ATREX ENERGY

POWERFUL POSSIBILITIES

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

Agenda

- **Introduction to Atrex Energy, Inc**
- **Application of Atrex Energy products**
- **Technical progress**
  - Cell technology improvements
  - $5kW_E$ stack Design
  - Production automation
- **Further work**
- **Acknowledgements**

About Atrex Energy

- **"Powder to Power"**
  - 250W to 10kW+ power generation products and prototypes, based on Solid Oxide Fuel Cell (SOFC) technology
  - Natural gas, LPG and Jet fuel/Diesel for deployment in remote applications
  - Reliable, efficient and clean
  - Field Replaceable stack
- **> 480 Commercial Units Deployed in field**
- **Commercial NG and LPG generators have accumulated >5 Million hours run time**
- **Units running in remote environments for >35,000hrs**
- **FC1 certification from the Canadian Standards Association**
- **Completed world first demonstrations of a packaged fuel cell generator working on high sulfur JP8/F24**

Atrex Energy – Capabilities and Resources

- SOFC - "Powder to Power", all in one 30,000 sq ft facility in Walpole, MA
- Disciplines: Electrical, Mechanical, Chemical, Material, Automation, Firmware engineers and Manufacturing staff
- Full Scale research, development and testing laboratory
  - Ceramics forming & processing
  - Commercial manufacturing
  - Power electronics
  - Prototype machining
  - Chemical reactor design
  - Thermo-mechanical design and integration
  - Ground up board and firmware development

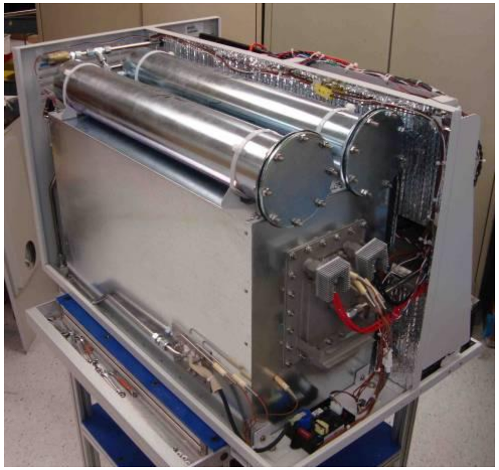
Remote Power Applications

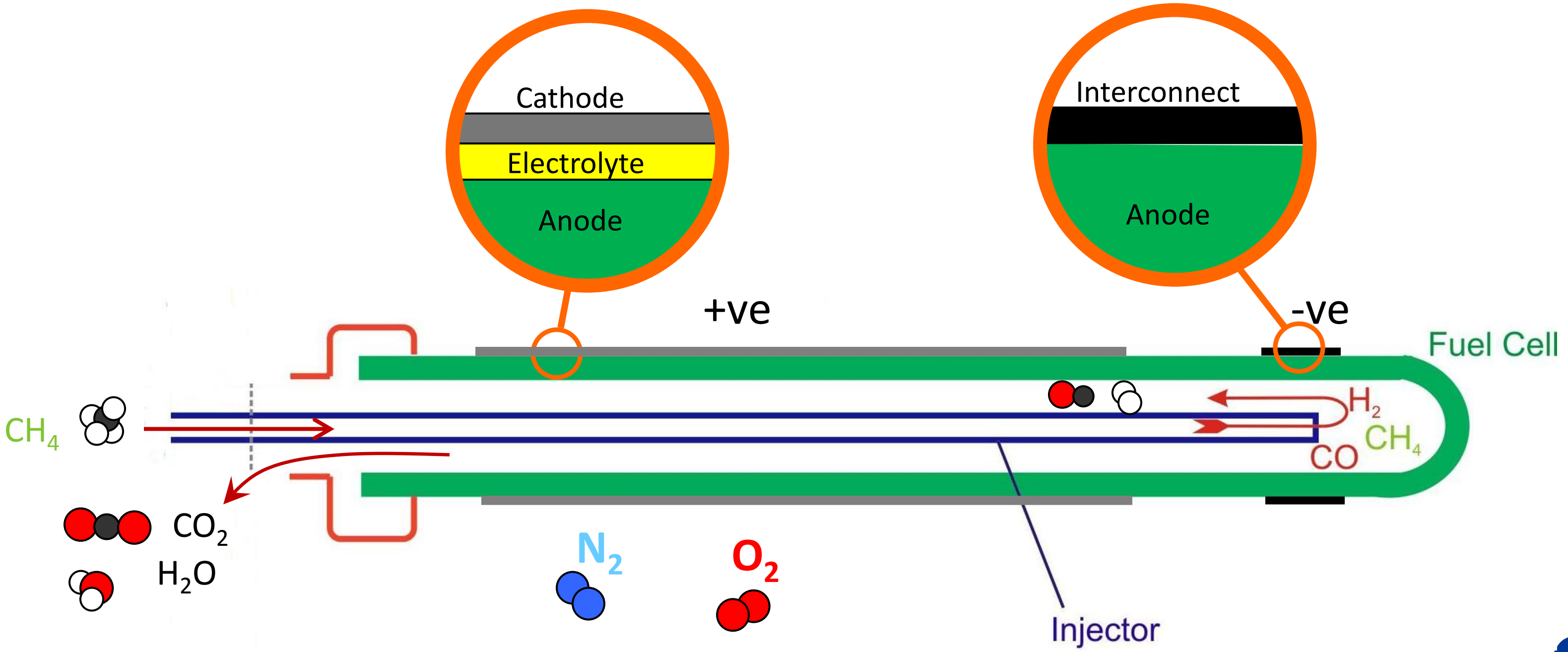
- ❑ US Coast Guard Radio Network Towers in Alaska
- ❑ LPG flown in by helicopter; fuel efficiency highly desirable

Remote LPG and NG Applications

Atrex Energy Tubular Cell Technology

Layer	Materials
Anode	Ni/YSZ
Electrolyte	YSZ
Barrier	Doped Ceria
Cathode	LSCF
Interconnect	LaCrO3

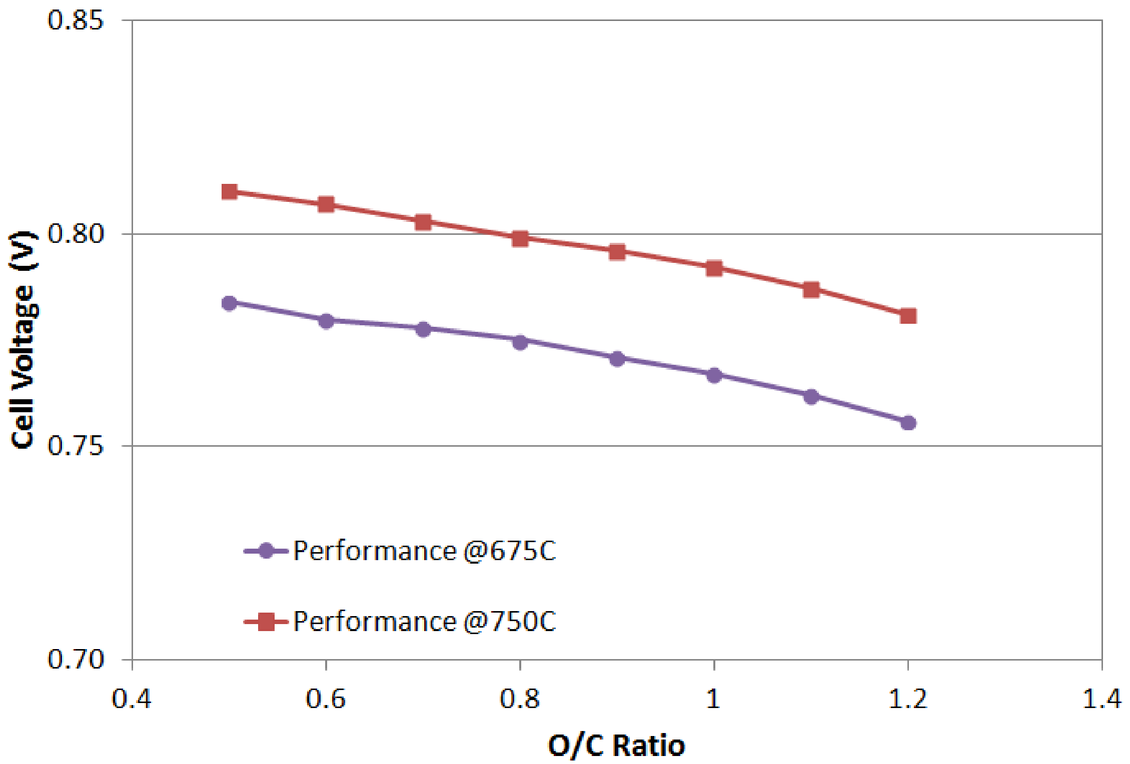




Cell Improvements

- **Sub-stoichiometric O/C (POX) for fuel efficiency and cell performance improvement**
  - Carbon tolerant catalyst
  - Tailored catalyst to enhance oxidation reactions and suppress fuel decomposition
- **Intermediate operating temperature for cost reduction and stack longevity**
  - Enabled by enhanced electrode performance
    - Cathode infiltration
    - Anode infiltration
- **Internal solid fuel element for durability enhancement**
  - Avoid the anode oxidation under fuel starvation condition

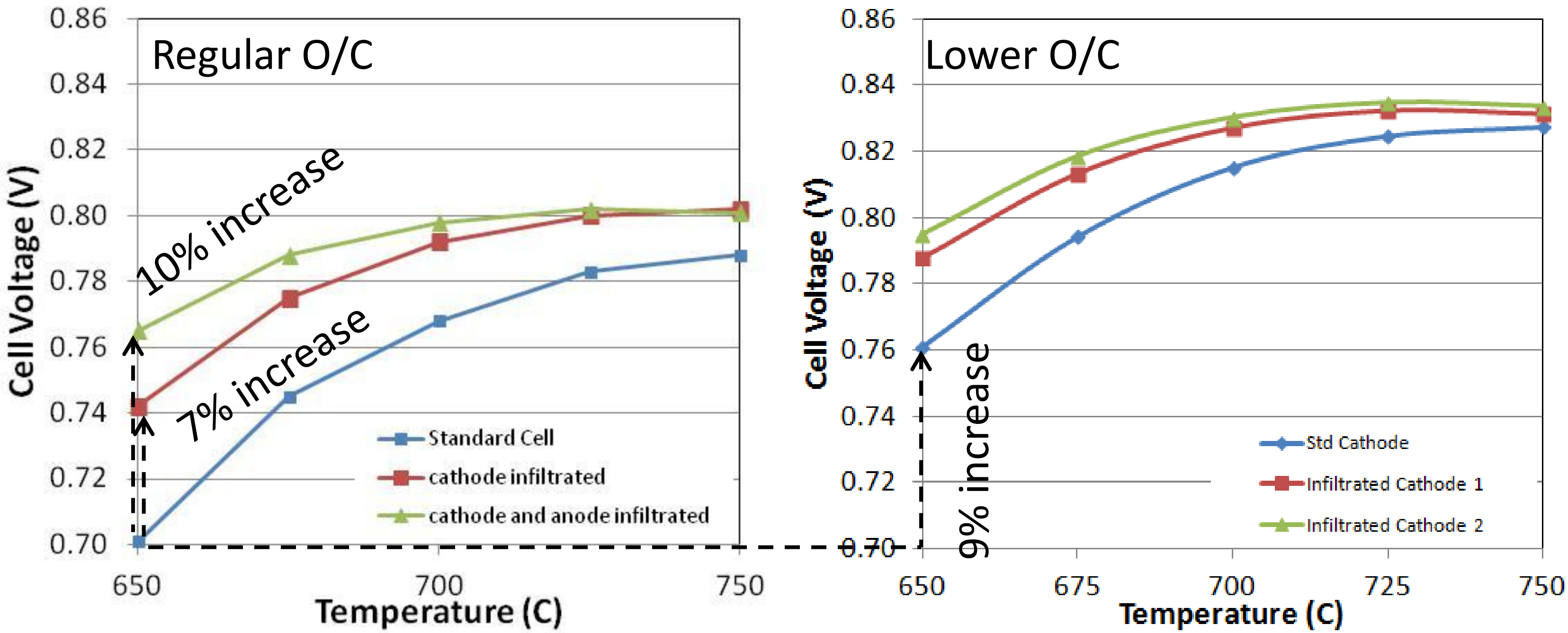
Sub-stoichiometric O/C Operation



Benefits:

- Cell performance enhancement
- Fuel saving over time

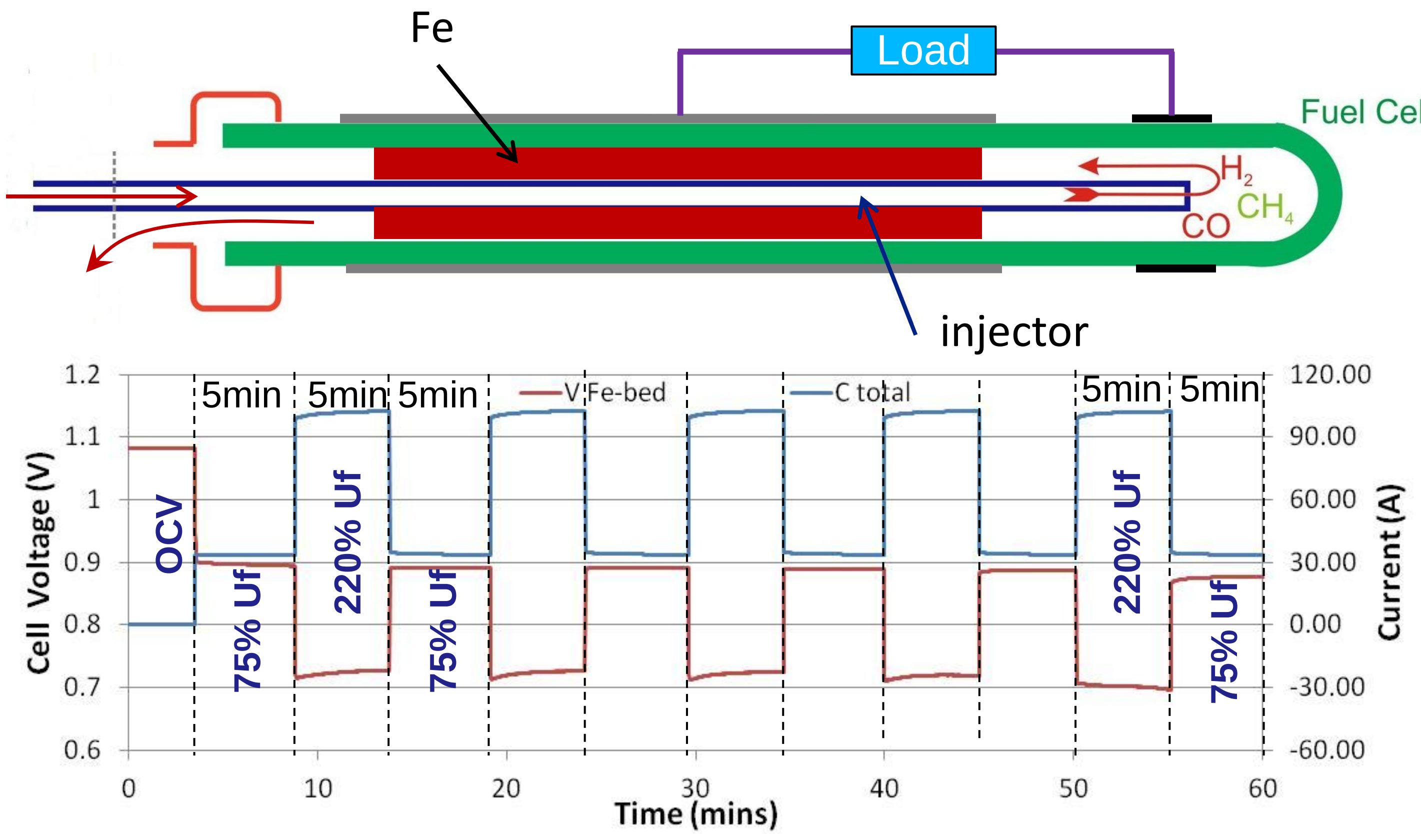
Intermediate Temperature Operation



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

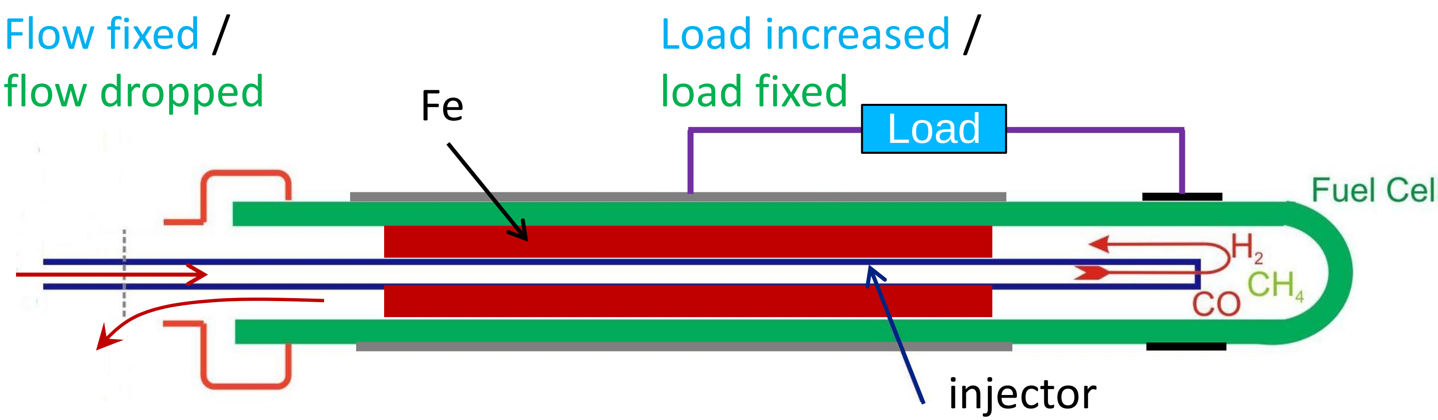
- Electrode infiltration
  - Cell performance improvement at lower temperature
  - Lower impact of thermal gradients across the stack
- Lower O/C fuel processing
  - Further improvement in cell performance at all temperatures with bigger boost at lower temperatures

Benefit of Integrated Solid Fuel Element



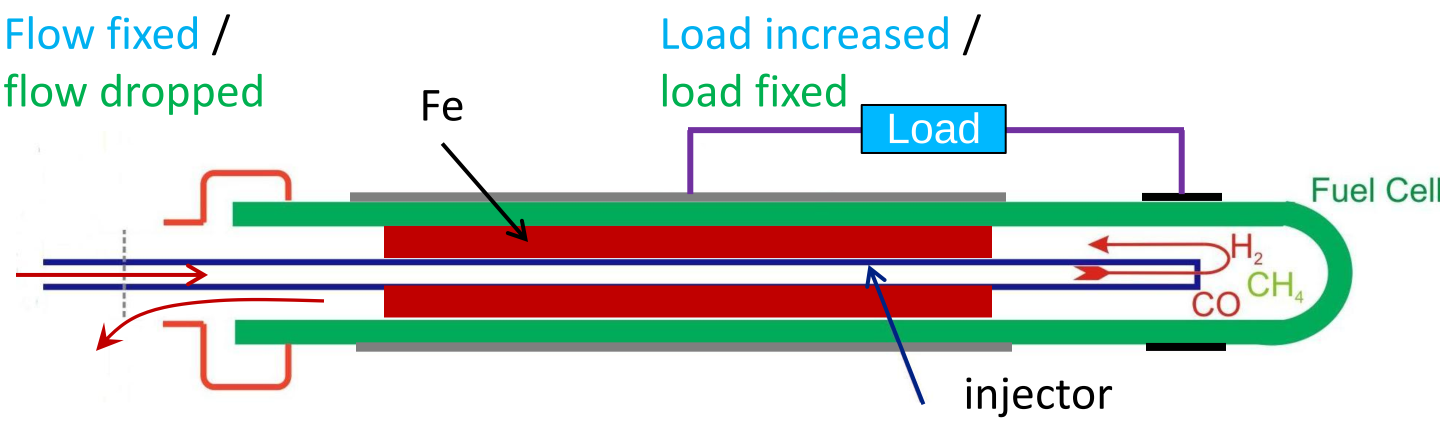
- **Anode protection: in fuel starvation situation, the solid fuel element can provide protection for anode before system shuts down.**
- **Load following: the response time of the solid fuel has been demonstrated to be less than 1 sec. If load suddenly increased, the solid fuel element can actively respond before the gas delivery system kicks in.**

In-situ Anode Protection at O/C > Stoichiometry



Steady Condition	Overloading Condition	Temp (C)	O/C Ratio	Overloading time (min)
65% U_f	115% U_f	750	1.2	0.5 (threshold voltage 0.6V)
65% U_f	98% U_f	750	1.2	16.7 (threshold voltage 0.6V)
65% U_f	115% U_f	700	1.2	0.2 (threshold voltage 0.6V)
65% U_f	98% U_f	700	1.2	6.2 (threshold voltage 0.6V)
65% U_f	98% U_f	650	1.2	3.7 (threshold voltage 90% of original value)

In-situ Anode Protection at O/C < Stoichiometry

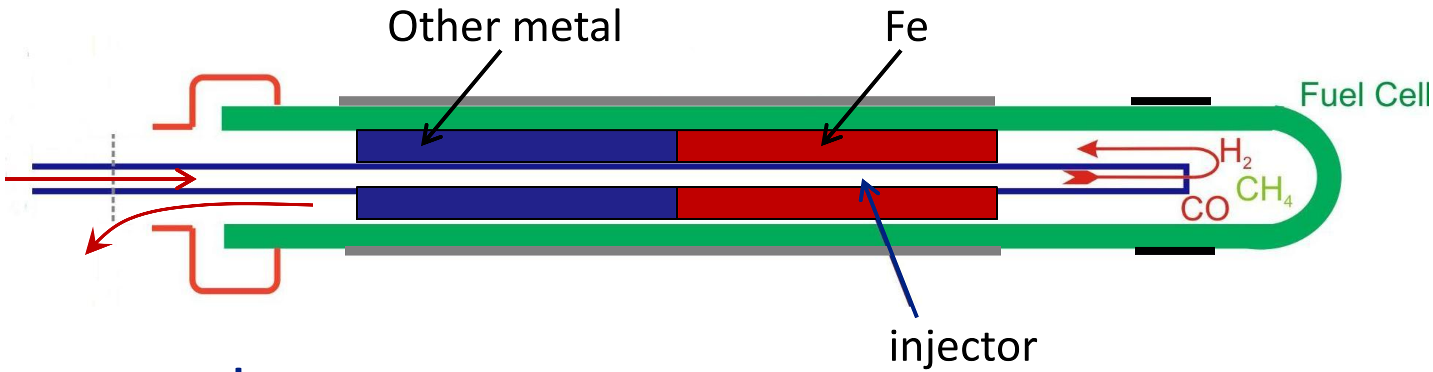


Steady Condition	Overloading Condition	Temp (C)	O/C Ratio	Overloading time (min)
65% U_f	115% U_f	750	0.5	5.8 (threshold voltage 0.6V)
65% U_f	98% U_f	750	0.5	42 (threshold voltage 0.6V)
65% U_f	115% U_f	700	0.5	0.3 (threshold voltage 0.6V)
65% U_f	98% U_f	700	0.5	28.5 (threshold voltage 90% of original value)
65% U_f	98% U_f	650	0.5	12.7(threshold voltage 90% of original value)

Solid Fuel Element - Design Improvement

Issues with current design

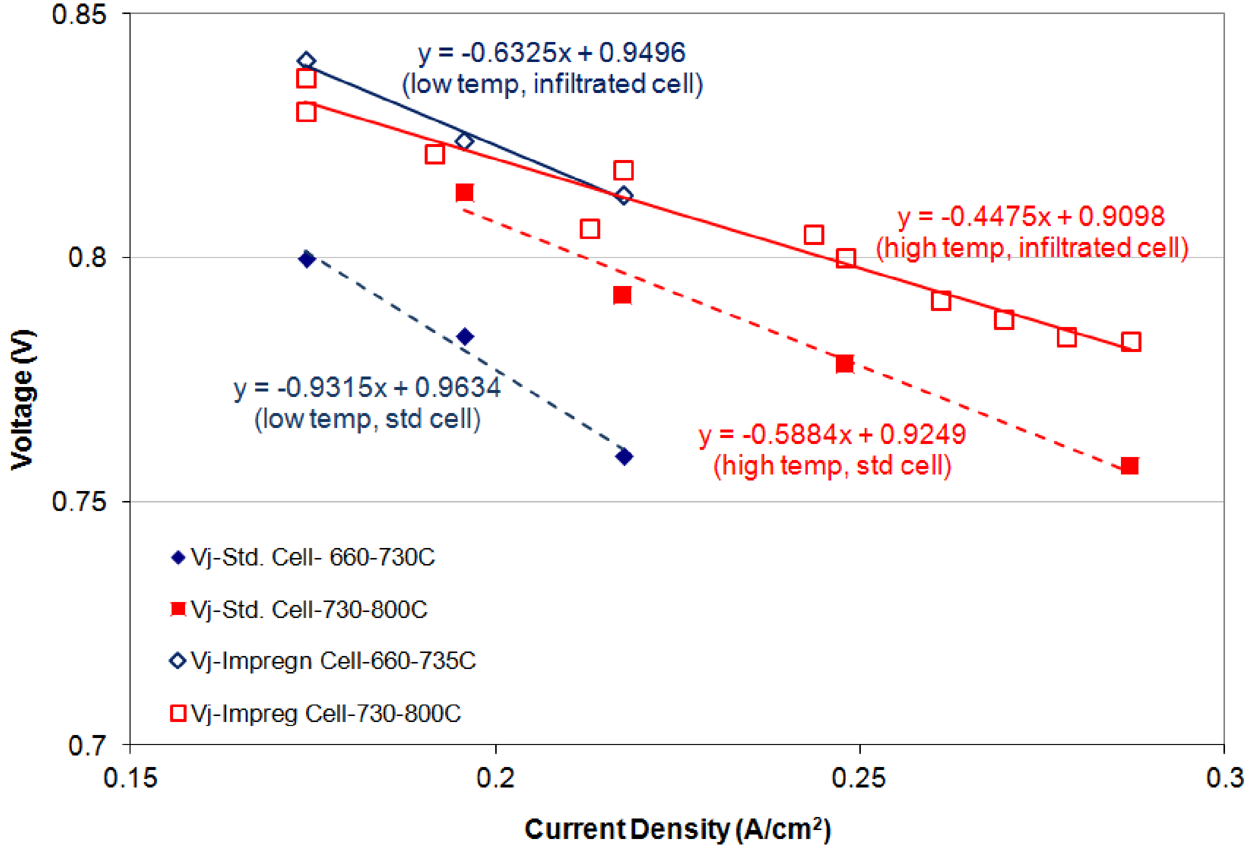
- **Solid fuel composed by Fe will not function at fuel lean region due to high oxygen partial pressure**



Design improvement

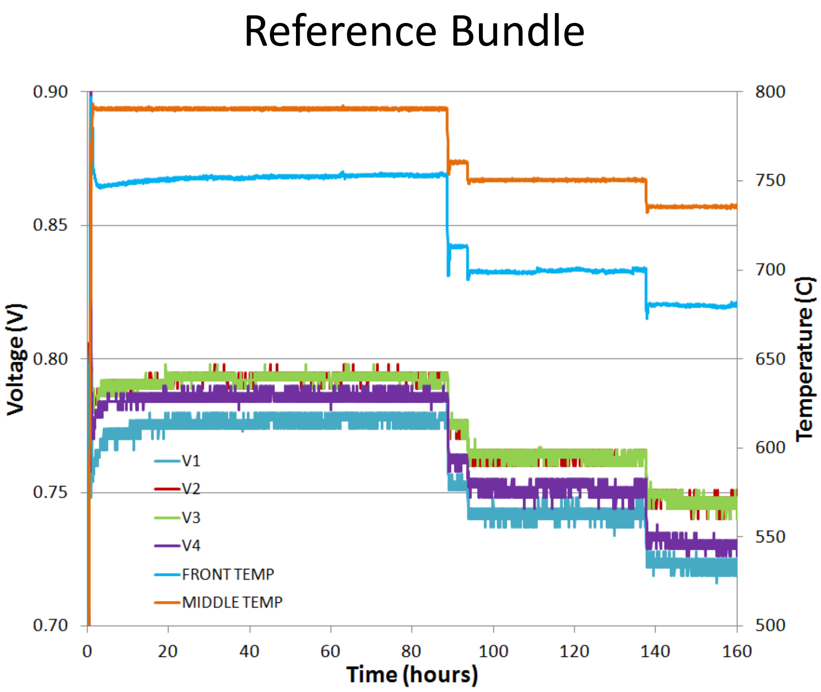
- **A chemically graded solid fuel element composed of multiple elements will be used instead of Fe only.**
- **Modify the current solid fuel element dimension or the stack manufacturing procedure**

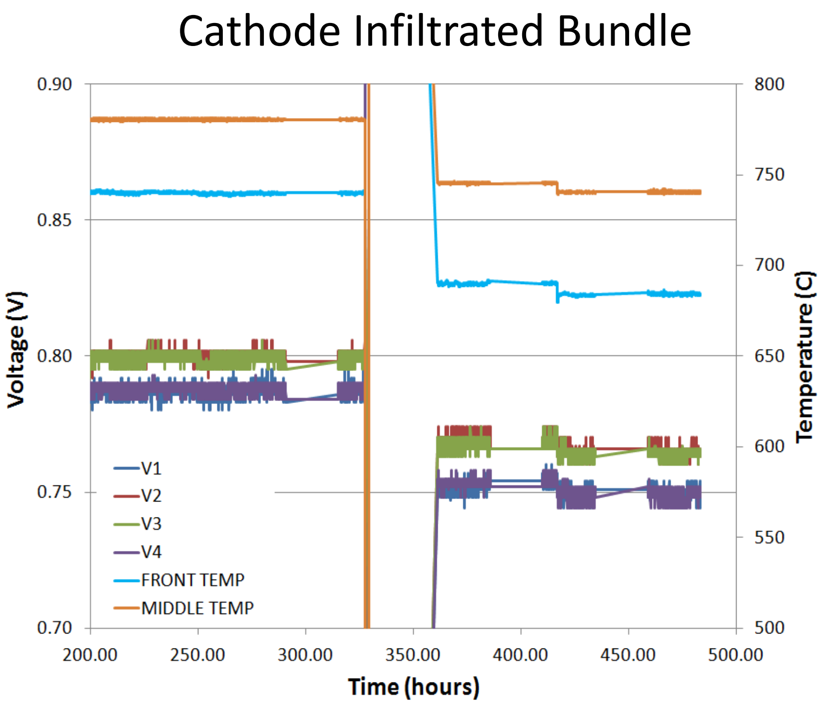
Stack Test Results, O/C > Stoichiometry



With cathode infiltration, the V-j slope in the stack approaches the value from individual cell test in isothermal condition.

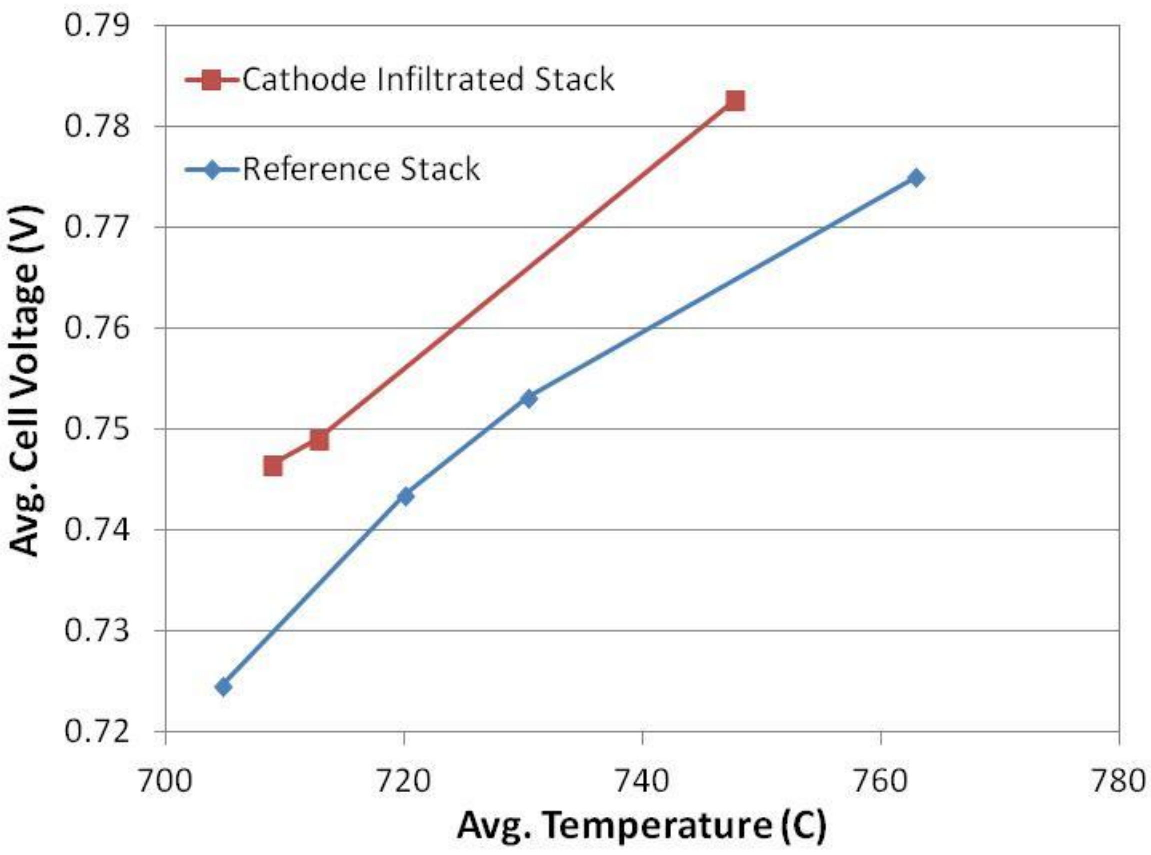
Stack Test Results, O/C < Stoichiometry





1. Test was done at 0.6 O/C ratio.
2. No carbon fouling and cell damage were observed.

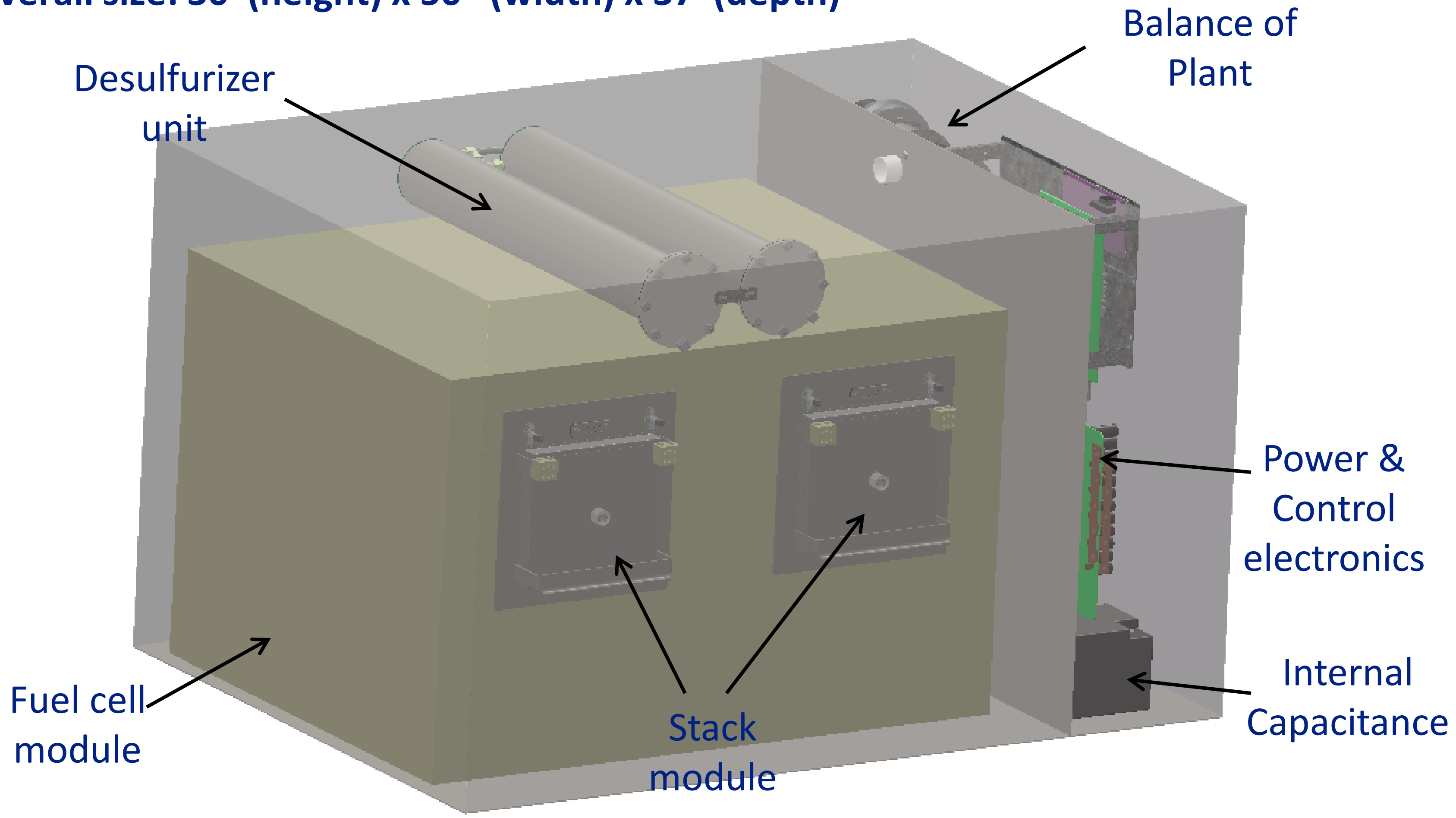
Oxygen Reduction Reaction Enhancement



1. Lowest measured temperature is ~680C, the true low temperature at the boundary of the hot box will be even lower.
2. The cathode infiltrated stack was able to run sub-stoichiometric O/C condition with enhanced performance.

5kW Natural Gas Unit Design

Overall size: 30"(height) x 50" (width) x 37"(depth)



Manufacturing Improvement by Automation

❑ Major Automation Tasks

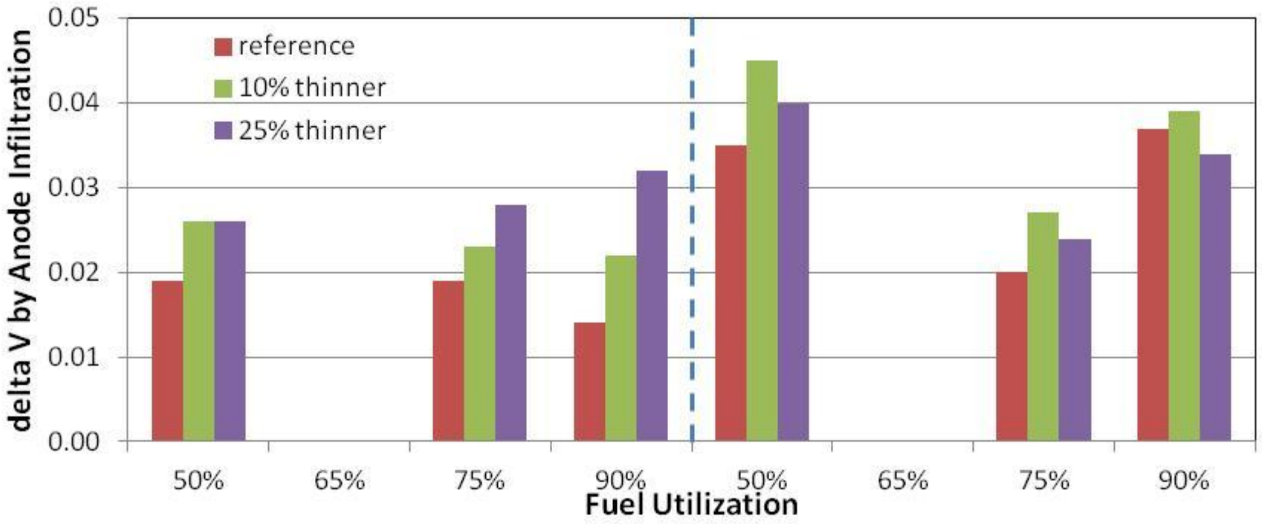
- ➢ Improved anode powder filling
- ➢ Cathode and anode infiltration
- ➢ Automatic stack assembly

❑ Cell Process modification to fit automation and reduce cost

- ➢ Thinner anode cell
- ➢ Printed cathode layer
- ➢ Alternative current collector configuration

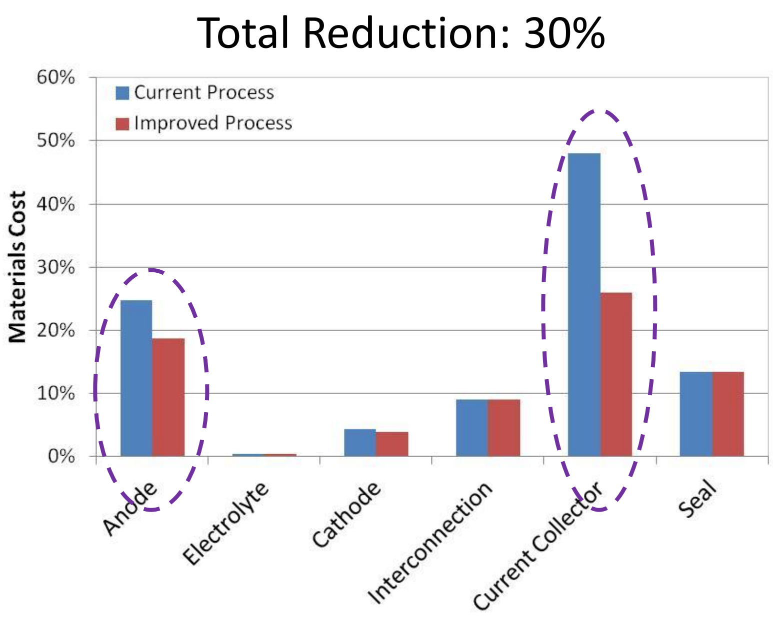
Thinner Anode Cell Performance

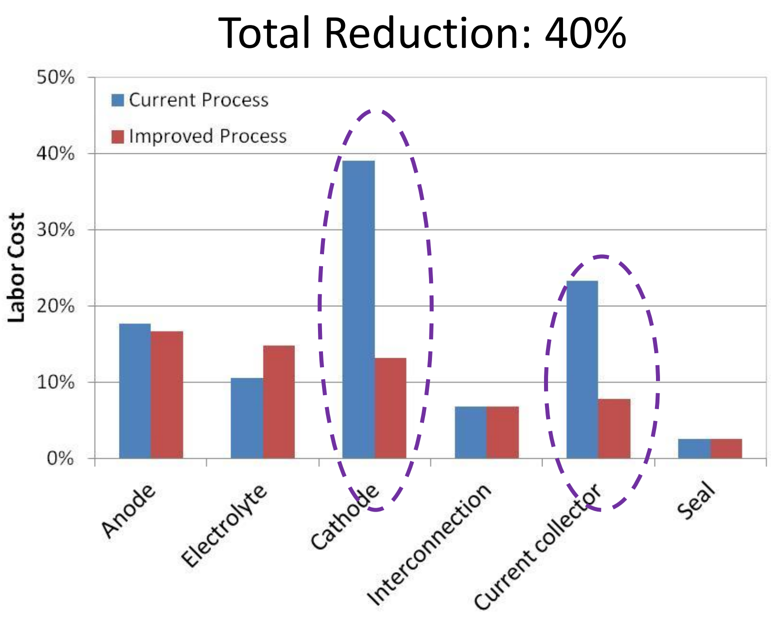
Thinner anode (25% thinner than reference) cell showed moderate improvement in performance. However, with anode infiltration, thinner anode cell showed greater enhancement.



Reduction in anode thickness does not compromise production yield.

Cost Reduction via Process Improvements

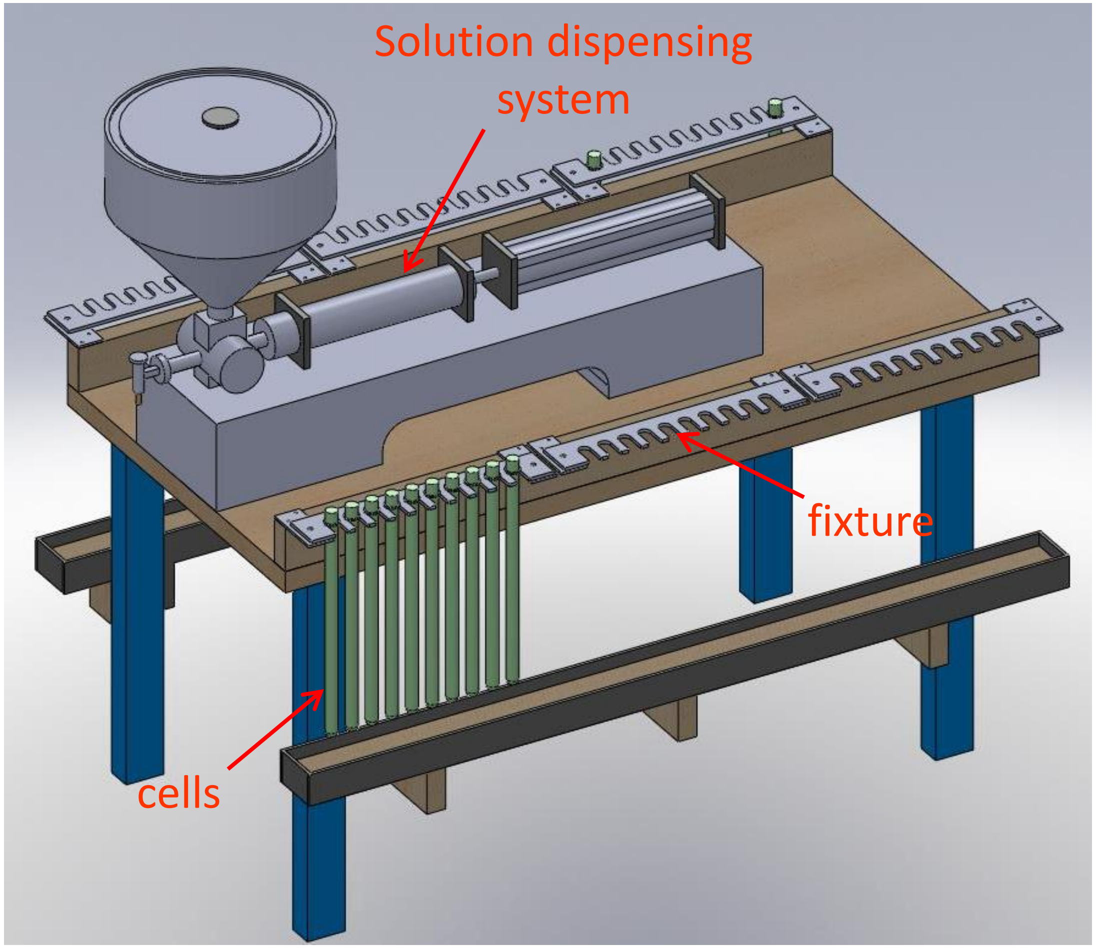




Three major changes are expected for the cell/bundle production

1. Thinner anode cell will reduce the amount of cermet per cell
2. Improved current collector – Ag reduction along with higher throughput
3. Improved cathode application method - Higher throughput

Automatic Anode Infiltration



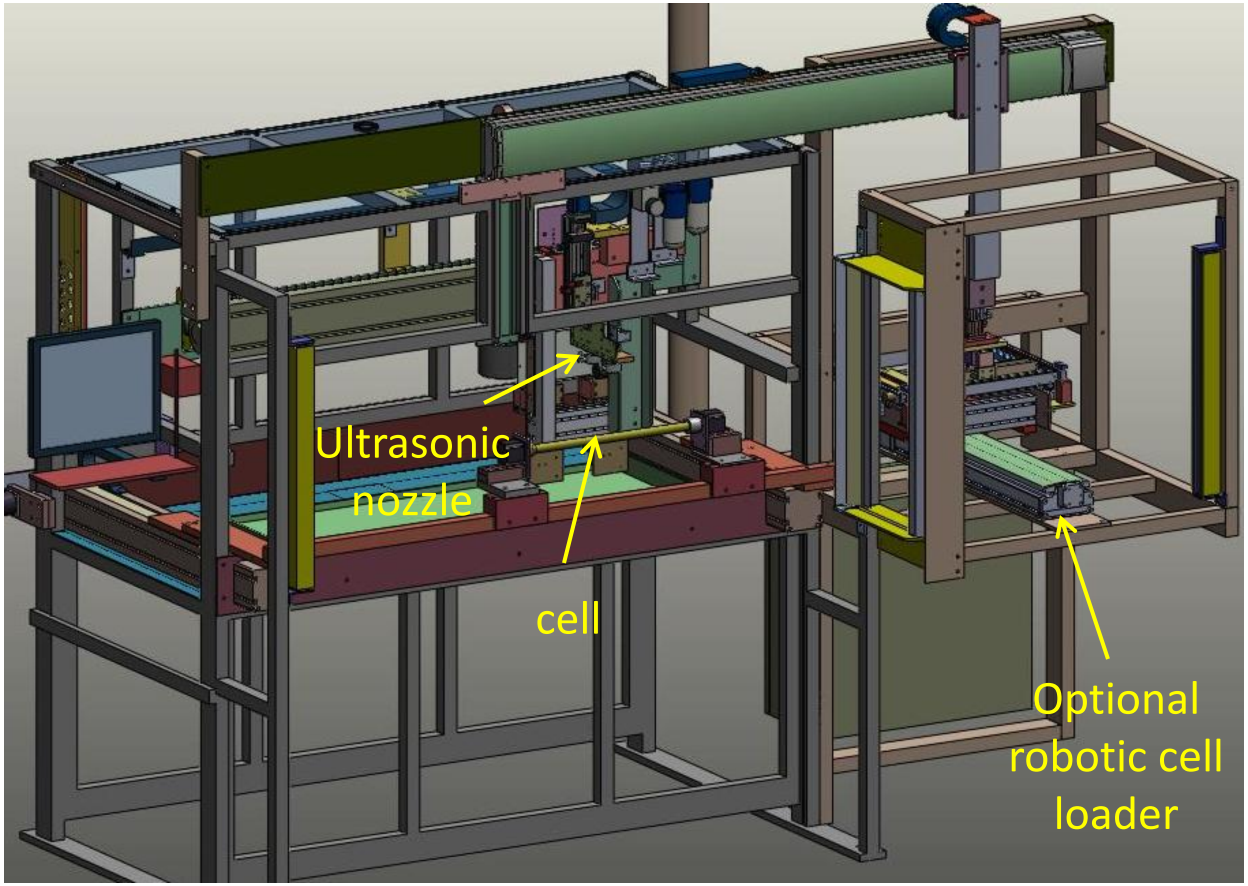
Features:

1)Automatic solution dispense with precise quantity control

2)Manual cell handling

3)Optional automatic cell handler

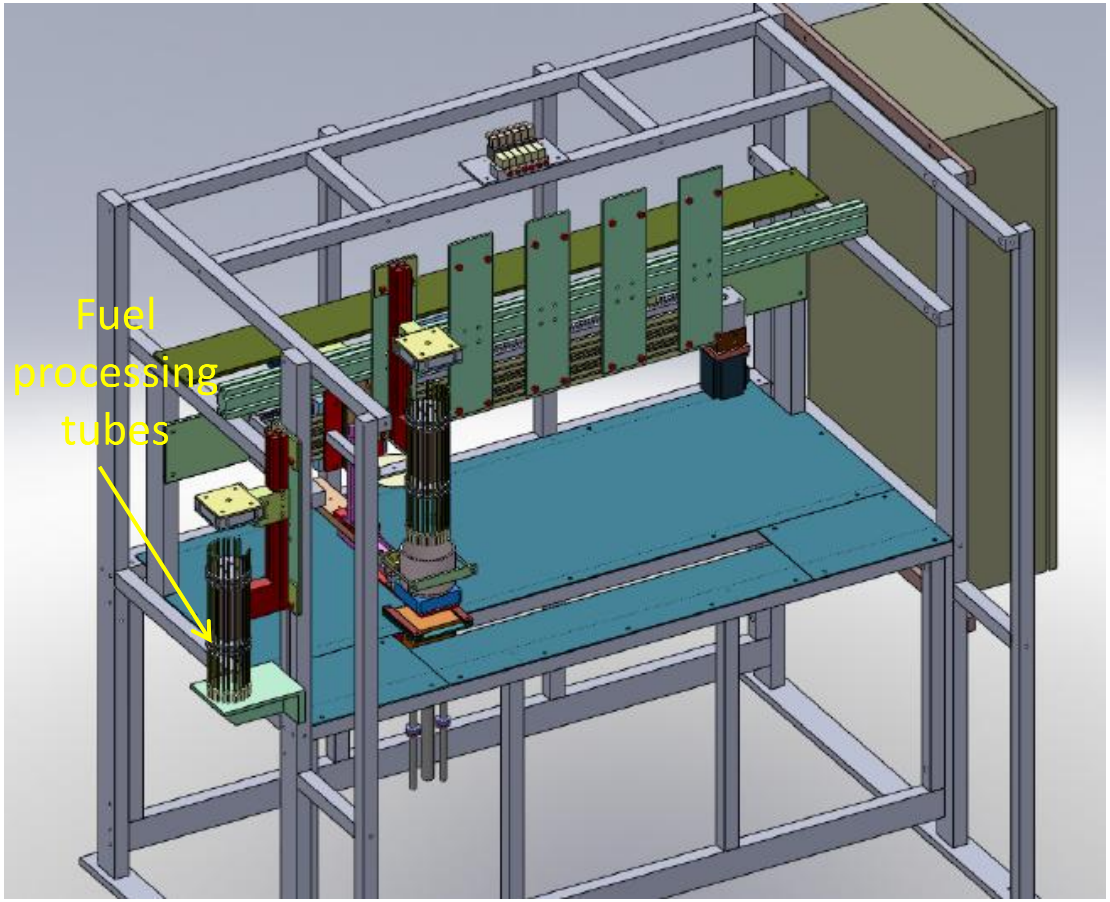
Automatic Cathode Infiltration



Features:

1) Automatic slurry spray with serial operation
2) Equipment compatible with NETL process
3) Automatic or manual cell loading
4) Automatic purge for the slurry delivery line

Automatic Fuel Processing Tube Coating



Features:

1) Serial batch process with adjustable batch size
2) Automatic slurry dispense with precise quantity control
3) Semi-automatic process
4) Manual tube assembly

Major Forward Activities

- **Technology verification in cell and bundle level**
  - Continue the Fe bed enhancement verification at the bundle level
- **5kW System Development**
  - Finalize the fuel cell module design, power/control electronics and Balance of Plant design
  - Design Verification Testing
- **Manufacturing Automation**
  - Qualify the fuel processing tube coating, anode and cathode infiltration equipment and process
  - Continue automation practice for anode powder filling and stack assembly

Acknowledgement

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  - University of South Carolina: Prof. Kevin Huang and his team
- **Atrex Energy**
  - Manufacturing team
  - Cell engineering team
  - System engineering
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