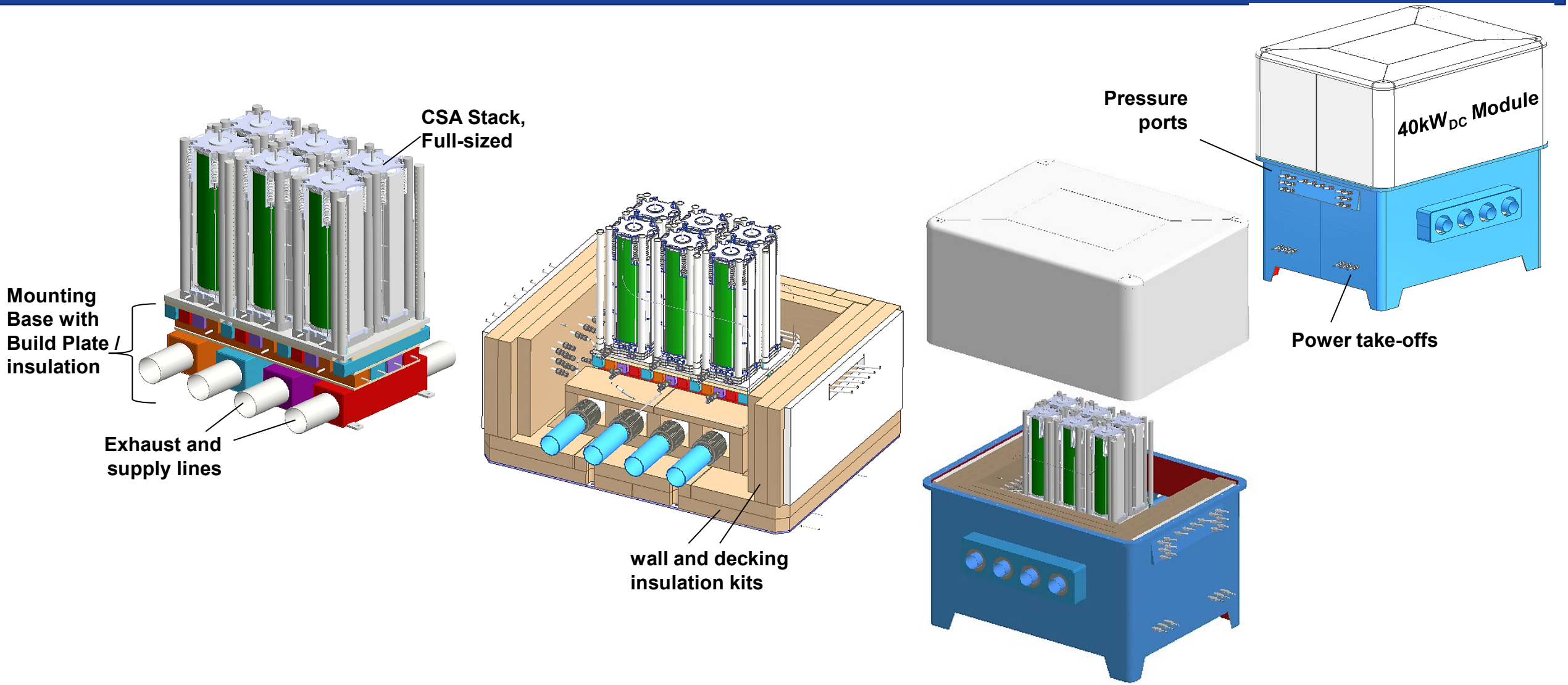
CSA-SOFC Stack Factory Cost Estimate

Yr2011 Costing for 1 GW stacks per Year – by Cost Category



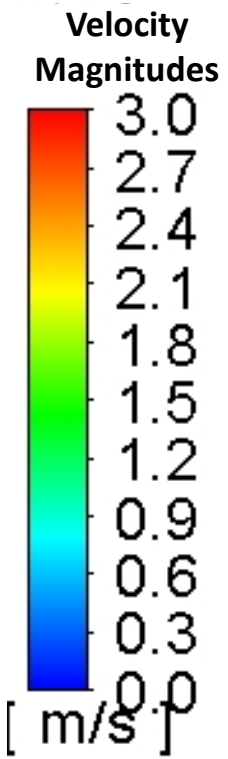
Top 3 cost contributors by **Cost Category** are:
1) Commodity Materials, 2) Procured Parts & 3) Overhead & Building

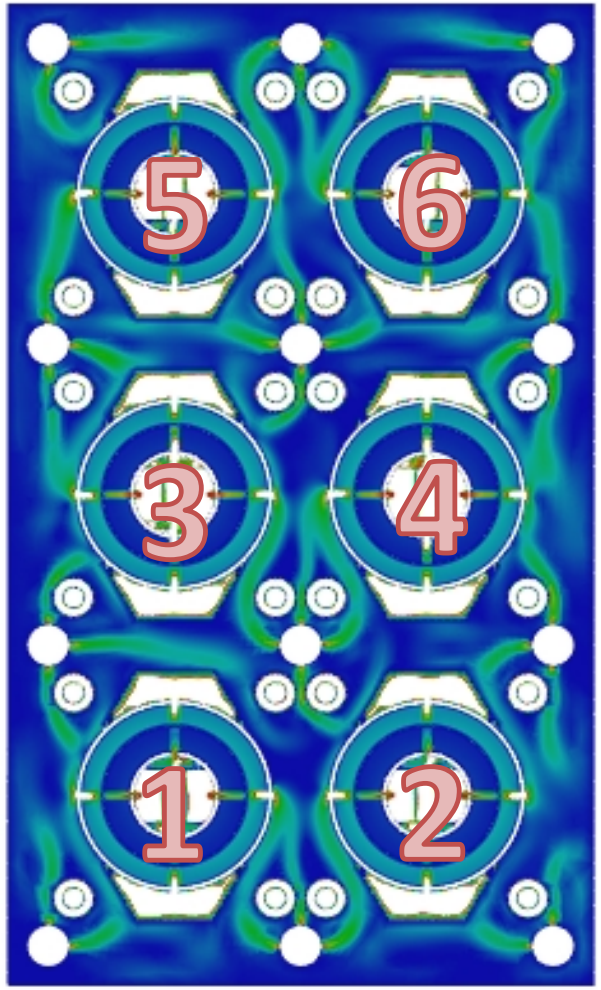
40kW Multi-Stack Module Development



First-of-a-kind 40 kWdc multi-stack module is being developed to test an array of 6 CSA stacks

CFD Analysis for Module Air Distribution



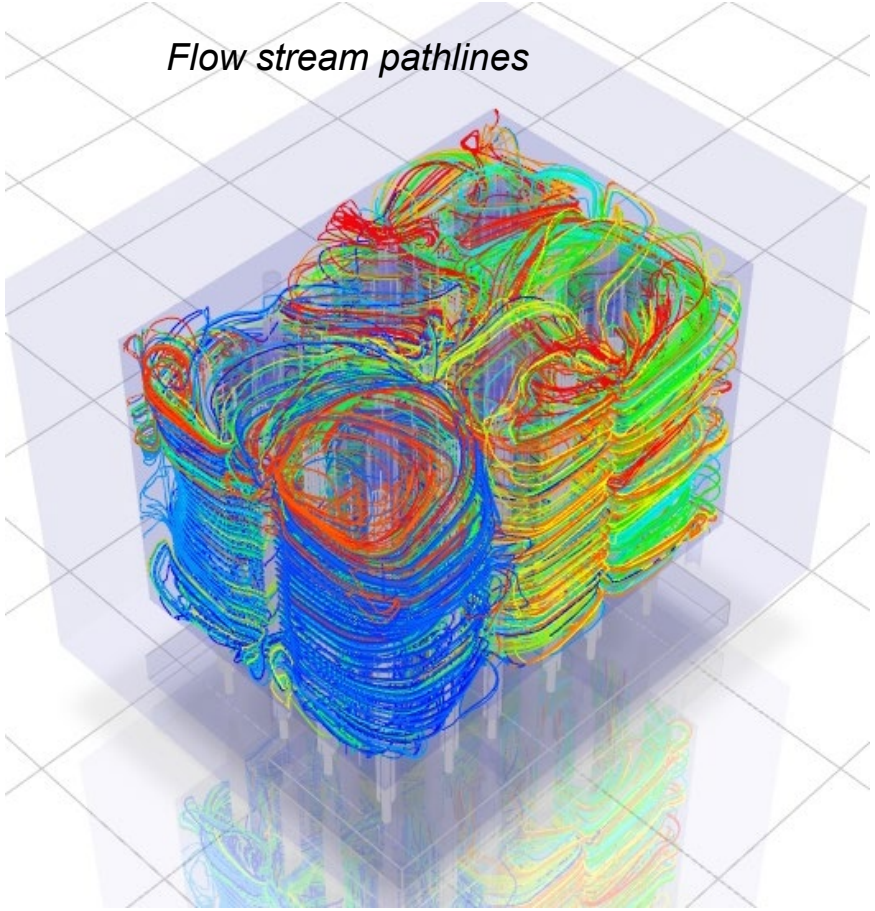


Stacks' flow variation from average
(a, b denote two sides of each stack)

stack-in-air-1a	0.1%
stack-in-air-1b	-0.2%
stack-in-air-2a	-0.1%
stack-in-air-2b	0.2%
stack-in-air-3a	0.1%
stack-in-air-3b	0.0%
stack-in-air-4a	-0.2%
stack-in-air-4b	0.1%
stack-in-air-5a	0.2%
stack-in-air-5b	-0.1%
stack-in-air-6a	-0.3%
stack-in-air-6b	0.1%

Min = -0.3%
Max – min = 0.5 %

Flow stream pathlines

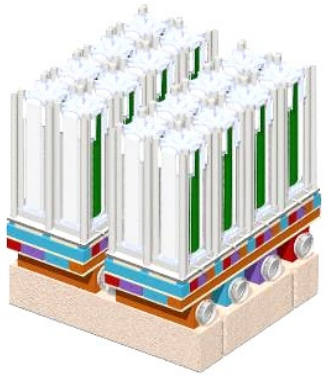


CFD modeling shows uniform flow distribution to stacks within the module enclosure

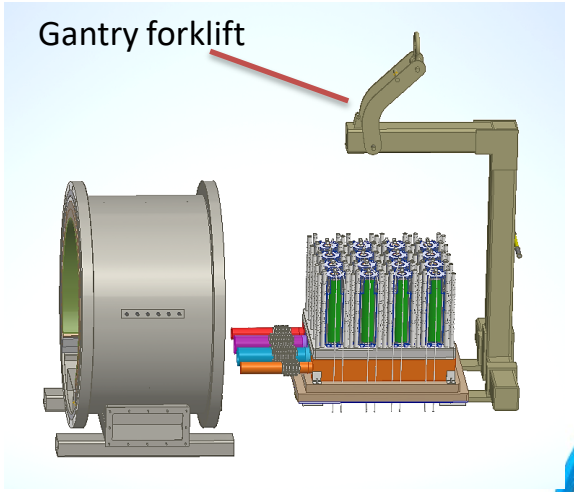
Solid Oxide Module Scale-up

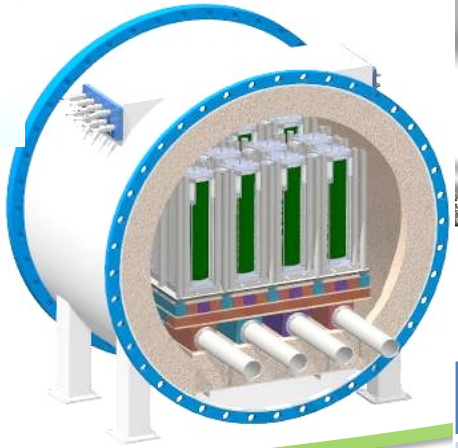
Configurable & Scalable Stack Arrays:

- Accommodate module structural designs for both present and future systems
- Forkliftable and serviceable stack module for integration in packaged systems

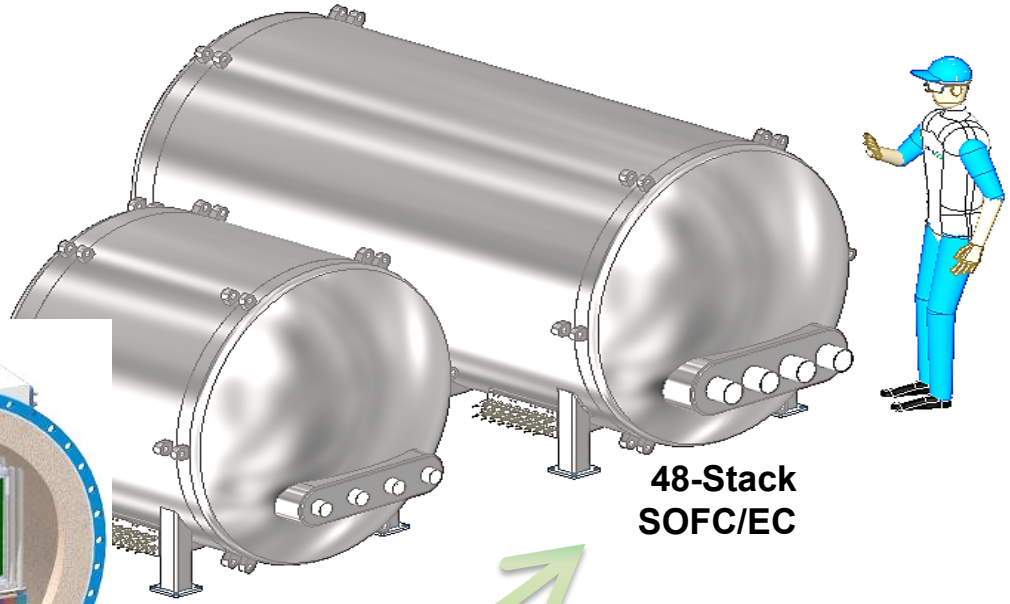


CSA Stack Array





16-Stack
SOFC/EC

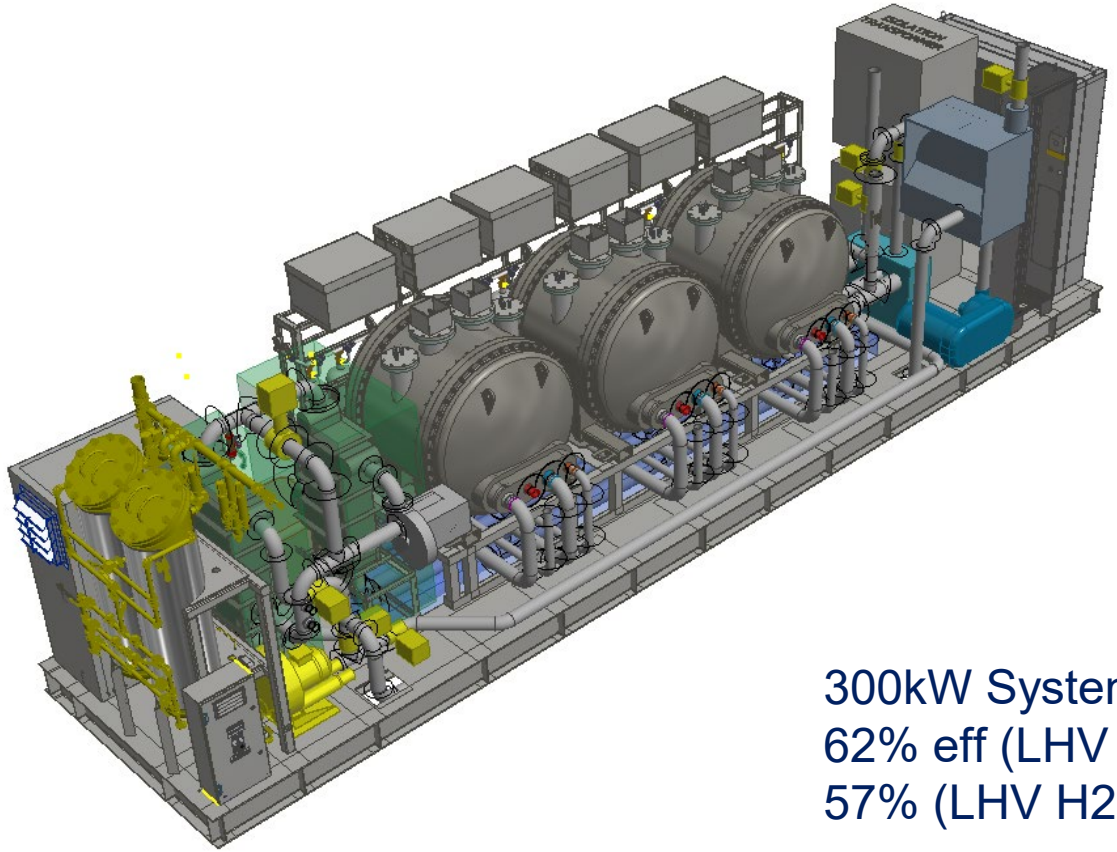


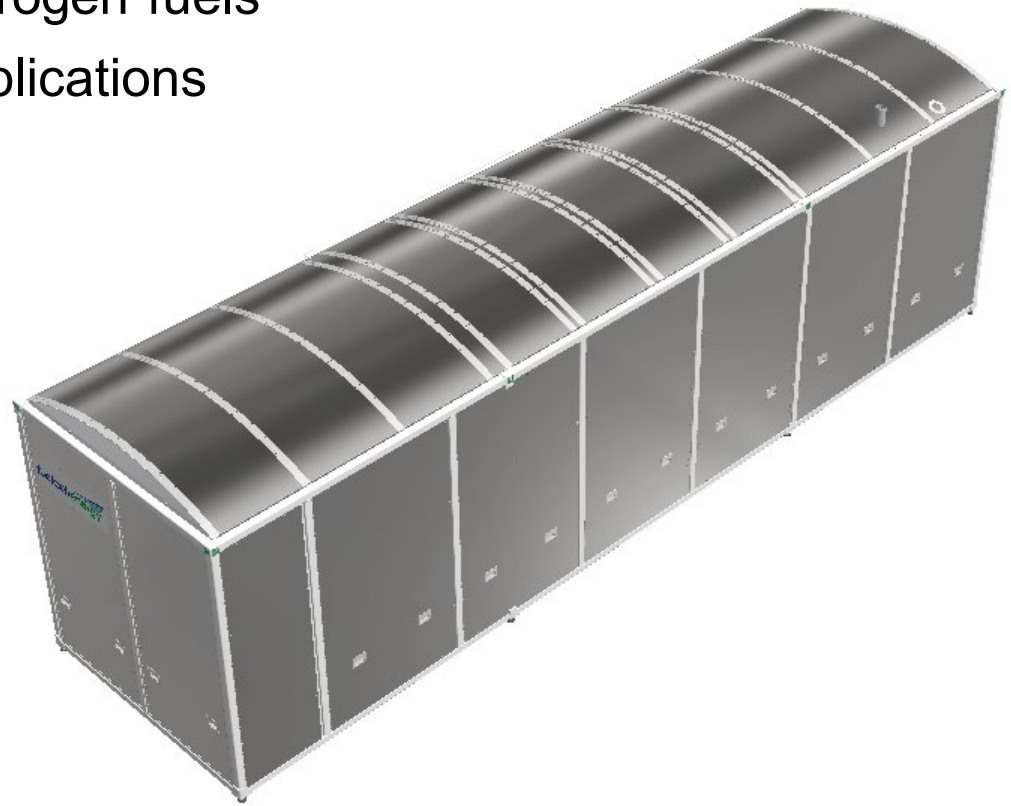
48-Stack
SOFC/EC

# of Stacks	Module Gross Output
16	6.7 x 16 = 107 kW
48	6.7 x 48 = 322 kW

Next Generation SubMW SOFC System

- Designed to operate with natural gas, biogas, and hydrogen fuels
- Provides waste heat for combined heat and power applications





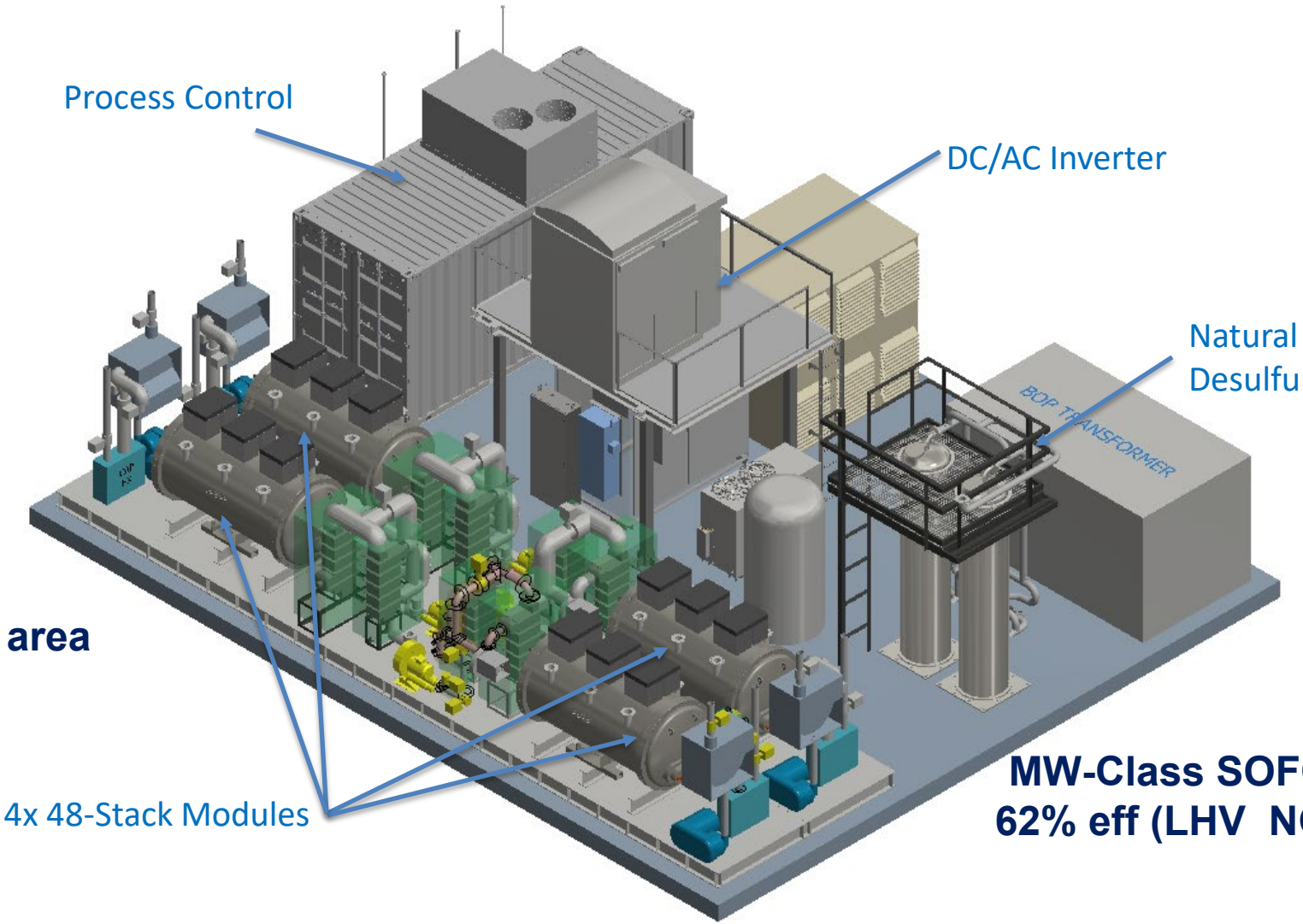
300kW System
62% eff (LHV NG)
57% (LHV H2)

Next generation SubMW system utilizes CSA stack technology

MW-Class SOFC System

SureSource™ 1500 Product
47% eff (LHV NG)

25% reduction in plot area



MW-Class SOFC
62% eff (LHV NG)

Layout of the 1200 kW system including 4 stack modules and the associated distributed BOP

Thank You

Acknowledgements:

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