FuelCell Energy

Progress in SOFC Technology Development at FuelCell Energy

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2022 SOFC Project Review Meeting
Pittsburgh, PA

FuelCell Energy

Our Technologies Will Provide Optionality as Energy Transition Evolves

Large Scale Grid Support

- Bridgeport Fuel Cell Park, a 14.9 MW project located in Bridgeport, CT, is a utility-scale distributed power solution that revitalized a 1½ acre brownfield site and contributes to the economic redevelopment in the area.

Micro-Grid

- FuelCell Energy has built several utility microgrid applications, including a microgrid fuel cell at the University of California – San Diego, that supports critical building loads with independent capabilities.

Distributed Hydrogen

- Building hydrogen distribution platform in Long Beach to support Toyota's operations to fuel zero emission FCEVs and provide clean water.
- Will enable hydrogen transportation
- No pipeline infrastructure needed

Carbon Capture / Carbon Separation

- Fuel cells can separate carbon dioxide from an external exhaust stream, making the carbon dioxide easier to capture and sequester (approximately 90% CO_2 capture, 70% NOx elimination).
- CO_2 can be either sequestered or used in applications such as food and beverage and agriculture.

Image:
Bridgeport Fuel Cell Park

Image:
UC San Diego microgrid enabled fuel cell platform

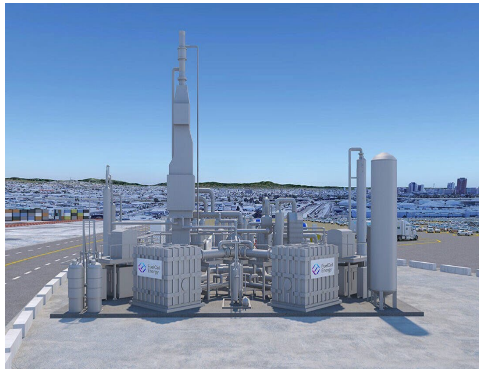


Image:
Rendering of Tri-Generation Fuel Cell Project at the Toyota Facility at the Port of Long Beach, California

Image:
The Scotford Upgrader, a Canadian oil sands bitumen processor, is the site of a recently announced carbon capture project with FuelCell Energy

SOFC Systems Development

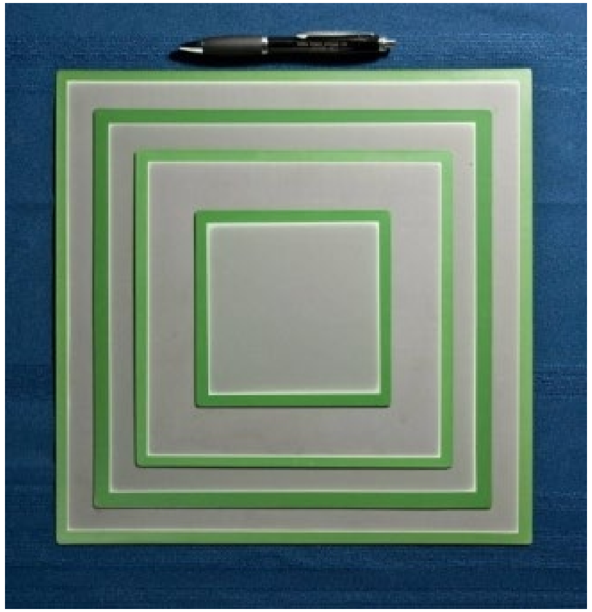
- Pathways to development of a low-cost, efficient, and reliable MWe-class SOFC power system towards commercial deployment in distributed generation applications:
  - Complete manufacturing analysis and planning to support efficient capacity expansion of 2nd generation cell and stack production processes to enable MW-class production rates at competitive cost
  - Design a multi-stack module to house low-cost Compact SOFC Architecture (CSA) stacks and serving as a building block for integration into MWe-class systems
  - Develop the conceptual process, electrical, and mechanical designs for a low-cost, high-efficiency, and reliable MWe-class SOFC pilot system
  - Complete a Techno-Economic Analysis to forecast the system cost

Field Tests of FCE's 200 kW SOFC System at Clearway Energy Center, Pittsburgh, PA

Highlight of Factory Tests + Clearway Site 4/9/2019 – 10/14/2020	
Total Hours Net AC Generated	5,895 hours
Total Net Energy Output from System	299,458 kW-h
Gross DC Efficiency Achieved	56% (LHV NG)

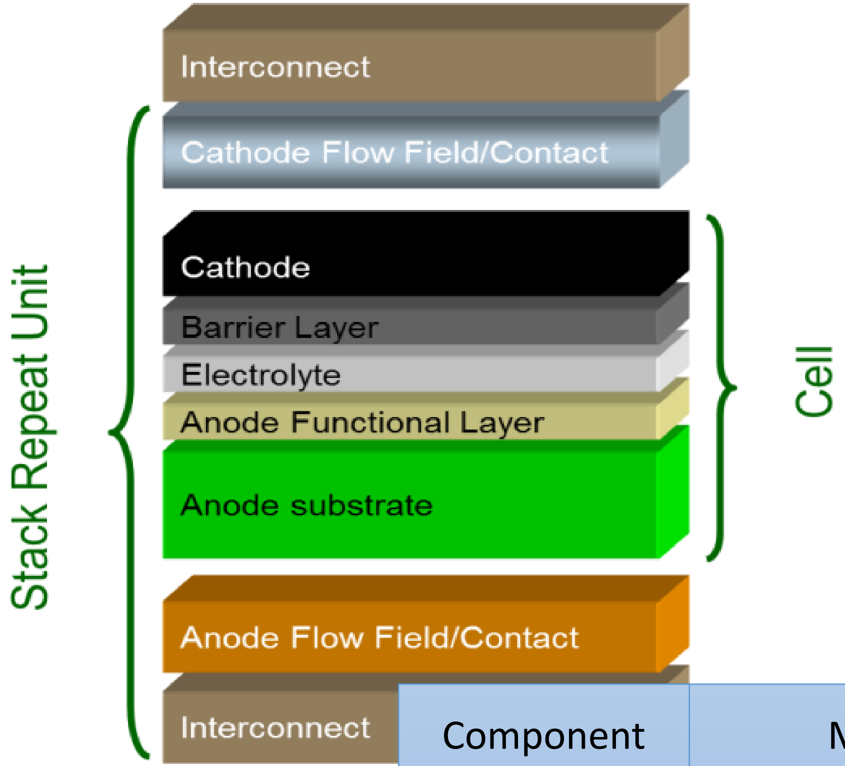
SOFC Technology

Solid Oxide Fuel Cell Technology Overview

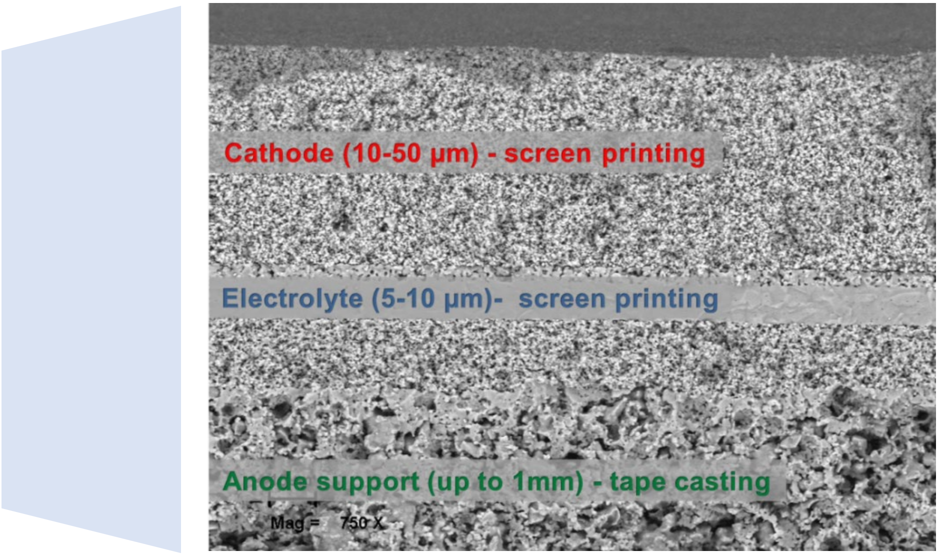


Anode-Supported Solid Oxide Fuel Cell

Scale up of cells up to 1000 cm^2 active area



Solid Oxide Fuel Cell Structure



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

Cell Fabrication Process

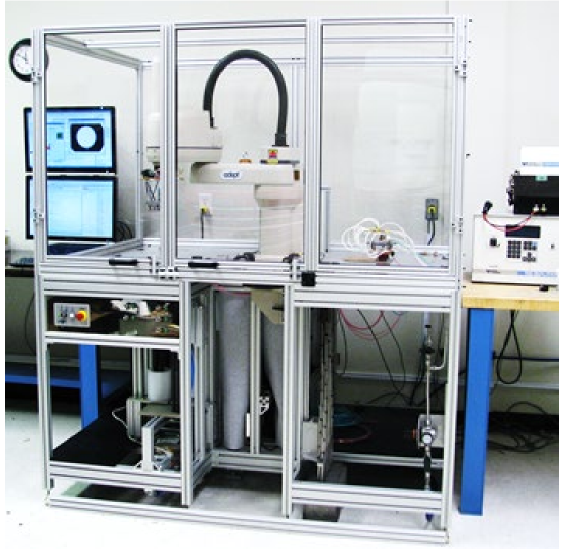
- SOFC Cell fabrication process has evolved from laboratory to pilot-production in 2001

Automated Screen Printing

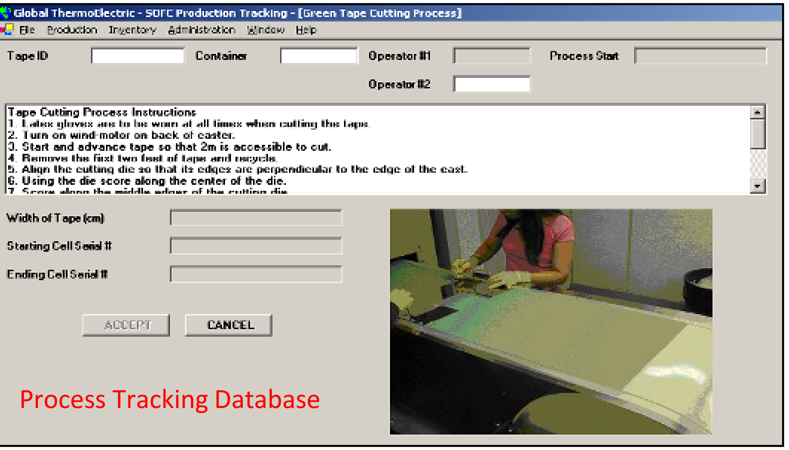
Anode Tape

Unfired Cell

Fired Cell



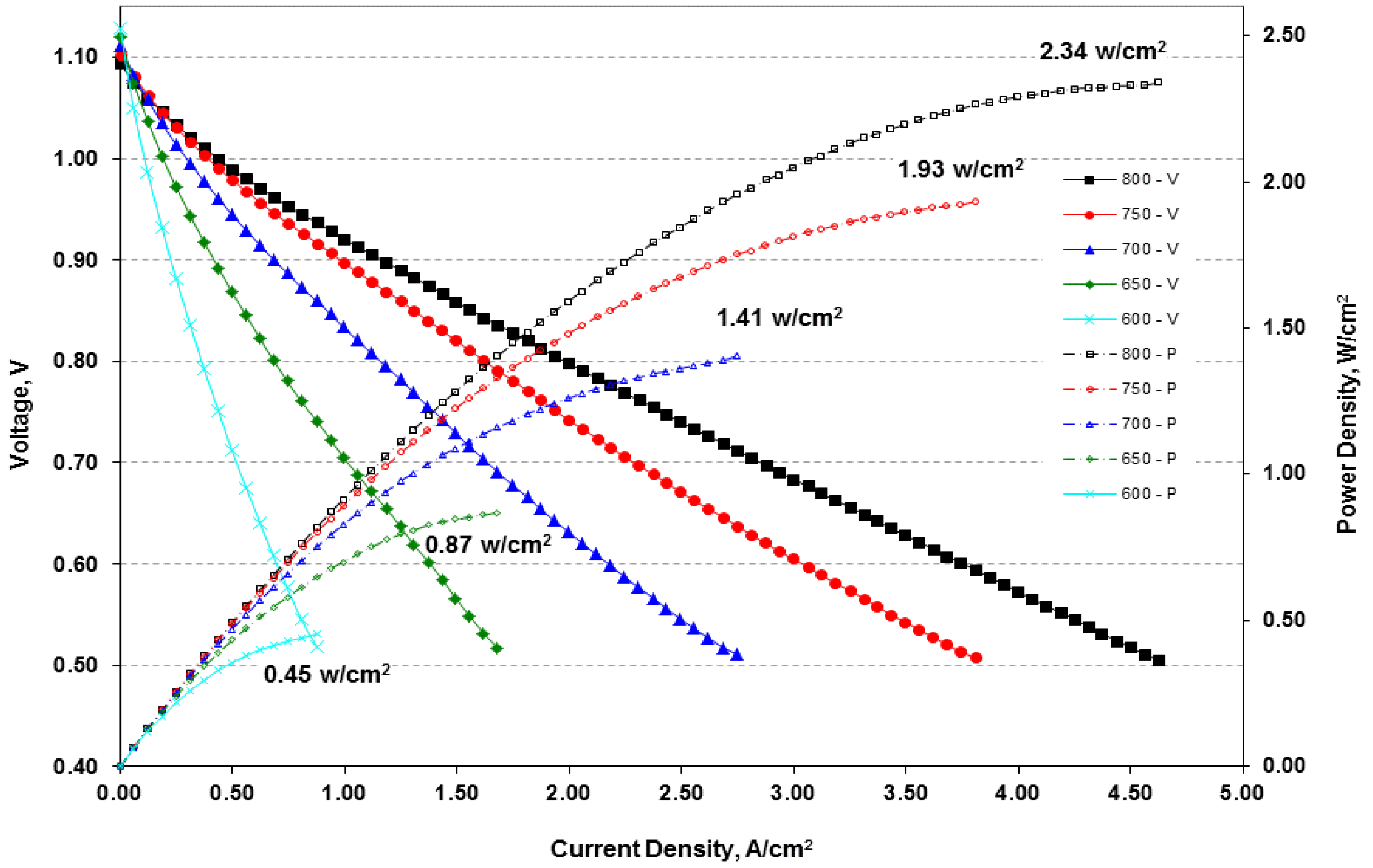
Automated QC / Stack Assembly

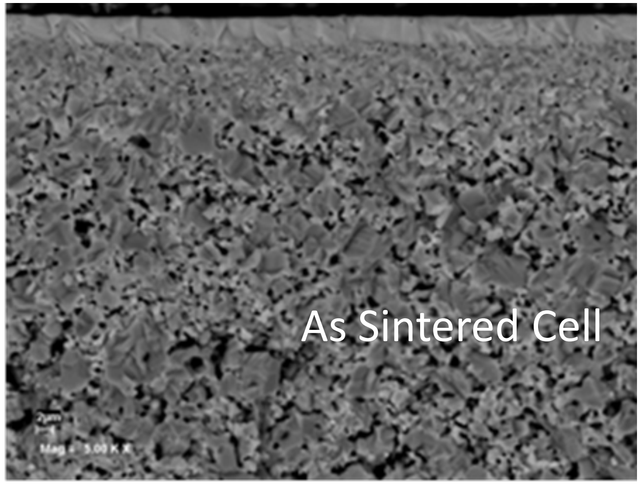


Process Tracking Database

"TSC" SOFC fabrication process is flexible & scalable to high volume and low-cost production

Typical 0.3 mm Thin Cell Performance

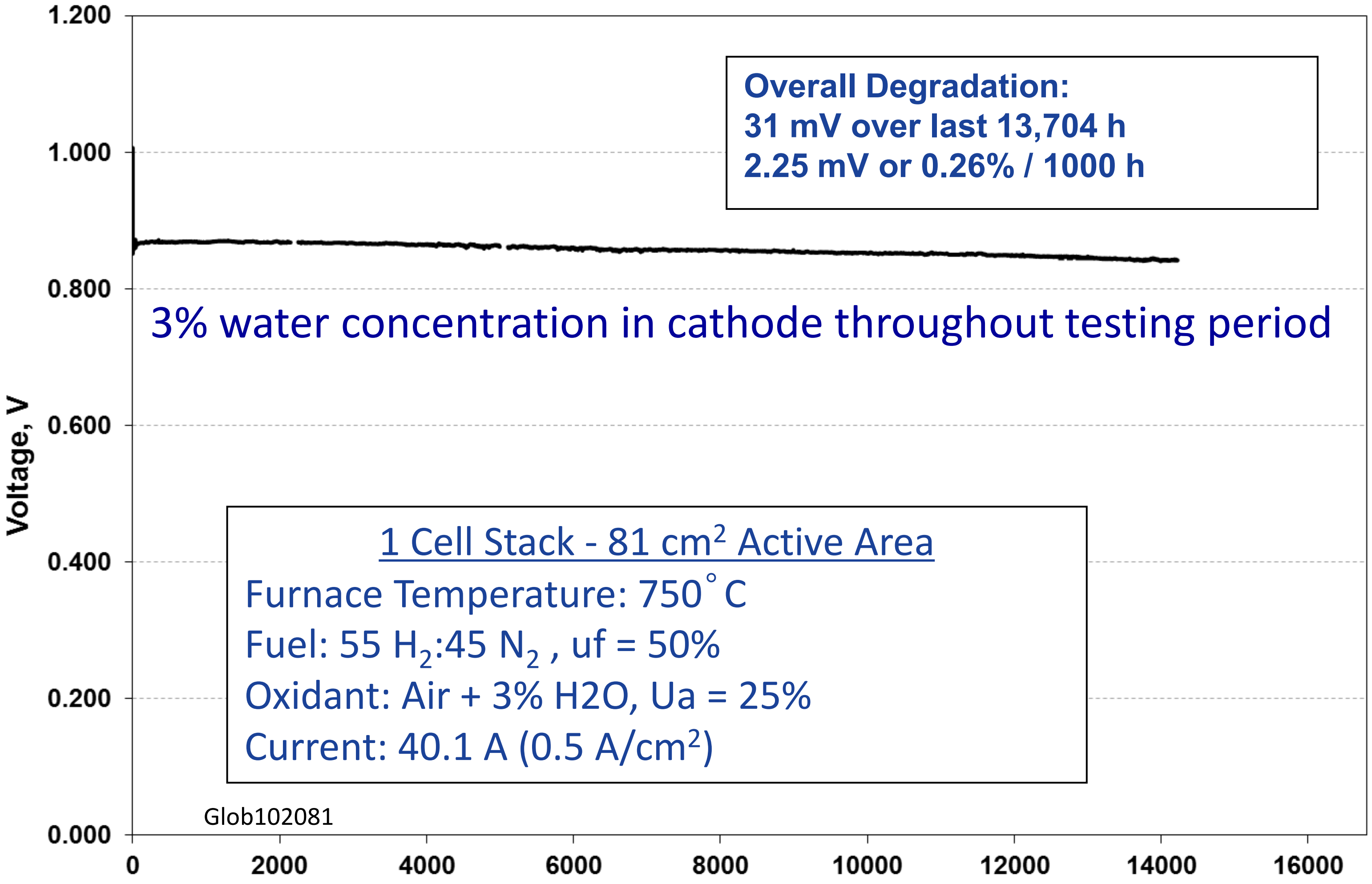


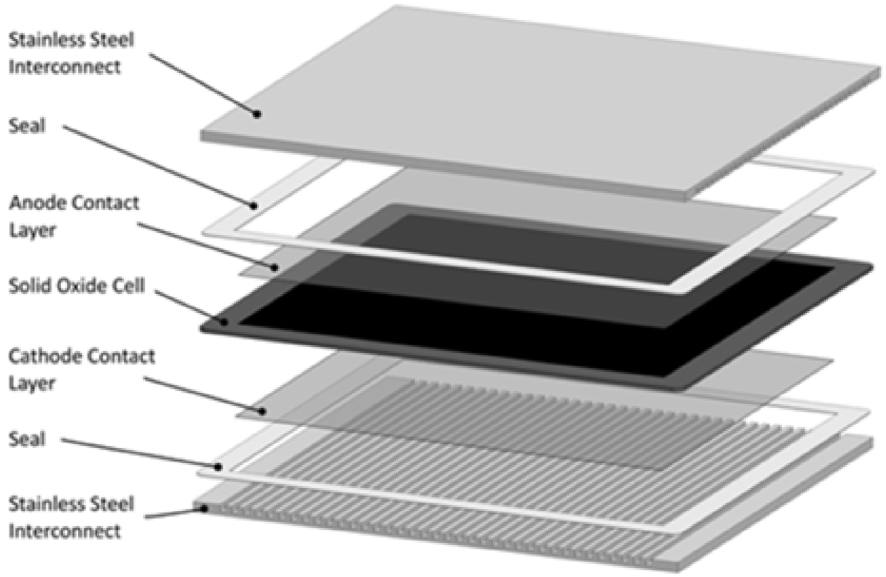


- Performance of cell at high fuel utilization is strongly dependent on anode thickness

Reduction of anode thickness has further improved cell performance (2.34 W/cm^2 at 4.7 A/cm^2)

Long-term Performance – Accelerated Testing





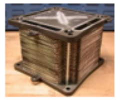
Single cell configuration consisting of stack features: cross-flow pattern, stack flow fields, electrode contact layers and seals

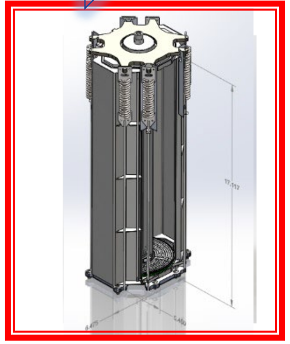
Verified long-term cell endurance test >1.5 years of operation with a 0.26%/1000h performance degradation with 3% cathode humidity throughout

SOFC Stack Development

Compact Solid Oxide Architecture (CSA) Stack

Solid Oxide Stack Design Progression





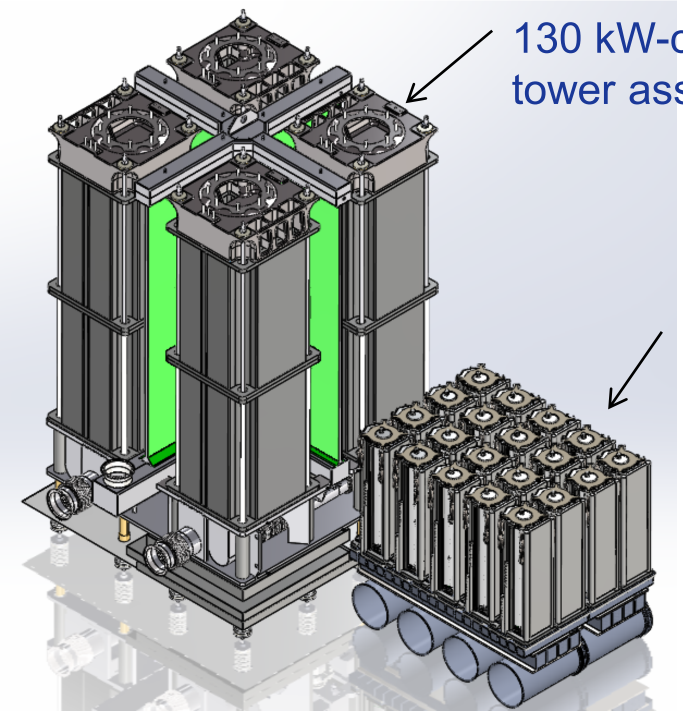
	Baseline PCI 390 mA/cm²	96 cell Wartsila 360 mA/cm²	120 cell coal based 290 mA/cm²	350 cell CSA Stack At 290 mA/cm²
Gross Power (W)	1100	14900	16200	7000
Stack voltage (Vdc)	24	75	101	295
Weight (kg)	17.3	185	213	15
Power to Weight Ratio (W/kg)	64	80	76	467
Approx. envelope (L)	5.3	69	88	9
Power to Volume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

6 X

4 X

- Thinned components (cell + interconnect) to minimize stack material content (~0.5 kW/kg)
- Simplified unit cells with fewer components
- Designed for automated assembly

- Comparison of Large Area Stack (LAS) stacks tower versus CSA stacks assembly

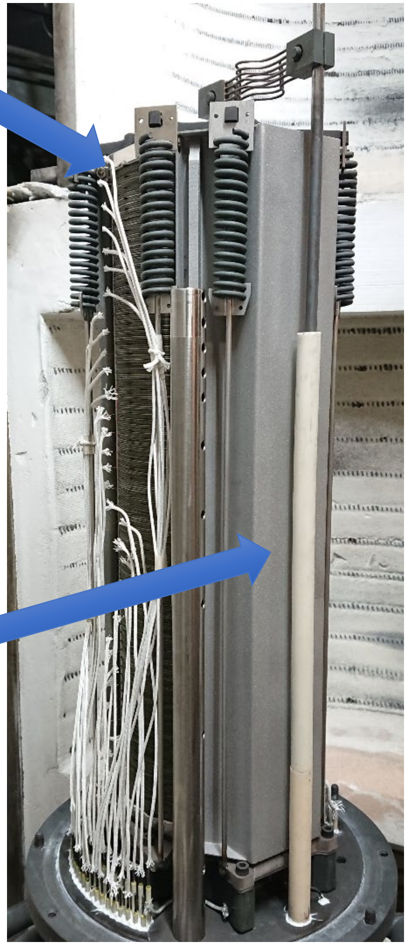


CSA stack design offers low material content for reduction in cost and superior thermal characteristics

CSA Stack Overview

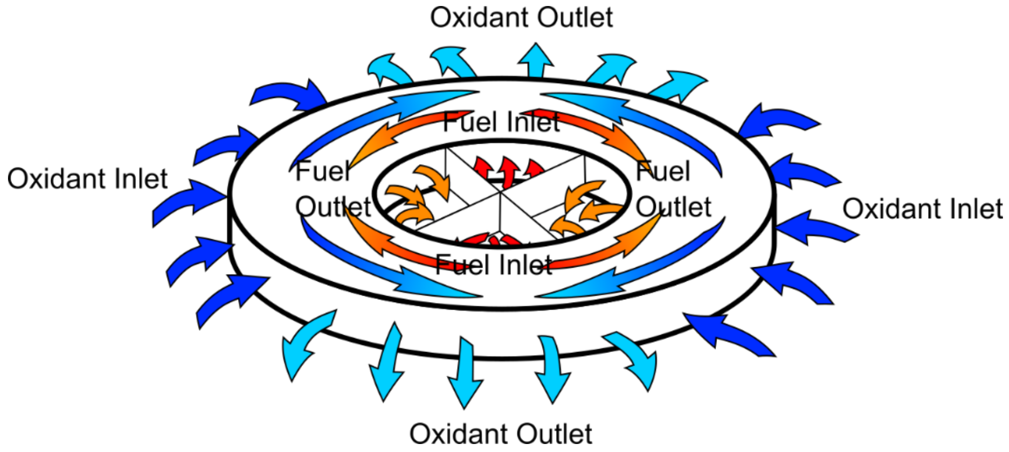
Integrated compression

Oxidant outlet manifold

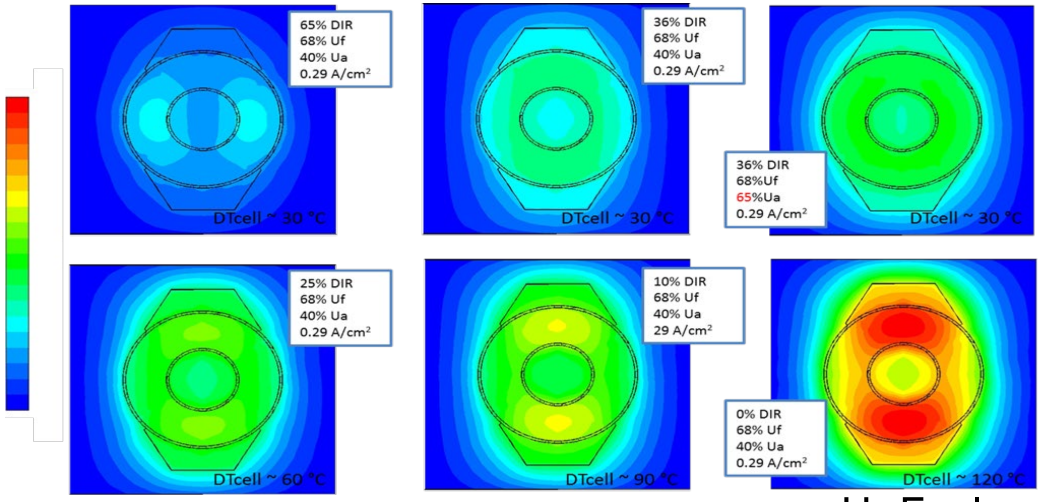


350 cells - 17” tall

Flow Geometry



NG Fuel



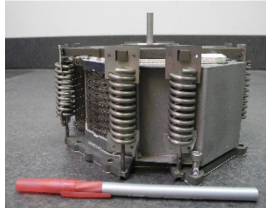
H_2 Fuel

Modeling and tests indicate that CSA stacks allow for flexible operation regarding fuels including Natural Gas with in-stack reforming as well as hydrogen

Flexible structure offers compliance and robustness

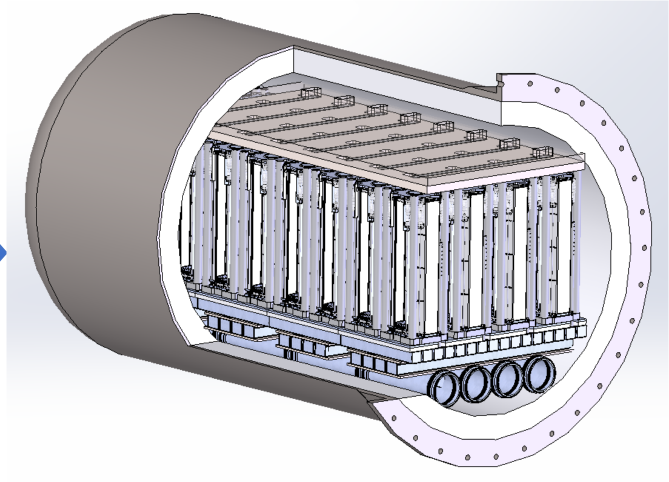
Compact SOFC Architecture (CSA) Stack Platform

Property	CSA Stack Scale			Comments
	Short	Mid	Full	
Cell count	50	150	350	
Fuel cell voltage, V	42	128	298	At 0.85 V/cell
Stack power, kW	1.0	3.0	7.0	At 0.29 A/cm^2
Height, cm	9.1	21.1	44	


Short


Mid

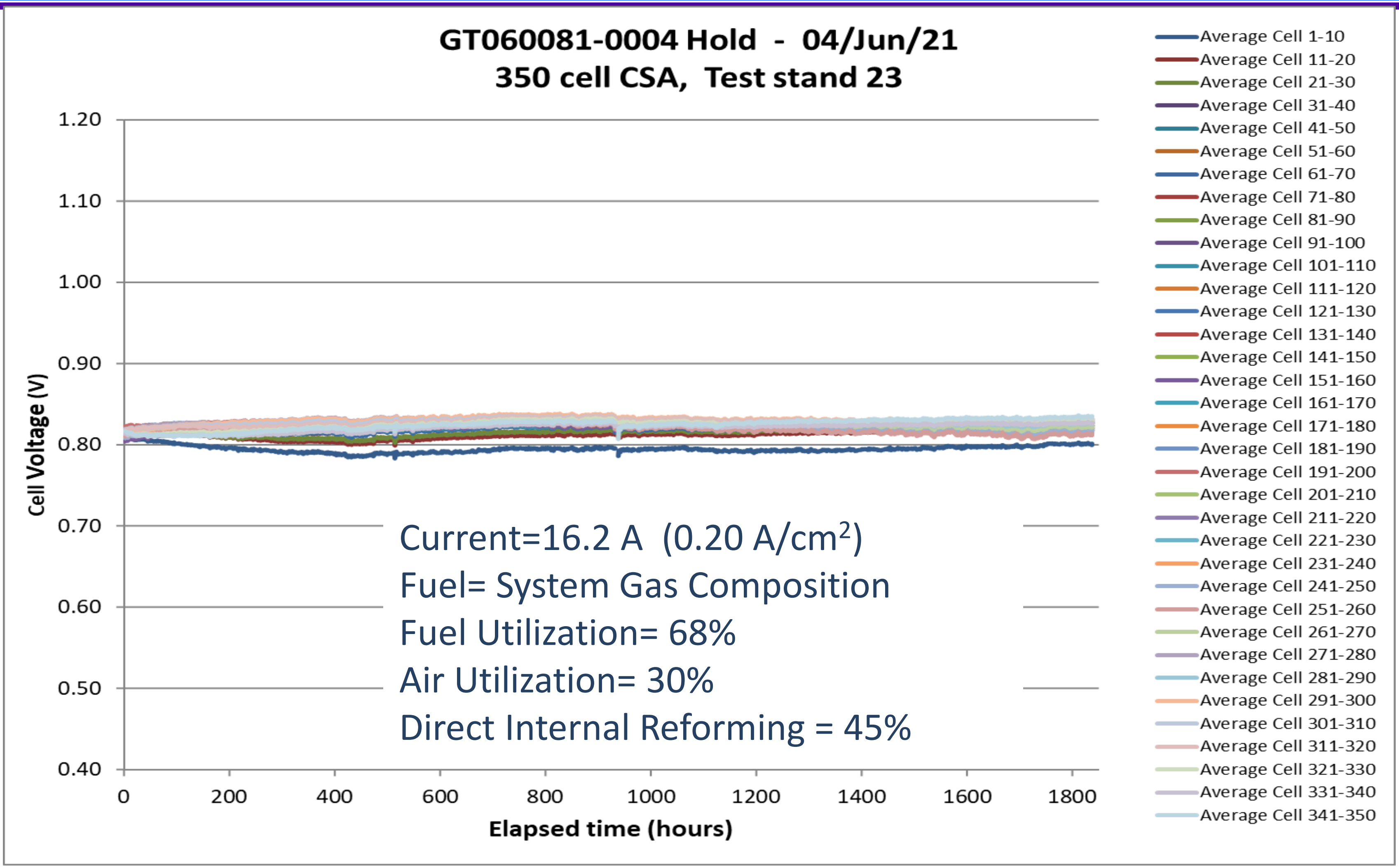

Full Size


Stack Module

New generation stack utilizes advanced thin and lightweight cell structure

Recent Full Height Stack Test

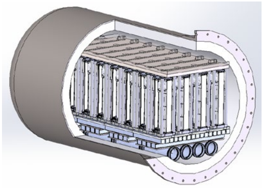
GT060081-0004



- Completed over 1800 hours of fuel cell operation on system gas compositions with good voltage stability and tight voltage spread (35 mV)

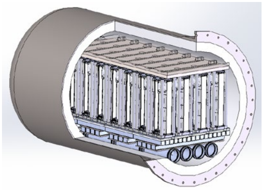
Solid Oxide Applications

SOFC Stack

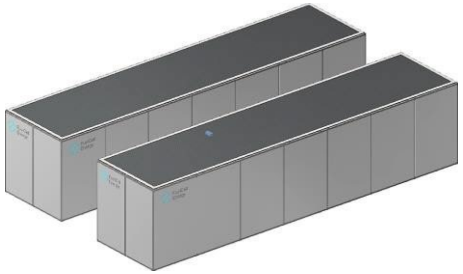


Power Generation Stack Module –Runs in power generation mode on a wide range of fuels, including natural gas, biofuels and hydrogen

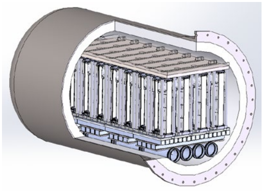
200 kW Power Generation System



Electrolysis Stack Module – Produces hydrogen from steam with power input



Electrolysis
600 kg/day H2 from 1.1MW



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

Energy Storage System
1MW, 8MWh

Versatile platform with multiple commercialization pathways

Cell And Stack Manufacturing

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High Volume Cell Manufacturing

- Utilize established baseline TSC3 cell design and manufacturing, (120 mm Ø) and anode-supported cell (0.3 mm thick)
  - Design for high-throughput manufacturing technologies for thin components taking cues from CD / DVD manufacture
- Manufacture high quality cells and stacks based on controlled documentation:
  - Drawing and Material Specifications
  - Work Instructions, and Incoming Inspection Plans
  - Continued emphasis on quality and Gage R&R for QC tools
- Identify and plan for resolving process gaps, equipment throughput bottlenecks, as well cost saving and efficiency improvements

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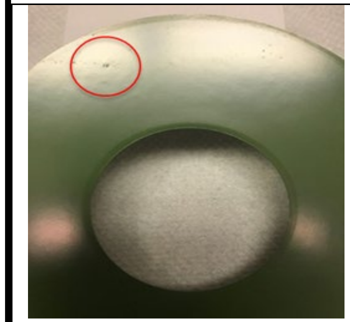
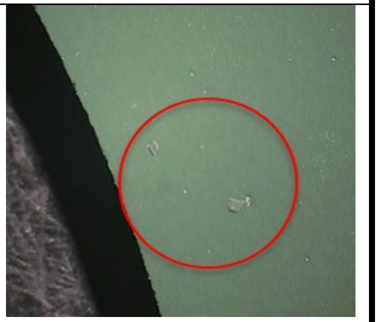
Cell Quality Control

Cell Quality Control and Multiple Steps

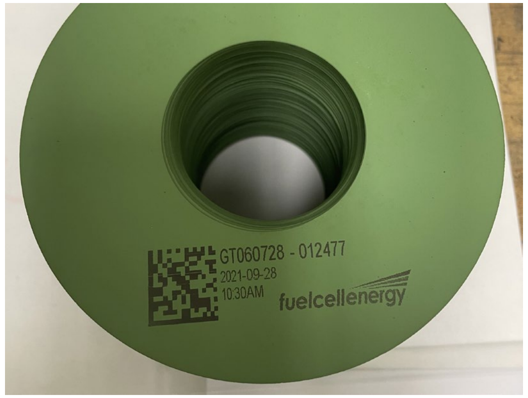
- Dimensional – Inner Diameter, Outer Diameter (via Machine Vision)
- Dimensional - thickness
- Electrolyte Integrity via leak check
- Visual for various cell defect types
- Cells individually serialized with QR coded tied to: cell history, input materials and QC data

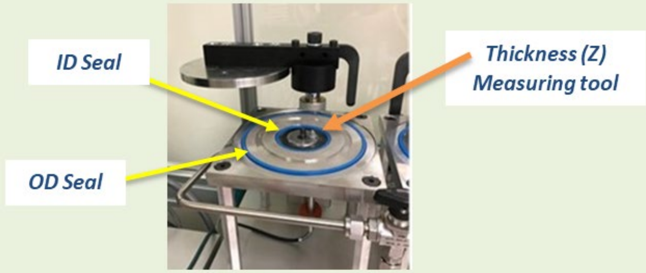
Visual Defects





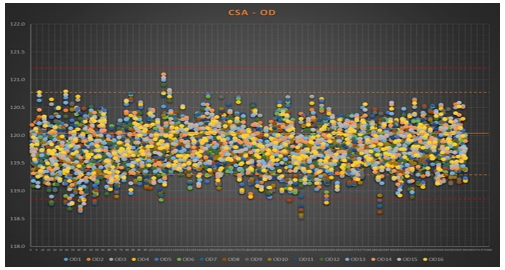
Hole	Air Bubble	Debris / Contamination





CSA Cell Leak Tester Jig with Thickness Measuring Tool

Leak Testing of CSA cell

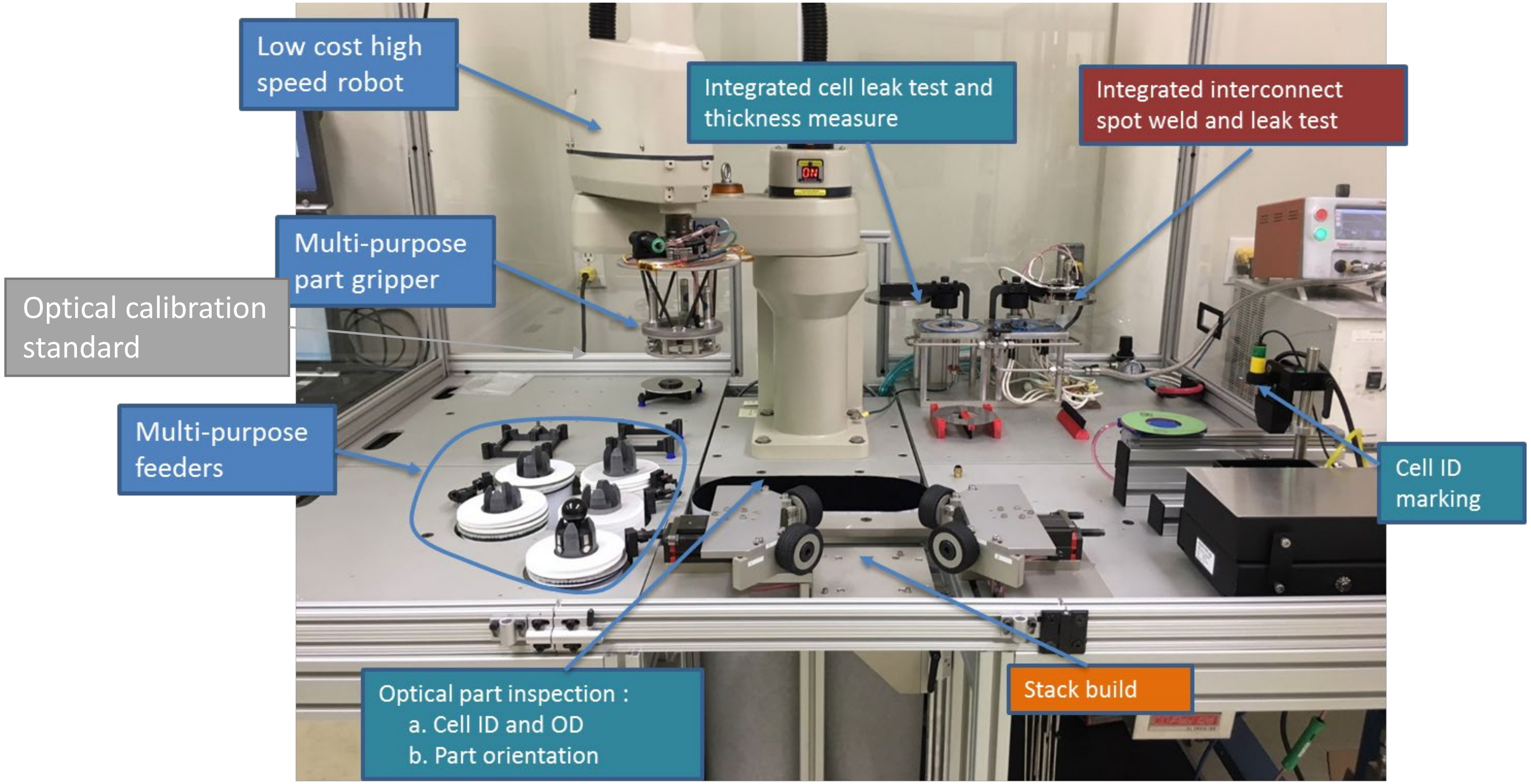


Robotic work cell for:

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

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

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



Stack Manufacturing Approach

- Utilize high speed pick and place robot for efficient sub-assembly build, cell and component QC and precise cell / stack assembly
- 50 minutes to assemble a 350-cell stack

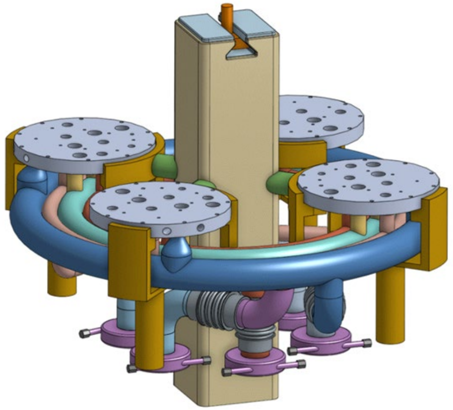
Manufacturing Expansion to Enable Sub-MW & MW-scale Systems

- Cell and stack fabrication yield improvements
- Automated screen printing on half-cells
- Multi stack conditioning
- Development of standardized work instructions
- Streamlined and efficient inventory management

Robotic Sprayer

Auto Screen Printer and Dryer

Stack Transporter



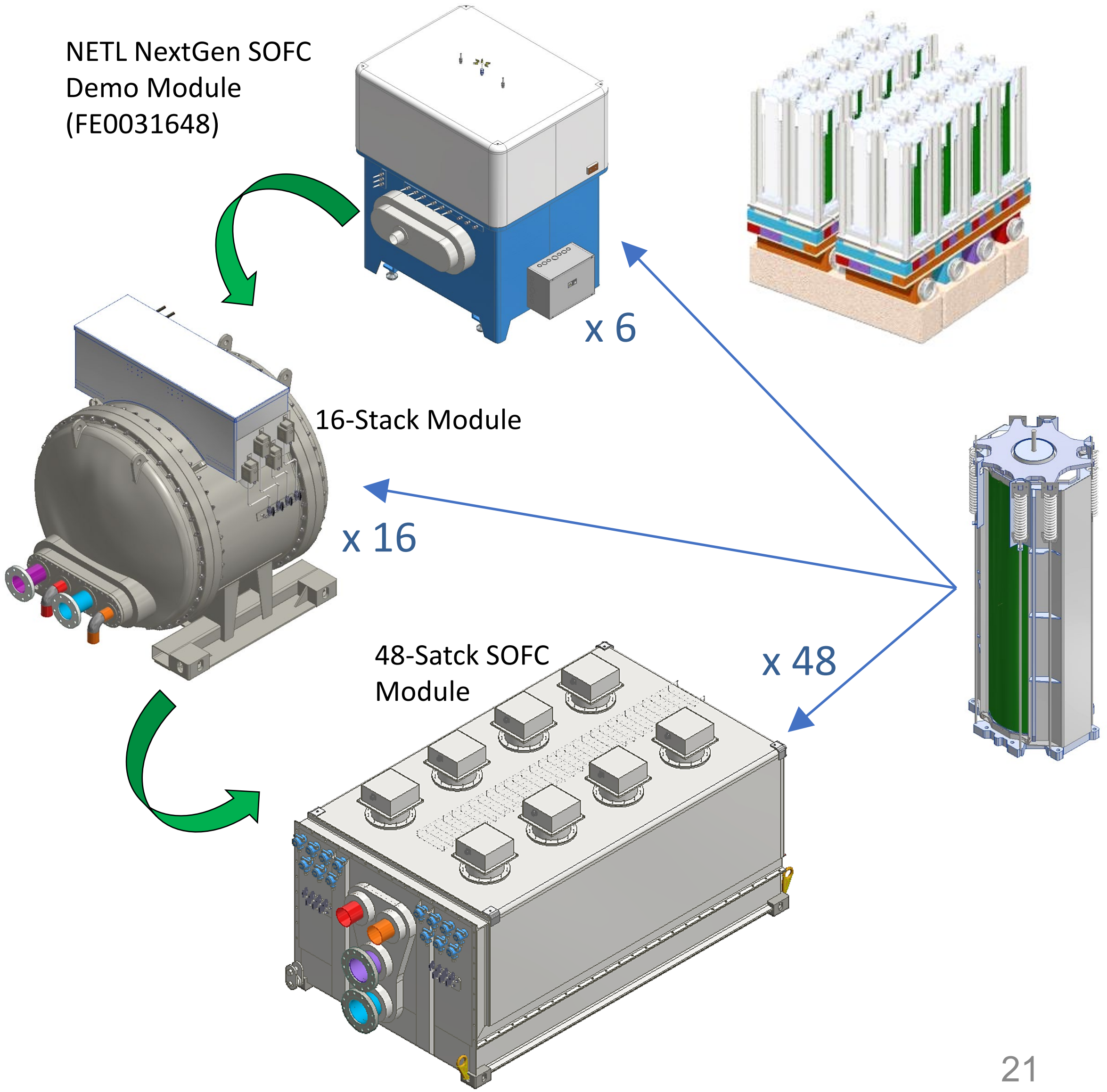
Multi-Stack Conditioning Manifold

Focused on new technology and automation

SOFC Stack Module Design

SOFC Module Development

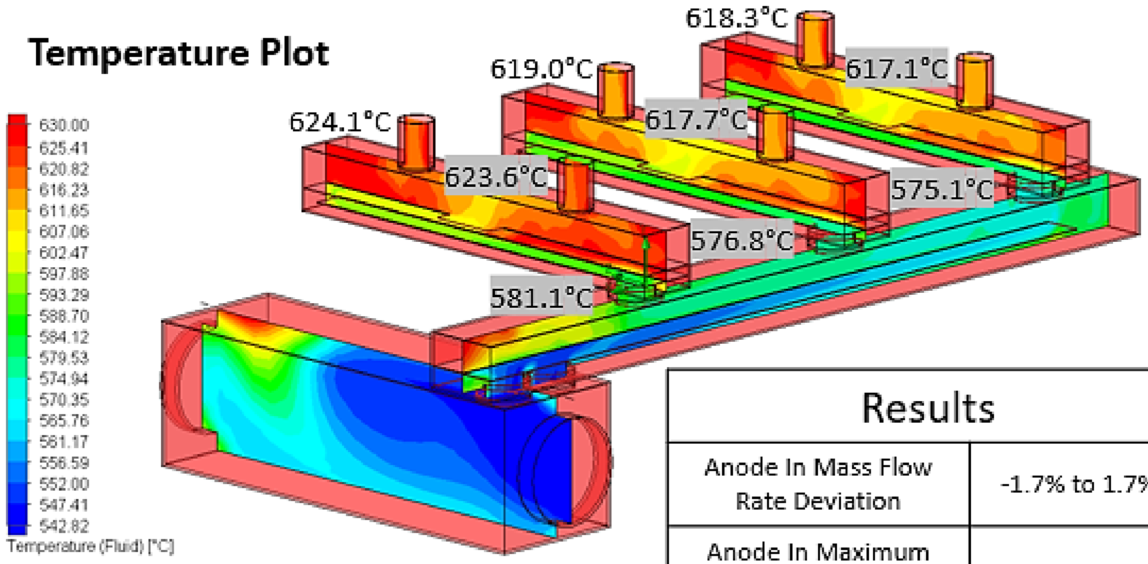
- Stack modules of various power ratings under development using stack arrays as building blocks:
  - 6-Stack SOFC Test Module
    - 40kW$_{DC}$ Rated Power
    - **Status**: Receiving final components to build and test
  - 16-Stack Solid Oxide Module
    - 100 kW$_{DC}$ Rated SOFC Power
    - Minimum 150 kg/day SOEC H_2 Production
    - **Status**: Being built for an electrolysis demonstration at Idaho National Laboratory (INL)
  - 48-Stack Solid Oxide Module
    - 318kW$_{DC}$ Rated SOFC Power
    - Leverage design work completed from 16-Stack Module
    - **Status**: Being developed as a basis for the future
- Lessons from fabrication and testing of smaller SOFC modules will feed into the design of the MW Plant 48-Stack module



Module Design and Component Development

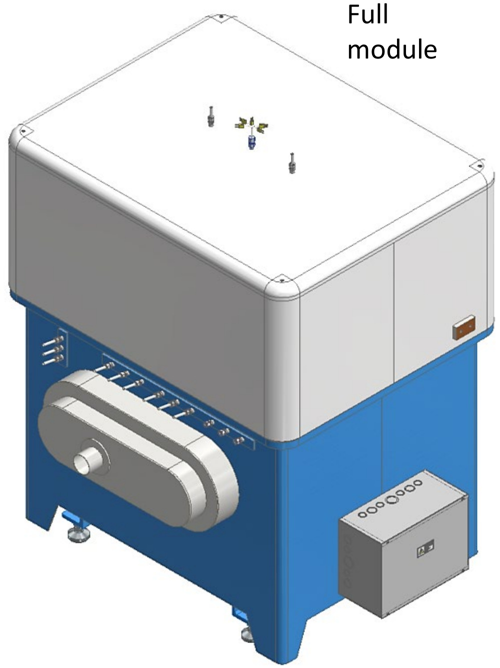
- Developments from NextGen SOFC Module
  - Process gases distributed to 6 stacks via multi-layered **Stack Distribution Base** connected to plumbing passing through sides of steel enclosure
    - CFD was used to achieve excellent flow and thermal distribution between stacks

Temperature Plot



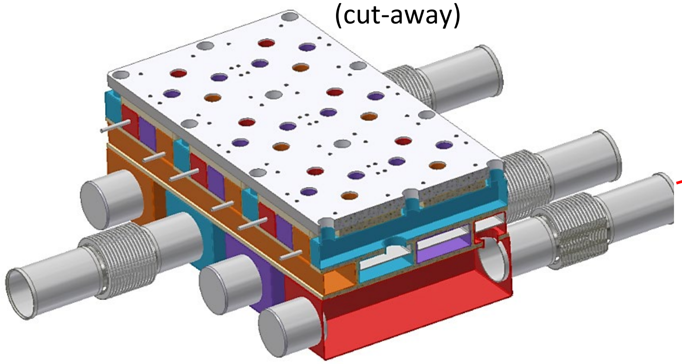
Results	
Anode In Mass Flow Rate Deviation	-1.7% to 1.7%
Anode In Maximum Outlet Temperature Variation	7.0°C
Total Anode Press Drop (In to Out of Module)	25.5 IWC

Full module

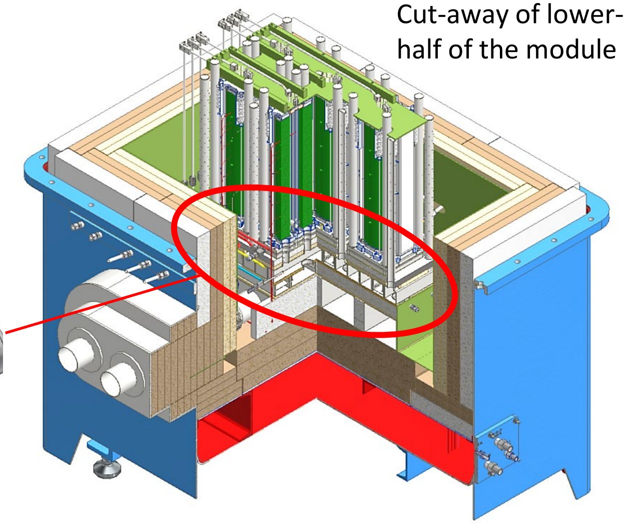


Vessel received in Danbury

Stack Distribution Base (cut-away)

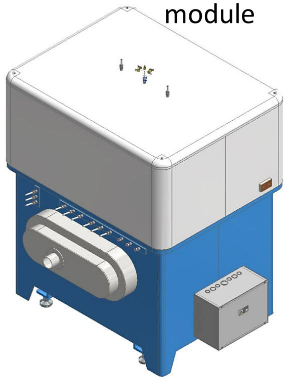


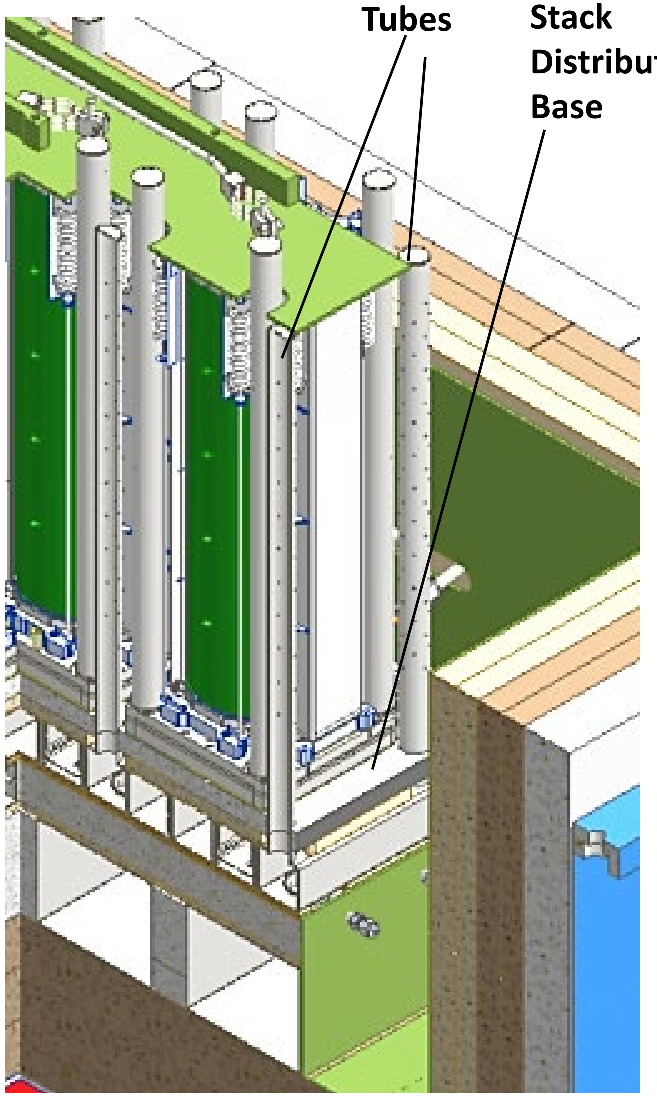
Cut-away of lower-half of the module

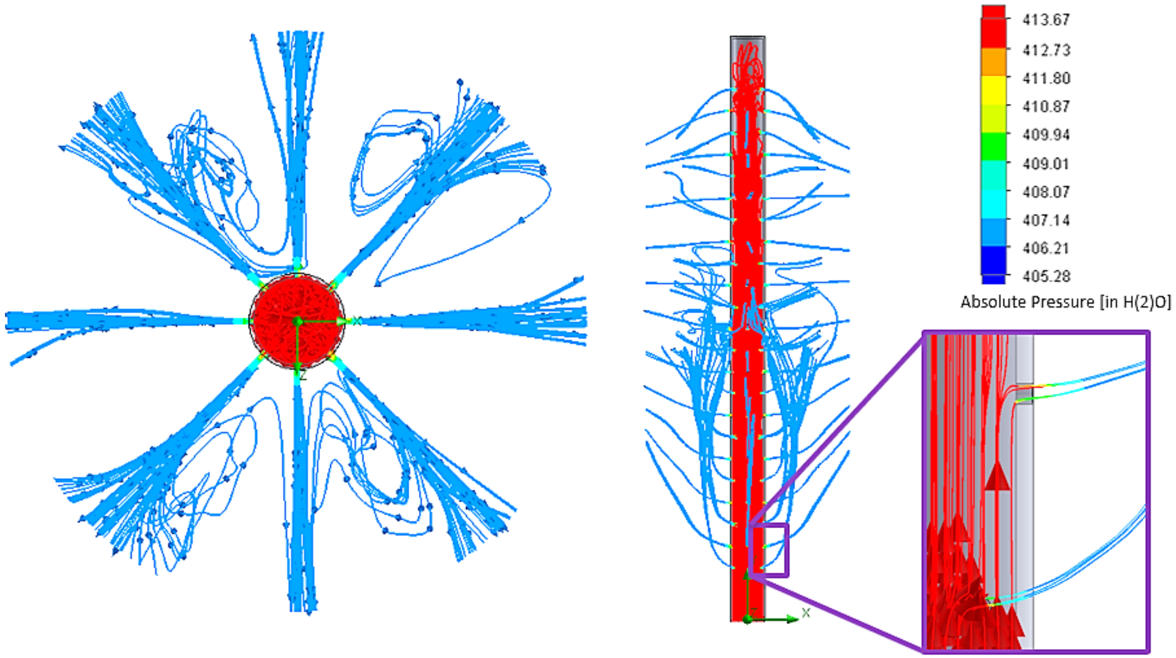


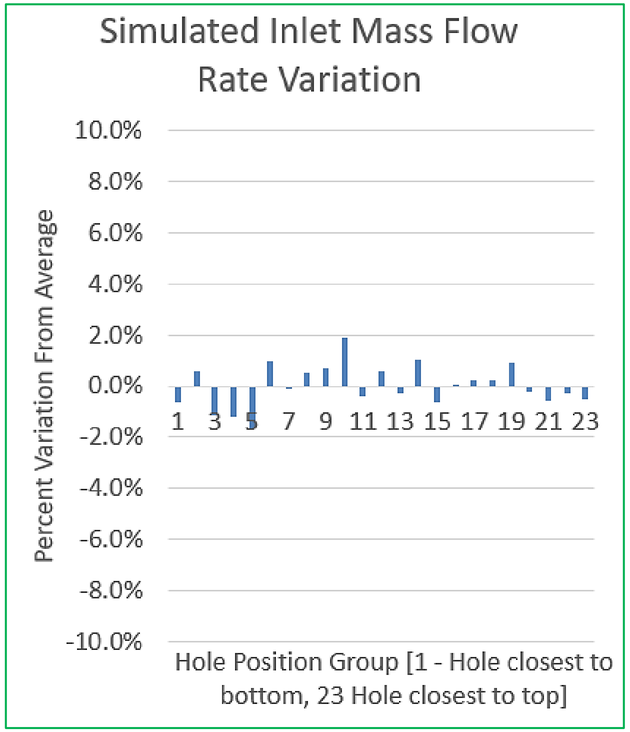
Air Distribution

- Developments from NextGen SOFC Module
  - **Air Distribution Tubes** (ADT) protrude vertically from the *Stack Distribution Base*
  - Dead-ended perforated tubing modeled in CFD software to evaluate flow distribution along height of tube.
  - Performance of the **ADT** meets basic requirements of:
    - Mass flow distribution
    - Maximum allowable pressure drop









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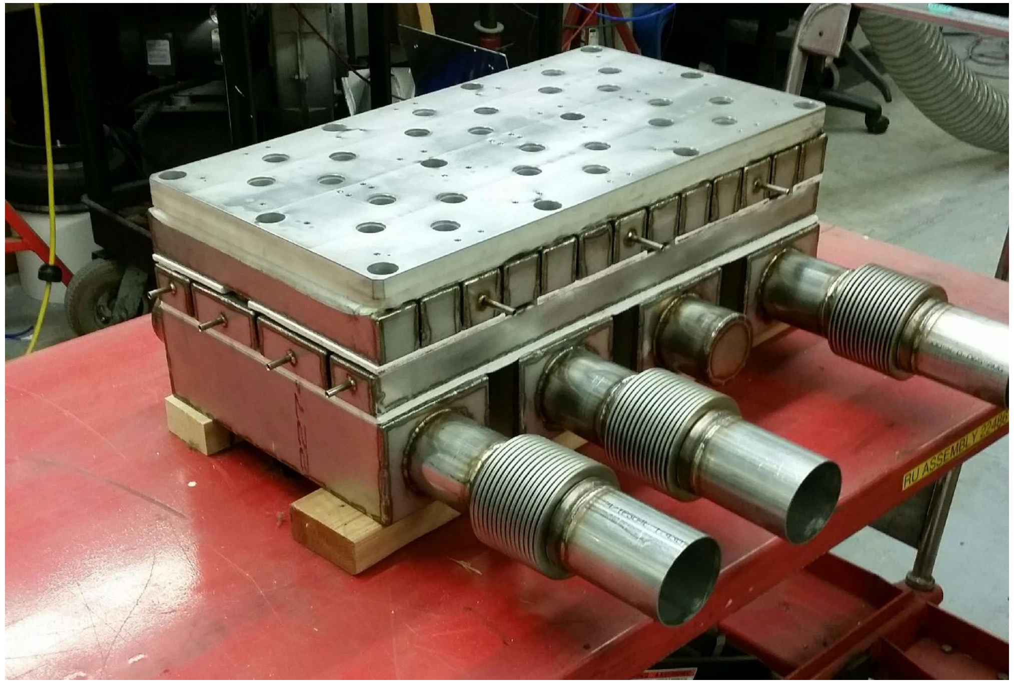
40 kW Stack Module Build Status

Upper Enclosure Insulated

Lower Enclosure

Power Take Off Bus Bar Hardware



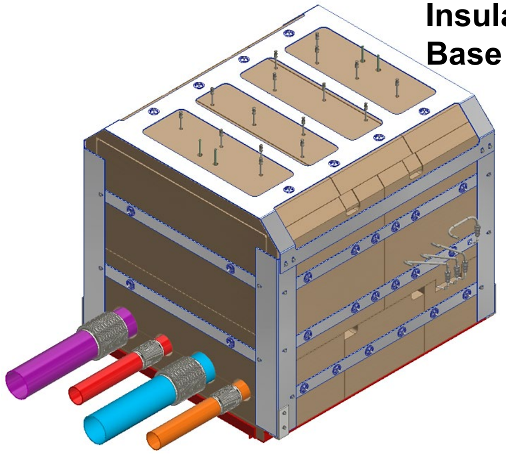
Stacks Base Plate

Two Stacks in Shipping Container

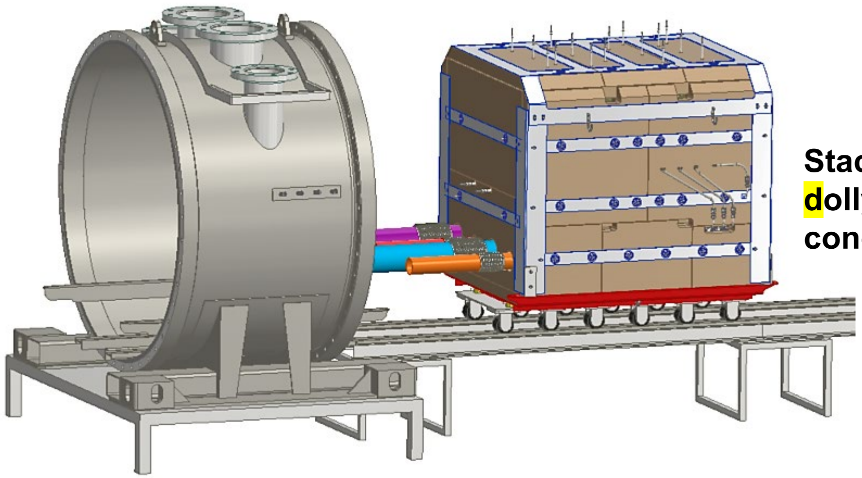
Components are fabricated for final assembly of 6-stack stack module

16-Stack Module Design

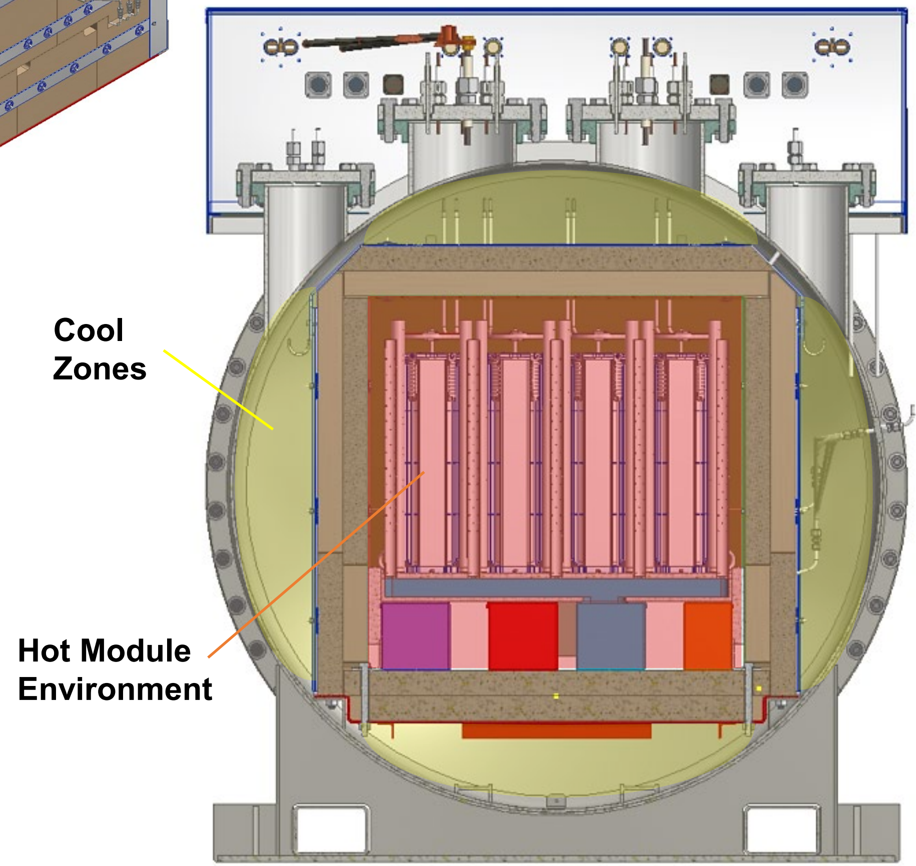
- 16-Stack Solid Oxide Module
  - Pre-assembled Stack Base Assembly maximizes access by production floor assemblers
  - Houses Stacks, Stack Distribution Base and accompanying I/O & power take-off hardware
  - Includes fitted insulation panels held together and secured by easily handled bolted sheet metal
  - Base Build Plate FEA determined appropriate material for low cost welded fabrication
  - Stack Base Assembly unit inserted into Module Enclosure shell via dolly and rails



Insulated Stack Base Assembly

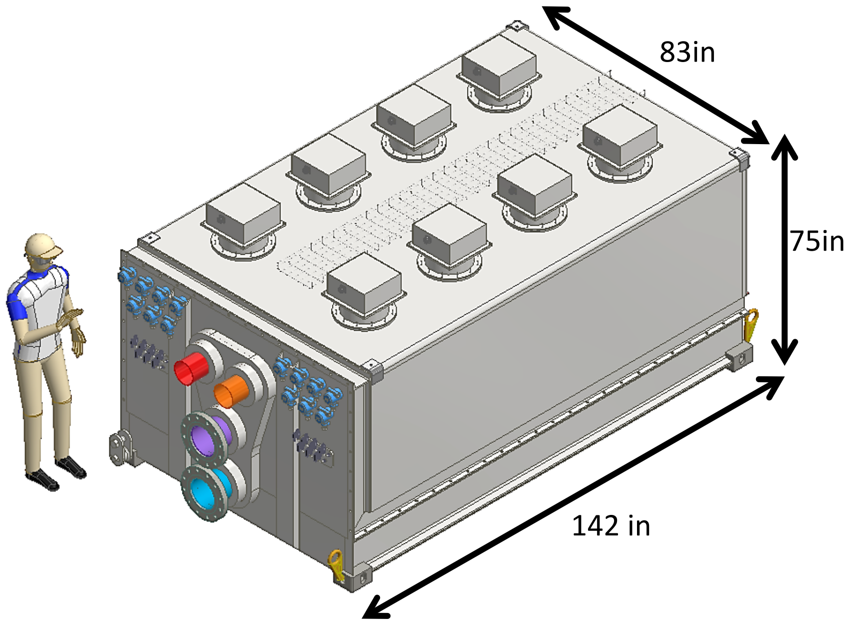


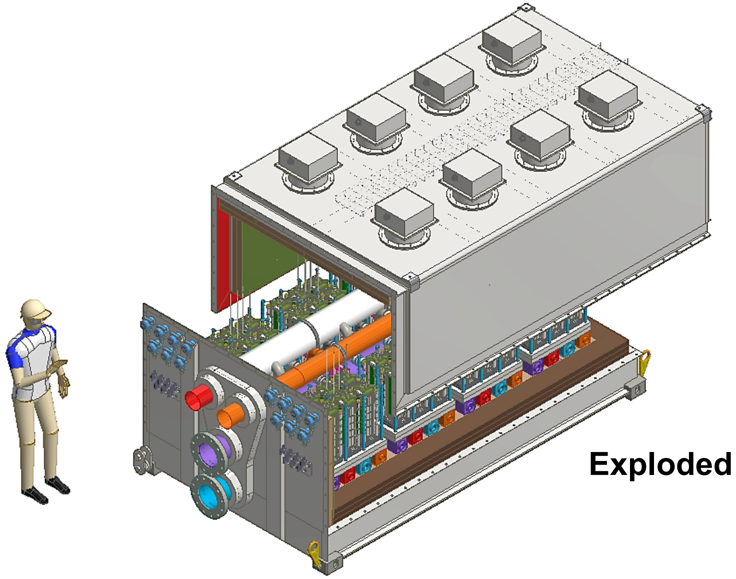
Stack Base Assembly dolly & rails loading concept

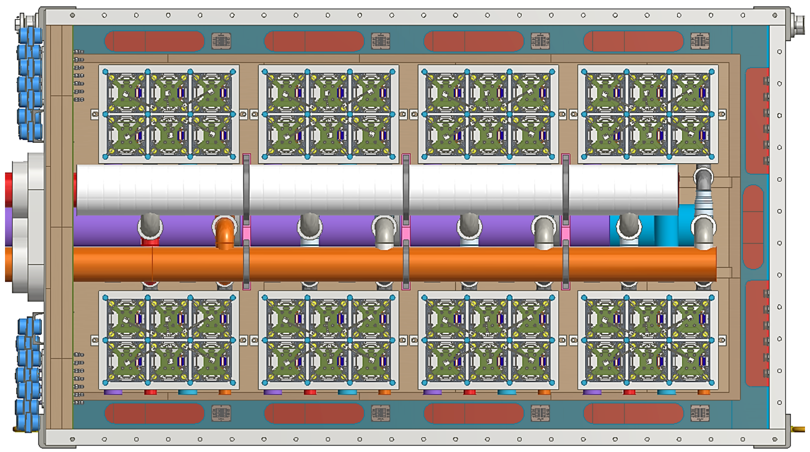


Scaling to MW Plant Module

- 48-Stack Solid Oxide Module for Large Scale Applications
  - Incorporate lessons learned from fabrication, assembly, and testing of the 40-kW stack module
  - Lifting access via standard ISO container corner blocks while providing option for forklift access
  - Process gas header channels that run underneath the multi-layered base designed for adequate gas flow to the entire length of the base
  - Designed for ease of factory assembly and future commercialization




Exploded View

Cut view of the full module


System Design

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SubMW SOFC System Development

- 50 kW (2014-2016)
- 1st Gen Stack
- Fuel: NG

- 200 kW (2017-2020)
- 1st Gen Stack
- Fuel: NG

- 250 kW Commercial Products
- CSA Stacks
- Muti-Fuel: NG, ADG, H2

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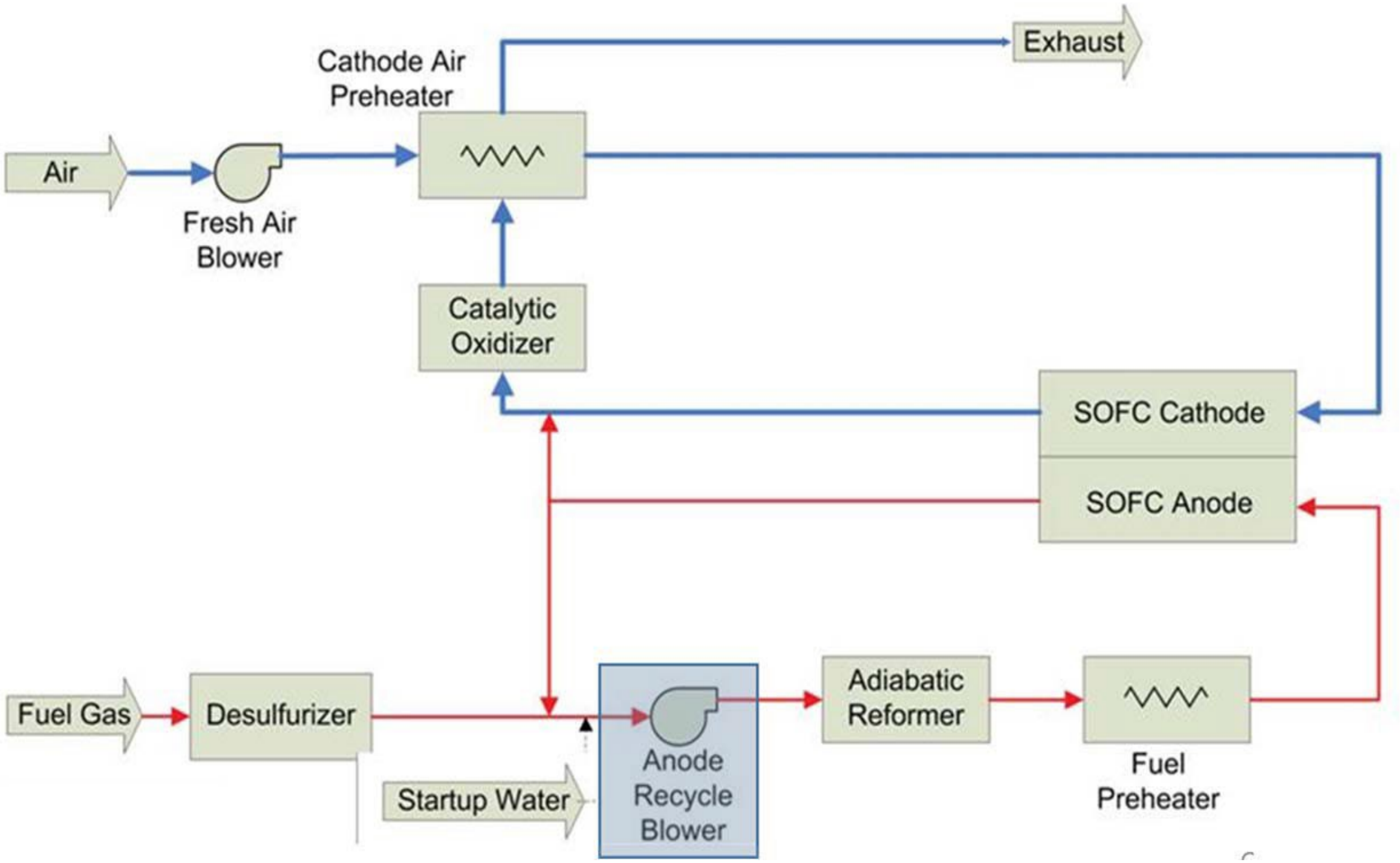
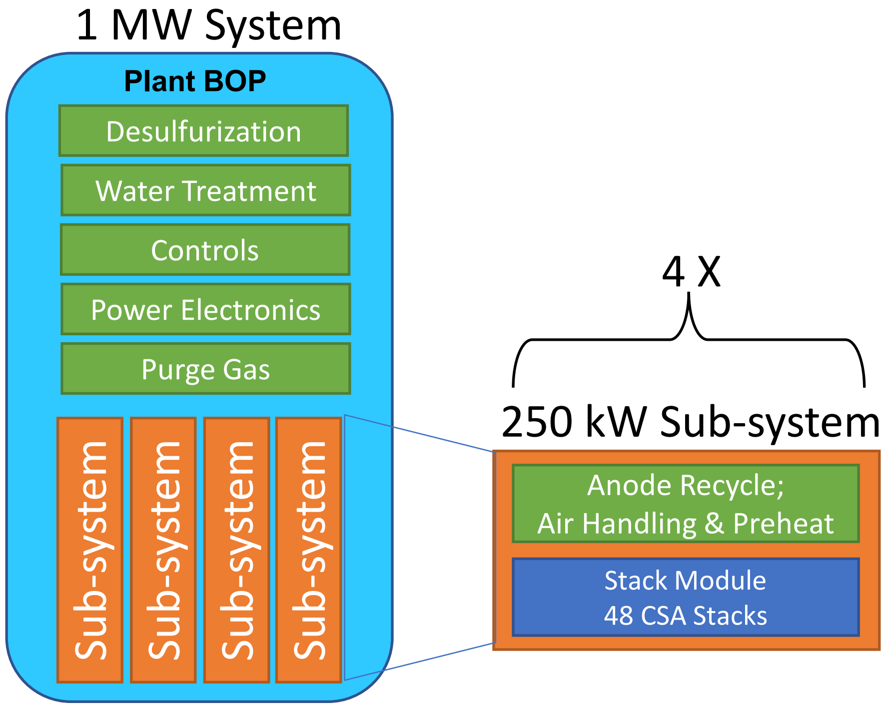
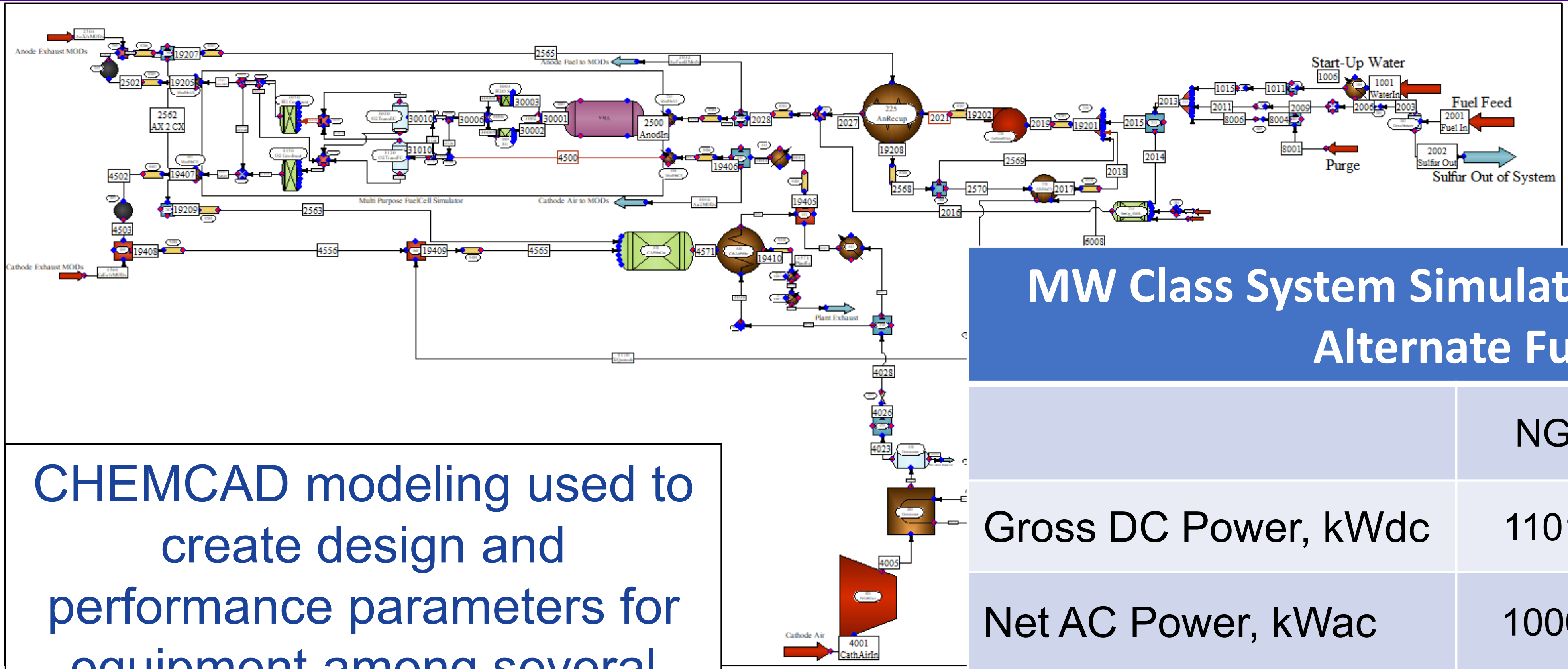
1 MW SOFC System Process Design





SubMW SOFC system design is used as the foundation for larger systems

Simulation Performance

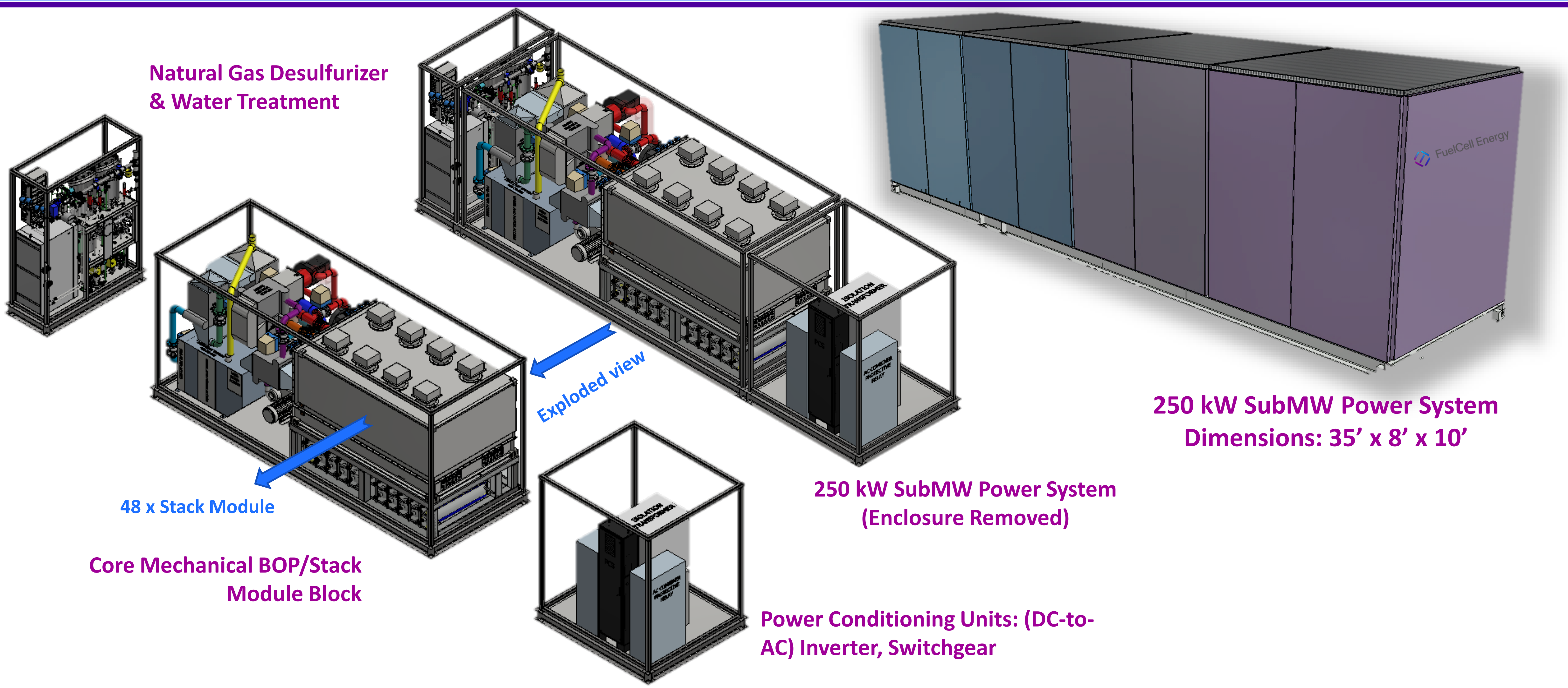


CHEMCAD modeling used to create design and performance parameters for equipment among several different operational modes for the plant

MW Class System Simulation Performance Alternate Fuels

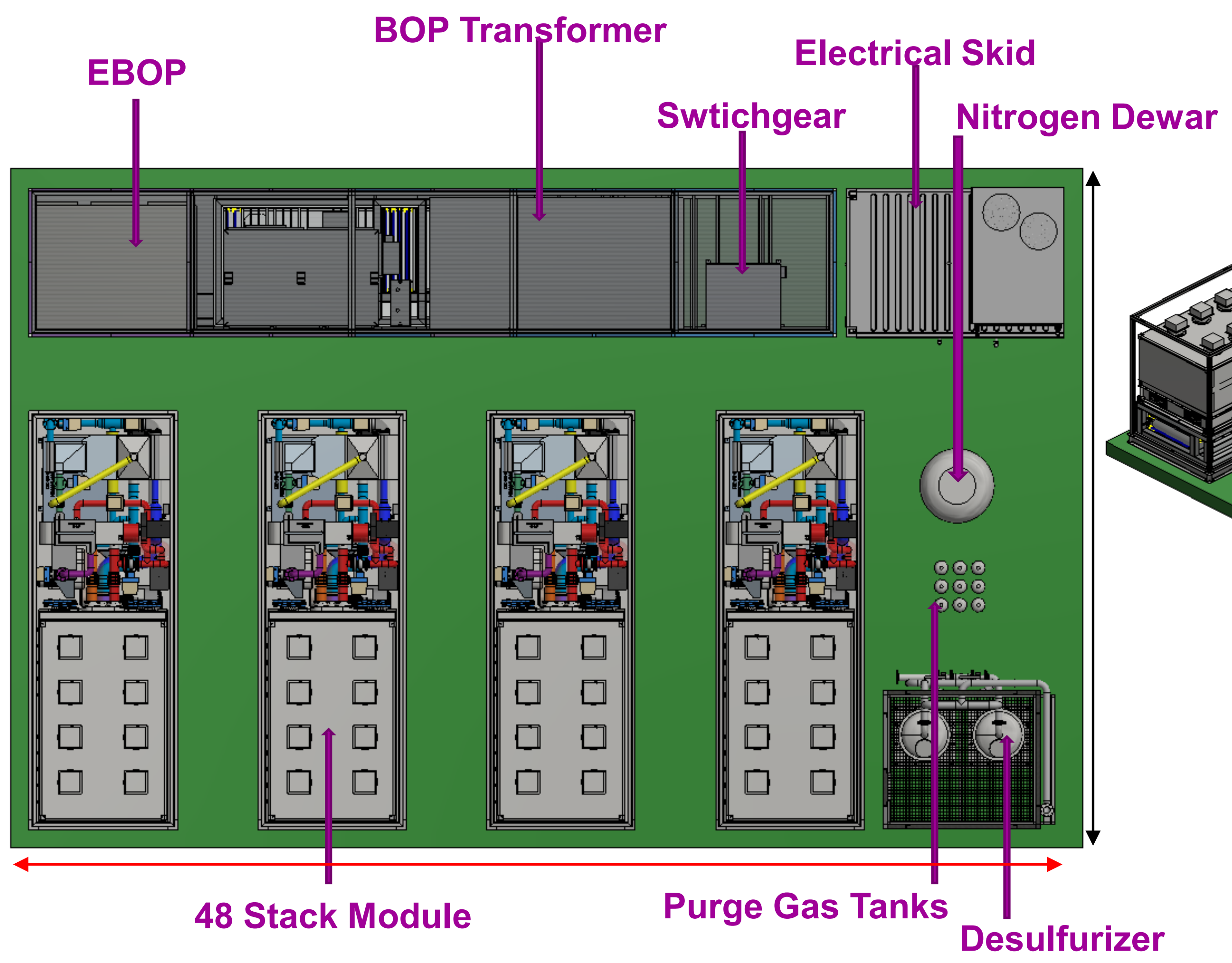
	NG	ADG	H_2
Gross DC Power, kWdc	1101	1143	1161
Net AC Power, kWac	1000	983	1000
Electrical Efficiency, [LHV / LHV with CHP]	62 / 86	55 / 82	65/77
CO_2 Emissions, $kgCO_2/MW_h$	331	597	< 1

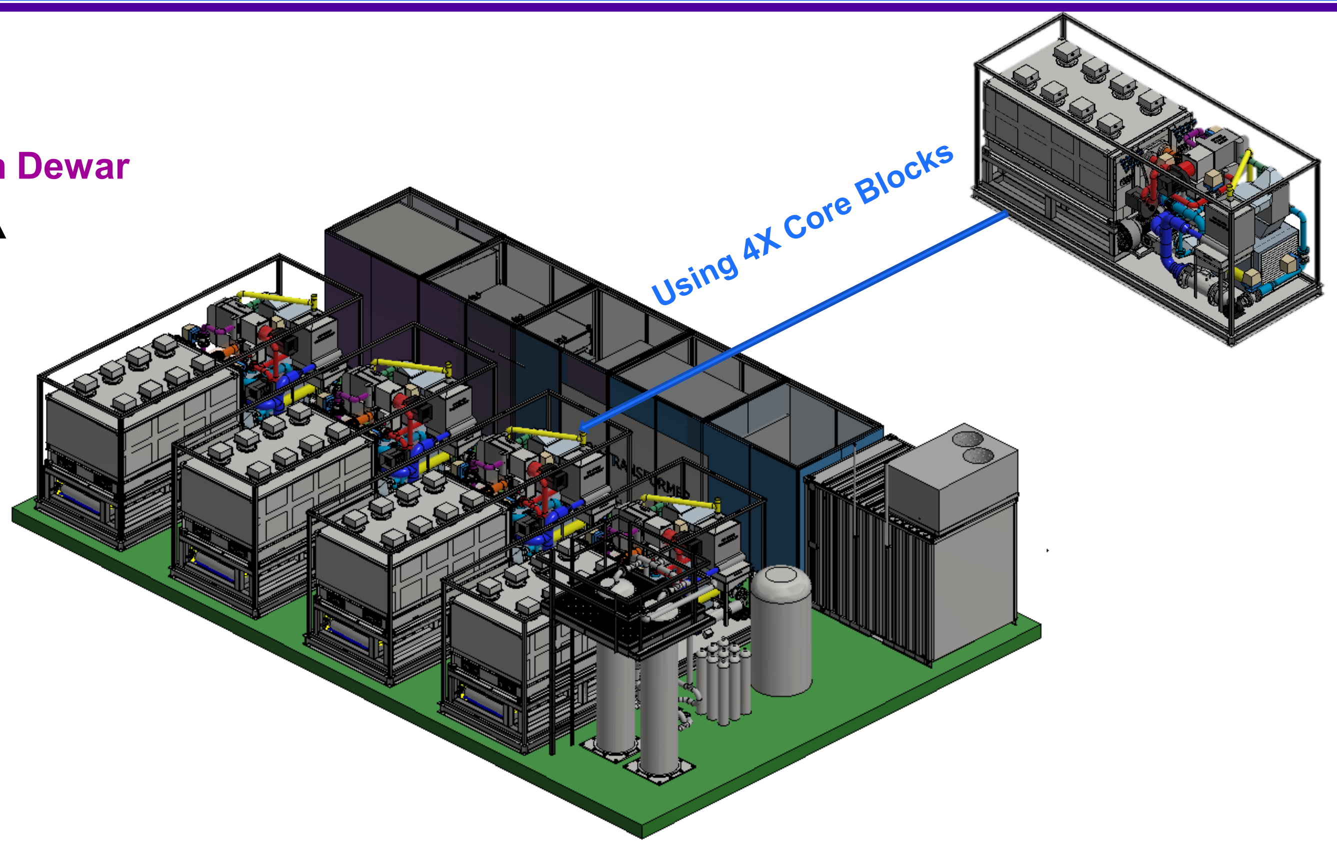
Repeating Core BOP/ Stack Module Block



Repeating Core BOP/Module Blocks for MW-Class System Based on Design of SubMW Systems

MW SOFC Plant Design





MW SOFC System Layout

Plant (**57.75' x 36.75'**) 2,122sf

Plant plus maintenance (**57.75'x 49.25'**) 2,844sf

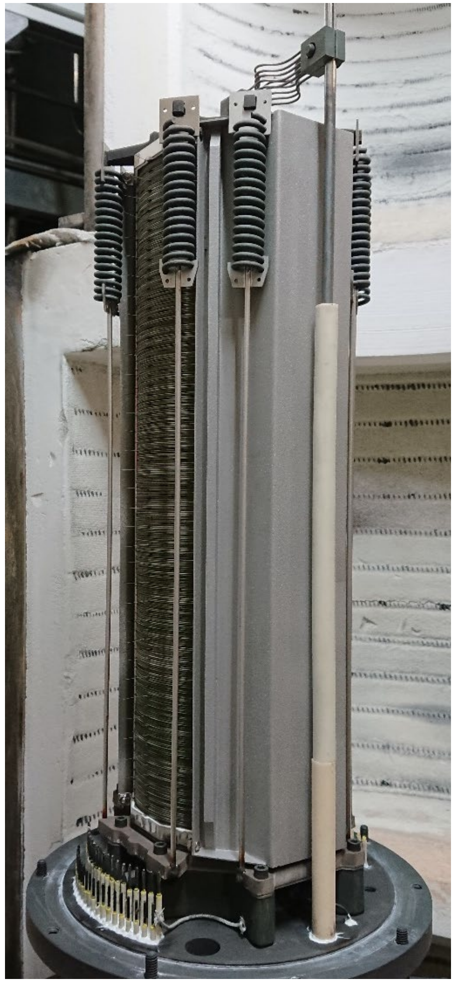
High Power Plant Availability Achievable Utilizing Repeatable Core Blocks

Techno-economic Analysis

FuelCell Energy

CSA Stack Cost Update @1 GWe/yr Production

- CSA Stack Factory Cost updated from 2019 estimate (DE-FE0026093) including the following modifications:
  - Cost sensitivity analysis of different parts containing nickel (part thickness and porosity) for high volume costing
  - Updated re-designed non-repeat parts (NRP) cost including top and bottom end plates and air manifolds
  - Advances in manufacturing automation
  - Cost trade-off analysis for protective Manganese-Cobalt Oxide (MCO) coating processes
  - 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

Costing following DOE Methodology and Recommended Inputs

1 GW CSA Stack Cost Distribution

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

$ 863 / stack
at
160,000 stacks/year

58% of the estimated cost is due to material

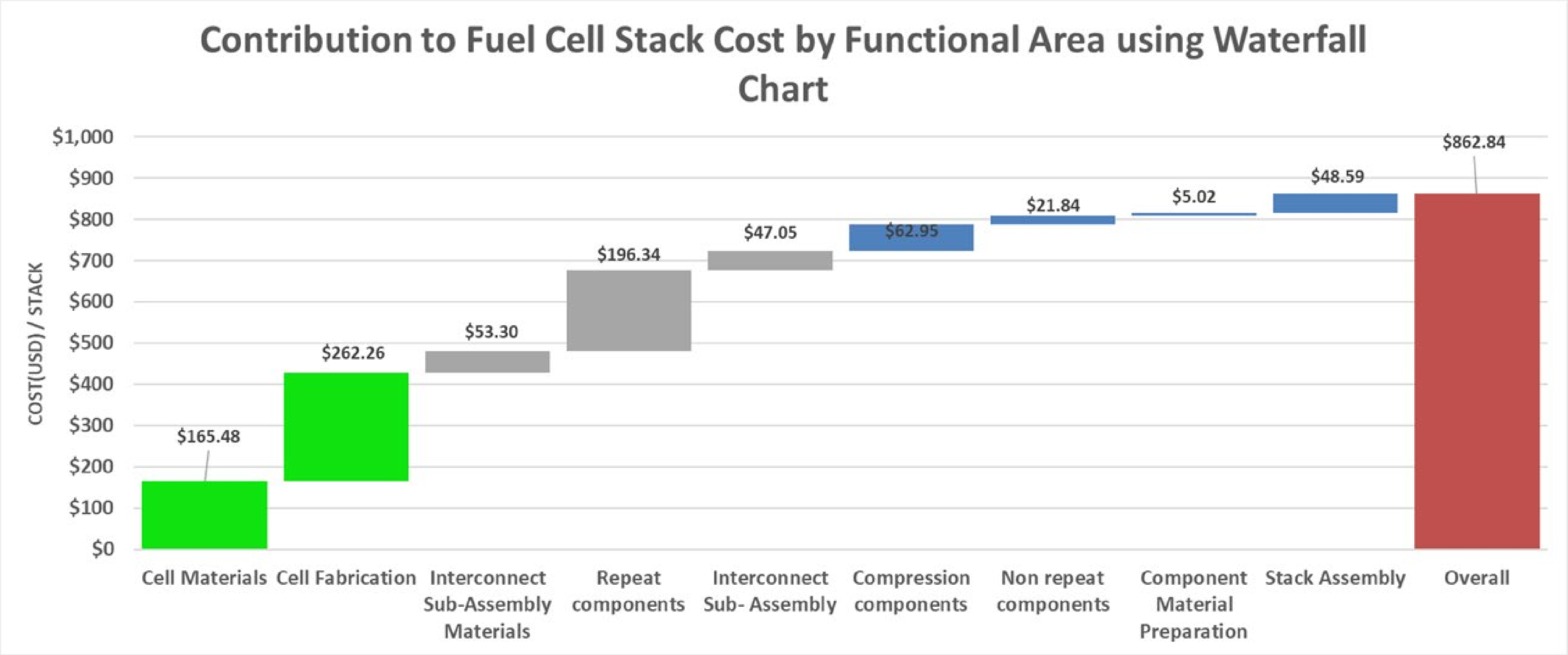
Stack cost per unit power produced:

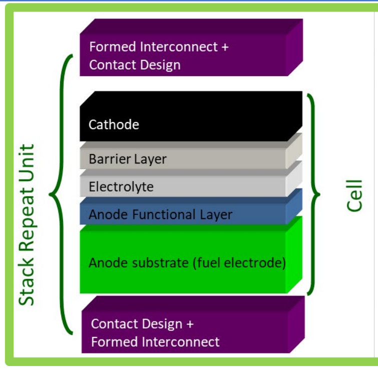
= *$122 $/kWe DC (gross)*

= *133 $/kWe AC (Net)*

< $225 / kWe AC DOE cost target

1 GW Factory Cost Estimate – Waterfall Chart

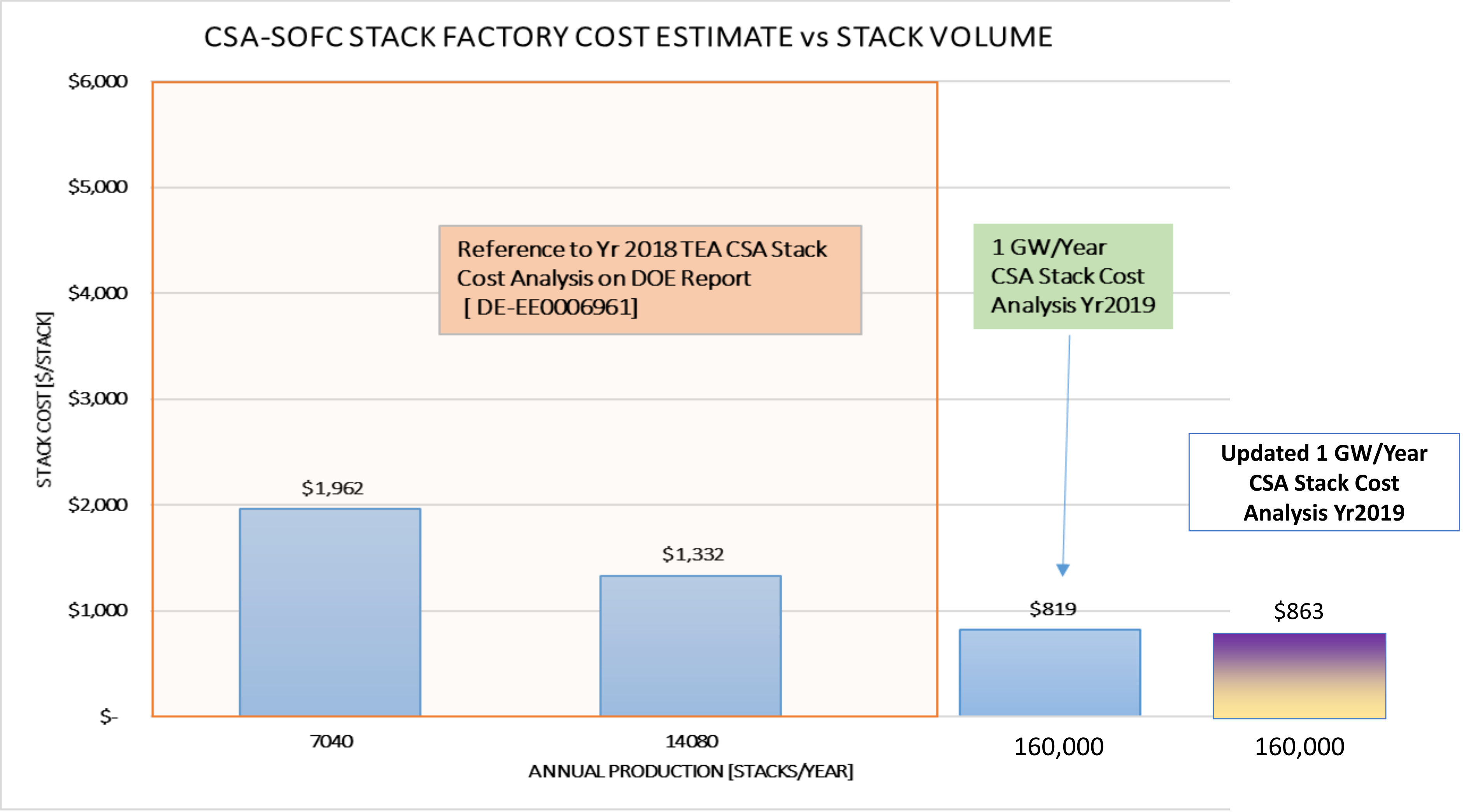




Top 3 cost contributors by **Functional Area** are:

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

Volume Impact / Previous Work



FCE In-house Methodology *DOE Methodology*

Wrap-Up

Wrap-up

- 48-stack module design has been developed utilizing key components derived from configuration of existing smaller modules (6 and 16 stacks):
- 1 MW SOFC system design development is being matured from conceptualization to the next level of detailed engineering:
  - System concept was developed achieving efficiency >60% on Natural Gas fuel and incorporating capability for utilizing hydrogen fuel
  - Balance-of-Plant (BoP) key equipment were identified, and design data sheets were prepared
  - Preliminary 3-dimentional CAD model and system layout were developed to ensure reduced installation cost and ease of maintenance
  - Technoeconomic analysis has shown that at low annual volume production of one MW, a plant cost of <$6000/kW is feasible meeting the DOE cost target for the first-of-a-kind 1MW SOFC system demonstration
- Factory cost of stacks at 1GW/year production is estimated to be $122/kWdc.

Thank You

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Our purpose:

Enable the world to be empowered by clean energy