# Low Temperature Solid Oxide Fuel Cells for Transformational Energy Conversion (DE-AR0000494)

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# 500-550 °C SOFC Stack: Project Approach

- **Increased Efficiency**
  - Doped $CeO_2$:
    - * > 10X conductivity of YSZ @ at 500°C
    - * electronic leakage in fuel conditions, lowers efficiency even at lower operating temperatures
  - *Solution*: a cathode functional layer demonstrated to boost open circuit potential
  - *Goal*: Optimize *cathode functional layer (CFL)* and scale-up to 10 cm by 10 cm size
    - * maximize efficiency (increase OCP to 0.9-1.0 V) & minimize ASR for >0.1 $W/cm^2$ (@ ~0.75 V) at ~500 °C
- **Higher, more Robust Power Density**
  - Improve carbon/sulfur tolerance with catalyst infiltration into as-fabricated porous anodes
  - Optimize cathode composition and infiltration to increase power density (reduce cost)
- **Optimized stack designs for LT operation**
  - Use Redox multi-physics model to optimize stack design for low temperature operation
  - Maximize internal versus external reforming
  - Conductive ceramic anodes for more robust cells and stacks
- **Stack demo for load following**
  - cell performance maps for stack, feed results back to model for design optimization
  - 100-250 Watt stack demo for load following applications, such as datacenters

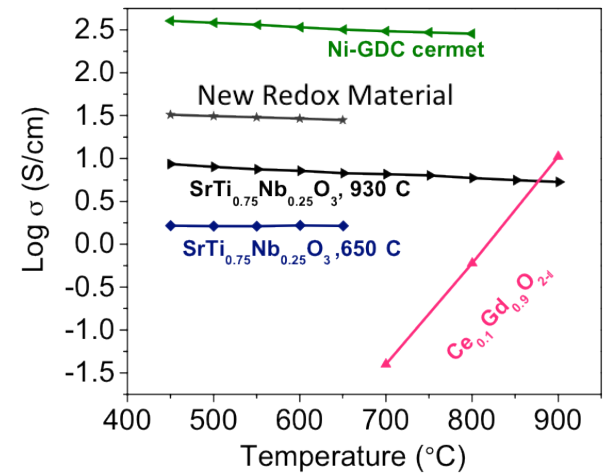
# Team and Project

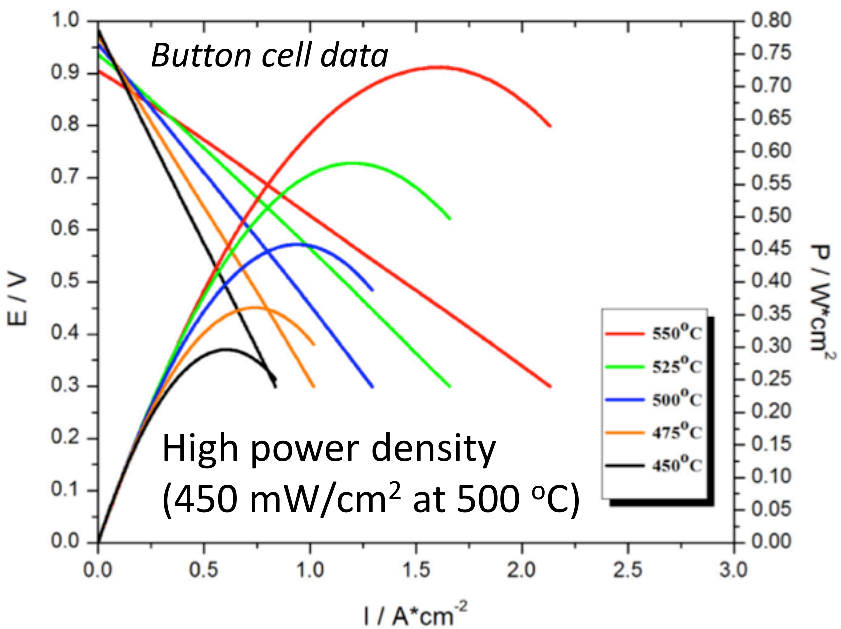
*Datacenter/Utility Partners*

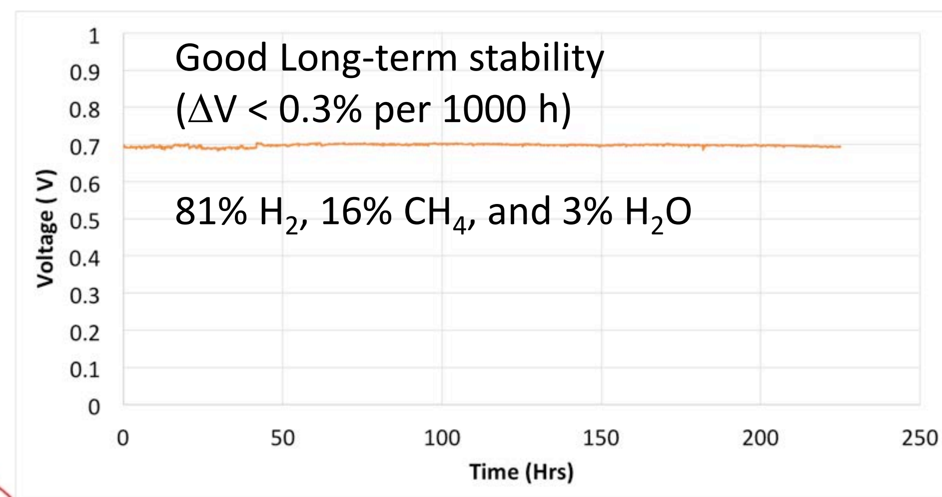
# All-Ceramic Anode

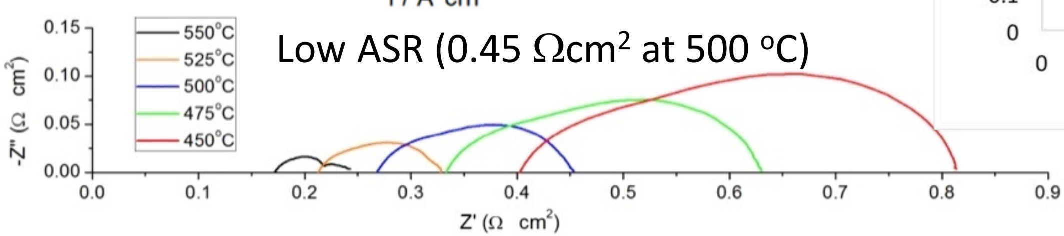
- Metal oxide anode → resistance to coarsening and volatility, customizable conductivity and catalytic activity
- New Redox Material (spun-off from UMD) → higher conductivity than other ceramic anodes without high temperature activation

High electrical conductivity



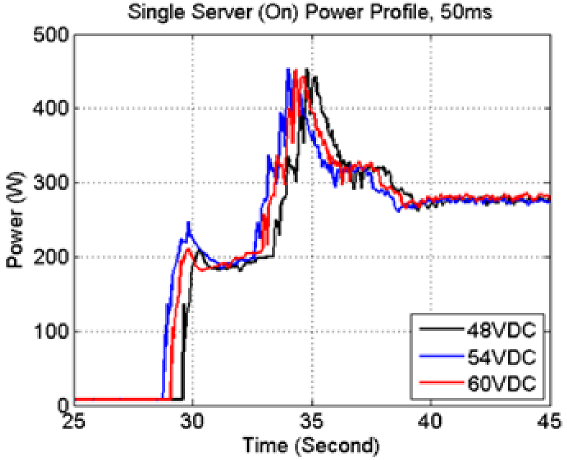



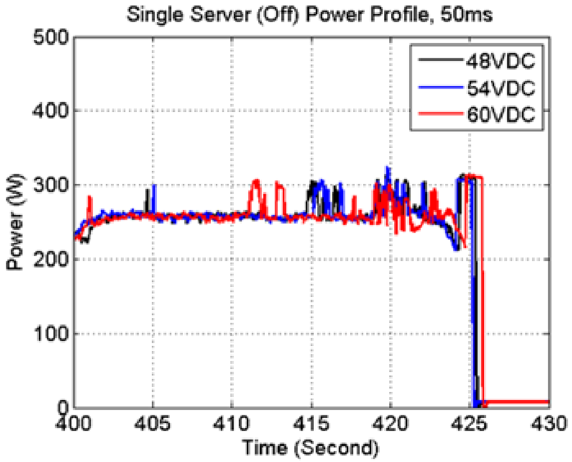



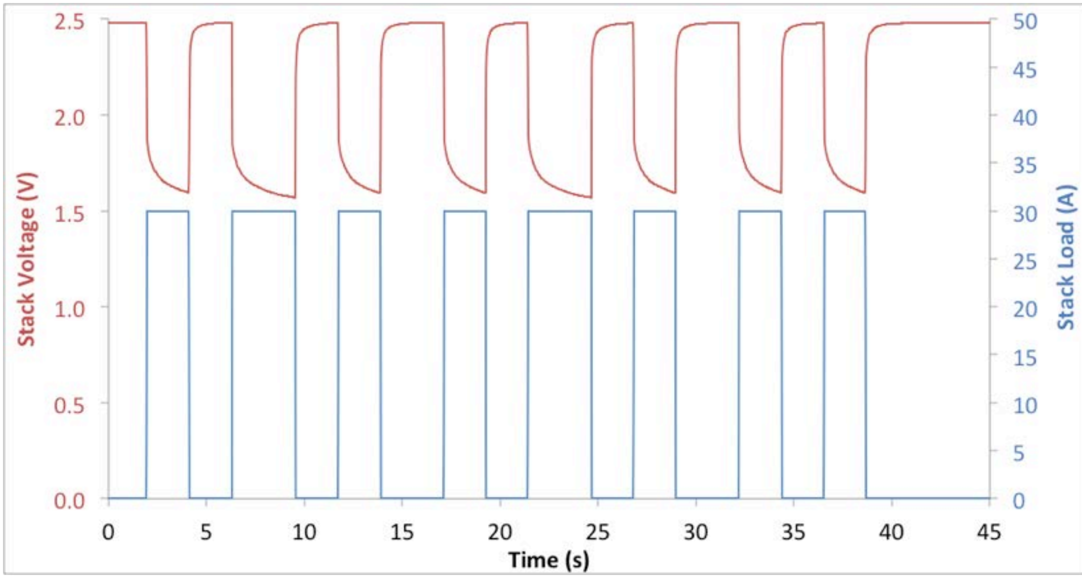
# Extreme Load Following

Examples of data center power demand



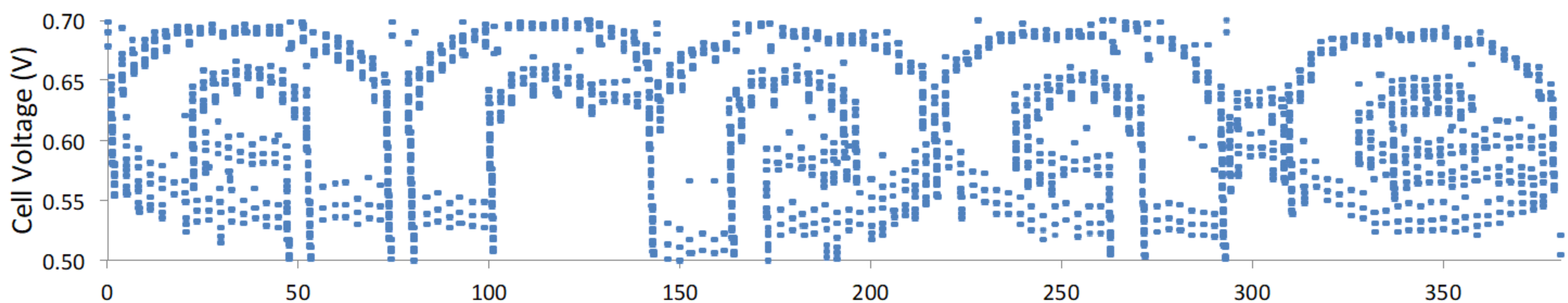

Redox Gen. 1 (Ni-cermet) Short Stack 3-Cell (10 cm by 10 cm) Load Following Capability

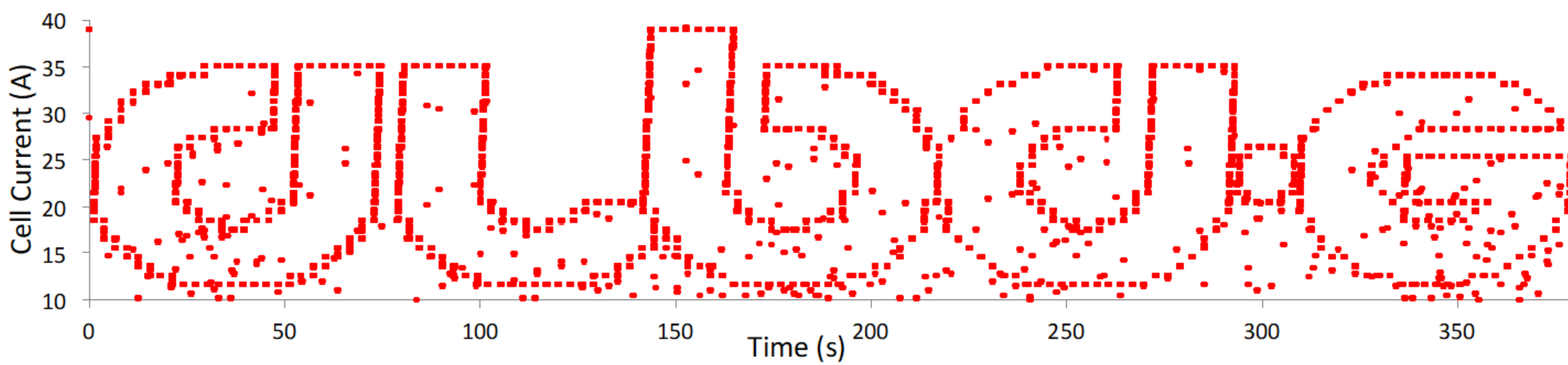



Voltage drops “smoothly” to follow load demand (i.e., no spikes in voltage)

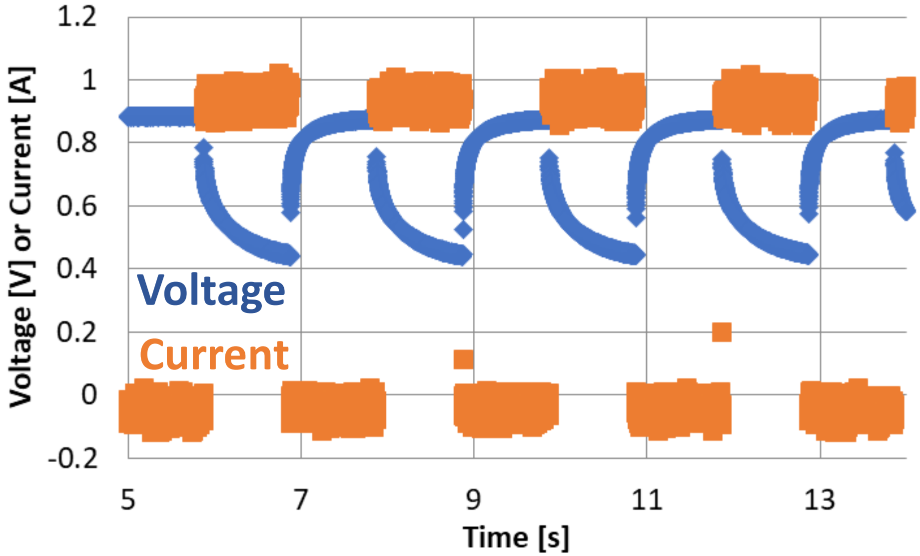
# Extreme Load Following

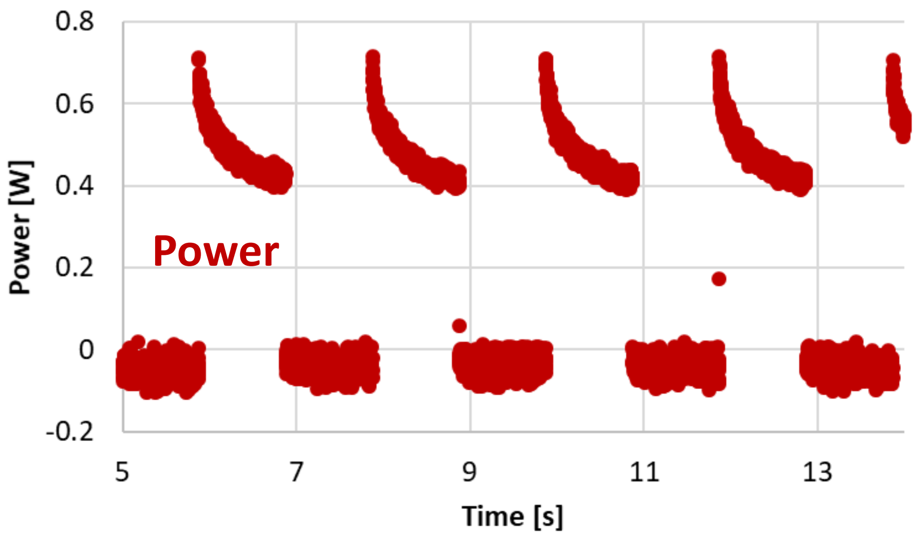
Redox Gen. 1 (Ni-cermet) Short Stack 3-Cell
(10 cm by 10 cm) Load Following Capability



# All-Ceramic Anode Load Following

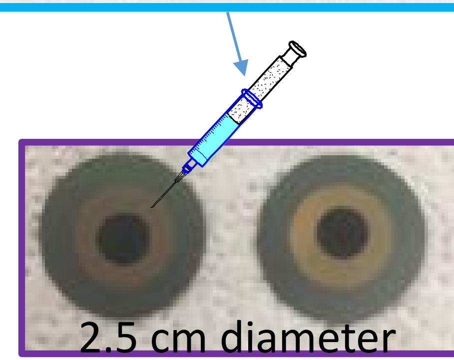



***5 cm x 5 cm all-ceramic anode SOFC at 550 °C***

- Voltage decays to equilibrium value in 1 s without spikes
- Cell meets rapid changes in power demand

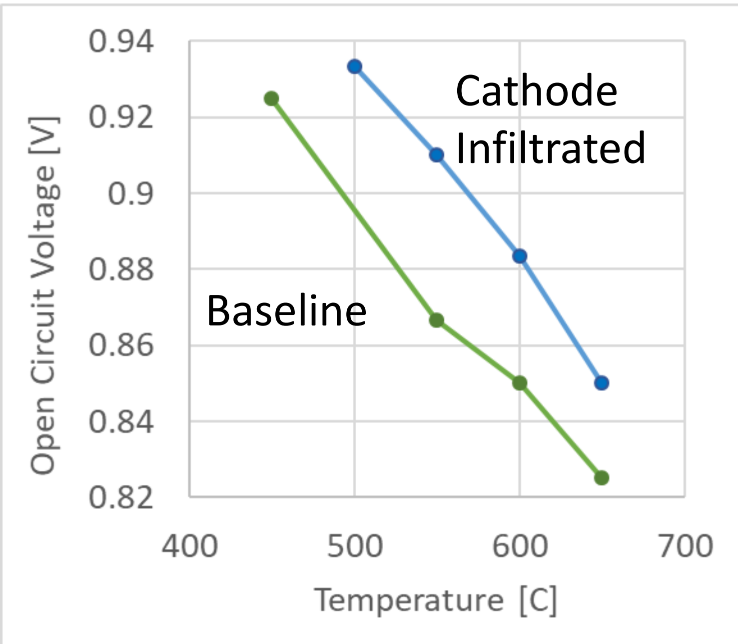
# All-Ceramic Anode Scale-Up

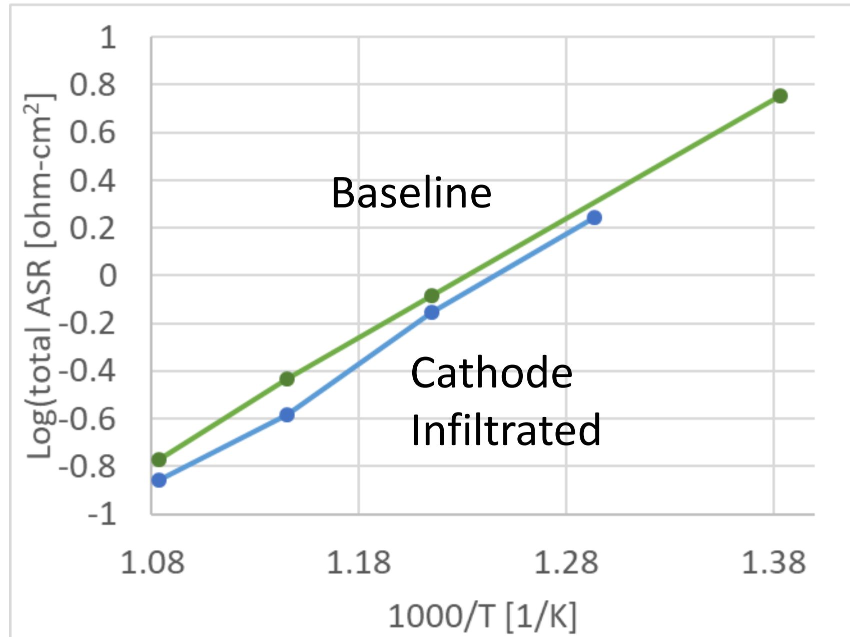




- Successfully scaled up ceramic anode half-cell to 10 cm by 10 cm
- Production partner currently fabricating 8 kg batches of material for large-scale tape casting
- Upgrades being developed in infiltrate process for scale-up

# Infiltration Advantage

Gen. 1 (Ni-cermet) 3-cell 5x5 stack



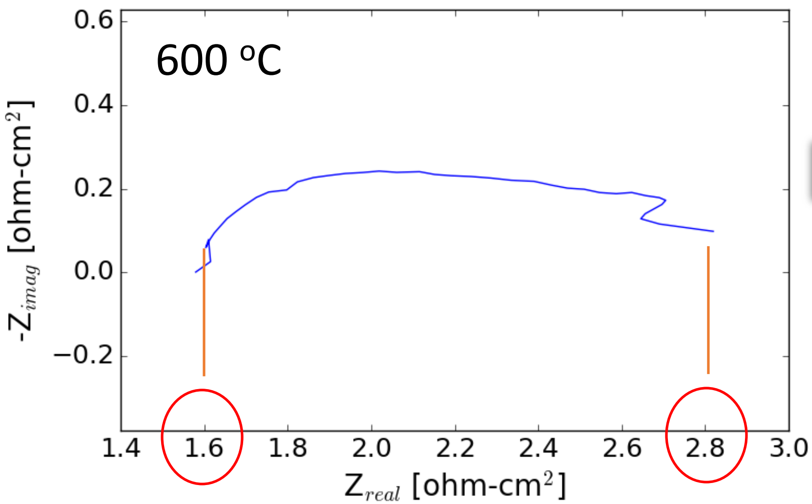




With cathode infiltration:

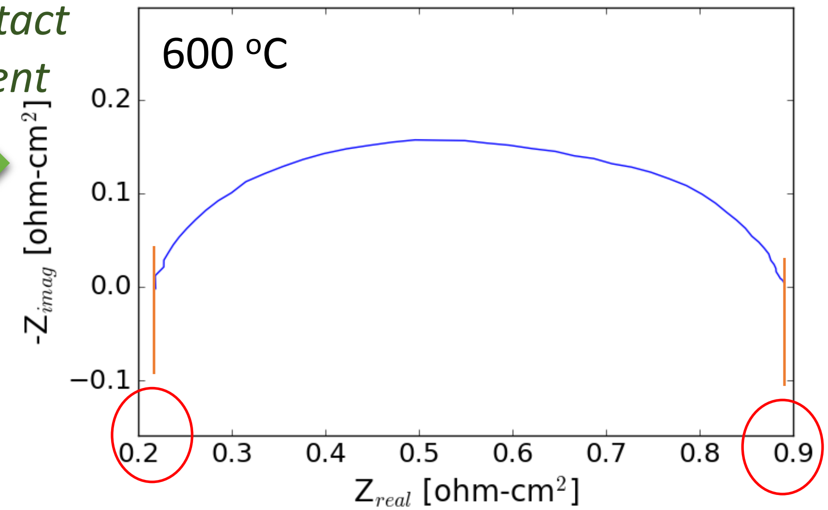
- ~30-40 mV increase in open circuit voltage consistently achieved with infiltration
- 10% decrease in area-specific-resistance (ASR)

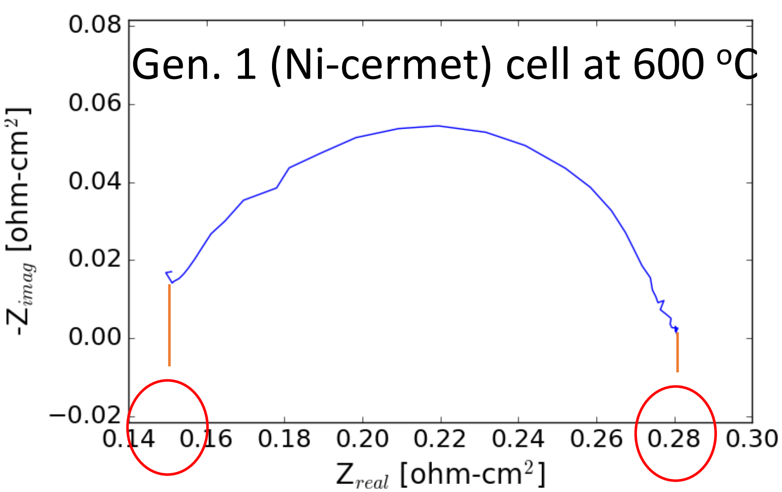
# All-Ceramic Cell Performance Improvements

5 cm x 5 cm SOFC (without CFL or cathode infiltration)



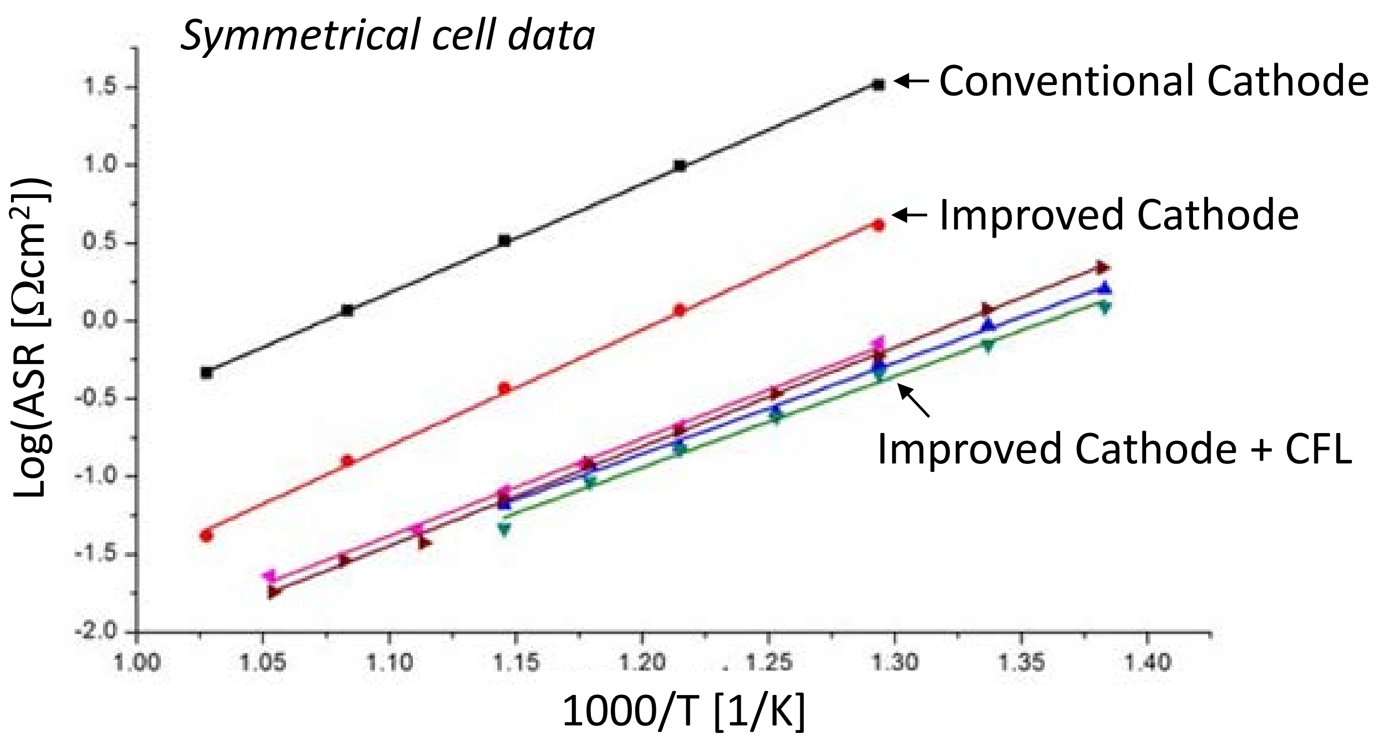

*Anode contact improvement*



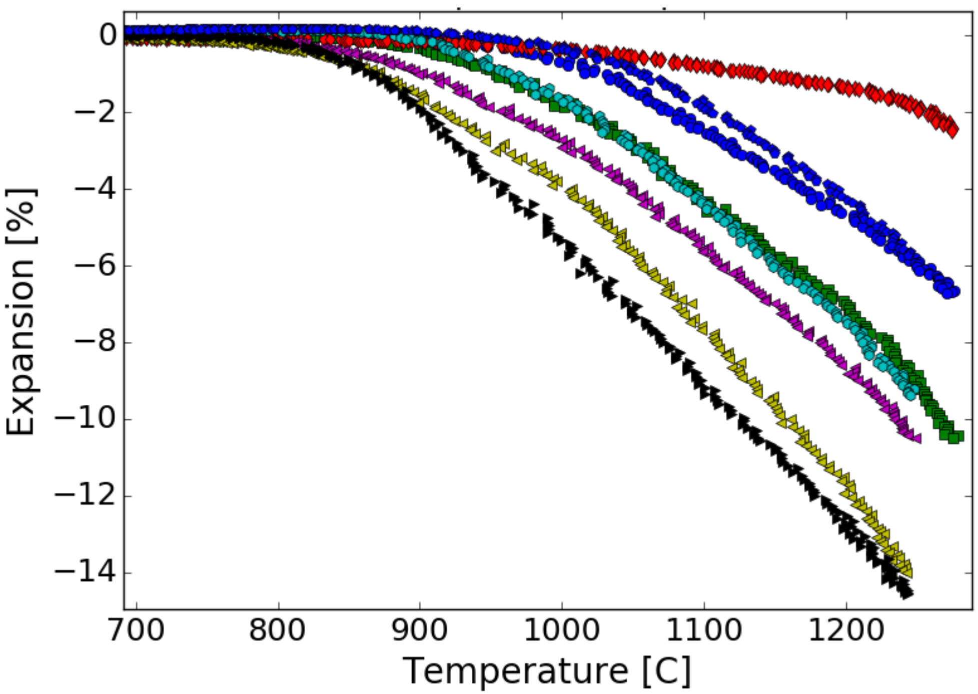

- **Improvement in contact → *88% drop in high frequency intercept, and 42% decrease in low frequency contribution***
- High frequency resistance still 1.4x larger than Gen. 1 cell, and low frequency is 3.8x higher → **focus on improvements in electrode activity (i.e., CFL and infiltration)**

# Cathode Performance with CFL




CFL decreases ASR ~100x at 500 $^{o}$C, as compared to conventional cathode

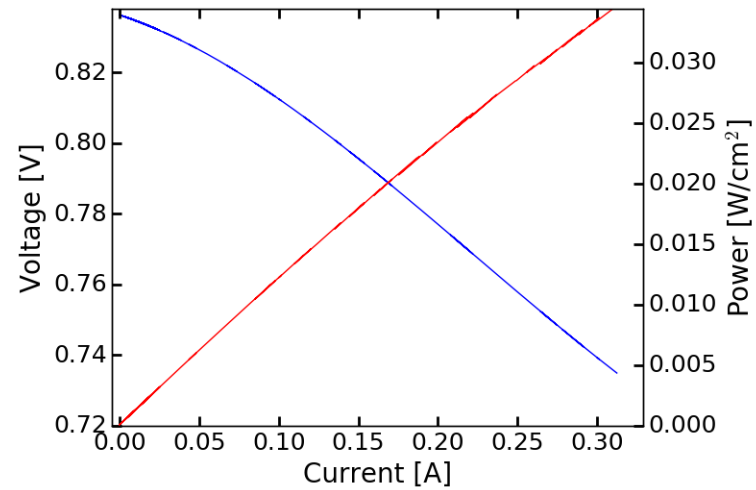
# All Ceramic 5x5 Cell Development

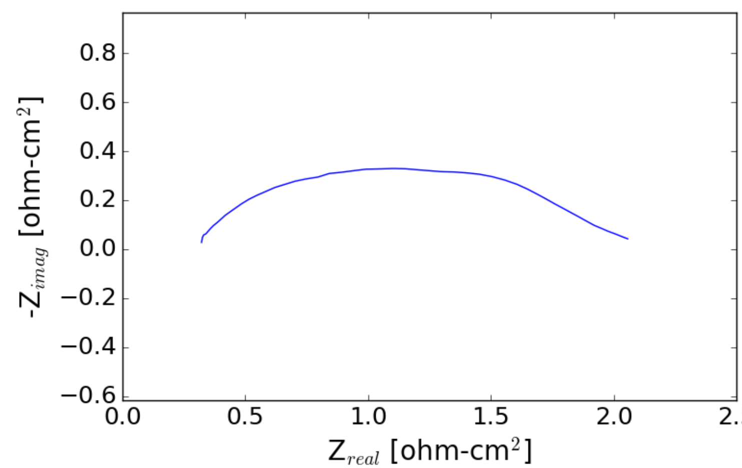



Tailor all-ceramic anode sintering shrinkage by control of particle size, pore former, and composite phase fraction

→ match electrolyte shrinkage for flatter, testable SOFCs

5 cm by 5 cm @ ~550°C
(no CFL and conventional cathode)



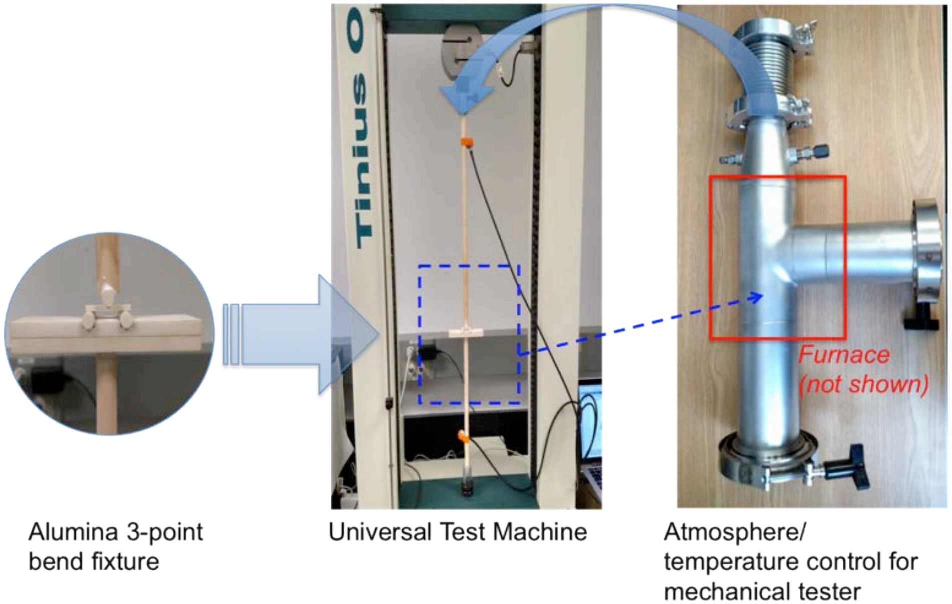
# Mechanical Strength

*4-point bend bar at room temperature*

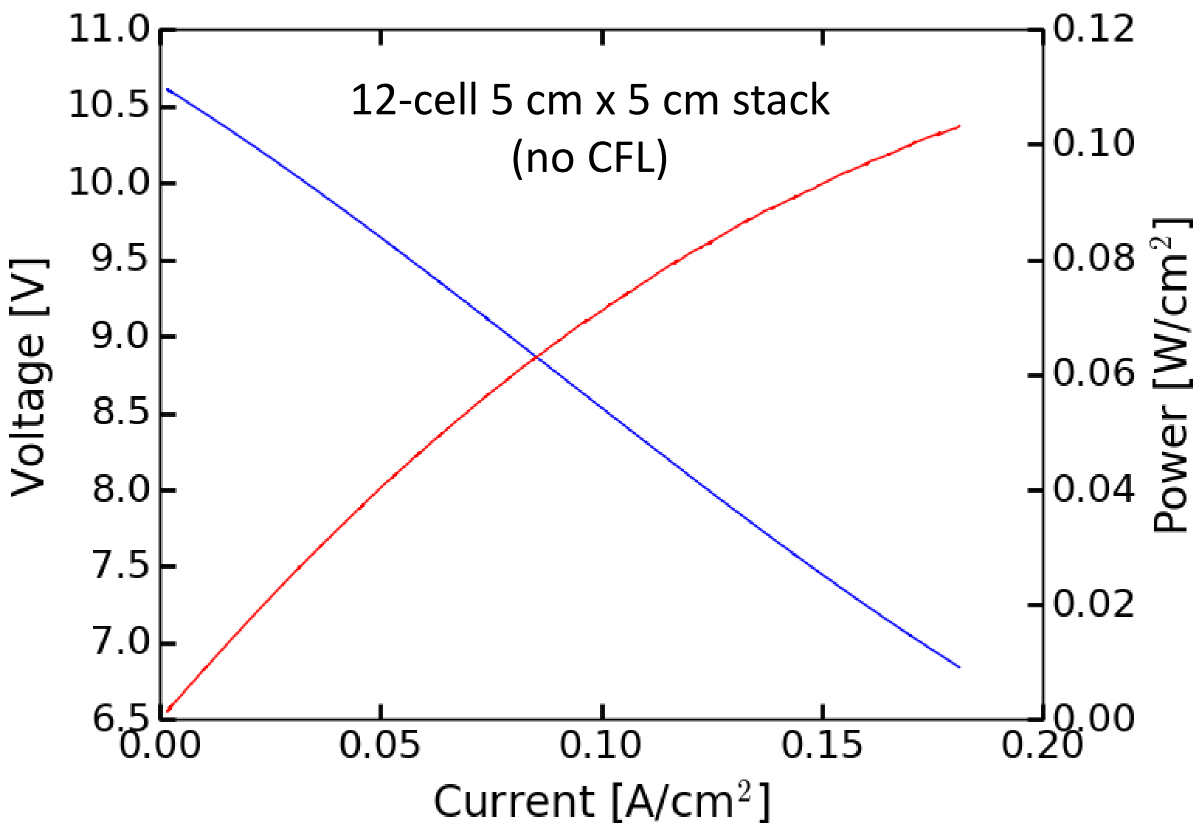
| Half-cell | Failure Stress [MPa] |
|---|---|
| Gen. 1 (Ni-cermet) | 161 |
| All-ceramic anode | 77 |

- All-ceramic anode cells are mechanically robust enough for SOFC testing
- For ease of scale-up, increased mechanical strength is desired
- 2$^{nd}$ phase additive with expected higher mechanical strength and with all-ceramic anode compatibility identified

*In situ* bend bar test rig (UMERC)



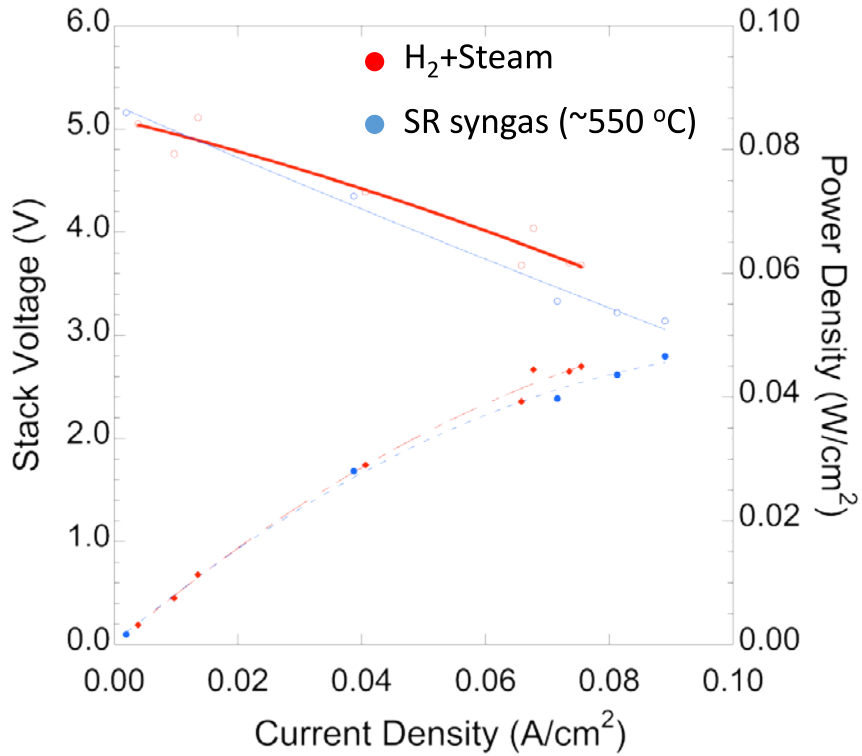
# Gen. 2 (porous Ni-cermet) at 500 $^oC$




- Stack designed for 600 – 650 $^oC$ operation (*development sponsored by DOE-EERE)*
- Gen. 1 (Ni-cermet) in separate studies:
  - Investigating dynamic and static operation of low temperature systems with reformed fuels

# Low Temperature Fuel Reforming System

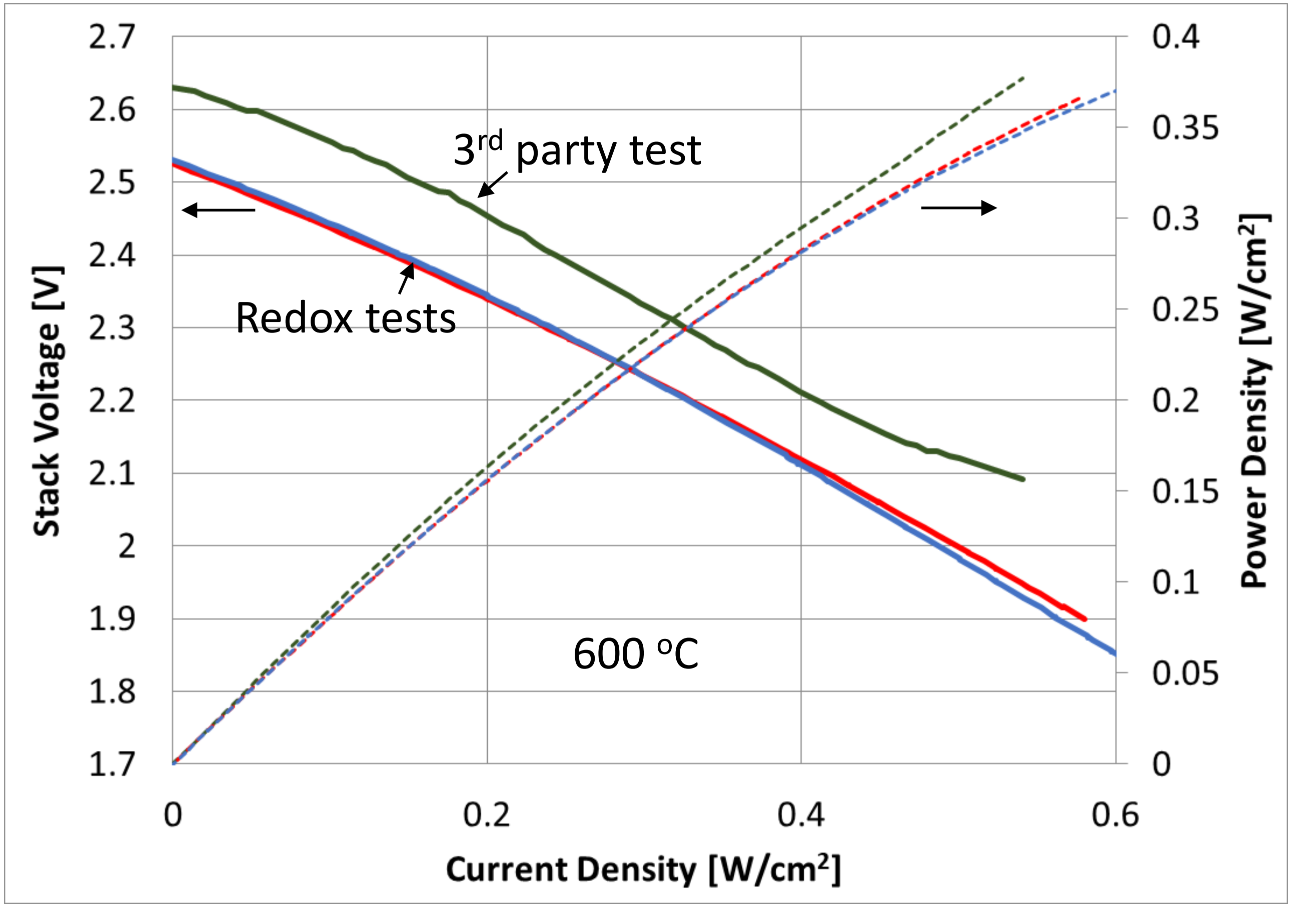
- Lab-scale independent system using a hot box (no electric heaters) with $CH_4$ fuel
- Successful operation of Gen-1 (Ni-cermet) stack at 490-500 °C and steam reformer at ~550 °C
- Low power from poor busbar to stack contact (650 °C ASR 2x larger than typical)




- Similar performance with hydrogen and steam reformer (SR) syngas

# Independent 3rd party validation

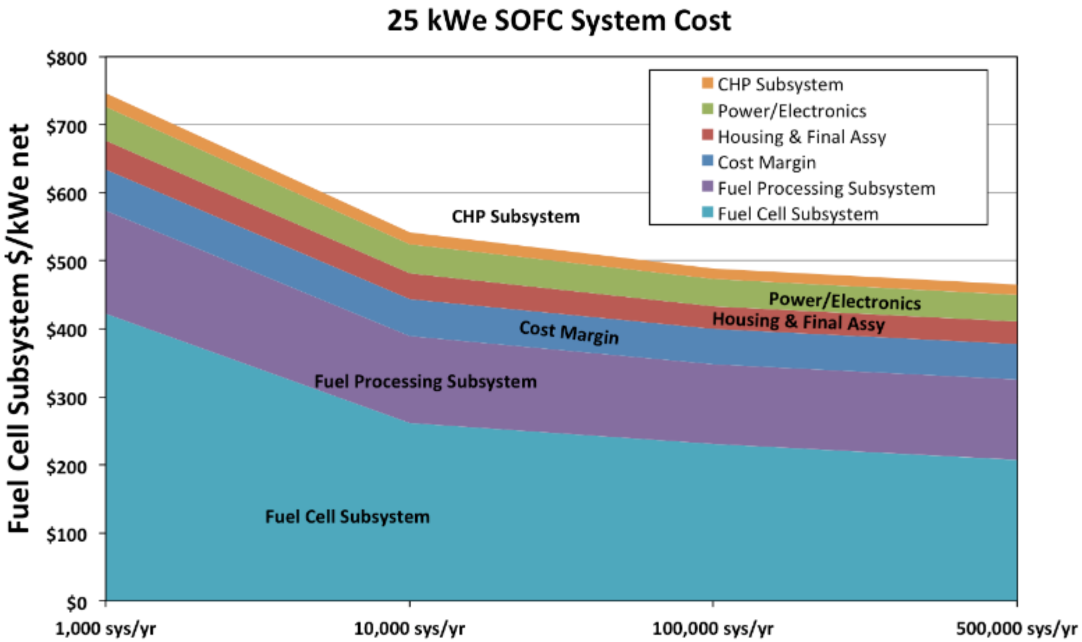
3 separate Gen. 1 (Ni-cermet) 3-cell 10 cm x 10 cm stacks fabricated by Redox




- Demonstrated reproducible power densities
- 4% higher voltage in 3rd party test

# Techno-Economic Analysis

- Implemented Design for Manufacturing and Assembly (DFMA)[1]
  - Process-based cost estimating methodology
  - Assessed costs at fuel cell (FC) stack, fuel processor (FP) subsystem, and balance of plant (BOP) level
  - Utilized detailed cell and stack manufacturing process sequences to capture costs (such as raw materials, capital equipment, and labor)
- Focused on FC, FP, and BOP economic assessment of lower operation temperature SOFC technology




Redox cost trends for 25kWe for increasing system annual production rate

- Cell and stack components (FC subsystem) are the primary focus → keys to product performance and the largest cost
- For high volumes (10,000 sys/yr) manufacturing costs fall below $550/kWe

[1] Brian James et al., *Manufacturing Cost Analysis of Stationary Fuel Cell Systems*, September 2012.

# Summary

- All-ceramic anode button cell has high power density, low ASR, and good long-term performance
- Successful 5x5 SOFC testing performed
  - Large reduction in ASR with improved contacts
  - Future incorporation of CFL and advanced cathode expected to result in further large gains
  - Successful fabrication of 10 cm x 10 cm half-cell
  - Strengthening additive identified for more mechanical robust cells
- Extreme load following demonstrated for data center partner
- 500 $^{o}$C operation with steam reformer in hot box demonstrated
- Techno-economic analysis shows fuel cell subsystem has largest cost share of system

# Acknowledgments


- ARPA-E Team
    - Paul Albertus (and formerly John Lemmon)
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