High Power, Low Cost SOFC Stacks For Robust And Reliable Distributed Generation

Award No. DE-FE0026189

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Redox Power Systems, LLC

Project Kickoff 12/02/2015

Redox Cube

- 25 kW, natural gas, stationary power system
- > 50% efficiency
- Compact (~1 m^3)
- Lightweight (< 1000 lbs)

For more info:
www.redoxenergy.com

NETL Project Partners

- *Univ. of Maryland Energy Research Center* (UMERC)
- *Center for Advanced Life Cycle Engineering* (CALCE) at the Univ. of Maryland

Commercial Partners:

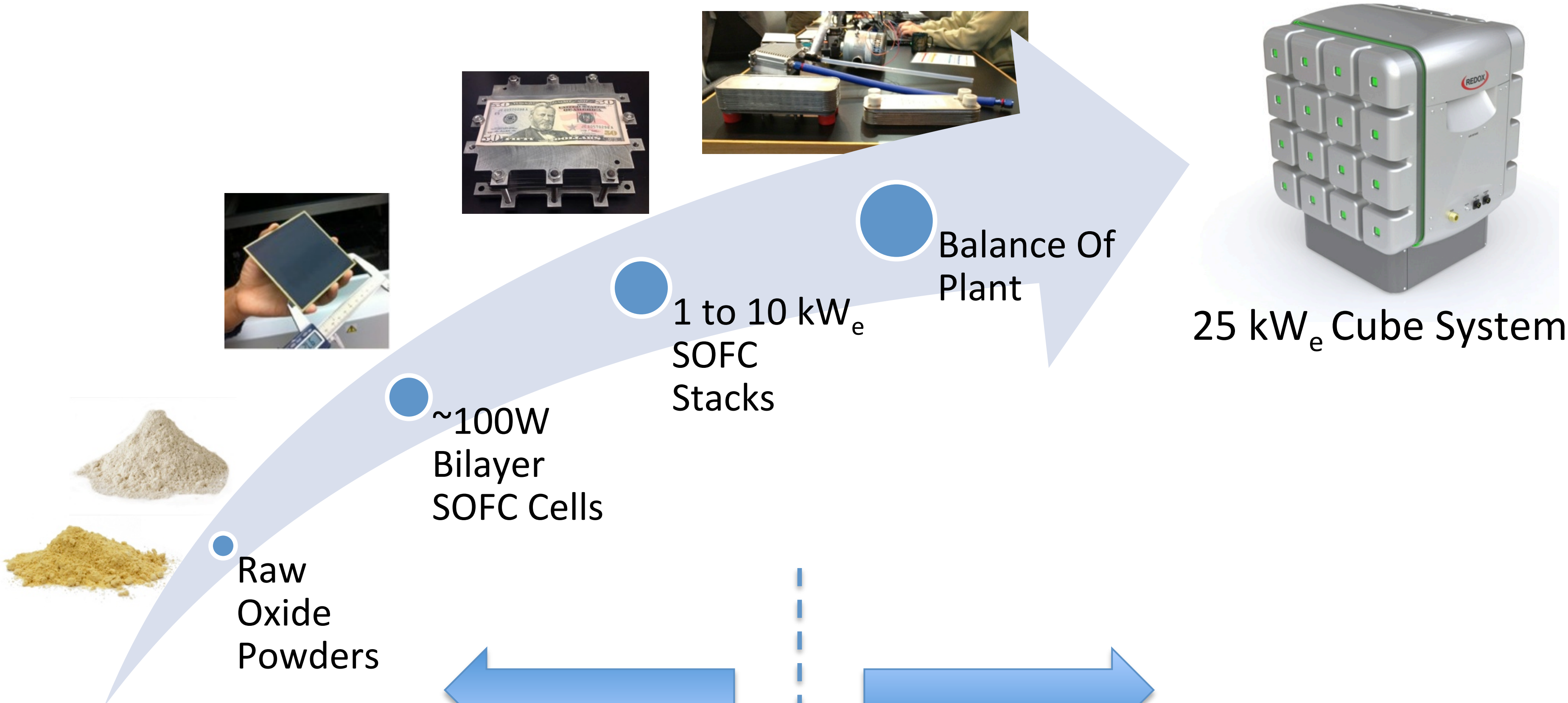
- Trans-Tech Inc.
- Strategic Analysis Inc.

Introduction to Redox

- Redox Power Systems founded in 2012, located in College Park, MD
- Over 25 years of Solid Oxide Fuel Cell (SOFC) development to achieve:
  - 10x higher power density than competing SOFCs
  - At 100s of degrees lower operating temperature
  - Using natural gas fuel
  - To result in a more compact and lower cost systen with improved load following capabilities
  - Using a proprietary bilayer cell structure

- Private + gov't funding: DoE (ARPAE, EERE, NETL) & DoD
- SOFC cells are manufactured with our ISO 9001 partner Trans-Tech Inc, a division of Skyworks Solutions

Redox Product Manufacturing Overview



Specialized manufacturing, custom components

Common high volume appliance and electronics manufacturing, COTs components

Introduction to Partner Organizations

- UMERC (under direction of Prof. Eric Wachsman)
  - multidisciplinary initiative dedicated to advancing the frontiers of energy science and technology, with a special focus on forward-looking approaches for alternative energy generation and storage
  - heavily involved in NETL SOFC degradation investigations for more than a decade
  - developed unique techniques for investigating degradation of cathode materials using isotope exchange
  - pioneered the use of FIB-SEM reconstruction to to quantify porous cathode microstructure at the sub-micron level and ultimately to develop higher performance cathodes

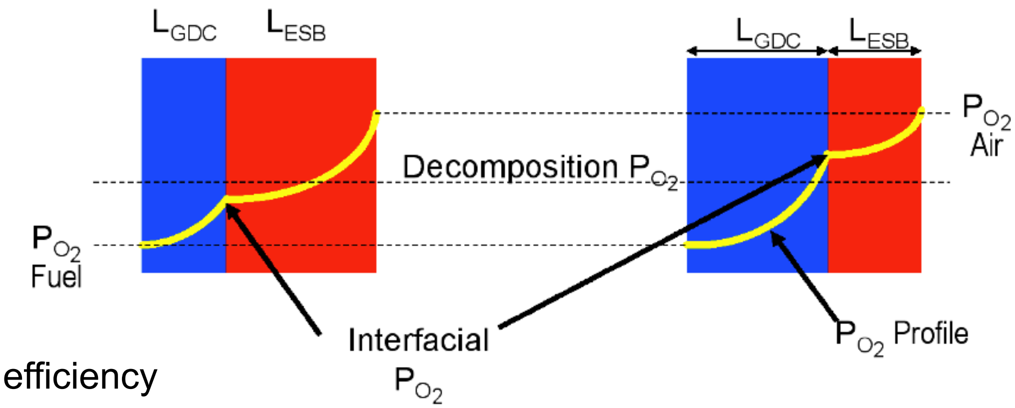
- CALCE (under direction of Prof. Michael Pecht)
  - founder and driving force behind the development and implementation of physics-of-failure (PoF) approaches to reliability
  - world leader in accelerated testing, electronic parts selection and management, and supply-chain management
  - first academic research facility in the world to be ISO 9001 certified
  - funded by over 150 of the worlds leading electronics companies at more than US$6M/year
  - Experience developing techniques for extending the lifetime of electrochemical devices, such as lithium ion batteries, under real world operating conditions

NETL Project Objectives

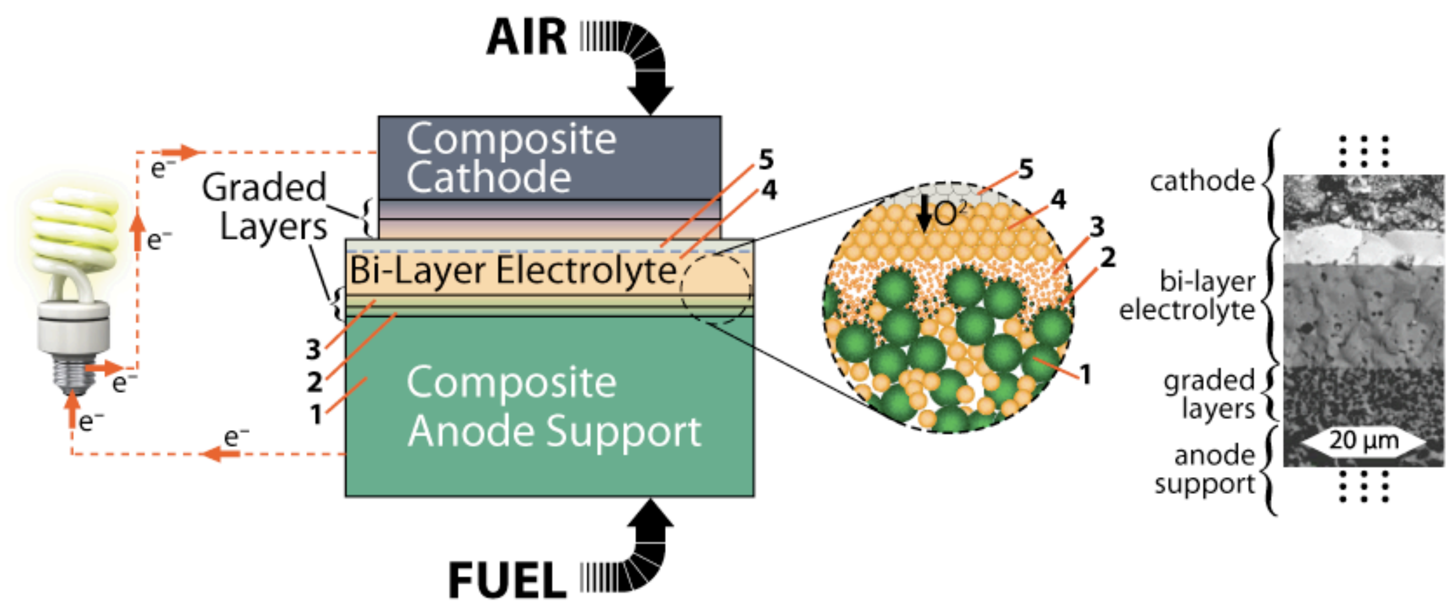
- **Purpose:** To further develop high power density, low cost SOFC stacks for robust and reliable distributed generation.
- The objective of the overall project is to improve performance/ durability of Redox stacks while reducing costs through:
  - the scale-up of current stack module designs to 5-10 kW
  - the determination of cell and stack degradation mechanisms between 500-650°C through accelerated testing and subsequent cell and stack optimization to improve long-term stability
  - the development and testing of a robust 5-10 kW stack design that can support electrical load and thermal cycling requirements
  - detailed cost analysis to show a 20% manufacturing cost improvement for the stack over current 2020 DOE cost targets

Approach Summary: IT-SOFC Stack

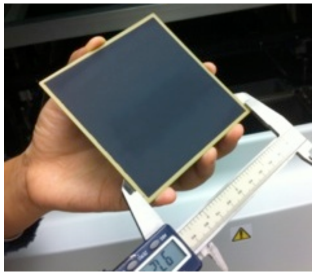
- **Increased Efficiency**
  - Er stabilized Bi_2O_3 (ESB):
    - * 60X conductivity of YSZ @ 600°C
    - * unstable at low PO_2 (fuel conditions)
  - Gd doped CeO_2 (GDC):
    - * > 5X conductivity of YSZ @ at 600°C
    - * electronic leakage in fuel conditions, lowers efficiency



  - *Solution*: a bilayer of GDC (fuel side) and ESB, stops ceria electronic leakage & Bi_2O_3 decomposition
  - *Goal*: Optimize bilayer for best compromise between stability and performance in stack up to 10 kW



Approach Summary: IT-SOFC Stack



- **The Cell**
  - Bilayer electrolyte +high performance cathode yield ultra high power density (> 2 W/cm^2 in lab testing)
  - Lower operating temperatures (down to < 400 °C, or 700 °F)
  - Current anodes can run on wide range of hydrocarbon fuels with high efficiency
  - New ceramic anodes can also be thermally cycled for enhanced load following

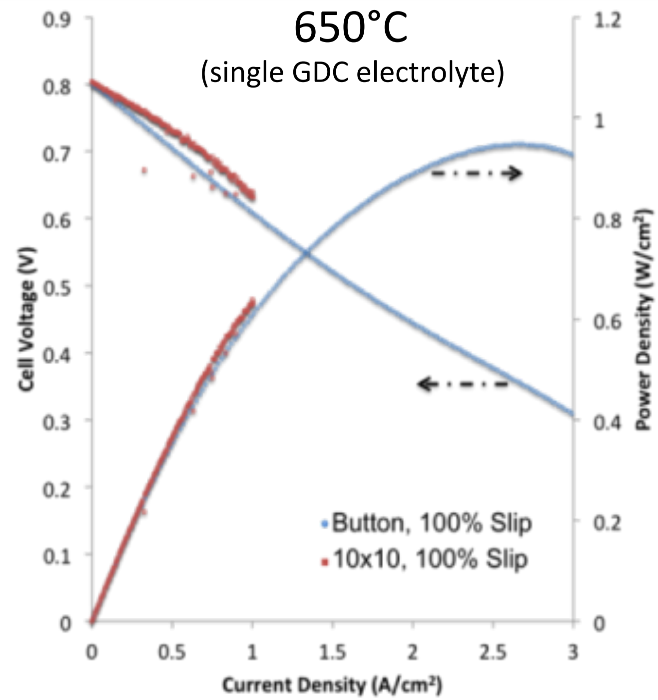
- **The Stack**
  - Lower operating temperatures = lower cost metal interconnects, less insulation
  - Conventional sealing materials like those used in automotive industry

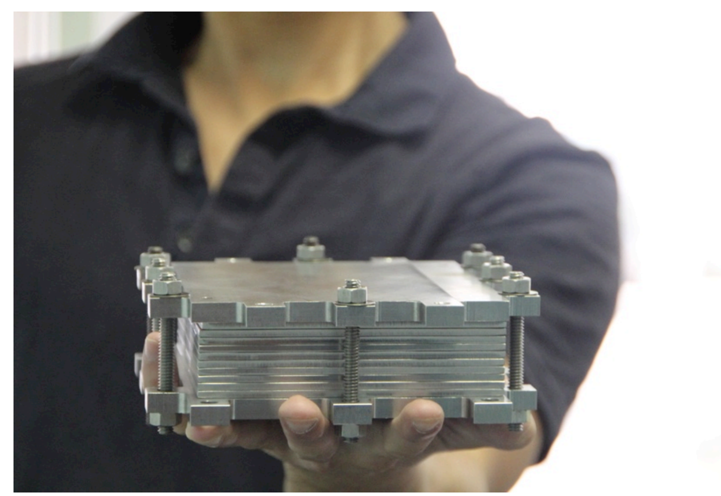
- **Optimized designs for 5-10 kW stacks and IT operation**
  - 500-650°C operating temperatures
  - Use proprietary Redox multi-physics bilayer model to optimize stack design for up to 10 kW
  - Support modeling with elevated temperature mechanical testing (stress concentrations and creep)
  - Improve assembly techniques (e.g., alignment and compression load)

- **5-10 kW stack demo**
  - Bilayer cell performance maps for up to 10 kW stack, feed results back to model for design optimization
  - Long term testing > 1,000 hours
  - Fully instrumented test setup for evaluation of fuel utilization, degradation, and performance

High Power, Robust Stack

- Large format cells with high power have been scaled in manufacturing
  - 10 cm by 10 cm cell performance matches button cell results in 100% slip condition (21% CH_4, 39% H_2, 4.4% CO)
- 1 kW stack size to be scaled to 5-10 kW size
  - Single stack, *or*
  - Stack module (no less than 2.5 kW each)





Project Task Summary

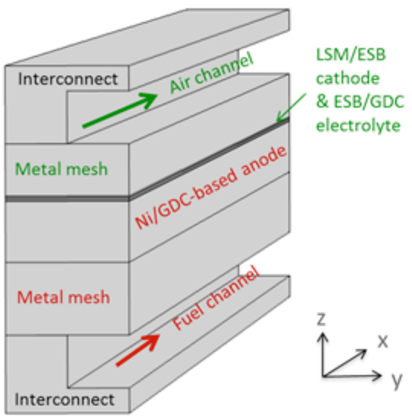
- Task 1: Project Management and Planning
- Task 2: Develop High Power, Robust, Low Cost IT-SOFC Stacks
- Task 3: Improve Long-Term Stability and Reliability of High Power, IT-SOFC Stacks
- Task 4: Demonstrate a Robust 5-10 kW Stack or Stack Module for Distributed Generation
- Task 5: Perform a Detailed Cost Analysis of High Power, IT-SOFC Stacks

Multi-Physics Tool for Stack Scale-up

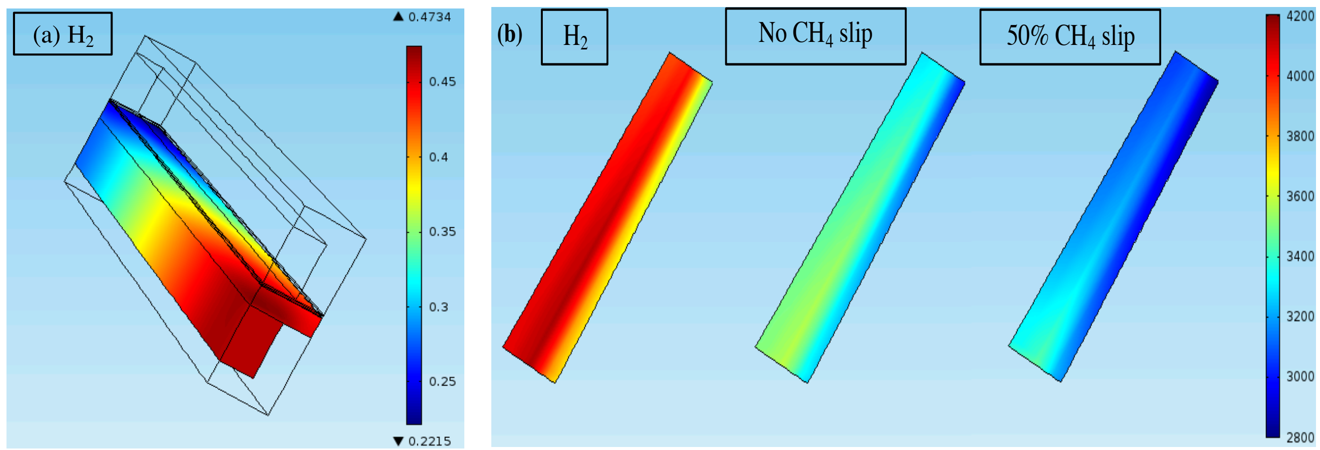
Task 2

- Custom 3D computational model takes into account the unique thermochemical and physical properties of the Redox materials as derived from more fundamental materials and electrochemical measurements
- Model considers impacts of leakage current (electron current) on the OCV drops from theoretical Nernst potential due to over-potentials associated with the electrolyte and electrodes
- Model also captures the kinetics of electrochemical and heterogeneous internal reforming reactions in the anode

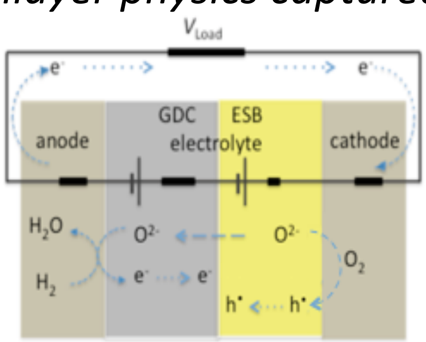
Detailed Single Channel Model



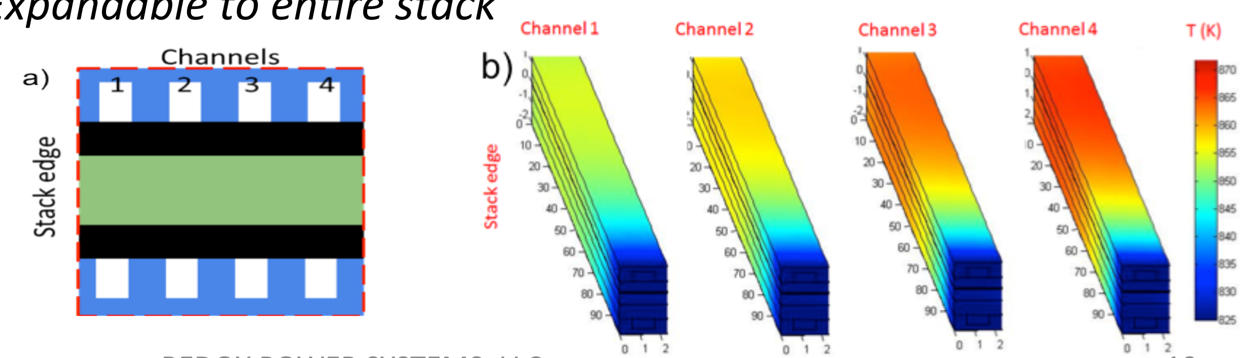
(a) Mole fraction of H_2 for 0.7V at standard fuel utilization for 0% CH_4 slip at 600°C inlet temp.
(b) 2D current distribution for 3 anode fuel feeds operating at 0.7 V and 600°C and a U_f of 80%



Bilayer physics captured



Expandable to entire stack



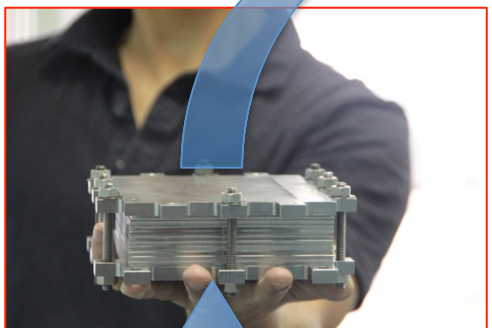
Modeling Effort in NETL Project

Task 2

- Optimize stack design through parametric studies
  - cell geometry/composition and interconnect flow field geometry) to minimize pressure drops, improve flow distribution, and minimize thermal gradients under rapid startup, normal operation, and load-following conditions
  - Mechanical degradation through thermal gradients and phenomena such as creep at elevated temperatures
- Evaluate cell/stack performance in conjunction with accelerated testing and lifecycle testing to help choose final operating conditions for tests and to help analyze results.

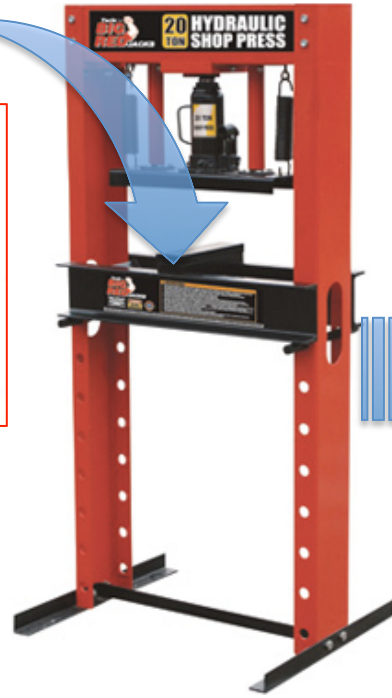
Stack Assembly Improvements

Task 2



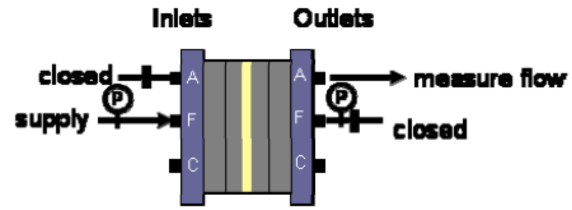
Stack

Redox Production Cells

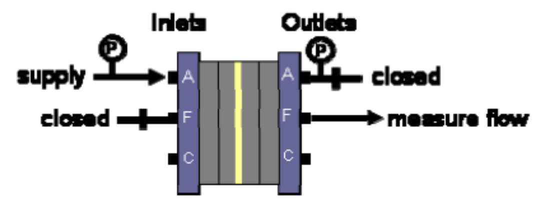


Stack Assembly Press Instrumentation Upgrade

-increase size & degree of automation
-acoustic emissions
-dynamic tracking of applied load & compression



Fuel to oxidant measurement



Oxidant to fuel measurement *

Leak Check QC

-improved procedures
-correlation to elevated temperature testing & manufacturing QC information

feedback for production optimization

*Ref. US Fuel Cell Council, Document No. 04-070

IT-SOFC Stack & Stack Module Testing *Task 2-4*

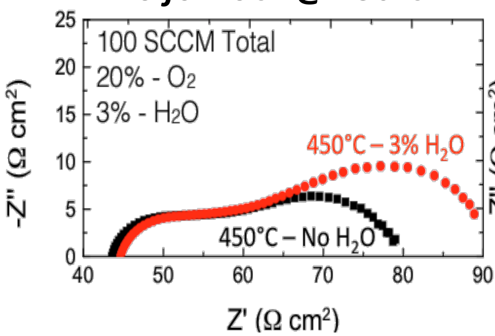
- As the size increases, stacks shall be tested under relevant conditions to validate the performance of optimized stack designs.
- Up to 3 separate test/analyze cycles to fully characterize cells and stacks for up to 1,000 hours.
- Shorter test durations are expected after design changes are initially made in order to fully characterize the changes in conjunction with validation of modeling efforts.
- Stacks shall be tested between 500-650 °C
  - I-V and impedance spectroscopy measurements
  - constant current loads for long-term tests

Improve Stability/Reliability of the Cell

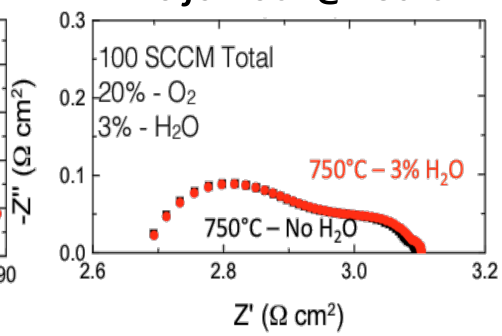
Task 3

- A variety of techniques will be used to investigate degradation mechanisms
  - -Impact of H_2O, CO_2, Cr vapor for LSM-ESB cathode
  - -EIS and oxygen isotope exchange
  - -FIB/SEM and TEM/EDS

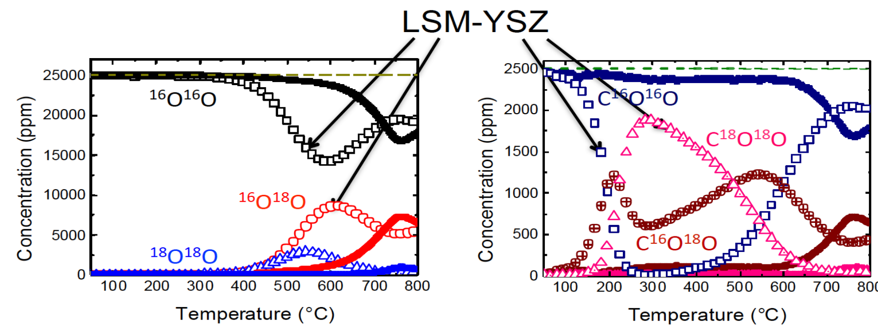
EIS for LSCF @ 450°C



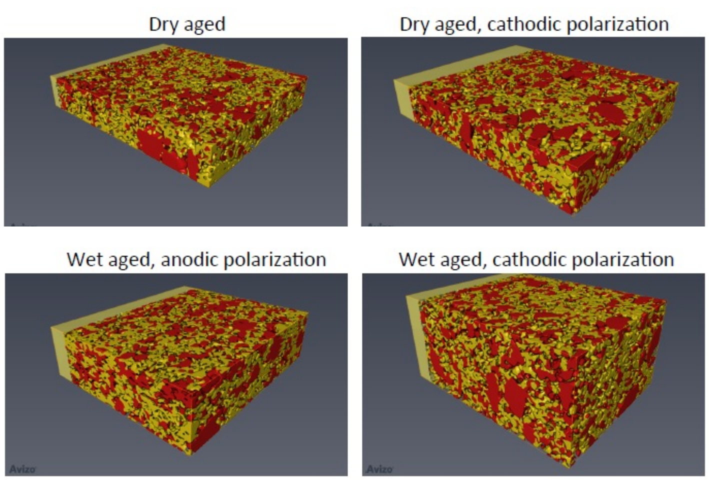
EIS for LSCF @ 750°C

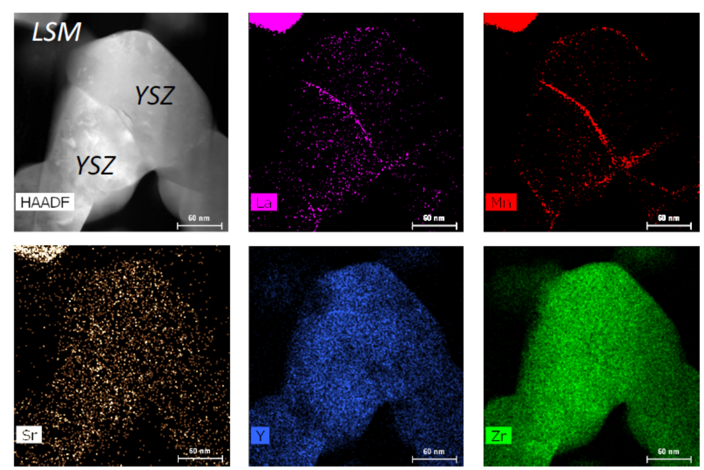


Isotope Exchange for impact of CO_2



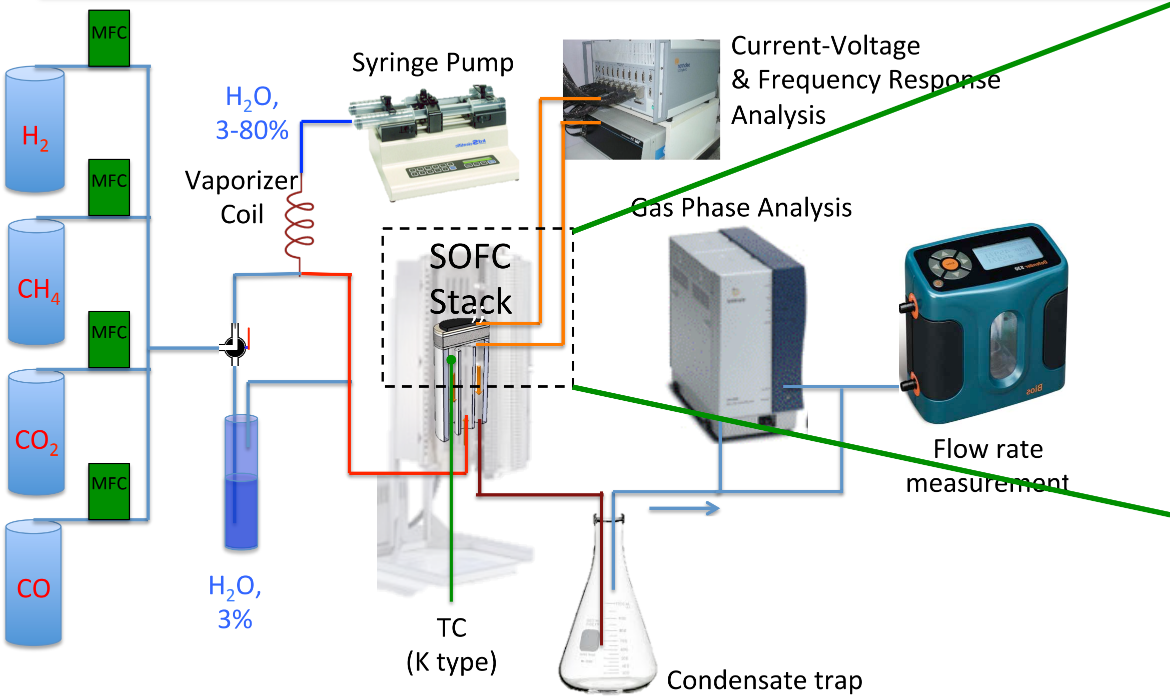
FIB/SEM + TEM/EDS for LSM/YSZ

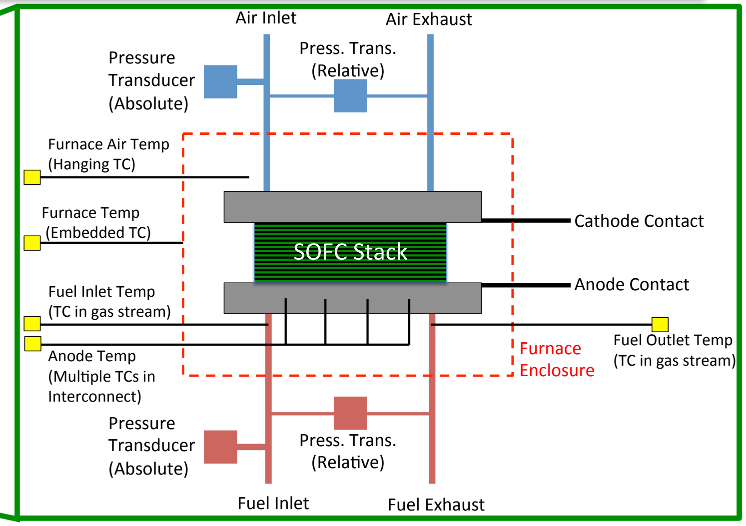




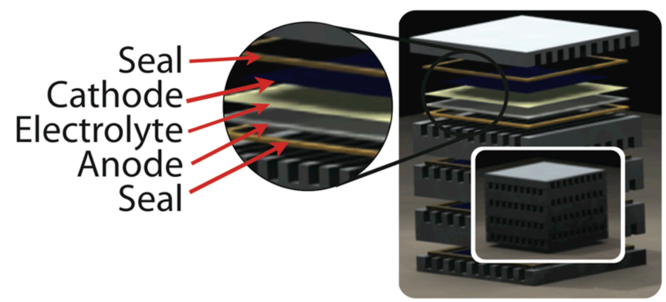
Reduce Stack Degradation

Task 2-4





Extensively instrumented to capture dynamic behavior



Stack Lifecycle Analysis Modeled and Evaluated Using:

- Strength, creep, and acoustic emission spectroscopy data of stack materials & components
- Multiphysics modeling of components
- Long-term measurements under normal operational conditions
  - Power output, voltage changes, component conductivity
- Accelerated stack testing under extreme temperature and load
- Modeling of material and operational costs over lifetime of stack

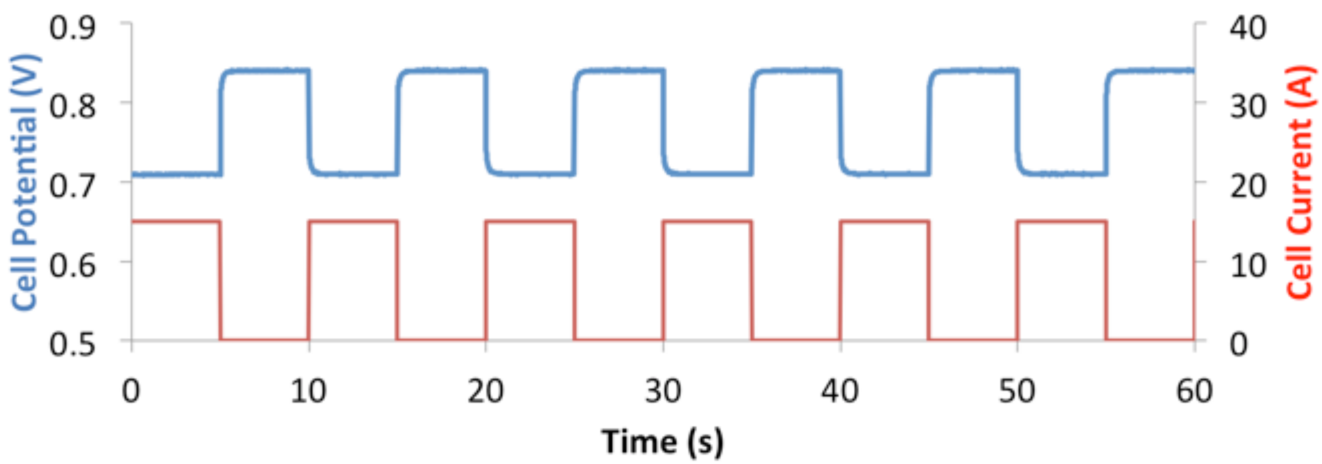
Testing Different Operating Conditions

Task 2-4

Dashboard and test sequence input

Gas flow control

Rapid pulse performance verification



Durability & Accelerated Testing

Task 3

- Physics-of-failure, durability, and accelerated tests will be developed by CALCE and Redox as test methodologies and protocols are optimized for assessing and quantifying cell/stack degradation and failure.
  - ❑ Temperature and pressure dependence of Ni particle sintering and relative morphology change, in particular in the presence of steam;
  - ❑ Accelerated electro-migration due to high operation current density
- Testing will result in an understanding of performance degradation mechanisms by both individual and combined contaminant effects, and will allow us to make enhancements.
  - ❑ Homogenizing stress, flow and temperature distributions of the stack as well as balancing leakage and mechanical failure
  - ❑ Infiltration to modify the cell components for mitigating both material intrinsic and extrinsic degradation modes.

Cell / stack failure	Mechanical	Chemical-Electrochemical
Cracks in cell	Creep in stack components, thermal cycling	Changes in cell porosity and tortuosity
Delamination of layers in cell	Poor adhesion of layers	Chemical reactions and phase changes
Leakage of stack (sealing failure)	Thermal cycling of seal materials	Contamination by impurities, corrosion, red-ox of materials
Malfunctions of cell/stack during conditioning, thermal and red-ox cycling, or load following	Sintering volume change due to high current density or steam	Electromigration and interdiffusion
Poor cell electrical conductivity	Thermo-mechanical failure due to extreme thermal gradients	Impact of steam on anode or cathode, corrosion of interconnect

Distributed Generation Demonstration

Task 4

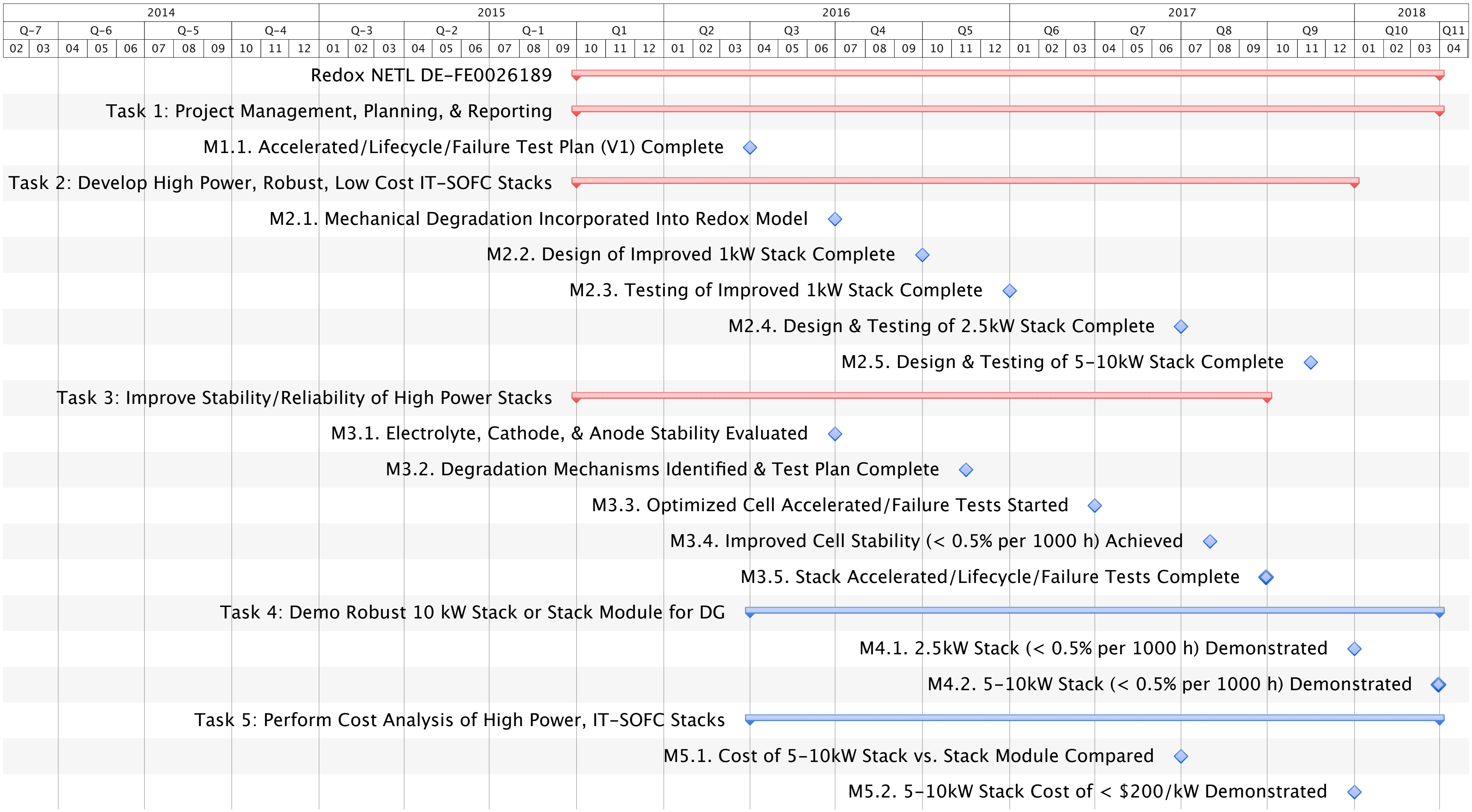
- 5-10 kW Demo
  - Initial stack demos at 0.5-1.0 kW size with reformate
  - Subsequent stack demos at 2.5 kW stack size
  - Final stack demos at 5-10 kW stack or stack module
  - Stack demonstrations conducted for up to 1,000 hours under normal operating conditions and various load profiles characteristic of perceived final application
  - The primary objective of these tests is to demonstrate low degradation rates (target: < 0.5% per 1,000 hours) and durability (thermal, load-following, and reduction-oxidation cycles) of the 5-10 kW stack or stack module.

Detailed Cost Analysis of Stacks

Task 5

- Cost Analysis
  - Demonstration of a 20% reduction in the current DOE cost target with a detailed cost analysis (Redox Target: \$180-\$200/kW)
  - Cost analysis will begin with production process flows and associated raw materials and handling costs
  - detailed study of actual ISO 9001 manufacturing processes and how various automation steps can decrease costs and improve product quality with the larger size stacks
  - trade studies on how best to form interconnects and seals in light of design changes that are likely to occur as a result of scaling the size of the stack
  - sensitivity studies of various aspects of the manufacturing process as it relates to specific design choices for the larger size stack
  - During the project we will adjust current cost estimate models for assembly cost projections with the larger size stacks

Project Schedule



Project Milestones

WBS	Description/Title	Start/ End	Verification Method
Task 1.0	**Project Management, Planning, & Reporting**	Q1/Q10	
M1.1	Accelerated/Lifecycle/Failure Test Plan (V1) Complete	Q1/Q2	Test Plans
Task 2.0	**Develop High Power, Robust, Low Cost IT-SOFC Stacks**	Q1/Q8	
M2.1	Mechanical Degradation Incorporated Into Redox Model	Q1/Q3	Model Validation
M2.2	Design of Improved 1kW Stack Complete	Q1/Q4	Report
M2.3	Testing of Improved 1kW Stack Complete	Q1/Q5	Test Data
M2.4	Design and Testing of 2.5kW Stack Complete	Q3/Q7	Test Data
M2.5	Design and Testing of 10kW Stack Complete	Q5/Q9	Test Data
Task 3.0	**Improve Stability/Reliability of High Power Stacks**	**Q1-Q8**	
M3.1	Electrolyte, Cathode, and Anode Materials Stability Evaluated	Q1/Q3	Report
M3.2	Cell Degradation Mechanisms Identified and Test Plan Complete	Q1/Q5	Test Plans
M3.3	Optimized Cell Accelerated/Failure Tests Complete	Q3/Q6	Test Data
M3.4	Improved Cell Stability (< 0.5% per 1000 h) Achieved	Q1/Q7	Test Data
M3.5	Optimized Stack Accelerated/Lifecycle/Failure Tests Complete	Q4/Q8	Report
Task 4.0	**Demonstrate a Robust 10 kW Stack or Stack Module for DG**	**Q3/Q10**	
M4.1	2.5kW Stack (< 0.5% per 1000 h) Demonstrated	Q4/Q9	Test Data
M4.2	5-10kW Stack (< 0.5% per 1000 h) Demonstrated	Q8/Q10	Test Data
Task 5.0	**Detailed Cost Analysis of High Power, IT-SOFC Stacks**	**Q3/Q10**	
M5.1	Cost of 5-10kW Stack vs. Stack Module Compared	Q3/Q7	Report
M5.2	5-10kW Stack Cost of < $200/kW Demonstrated	Q3/Q9	Report