

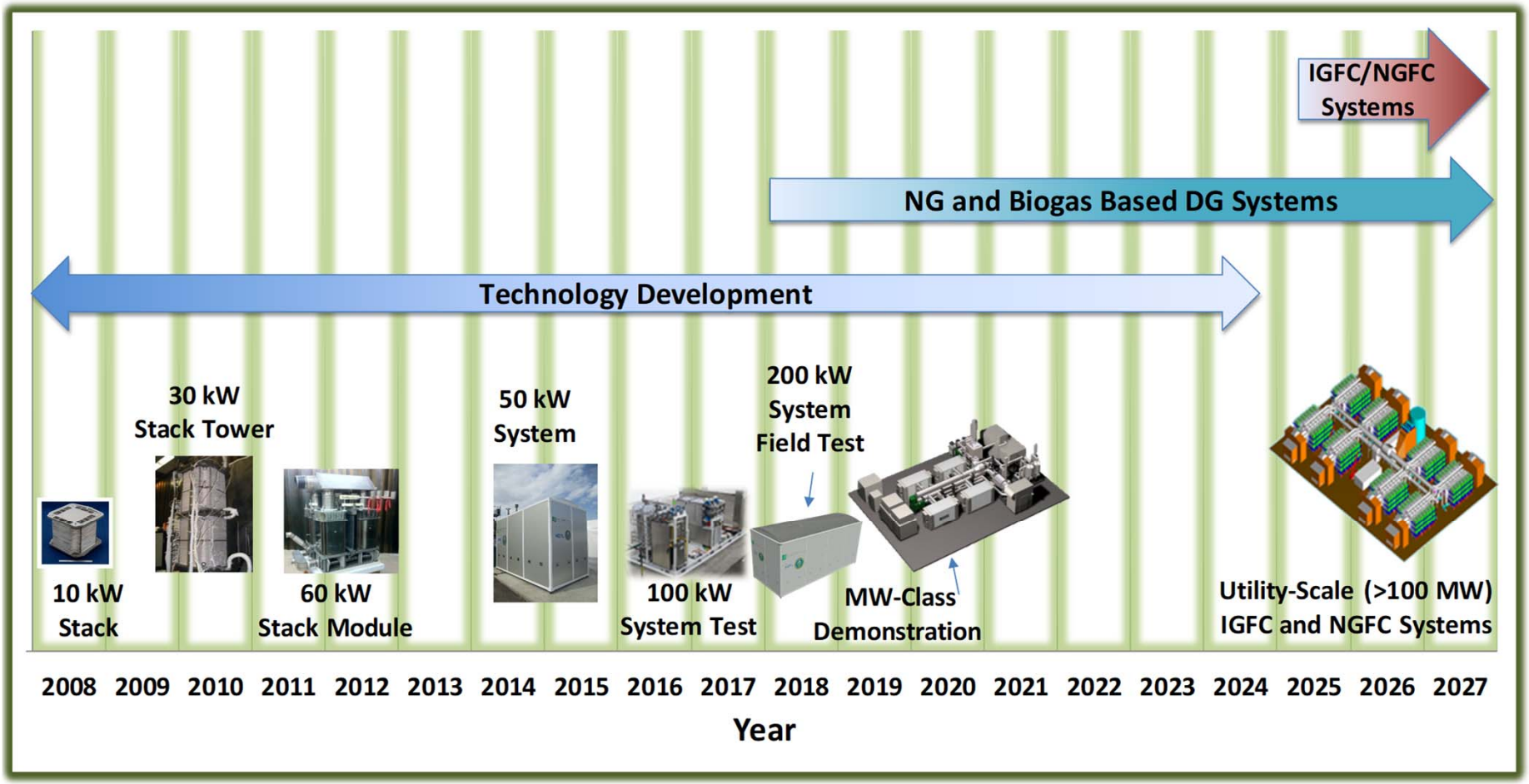

Progress in SOFC Technology Development at FuelCell Energy

Hossein Ghezel-Ayagh (PI)

20th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting
Washington, DC

April 30, 2019

SOFC Technology Development & Deployment Roadmap

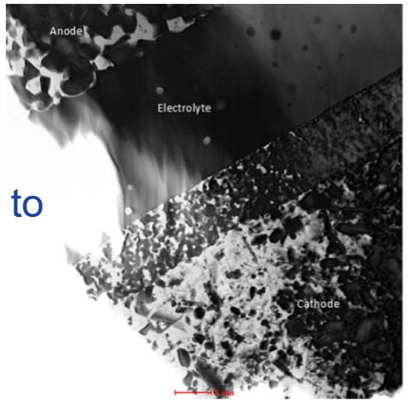


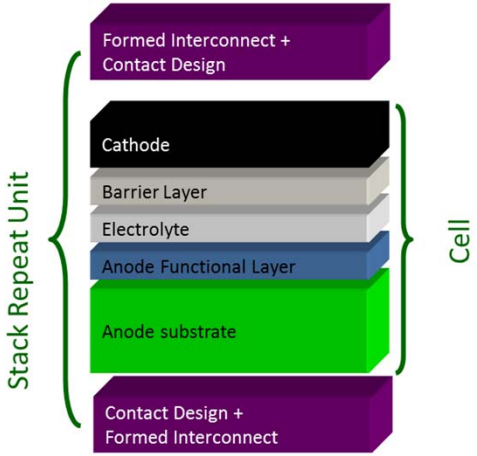
- Ongoing technology development and system field testing is laying the foundation for cost-competitive DG and centralized SOFC power systems

Cell & Stack Technology

TSC Cell Manufacturing Process

- Cell fabrication process evolved from laboratory to pilot-production in 2001
- Techniques utilized are tape casting, screen printing and electric tunnel kiln for continuous firing
- These processes are flexible & scalable to high volume and low cost production





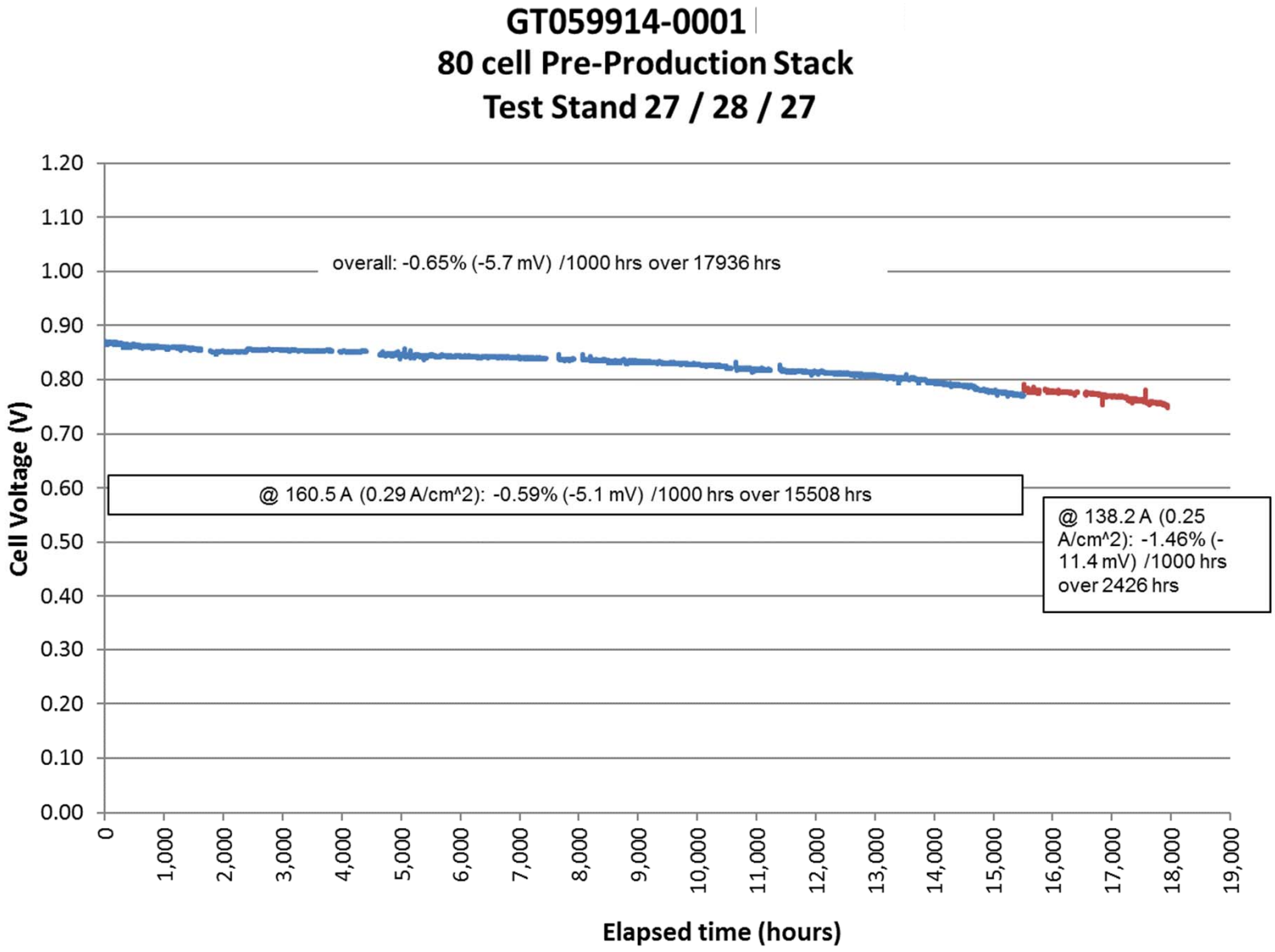
Component	Materials	Thickness
Cathode	Perovskites	~ 50 μm
Barrier	CGO	~ 4 μm
Electrolyte	YSZ	~ 5 μm
AFL	Ni/YSZ	~ 8 μm
Anode Substrate	Ni/YSZ	~ 350 μm

80-Cell Large Area Stack (LAS)

GT059914-0001

- Stack built using 80 planar anode-supported cells (0.6 X 254 X 254 mm) with 550 cm^2 active area
  - Built: Aug 2016; End of Test: Feb 2019
- Same configuration as production stacks
  - Ferritic stainless steel sheet interconnect
  - Compressive ceramic seal
  - Integrated manifolding with formed flow field layers
- 14 thermal cycles, and moved twice between test stands
- Tested at 2 different current densities
  - Cathode inlet temperature reduced to maintain stack temperature
  - De-rated current by 14% to extend life
- Overall demonstrated 0.65% / kh over 17,936 h (> 2 years) on load

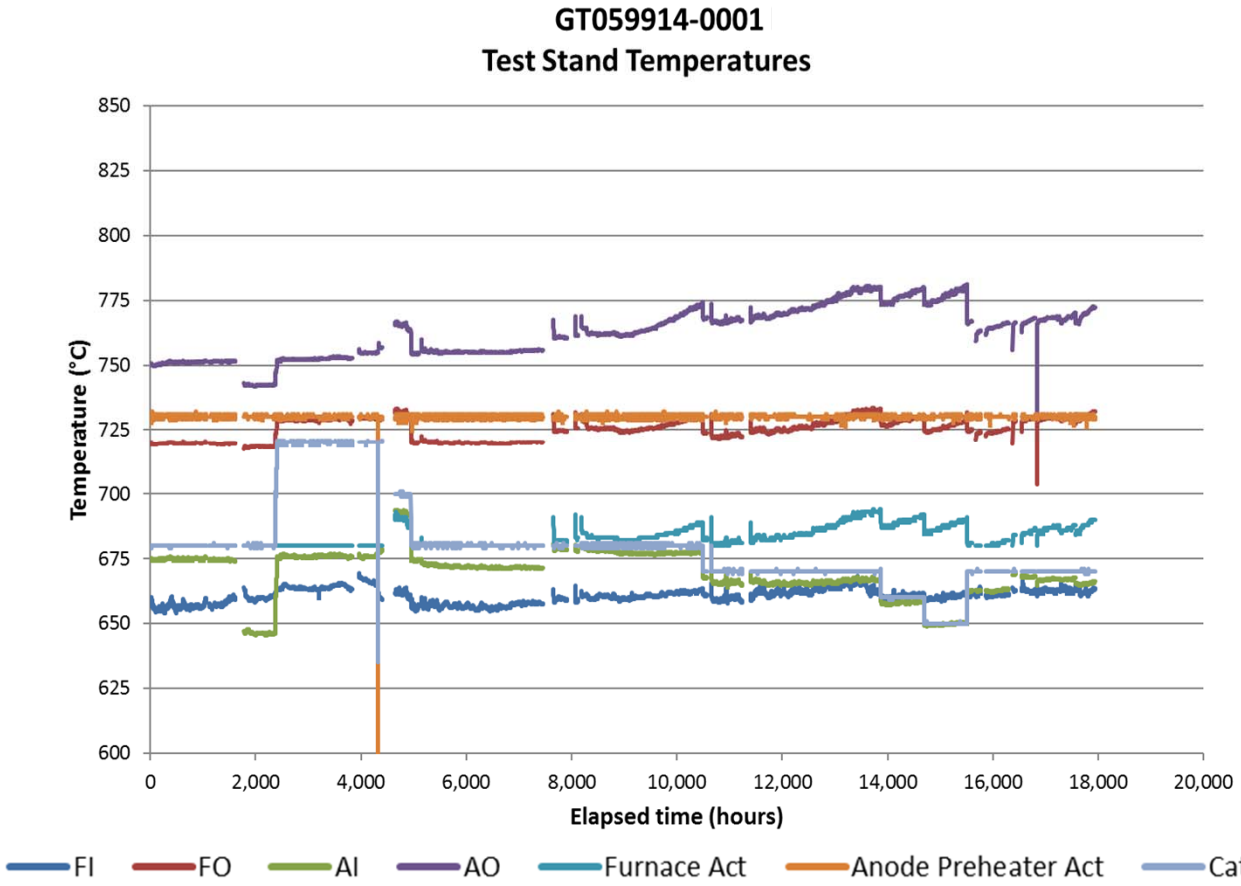
80-Cell LAS – Average Cell Voltage



%
35.1%
8.6%
23.3%
33.0%
100.0%

80-Cell LAS - Temperatures

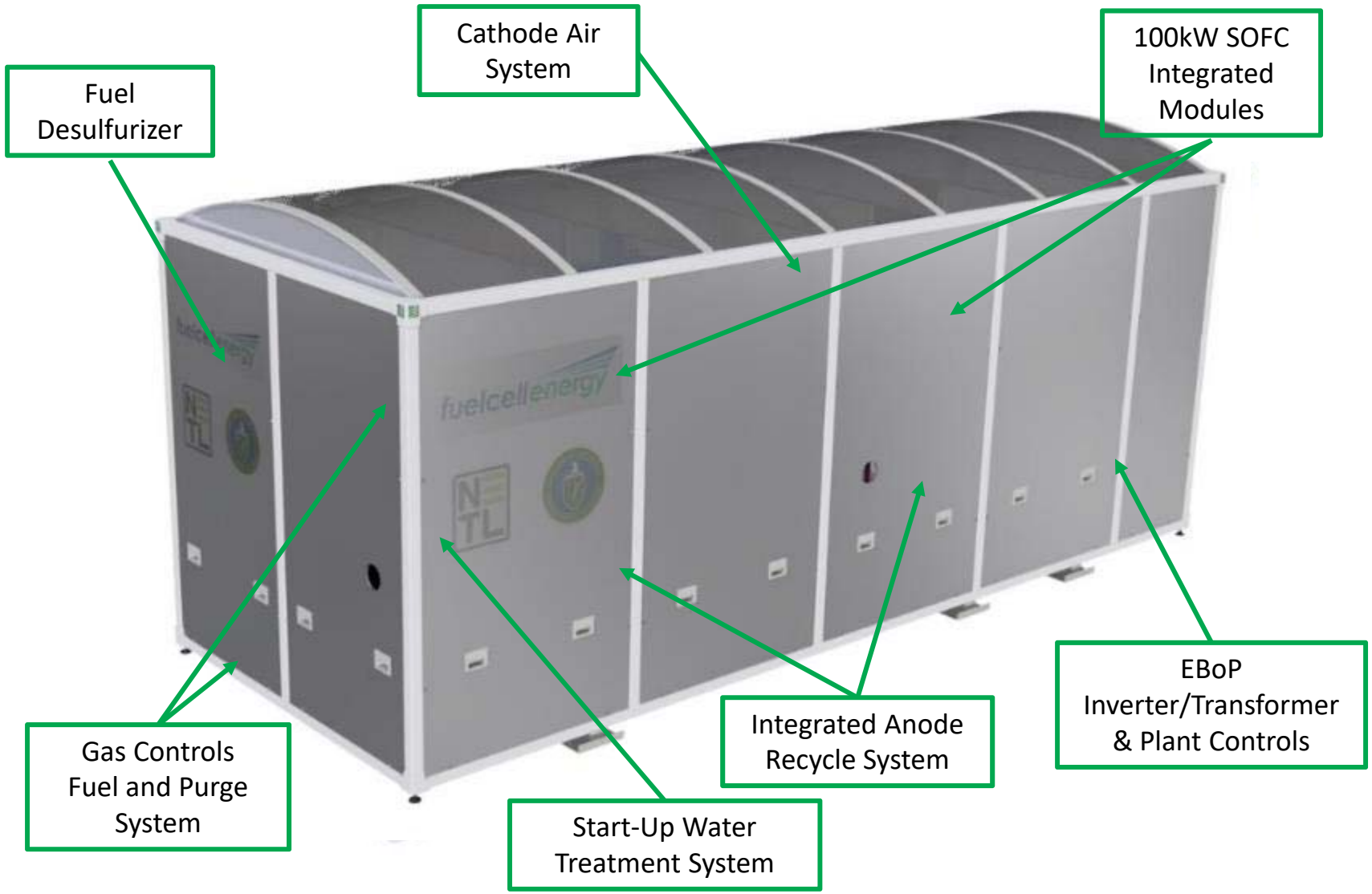
- Cathode inlet temperature reduced periodically to maintain reduce peak on-cell temperature
- De-rated current and increased DIR to 50% + lower uf -- impacted stack thermal profile, but did not improve degradation



- Stack to be cold leak tested and autopsied to determine cell failure root cause
  - Chromium poisoning leading suspect

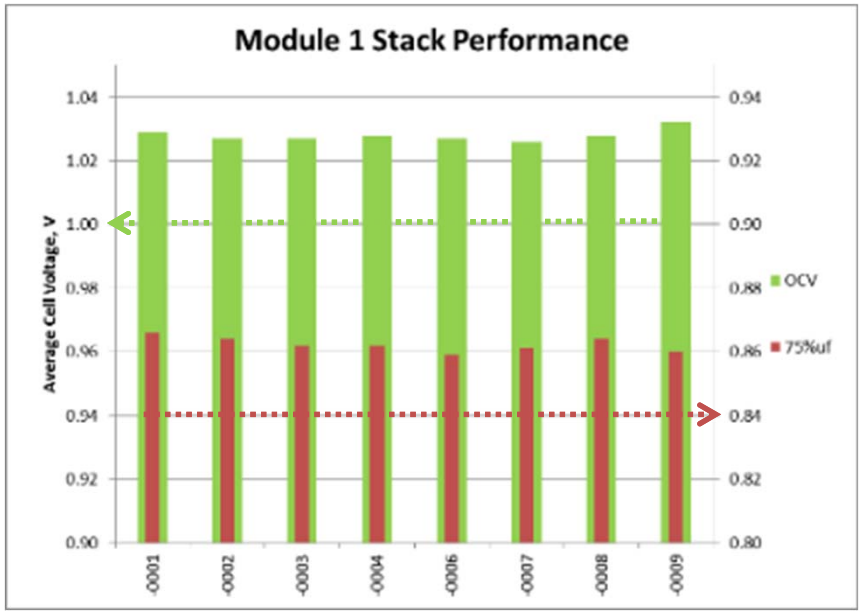
200 kW System Update

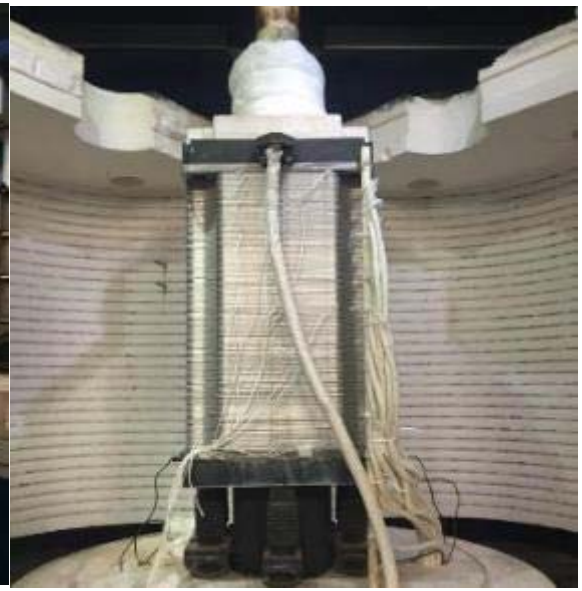
200kW SOFC Power System Overview

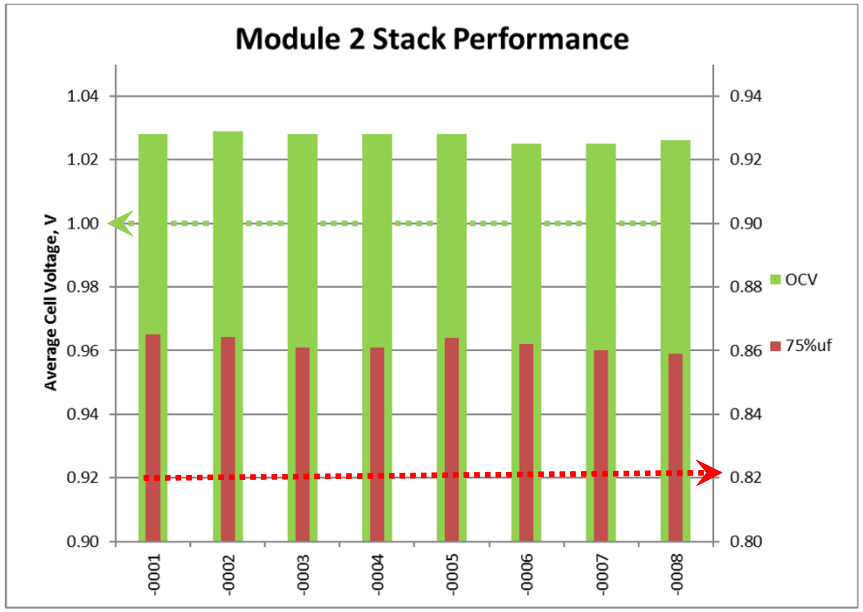


- Includes (2) 100kW SOFC stack modules designed to operate independently
- Factory assembled & shipped as a standard ISO 20' x 8' container

200 kW System Stack Manufacturing

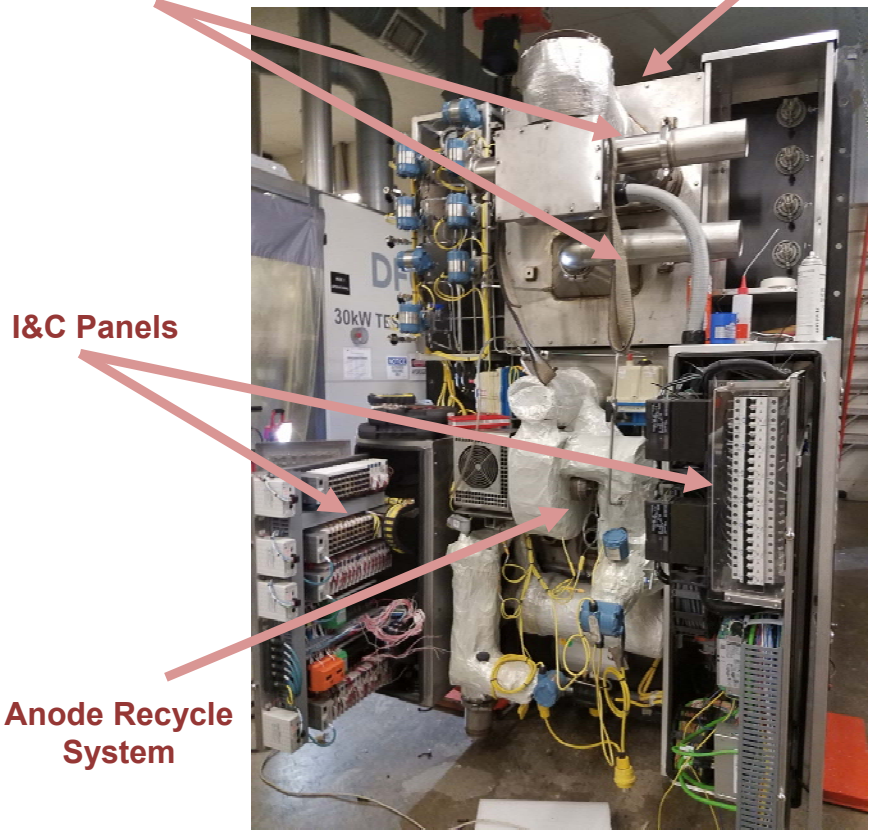






- Excellent stack to stack performance reproducibility
- Stacks for 200 kW system meet cell voltage criteria
- Stacks shipped to FCE Danbury, CT and integrated into 100 kW modules

100 kW Module Design & Fabrication



100 kW Stack Module Architecture:

- Fully integrates all hot BoP equipment within the module
- Eliminates high-temperature plant piping & valves
- Reduces Cr evaporation protective coatings within plant/module
- Integrated anode blower & module-specific instruments greatly decreases plant footprint

200 kW SOFC System Factory Testing

200 kW system installed at FCE's Danbury, CT Test Facility.

Factory Acceptance Test Results at 100% Load

Module A Voltages

Module B Voltages

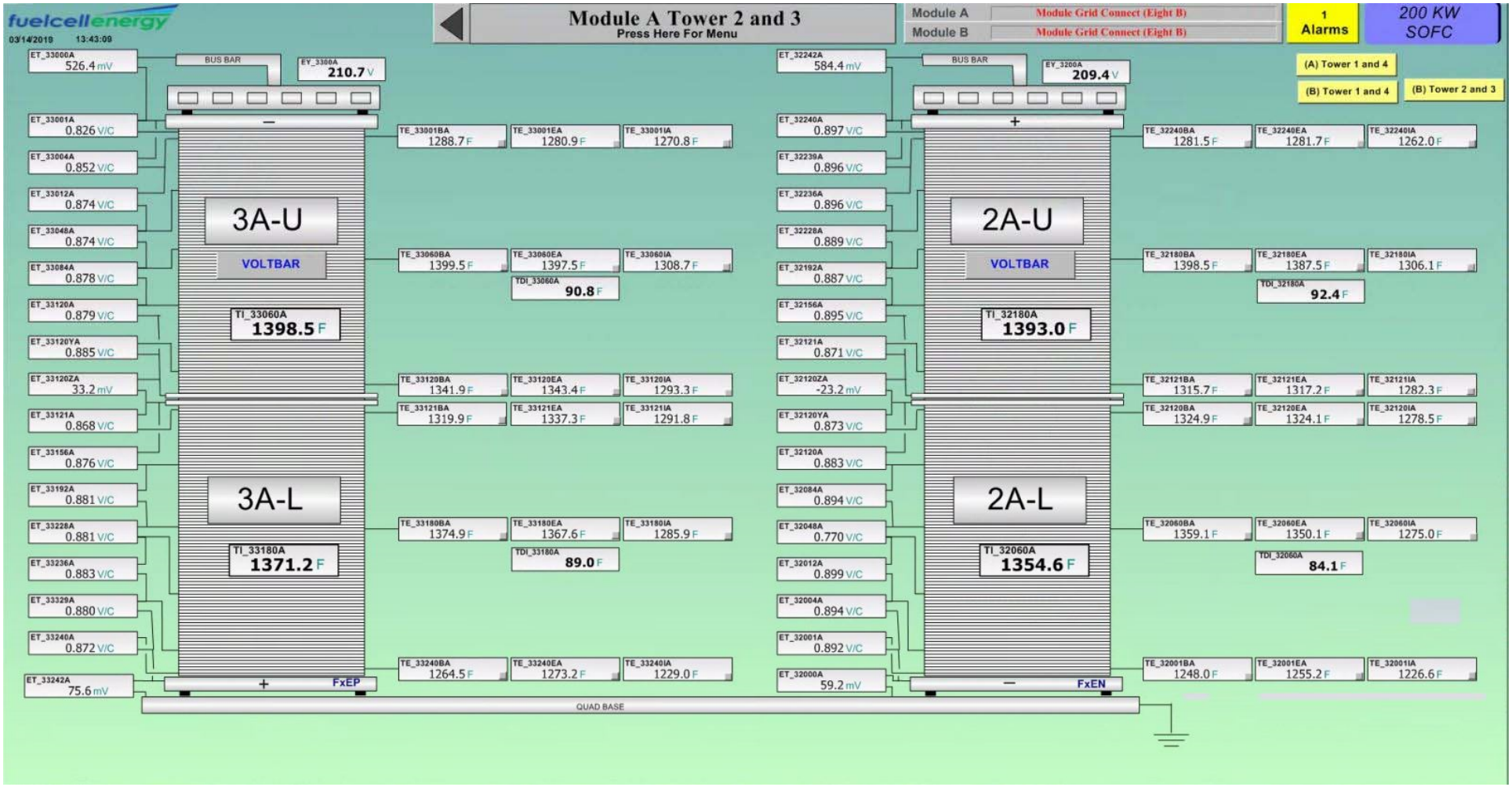
Installation at Demonstration Site

Energy Center Pittsburgh - Clearway Energy (Formerly NRG Yield)

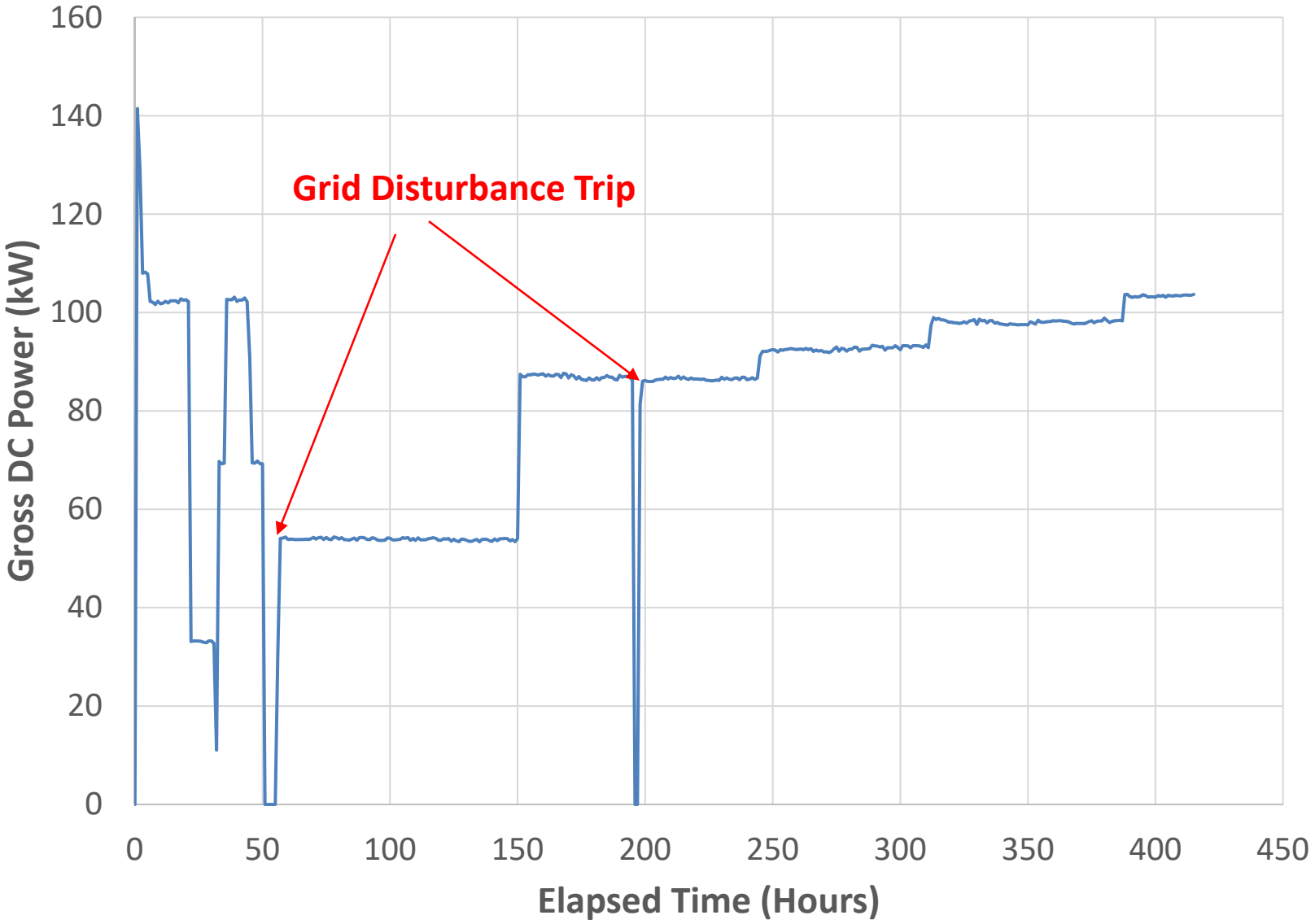
Commissioning at Site 3/2019: 75% Load Module A Voltages

Commissioning at Site 3/2019: 75% Load Module B Voltages

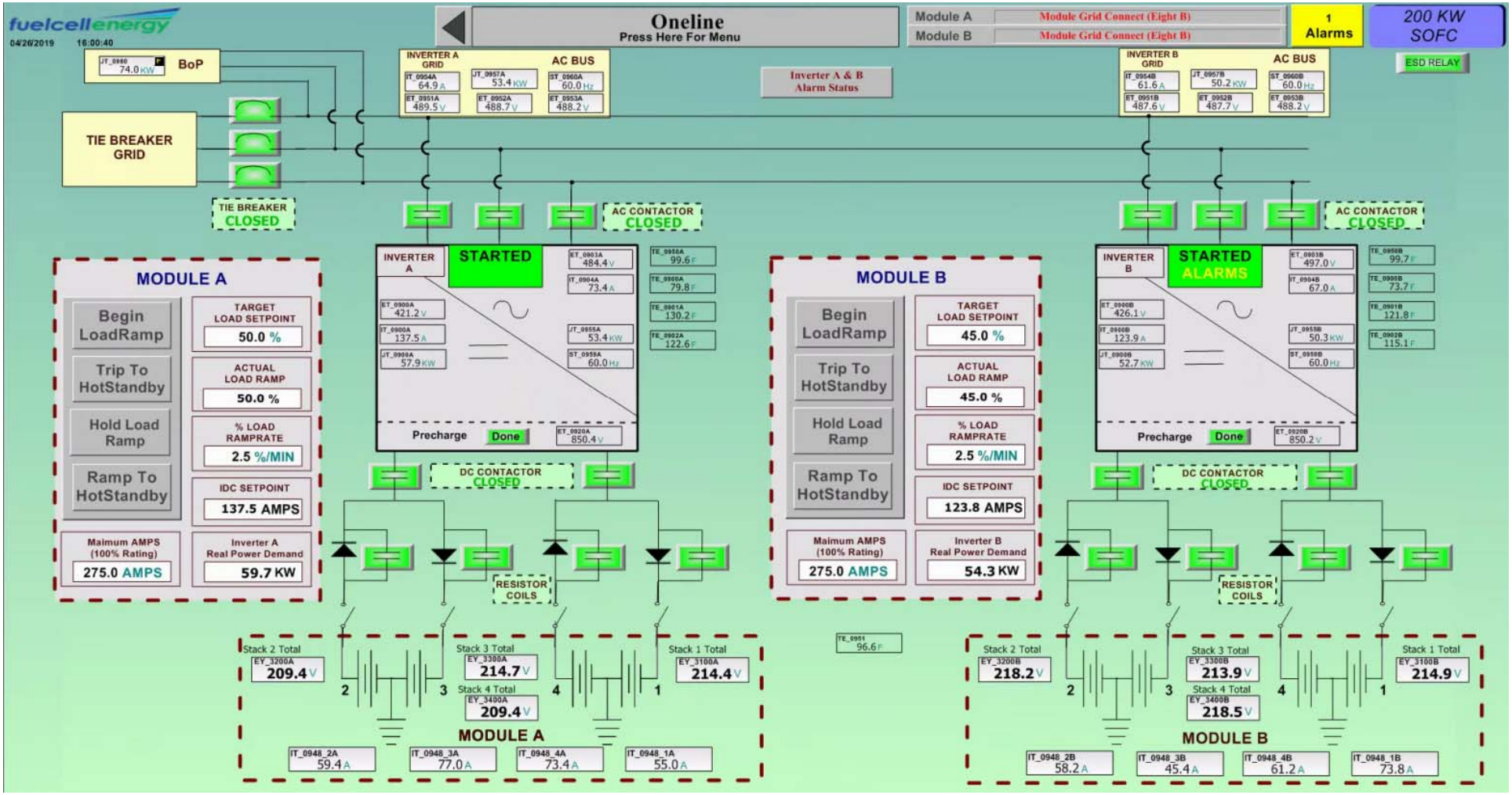
Commissioning at Site 3/2019: 75% Load Module "A" Temperatures



200 kW Operation since onsite Restart



System One-Line Diagram
4/26/19 4:00 PM



Since start of commissioning in Pittsburgh, the 200 kW SOFC system has accumulated >500 hours of hot operation

Next Generation SOFC Stack Technology Development

Compact Solid Oxide Architecture (CSA) Stack

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

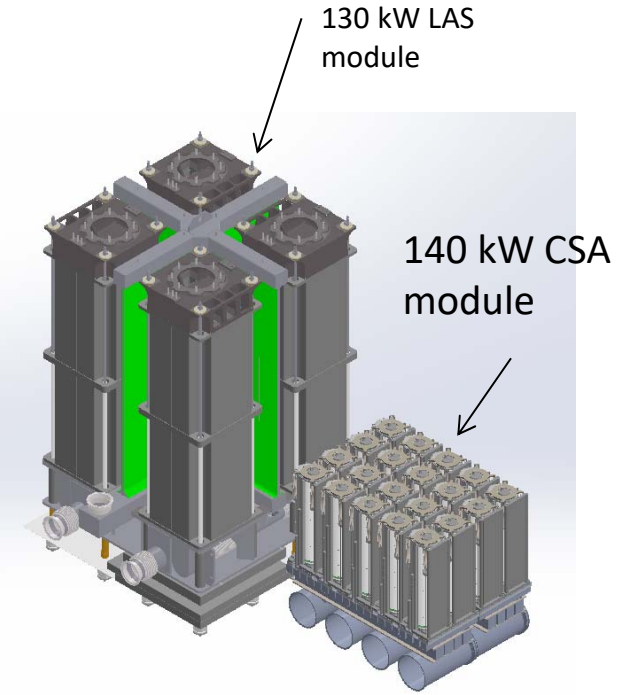
Number of Cells	350
Active Area	81 cm^2
Power @ 0.25 W/cm^2	7 kW
Seal Technology	Crystallized glass

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

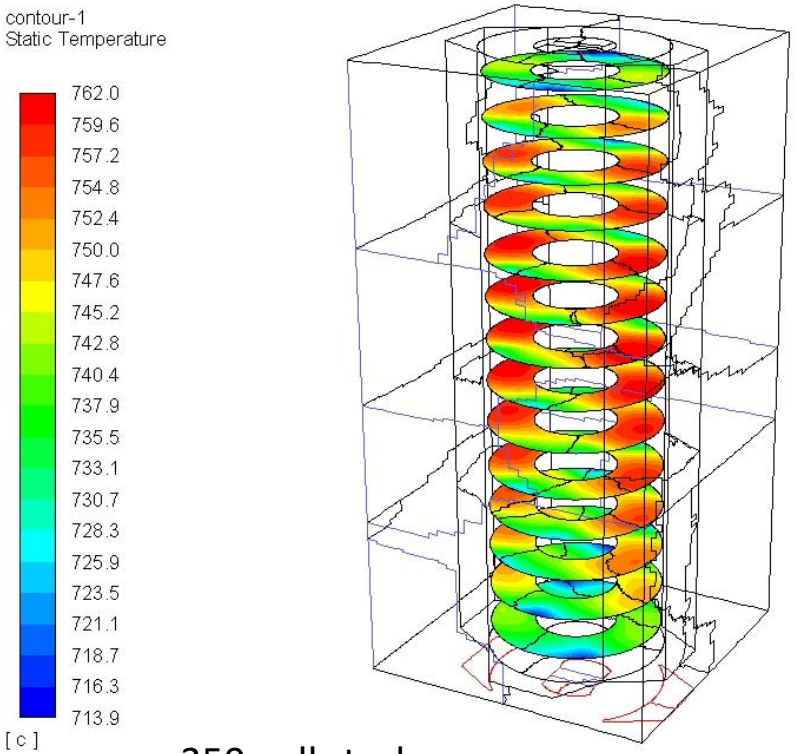
4 X



Modelling to Support Stack Operation

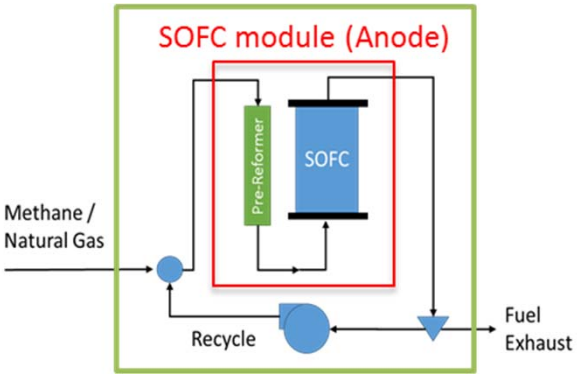
- Fully coupled CFD/electrochemical stack models developed at 3 levels
  - Full stack (lumped porous body model)
  - Partial stack (per layer porous body model)
  - Unit cell (porous body and full detail models being compared)
- Use of ANSYS HPC Pack licensing and cluster computing services to run models
- High current and complex geometry of CSA stack drive large computing requirements

Example Fuel Cell Run (under DOE-DE-FE0026093 Innovative SOFC Technologies)
68%Uf 40%Ua 25% internal reforming, 0.3 A/cm^2



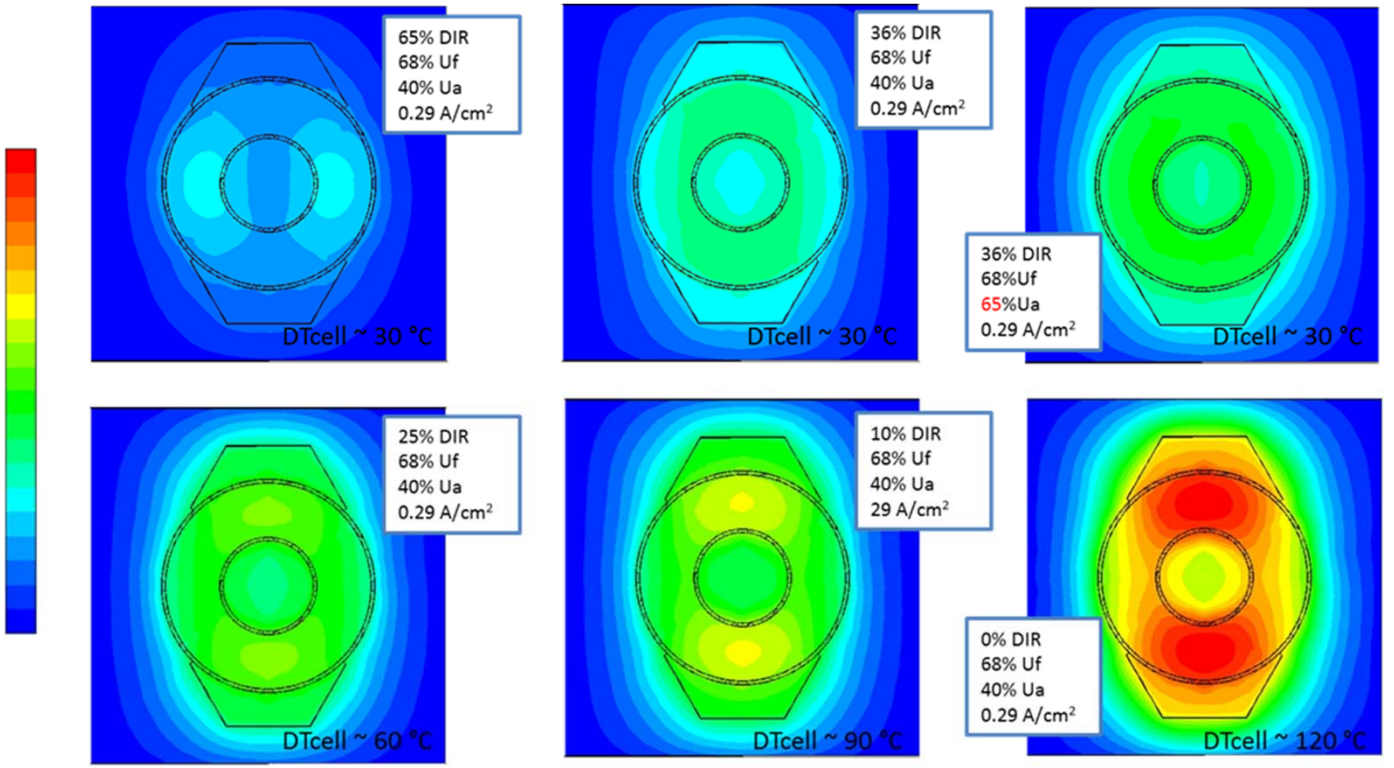
350-cell stack
Select cell layers shown

SOFC Stack Operating Point



Via modeling and test experience, optimal operating point for long term operation were studied :

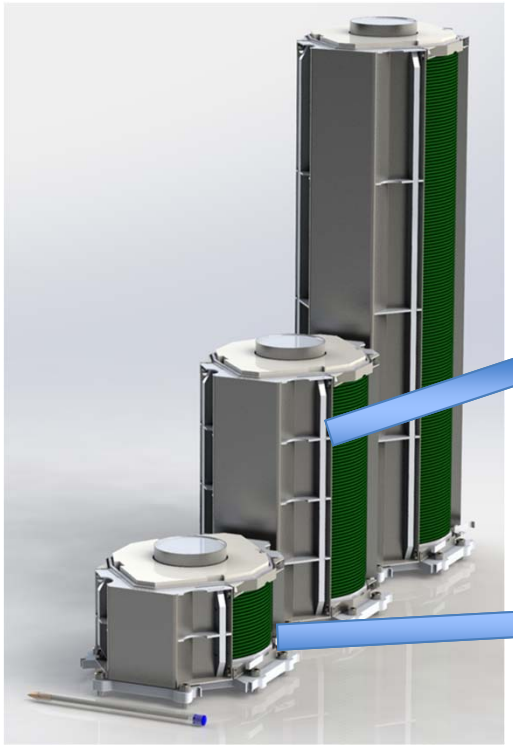
- Air and Fuel Utilizations (ua, uf)
- Extent of Methane Internal Reforming (DIR) with anode recirculation

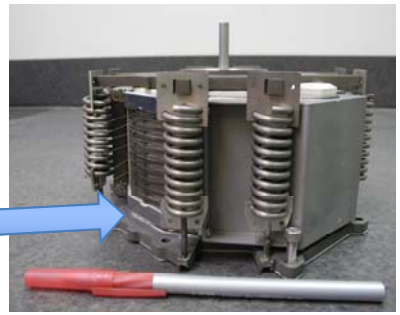


Lower DIR results in higher DT across cell

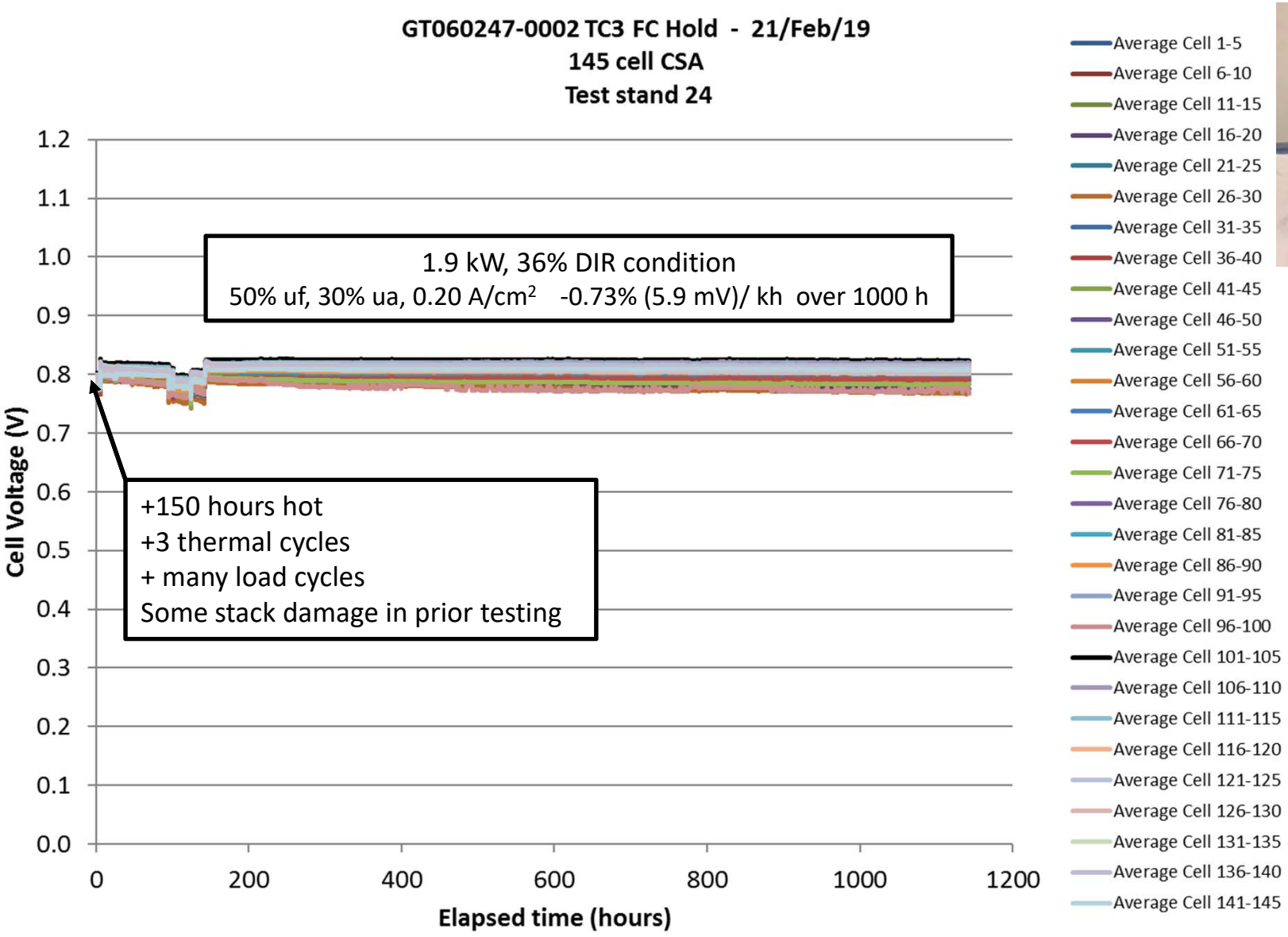
CSA Stack Family

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
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	



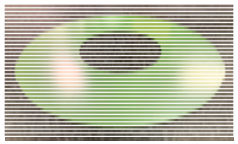


145-cell CSA Stack
Fuel Cell Hold (TC3 data)



Path to Low-Cost MWe Systems

20 W



Cell

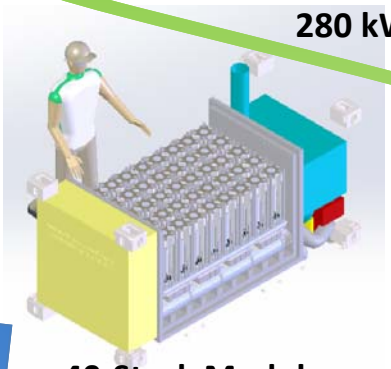
7 kW

CSA Stack

DE-FE0026093
Innovative SOFC

DE-FE0031648
Next-Gen Module

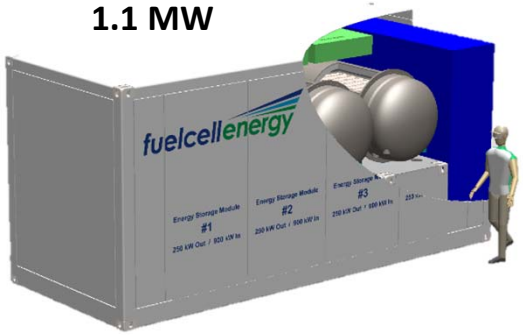
280 kW



40-Stack Module
7kW x 40 =
280kW Power
Generation Output

Technology Trajectory

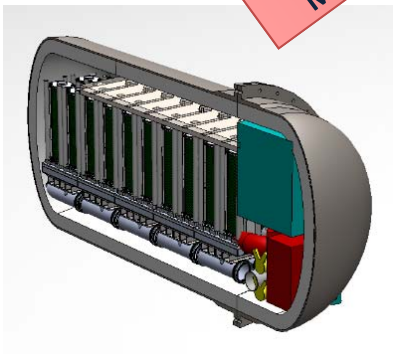
1.1 MW



Core 1MWe SOFC system

40 kW CSA Array Module
With common design elements

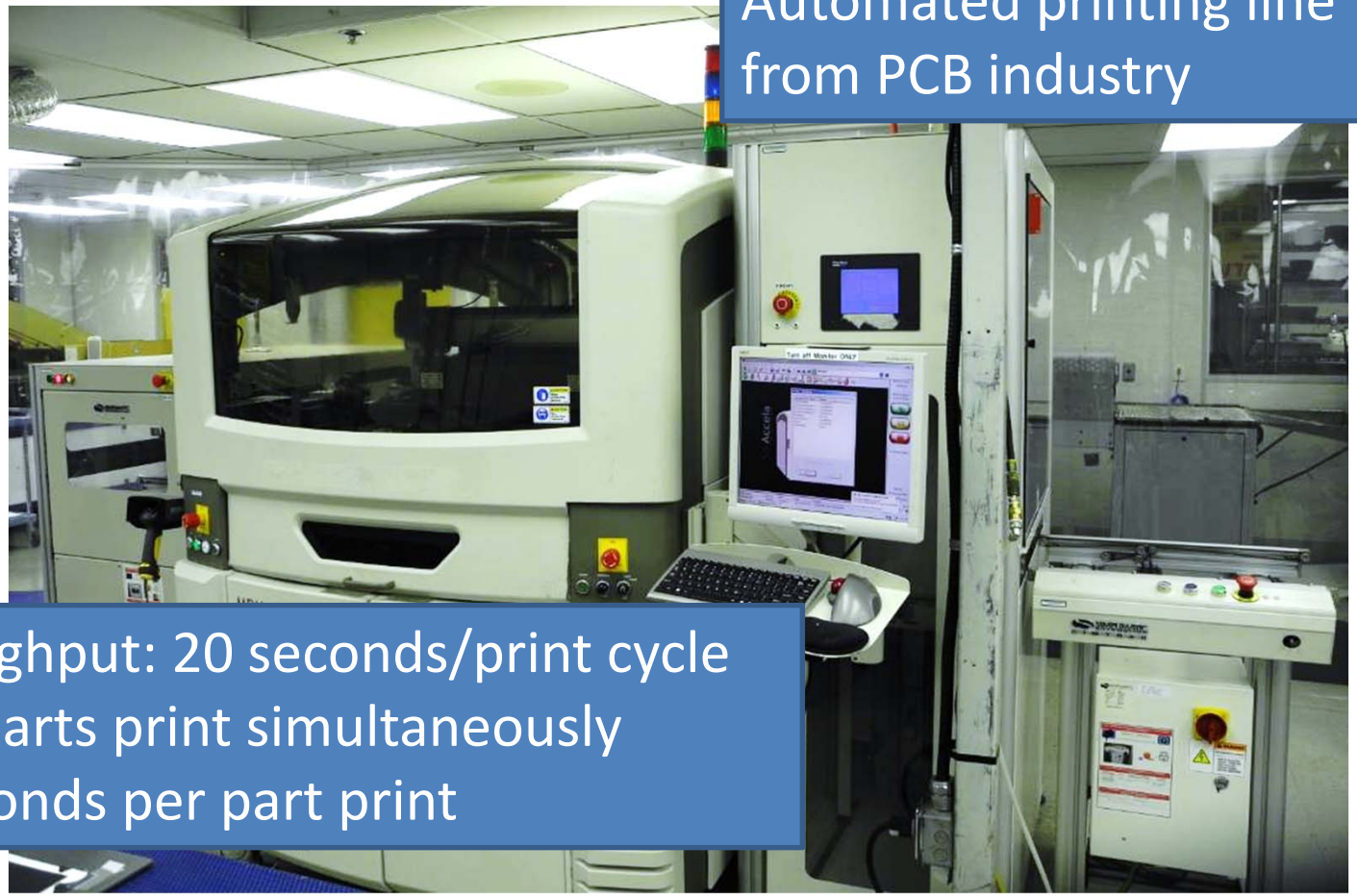
DE-FE0031639
MW Pilot – Phase I



1 MWe SOFC System Deployment (MW Pilot – Phase II)

CSA Stack Manufacturing

Automated Cell Printing



Automated printing line from PCB industry

Line throughput: 20 seconds/print cycle
Target: 9 parts print simultaneously
=> 2.2 seconds per part print

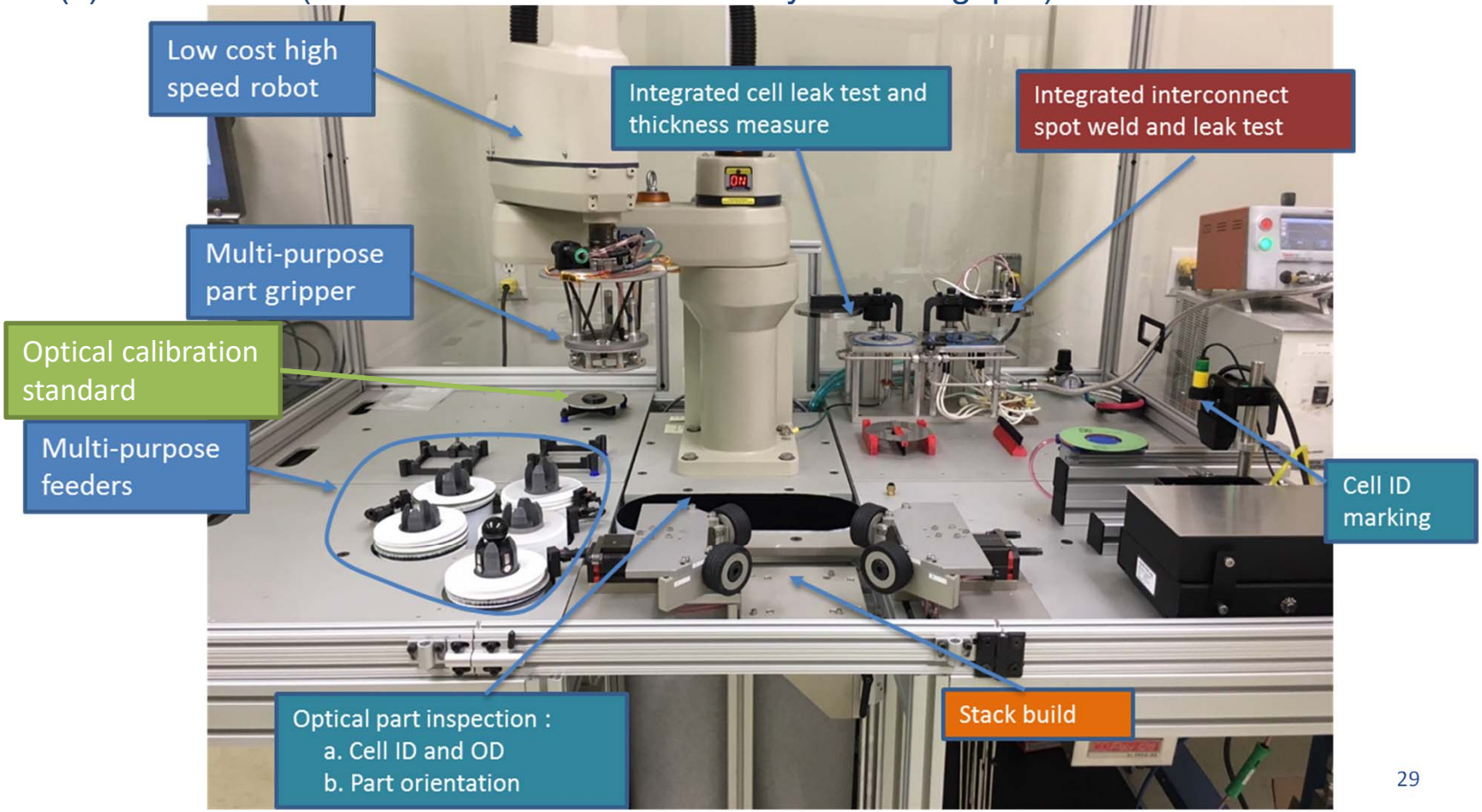
Automated Integrated Stacking &QC Station

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 Scale-up

- Manufacturing success with short to mid-height stack transition include:
  - Automated stack build
  - Stack firing/consolidation & final assembly
- Next step: complete scale-up to high performing full height ~350-cell stack addressing manifolding and flow distribution challenge

Acknowledgements

- The progress in SOFC technology was supported by DOE/NETL Cooperative Agreements: DE-FE0023186, DE-FE0026199, DE-FE0026093, DE-FE0031639 and DE-FE0031648
- Guidance from NETL Management team: Shailesh Vora, Joseph Stoffa, and Patcharin Burke