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Efficient Reversible Operation and Stability of Novel Solid Oxide Cells

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Project ID #
fc314

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Project Goal

- Develop Reversible Solid Oxide Cells (ReSOCs) for electrical energy storage with high (60-90%) round-trip efficiency at ~ 1 A cm^{-2}
- Assess long-term stability versus operating conditions
- Determine effects of pressurized operation
- Scale up from button cell to > 50 cm^2 cells
- Develop systems concepts for high efficiency
- Use techno-economic modeling to validate technology viability

Overview

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Timeline

- Project Start Date: 10/01/18
- Project End Date: 09/31/22

Budget

- Total Project Budget: $1,218,500
  - Total Recipient Share: $243,800
  - Total Federal Share: $974,700
  - Total DOE Funds Spent*: $913,600

* As of 3/31/22

Barriers

A. Durability
   – Durability of reversibly-operated solid oxide cells remains a key question

B. Performance
   – Improved cell performance is needed to meet cost and efficiency targets

Funded Partners

- Northwestern University
- Colorado School of Mines

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Relevance

- Objectives:
  - Develop Reversible Solid Oxide Cells (ReSOCs) for electrical energy storage with high (60-90%) round-trip efficiency at ~ 1 Acm^{-2}
  - Assess long-term stability versus operating conditions
  - Determine effects of pressurized operation
  - Scale up from button cell to > 50 cm^2 cells
  - Develop systems concepts with thermal energy storage (TES) for high efficiency
  - Use techno-economic modeling to validate technology viability
- Impact in the last year:
  - A large-area (80 cm^2) cell test has been carried out, providing detailed information about reversible solid oxide cell characteristics and degradation
  - Ni-YSZ fuel electrode performance under pressurization has been characterized
  - A PrO_x-infiltrated oxygen electrode has shown excellent long-term performance stability
  - Above 50% system AC RTE can be achieved by employing a steam accumulator as low temperature thermal energy storage (LTES), assuming constant charge balance in both modes

Approach

- Unique aspects:
  - Develop high temperature cells for reversible operation with high current density, good long-term stability, and high round-trip efficiency
  - Experiments coupled with system modeling and techno-economic analysis to provide early feasibility evaluation
- Addressing Program technical barriers
  - Development of solid oxide cells allowing high round-trip efficiency
    - Go/no-go: cell ASR < 0.15 Ωcm^2 achieved (FY20)
  - Life testing of reversible operation to establish long-term stability
    - Go/no-go: degradation rate ≤6%/kh at 0.75 Acm^{-2} (FY20)
  - Determine pressurized cell characteristics
  - Extend button-cell to large-area cell testing and life testing
  - Modeling to establish realistic efficiency and cost estimates
    - Develop electrochemical models that accurately depict experimentally measured characteristics
    - Delineation of system definition & component requirements
    - Go/no-go: Viable RFC system with system LCOS of <30¢/kWh (FY20, ongoing)

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Progress Summary

Milestone M3.1.1: Reversible cells fabricated and tested to determine factors causing degradation

Milestone M3.2.1: Electrochemical testing

- An extended large area (80 cm^2) solid oxide cells life test was carried out over a range of cycling conditions over 2500 h
- Oxygen and fuel electrode pressurized testing completed

Milestone M3.4.1: Selected anode-supported solid oxide cells for remainder of project

Milestone M2.5.2: System definition and component spec-sheets provided for the “without-TES” case for minimum LCOS.

- Above 50% system AC RTE can be achieved by employing a steam accumulator as a low temperature thermal energy storage (LTES), assuming constant charge balance in both modes

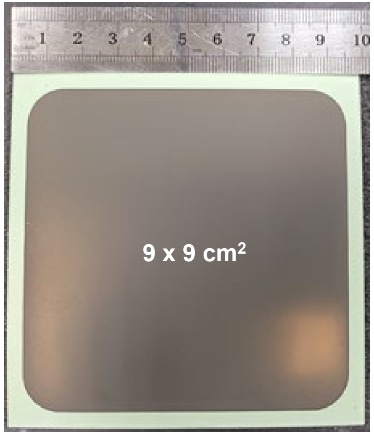
Milestone M2.6.1

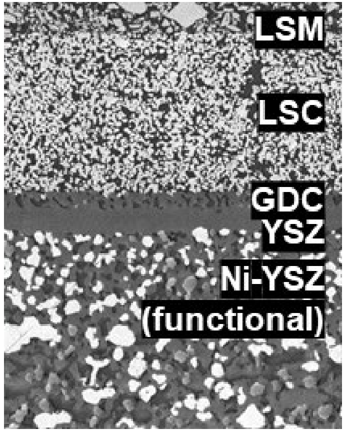
- The stack manufacturing cost model is developed based on the provided raw material list and the manufacturing steps

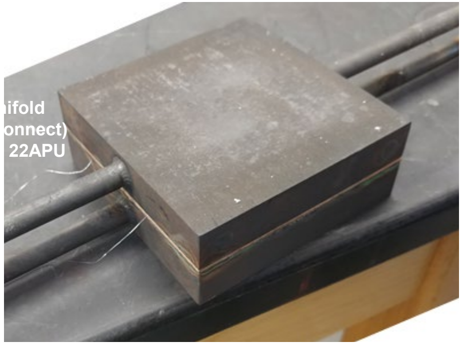
Milestone M3.6.1

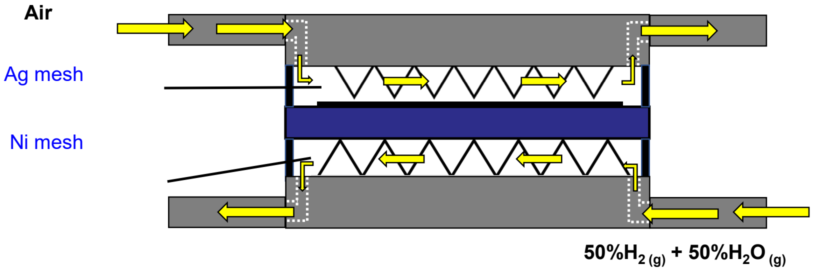
- The final system techno-economic analysis is continued and will be reported

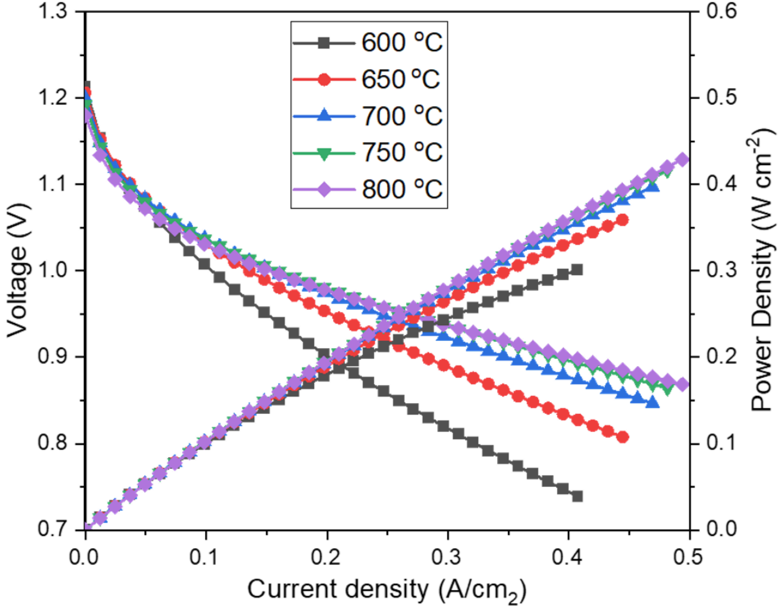
Large-Area Reversible Solid Oxide Cells





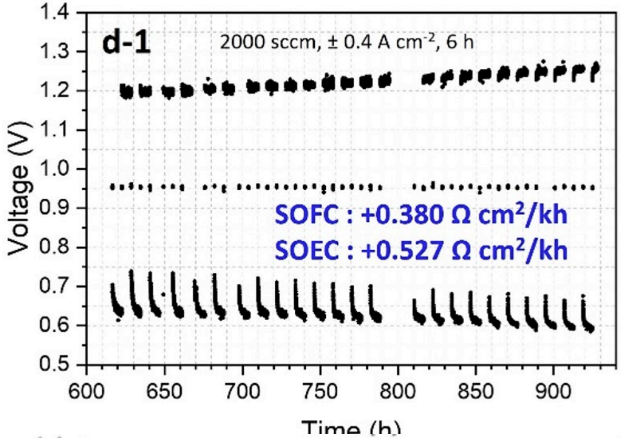


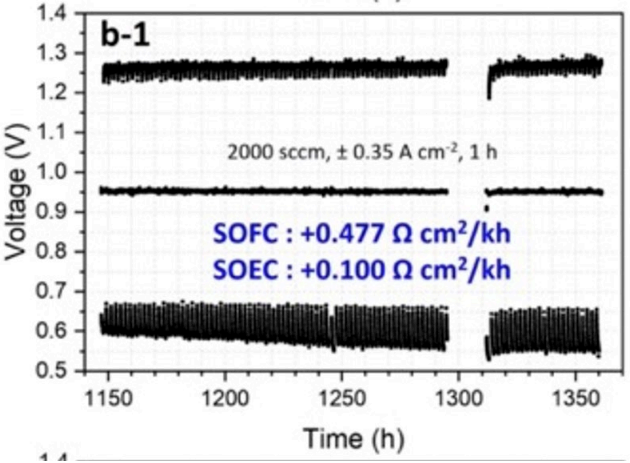




Large-Area Single Cell Life Test: Early stages

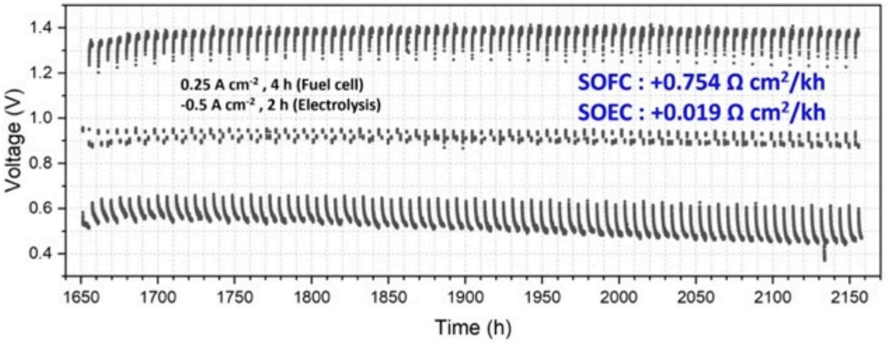
- 2500 h life test of a 80 cm^2 area solid oxide cell: LSC│GDC/YSZ│Ni-YSZ
- 750 ^oC in 50%H_2 - 50%H_2O
- Cell operated for ~ 1400 h at 0.4 or 0.35 A/cm^2 with symmetric electrolysis / fuel cell cycle
  - Either 12 h or 2 h period
- Gradual degradation
  - Increase in electrolysis voltage
  - Decrease in fuel cell voltage
  - Also rapid voltage drop within each fuel cell cycle
  - Cell tended to stabilize with time

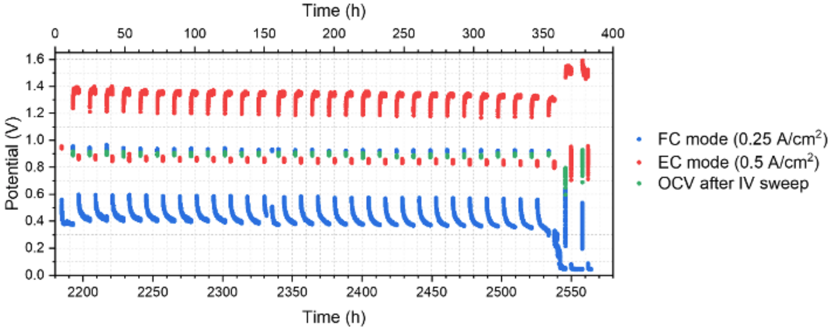




Large-Area Single Cell Life Test: Later Stages

- Cell was then operated in asymmetric cycle:
  - Electrolysis: 2 h at -0.5 A/cm^2
  - Fuel cell: 4 h at 0.25 A/cm^2
- Cells degraded slowly, including slow OCV decrease
- Rapid voltage decreases within cycles became more pronounced





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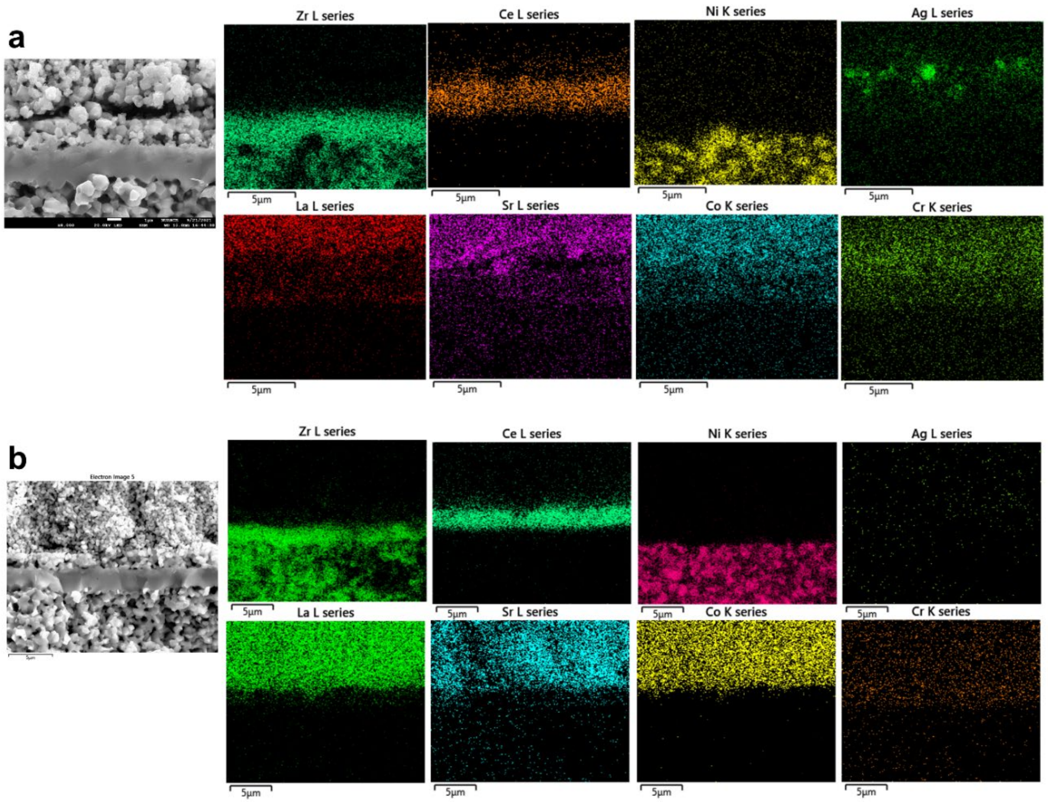
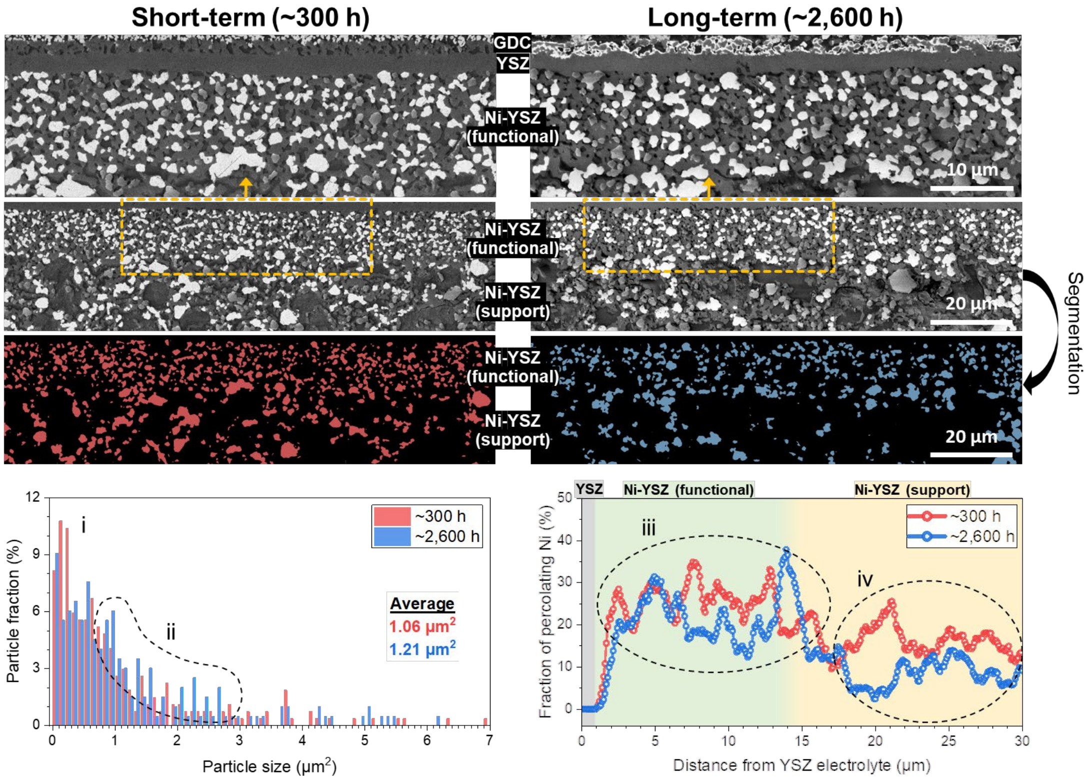
SEM-EDS Mapping After Long and Short Life Test

- SEM images and EDS mapping images of cell cross-sections (a) after long-term test (~2,500 h) and (b) short-term test (~100 h)
- Key changes:
  – Development of cathode/Gd-doped Ceria (GDC) separation
  – Cation migration from the (La,Sr)CoO_3 LSC cathode into the GDC barrier layer
  – Ag impurity (from current collector) detected in GDC layer
  – LSC cathode coarsens and has Cr impurity (from interconnect)



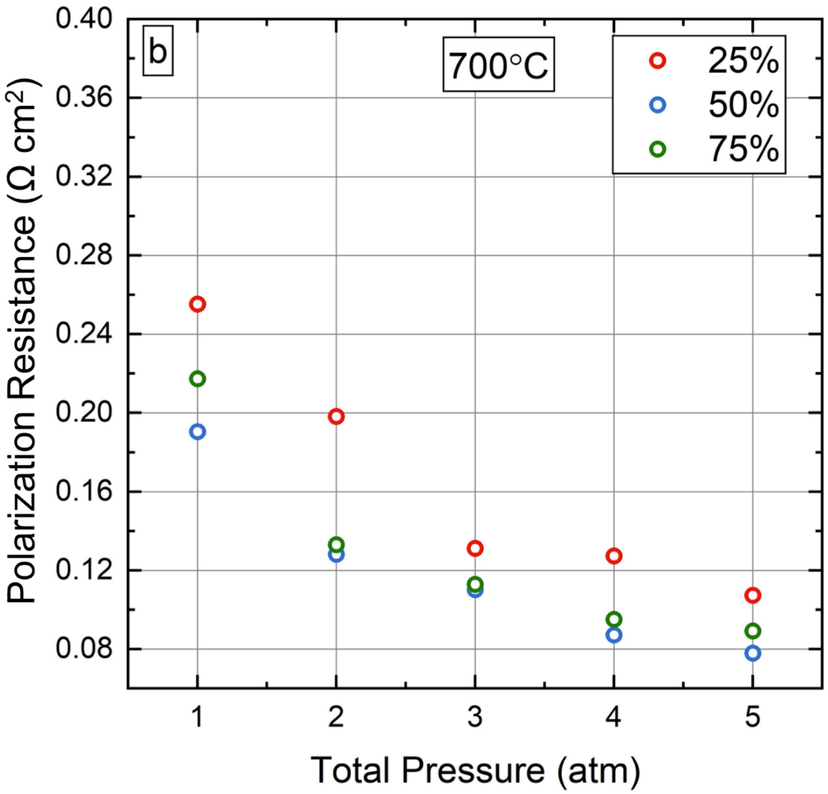
Large-area Reversible Solid Oxide Cells: Fuel Side



- ► Ni particles coarsen during 2,600 h test
- ► Decrease of connected Ni particles (bright) near YSZ electrolyte

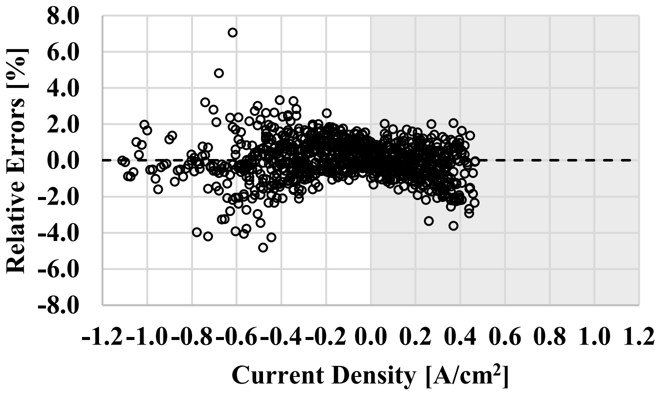
Pressurization: Ni-YSZ

- Polarization resistance of Ni-YSZ fuel electrode versus total pressure
  - Different H_2O percentages (balance H_2)
- Polarization resistance decreases with increasing pressure
- Similar to decrease reported previously for air electrode
- Together these decreases substantially improve cell performance

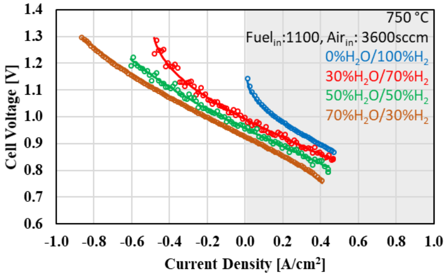


Large-Area Cell Model

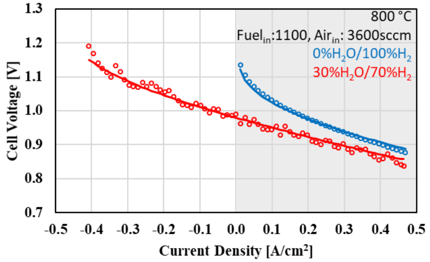
- V-j data used for model calibration & validation including different inlet fuel flow rates
- Model prediction is in good agreement with experimental data



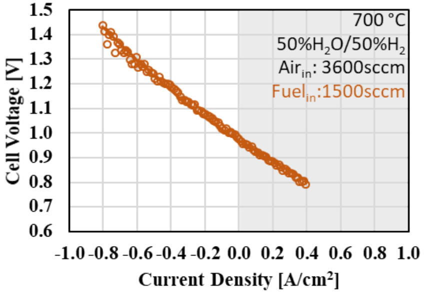
Relative error values



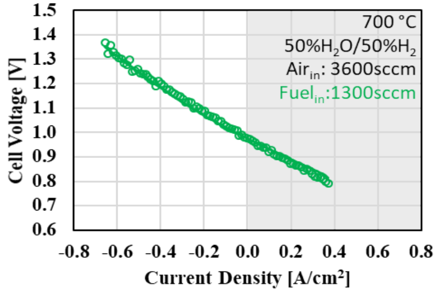
(b.) Validation at 750°C



(a.) Validation at 800°C



(d.) Validation at 700°C
& 1500 sccm fuel flow rate



(c.) Validation at 700°C
& 1300 sccm fuel flow rate

M2.5.2 State-Points using TES via Packed Bed Configuration: Electrolysis Mode

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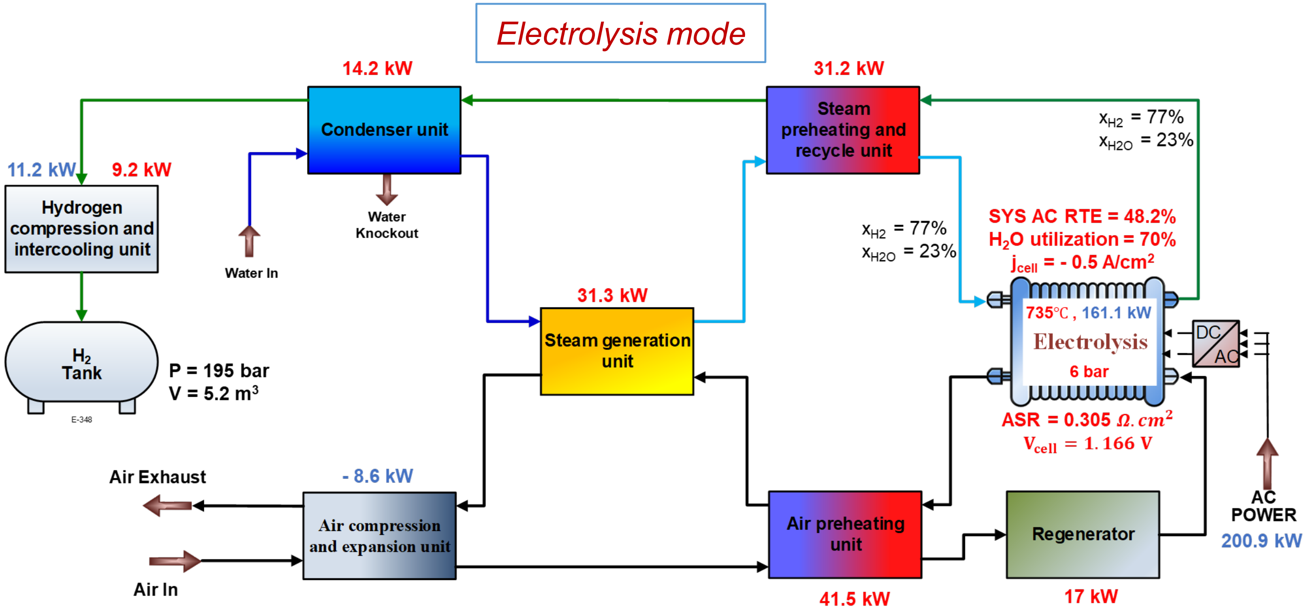
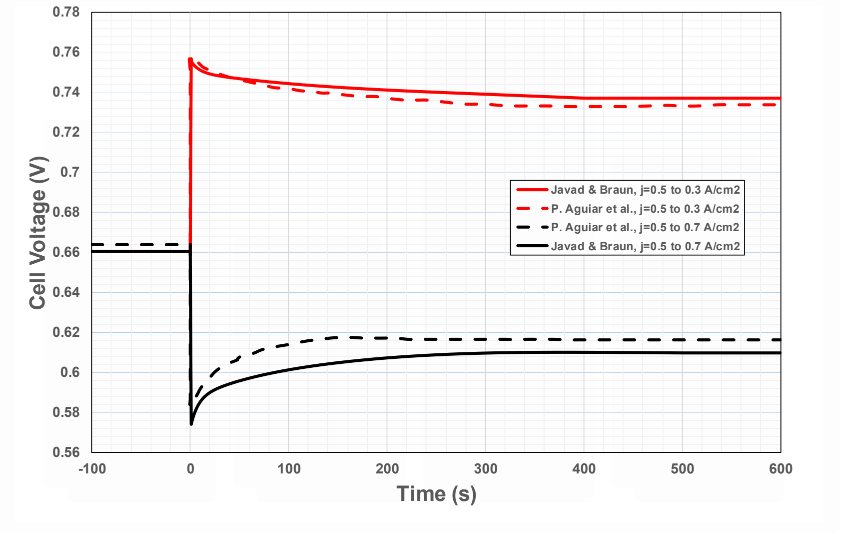
- No significant change in system RTE is seen for base operating conditions compared to No-TES configuration
- Regenerator significantly decreases external electrical load in air side of SOEC mode

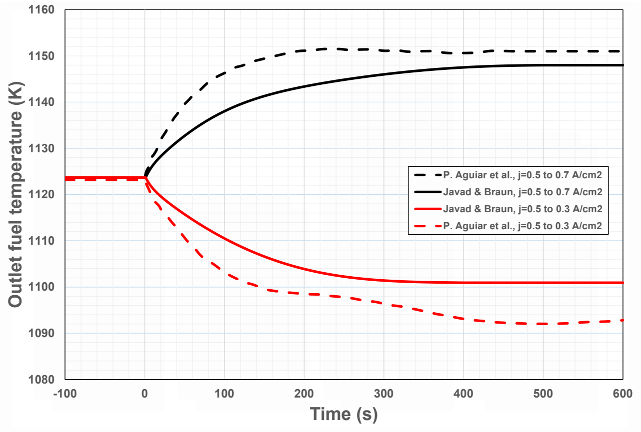


Transient model developed to study mode switching

- All the mass and energy balances are modified to incorporate the transient terms
- Developed transient model is verified against Aguiar's model[1]
- Cell voltage and outlet fuel temperature response are studied during load change in SOFC mode



(a.)



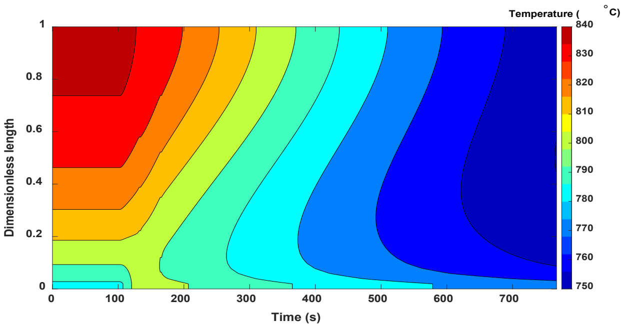
(b.)

The transient response of the cell during load change in SOFC mode (a.) cell voltage response, (b.) Outlet fuel temperature response

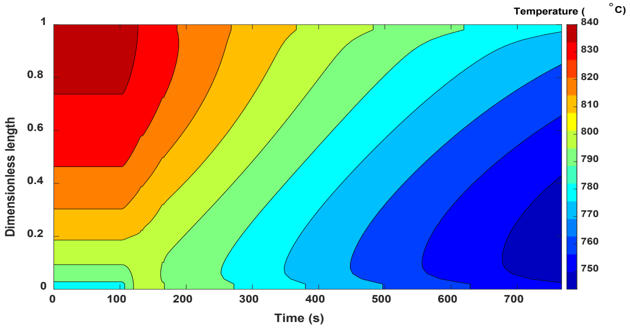
1. Aguiar, P., et al. Journal of Power Sources 147, no. 1-2 (2005): 136-147.

Transient response of MEA temperature to different flow configurations

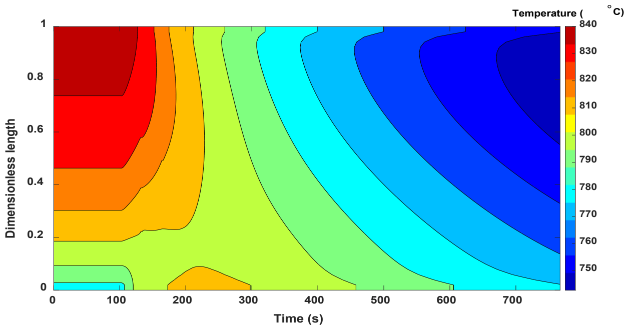
- Stack is operated in steady state FC mode for 60 s before it is switched to EC mode
- Change in air flow direction enables a slightly more gradual decrease in temperature of MEA near dimensionless length of zero
- Air flow direction change can potentially reduce air flow rate which then decreases BoP
- Change in fuel flow direction shifts the highest gradient position from one side to the other



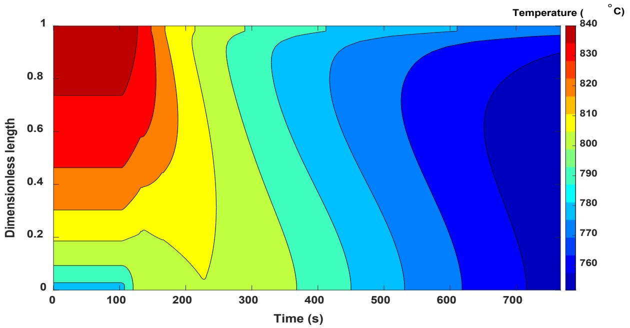
(a.) Same flow direction in both modes



(b.) Only air flow switched



(c.) Only steam flow direction switched



(d.) Both air and steam flow directions switched

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Collaboration & Coordination

- Northwestern University (NU)
  - Prime
  - Cell development, fabrication and scaleup, electrochemical and microstructural characterization
- Colorado School of Mines (CSM)
  - Subcontractor
  - Stack and system modeling, techno-economic analysis
- Collaborative relationships
  - NU provides experimentally-measured cell characteristics as input to CSM stack and system models, allowing accurate prediction of expected system characteristics
  - CSM provides input to NU regarding desired cell characteristics and operating parameters, ensuring that test results are relevant

Remaining Challenges and Barriers

- Further reduction of ReSOC degradation rates
  - Identification and modeling of degradation mechanisms, and their mitigation
- Extend pressurized characterization from oxygen electrodes to Ni-YSZ with infiltrated Ceria, and full cells
- Extend electrochemical model to pressurized and large-area cells
- Techno-economic analysis of ReSOC concept and installed cost estimates
  - Utilizing finalized system definition & component requirements
  - For various system scales
  - Will be combined with system efficiency calculations to provide overall assessment

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Proposed Future Work

- Further studies of ReSOC degradation rates and mechanisms (FY21 3.4.1)
  - Identify main degradation mechanisms and develop preliminary models
  - Both button cell and large-area single cell tests
  - Compare degradation in reversing and electrolysis operating modes
- Continued techno-economic analysis of the system incorporating high temperature and low temperature thermal energy storage (FY31 Milestone 3.6.1)

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Summary

- Project combines reversible solid oxide cell (ReSOC) development, testing, and stability studies with system modeling and techno-economic analysis
  - Assess overall potential of the technology regarding cost/efficiency
  - Large-area cell tests has confirmed viability of reversible solid oxide cell operation
- Cell ASR and degradation rate targets met
  - Performance data fit well using developed electrochemical model
- Experimental data obtained for pressurized cells and large-area cells
  - Important input to achieve accurate system-level models and TEA
- Developed systems concepts with thermal energy storage (TES) for high efficiency
  - Above 50% system AC RTE can be achieved by employing a steam accumulator as low temperature TES
- Used techno-economic modeling to validate technology viability

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Technical Backup and Additional Information

Technology Transfer Activities

- Reversible fuel cell storage concept needs validation from the button cell to large cell level (this project)
  - Beyond this, we plan to further validate at the stack/system level
  - After this, we believe it will be possible to obtain private funding for further development
- Our universities aggressively market inventions
- Both NU and CSM hold patents on reversible solid oxide cell energy storage
  - NU (Barnett) recently had a relevant patent issued titled: "Three Dimensional Extrusion Printed Electrochemical Devices," US patent # 10,236,528