FuelCell Energy

# MW-Class SOFC Pilot System Development (FE0031639)
# Next Generation SOFC Module Development (FE0031648)

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2023 FECM/NETL SPRING R&D PROJECT REVIEW MEETING

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# SOFC Systems Development

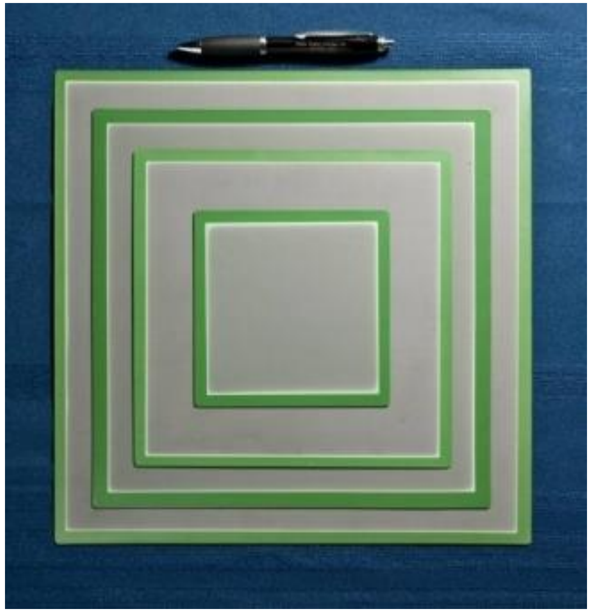
- Pathways to development of a low-cost, efficient, and reliable MWe-class SOFC power system towards commercial deployment in distributed generation applications:
  - Complete manufacturing analysis and planning to support efficient capacity expansion of 2nd generation cell and stack production processes to enable MW-class production rates at competitive cost
  - Design and test 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) |

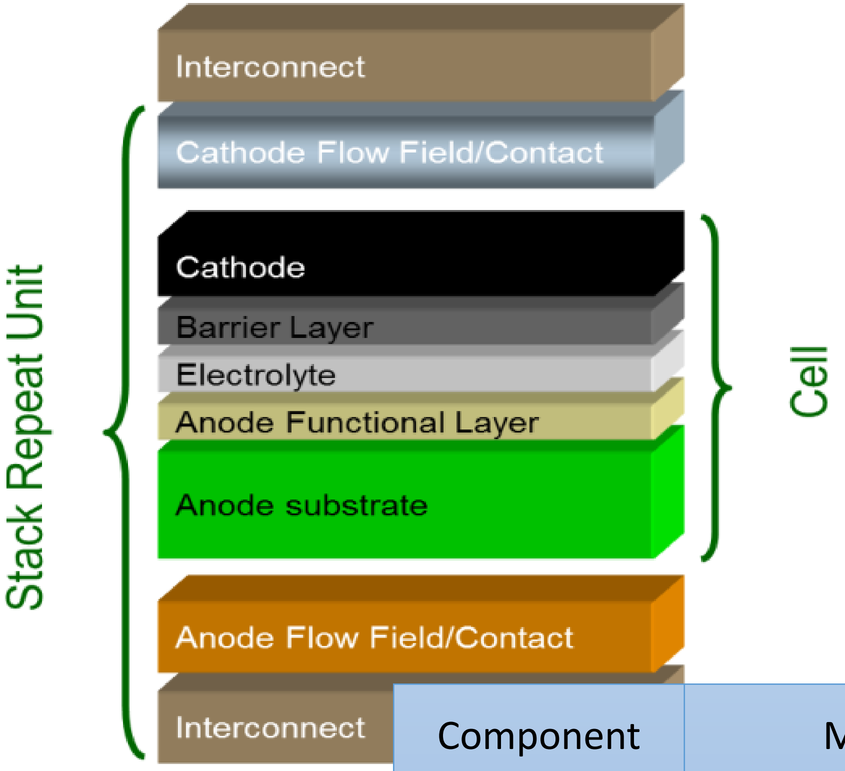
# SOFC Technology

# Solid Oxide Fuel Cell Technology Overview

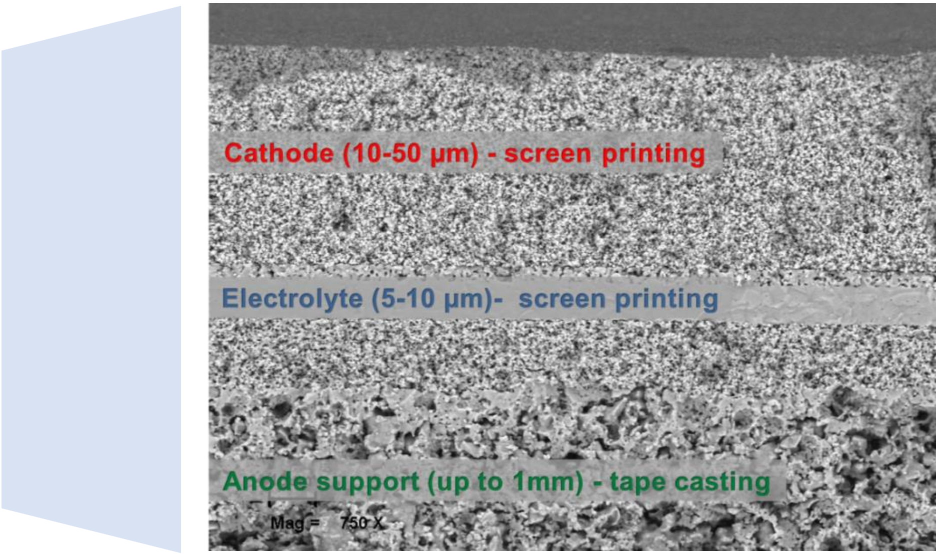


**Anode-Supported Solid Oxide Fuel Cell**

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

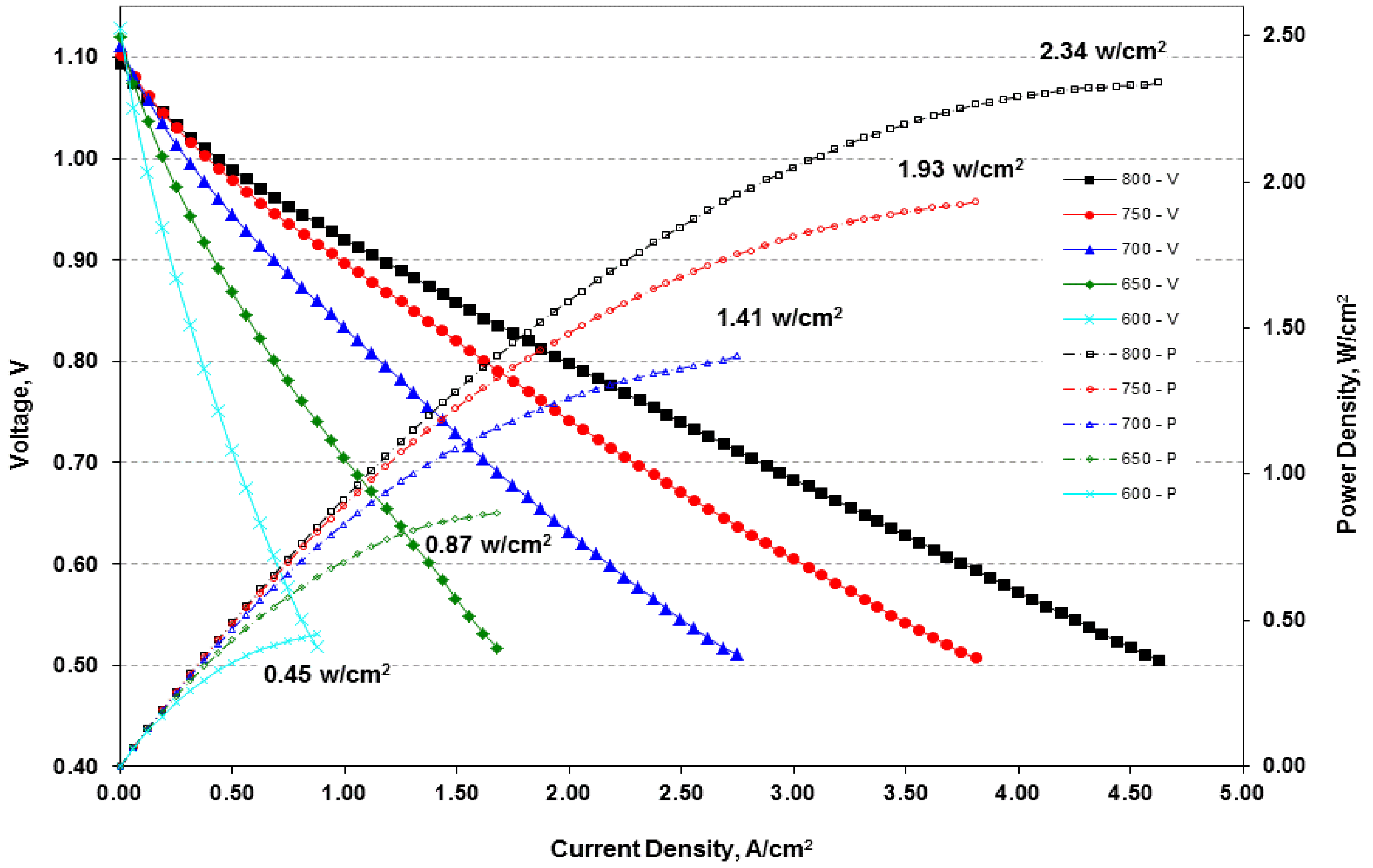


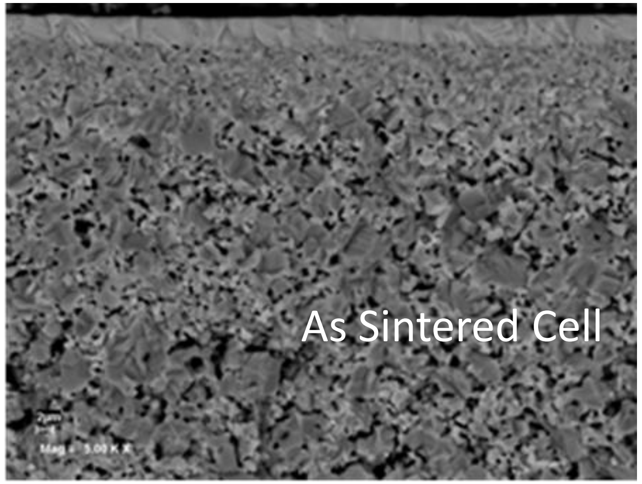

## Solid Oxide Fuel Cell Structure




| 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 |

# 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$^2$)**

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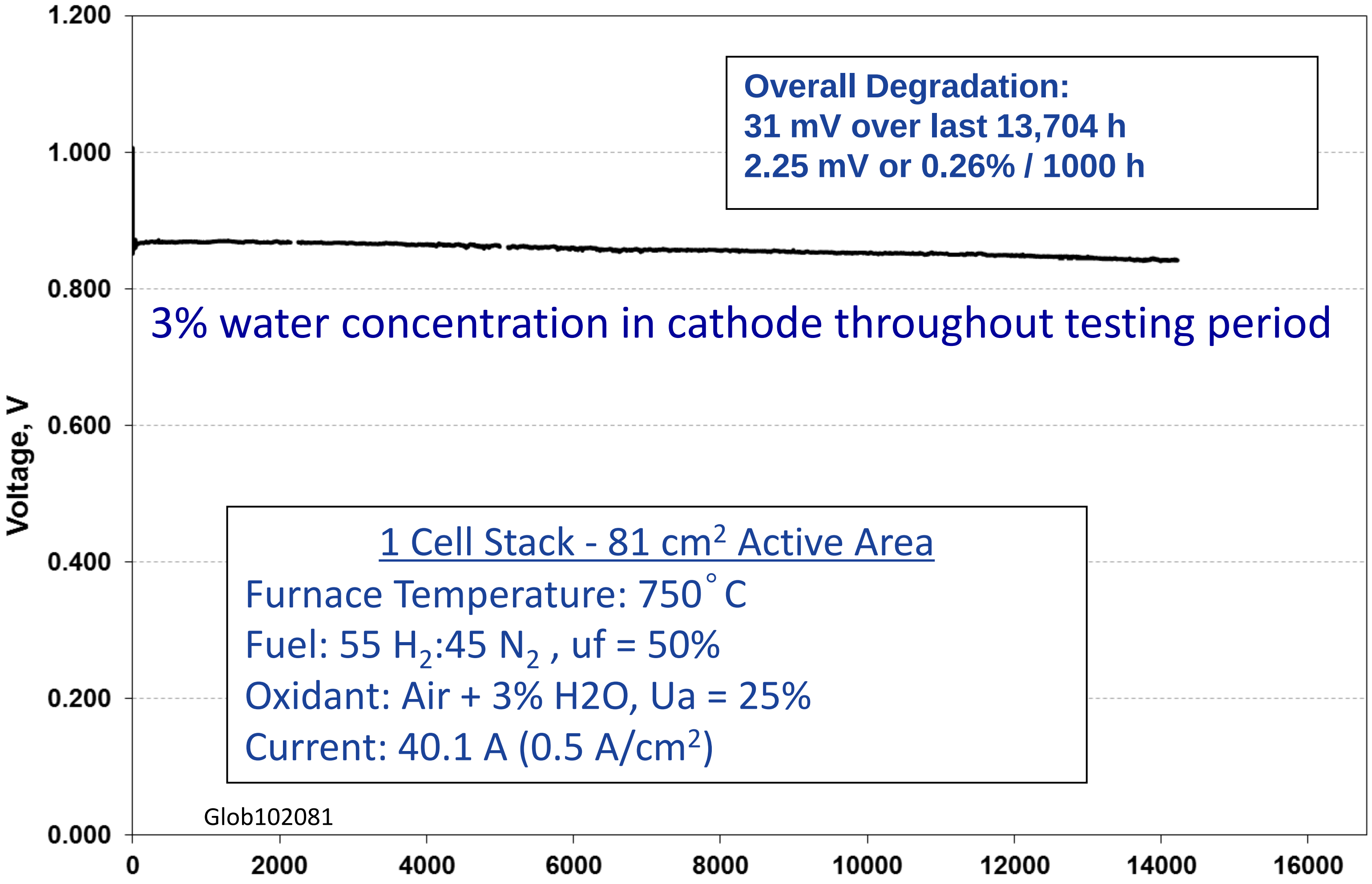
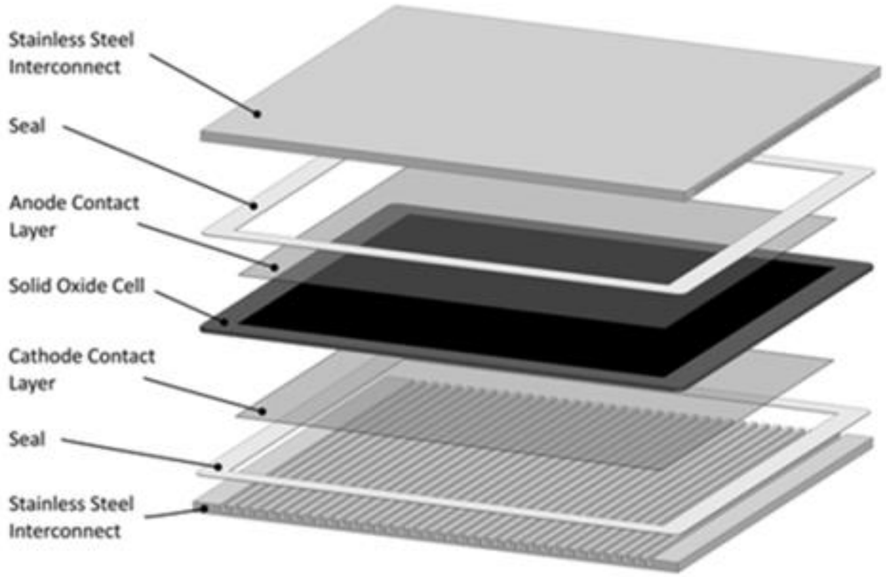
# Long-term Performance – Accelerated Testing




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

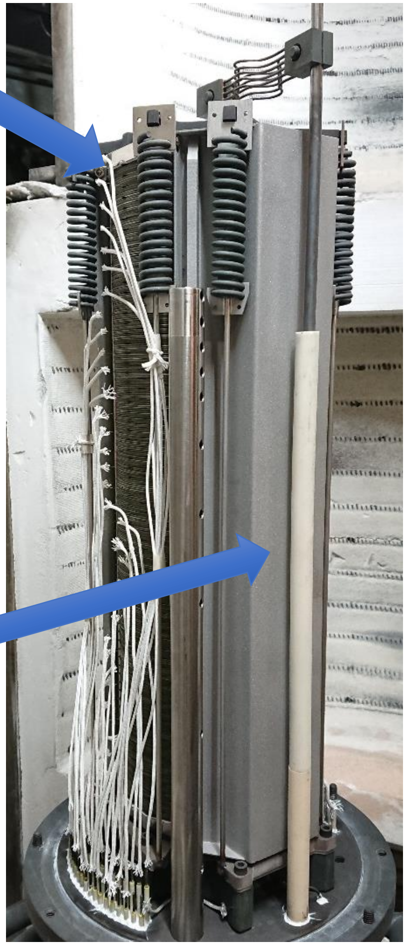
**Verified long-term cell endurance test >1.5 years of operation with a 0.26%/1000h performance degradation with 3% cathode humidity throughout**

# SOFC Stack Development

# CSA Stack Overview

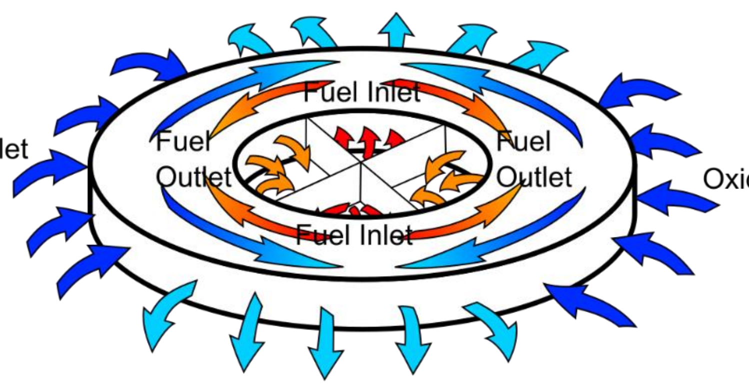
**Integrated compression**

**Oxidant outlet manifold**

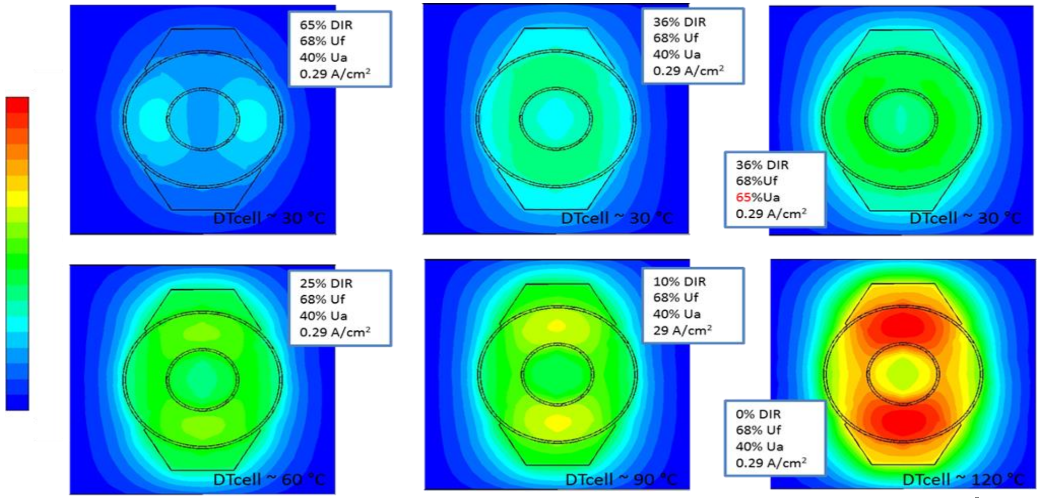


**350 cells - 17” tall**

## Flow Geometry




NG Fuel



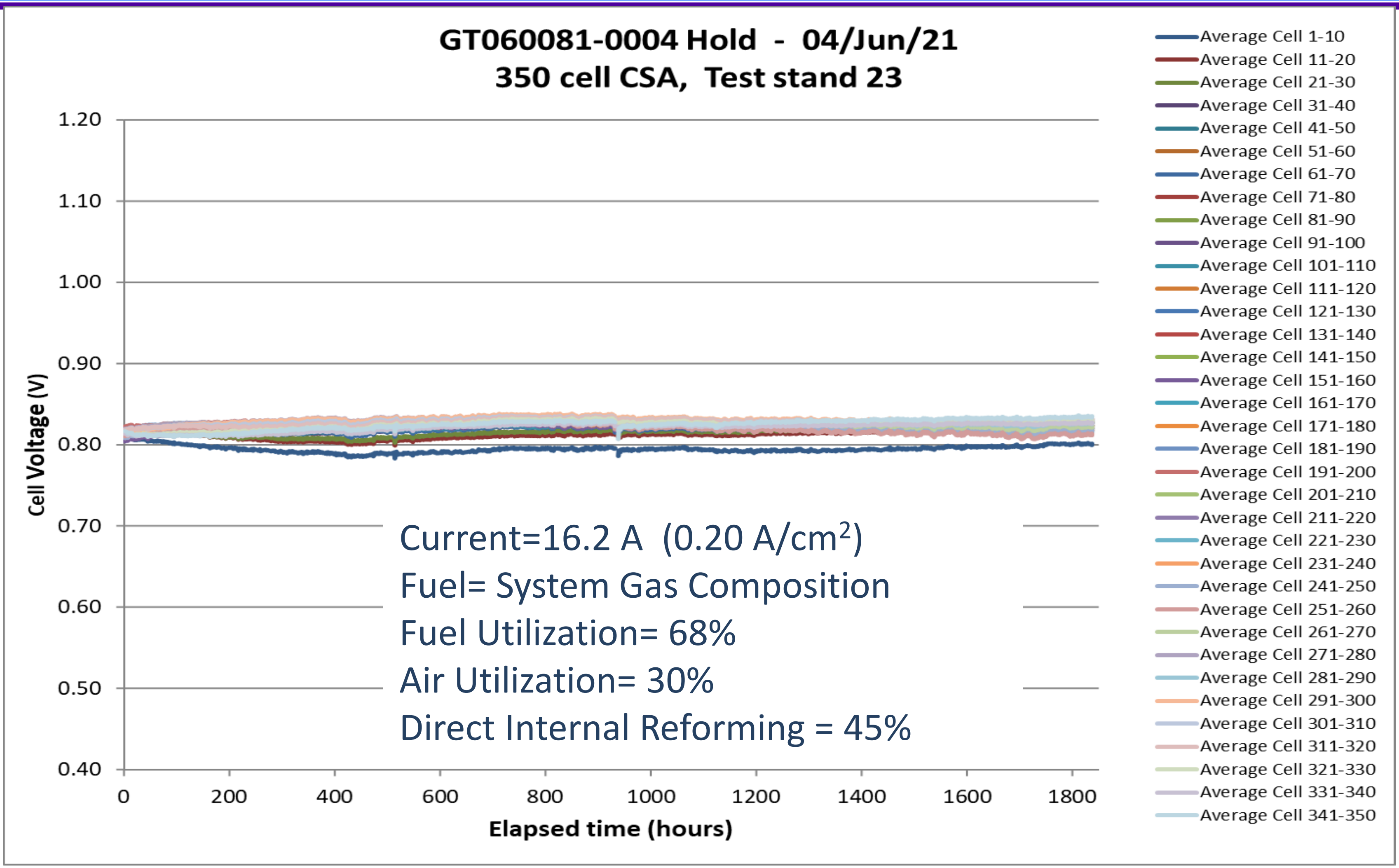

$H_2$ Fuel

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**

# Recent Full Height Stack Test

GT060081-0004

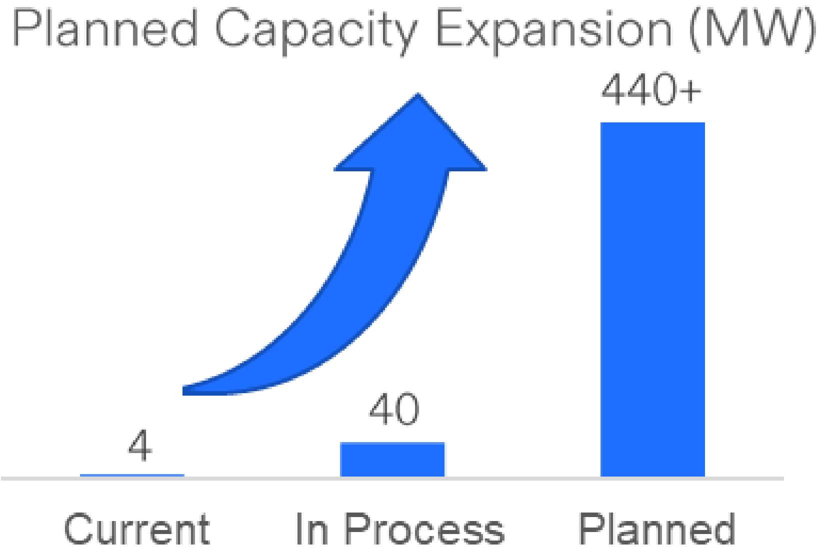



- Completed over 1800 hours of fuel cell operation on system gas compositions with good voltage stability and tight voltage spread (35 mV)

# Cell And Stack Manufacturing

# High Volume Cell Manufacturing

Calgary + US Site, To Be Determined




- 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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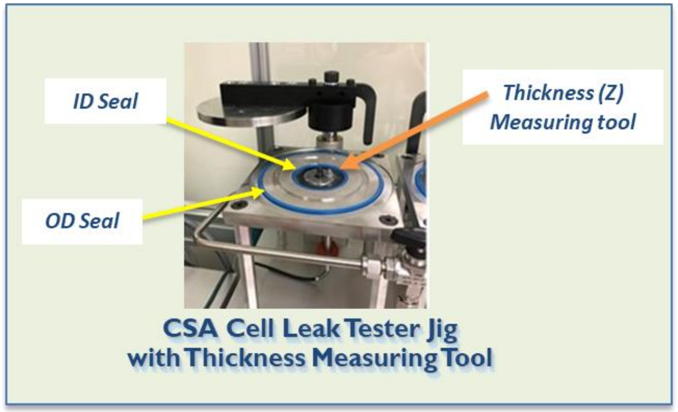
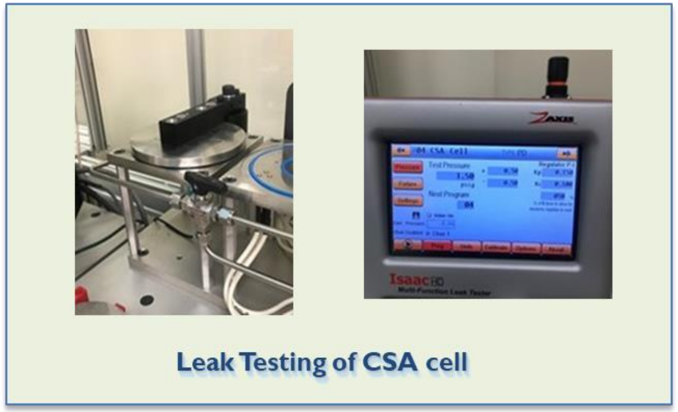
# Cell Quality Control

## Cell Quality Control and Multiple Steps

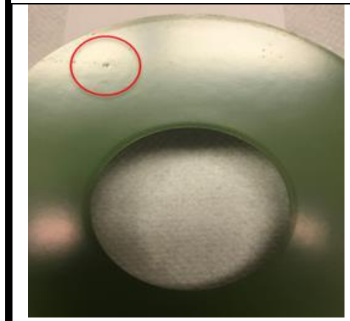
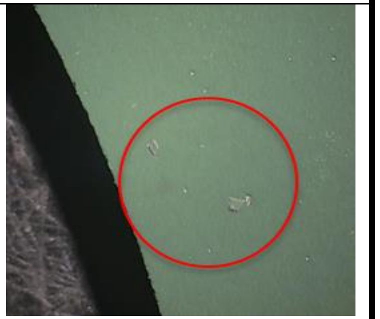
- Dimensional – Inner Diameter, Outer Diameter (via Machine Vision)
- Dimensional - thickness
- Electrolyte Integrity via leak check
- Visual for various cell defect types
- Cells individually serialized with QR coded tied to: cell history, input materials and QC data

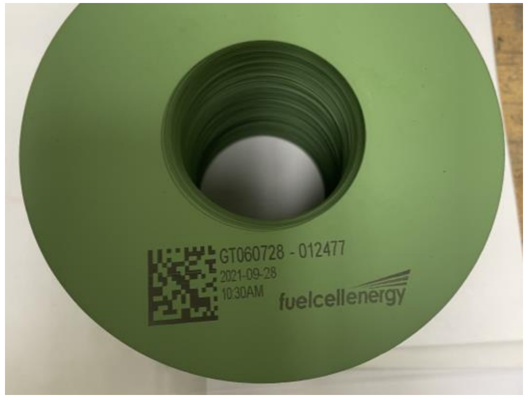


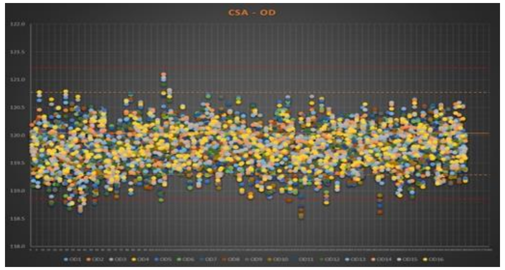

CSA Cell Leak Tester Jig with Thickness Measuring Tool



Leak Testing of CSA cell

| Visual Defects | | |
|---|---|---|
|  |  |  |
| Hole | Air Bubble | Debris / Contamination |



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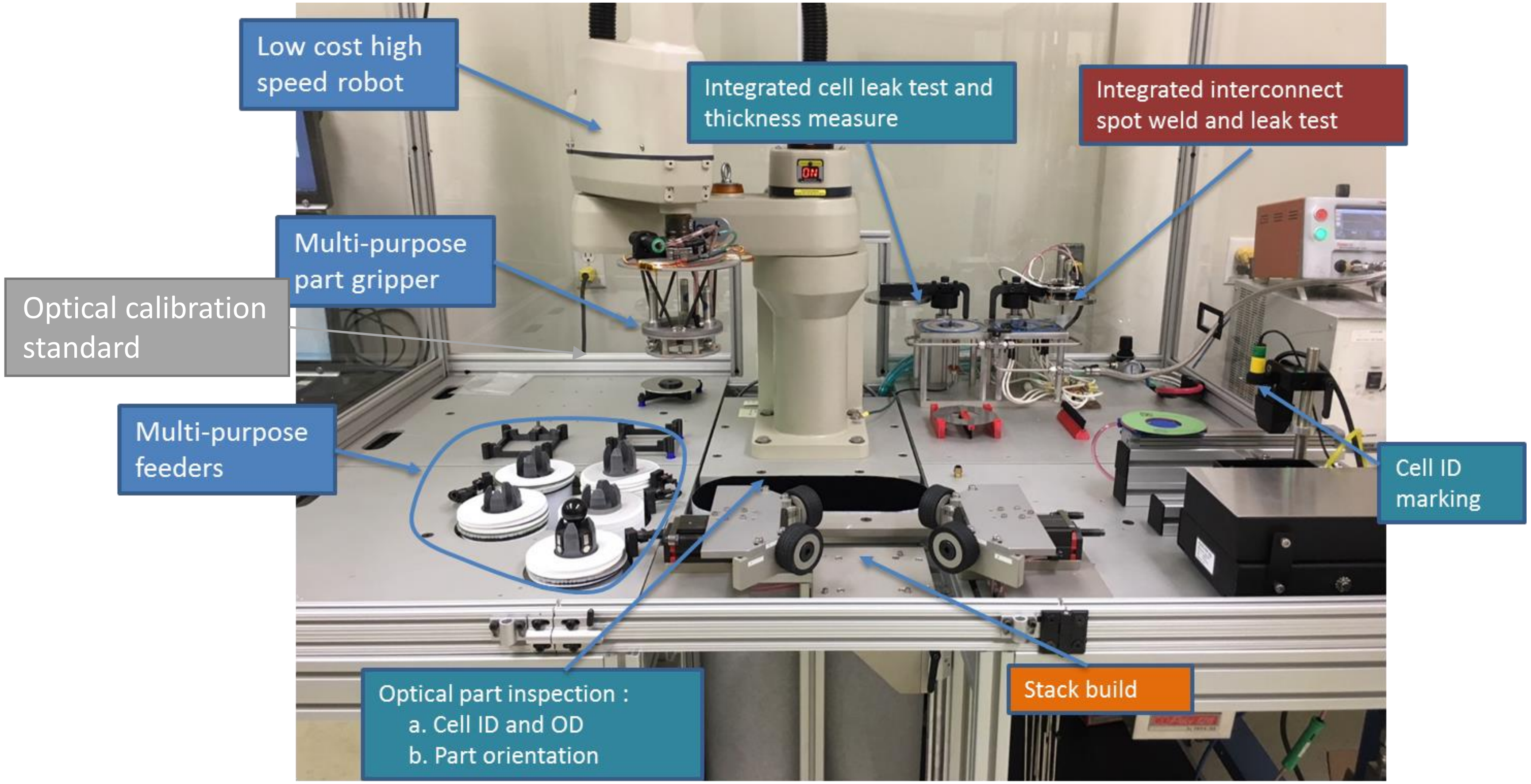
# Stack Manufacturing Robotics & Quality Control

## 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

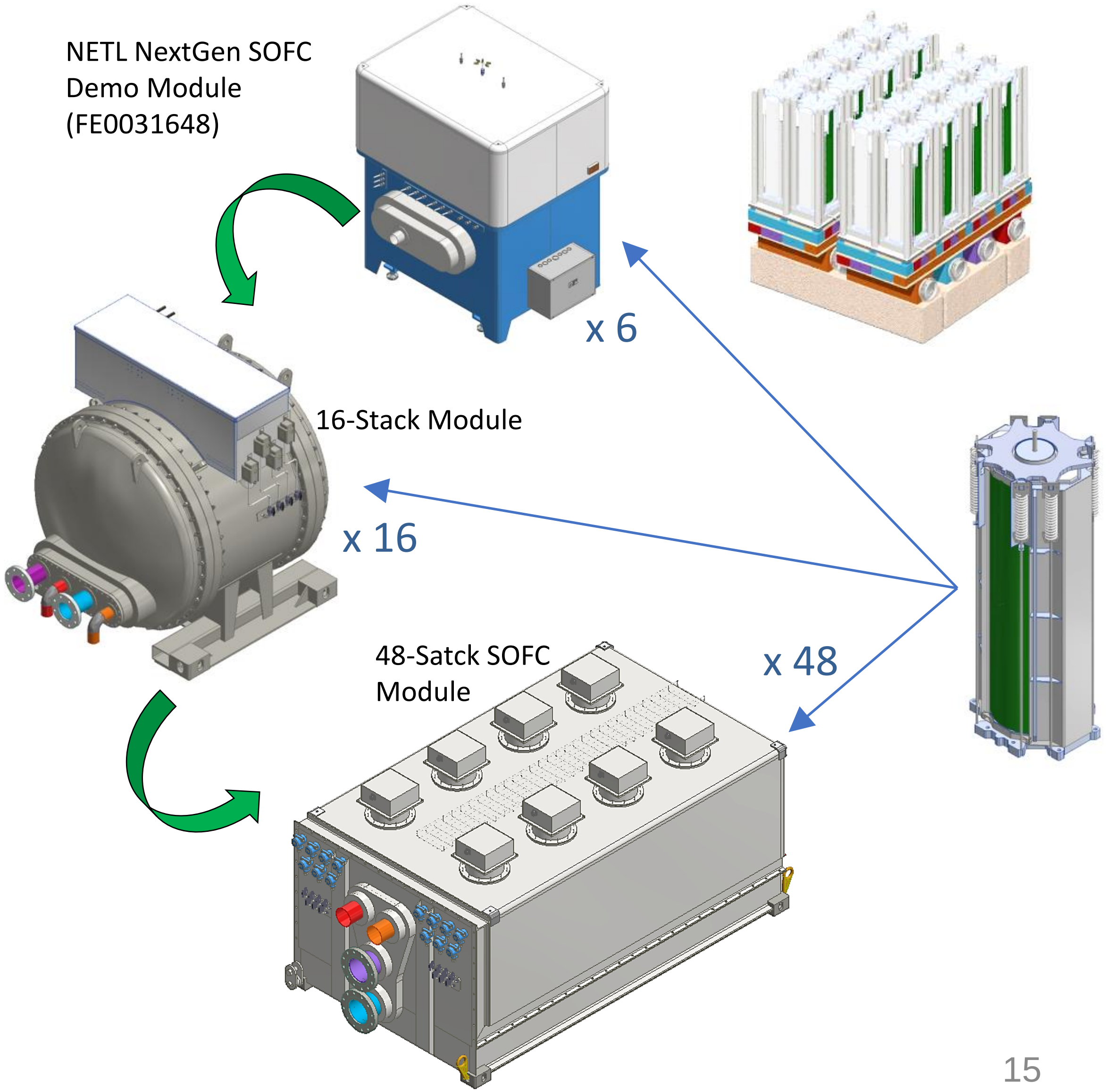
- Utilize high speed pick and place robot for efficient sub-assembly build, cell and component QC and precise cell / stack assembly
- 50 minutes to assemble a 350-cell stack

# SOFC Stack Module Design

# SOFC Module Development

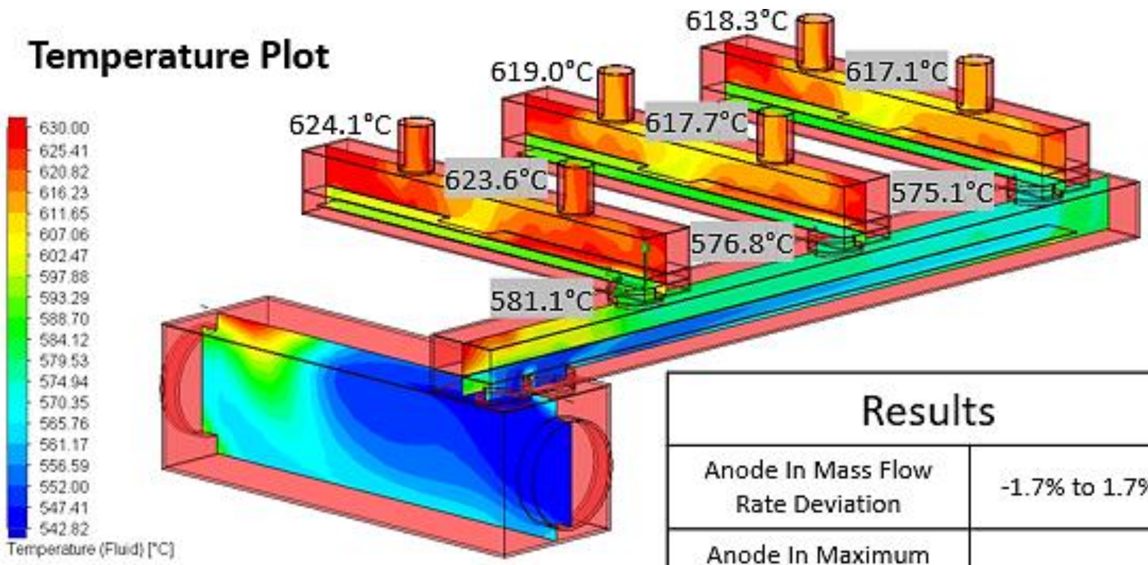
- Stack modules of various power ratings under development using stack arrays as building blocks:
  - 6-Stack SOFC Test Module
    - 40kW$_{DC}$ Rated Power
    - **Status**: Receiving final components to build and test
  - 16-Stack Solid Oxide Module
    - 100 kW$_{DC}$ Rated SOFC Power
    - Minimum 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

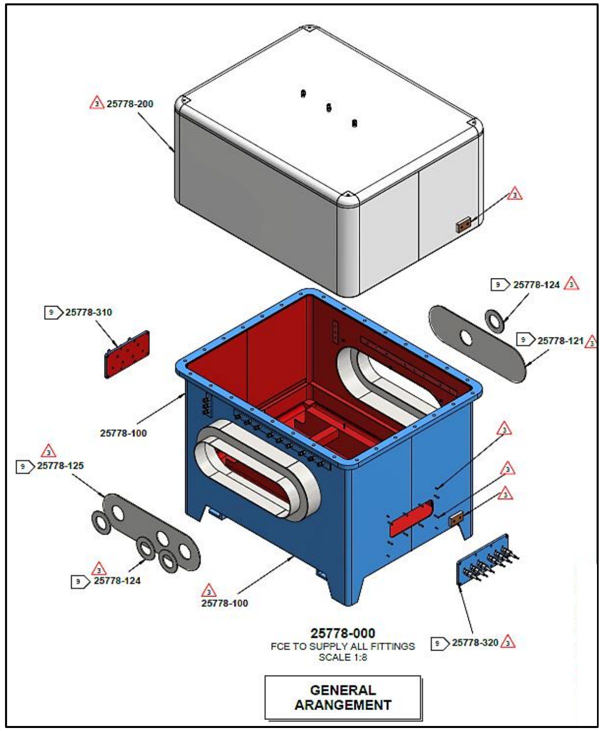


# Module Design and Component Development

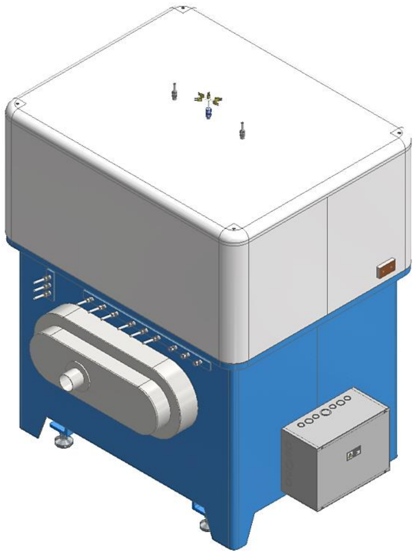
- Process gases distributed to 6 stacks via multi-layered **Stack Distribution Base** connected to plumbing passing through sides of steel enclosure
  - CFD was used to achieve excellent flow and thermal distribution between stacks



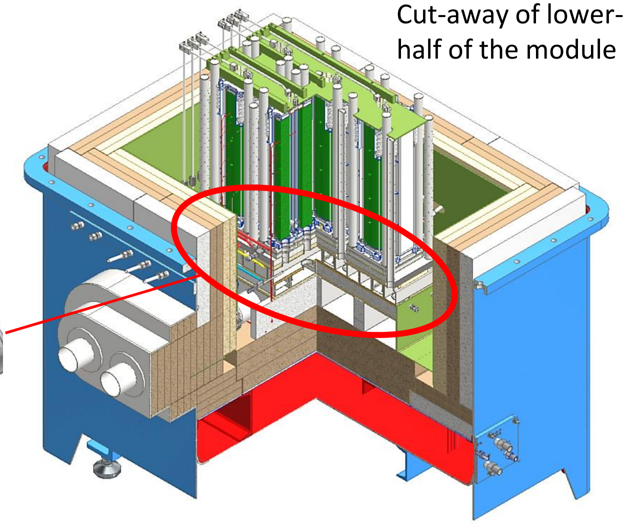

| Results | |
|---|---|
| Anode In Mass Flow Rate Deviation | -1.7% to 1.7% |
| Anode In Maximum Outlet Temperature Variation | 7.0°C |
| Total Anode Press Drop (In to Out of Module) | 25.5 IWC |



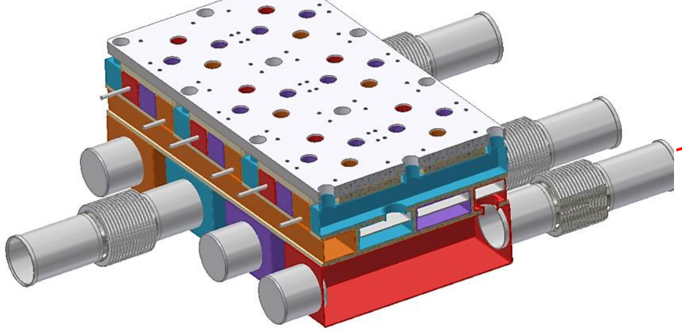

Full module



Cut-away of lower-half of the module

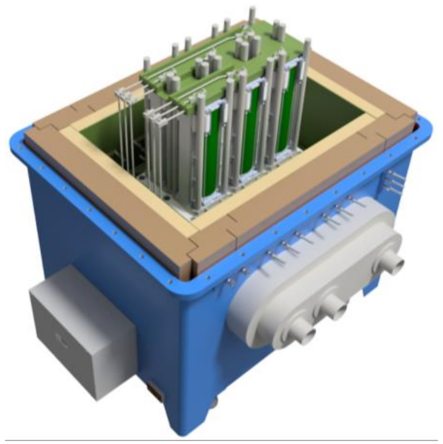


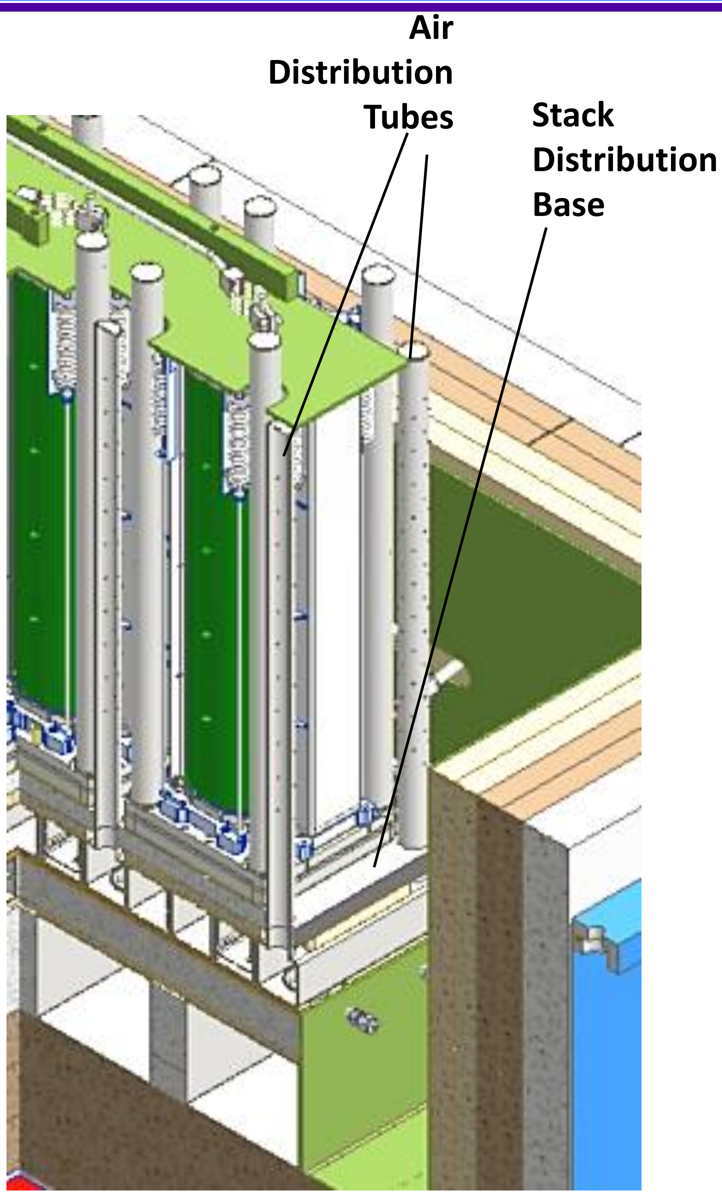
Stack Distribution Base (cut-away)

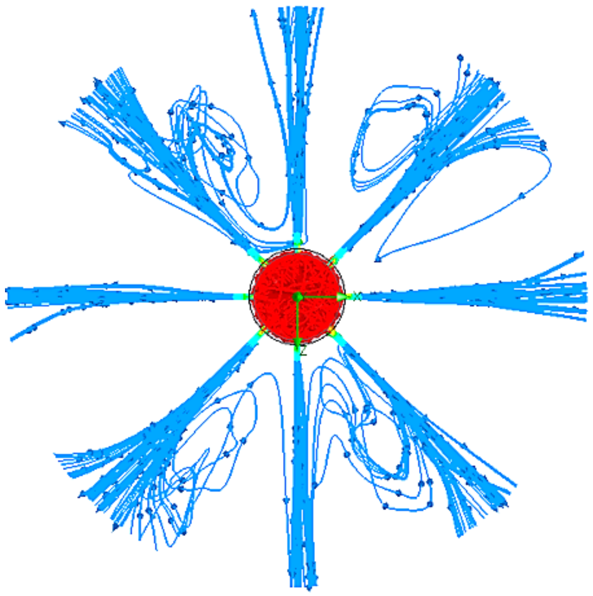


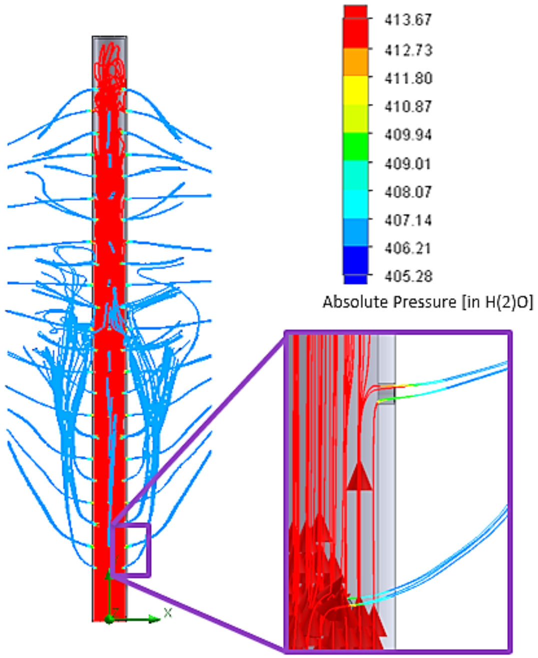
# Air Distribution

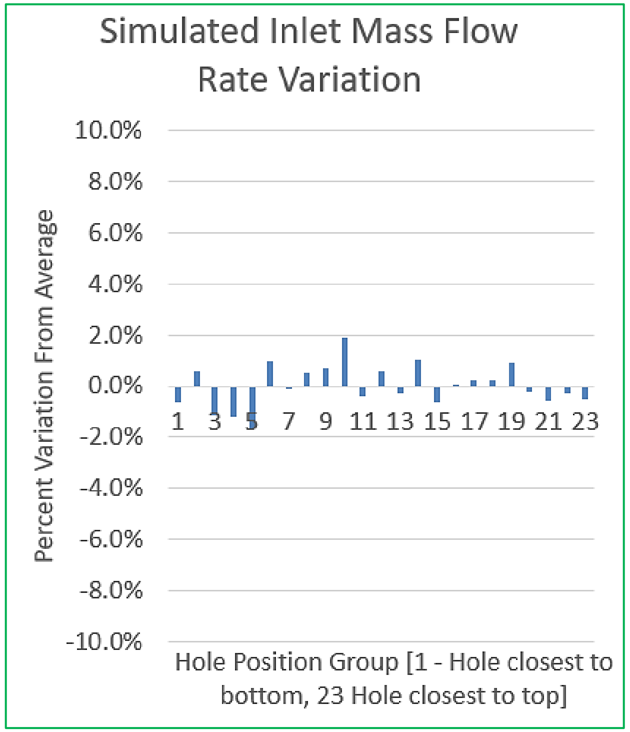
- **Air Distribution Tubes** (ADT) protrude vertically from the *Stack Distribution Base*
- Dead-ended perforated tubing modeled in CFD software to evaluate flow distribution along height of tube.
- Performance of the **ADT** meets basic requirements of:
  - Mass flow distribution
  - Maximum allowable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







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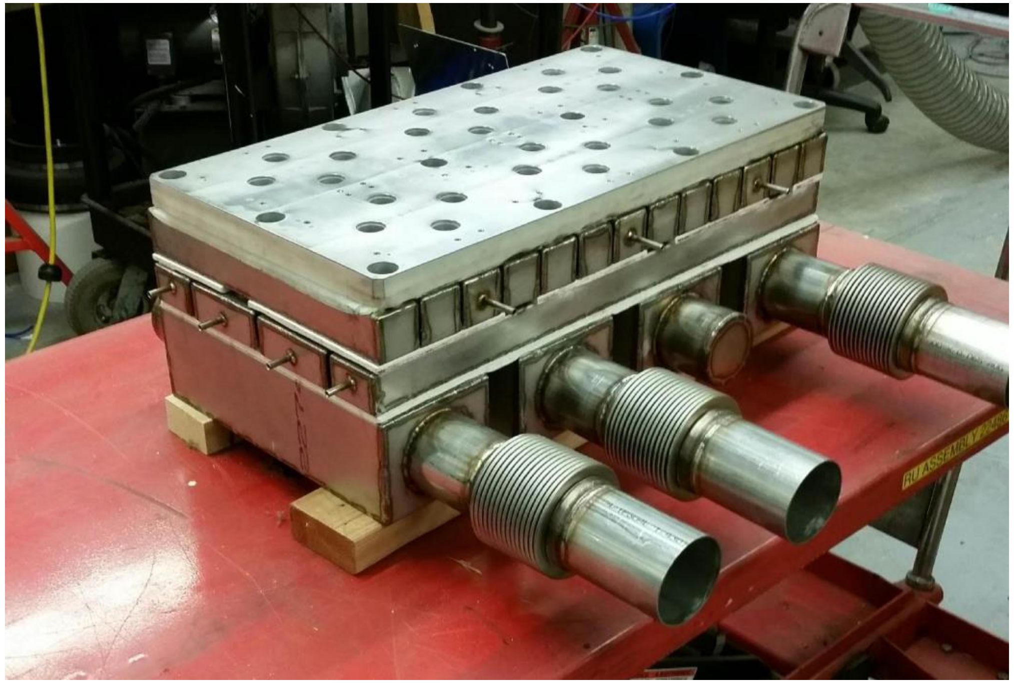
# Multi-Stack Module Demonstration Test

**Upper Enclosure Insulated**

**Power Take Off Bus Bar Hardware**



**Stacks Base Plate**

**Two Stacks in Shipping Container**

**Lower Enclosure**

**Components are fabricated for final assembly of stack stack module**

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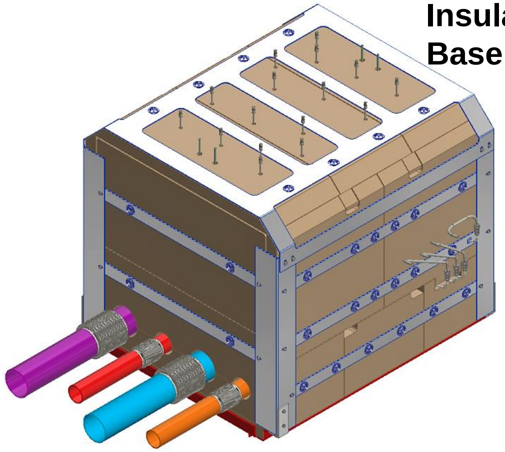
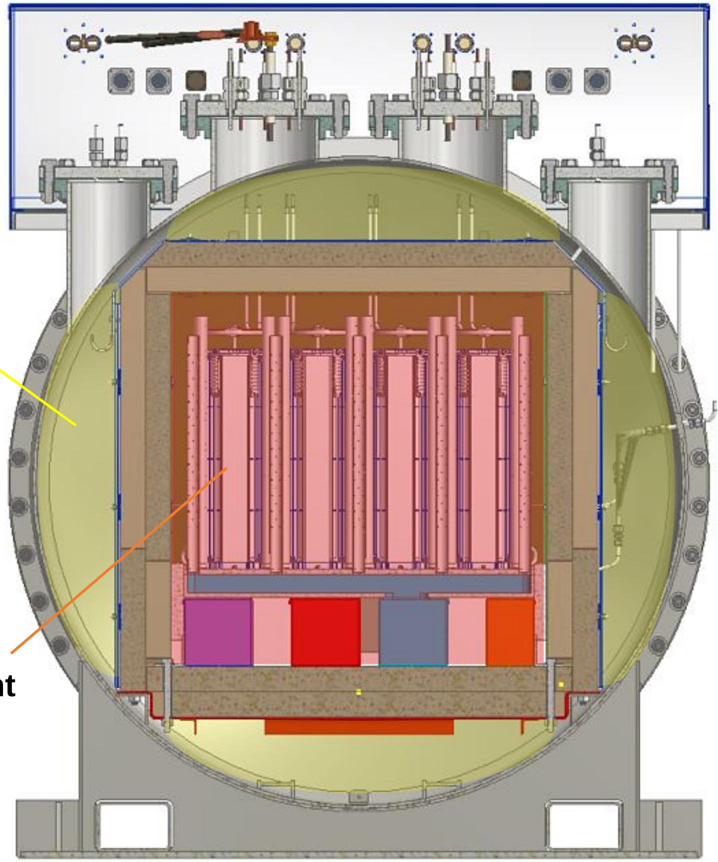
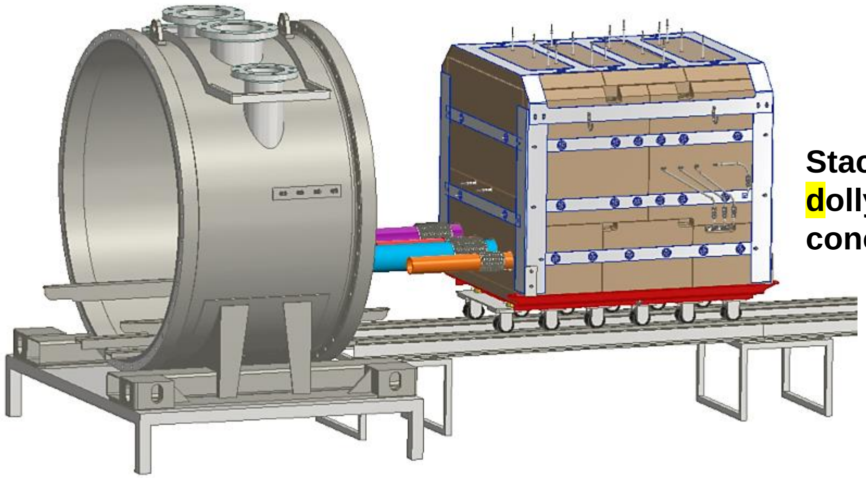
# 16-Stack Module Design

- 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

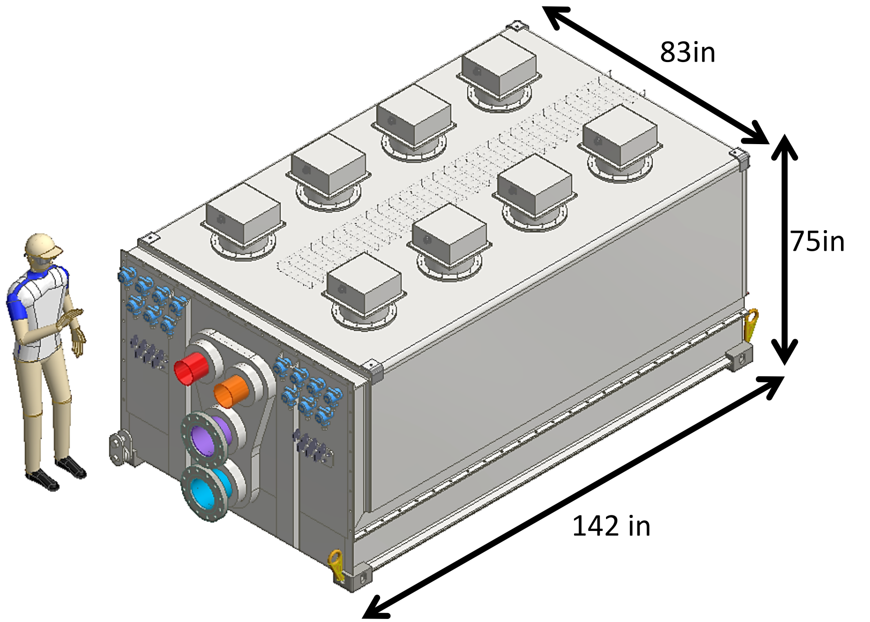


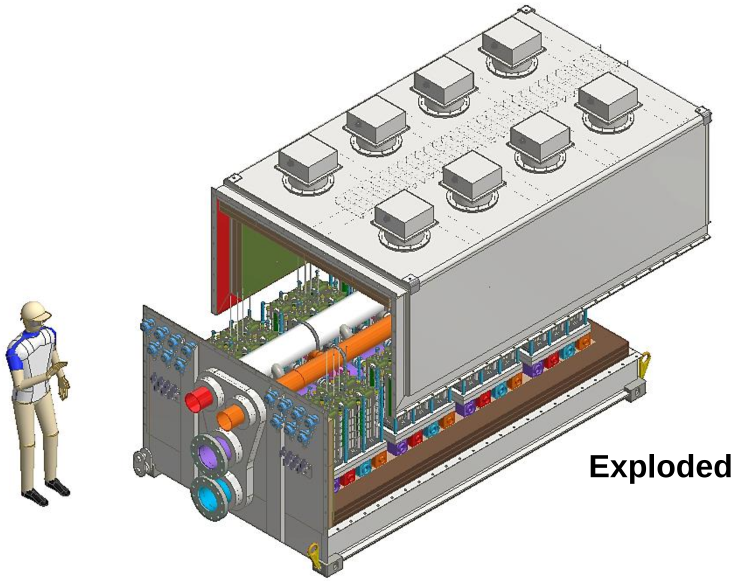



Stack Base Assembly dolly & rails loading concept

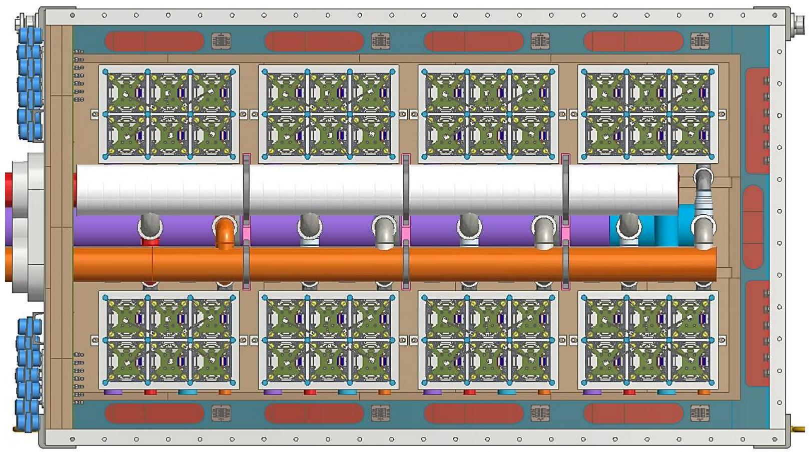
# Scaling to MW Plant Module

- 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

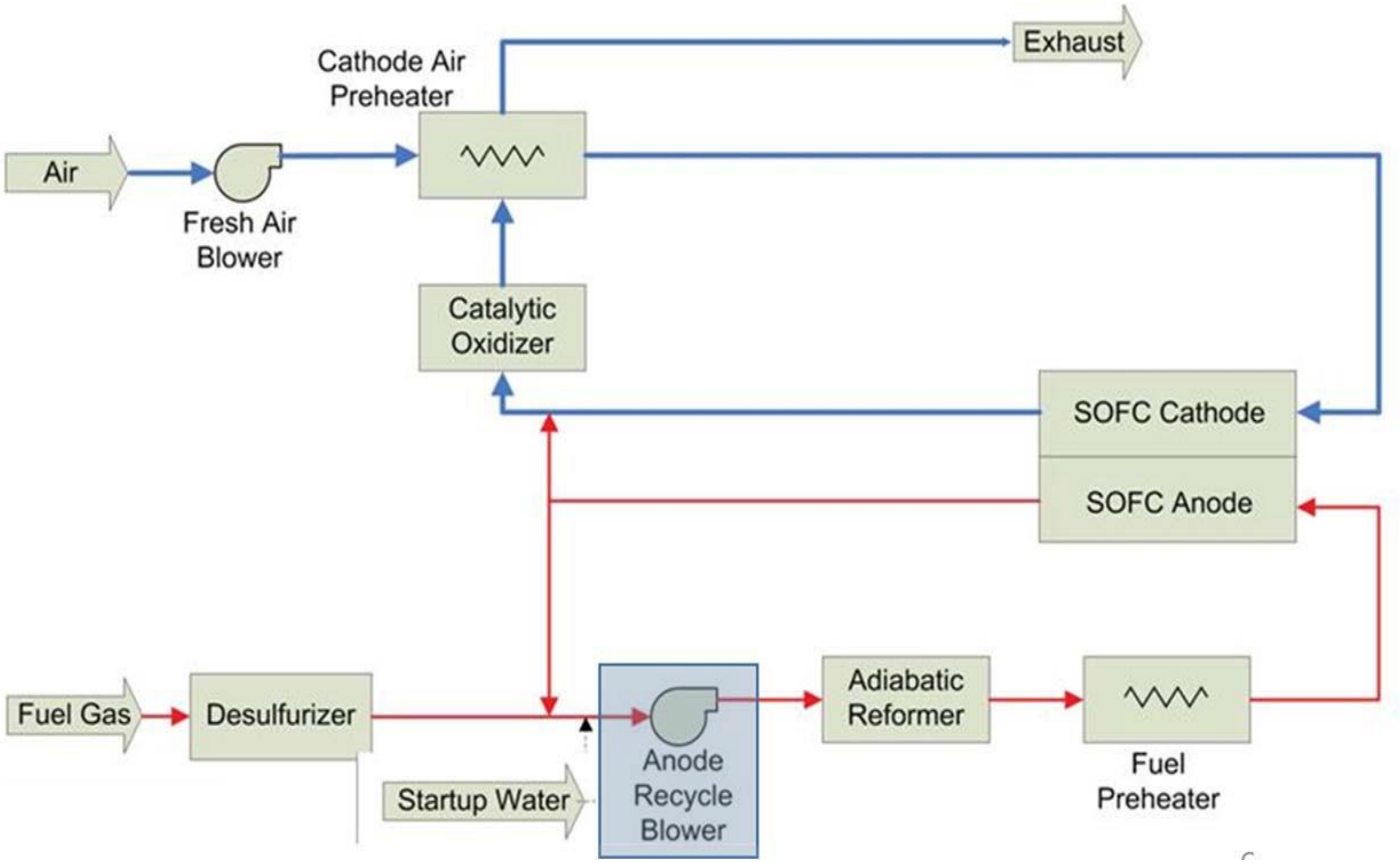

# SubMW SOFC System Development

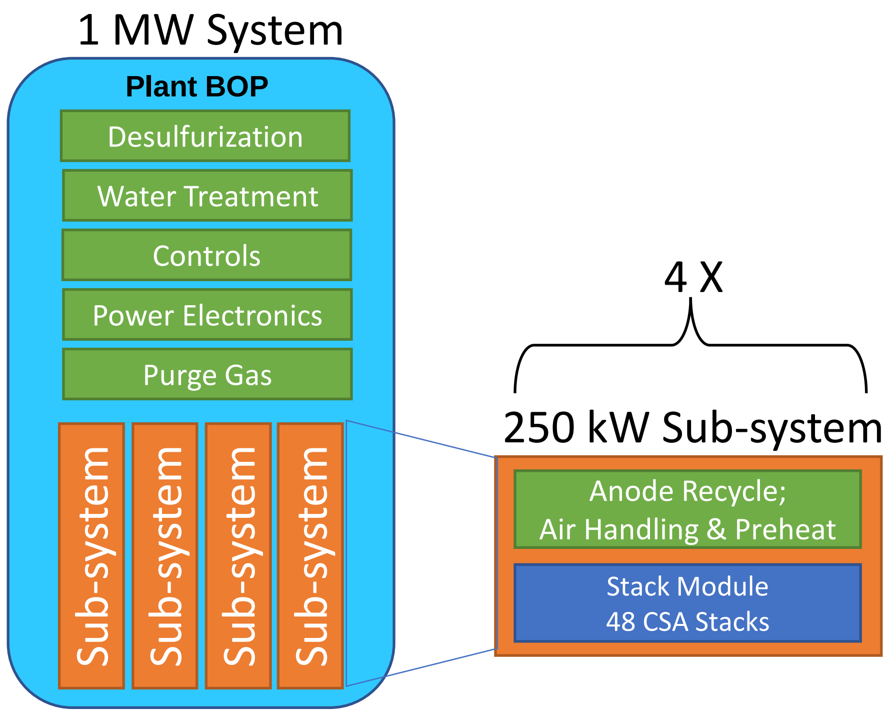

- 50 kW (2014-2016)
- 1st Gen Stack
- Fuel: NG

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


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

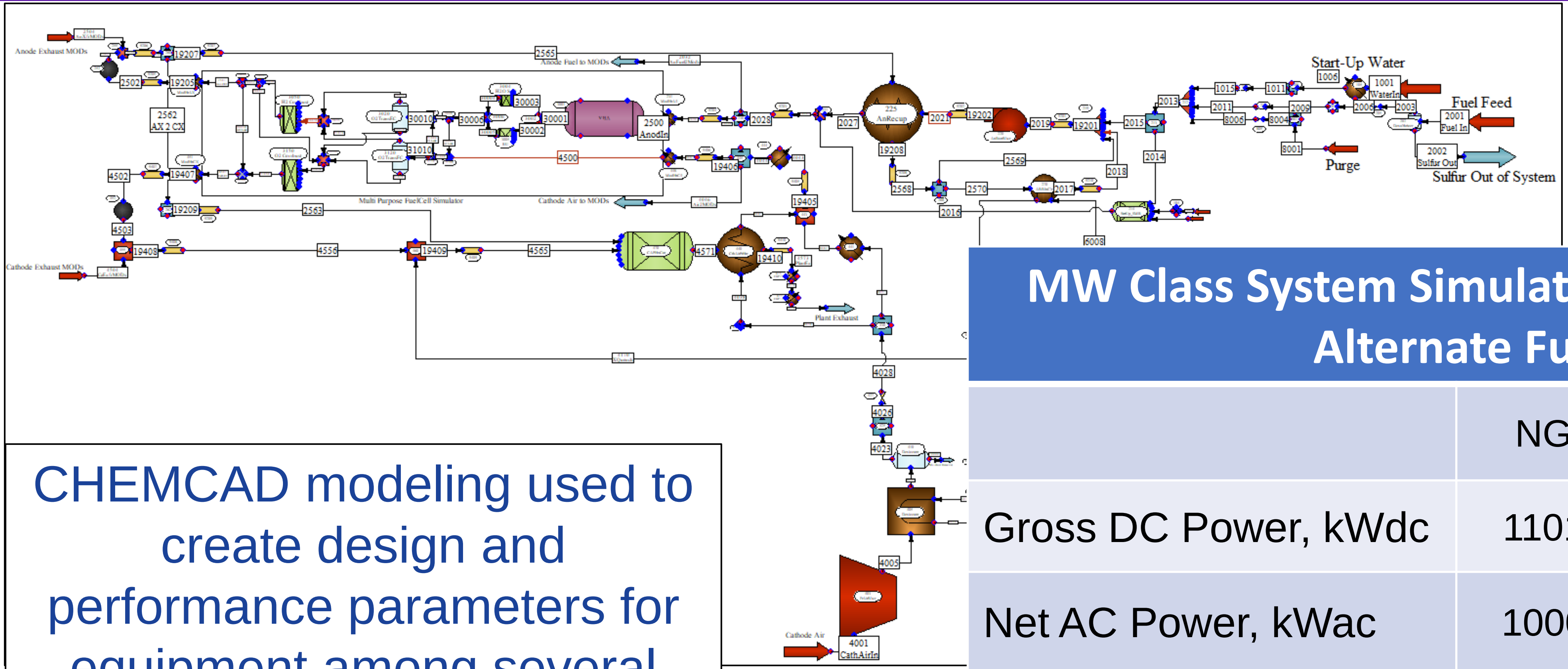
# 1 MW SOFC System Process Design




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

# Simulation Performance

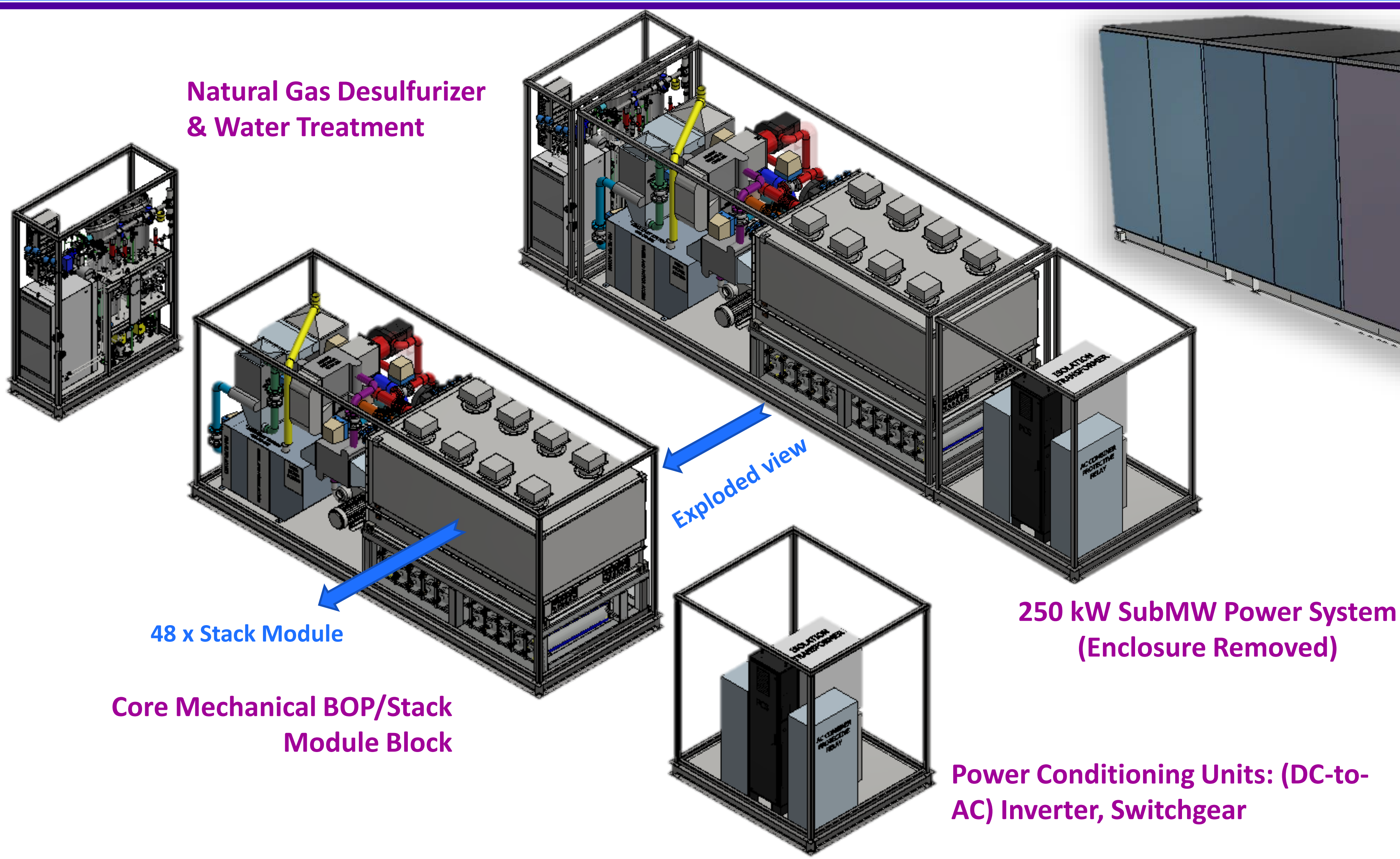


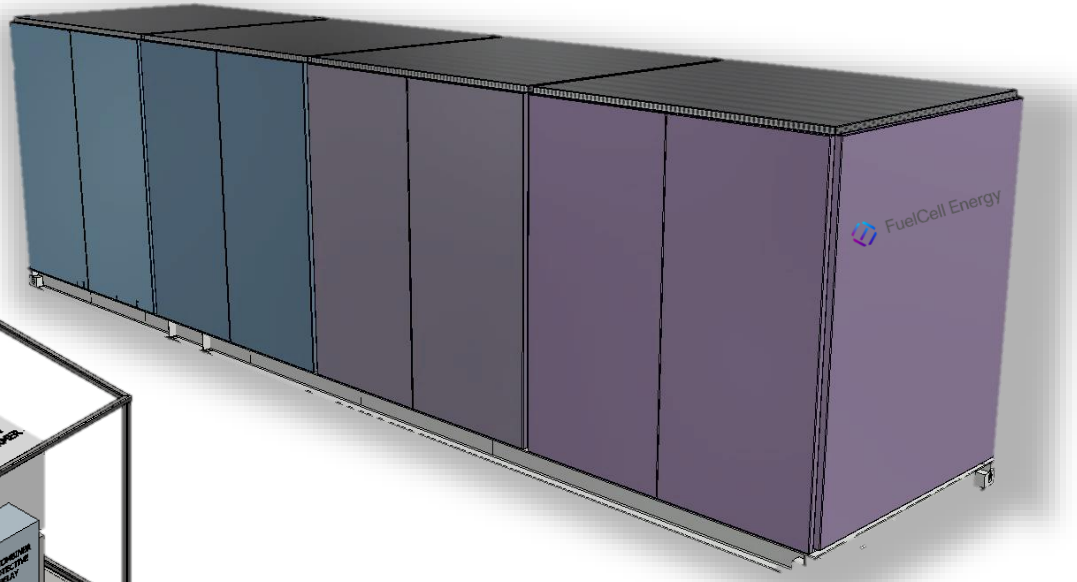

CHEMCAD modeling used to create design and performance parameters for equipment among several different operational modes for the plant

## 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




250 kW SubMW Power System
Dimensions: 35’ x 8’ x 10’

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

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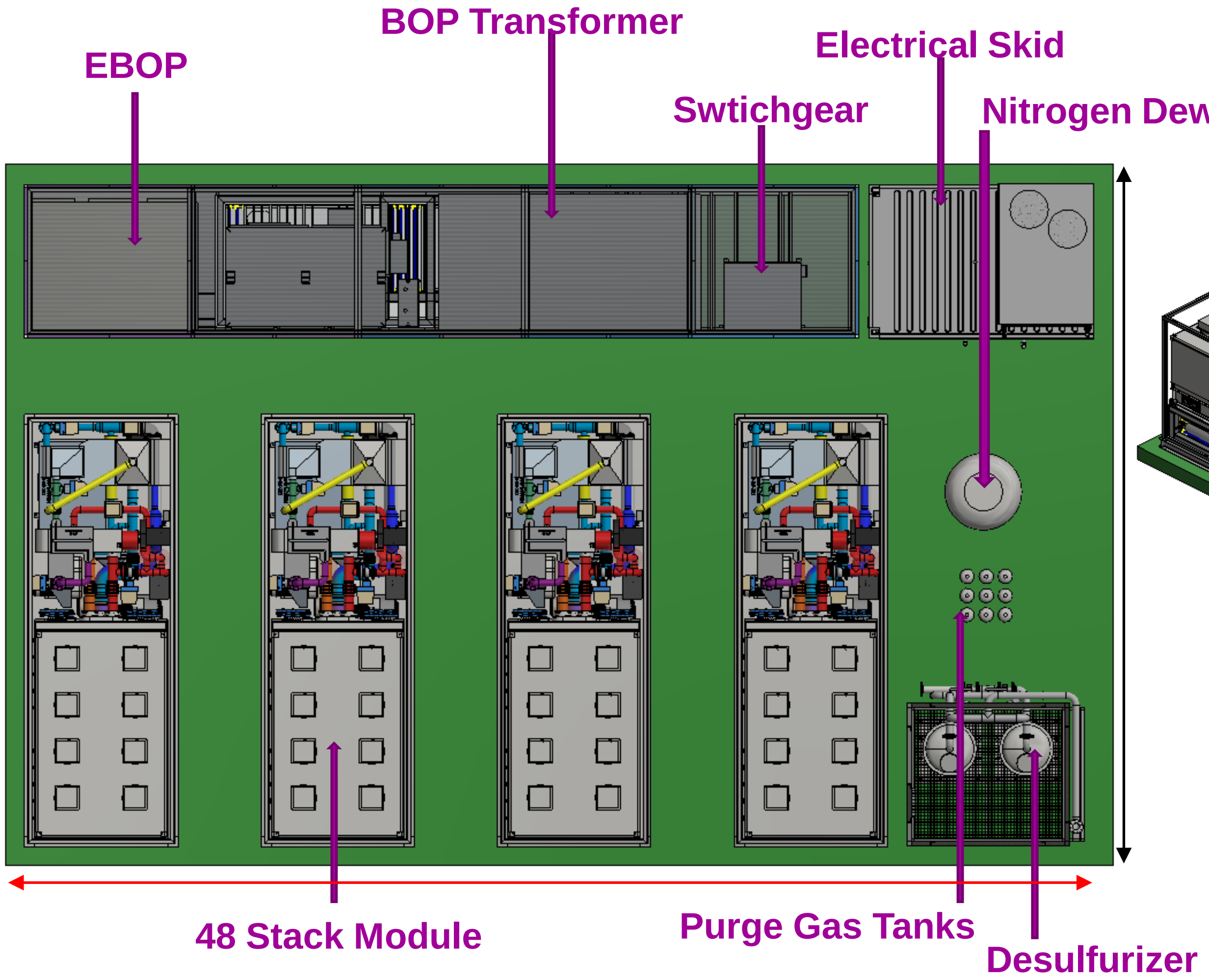
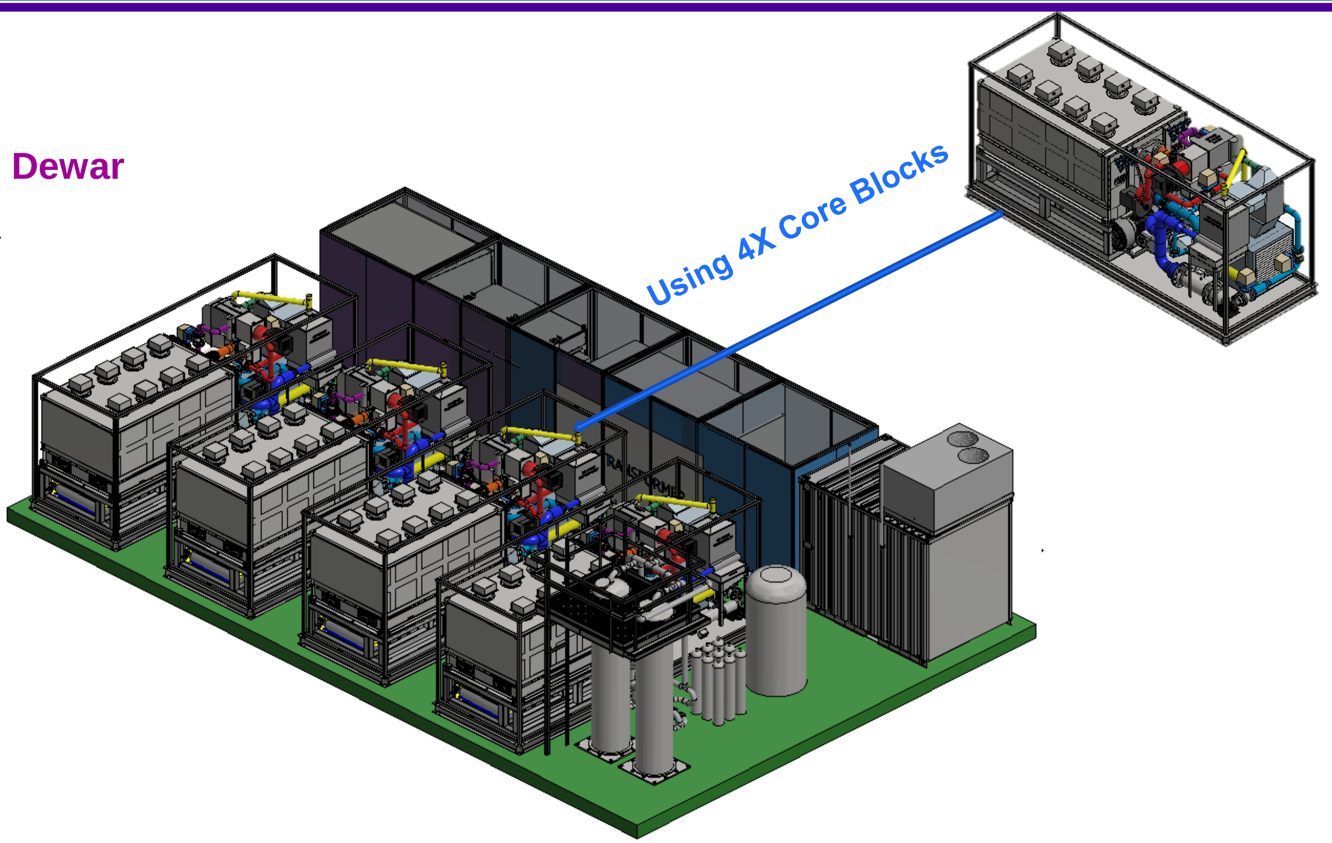
# MW SOFC Plant Design



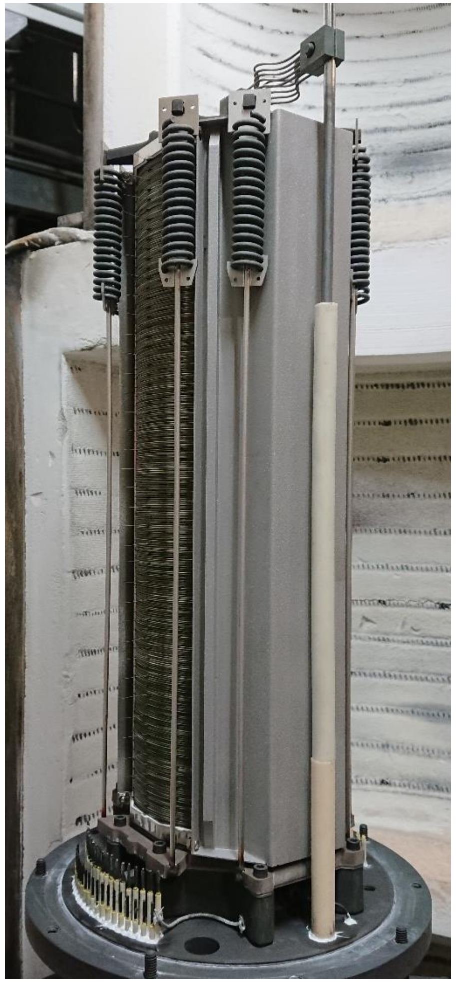

MW SOFC System Layout
Plant (**57.75’ x 36.75’**) 2,122sf
Plant plus maintenance (**57.75’x 49.25’**) 2,844sf

**High Power Plant Availability Achievable Utilizing Repeatable Core Blocks**

# Techno-economic Analysis

# 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:**

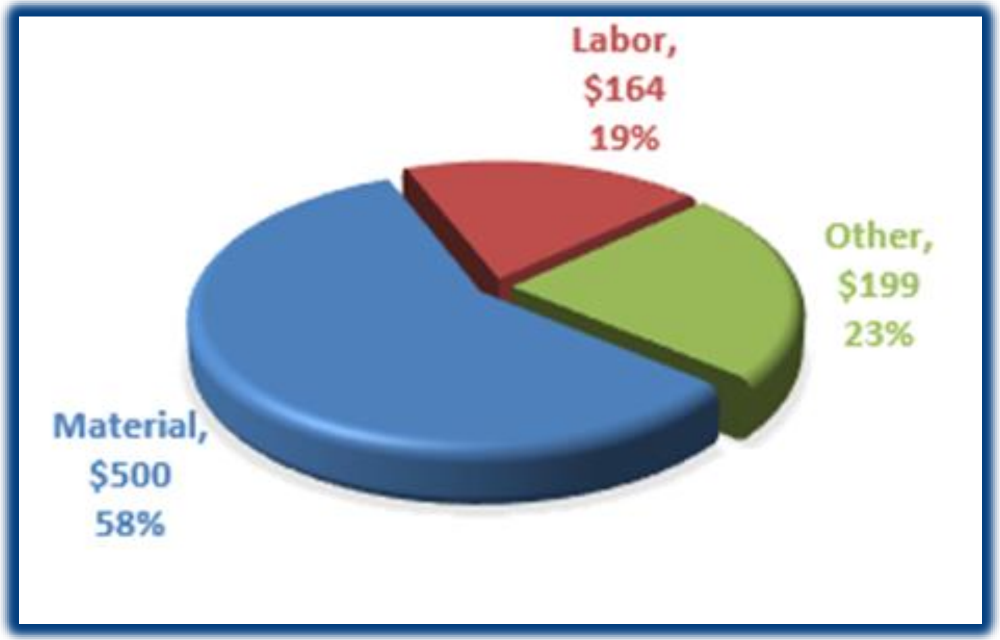
- R&D, sales and marketing, G&A, warranty expenses and taxes

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

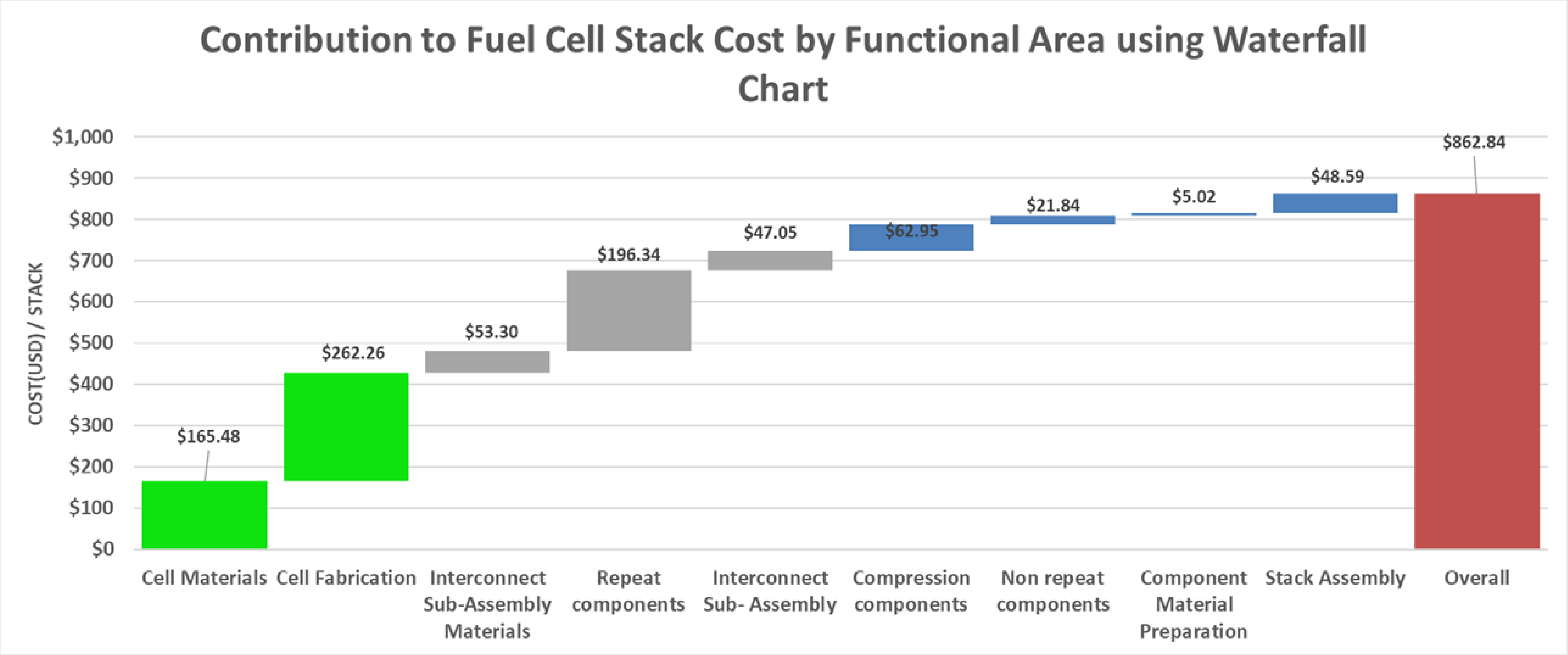
Stack cost per unit power produced:

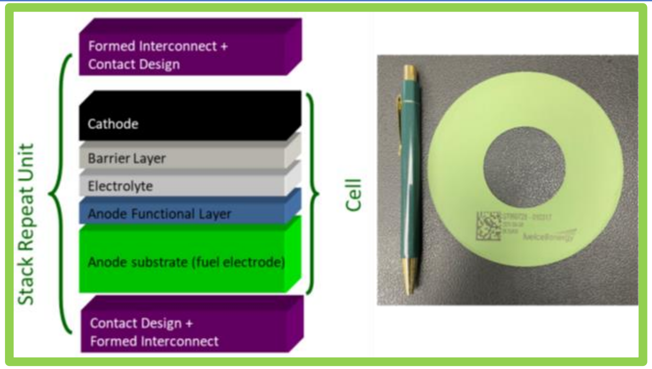
*= $122 $/kWe DC (gross)*

*= 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

# 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.

# Summary: Solid Oxide Products



### Solid oxide fuel cell power generation platform

- 250kW rated output
- >60% LHV Efficiency in power generation
- Natural gas, biogas, or hydrogen fuel
- Capable of combined heat and power applications, reaching 85-95% LHV efficiency

### Solid oxide electrolysis platform

- 1.1MW rated input (43.8 kWh/kg $H_2$)
- 600 kg/day hydrogen production
- Power input reduced to 1.0 MW with supplied waste heat (39.4 kWh/kg $H_2$)
- Two modules – stack/mechanical BOP and electrical BOP

# Thank You

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Our purpose:

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