ATREX ENERGY

POWERFUL POSSIBILITIES

Progress Report on Performance and Reliability Advancements in a Durable Low Temperature Tubular SOFC

14th June 2018

Praveen Cheekatamarla

Agenda

- **About Atrex Energy, Inc.**
- **Applications of remote power generators**
- **Technical progress**
  - Cell technology improvements
  - $5kW_{EL}$ stack
  - Manufacturing automation
- **Further work**
- **Acknowledgements**

About Atrex Energy

- "Powder to Power"
- Commercially developed tubular Solid Oxide Fuel Cell (SOFC) technology and systems with ~ 600 stacks shipped – NG, Biogas & Propane, accumulating >6 Million hours of run time
  - Fielded units include configurations up to 1.5kW but demonstrated up to 10kW prototypes
  - Customers include oil and gas, telecommunications, rail, environmental monitoring, mining, construction, maritime and US Coast Guard
  - Units running in remote environments for >35,000hrs
- FC1 certification from the Canadian Standards Association
- Military Technology Product Development – Fuel Flexible Solutions using JP8, DF2, F24, S8, GTL – 2nd generation technology with >40% net DC efficiency
- Hybrid Energy Storage Module – Intelligent power management with ability to connect 6 different power sources for optimal fuel efficiency

Atrex Energy continues to transition its commercially available SOFC technologies for advanced power applications with fuel flexible solutions

Remote NG and Propane Applications

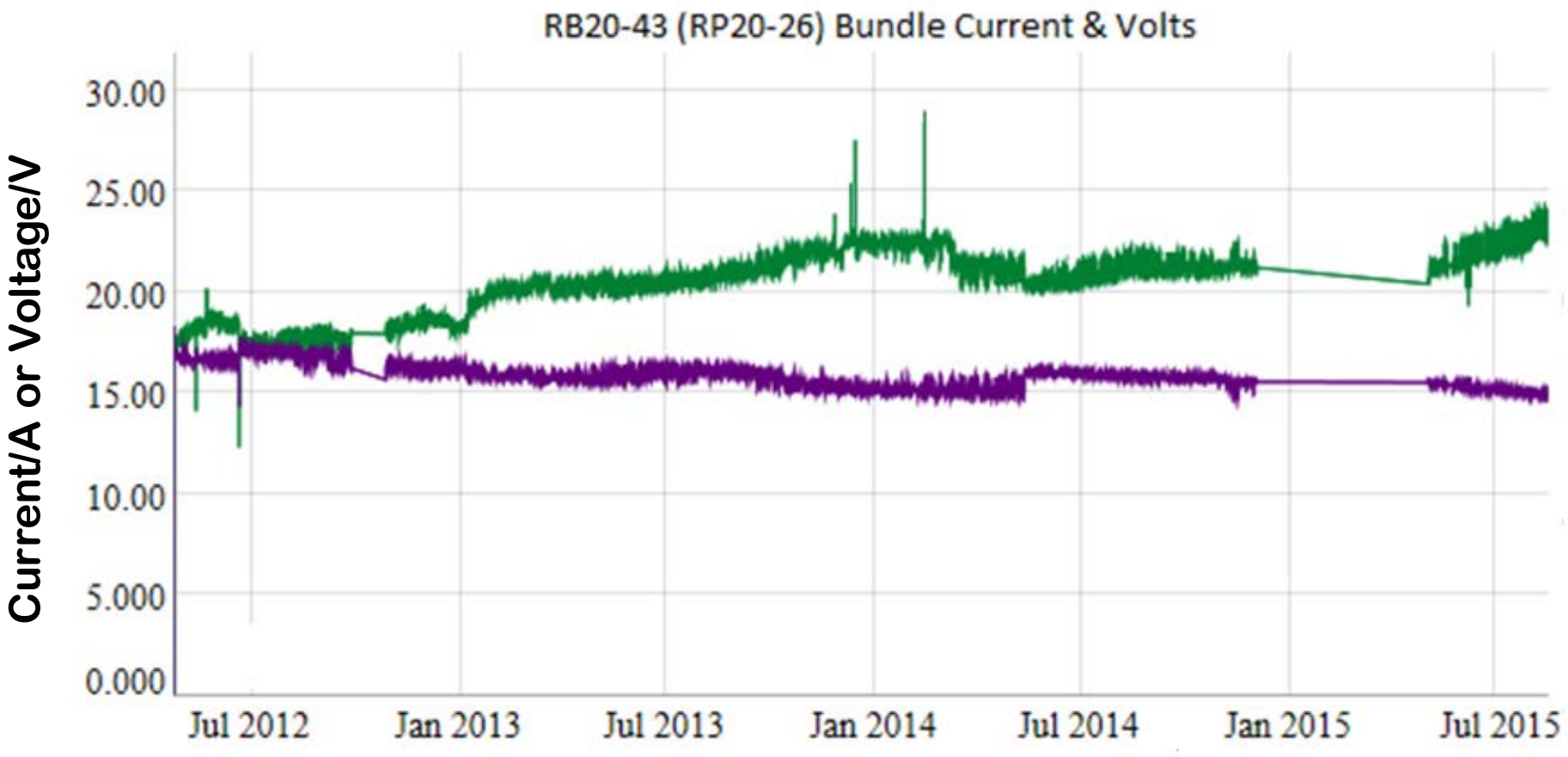
LPG, Alaska

NG, PA

NG, TX

LPG, Wyoming

3+ yr operation on well head natural gas (Texas)

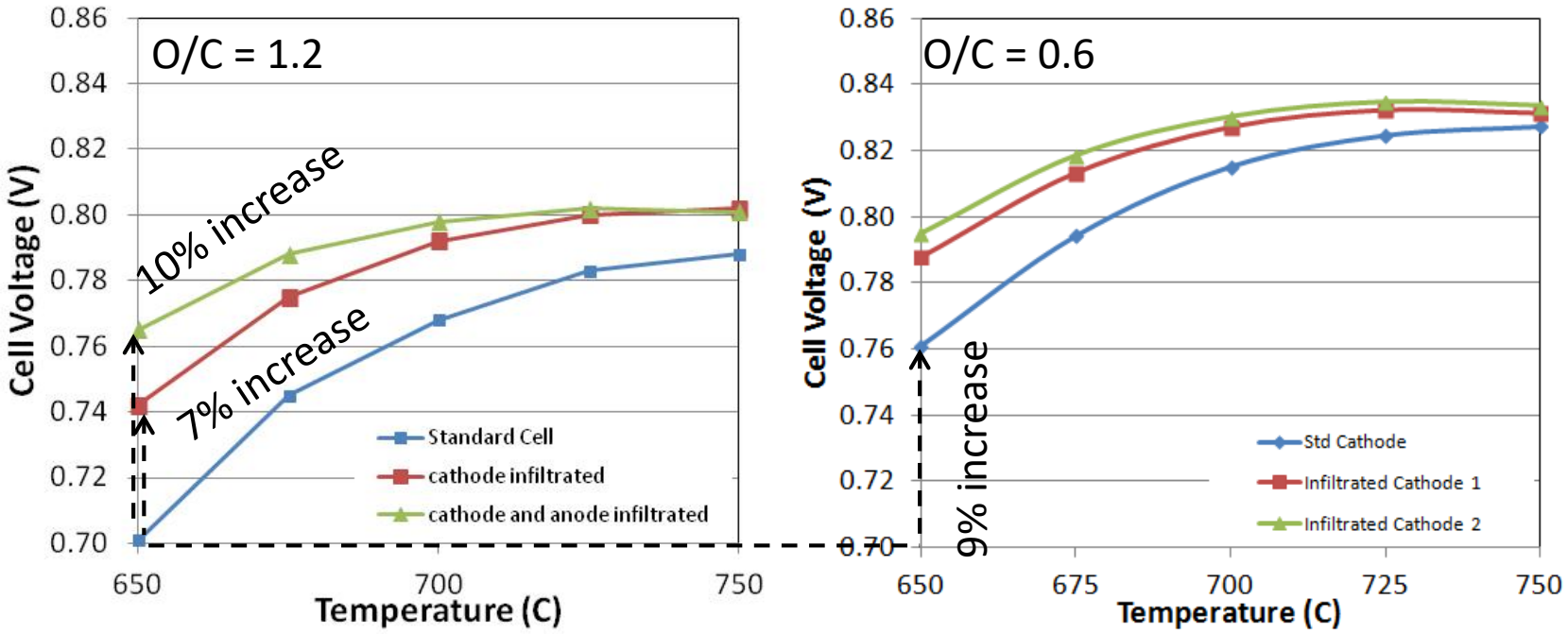


Technical Progress: Performance and Durability Enhancements

SOFC Improvements

- **Sub-stoichiometric O/C (POX) for fuel efficiency and cell performance improvement**
  - Integral/internal reforming catalyst – high carbon tolerance
  - Tailored catalyst to enhance oxidation reactions and suppress fuel decomposition
  - Fuel LHV-to-electricity efficiency of >55%
- **Intermediate operating temperature for cost reduction and stack longevity**
  - Enabled by enhanced electrode performance
    - Cathode infiltration for improved ORR
    - Anode infiltration for improved kinetics and conductivity
- **Internal solid fuel element for durability enhancement**
  - Resilient against high fuel utilization operation

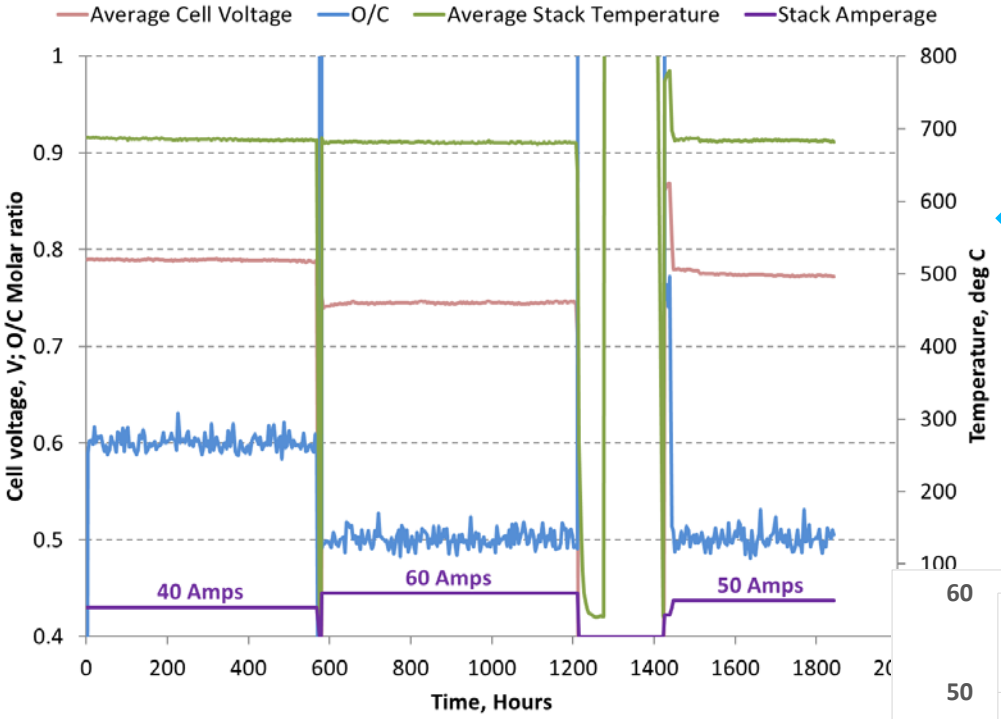
Low Temperature, O/C< Substoich. – Cell Performance Improvement



Major improvement by combining electrode infiltration and low O/C fuel processing

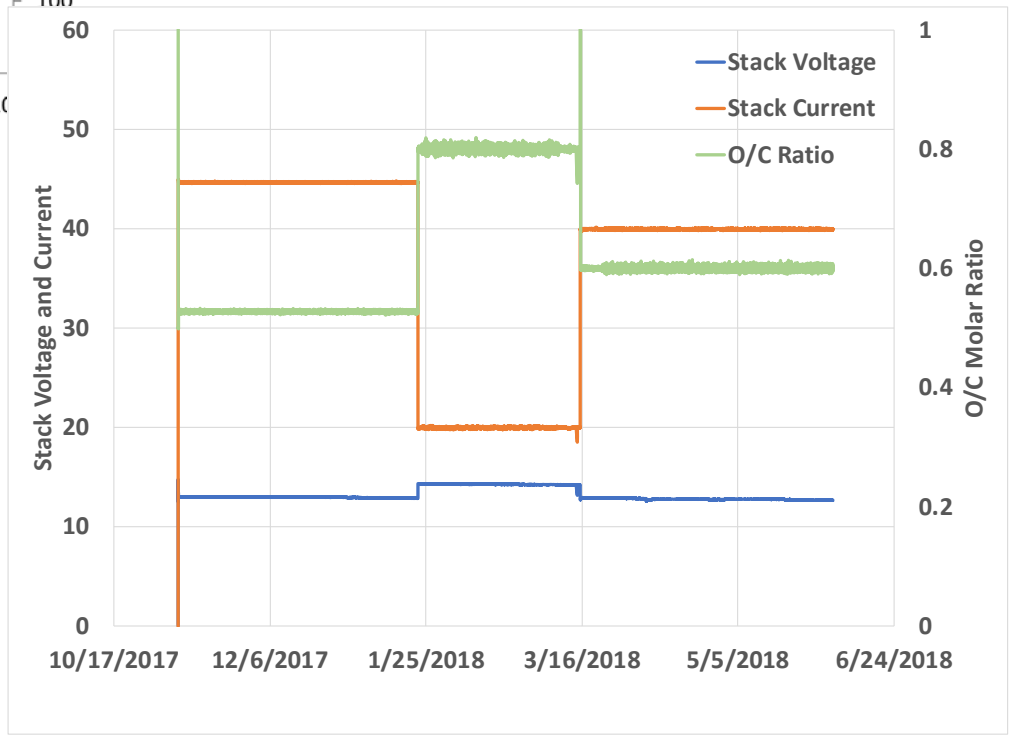
- Electrode infiltration
  - Cell performance improvement at lower temperature
  - Lower impact of thermal gradients across the stack
- Lower O/C fuel processing
  - Further improvement in cell performance at all temperatures with bigger boost at lower temperatures

Sub-stoich. O/C Operation at Low Temperature

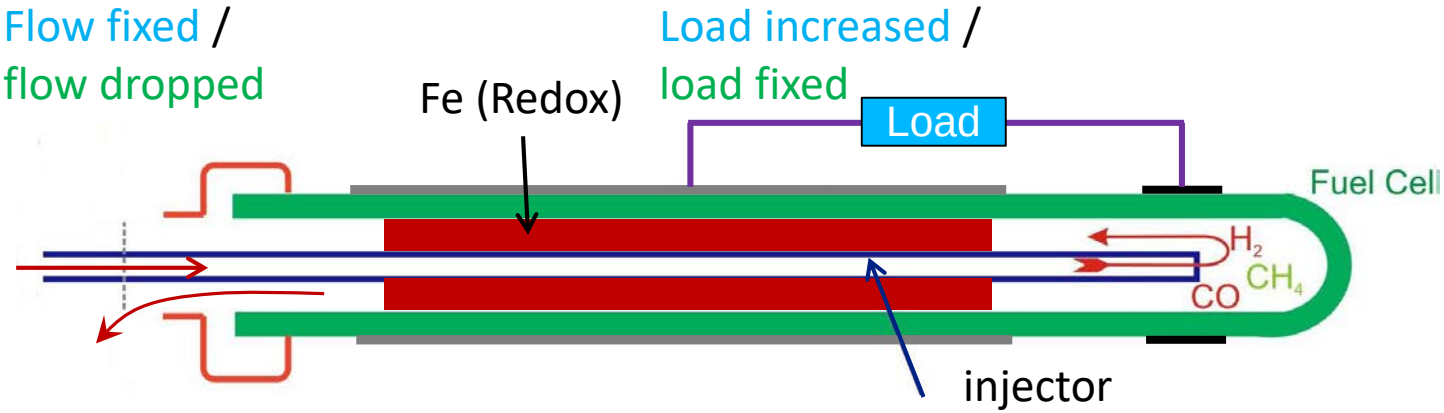


- 20 cell stack
- **Stack temperature: 680 deg C**
- **Partial Oxidation of Natural gas at O/C < stoichiometry (0.5-0.6)**
- 1800+ hours of operation without carbon fouling or degradation

- 48 cell stack
- Stack temperature: 730-760 deg C
- **Partial Oxidation of Natural gas at O/C < stoichiometry (0.5-0.6)**
- No degradation over the course of the test - >5000 hours

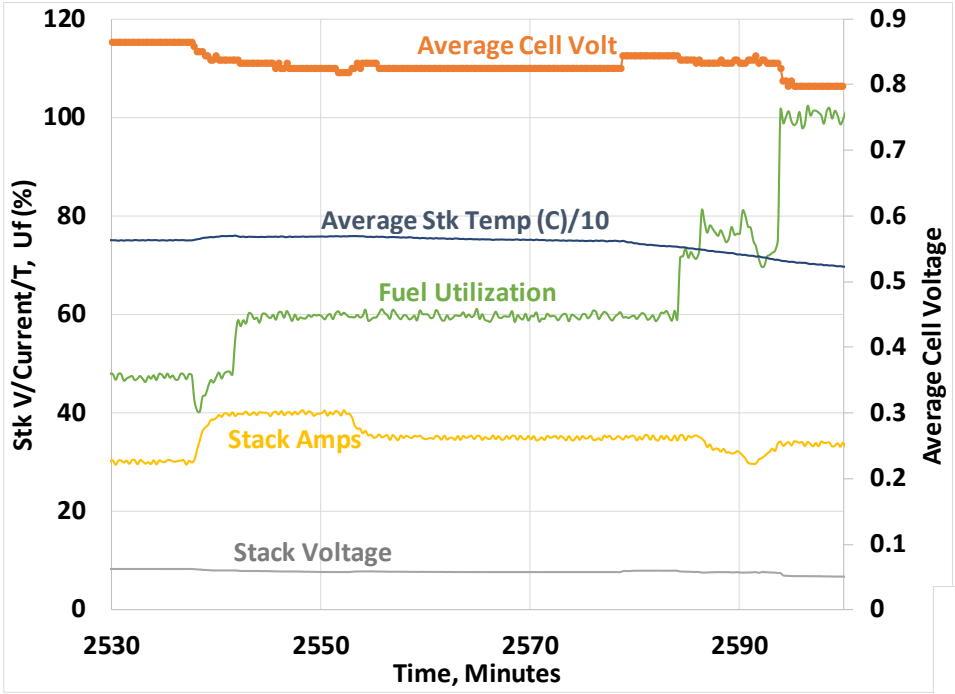


Integrated Solid Fuel Element



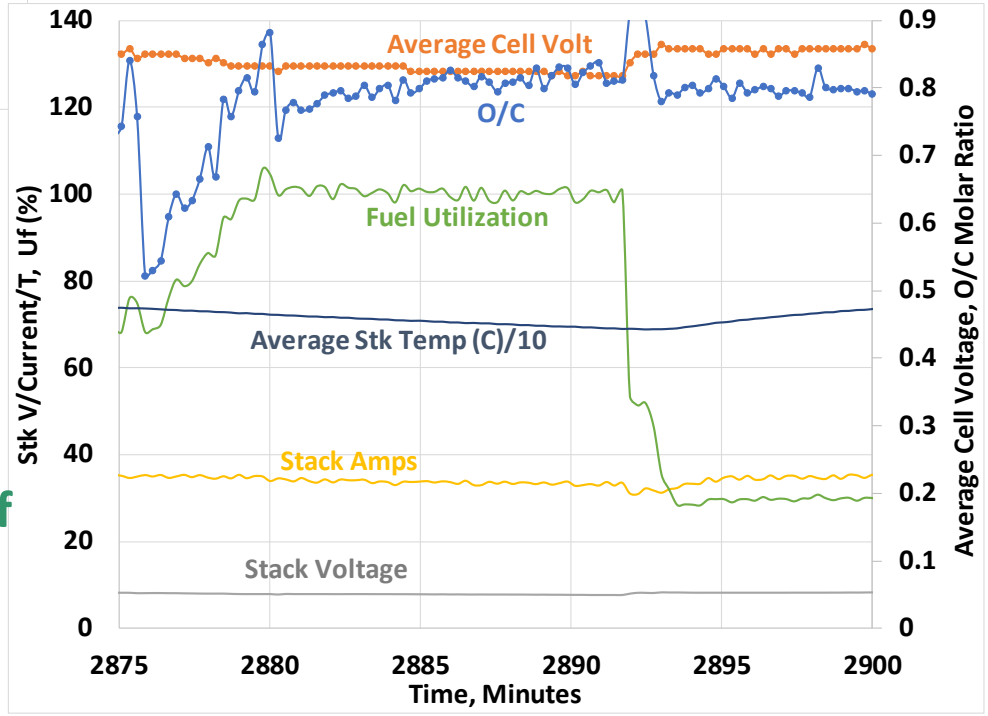
- **<u>Anode protection</u>: Redox chemistry supplements the fuel requirement under high Uf conditions**
- **<u>Peak shaving</u>: The response time of the solid fuel has been demonstrated to be less than 1 sec. The solid fuel element can actively respond during sudden load changes**

Combined Impact of SOFC Improvements (Stack) – High U_f, Low O/C

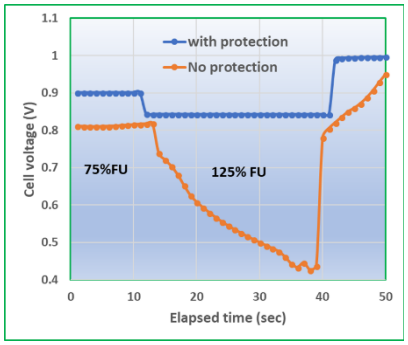


- Stack: 20 cells
- O/C: 1.2
- **U_f: 45-100%**
- T: 700-750 C
- **Avg Cell V: 0.86 – 0.8V**

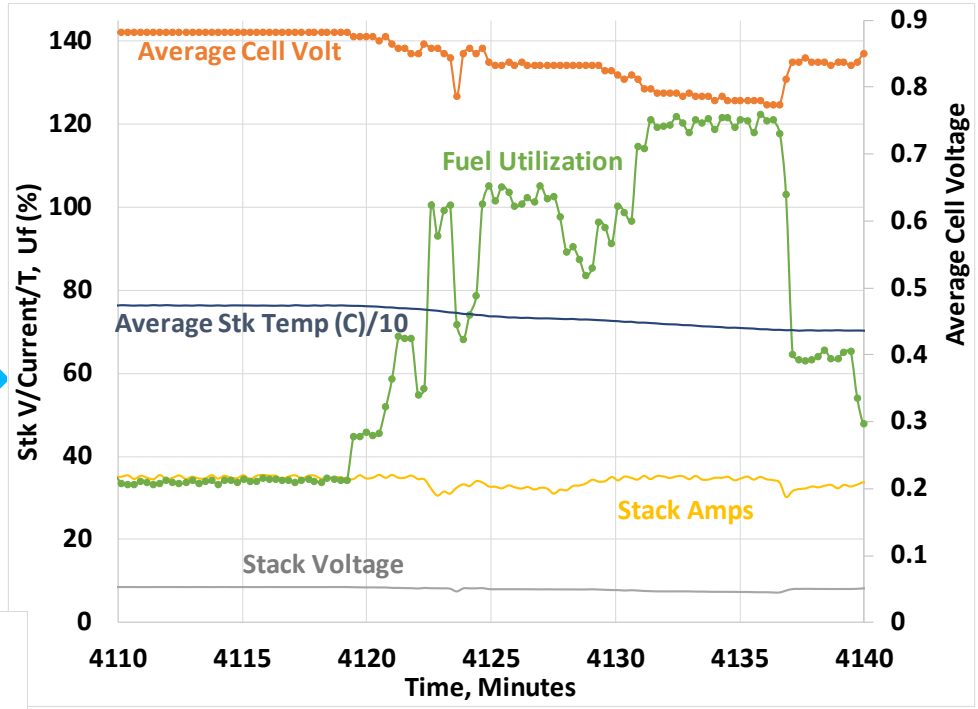
- Stack: 20 cells
- **O/C: 0.8**
- **U_f: 70-100%**
- T: 700-750 C
- Avg Cell V: 0.84 – 0.81V (30mV drop)
- **Sustainability: >12 minutes @ 100% Uf**

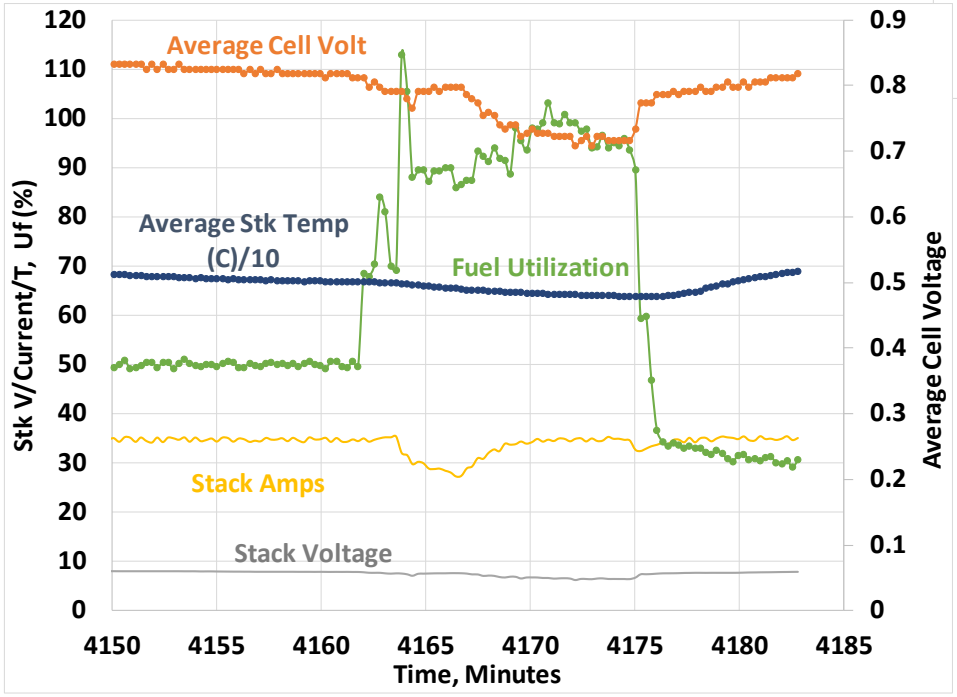


Combined Impact of SOFC Improvements (Stack) – Low Temp., High U_f, Low O/C



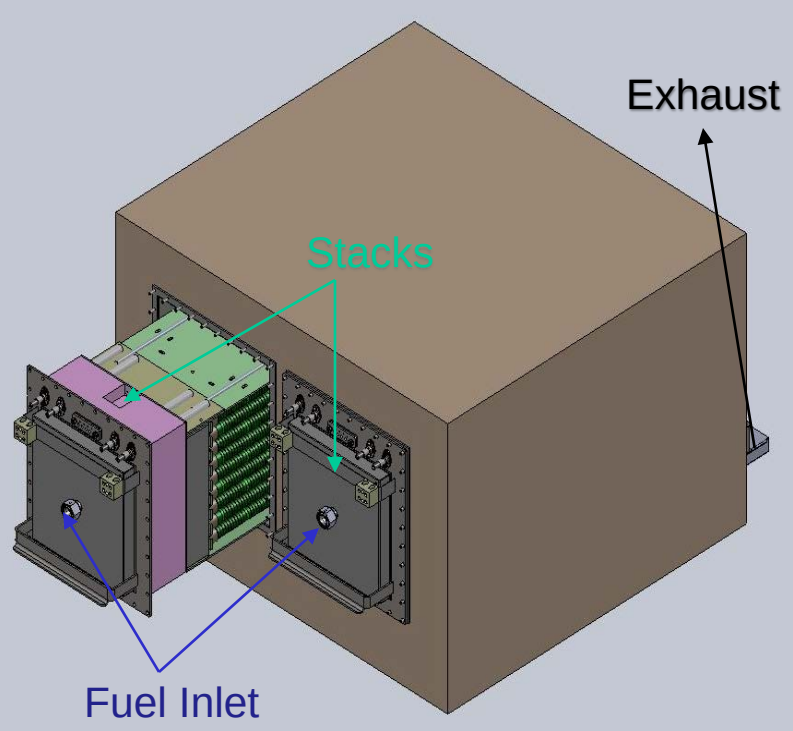
- Stack: 20 cells
- **O/C: 0.7 - 0.8**
- **Uf: 70-120%**
- T: 700-725 C
- Avg Cell V: 0.80 – 0.77V (30mV drop)
- **Sustainability: >5 minutes @ 120% Uf**



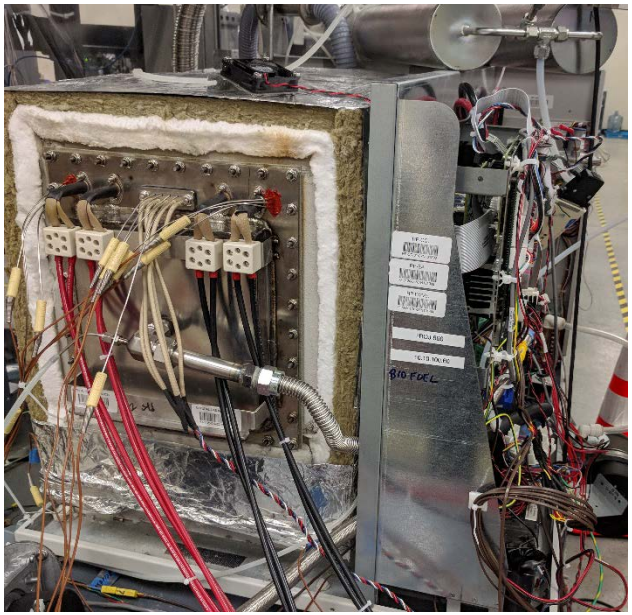


- Stack: 20 cells
- **O/C: 0.5-0.6**
- **Uf: 90 - 100%**
- **T: 630-680 C**
- Avg Cell V: 0.80 – 0.77V (30mV drop)
- **Sustainability: >5 minutes @ 100% Uf**

5KW Natural Gas SOFC Generator

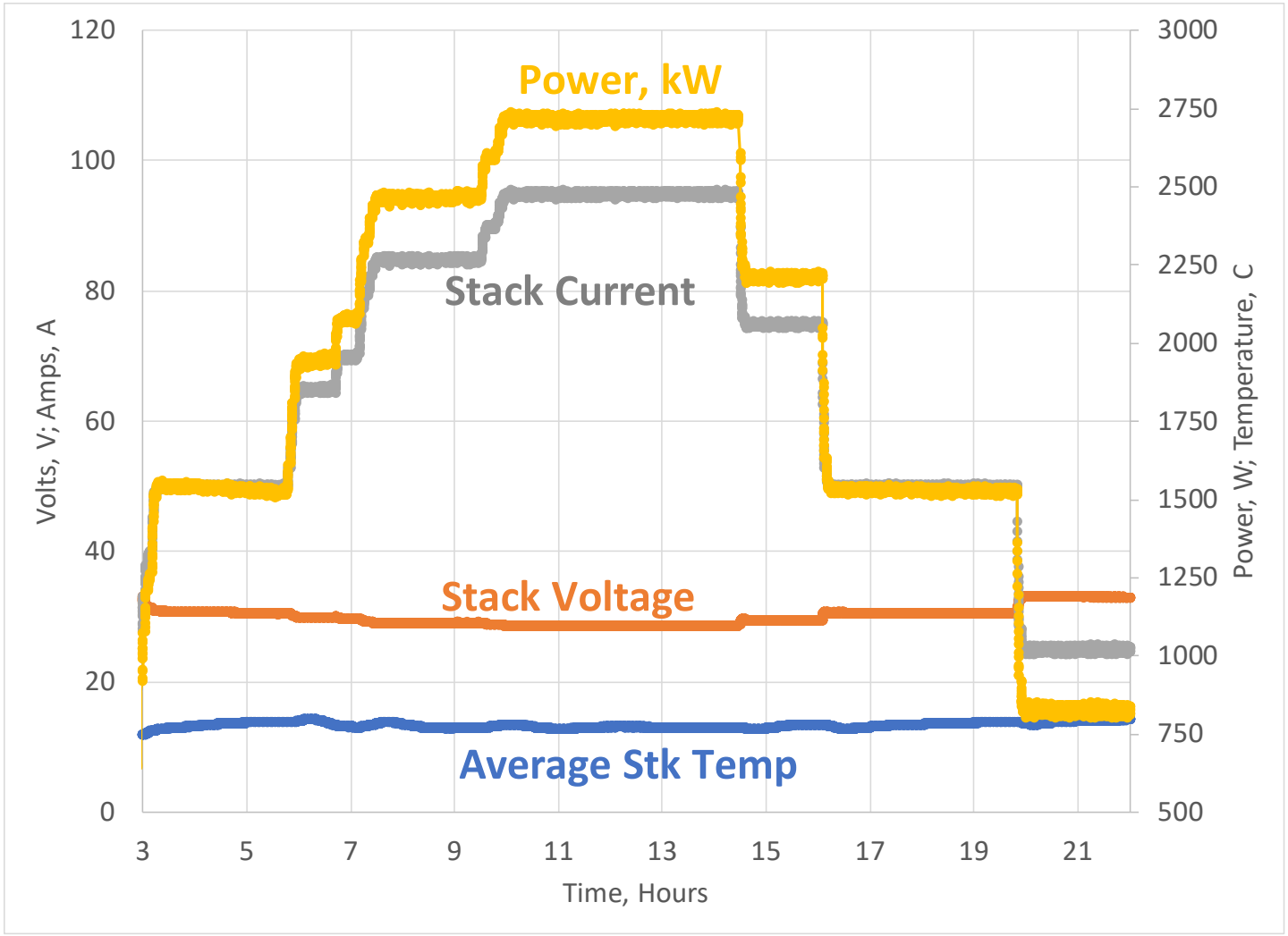


- 2.5kW sub-module tests complete
- Developed an 85% effective heat exchanger
- Balance of plant design complete
- Design based on the commercial platform
- Spatial thermal gradient <50deg C
- ~ 30” * 50” * 37”



5KW Natural Gas SOFC Generator

- Baseline tests complete
- Construction of enhanced stacks underway

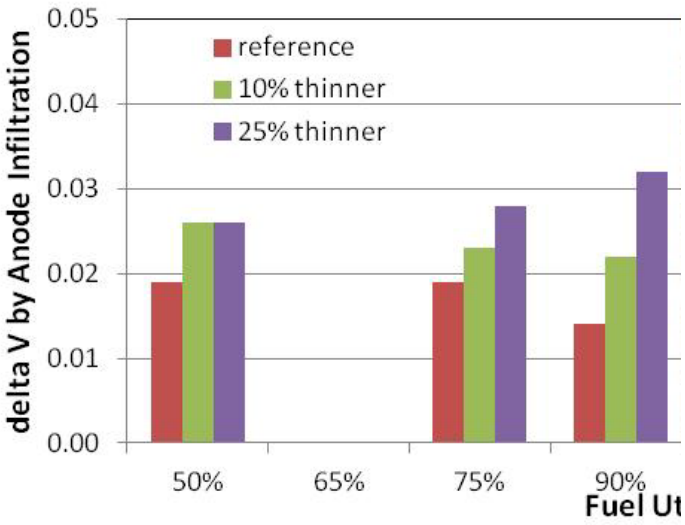


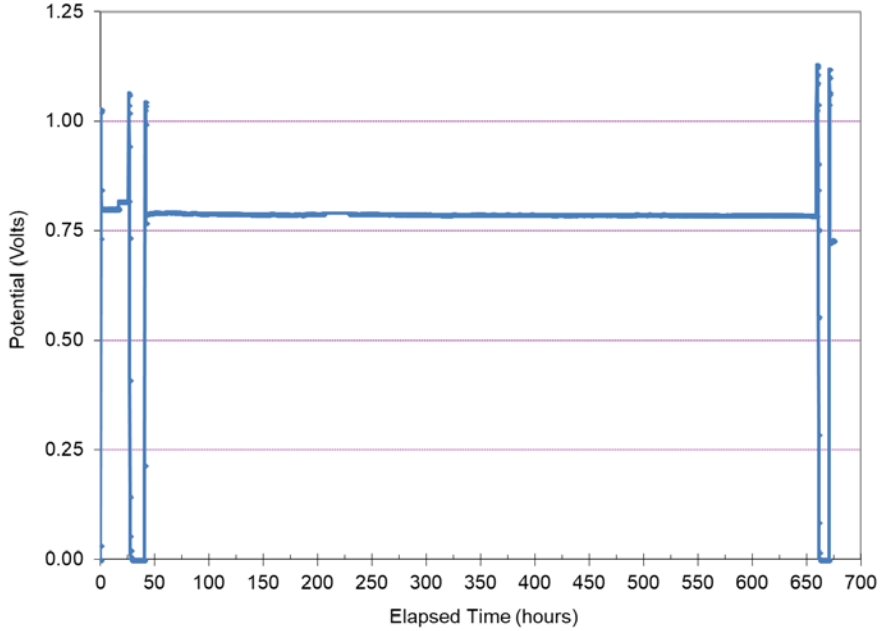
Process Modification – Automation & Cost Reduction

- **Cell fab. process modification for automation and cost reduction**
  - Thinner anode wall
  - Simplified functional layer deposition

- **Process Automation Tasks**
  - Improved anode powder filling
  - Cathode and anode infiltration
  - Fuel processor tube fabrication

Thinner Anode Cell Performance

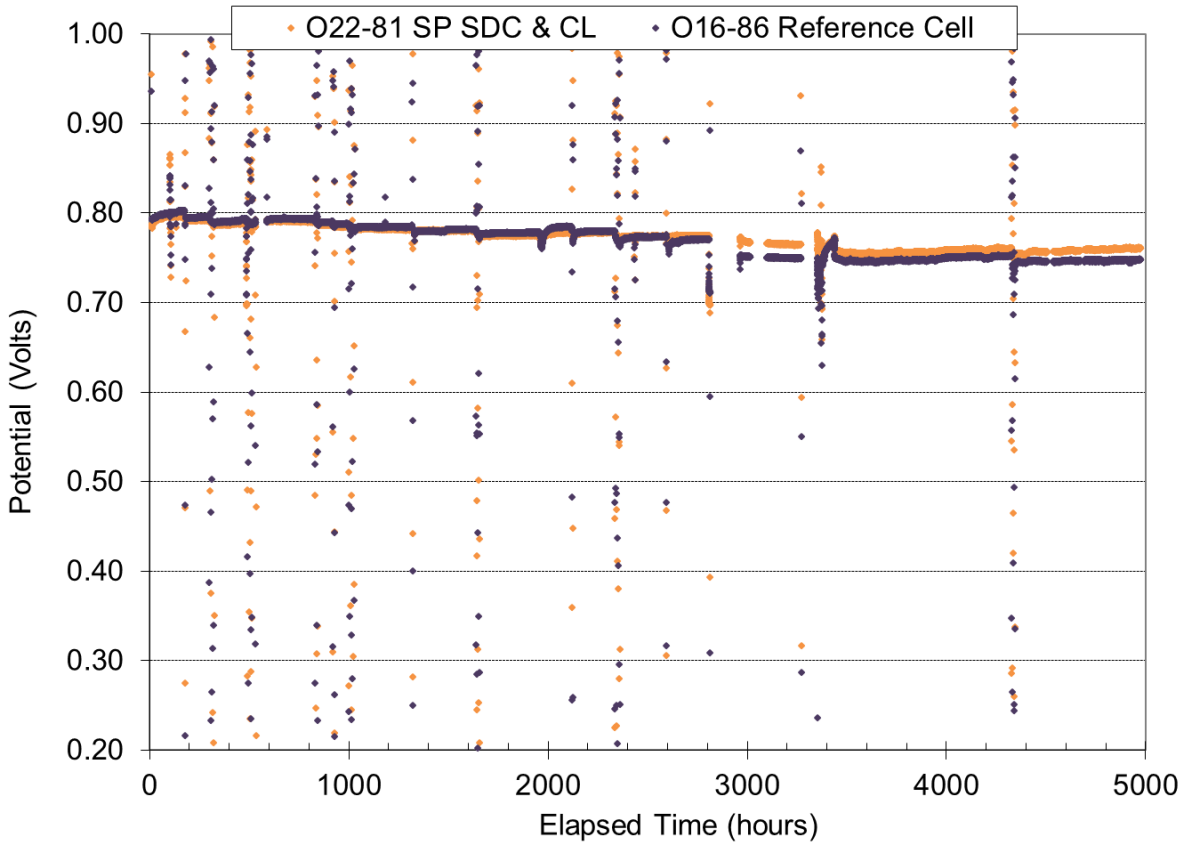




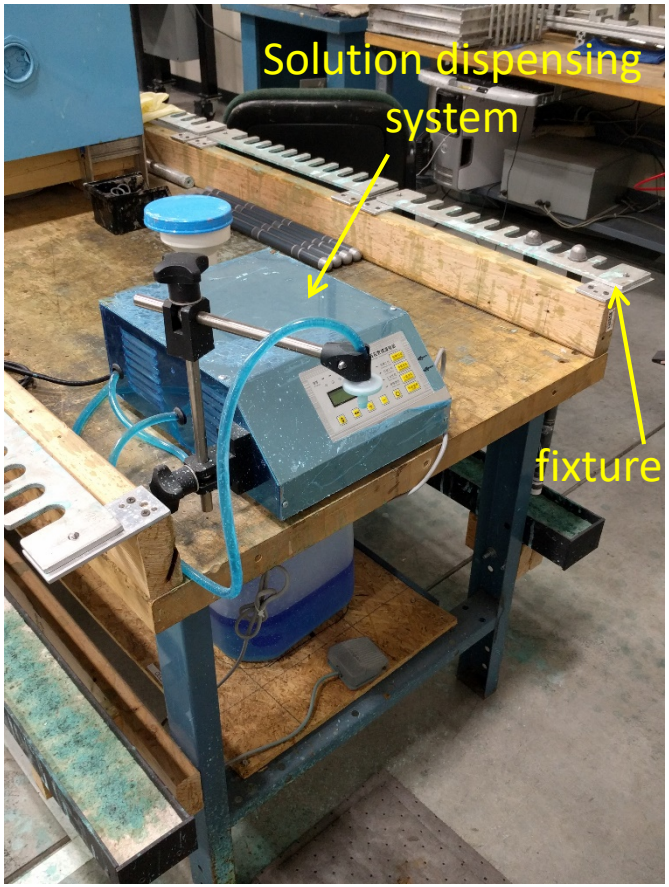
- Thinner anode cell showed moderate improvement in performance
- 600+ hours of operation at O/C of 0.5, Temperature of 700 deg C, and with infiltrated Cathode showed stable performance
- Manufacturing yield is comparable to the current standard process

Cost Reduction via Process Improvements

- **Cell fabrication process modification for cost savings**
  - Printed barrier, cathode and current collection layers
  - 48% cost reduction
  - 4500+ hours of continuous operation under aggressive operating conditions shows stable performance
    - 825 deg C, thermal cycling, load cycling



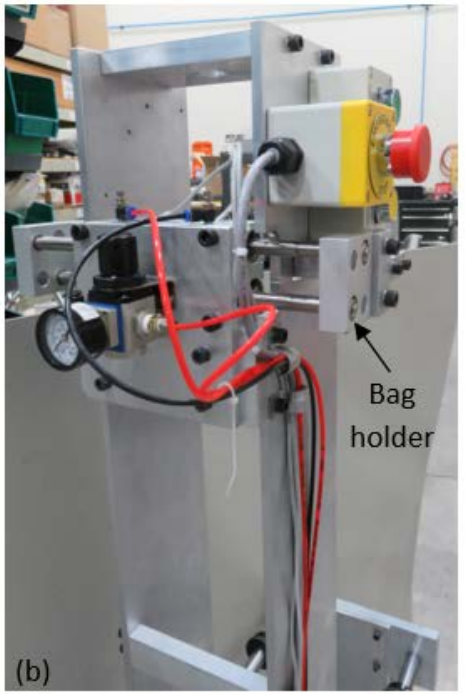
Semi-Automatic Anode Infiltration

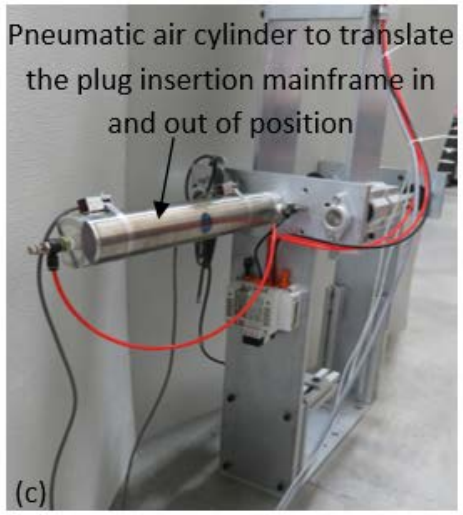


- Features:
  - Automatic solution dispense with precise quantity control
  - Manual cell handling
  - Optional automatic cell handler for higher capacities

Powder Filling - Process Automation

- Features:
  - Completely automated process for dispensing, packing the high durometer bag
  - Improved quality control
  - High throughput processing



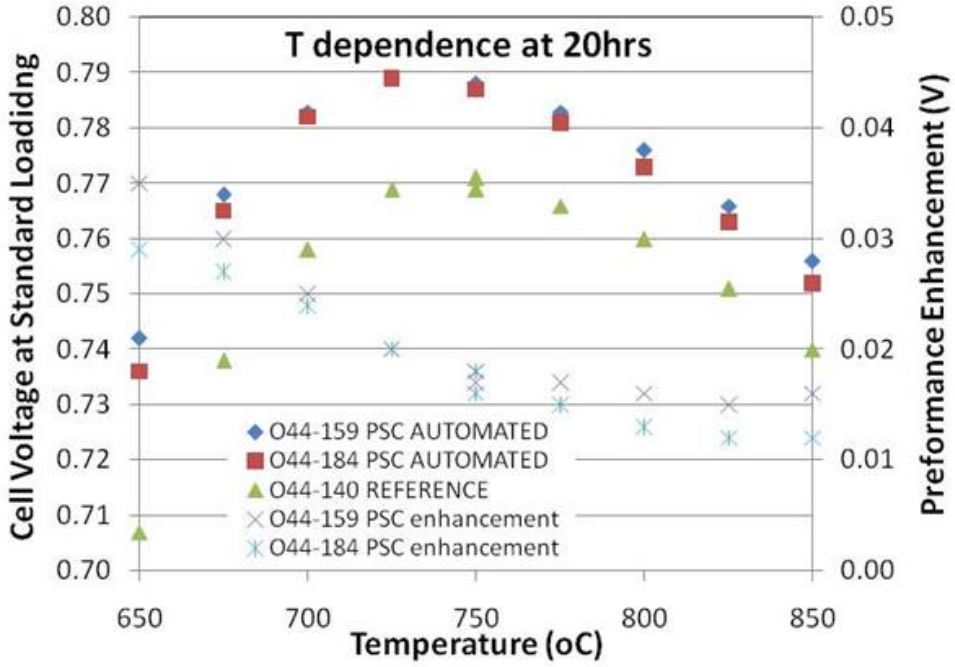


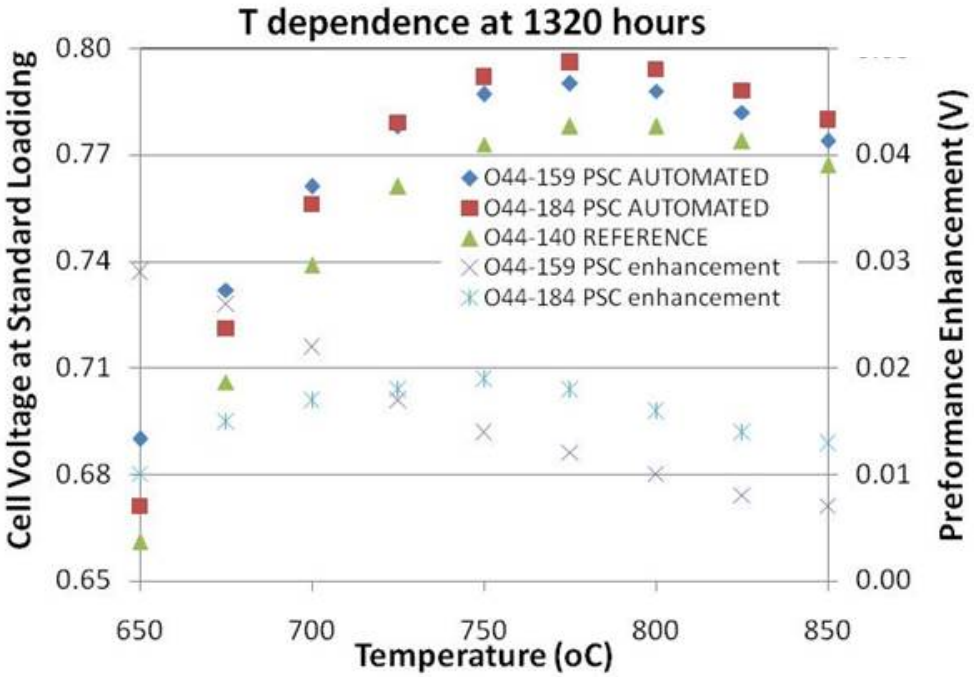
Automatic Cathode Infiltration

- Features:
  - Automatic slurry spray
  - Automatic or manual cell loading
  - Automatic purge for the slurry delivery line

Automatic Cathode Infiltration

- Verified to be compatible with NETL's process/materials
- Improved SOFC performance at lower temperatures
- Stability tests in progress, >2000 hours





Major Forward Activities

- **Integration and evaluation of enhancements in a 0.5 kWe SOFC system**
  - Evaluate thin wall anode cell with enhanced electrode (infiltration) for low temperature and high efficiency (low O/C)
- **5kW System Development**
  - Integrate and evaluate low temperature, sub-stoichiometric O/C operation
  - Finalize 5KW system packaging
  - Demonstration
- **Manufacturing Automation**
  - Fuel processing tube fabrication automation
  - Stack assembly

Acknowledgement

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- **Collaborators**
  - University of South Carolina: Prof. Kevin Huang and his team
  - NETL Team: Dr. Hackett, Dr. Shiwoo
- **Funding Support from SECA through contract number DE-FE0028063**
  - 2.5kW/5kW product dev.
  - Durable, Efficient SOFC
  - Increased presence of SOFCs in the US Natural Gas and Telecom markets