FuelCell Energy

Project Kickoff Meeting
Transformational SOFC Technology
(DE-FE0027584)

Presented To:

National Energy Technology Laboratory (NETL)

November 16, 2016

Webconference

Public Version

Ultra-Clean, Efficient, Reliable Power

Meeting Agenda

Attending Organizations: National Energy Technology Laboratory (NETL/DOE), FuelCell Energy, Inc. (FCE), Northwestern University (NU)

12:15 pm - 12:30 pm	Introductions and brief procurement discussions	NETL
12:30 pm – 12:40 pm	Project Overview	H. Ghezel-Ayagh
12:40 pm – 1:05 pm	Cell Technology and Manufacturing	Scott Barnett / Eric Tang
1:05 pm - 1:25 pm	Stack Design and Fabrication	Scott Corey / Keith Davis
1:25 pm - 1:30 pm	Q&A and Follow up Discussion	All

* Times are in EDT (Eastern Daylight Saving Time)

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Project Overview

Project Objectives

The overall project goal is to advance the SOFC technology at the cell and stack levels by focusing on the following objectives:

- Enhancements in reliability, robustness and endurance
- Reduction in overall system cost
- Reduction in operating and maintenance cost

The approach in meeting the objectives are targeted on:

- Increased redox stability of the existing cell technology
- Developing a new novel single-stage sintered cell technology
- Develop an integrated stack architecture incorporating balance-of-plant functionality and enabling reduction in materials usage
- Simplify plant maintenance and repair

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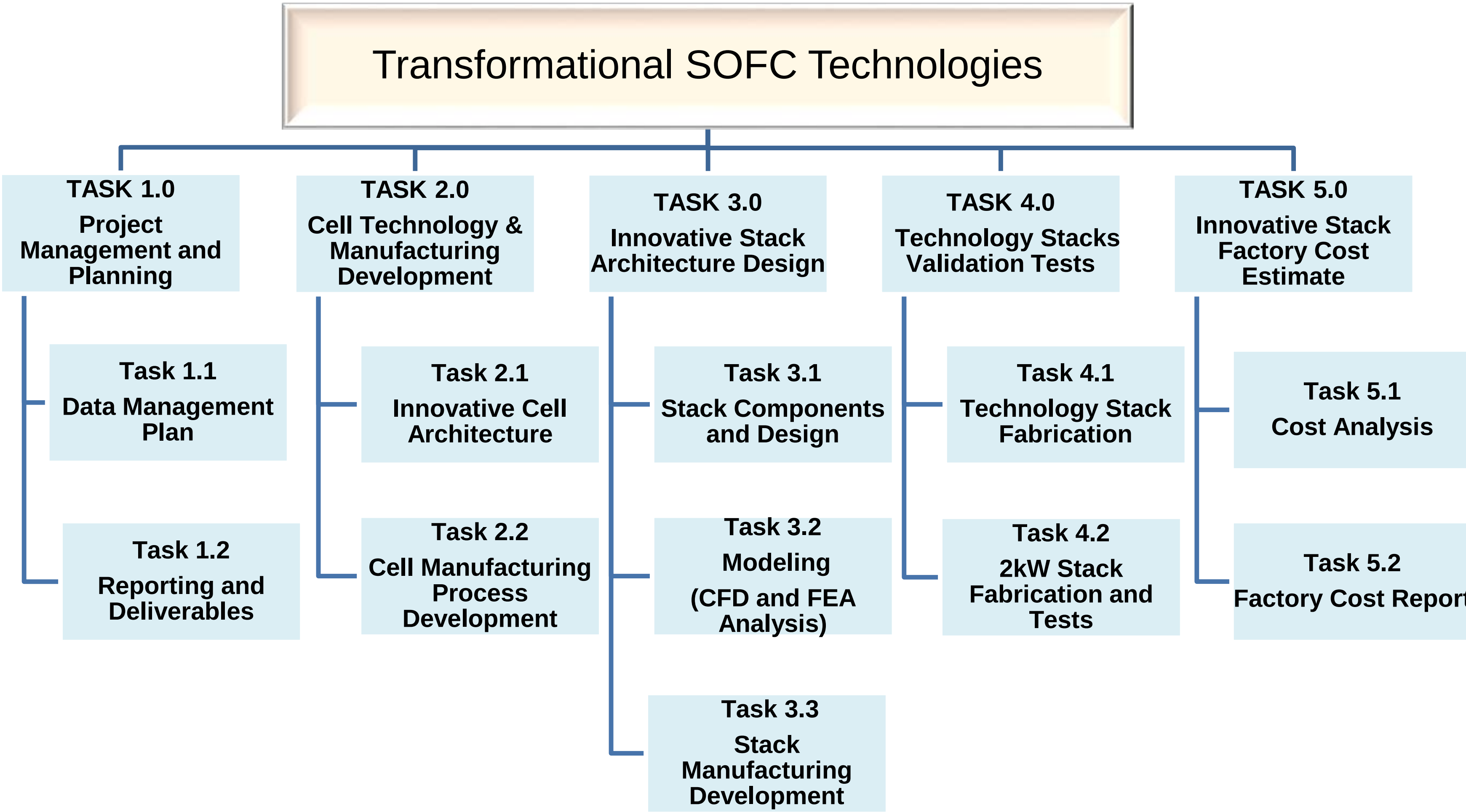
Work Breakdown Structure



The work breakdown structure is designed to ensure success in achieving the program objectives with minimal risk.

Project Team Structure

FuelCell Energy Danbury

- Project Coordination
- Integrated Stack Design
- BOP Components Design and Integration
- Validation Tests
- Factory Cost Estimate

FuelCell Energy Calgary

- TSCIII Optimization for Redox Tolerance
- Cell Manufacturing Process Modification
- Stack Repeat Components Design
- Technology Cell & Stack Tests

Northwestern University

- Single-Stage Sintered Cell
- Bi-layered Electrolyte

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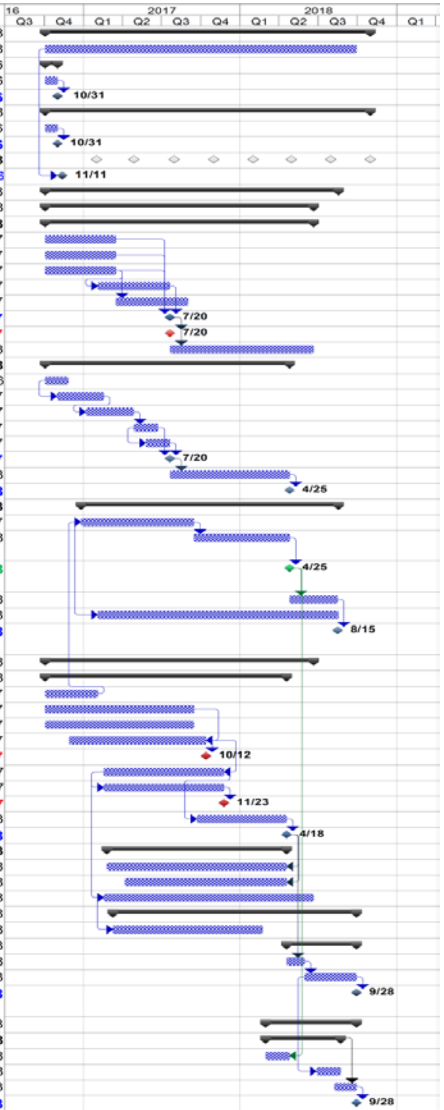
Projects Schedule

Two-Year Project Schedule

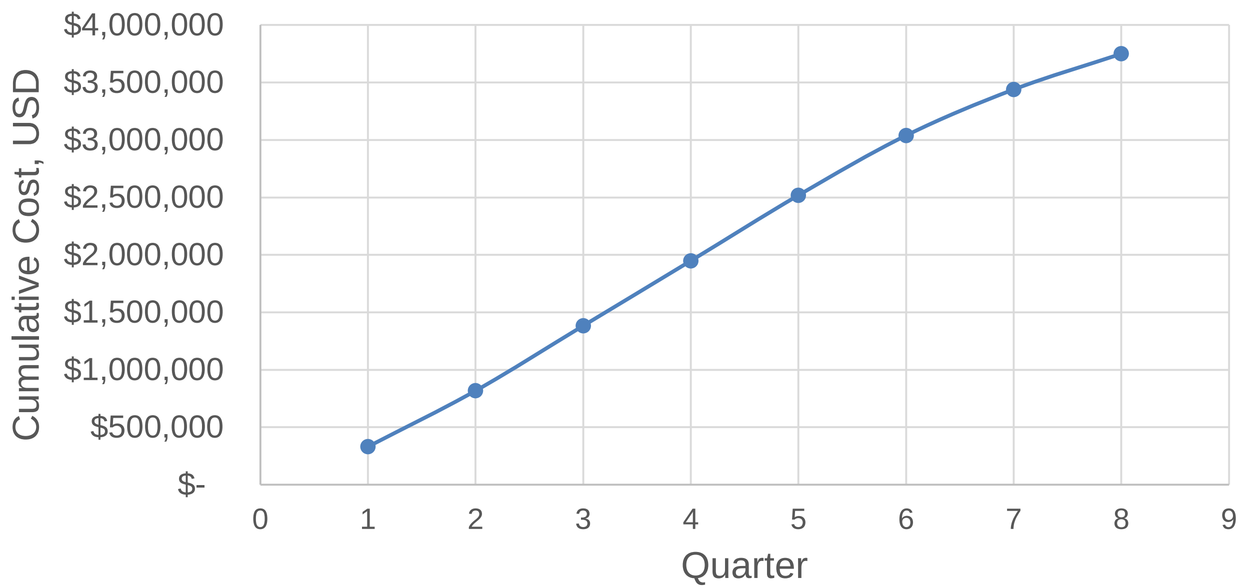
ID	Task Name	Start	Finish
1	**1.0 Project Management and Planning**	Mon 10/3/16	Wed 10/31/18
2	Project Management and Planning	Mon 10/3/16	Fri 9/28/18
3	**1.1 Data Management Plan (DMP)**	Mon 10/3/16	Mon 10/31/16
4	Update Data Management Plan	Mon 10/3/16	Mon 10/31/16
5	**Updated Data Management Plan**	**Mon 10/31/16**	**Mon 10/31/16**
6	**1.2 Reports and Deliverables**	Mon 10/3/16	Wed 10/31/18
7	Update Project Management Plan (PMP)	Mon 10/3/16	Mon 10/31/16
8	**Updated Project Management Plan**	**Mon 10/31/16**	**Mon 10/31/16**
9	**Quarterly Reports**	**Tue 1/31/17**	**Wed 10/31/18**
18	**Kickoff Meeting**	**Fri 11/11/16**	**Fri 11/11/16**
19	**2.0 Cell Technology & Manufacturing Development**	Mon 10/3/16	Fri 8/17/18
20	**2.1 Innovative Cell Architecture**	Mon 10/3/16	Wed 6/20/18
21	**2.1.1 Single Stage Sintered Cell Development**	**Mon 10/3/16**	**Wed 6/20/18**
22	Anode support / AFL development	Mon 10/3/16	Thu 3/16/17
23	Bi-layer Electrolyte development	Mon 10/3/16	Thu 3/16/17
24	CFL Development	Mon 10/3/16	Thu 3/16/17
25	Infiltration of Anode & Cathode Electocatalysts	Fri 2/3/17	Thu 7/20/17
26	Atomic Layer Deposition process development	Fri 3/17/17	Thu 8/31/17
27	**Demonstrate Feasibility of Single Stage Cell Sintering Process**	**Thu 7/20/17**	**Thu 7/20/17**
28	**Decision Point: Select the Cell Sintering Temperature**	**Thu 7/20/17**	**Thu 7/20/17**
29	Process Standardization and Optimization	Fri 7/21/17	Wed 6/20/18
30	**2.1.2 TSC III Microstructure Optimization**	**Mon 10/3/16**	**Wed 4/25/18**
31	Develop strengthened anode support and AFL	Mon 10/3/16	Fri 11/25/16
32	AFL Catalyst Grading	Mon 10/31/16	Thu 2/16/17
33	Redox barrier layer development	Fri 1/6/17	Thu 4/27/17
34	Fabrication and Testing of Redox Tolerant TSC III Cells	Fri 4/28/17	Thu 6/22/17
35	Pre-Oxidation processing development	Fri 5/26/17	Thu 7/20/17
36	**Complete Feasibility Evaluation of Redox-Tolerant TSC III Cell Technology**	**Thu 7/20/17**	**Thu 7/20/17**
37	Single Cell Fabrication, Testing, and Optimization	Fri 7/21/17	Wed 4/25/18
38	**Demonstrate Redox Tolerant TSC III Cell Technology over 10 cycles**	**Wed 4/25/18**	**Wed 4/25/18**
39	**2.2 Cell Manufacturing Process Development**	**Mon 12/26/16**	**Fri 8/17/18**
40	Develop cell design geometry	Mon 12/26/16	Thu 9/14/17
41	Develop scalable manufacturing processes for Single Stage Sintered + Redox Tolerant TSC III Cells	Fri 9/15/17	Wed 4/25/18
42	**Go/No-Go Decision Point: Incorporate Redox Tolerant TSC III Cells OR Single Stage Sintered Cell Technology into Deliverable Stack Test**	**Wed 4/25/18**	**Wed 4/25/18**
43	Single Cell Production Trials	Thu 4/26/18	Wed 8/15/18
44	Single Cell Performance Testing	Fri 2/3/17	Fri 8/17/18
45	**Demonstrate feasibility of cell technology for scalable, high-yield manufacturing process**	**Wed 8/15/18**	**Wed 8/15/18**
46	**3.0 Innovative Stack Architecture Design**	Mon 10/3/16	Wed 6/20/18
47	**3.1 Stack Components and Design**	Mon 10/3/16	Wed 4/18/18
48	Thin Interconnect Development	Mon 10/3/16	Thu 2/2/17
49	Fuel Reformer Development	Mon 10/3/16	Thu 9/14/17
50	Catalytic Oxidizer Development	Mon 10/3/16	Thu 9/14/17
51	Integrated Fuel Recycle Development	Mon 11/28/16	Thu 10/12/17
52	**Decision Point: Implement Integrated Fuel Recycle in Deliverable Stack**	**Thu 10/12/17**	**Thu 10/12/17**
53	Manifold Design	Fri 2/17/17	Thu 11/23/17
54	Horizontal Stack Design	Fri 2/17/17	Thu 11/23/17
55	**Decision Point: Horizontal or Vertical Stack Orientation**	**Thu 11/23/17**	**Thu 11/23/17**
56	Stack Enclosure/Containment Development	Fri 9/22/17	Wed 4/18/18
57	**Complete Integrated Stack Design**	**Wed 4/18/18**	**Wed 4/18/18**
58	**3.2 Modeling (CFD & FEA)**	**Fri 2/24/17**	**Wed 4/18/18**
59	CFD Modeling	Fri 2/24/17	Wed 4/18/18
60	Finite Element Analysis	Fri 4/7/17	Wed 4/18/18
61	**3.3 Stack Manufacturing Process Development**	Fri 2/17/17	Wed 6/20/18
62	**4.0 Technology Stacks Validation Tests**	Fri 3/10/17	Fri 9/28/18
63	**4.1 Technology Stacks Fabrication and Testing**	Fri 3/10/17	Wed 2/21/18
64	**4.2 Stack Fabrication and Testing**	Thu 4/19/18	Fri 9/28/18
65	Deliverable Stack Fabrication	Thu 4/19/18	Wed 5/30/18
66	Performance & Endurance Testing of Deliverable Stack	Thu 5/31/18	Fri 9/28/18
67	**Complete >1000 hrs. Tests of the Deliverable Stack with <1% per 1000 hrs. Degradation**	**Fri 9/28/18**	**Fri 9/28/18**
68	**5.0 Advanced Stack Factory Cost Estimate**	Thu 3/1/18	Fri 9/28/18
69	**5.1 Cost Analysis**	**Thu 3/1/18**	**Wed 8/22/18**
70	Preliminary Technology Screeening Cost Analysis	Thu 3/1/18	Wed 4/25/18
71	Final Stack Cost Analysis	Thu 6/28/18	Wed 8/22/18
72	**5.2 Factory Cost Report**	Thu 8/9/18	Fri 9/28/18
73	**Complete Validation of SOFC Stack Cost Reduction**	**Fri 9/28/18**	**Fri 9/28/18**



Project Budget

	Project Period 10/01/16-09/30/18		Total
	Government Share	Cost Share	
Total	$3,000,000	$750,000	$3,750,000
Percentage	80.0%	20.0%	

Spending Plan



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Project Risks

Risk Categories:

- Technology
- Resources
- Management

Degree of Risk Calculation Chart

PROBABILITY		IMPACT: LOW	IMPACT: MODERATE	IMPACT: HIGH
	HIGH	Moderate	High	High
	MOD	Moderate	Moderate	High
	LOW	Low	Moderate	Moderate
		LOW	MODERATE	HIGH
		IMPACT		

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Milestone Log

Id.	Task /Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1.1	Updated Data Management Plan (DMP)	10/31/16	10/31/16	DMP File
2	1.2	Updated Project Management Plan (PMP)	10/31/16	10/31/16	PMP File
3	1.2	Project Kickoff Meeting	11/11/16	11/16/16	Presentation File
4	2.1.1	Demonstrate Feasibility of Single Stage Cell Sintering Process	7/20/17		Quarterly Report
5	2.1.2	Complete Feasibility Evaluation of Redox-Tolerant TSC III Cell Technology	7/20/17		Quarterly Report
6	2.1.2	Demonstrate Redox Tolerant TSC III Cell Technology over 10 Testing cycles	4/25/18		Quarterly Report
7	2.2	Demonstrate Feasibility of Cell Technology for Scalable, High-Yield Manufacturing Process	8/14/18		Quarterly Report
8	3.1	Complete Integrated Stack Design	4/18/18		Quarterly Report
9	4.2	Complete >1000 hrs. Tests of the Deliverable Stack with <1% per 1000 hrs. Degradation	9/28/18		Quarterly Report
10	5.2	Complete Validation of SOFC Stack Cost Reduction	9/28/18		Factory Cost Report

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Decision Points

Decision Point	Date	Success Criteria
Select Cell Sintering Temperature	7/20/17	The lowest single stage cell sintering temperature (<1350 ºC) will be selected which provides adequate electrolyte densification and also prevents interdiffusion amongst layers. The decision will be based on the results of cell testing.
Implement Integrated Fuel Recycle in Deliverable Stack	10/12/17	CFD modeling, and/or bench-testing, shows the feasibility of integrated anode recycle concepts to provide sufficient levels of steam to achieve a steam-to-carbon ratio >1.6 at the anode inlet.
Implement Horizontal or Vertical Stack Orientation in Deliverable Stack Test	11/23/17	Based on the results of CFD and FEA modeling, horizontal stack architecture will be selected if it shows promise to enable larger stacks without introducing significantly-greater technical risks.

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Work Scope
Task 2

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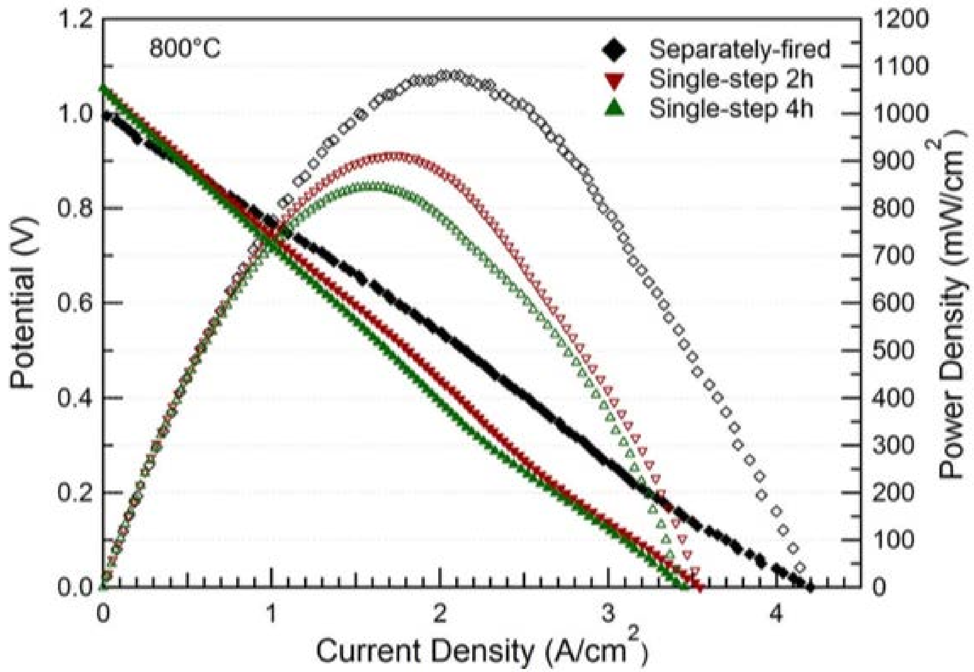
Task 2.1.2 TSCIII Microstructure Optimization

- Objective
  - To develop cell materials that are tolerant to reduction and oxidation cycling (Redox cycling) which can be expected in real-world system operation
- Approach
  - Building on VPS' strong anode-supported cell development experience since 1997
  - Leveraging cell and stack advancements from previous SECA projects
  - Implementing multi-prong approaches in developing innovative redox tolerant anode-supported cell through reducing anode strain upon Ni re-oxidation
- Work Plan
  - Promising results from several approaches will be incorporated in a redox tolerant TSCIII cell technology
  - The final cell design will undergo a testing regime with 10 thermal cycles and 10 Redox cycles in single-cell (10 cm x 10 cm) test platform
  - Single-cell tests will be deemed successful by targeting equivalent or lower performance loss on redox cycling than that is found with thermal cycling.

Single-Step Reduced-Temperature Firing

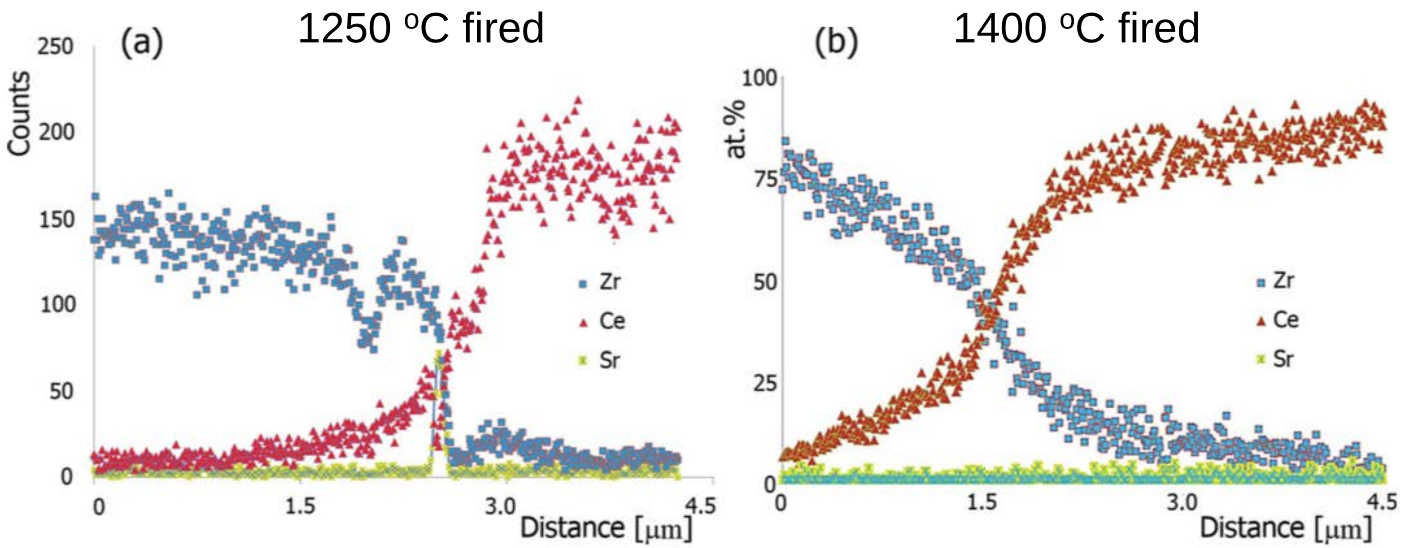
- Single-step firing: process simplification
- Reduced temperature firing
  - Essential to minimize cathode sintering, electrolyte interactions
    - Single-step (1250 ºC) fired cells (Ni-YSZ / YSZ / LSM-YSZ) show similar performance as conventional cells



Wang et al. J Electrochemical Society 163, F196-F201 (2015)

Single-Step Reduced-Temperature Firing

- Single-step firing: process simplification
- Reduced temperature firing
  - Essential to minimize cathode sintering, electrolyte interactions
  - Essential to minimize YSZ/GDC interdiffusion
    - Reduced interdiffusion eliminates large ohmic resistance



Gao et al., J. Mater. Chem. A (2015).

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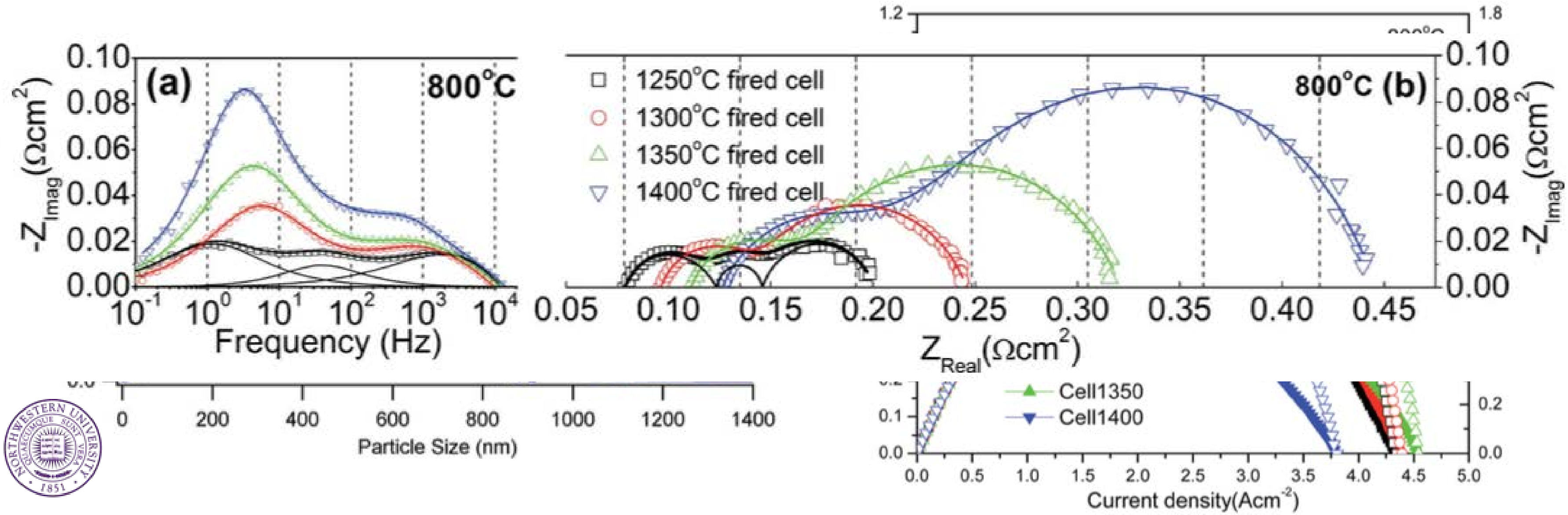
Single-Step Reduced-Temperature Firing

- Single-step firing: process simplification
- Reduced temperature firing
  - Essential to minimize cathode sintering, electrolyte interactions
  - Essential to minimize YSZ/GDC interdiffusion
  - Finer-scale anode microstructure - improved performance
    - Data from Ni-YSZ / YSZ / GDC / LSCF cells



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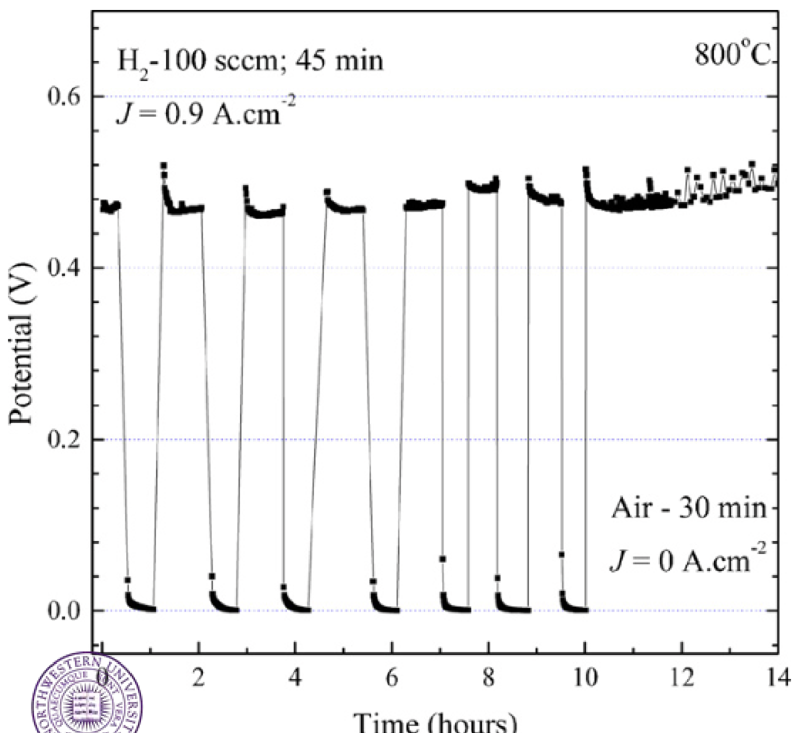
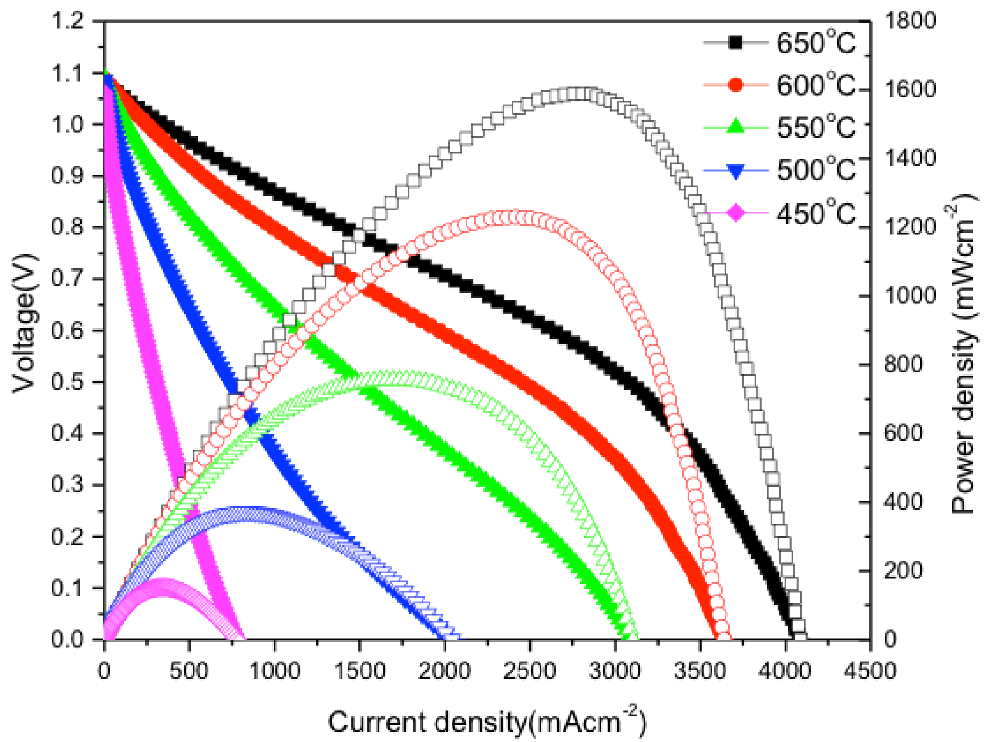
Gao et al., J. Mater. Chem. A (2015)

Advantages of Ceramic Anode Support

- Redox cycle stability: (left) stable operation after several redox cycles of a cell with (Sr,La)TiO_3 support, Ni-YSZ AFL, YSZ electrolyte, and LSM-YSZ cathode
- Good low-temperature performance of cell after infiltration of nano-scale Ni particles into anode



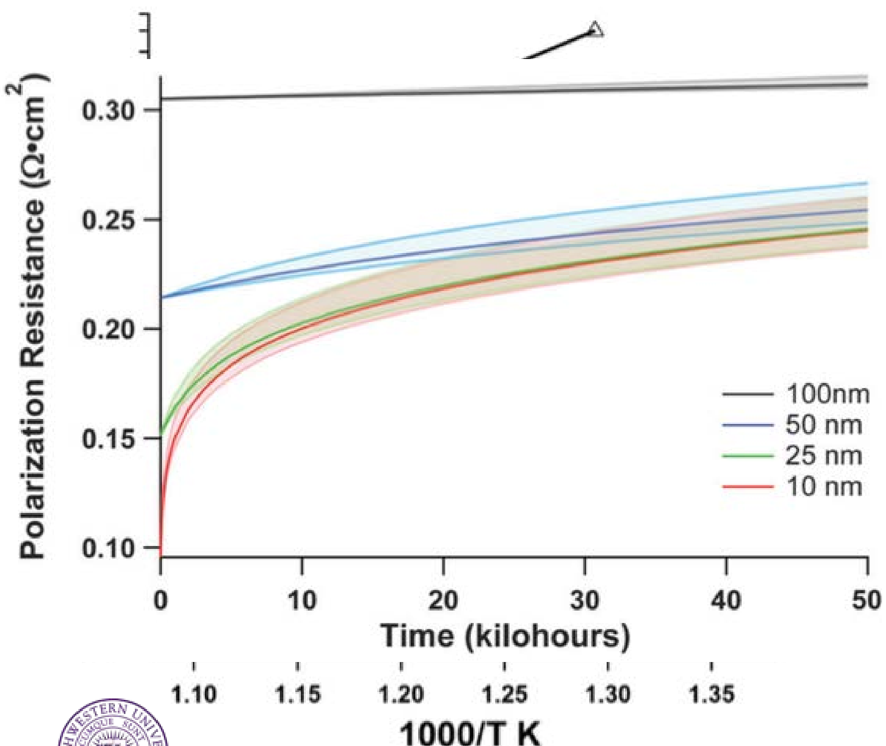


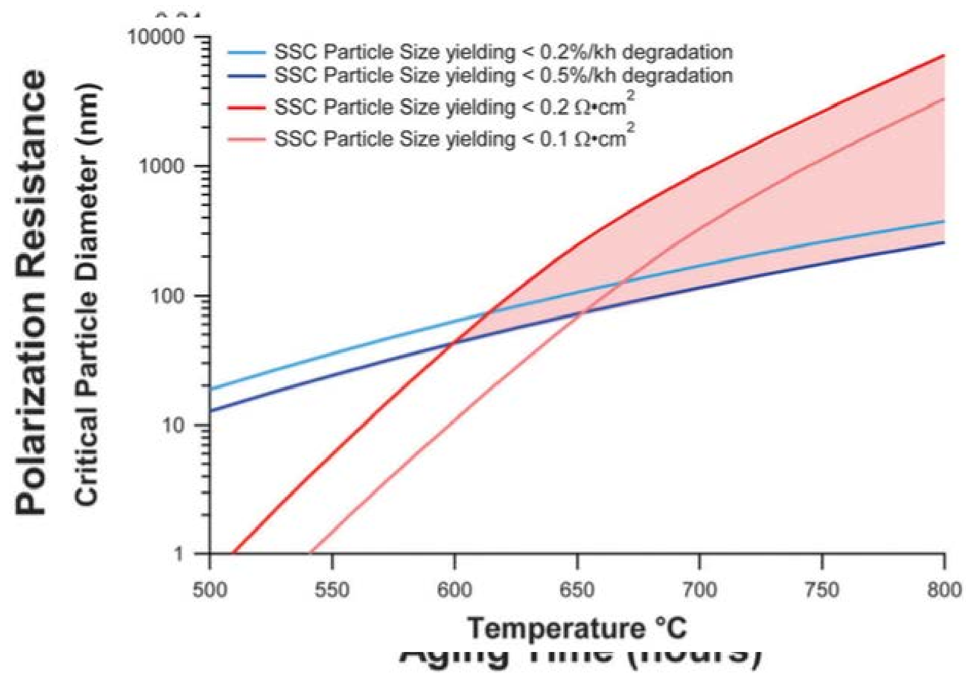
Pillai et al., J Power Sources 185 (2008) 1086-1093

Gao, Barnett, et al., submitted

Infiltrated Cathode Materials

- Selection of best infiltrate/scaffold combinations
- Performance and long-term stability validation
  - Accelerated testing and modeling





Railsback, J. G., Gao, Z. & Barnett, S. A. Solid State Ionics 274 (2015) 134-139
Call et al., PCCP 18, 13216-13222 (2016)

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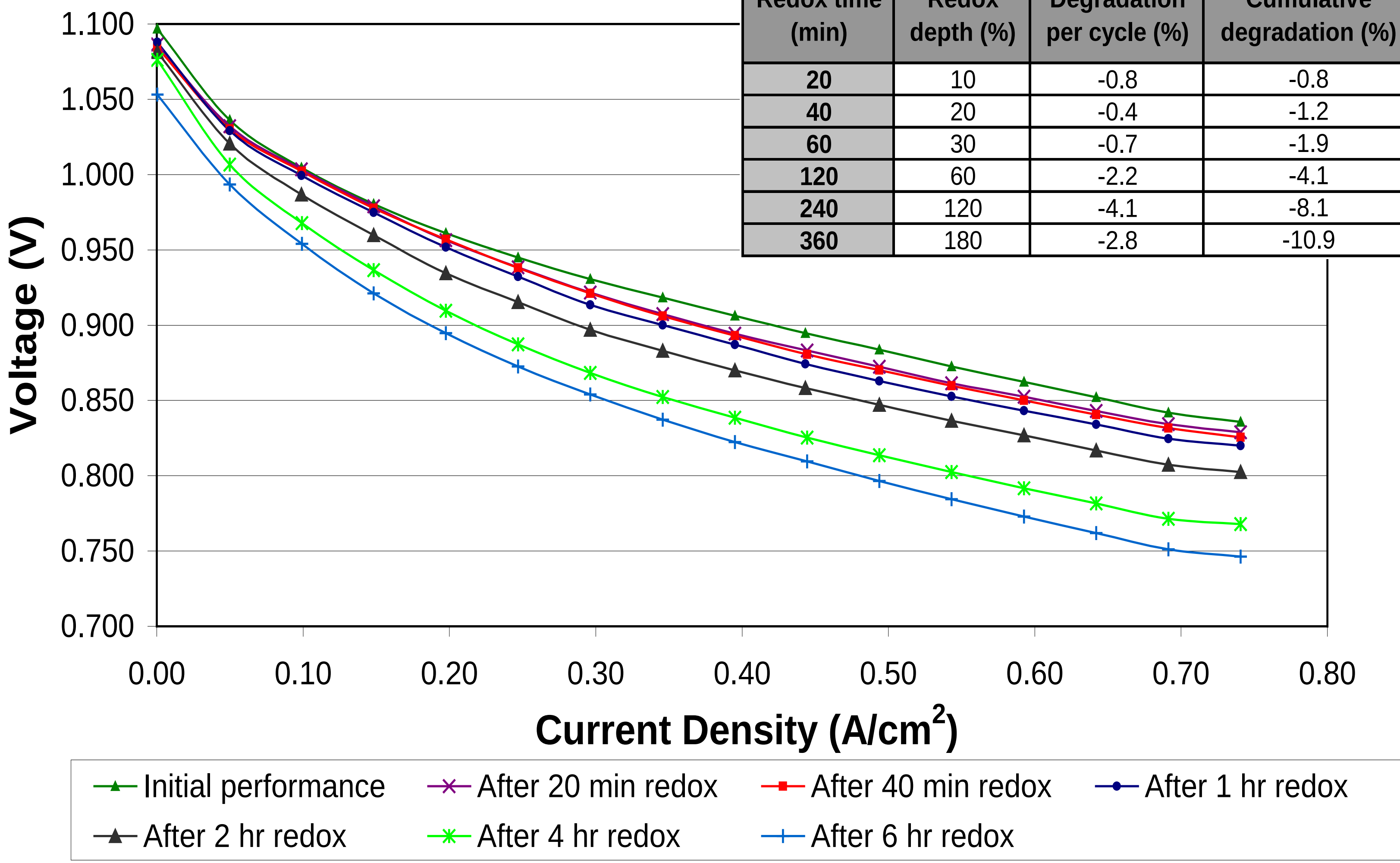
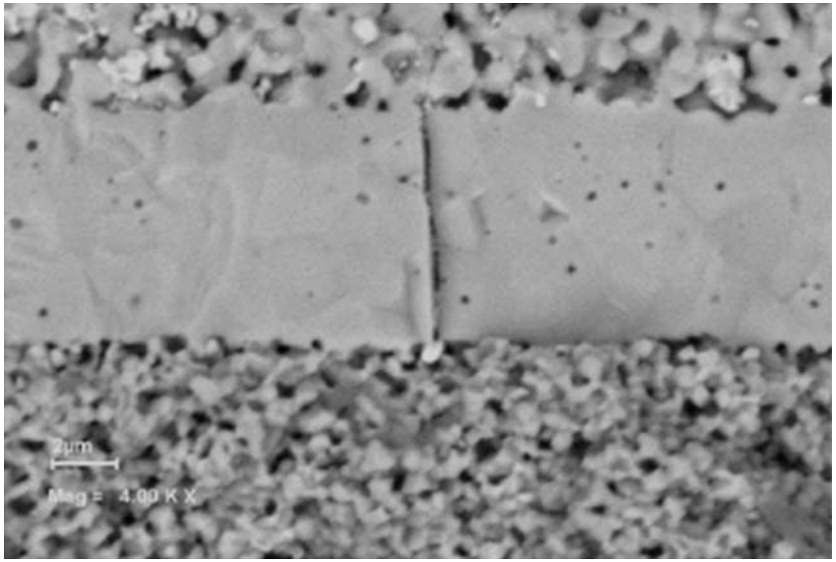
Baseline Cell Redox Tolerance

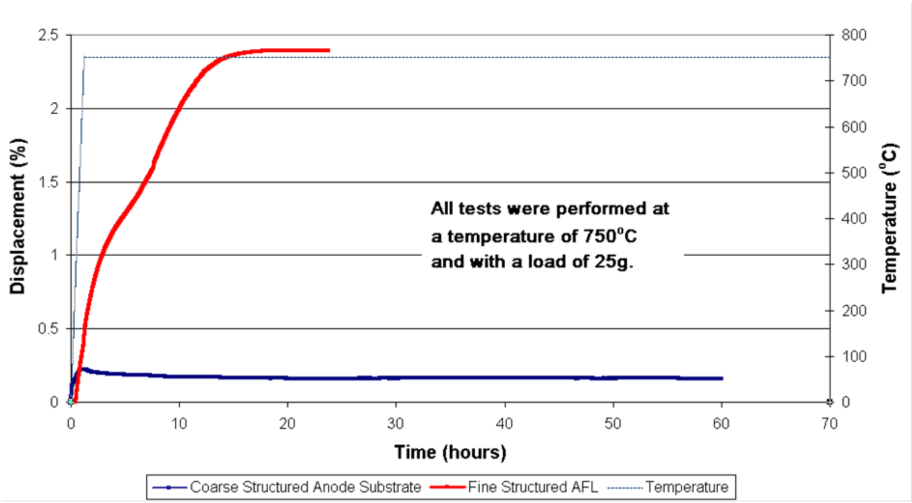
Redox time (min)	Redox depth (%)	Degradation per cycle (%)	Cumulative degradation (%)
20	10	-0.8	-0.8
40	20	-0.4	-1.2
60	30	-0.7	-1.9
120	60	-2.2	-4.1
240	120	-4.1	-8.1
360	180	-2.8	-10.9



The Mechanism of Redox Failure

- Nickel in the anode expands 69% by volume upon oxidation to nickel (II) oxide
- Sarantaridis *et al* showed numerically that mechanical failures occur by different mechanisms and result in different allowable anode expansions before failure for different SOFC cell architectures
- Anode-supported cells fail by tensile cracking of the electrolyte and may tolerate very limited anode expansion using 7-8 um electrolyte
- Redox tests of baseline cells showed electrolyte cracking in SEM posttest analysis





- Ni-YSZ anode support and anode functional layer has porosity of 15-25% as prepared and 35-45% reduced
- Thermomechanical analysis of pressed bars with AFL microstructure showed that upon re-oxidation:
  - Anode substrate does not change measurably in bulk dimensions due to the nickel content, porosity and microstructure
  - Anode functional layer (AFL) expanded by more than 2%

D. Sarantaridis and A. Atkinson; Proceedings of the 7th European SOFC Forum; Bossel, U., Ed.; EFCF:Lucerne, Swizerland, 2006; p. P0728.

Task 2.2 Cell Manufacturing Process Development

- Objective
  - Major cell material improvements, breakthroughs and cost reduction achievements from Task 2.1 will be validated and incorporated into the improved production cells through extensive cell manufacturing process development
- Approach
  - Explore cell fabrication boundary for cell size and thickness for various stack design approaches.
  - Computational thermo-mechanical modeling will be further developed and expanded for the analysis of various cell designs to improve compliance and reliability during manufacturing and normal operating conditions.
  - Cell geometry, including aspect ratio, will be cost-benefit-analyzed and defined.
  - Various cell component design parameters will be evaluated to identify the optimum cell configuration for system operation.
- Work Plan
  - A new baseline cell technology will be established based on inputs from Task 2.1
  - After meeting cell performance and endurance criteria, a sufficient number of cells will be produced for assembly for the technology stacks and the 2-5-kW validation stack

Work Scope
Tasks 3, 4, and 5

Overview
Tasks 3, 4 and 5

- **Goals**
  - Develop a transformational hot-swappable stack that enables low-cost, densely packaged SOFC systems.
  - Demonstrate performance of stack with integrated system elements at 2-to-5 kW power level for ≥1000 hours of operation.
  - Develop factory and integration cost estimates that undercut DOE's cost goals for SOFC plants.

- **General approach**
  - Investigate incorporating system level elements (heat exchangers, oxidizer, anode gas recycle) into the Innovative stack assembly.
  - Focus component designs amenable to high volume, low cost fabrication.
  - Reduce installation and maintenance costs significantly
  - Aim for **reducing $/kWdc, not just increasing W/cm^2**
    - >2x reduction in $/kWdc is a plausible target

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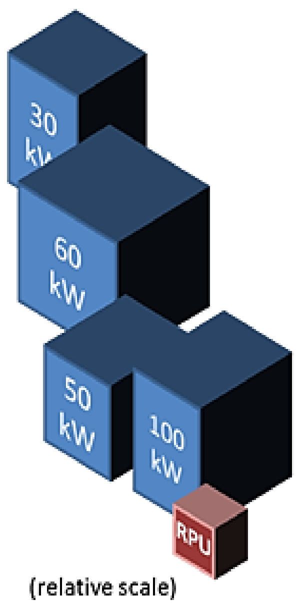
Lessons from Prior DOE Projects

Each integration of BOP into the Modular Power Block (MPB) resulted in a number of benefits

- Improved cell thermal performance
- Reduced chrome poisoning
- Increased power density and decreased parasitic losses
- Reduction in plant footprint, material costs, and capital costs

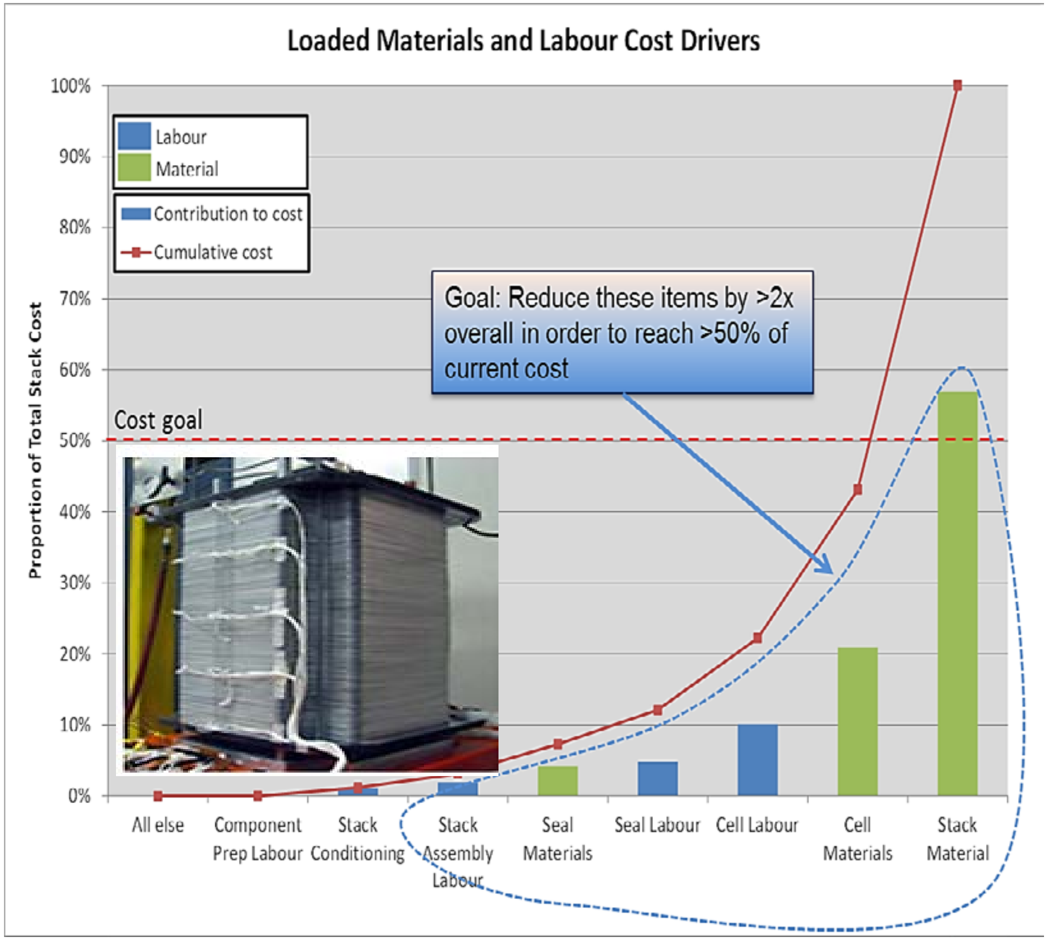


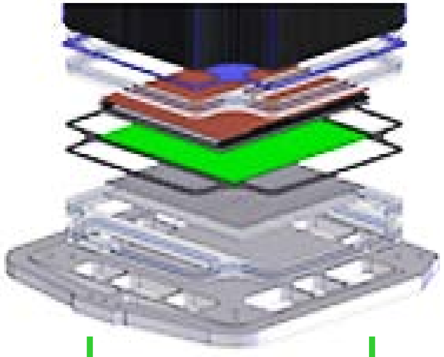
MODULE (kW)	STATUS	Level of Integration	WIDTH (in)	DEPTH (in)	HEIGHT (in)	Volume (ft^3)	Vol % vs. 60kW	Pwr Dens % kW/ft^3
30	Built	No Integration. Single Stack or Tower	64.0	64.0	96.4	228	58%	.132
60	Built	Quad Base, Fuel Radiator HX, Elec. Series Towers	90.5	86.0	87.6	394	100%	.152
50	In Test	60 Plus: Cat. Ox/HX & Reformer	59.5	76.5	69.7	184	47%	.272
100	In Mfg	50 Plus: Anode Recup., Desiccant Regen HX, Ceramic Start-up Heaters	61.5	69.9	91.5	228	58%	.438
100 (RPU)	Proposed	*Stack-Level* Integration of all Hot System Processes	36	25	36	19	<5%	5.25

SOFC system power density, kW/ft^3 > 5

Building Upon DE-FE0026093

- Design activities will build upon cost reduction development activities from DE-FE0026093





stack material reductions

70% reduction of required seal material

external manifold

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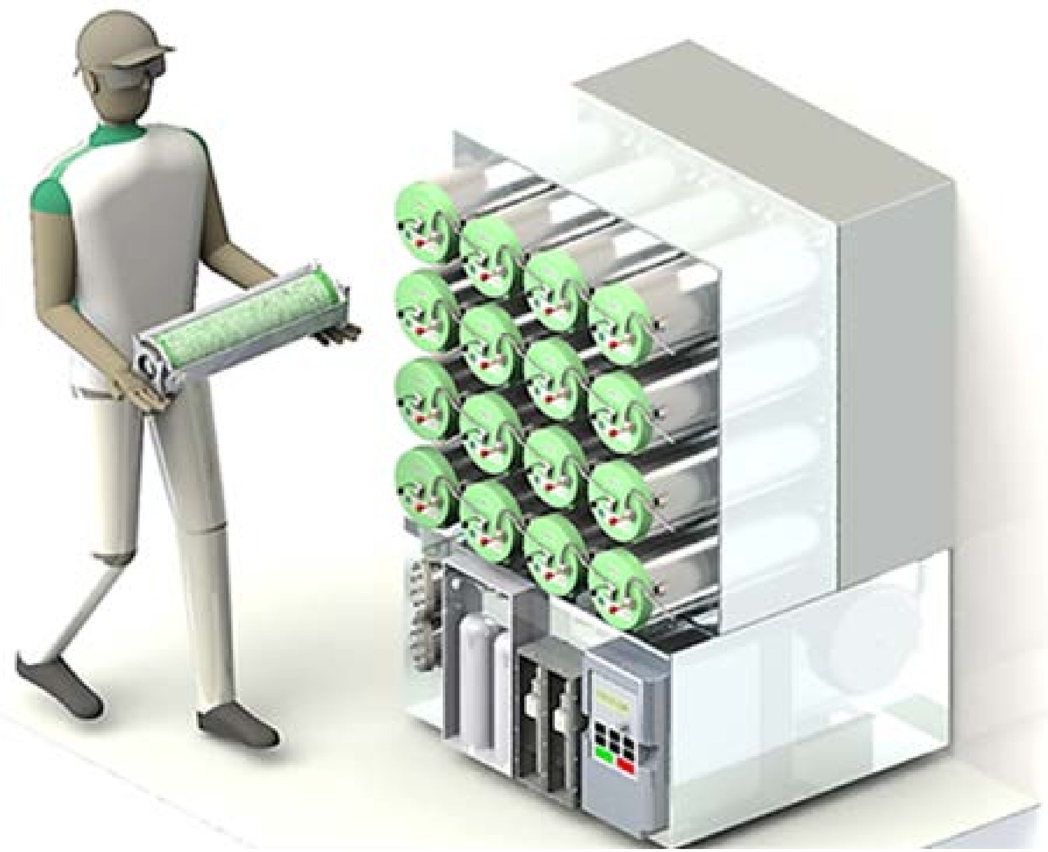
Task 3.0 -Transformational SOFC

- Serviceable by a single technician, minimal tooling
- No heavy equipment required during maintenance
- Hot-swappability minimizes number of shutdowns during plant lifecycle
- Reduction in equivalent forced outage rates (EFOR)
- Lower \$/kW, Higher kW/ft^3



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Task 4.0 - Validation Testing

Objective

- Validate the advanced cell architectures and stack design features developed under Tasks 2.0 and 3.0.

Test Plan

- Fabricate and test (@ NOC) a 2-5 kW stack (RPU)
- Test duration for ≥ 1000 hours to demonstrate the performance and stability improvements of the integrated stack system
- Lead-up activities include testing of reduced cell-count (250 W to 500 W) to prove-out the cell / stack design features and manufacturing processes developed
  - Validate CFD models to iteratively arrive at the optimum stack design
- Test stand modifications will be made, as necessary, to accommodate the new stack architecture interfaces

Task 5.0 – Factory Cost Estimation

- A factory cost model will be developed for RPU
  - Will include capital costs, depreciation and maintenance costs
  - Will include labour estimates and allowance for labour efficiency and yield
  - Will include representative overhead costs
- Quotes will be secured for components at target volumes
  - Start at 250 kW/yr volumes to avoid costs that are only feasible at higher volumes
  - Extend cost exercise up to 250 MW/year to show potential and identify roadblocks to large volumes
- Estimates of installation and maintenance costs will also be developed