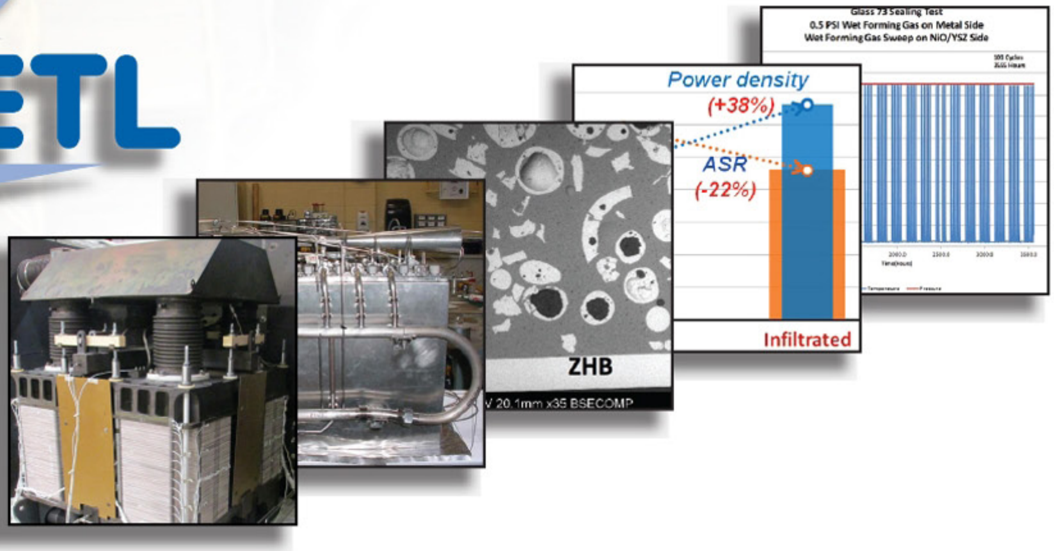
Office of Fossil Energy
Solid Oxide Fuel Cells Program

2013 Project Portfolio

NETL



U.S. DEPARTMENT OF
ENERGY

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DISCLAIMER

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SECTION 1: INTRODUCTION

The U.S. Department of Energy's (DOE) Office of Fossil Energy (FE) and the National Energy Technology Laboratory (NETL) are pleased to present this fiscal year (FY) 2013 *Solid Oxide Fuel Cells Program Portfolio*. This portfolio provides an overview of the Solid Oxide Fuel Cells program, a description of the program structure, and a summary of the research and development (R&D) that is focused on the development of low-cost, high-efficiency solid oxide fuel cell (SOFC) power systems that are capable of simultaneously producing electric power from fossil fuels and facilitating carbon capture.

SOFCs are a Transformational technology whose inherent characteristics make them uniquely suitable to address the environmental, climate change, and water concerns associated with fossil-fuel-based—and in particular coal-based—electric power generation. Broad deployment of SOFC power systems, through a combination of coal gasification-based central power stations and natural-gas-fueled distributed generation applications will contribute to the foundation of a secure energy future for the United States.

WHY SOLID OXIDE FUEL CELLS?

Fuel cells are electrochemical devices similar to batteries that convert chemical energy of a fuel and oxidant directly into electrical energy, rather than indirectly as does a heat engine via combustion. The solid oxide fuel cell has inherent—and unique from other fuel cell types—characteristics and attributes that can be leveraged to meet and exceed the Department's Clean Coal Research Program (CCRP) goals for cost, efficiency, environmental impact, and carbon capture. Specifically:

- **High Efficiency—**SOFCs produce electricity through an electrochemical reaction; consequently, their thermal efficiency is not constrained by Carnot-cycle limitations. They also produce high-quality by-product heat for utilization in a bottoming cycle to further enhance efficiency.
- **Low Emissions—**SOFCs operate at lower temperatures than those of combustion-based processes and therefore do not form NO_x.
- **Ease of CO_2 Capture—**carbon capture is facilitated since the anode (fuel) and cathode (air) streams are separated by the electrolyte. All carbon enters the SOFC with the fuel on the anode side and exits in the anode off-gas as CO_2.
- **Low Water Consumption—**water in the anode effluent is easily and reused in the system. SOFC power systems use approximately one-third the amount of water relative to conventional power systems.
- **Fuel Flexibility—**SOFCs operate on H_2, carbon monoxide, and methane—making them suitable for a broad spectrum of hydrocarbon fuels, including coal-derived syngas and natural gas.
- **Modularity—**SOFC systems may consist of one or more modules that, in turn, are comprised of numerous SOFC stacks. Multiple modules may be connected to provide the desired power rating.

In tandem, fuel flexibility and modularity enable fuel cell technology to be applied in a variety of applications. SOFC technology, due to its relatively high operating temperature compared to that of other fuel cell technologies, is uniquely suitable for direct use with conventional fossil fuels such as coal-derived syngas and natural gas. The primary focus of the Solid Oxide Fuel Cells program is the development of SOFC power systems utilizing coal-derived syngas produced via gasification. However, with the SOFC's ability to internally reform methane, a common module design can be employed for use in either fuel—coal-derived syngas or natural gas. Figure 1 illustrates the use of a common SOFC module in either an integrated gasification fuel cell (IGFC) power system or a natural gas fuel cell (NGFC) power system.

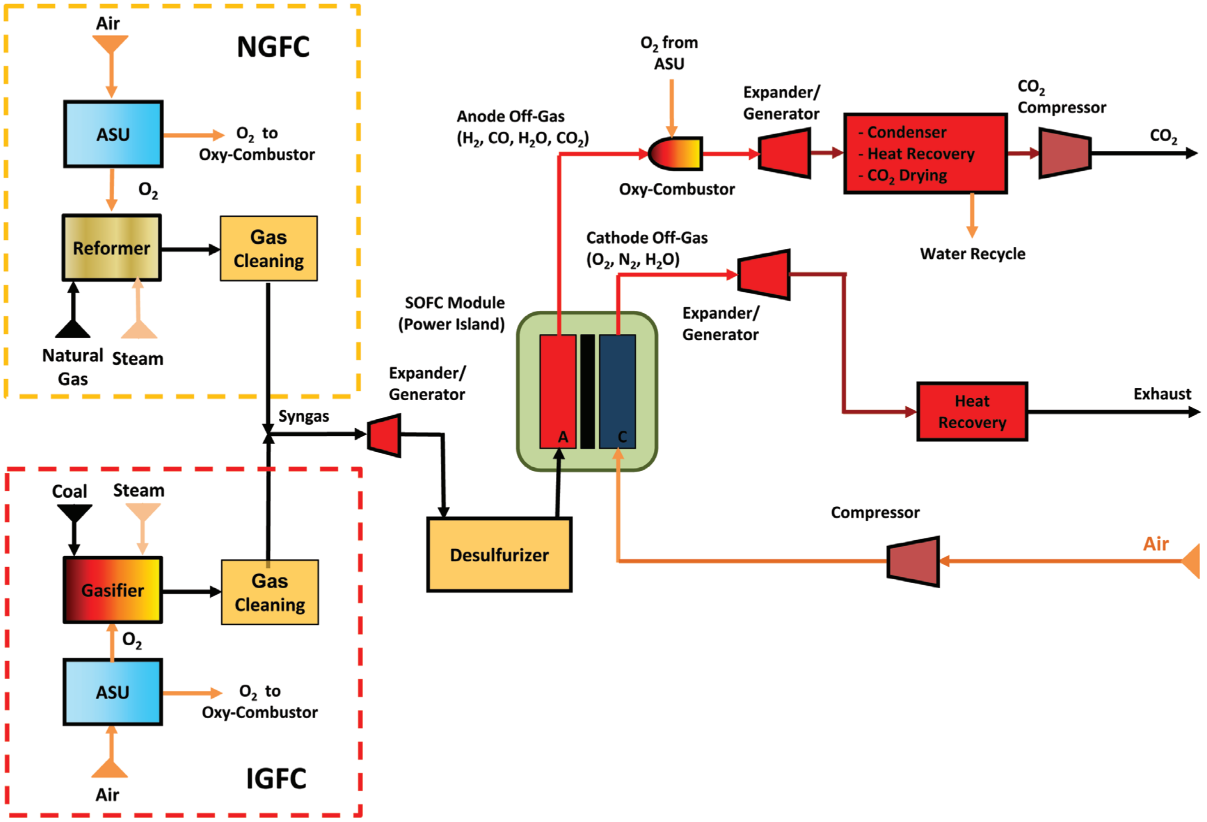

Figure 1. IGFC/NGFC Power System Diagram

THE DEPARTMENT OF ENERGY'S MISSION

The mission of DOE is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions. To achieve this mission, a stated goal of DOE is to catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies, which includes clean coal technology.

THE CLEAN COAL RESEARCH PROGRAM

FE is responsive to the DOE mission through its Office of Clean Coal by ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal. The Office of Clean Coal carries out three primary activities: (1) managing and performing energy-related research that reduces market barriers to the environmentally sound use of fossil fuels; (2) partnering with industry and others to advance fossil energy technologies toward commercialization; and (3) supporting the development of information and policy options that benefit the public.

The Clean Coal Research Program (CCRP), administered by the Office of Clean Coal and implemented by NETL's Strategic Center for Coal (SCC), is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit. The CCRP is designed to remove environmental concerns related to coal use by developing advanced clean and affordable coal-based carbon capture and storage (CCS) technologies to realize 90 percent carbon capture at electricity costs competitive with all other baseload generation technologies. The CCRP is organized into two major program areas: CCS and Power Systems R&D and CCS Demonstrations.

The CCS and Power Systems R&D program area conducts and supports long-term, high-risk R&D to significantly reduce fossil fuel power plant emissions (including CO_2) and substantially improve efficiency, leading to viable, near-zero emissions fossil fuel energy systems. The technology advancements resulting from the CCS and Power

Systems R&D program area are complemented by the CCS Demonstrations program area, which provides a platform to demonstrate advanced coal-based power generation and industrial technologies at commercial scale through cost-shared partnerships between the Government and industry.

The CCRP, through the CCS and Power Systems program, is pursuing three classes of CCS and related technologies.

- **1st-Generation Technologies**—include state-of-the-art technology components and/or technologies that are being demonstrated or that are commercially available.
- **2nd-Generation Technologies**—include technology components and/or technologies currently in R&D that will be ready for demonstration in the 2020–2025 timeframe.
- **Transformational Technologies**—include technology components and/or technologies that are in the early stage of development or are conceptual in nature that offer the potential for improvements in cost and performance beyond those expected from 2nd-Generation technologies. The development and scaleup of these "Transformational" technologies are expected to occur in the 2016–2030 timeframe, and demonstration projects are expected to be initiated in the 2030–2035 time period. SOFCs are considered a Transformational technology.

The success of the research and related program activities will enable CCS technologies to overcome economic, social, and technical challenges including cost-effective CO_2 capture, compression, transport, and storage through successful CCS integration with power-generation systems; effective CO_2 monitoring and verification; permanence of underground CO_2 storage; and public acceptance.

The CCS and Power Systems R&D program consists of four subprograms, each of which maintains a portfolio of projects that span the three classes of CCS technology.

- **Advanced Energy Systems**—developing a new generation of clean fossil-fuel-based power systems capable of producing affordable power while significantly reducing CO_2 emissions.
- **Carbon Capture**—focusing on the development of pre- and post-combustion CO_2 capture technologies for new and existing power plants.
- **Carbon Storage**—advancing safe, cost-effective permanent geologic storage of CO_2.
- **Crosscutting Research**—serving as a bridge between basic and applied research.

The program structure of the CCRP is shown in Figure 2.

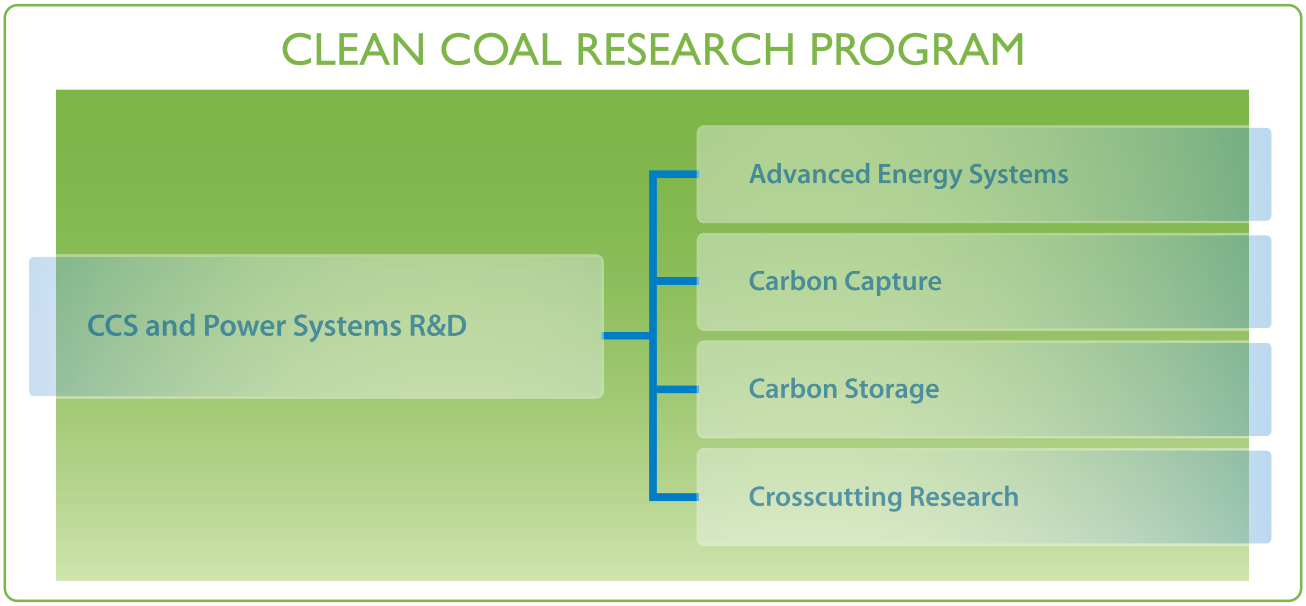

Figure 2. CCRP Program Structure

Each of the four subprograms is further divided into a number of Technology Areas. The four Advanced Energy Systems (AES) Technology Areas sponsor early applied research at laboratory scale, validate promising technologies at pilot scale, and support large-scale field projects at pre-commercial scale to confirm system performance and economics. The Solid Oxide Fuel Cells program[1] is one of the four Technology Areas within the AES subprogram, as shown in Figure 3.

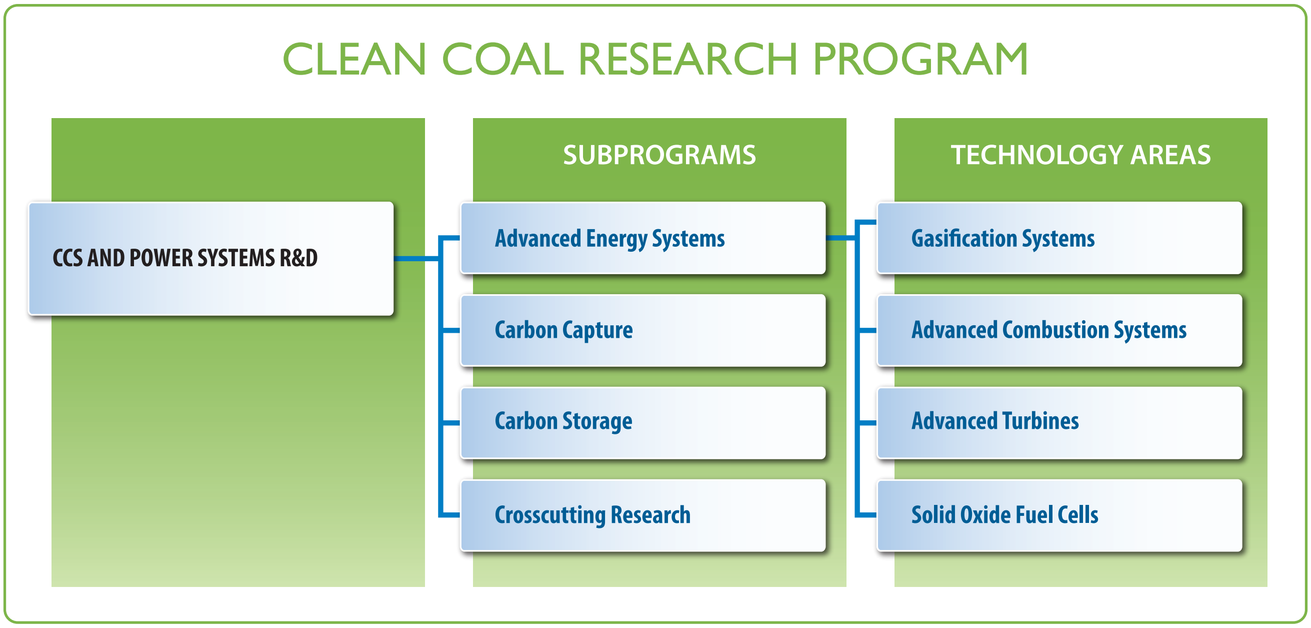

Figure 3. CCRP/AES Program Structure

CCRP GOALS

Currently, the CCRP is pursuing the demonstration of 1st-Generation technologies with existing and new power plants and industrial facilities using a range of capture alternatives and storing CO_2 in a variety of geologic formations. In parallel, to drive down the costs of implementing CCS, the CCRP is pursuing RD&D to decrease the cost of electricity (COE) and capture costs and increase power plant efficiency, thereby reducing the amount of CO_2 that has to be captured and stored per unit of electricity generated.

There are a number of technical and economic challenges that must be overcome before cost-effective CCS technologies can be implemented. The experience gained from the sponsored demonstration projects focused on state-of-the-art (1st Generation) CCS systems will be a critical step toward advancing the technical, economic, and environmental performance of 2nd-Generation and Transformational systems and technologies for future deployment. The following long-term performance goals have been established for the CCRP.

- Develop 2nd-Generation technologies that:
    - Are ready for demonstration in the 2020–2025 timeframe, with commercial deployment beginning in 2025
    - Cost less than \$40/tonne of CO_2 captured
- Develop Transformational technologies that:
    - Are ready for demonstration in the 2030–2035 timeframe, with commercial deployment beginning in 2035
    - Cost less than \$10/tonne of CO_2 captured

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[1] Although Solid Oxide Fuel Cells is a Technology Area within the Advanced Energy Systems subprogram, it represents a program of research designed to help meet DOE goals. Thus throughout this document the term Solid Oxide Fuel Cells program is used interchangeably with Solid Oxide Fuel Cell Technology Area.

The CCRP maintains a portfolio of technologies, through its four subprograms, which are singularly focused on achieving these goals.

The AES subprogram supports achievement of the CCRP goals by developing and demonstrating advanced, efficient technologies that produce ultraclean, low-cost energy with low water use. Shown in Table 1 are the specific cost and performance goals for 2nd-Generation and Transformational Technologies, respectively, that support the CCRP goals.

Table 1. Advanced Energy Systems Program Goals*

Performance Measure	Performance Goal (with 90% CO_2 Capture)	
	2025	*2035*
Capital/Operating and Maintenance (O&M) Cost Reduction (%)†	13–18	0–27
Cost of Electricity Reduction (%)†	≥20	≥40
Efficiency (%)	35–40	43–56
Cost of CO_2 capture (\$/tonne)	≤40	<10

NOTES:
* All costs are in 2011 dollars.
† Relative to the first-year COE of today's state-of-the-art integrated gasification combined cycle (IGCC) plant with 90 percent carbon capture operating on bituminous coal, which is currently estimated at $133 per megawatt hour.

THE ROLE OF THE SOLID OXIDE FUEL CELLS PROGRAM

The Solid Oxide Fuel Cells program supports the AES goals, and implicitly the priorities, mission, goals, and targets of the CCRP, through the development of SOFC power systems and the R&D that addresses the technical hurdles and barriers to deployment of those power systems. The CCRP/AES long-term goal is to develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy production that will be available for deployment in the 2030–2040 timeframe. Specifically, these goals are to reduce the cost of CO_2 capture from the present-day $60/tonne to less than $10/tonne, while reducing the COE by more than 40 percent. The Solid Oxide Fuel Cells program will contribute to the achievement of the CCRP/AES Transformational goals through the deployment of SOFC power systems with efficiencies greater than 56 percent (higher heating value [HHV]) and capture more than 97 percent at a cost that is projected to be approximately 40 percent below presently available IGCC systems with carbon capture. To meet these performance and cost metrics, the Solid Oxide Fuel Cells program has established the following goals:

- 20 percent reduction in cells and stacks (cumulative)
- 50 percent reduction in overpotential
- >85 percent reduction in degradation rate

The individual and cumulative contribution of these goals to the overall CCRP/AES Transformational goals for commercial deployment in the 2030–2040 timeframe is summarized in the following Table 2.

Table 2. Solid Oxide Fuel Cells Program Contribution to the AES Goals

Solid Oxide Fuel Cells Program Goal	Contribution to AES Goal	
	Cost of Electricity	*Cost of CO_2 Captured*
20% Cost Reduction	1% decrease	\$2/tonne decrease
50% Reduction in Overpotential	6% decrease	\$5/tonne decrease
>85% Reduction in Degradation Rate	7% decrease	\$11/tonne decrease
TOTAL	**14% decrease**	**\$18/tonne decrease**

The Solid Oxide Fuel Cells program is structured into four key technologies:

- Atmospheric Pressure Systems
- Pressurized Systems
- Anode Electrolyte Cathode (AEC) Development
- Alternative AEC Development

Two of the key technologies, AEC Development and Alternative AEC Development, are R&D in nature and the efforts therein support the development, demonstration, and deployment of the SOFC power systems developed under the systems-related key technologies. The four key technologies and their respective research focus areas are depicted in Figure 4.

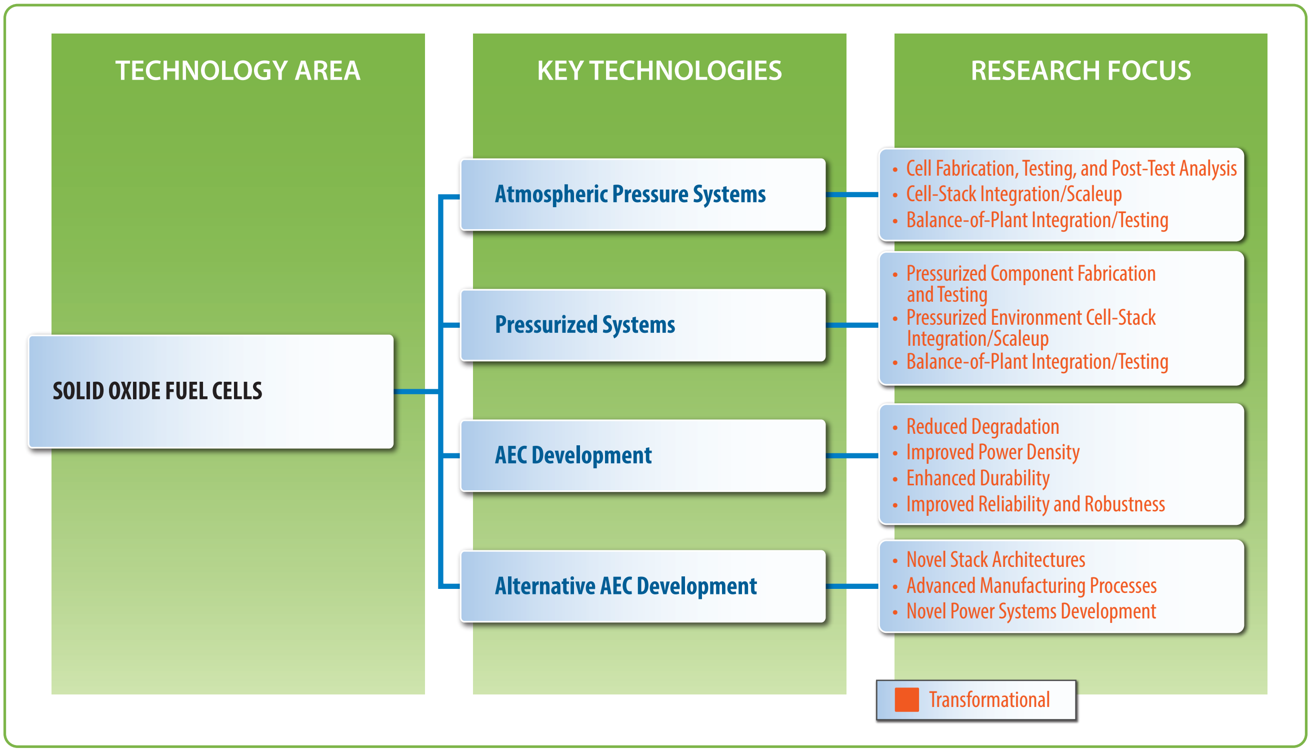

Figure 4. Solid Oxide Fuel Cells Program Structure

- **Atmospheric Pressure Systems**—This key technology focuses on the design, scaleup, and integration of SOFC technology, ultimately resulting in atmospheric-pressure modules suitable to serve as the building blocks for distributed generation, commercial, and utility-scale power systems. Activities include fabrication, testing, post-test analysis of cells, integrating cells into stacks, and the development and validation testing of progressively larger stacks (>10 kWe) to meet performance, reliability, endurance, and cost.
- **Pressurized Systems**—SOFCs demonstrate enhanced performance by increasing the cell pressure. Thus, IGFC systems with pressurized SOFC technology have the potential to achieve efficiencies greater than 60 percent (HHV) with greater than 97 percent carbon capture, near-zero emissions, and low water usage. The Pressurized Systems key technology is developing a deeper understanding on the behavior of the state-of-the-art SOFC material set under pressurized operation; quantifying the effects of pressure on cell performance, reliability, and degradation; and identifying and resolving the operational issues associated with pressurizing the SOFC stack.
- **Anode Electrolyte Cathode (AEC) Development**—The AEC Development key technology—comprising universities, national laboratories, small businesses, and other R&D organizations—consists of projects that will lead to substantially improved power density and more reliable and robust systems. Research is focused on the technologies critical to the commercialization of SOFC technology, such as cathode

performance, gas seals, interconnects, failure analysis, coal contaminants, fuel processing, and balance of plant components. The data and results are available to all Industry Teams ensuring broad technology development and avoiding the duplication of R&D activities.

- **Alternative AEC Development—**The Alternative AEC Development key technology evaluates, develops, and implements advanced technologies to reduce costs and enhance performance, robustness, reliability, and endurance of SOFCs. It supports activities that will contribute critical information to assess the viability and benefits of new novel cell and stack architectures (including alternative anodes, cathodes, electrolytes, materials, and configurations), advanced processing techniques, and novel SOFC power systems.

To successfully complete the maturation of the SOFC technology from its present state to the point of commercial readiness all program efforts are channeled through one of these key technologies.

The Solid Oxide Fuel Cells program efforts are coordinated through the Solid State Energy Conversion Alliance (SECA). SECA—which is dedicated to the development of low-cost, modular, fuel-flexible SOFC technology—consists of three groups: Industry Teams, the Core Technology program, and Federal Government management, as shown in Figure 5. Industry Teams, which fall under the Atmospheric Pressure Systems and Pressurized Systems key technologies, focus on the development and commercialization of SOFC technology. The Core Technology program, the R&D element, is focused on the critical crosscutting technology hurdles and on the development and assessment of the viability of advanced concepts and technologies and are within the AEC Development key technology or Alternative AEC Development key technology. The Federal Government management facilitates interaction between Industry Teams and the Core Technology, as well as establishes technical priorities and approaches.

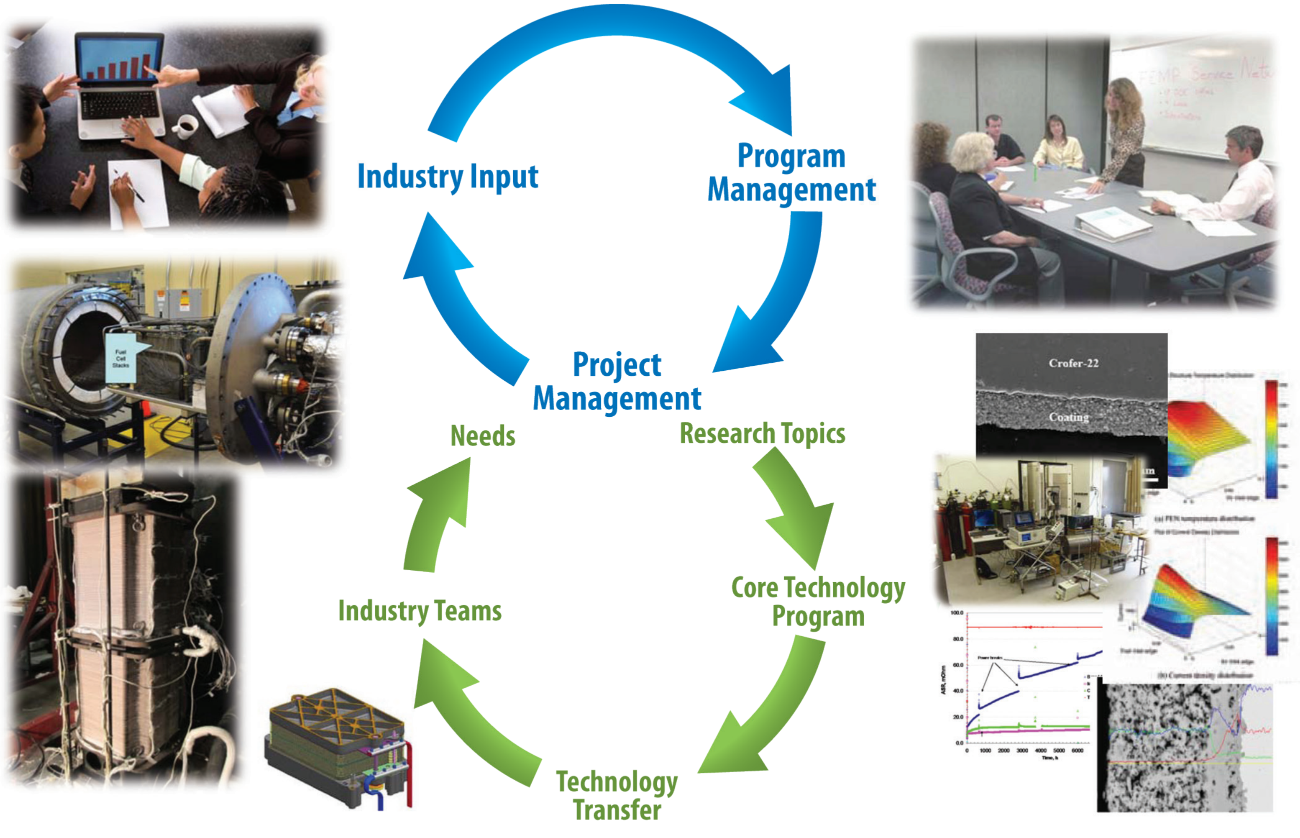

Figure 5. SECA Program Structure

The Industry Teams are independently developing unique and proprietary SOFC technology suitable for either syngas- or natural-gas-fueled applications. They are responsible for the design and manufacture of the fuel cells, hardware development, manufacturing process development, commercialization of the technology, and market penetration. These teams also focus on the scaleup of cells and stacks for aggregation into fuel cell modules and the validation of technology that evolves from the Core Technology program. Stack tests (laboratory scale), proof-of-concept systems, pilot-scale demonstrations, and deployment of commercial power systems are the responsibility of the Industry Teams. The multi-Industry Team approach not only provides technology diversification but also offers insurance against business environment risk, reducing program dependency on a single developer. The Industry Teams have the opportunity to determine relevant R&D topics based on their design-specific experience and needs and are held to a common set of performance and cost metrics.

The Core Technology program—made up of universities, national laboratories, small businesses, and other R&D organizations—addresses applied technological issues common to all Industry Teams, provides vital R&D, and laboratory-scale testing. Multiple paths to solving the technical hurdles are pursued by the R&D teams.

HISTORY OF THE SECA PROGRAM

In 1999, DOE-FE, through the NETL, established the SECA program to develop low-cost, environmentally-friendly SOFC technology. From its inception, and through today, SECA was structured as a unique alliance between Government, industry, and the scientific community, comprising the three aforementioned groups: Industry Teams, Core Technology participants, and Federal Government management. Program funding was established and maintained at approximately 65 percent for the Industry Teams and 35 percent for the Core Technology program.

At the time of its founding, SECA was part of the natural gas program, with an emphasis on distributed generation (DG) applications. The SECA approach was mass customization of a common 3–10 kWe module that could address diverse markets—stationary power generation, military applications, and the transportation sector (e.g., as auxiliary power units). Primary fuels under consideration were diesel and natural gas. Targets were established for stack and system costs to be met in 2010, based upon a production rate of 50,000 5-kWe systems (50 MWe) per year—$100/kWe and $400/kWe, respectively, in year 2000 dollars. These 2010 targets reflected an approximately five-fold reduction in cost compared to the state-of-the-art that existed in 1999. Performance metrics—such as degradation rate, durability, and power density—were also established at that time. The program also included rigorous periodic testing protocols for benchmark performance, with independent audits of the associated cost estimates.

Between 2001 and 2003 the inaugural Industry Teams were selected: General Electric, Siemens Energy, Delphi Corporation, Cummins Power Generation/SOFCo, FuelCell Energy/Versa Power Systems (FCE/VPS) and Accumentrics.

The initial round of Industry Team system tests (3–10 kWe) were conducted between 2005 and 2007. All teams met the interim system cost target ($800/kWe) and steady-state degradation rate (4 percent/1,000 hours) over the required 1,500-hour test duration. The efficiency of these small simple-cycle tests ranged from 35 percent to 41 percent (based on the lower heating value [LHV] of natural gas).

In 2005, SECA transitioned into NETL's Strategic Center for Coal, with an emphasis on coal-fueled central generation with carbon capture. New solicitations in 2005 and 2007 added projects to scaleup the SECA fuel cells for application in large central station generation applications. The new awardees included General Electric, Siemens Energy, FCE/VPS, Rolls-Royce (now LG Fuel Cell Systems[LGFCS]), and United Technologies/Delphi (UTC/Delphi). By the end of 2008 there were four Industry Teams—Siemens, FCE/VPS, UTC/Delphi, and LGFCS—as three Industry Teams (General Electric, Accumentrics, and Cummins) withdrew from the program; one for business reasons, one elected to focus on what it saw as key SOFC technology hurdles (electing to become a Core Technology participant), and one program was transferred to DOE's Office of Energy Efficiency and Renewable Energy. The same year, 2008, saw another round of stack metric testing, with the interim cost ($600/kWe) and degradation targets met by two Industry Teams, Siemens and FCE/VPS, in 5,000-hour tests.

In 2010, FuelCell Energy met the ultimate $400/kW target in testing of 120-cell, 25-kWe stacks comprising scaled (550 cm^2) cells. By way of comparison, the typical planar SOFC stack at SECA's inception consisted of maximum 40 cells, each with an active area of ≈100 cm^2, capable of perhaps 2 kWe. At the end of 2010, Siemens made a corporate decision to end its SOFC R&D program and withdrew from SECA, leaving three Industry Teams.

The previously discussed technical advantages of SOFCs have attracted interest in the technology for spinoff applications. SECA has supported these spinoff applications to establish a manufacturing base and increase the operational experience base. For example, the U.S. Navy's Office of Naval Research (ONR) is interested in SOFCs for use in advanced unmanned undersea vehicles (UUVs). Similar to the way that unmanned aerial vehicles (UAVs or drones) have transformed the capabilities of the U.S. military, the U.S. Navy is developing UUVs to address ever-broadening mission profiles and maintain maritime superiority into the future. A significant challenge in UUV development is the source of propulsion power, which must conform to strict size limits and be able to meet projected endurance requirements, ranging from days to weeks. Additional considerations include reliability; air-independent operation; refuelability; rapid startup, shutdown, and load following; and the ability to operate with little to no "observables," such as noise or hull discharges. To address these challenges, ONR selected several SOFC projects with roots in the Solid Oxide Fuel Cells program that have the potential to exceed the limits of current and future high-energy-density batteries.

In 2012, NexTech Materials in partnership with Northrop Grumman, Precision Combustion, and Alliant Techsystems, received a contract from ONR to develop an SOFC-based system under the Long Endurance Undersea Vehicle Propulsion program. FE has supported NexTech's development of SOFC technology for large-system applications through projects on seals, interconnect coating applications, novel cell design, and manufacturing analysis. In addition, Precision Combustion was previously supported by the Solid Oxide Fuel Cells program in the development of logistics fuel processors for SOFC power-generation systems.

Also in 2012, FuelCell Energy received an ONR contract under the Large Displacement Unmanned Underwater Vehicle Innovative Naval Prototype program. In the U.S. Navy project, FuelCell Energy is partnered with NASA, Yardney Technical Products, the Naval Undersea Warfare Center (NUWC), and Pacific Northwest National Laboratory (PNNL). SECA previously funded SOFC research by both PNNL and NUWC; PNNL is the lead national laboratory developing core SOFC technologies under the SECA program and NUWC has received funding to evaluate SOFCs, including those manufactured by FuelCell Energy and Delphi, under extreme conditions.

Lastly, Delphi, PNNL and Boeing are working on a DARPA/Department of the Navy UUV project. Little information is currently available on this effort due to security regulations.

In 2011 and 2012, NETL conducted studies on the performance of natural-gas-fueled SOFC (NGFC) systems for central generation, as a natural extension of earlier IGFC work. Efficiencies of 61 percent to 66 percent (HHV) are possible, with >97 percent CO_2 capture, zero NO_x, and low water consumption, with COEs approaching that of current natural gas combined cycle power systems without capture.

PRESENT STATUS OF THE SOLID OXIDE FUEL CELLS PROGRAM

Current status of the technology is characterized by high performance and low capital cost at full production volume (>250 MW per year); however, reliability and endurance are inadequate. Although single-cell modules have achieved approximately 4 years of operating time, experience with full-size cells and stacks has shown limits at approximately 1 year. Furthermore, performance degradation over time, although greatly improved over the past decade, remains too high. Large stacks under real-world operating conditions degrade at approximately 1.5–2 percent per 1,000 hours. The lack of reliability and endurance, resulting in frequent stack replacements, has a significant deleterious impact on the capital and O&M costs of the system. Multiple studies (by NETL and others) have shown that stack life must be at least 4 years, and degradation reduced to approximately 0.2 percent per 1,000 hours, to ensure competitiveness with other technologies.

The three organizations that comprise the SECA Industry Teams are currently at parity in regards to these important metrics; however, the designs and materials used vary, affording a greater opportunity for one or more concepts to succeed and achieve the DOE goals. This path is consistent with the strategy employed since SECA's inception: multiple teams—each pursuing unique proprietary SOFC technologies—provide programmatic risk mitigation for the development of these nascent Transformational technologies and contribute to a competitive marketplace upon commercialization.

In 2013, the Industrial Teams are scheduled to complete testing of 25–60 kWe stacks. These tests will demonstrate reliability of operating fuel cell systems under realistic conditions.

SOLID OXIDE FUEL CELLS PROGRAM BUDGET

Since its inception more than a decade ago, the average appropriation to the Solid Oxide Fuel Cells program budget was ≈$50 million per year. In FY 2013, the budget is ≈$23.8 million. The annual appropriation for the Solid Oxide Fuel Cells program is shown in Figure 6. Through 2012, the cumulative appropriations are ≈$564 million.

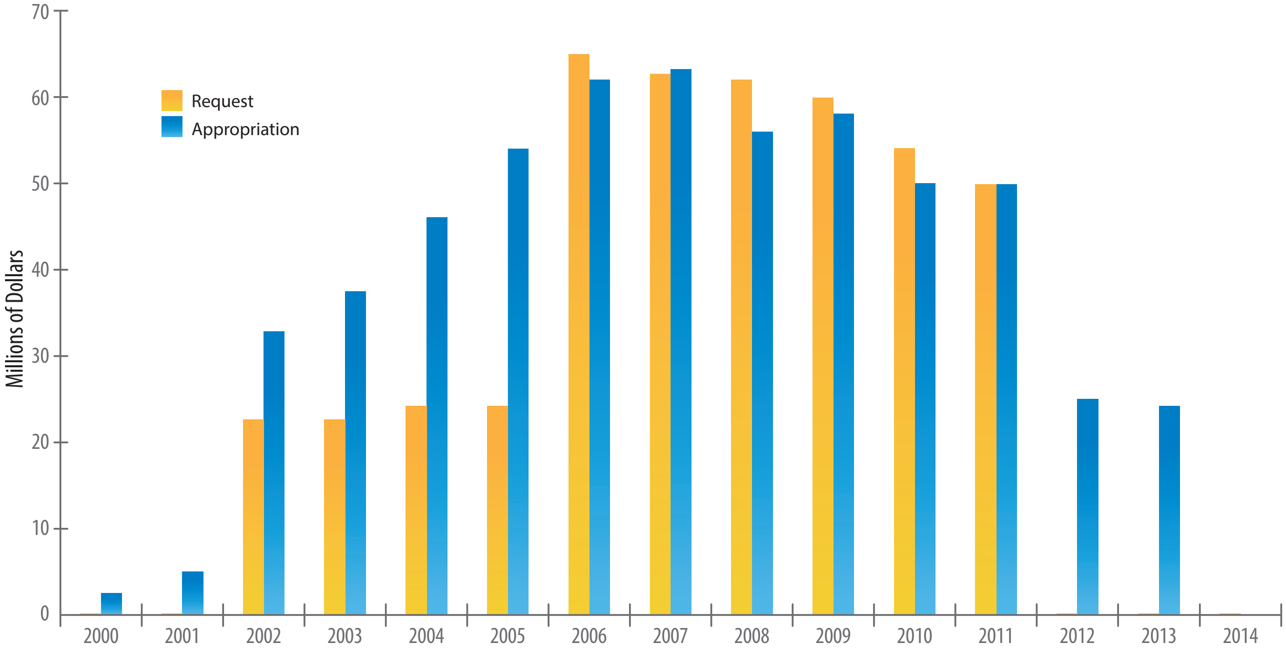

Figure 6. Solid Oxide Fuel Cells Program Budget

SOLID OXIDE FUEL CELLS PROGRAM PLAN

The focus of SECA and the remaining three Industry Teams has turned to developing the reliability, robustness, and endurance required for commercial central generation. Systems studies have consistently shown that long stack life and low performance degradation are critical to the economic viability of SOFC technology in commercial power-generation applications. This is true regardless of the system scale to be deployed—distributed generation (250 kWe–1 MWe) and central generation. To date, each of the SOFC technology developers have made significant strides in all aspects of the technology, including manufacturability, cell and stack scale, performance (e.g., power density, fuel utilization) and capital cost. Stack life (target ≥4 years) and performance stability (target ≤0.2 percent per 1,000 hours power degradation) are the remaining significant technical hurdles to commercial viability.

Future work will encompass materials R&D, design, failure analysis, and manufacturing development. It will also consist of considerable stack testing, including larger stacks, to validate performance and gather the required data to make further enhancements to the stack technology. The program will conduct R&D to achieve the requisite four-fold increase in stack life and order-of-magnitude reduction in degradation rates. Recent SECA Core Technology support projects have improved the understanding of the cathode mechanisms for oxygen reduction, adsorption and transport, and cathode-related degradation. These efforts have identified potential paths to further improve performance and stability over a range of operating conditions. The Industry Teams, based upon these recent learnings, will work to further develop and incorporate advances into their existing baseline designs. Progress will be assessed by frequent cell and stack validation testing.

By 2015, testing of ≈125-kWe SOFC proof-of-concept modules will be initiated, followed in 2017 by testing of progressively larger sized modules (up to 250 KWe), depending upon the design adopted by individual Industry Team. These modules would be sized as building blocks of future multi-megawatt coal-based power plants with carbon capture. By 2020, these modules would have operated for 5,000–10,000 hours providing valuable operating experience from multiple 25–250 kWe fuel cell systems. It is anticipated that some of these early systems will be operated on natural gas. However, the fuel cell stack technology is independent of fuel. These systems could be installed as demonstration units in various distributed generation applications. Cell development—power density improvement, reliability enhancement, and cost reduction activities—will continue in parallel throughout this period to increase the commercialization potential. Fuel cell modules will be scaled up to 1–5 MWe by aggregating the building blocks mentioned previously and by 2025, multiple kilowatt- to megawatt-scale fuel cell systems could be installed, further increasing the operating experience base. This will allow, by 2025, for initial manufacturing of highly efficient multi-megawatt coal- and natural-gas-fueled SOFC power-generation systems with >99 percent CO_2 capture.

NATURAL GAS DISTRIBUTED GENERATION—EARLY ENTRY TO MARKET

SOFCs are uniquely suitable for direct use with conventional fossil fuels such as coal-derived syngas and natural gas. In support of the CCRP's mission to develop a new generation of clean fossil-fuel-based power systems capable of producing affordable electric power while significantly reducing CO_2 emissions and minimizing water consumption, the primary focus of the Solid Oxide Fuel Cells program is central generation power using coal-derived syngas. However, with the SOFC's ability to internally reform methane (the primary constituent of natural gas), a common module design can be employed for use with either fuel (syngas or natural gas). Thus, the Solid Oxide Fuel Cells program supports natural-gas-fueled distributed generation applications as an intermediate goal. SOFCs are an emerging technology; initial market penetration and success in natural gas distributed generation applications will accelerate development progress and reduce cost.

Global capacity of distributed fuel cell power generation has reached an estimated 100–150 MWe including an estimated 35–50 MWe in the United States. Fuel cells are an attractive option for applications such as natural gas compressor stations, data centers, and grid strengthening (see Table 3). The costs of fuel cells for distributed generation have come down significantly. For example, FuelCell Energy has reported cost reductions of a factor of five for its molten carbonate fuel cells (MCFC) systems over the period from 1996 to 2008. Fuel cell systems (SOFC/MCFC) for distributed generation produced in low volumes, with minimal automation, cost \$5,000–\$10,000/kWe today. The Federal investment tax credit of up to 30 percent of capital costs and State incentives such as California's Self-Generation Incentive Program are currently necessary for fuel cells to be competitive with available distributed generation technologies. Numerous studies have shown there is a potential of developing a commercial 1-MWe-class SOFC distributed generation product by 2025 that has a capital cost of <\$2,000/kWe in low-volume production.

Table 3. Distributed Generation Market Potential

Market Segment	2011–2018 Market Growth	DG Unit Size (80% of market)
Natural Gas Compressor Stations' Power	1.4 GW	5 kW–1 MW
Electrical Substations: Grid Strengthening	500 MW	1–2 MW
Data Centers (central): Prime Power	6 MW	5 kW–1 MW

PROGRAM PARTICIPANTS

Throughout its history, the Solid Oxide Fuel Cells program has maintained a diversified portfolio of R&D projects to address the technical challenges and ensure a high-probability of achieving the desired cost and performance targets. The strategy includes a mix of near-, mid-, and long-term R&D projects as well as laboratory, proof-of-concept, and pilot-scale projects to foster the advancement of SOFC technologies for deployment in diverse applications, including those fueled by coal-derived syngas or natural gas, which meet or exceed the targets for efficiency, cost, and carbon capture.

In FY 2013 the Solid Oxide Fuel Cells program portfolio contains 33 projects that range from understanding the fundamental reaction kinetics of the cathode reduction mechanism to the development of a proof-of-concept module rated at near-commercial scale. Figure 7 presents the project portfolio for FY 2013; Figure 8 shows the geographical distribution of the respective projects.

SOLID OXIDE FUEL CELLS PROGRAM

(excluding NETL Site Support)

Atmospheric Pressure Systems

FuelCell Energy & Versa
UTC Power & Delphi

Pressurized Systems

LG Fuel Cell Systems

Anode Electrolyte Cathode (AEC) Development

ANL
Boston U.
Boston U.
CMU
Faraday
Georgia Tech
MIT
Montana State
NETL/RUA*
NUWC
ORNL
PNNL*
Stanford U.
U. Connecticut
U. Maryland
U. Wisconsin
WVU
WVU – EPSCoR

Small Business Innovative Research

Mo-Sci
MSRI
NexTech
nGimat
QuesTek
SEM-COM

Congressionally Directed Projects

LG Fuel Cell Systems
Penn State U.

Alternative AEC Development

GE Global

Congressionally Directed Projects

NuVant
U. Akron

* single project with multiple activities
EPSCoR = Experimental Program to Stimulate Competitive Research

Figure 7. FY 2013 Solid Oxide Fuel Cells Program Project Portfolio

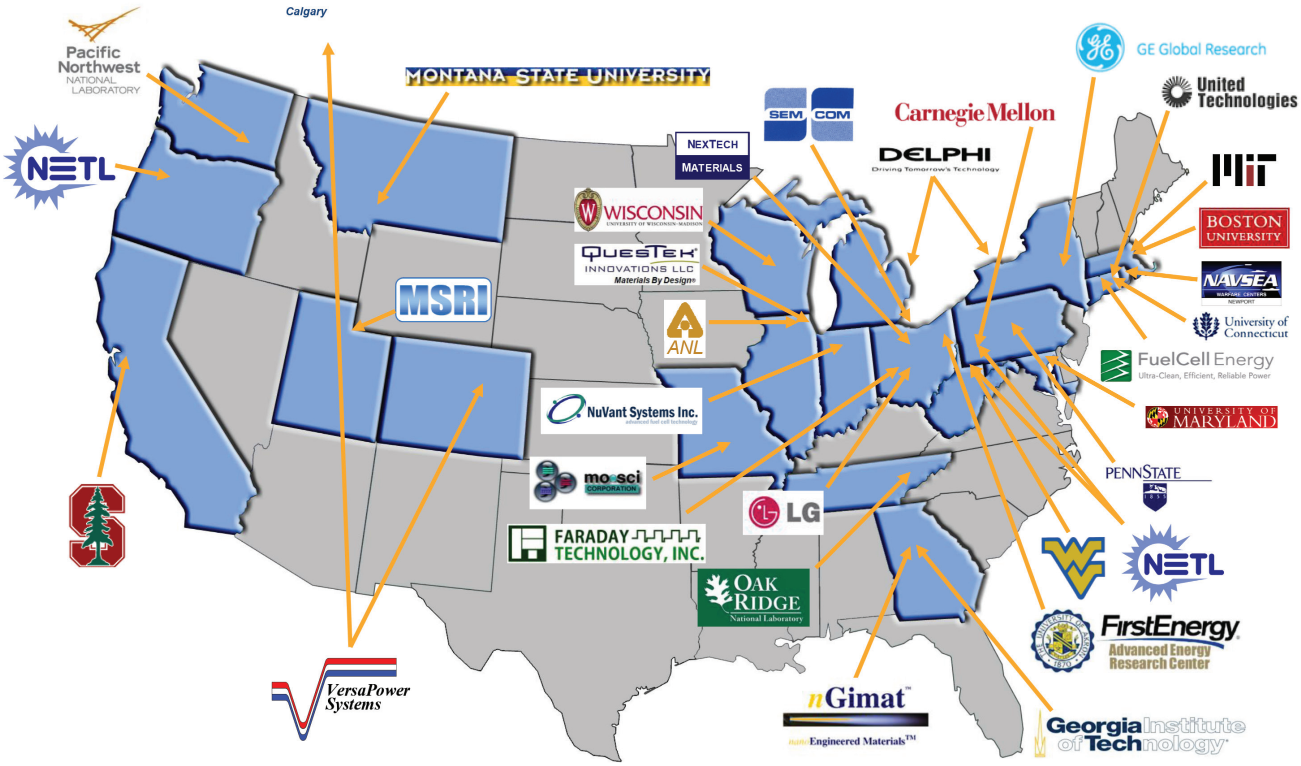

Figure 8. Geographical Distribution of the FY 2013 Solid Oxide Fuel Cells Program Project Portfolio

A list of all active projects, by State and congressional district, is provided in Table 4.

Table 4. 2013 Solid Oxide Fuel Cells Portfolio Projects by State and District

State	Project Title	Performer Name	Congressional District
California	Surface-Modified Electrodes: Enhancing Performance Guided by In-Situ Spectroscopy and Microscopy	Stanford University	CA14
Connecticut	SECA Coal-Based Systems—FuelCell Energy	FuelCell Energy	CT05
	SECA Coal-Based Systems—UTC Power	UTC Power	CT01
	Study of the Durability of Doped Lanthanum Manganite Cathode Materials "Real World" Air Exposures Atmospheres	University of Connecticut	CT02
Georgia	Fundamental Investigations and Rational Design of Durable, High-Performance SOFC Cathodes	Georgia Institute of Technology	GA05
	Low-Cost Spray-On Coatings for Protection of SOFC Interconnects and BOP Components	nGimat Company	GA04
Illinois	Synchrotron X-Ray Studies of SOFC Cathodes	Argonne National Laboratory	IL13
	Low-Cost Alloys for High-Temperature SOFC System Components	QuesTek Innovations	IL09
Indiana	Improved Flow-Field Structures for Direct Methanol Fuel Cells	NuVant Systems, Inc.	IN01
Maryland	Mechanistic Enhancement of SOFC Cathode Durability	University of Maryland	MD05
Massachusetts	Chemistry of SOFC Cathode Surfaces: Fundamental Investigation and Tailoring of Electronic Behavior	Massachusetts Institute of Technology	MA08
	Solid Oxide Fuel Cell Cathodes: Unraveling the Relationship Among Structure, Surface Chemistry, and Oxygen Reduction	Boston University	MA08
	Unraveling the Role of Transport, Electrocatalysts, and Surface Science in the SOFC Cathode Oxygen Reduction Reaction	Boston University	MA08
Missouri	High-Temperature Viscous Sealing Glasses for Solid Oxide Fuel Cells	Mo-Sci Corporation	MO08
Montana	Synchrotron Studies of SOFC Cathode Degradation	Montana State University	MT01
Multiple	NETL-RUA Fuel Cells Initiative	National Energy Technology Laboratory	Multiple
New York	Performance Degradation of LSCF Cathodes	GE Global Research	NY21
Ohio	SOFC Protection Coatings Based on a Cost-Effective Aluminization Process	NexTech Materials	OH12
	Phase III Xlerator Program: Electro-Deposited Mn-Co Alloy for Solid Oxide Fuel Cell Interconnects	Faraday Technology	OH03
	SOFC Model Development	LG Fuel Cell Systems Inc.	OH16
	SECA Coal-Based Systems—LG Fuel Cell Systems	LG Fuel Cell Systems Inc.	OH16
	Stable Glass-Ceramic Nanocomposites as Compliant Seals for SOFCs	SEM-COM Company	OH09
	Techno-Economic Analysis of Scalable Coal-Based Fuel Cells	University of Akron	OH13
Pennsylvania	SOFC Cathode Surface Chemistry and Optimization Studies	Carnegie Mellon University	PA14
	Solid Oxide Fuel Cells Operating on Alternative and Renewable Fuels	Pennsylvania State University	PA05
Rhode Island	Understanding of Solid Oxide Fuel Cell Stack in Pressurized Conditions	Naval Underwater Warfare Center	RI01
Tennessee	Reliability and Durability of Materials and Components for Solid Oxide Fuel Cells	Oak Ridge National Laboratory	TN03
Utah	Solid Oxide Fuel Cell Cathode Enhancement Through a Vacuum-Assisted Infiltration	Materials and Systems Research, Inc.	UT01
Washington	Low-Cost, Modular SOFC Development	Pacific Northwest National Laboratory	WA04
West Virginia	Direct Utilization of Coal Syngas in High-Temperature Fuel Cells	West Virginia University	WV01
	Fundamental Understanding of Oxygen Reduction and Reaction Behavior and Developing High-Performance and Stable Cathodes	West Virginia University	WV01
Wisconsin	Enhancement of SOFC Cathode Electrochemical Performance Using Multi-Phase Interfaces	University of Wisconsin	WI02

IN SUMMARY

The Solid Oxide Fuel Cells program achieved its power block cost target of $400/kWe (year 2000 dollars) in 2010. Driven by Industry Team feedback and extensive systems analysis, the program is aggressively pursuing R&D to address the remaining technical hurdles, with particular emphasis on stack reliability, endurance, and robustness. The near- to mid-term goal is the validation of scaled, low-cost stacks in a system configuration, up to and including modules suitable for use as the building blocks of systems for use in natural-gas-fueled DG applications (hundreds of kilwatt through megawatt-class) and in central station IGFCs.

The Solid Oxide Fuel Cells program will ultimately enable construction and utilization of SOFC-based, near-zero-emission coal and natural gas power systems with greatly reduced water consumption capable of capturing >97 percent of the incoming carbon at costs not exceeding the typical COE available today. Achievement of this goal will have significant impact for the nation—given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. This is particularly important to the nation's energy security, given the abundant domestic fossil energy reserves. Federal funding support of this program is appropriate given the game-changing Transformational nature of the SOFC technology, accompanied by the risks that are higher than the private sector initially accept. In parallel, Industry Teams will take advantage of the inherent scalability and fuel flexibility of SOFCs in seeking nearer term, smaller scale commercial applications for this efficient, environmentally friendly technology, which will have less risk than first-of-a-kind full-scale IGFC or NGFC systems. Success in spinoff applications (e.g., distributed generation, military) will further SOFC technology advancement and widespread deployment through the resultant manufacturing and operational experience.

As such, the DOE Office of Fossil Energy and NETL are pleased to present this *FY 2013 Solid Oxide Fuel Cells Program Portfolio*.

SECTION 2: ACCOMPLISHMENTS

Key program accomplishments for the Solid Oxide Fuel Cells program are presented in the following.

ATMOSPHERIC PRESSURE SYSTEMS

PROJECT TITLE: SECA Coal-Based Systems—FuelCell Energy
PARTICIPANT: FuelCell Energy
PROJECT NO.: NT41837

FuelCell Energy has achieved landmark efficiency in a 60-kW (peak power rating) SOFC module. This milestone was accomplished by testing an SOFC proof-of-concept module (PCM) consisting of four identical stacks, each assembled using 96 standard cells of 550 cm^2 active area per cell. The PCM assembly included the non-repeat hardware such as the base structure, stack compression assembly, a radiative heat exchanger for preheating the anode inlet gas using the radiated heat from the fuel cell stacks, and piping for distribution and collection of anode and cathode gases for the individual stacks. The PCM unit assembly also included instrumentation for data acquisition and process control, as well as a power collection bus for transferring direct current (DC) power from the stacks to the module external power takeoff points.

The tests were performed in a power plant facility equipped with a DC-to-AC (alternating current) inverter connected to the local utility line (grid), heat exchangers for preheating the air and fuel feeds, an anode recycle subsystem to provide water required for the fuel cell, a pre-reformer to convert high hydrocarbons (C2+) present in the natural gas to hydrogen, desulfurization beds for removal of sulfur species from natural gas fuel, and a control system for local and remote monitoring and automated control of the plant.

The PCM unit achieved a peak power output level of 60.6 kW DC and a gross fuel cell (DC) efficiency of >67 percent (low heating value of natural gas). The generated DC power was converted to AC power and fed to the power line at the facility. The operation of the multi-stack PCM unit marks a significant first-of-a-kind achievement for the SECA-developed SOFC technology. It also meets the project objectives of progressively larger fuel cell systems, and shows continued progress toward demonstrating reliability of stack modules that are building blocks for megawatt-class integrated gasification fuel cell (IGFC) systems suitable for near-complete carbon capture.

PROJECT TITLE: SECA Coal-Based Systems—UTC Power
PARTICIPANT: UTC Power
PROJECT NO.: DE-NT0003894

UTC Power improvements in glass seals, braze seals, and increased endurance contributed to increased power on button cells. On the stack front, UTC/Delphi developed accelerated test strategies for the glass seal and the braze seal, and the seals successfully completed hundreds of thermal cycles. A 30-cell Gen 4 stack was built with several interfacial control concepts and was tested for 5,000 hours with the best treatment combinations degrading an average of 0.64 percent per 500 hours. Optimization of solids loading, firing parameters, and print screen mesh for the interlayer was completed, leading to an increase in power of greater than 50 percent on button cells. A Gen 4 stack is currently being tested and has successfully completed over 90 deep thermal cycles from 750 °C operating temperature to under 100 °C with a total power degradation of less than 1 percent. It continues to thermal cycle. The latest design of cathode interconnect for Gen 4 stacks exhibits a 20 percent lower pressure drop as compared to Gen 3 interconnects from 2011.

On the system front, UTC Power successfully completed test stand modifications to support natural gas operation of the breadboard power plant. Risk mitigation plans for high-risk components—anode recycle blower, pre-reformer, and new design of anode startup heater—were successfully executed. Startups and unattended operation were successfully demonstrated for a breadboard power plant using a debug stack. Four stack assemblies were integrated in the breadboard power plant and achieved 6.5-kW steady-state operation using natural gas.

PRESSURIZED SYSTEMS

PROJECT TITLE: SECA Coal-Based Systems—LG Fuel Cell Systems
PARTICIPANT: LG Fuel Cell Systems Inc.
PROJECT NO.: FE0000303

LG Fuel Cell Systems (LGFCS) has performed two block-scale tests of its integrated planar-SOFCs, consistently demonstrating degradation rates of approximately 0.6 percent per 1,000 hours (equivalent to 1.5–2-year service life to meet efficiency targets).

The block is the ≈20-kW repeat unit designed to be the building block of megawatt-scale power-generation systems, first planned to be commercialized for distribution power generation, but suitable as well for centralized IGFC plants. The block-scale tests closely match product configurations and system conditions to provide accurate validation testing of the SOFC cell and stack technology for commercial readiness. Accelerated testing methodologies have been developed that serve to provide more rapid iterative screening of alternate cathode materials and have resulted in the selection of optimized cathode compositions to overcome key degradation mechanisms present in the current technology; SOFC strips are being prepared for block-scale validation in late FY 2013. Identification and resolution of degradation mechanisms associated with the electrical interconnections between cells has also been achieved. Such advancements are critical to extending the lifetime of the SOFC to the 3–5-year range for market competitiveness.

The key functionality of the SOFC is power generation (at a low degradation rate); however it must operate reliably over its design lifetime. As with other SOFC technologies, the LGFCS integrated planar-SOFC stack utilizes ceramic components. LGFCS, through it collaborations with Oak Ridge National Laboratory, has extended the mechanical property database of the porous substrate support structure upon which the active fuel cell layers are applied, and more importantly matured the understanding of the time-dependent mechanical characteristics of the substrate. A design methodology combined with the relevant mechanical property test data is providing a level of confidence in the materials selection for the LGFCS stack technology to provide the necessary structural reliability for >5 years of service; validation of these reliability predictions is the next important step for commercial readiness. LGFCS produces fuel cell modules on their prototype production line in Canton, OH. Design, procurement, and SOFC fabrication is underway for a grid-connected 250-kW-scale test demonstration in late 2014 at the Canton facility.

ANODE ELECTROLYTE CATHODE DEVELOPMENT

PROJECT TITLE: Synchrotron X-Ray Studies of SOFC Cathodes
PARTICIPANT: Argonne National Laboratory
PROJECT NO.: FWP49071

Argonne National Laboratory is using in-situ X-ray diffraction to investigate the oxygen exchange reaction mechanisms under applied electrochemical potential using pseudo half-cells. The cells consisted of an epitaxial $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$-δ (LSCF) thin film (60 nm) grown on an yttria-stabilized zirconia (YSZ) substrate with a gadolinium-doped ceria (GDC) interlayer. The dependence of the oxygen vacancy concentration on electrochemical potential was indirectly measured by analyzing c-lattice parameter changes as a function of applied cathodic and anodic overpotential at different oxygen partial pressures and temperatures. This work demonstrated that oxygen transport across the LSCF/atmosphere interface has a larger energy barrier than transport across the LSCF/GDC interface under both anodic and cathodic conditions, and has provided insight into the oxygen partial pressure (pO_2) dependence of the behavior. Unlike overall electrochemical measurements, the X-ray results are sensitive to local variations in the device performance and provide an important opportunity to understand the working of SOFC cathodes. Using standard synchrotron X-ray techniques, it is straightforward to measure lattice parameters in thick structures with a resolution of 1 µm in position and 10^{-4} in strain. The in-situ X-ray techniques developed at Argonne are now being used to understand the performance enhancement of SOFC cathode infiltrants.

PROJECT TITLE: Solid Oxide Fuel Cell Cathodes: Unraveling the Relationship Among Structure, Surface Chemistry, and Oxygen Reduction
PARTICIPANT: Boston University
PROJECT NO.: NT0004104

Boston University's total X-ray fluorescence (TXRF) analysis of deposited thin films of LSM-20 $(La_{0.8}Sr_{0.2})_{0.95}MnO_{3\pm\delta}$ composition exhibit surface enrichment of Mn. By contrast, hard X-ray photoelectron spectroscopy (HAXPES) analysis of epitaxial LSCF films of the composition $(La_{0.6}Sr_{0.4})(Co_{0.2}Fe_{0.8})O_3$ (LSCF-6428) exhibit Sr segregation to the surface followed by formation of $SrCO_3$ in air. This has critical implications for the application of LSCF compositions as SOFC cathodes. Companion impedance measurements on LSM and LSCF thin films and transport modeling have confirmed the predominance of a surface transport pathway for oxygen reduction in LSM and bulk and surface mediated transport pathway for oxygen reduction in LSCF thin films. In particular in LSCF-6428 films, at the lowest temperature and pO_2 the bulk path dominates transport, whereas at high temperature and pO_2 there is competition, or surface transport dominance.

PROJECT TITLE: Phase III Xlerator Program: Electro-Deposited Mn-Co Alloy Coating for Solid Oxide Fuel Cell Interconnects
PARTICIPANT: Faraday Technology
PROJECT NO.: FE0006165

A cost-effective electro-deposition process to apply high-quality coatings to SOFC interconnects in a mass production scenario is being developed, optimized, and validated by Faraday Technology and West Virginia University. The FARADAYIC℠ electro-deposition process can be used to deposit a Mn-Co alloy with a controlled composition and thickness that can subsequently be converted to a spinel by thermal exposure at high temperatures in an oxidizing environment. Faraday has scaled its process capabilities from 25 cm^2 to 100 cm^2 SOFC interconnects and demonstrated the ability to coat interconnects containing gas flow field features. Continued analysis and refinement of the economic assessment based on using batch manufacturing for the pulse reverse electro-deposition process demonstrated that the innovative coating technology can meet DOE's high-volume target of 1.6-million plates per annum for 250-MW fuel cell stacks at a cost of ≈\$1.85 per 625 cm^2 coated interconnect.

Faraday has completed long-term thermal evaluation of Mn-Co-coated T441 stainless steel samples. Samples were subjected to a humidified air atmosphere at 800 °C and 850 °C for 2,000 hours. Post-thermal-soak evaluation included visual inspection for spallation; scanning electron microscopy (SEM)/energy-dispersive spectrometry (EDS) analysis to examine the coating microstructure, coating thickness, chemical composition uniformity, chromia scale adhesion, and scale thickness; X-ray photoelectron (XPS) to examine the elemental composition of the coating surface and the electronic state of the elements present; X-ray diffraction (XRD) to determine spinel composition and area-specific resistance (ASR) to examine the coating conductivity. Results of the analysis suggests that the Mn-Co alloy coatings deposited by the FARADAYIC electro-deposition process are converted to spinel structures at elevated temperatures through the incorporation of oxygen from the air atmosphere with Co_2MnO_4 and Co_3O_4 dominating the coating surface, the chromia scale grows to approximately 4 µm after 2,000 hours and the scale exhibits good adhesion with the stainless steel, the coatings thickness is uniform in the regions examined, and the coated samples exhibit a low ASR of less than 30 mΩ cm^2.

PROJECT TITLE: Fundamental Investigations and Rational Design of Durable, High-Performance SOFC Cathodes
PARTICIPANT: Georgia Institute of Technology
PROJECT NO.: FE0009652

Georgia Tech has carefully characterized the changes in cell performance as the cathode gas was switched from dry air to wet air or to air containing different concentrations of CO_2 using the same cell under the same testing conditions to minimize the effect of performance variation from cell to cell. It also eliminates uncertainty introduced by other time-dependent degradation often observed during long-term stability testing. The magnitude in performance change was also correlated with the concentration of contaminants and the degree of DC polarization, providing valuable information for quantifying the effect of contaminants on cathode performance. It also offers insights into the reversibility of the poisoning effect and the condition best suited for effective screening of new catalysts for mitigating the poisoning effect. In addition, a thin-film LSCF cathode was successfully fabricated using radio frequency (RF) sputtering, which is vital to fundamental study of the degradation mechanisms.

PROJECT TITLE: Chemistry of SOFC Cathode Surfaces: Fundamental Investigation and Tailoring of Electronic Behavior
PARTICIPANT: Massachusetts Institute of Technology
PROJECT NO.: NT0004117

Massachusetts Institute of Technology quantitatively assessed and demonstrated that the mechanism of dopant segregation on perovskite oxides includes both the elastic and electrostatic energy contributions, shown explicitly on the model perovskite compounds, $LnMnO_3$ (host cation Ln = La, Sm, and dopants Ca, Sr, and Ba). A smaller size mismatch between the host and dopant cations and a chemically expanded lattice were found to reduce the segregation level of the dopant and to enable more stable cathode surfaces. Ca-doped $LaMnO_3$ was found to have the most stable surface composition with the least cation segregation among the compositions surveyed. Lastly, scanning probe image contrast showed that the surface chemical heterogeneities made of dopant oxides upon segregation were electronically insulating.

PROJECT TITLE: Synchrotron Studies of SOFC Cathode Degradation
PARTICIPANT: Montana State University
PROJECT NO.: FWP49071

X-ray absorption spectroscopy (XAS) measurements of the L_{23}-edge of Co in a $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ ($LSC_{20}F_{80}$) and $La_{0.6}Sr_{0.4}Co_{0.5}Fe_{0.5}O_{3-\delta}$ ($LSC_{50}F_{50}$) thin films deposited on a $Gd_{0.1}Ce_{0.9}O_{2-\delta}$ layer on a YSZ electrolyte generated at Montana State University were conducted at the Advanced Light Source of Lawrence Berkeley National Laboratory to determine the spatial variation of the surface Co valence with changes in operational conditions including bias potential and humidity. Based valence mapping studies it is concluded that having full X-ray absorption spectra facilitates the extraction of chemical information over the entire sample surface with a spatial resolution determined by the X-ray beam dimensions (at beamline 6.3.1 the minimum beam size on the sample is approximately 25 × 500 µm). Additionally, this beamline has a fully automated x, y, and z positioning system which enables the data acquisition to be fully automated. The mapping of a 1 × 1 cm sample with 200 data points (pixels) in normal mode would take approximately 44 hours, not including the sample movement. Fast scanning reduces the acquisition time to a total of 5 hours, making this type of study feasible, since the normal beamtime available to users is on the order of 2–4 days. It was also found that the average valency of Co and Fe is reduced, with the largest reduction in the Co valence. Additionally, on the positive anode side the decrease in oxygen vacancies should reduce the amount of Co^{2+} and Fe^{2+} formed and thus also reduce Sr segregation. The cathode side has much more Co^{2+} than the anode side, resulting in a much more yellow map. That the anode shows Co^{2+} even though the oxygen vacancy concentration is probably low means the Sr segregation is directly linked to the appearance of low valence transition metal ions.

PROJECT TITLE: NETL-RUA Fuel Cells Initiative
PARTICIPANT: National Energy Technology Laboratory
PROJECT NO.: FWP-2012.03.04

State-of-the-art SOFC electrode design requires specific assignment of performance to electrode properties. The conventional tool for evaluation is known as the reference electrode, however such electrodes have been shown to fail in SOFC systems. Therefore, NETL-Regional University Alliance (RUA) researchers have applied techniques known as impedance deconvolution and equivalent circuit fitting to improve the quality of electrode performance and degradation examinations. Deconvolution analysis was aided by careful control and manipulation of the experimental variables, and analyses were applied to commercially relevant cell architectures. The complete method enabled improved assignment of the physical processes occurring in real SOFC electrode systems, and resulted in an enhanced tool useful for examining cell and stack performance.

Cathode infiltration technology has been pursued by NETL researchers for more than 3 years, initially beginning with proof of concept in FY 2010 and continuing through stack demonstrations and technology transfer in the current year. Based on the quality and volume of data demonstrating the infiltration technology in FY 2010 through FY 2012, two independent commercial cell manufacturers engaged NETL researchers to complete a small-scale validation test known as a short stack test. Manufactured one and delivered five commercial cells with active area greater than 100 cm^2, and manufactured two and delivered five commercial cells with active area greater than 50 cm^2. Both sets of commercial cells were infiltrated by NETL researchers and returned to the manufacturers. Short-stack tests containing multiple cells operating in a commercially relevant environment were subsequently completed by each manufacturer.

PROJECT TITLE: Understanding of Solid Oxide Fuel Cell Stack in Pressurized Conditions
PARTICIPANT: Naval Undersea Warfare Center
PROJECT NO.: FE0005652

Naval Undersea Warfare Center (NUWC) test capability has been established for evaluating SOFC planar stacks and related systems under elevated pressure up to 45 psia (3 atm). The Office of Naval Research (ONR) has funded the construction of the pressurized test vessel and testing of a 60-cell SOFC stack fabricated by Materials and Systems Research, Inc. The Materials and Systems Research SOFC stack was delivered to NUWC under an Office of the Secretary of Defense (OSD)-sponsored Phase II SBIR contract. Much of the hardware and control methods developed in this ONR program can now be applied to the testing of a Delphi Gen 4 SOFC stack in this DOE research program. Test plans and procedures have been drafted for running the pressurized Delphi stack tests.

PROJECT TITLE: Reliability and Durability of Materials and Components for Solid Oxide Fuel Cells
PARTICIPANT: Oak Ridge National Laboratory
PROJECT NO.: FEAA066

Oak Ridge National Laboratory has developed and engineered glass seals for SOFCs. These seals are self healing, microstructurally stable in SOFC environments, and their viscosity and thermal expansion can be tailored to address the wide range of temperatures in an SOFC stack. These engineered glass seals retain their functionality even after multiple thermal cycles. The engineered microstructure was designed to seal surfaces that are not flat or parallel. Current work is focused on developing low cost manufacturing processes for producing these seals.

PROJECT TITLE: Low-Cost, Modular SOFC Development
PARTICIPANT: Pacific Northwest National Laboratory
PROJECT NO.: FWP40552

Pacific Northwest National Laboratory's surface modification of stainless steel improves spallation resistance $(Mn,Co)_3O_4$ (MC) spinel that offers a number of benefits as a protective layer applied to candidate SOFC interconnect steels, including mitigation of Cr volatility, reduction in oxidation rate, and low electrical resistance. In particular, spinel-coated AISI 441 (a conventional ferritic stainless steel) exhibits promising behavior as a cost-effective candidate material system for SOFC interconnects. For example, spinel-coated AISI 441 exhibited low, relatively stable area-specific resistance for 25,000 hours at 800 °C. This coating/steel combination also exhibited excellent performance in a ≈6,000-hour test under realistic SOFC stack operating conditions (using the SECA Core Technology program stack test fixture). To mitigate possible oxide scale spallation issues beneath the coating, a variety of physical surface modifications to the AISI 441 were subjected to long-term investigation. MC spinel coatings were applied to the surface-treated AISI 441, which were then subjected to oxidation testing at 800 °C or 850 °C in air. All of the surface treatments offered improved scale adhesion compared to coated AISI 441 without surface modification. The best performance was obtained with surface blasted or surface ground specimens; for example, surface blasted coupons exhibited excellent scale adhesion for 24,000 hours of testing at 800 °C, and 20,000 hours of testing at 850 °C. The long-term evaluation of the surface modified AISI 441 is still in progress.

Anode-supported button cells with LSCF-6428 and LSM-20/YSZ cathodes were fabricated and tested to determine the effects of cathode air humidity on cell performance. Cells with each cathode composition were fabricated using the same materials and processes in order to make them as similar as possible. LSCF cells were tested at temperatures ranging from 650 °C to 800 °C; LSM/YSZ cells were tested at temperatures ranging between 800 °C and 950 °C. At each temperature, six cells of each composition were tested for 1,000 hours at constant current corresponding to an operating voltage of ≈0.8 V. Two of the six were tested in dry air with a dew point of approximately -40 °C over the entire duration of the test, two were tested in moist air bubbled through water at room temperature over the entire duration of the test, and two were alternated between dry and moist air every 250 hours. The tests of LSCF cells suggest that at temperatures below 750 °C, 3 percent water in the cathode air accelerates degradation of LSCF cathodes, while above 750 °C, 3 percent water may decrease their degradation rate. At 750 °C, the cells did not exhibit a significant response to moisture. The tests of LSM/YSZ at 950 °C suggest that for cells in which the cathode air humidity was held constant over the entire test duration, there was no difference in degradation rate between moist and dry cells. However, at all temperatures below 950 °C, cells degraded faster when tested exclusively in moist air for 1,000 hours than exclusively in dry air. Additionally, cells in which the cathode air was cycled between dry and moist air exhibited higher degradation rates during moist periods than during dry periods at all temperatures, including 950 °C.

Two 1,000-hour in-situ XRD tests were demonstrated on the cathodes of anode-supported cells in the high temperature XRD test fixture. To complement previous tests that were conducted on cells at 750 °C, the recent tests provided data on cells operating at 700 °C and 800 °C. Both of these cells were operated under constant current conditions approximating an operating voltage of 0.8 V. Because in-situ XRD experiments entail the acquisition of numerous XRD scans collected continuously throughout the extended duration test, the summation of scans over intervals of 200 hours or more were found to accumulate count times sufficient to enable the resolution of trace phases with concentrations of less than 2 wt % in the cathode, which included $LaCoO_3$, Fe_3O_4, and Co_3O_4. Using these integrated patterns, it was also possible to detect peak shifts that occurred in Fe_3O_4, and Co_3O_4 due to gradual lattice strain.

A three-dimensional (3-D) thermo-visco-elastic continuum damage-healing modeling framework for the compliant self-healing glass sealant material has been developed. The model accounts for the stress and temperature dependent nonlinear material behavior as well as the two major damage sources within the seals: mechanical cracking and internal pores. It was further implemented into a highly detailed finite element model that was established for an in-service single-cell SOFC stack test fixture through user subroutines in the commercial finite element software, Abaqus. Model simulations were found to be able to capture the evolution of damage initiation, growth, and annihilation within the glass sealant in response to an abrupt operating temperature changing event. The numerical predictions matched well with the experimental observations qualitatively. Sensitivity studies on the seal design parameters were then performed to evaluate the effects of a variety of material properties and operating conditions. These results quantitatively determine the relationship between the glass material properties and its structural performance within the SOFC stack, and thus are particularly useful in assisting the material development and seal design engineering efforts. Furthermore, the present modeling framework also provides a computational tool that allows material developers and stack designers to conduct virtual engineering fabrication tests which can help greatly accelerate the design and development process.

A modeling framework that automatically creates reduced order models (ROMs) for SOFC. Simulations for operation and control of an entire power-generation system require numerical submodels for every individual component. Computationally fast thermodynamic submodels are conventionally used for SOFCs but lack any insight to distributions of temperature and other key parameters within the stack. Highly detailed SOFC stack models exist for design purposes but are much too computationally slow for use in system-level simulation. The developed tool solves this dilemma by utilizing the existing detailed model to generate a computationally efficient ROM. The framework interface guides the user through the analysis procedure, samples and interrogates the multi-parameter operating space using the detailed stack model, performs regression to generate the response surfaces, and implements the response surfaces into a ROM submodel for general use within system modeling software. The framework supports sampling of fuel and oxidant composition parameters while enforcing multiple constraints (total fuel composition and steam-to-carbon ratio). The framework handles failed/unstable simulations and discards them from the final ROM submodel. It also contains integrated graphical tools for sensitivity and error analysis to ensure that the design space sampling and regression is sufficient for the ROM to approximate the highly nonlinear stack response. Therefore, this ROM tool provides a useful way for the modeler to leverage deep knowledge from a detailed SOFC model and package it within a fast submodel for study of power-generation systems.

The SOFC multi-physics software tool was developed to predict the temperature and current density distributions within planar multi-cell SOFC stacks and has been successfully benchmarked against experimentally measured data from a state-of-the-art stack. Based on feedback from SECA collaborators, a user-friendly graphical user interface (GUI) has been developed to promote the usage of this tool in the SOFC industry. The GUI allows users to do both preprocessing and post-processing for SOFC evaluations. The preprocessing capability enables users to enter and modify SOFC model geometry, stack operating conditions, and simulation control parameters. The post-processing capability helps users to visualize the results for various physical properties across the entire two-dimensional (2-D) domain. The GUI makes it easier for users to take full advantage of the rich features in the 2-D tool, e.g., the cell-to-cell variation feature for evaluation of realistic stack experiments and the multi-step framework for long term stack performance analysis. The 2-D GUI software works seamlessly with the SOFC multi-physics solver and is now an integrated part of the SOFC multi-physics package.

PROJECT TITLE:	Surface-Modified Electrodes: Enhancing Performance Guided by In-Situ Spectroscopy and Microscopy
PARTICIPANT:	Stanford University
PROJECT NO.:	FE0009620

Stanford University and Sandia Labs have made significant progress toward understanding and controlling oxygen-reduction reaction (ORR) activity in SOFCs. New understanding of the ORR of iron-perovskite fuel cell cathodes by using in-situ X-ray spectroscopy, they directly observed the composition and electronic structure the active phase in alkali-earth-doped $LaFeO_3$ fuel cell cathodes while the oxygen-reduction reaction is taking place. Specifically, X-ray spectroscopy probes the first few nanometers of the active phase under typical SOFC conditions. Our characterization platform is allowing us to directly probe the electronic structure under SOFC conditions, that is, at elevated temperature, pressure and under bias. Specifically, the crucial electronic species that participates in the reaction were identified. These results are expected to (1) change the way researchers think about electrochemistry in oxide materials and (2) lead to rational ways to improve the performance of SOFCs.

PROJECT TITLE: Mechanistic Enhancement of SOFC Cathode Durability
PARTICIPANT: University of Maryland
PROJECT NO.: FE0009084

The University of Maryland finalized setup of an in-situ isotope exchange system and initiated O_2 and CO_2 exchange experiments with $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-x}$ (LSCF) and $(La_{0.8}Sr_{0.2})_{0.95}MnO_{3-x}$ (LSM) cathode powders. Included setup of mass spectrometer, all gas lines and manifolding, and flow and system calibrations. This will allow determination of fundamental cathode ORR rates and the influence of contaminant gasses on ORR.

LSM-YSZ/YSZ/LSM-YSZ and LSCF-GDC/GDC/LSCF-GDC symmetric button cells were fabricated for degradation studies and developed 3-D focused ion beam (FIB)/SEM reconstruction capabilities using National Institute of Standards and Technology (NIST) facilities. This will allow determination of effect of contaminants on microstructural and compositional cathode degradation mechanisms.

PROJECT TITLE: Enhancement of SOFC Cathode Electrochemical Performance Using Multi-Phase Interfaces
PARTICIPANT: University of Wisconsin
PROJECT NO.: FE0009435

University of Wisconsin performed a comparative investigation of patterned films containing interfaces of $La_{0.8}Sr_{0.2}CoO_{3-\delta}$ (LSC-113) and $LaSrCoO_{4\pm\delta}$ (LSC-214). Previous work has shown that pulsed laser deposited catalysts consisting of partial or complete thin layers of LSC-214 on LSC-113 films enhanced oxygen reduction reaction catalytic activity by orders of magnitude compared to LSC-113 alone. Related work with sintered powders has also shown enhanced activity at the LSC-113/LSC-214 interface compared to either phase far from the interface. These findings suggest that the LSC-113/LSC-214 interface is intrinsically more active than the single-phase materials. Studies of LSC-214 films with partial to complete decoration with LSC-113 did not demonstrate any activity enhancement over the undecorated LSC-214 films. This lack of enhancement in a controlled geometry suggests that the interfacial effects may depend on details of how the interface is formed. Auger electron spectroscopy results suggest distinctions between the surface chemistry associated with surface Sr segregation between the two cases, and these differences are under further investigation. Furthermore, the catalystic performance of these LSC-113/LSC-214 structures could be influenced by diffusion limitations due to the thickness of the LSC-214 (≈250 nm), and thinner films are being tested.

PROJECT TITLE: Fundamental Understanding of Oxygen Reduction and Reaction Behavior and Developing High-Performance and Stable Cathodes
PARTICIPANT: West Virginia University
PROJECT NO.: FE0009675

West Virginia University's studies indicate the ORR kinetics of LSCF are significantly improved by infiltrated catalyst. Efforts have been devoted to the development and performance evaluation of new catalyst infiltrated LSCF cathode. XRD analyses and morphology characterizations indicate that solution composition has a significant impact of on the formation of pure phase and particle size of catalyst materials. In comparison to LSCF backbone, the measurements of symmetric cells shed light on beneficial role of our catalyst in decreasing the polarization resistance (by about 50 percent) and activation energy (by about 20 percent) of LSCF cathode. The preliminary results indicate further optimization of the process conditions for formation of catalyst on LSCF will lead to even better cathode performance and stability.

PROJECT TITLE: Direct Utilization of Coal Syngas in High-Temperature Fuel Cells
PARTICIPANT: West Virginia University
PROJECT NO.: ER46299

Trace impurities such as arsine and phosphine found in coal-derived syngas cause performance degradation on SOFC anodes. Researchers from the National Institute for Fuel Cell Technology (NIFT) at West Virginia University have made new discoveries using multiple expertise and refined experimental and modeling techniques to understand underlying mechanisms of degradation caused by aforementioned impurities. A uniquely patterned electrode is designed using nano-technology to clearly define the triple and two-phase boundaries of ionic and electronic conductors in the anode active layer. Experiments are being performed to investigate the mechanism by which the steam accelerates degradation in the presence of phosphine. An environmental SEM has been purchased and made operational to conduct in situ observation. Initial results indicate that there is no softening or melting of the secondary phase of Ni-P at 800 °C, contrary to previous postulations. The degradation model is extended and applied to a planar cell. It seems that the degradation rates for larger planar cells is lower compared to those observed on button cells operated under similar conditions. Experiments are under way to validate these results.

ALTERNATIVE AEC DEVELOPMENT

PROJECT TITLE: Performance Degradation of LSCF Cathodes
PARTICIPANT: GE Global Research
PROJECT NO.: NT0004109

General Electric's thermal spray manufacturing of SOFCs was successfully demonstrated on 25 cm^2 cells. A key barrier to the commercialization of SOFCs is the excessively high capital cost involved with developing a manufacturing infrastructure for fabricating sufficient quantities of the multi-layered cells for demonstration units. In addition, to accommodate low initial rates of market adoption, low-cost manufacturing is imperative to establishing a commercially viable fuel cell technology business.

Recent progress in thermal spray manufacturing technology at GE Global Research, through support of the DOE SECA program, has demonstrated dramatically reduced low-volume SOFC manufacturing costs. Recent scaleup efforts have demonstrated 25 cm^2 cell performances of >0.25 W/cm^2 with excellent repeatability. In addition to significantly diminished capital costs, thermal spray manufacturing builds an integrated electrolyte-to-metal seal that is formed during thermal spray deposition, eliminating the need for the traditional post-fabrication glass sealing methods. The 25 cm^2 cells also include this inherent seal and were able to achieve very high fuel utilizations (>90 percent).

The thermal spray manufacturing process is scalable to a large cell area that reduces part count, and is a modular process that allows flexibility in accommodating production volume and design changes that is critical for demonstration/prototype units. Continued development with the DOE SECA program will focus on optimizing the manufacturability of these cells and implementing degradation mitigation strategies to ultimately build stacks and systems.

SMALL BUSINESS INNOVATION RESEARCH

PROJECT TITLE: High-Temperature Viscous Sealing Glasses for Solid Oxide Fuel Cells
PARTICIPANT: Mo-Sci Corporation
PROJECT NO.: SC0002491

Mo-Sci's high-temperature viscous sealing glasses have exhibited promising behavior for SOFCs. Glass compositions have been formulated and tested for use as viscous seals for SOFCs. These alkali-free borosilicate glasses possess desirable thermo-mechanical properties and thermo-chemical characteristics, and exhibit promising hermetic sealing and healing behavior under SOFC operational conditions. The dilatometric softening points (Ts) and the glass-transition temperatures (Tg) of the glasses are generally under 650 °C, the lower bound of the SOFC operating temperature. To date, glass seals between a NiO/YSZ bilayer and aluminized 441 stainless steel have survived 103 thermal cycles (room temperature to 750 °C) under wet forming gas at a differential pressure of 0.5 psi (26 torr) over the course of >3,500 hours without failure, and 100 thermal cycles in dry air. Seals intentionally cracked upon quenching from 750 °C to room temperature at >25 °C/s become hermetic upon reheating to 725 °C and higher.

PROJECT TITLE: Solid Oxide Fuel Cell Cathode Enhancement Through a Vacuum-Assisted Infiltration
PARTICIPANT: Materials and Systems Research, Inc.
PROJECT NO.: SC0006374

A cost-effective, single-step vacuum-pressure-infiltration thermal-treatment (VPIT) technique was developed at Materials and Systems Research, Inc. Refinement of this single-step infiltration technique is currently being carried out and implemented on scalable SOFCs with per-cell active area varying from 2 cm^2 to 100 cm^2. LSM-based cathode backbone microstructures were engineered for allowing an efficient infiltration of an active catalyst onto cathode grains. Various perovskites, such as strontium-doped samarium cobaltite (SSC), are being investigated as the electrocatalysts. Important parameters affecting the single-step infiltration process have been tailored to improve the infiltration efficiency, including the solvent physical properties (e.g., polarity, surface tension, and gelation rate) and infiltration conditions (catalyst precursor concentrations and loading level). Extensive experimental and microstructure characteristic studies have shown that an optimum loading of 2.5 mg/cm^2 to ≈3 mg/cm^2 of a catalyst was most desirable from the standpoint of performance improvement and material costs.

Reestablishing the catalyst structure is also being conducted to sustain the performance enhancement longevity. Resulting cells were evaluated and showed significant improvement by demonstrating 100 percent performance improvement (compared to the baseline cell performance) and a degradation rate less than 2 percent per 1,000 hours over a 5,100-hour long-term test. Periodical voltage-current sweeps and electrochemical impedance spectroscopy (EIS) measurements (weekly) over a course of 7-month tests suggested that the activity of a nano-sized catalyst was successfully retained. Efforts were made to characterize catalyst infiltration effects on large cells and stacks. Design and construction of a metal-free test bed was completed to accommodate single cell characterization (100 cm^2 active area). Proof-of-concept tests of single cells and stacks will be continued to demonstrate the feasibility of implementing the advanced single-step VPIT technique for practical large-scale applications.

PROJECT TITLE: SOFC Protection Coatings Based on a Cost-Effective Aluminization Process
PARTICIPANT: NexTech Materials
PROJECT NO.: SC0008203

NexTech's SOFC protection coatings based on a cost-efffective aluminization process have demonstrated a protective aluminide/alumina coating for alloys. The process achieves excellent aluminide coating fidelity to fine-scale interconnect features as well as scalability of the process to coat large components. In addition, it's the aluminization process was modified to control aluminum diffusion depth to make it possible to co-anneal the aluminide coatings with commercially available manganese cobalt oxide active area coatings. Cost-modeling indicates the cost for dual coated parts to be less than \$3/part (15 cm × 15 cm part at 1 million parts/year volume production). The aluminization technique was demonstrated across a range of ferritic, and austenitic stainless steel and nickel superalloy formulations, enhancing thermal oxidation, coking, and chromium volatilization resistance. These scientific achievements create opportunities for coated mild-steel components to be used in more demanding applications.

PROJECT TITLE: Low-Cost Spray-On Coatings for Protection of SOFC Interconnects and BOP Components
PARTICIPANT: nGimat Company
PROJECT NO.: SC0008267

nGimat's Phase I, a system for depositing both Al_2O_3 and $(Mn,Co)_3O_4$-based coatings with minimal substrate damage was developed. High quality coatings with thicknesses ranging from 300–900 nm were deposited and the coating thickness was correlated to a simple process parameter (number of coating laps). Using this system, sample coupons were made and subjected to oxidation exposures at 800 °C in static ambient air. Post oxidation analysis showed the merit and benefit of NanoSpray℠ combustion chemical vapor deposition (CCVD) coating based on Al_2O_3 and $(Mn,Co)_3O_4$ for oxidation protection of both SOFC interconnect and balance-of-plant ferritic stainless steels. The coated and uncoated stainless steel samples exhibited parabolic weight gains with the rate for uncoated 430 is ≈10 times higher than coated 430 and the rate for uncoated 441 is ≈5 times higher than coated 441 stainless steel. The oxide scales that formed on the coated substrates were also significantly thinner than uncoated and better adhered as the uncoated and oxidized scale consistently spalled while the coated scale remained well adhered for both substrates. In addition, NanoSpray CCVD Al_2O_3 and $(Mn,Co)_3O_4$ coatings were also found to provide oxidation protection on smooth and mill finish surfaces. This is significant as it may eliminate the need for any surface preparation during production.

PROJECT TITLE: Low-Cost Alloys for High-Temperature SOFC Systems Components
PARTICIPANT: QueTek Innovations
PROJECT NO.: SC0008236

QuesTek has demonstrated the feasibility of applying its Materials by Design® approach to computationally design new alloys to address the technical challenges related to SOFC components. Prototype austenitic stainless steels were designed and fabricated that exhibited:

- Stable, continuous Al_2O_3 oxide layer with suppressed Al-N formation
- Good high temperature moist-air oxidation resistance
- Low Cr volatility at high temperature and under moist conditions
- Improved high temperature strength over 310 stainless

The performance of these prototype alloys approaches that of much more costly Ni-based alloys, and they exceed the performance of existing steels considered leading candidate materials.

Because of the successful performance of one of these alloys, the process will be scaled up to the ≈1,000-pound melt level in order to produce enough material for more elaborate and extensive testing and evaluation of this alloy for use in SOFCs.

This testing will include longer term moist air oxidation testing and Cr volatility testing and various temperatures, creep testing to allow for component life estimation, weldability and formability, and static strength and ductility performance.

PROJECT TITLE: Stable Glass-Ceramic Nanocomposites as Compliant Seals for SOFCs
PARTICIPANT: SEM-COM Company
PROJECT NO.: SC0007608

SEM-COM has developed compliant seal systems for SOFCs operating in the temperature range of 800–950 °C. This project has focused on iterations in materials systems consisting of composites of a base glass with appropriate ceramic components in order to identify a stable sealing system with adequate and acceptable thermal characteristics, such as, the viscosity and coefficient of thermal expansion. Viscosity variation in the composites was achieved by the selection of ceramic additives; a large number of candidates ranging from phase pure alumina, magnesia, ceria, and barium zirconate, to ceria doped with 10 mol % gadolinium oxide (Gd_2O_3), and zirconia stabilized with 10 wt % yttrium oxide (Y_2O_3). In one case, metallic silver (in the amount of 1 and 5 wt % of the ceramic additives) was also employed.

SCN1 glass was used as the base component, whose composition was such as to provide a coefficient of thermal expansion (CTE) match with the SOFC system (in the RT–Tg range), when composited with a second ceramic phase. Additives in both nano- and microscale dimensions (as fine powders or in the form of fibers) were introduced mainly to block the bubbles from moving but also to make the composite structure stronger. In addition, their role was also to inhibit the growth of air bubbles within the glass matrix and to or prevent their coalescence during long soak-time at 850 °C, with the goal of eliminating or minimizing the CTE drift in the resultant glass composition. A systematic and improved strategy for mixing the glass and the second phase was developed by researchers at the University of Toledo. Thermal analyses data provided a path to select the heating schedules. No reaction between SCN1 glass and the additives was discerned. Moreover, the bubbles remained small and did not move or coalesce. The CTE of the some of the composites was very close to the targeted value and did not change significantly when aged up to 232 hours at 850 °C in air.

CONGRESSIONALLY DIRECT PROGRAMS

PROJECT TITLE: SOFC Model Development
PARTICIPANT: LG Fuel Cell Systems Inc.
PROJECT NO.: DE-FE0000773

LG Fuel Cell Systems (formerly Rolls-Royce Fuel Cell Systems) has developed a multi-physics computer code (MPC) for SOFC performance calculations of the LGFCS fuel cell structure to support fuel cell product design and development. The MPC is based in the CD-adapco STAR-CCM+ computational fluid dynamics software package which has been enhanced with new models that allow for coupled simulations of fluid flow, porous flow, heat transfer, chemical, electrochemical, and current flow processes in SOFCs. The MPC has been integrated into a GUI, which is embedded into STAR-CCM+ and provides an interactive environment for engineering staff to automatically perform simulation tasks. The GUI provides detailed feedback to guide new users through the simulation workflow and this tool is now being used by six engineers outside of the MPC project team. The MPC is being used to perform a wide range of analysis tasks including but not limited to SOFC applications. In addition several new features have been implemented into the GUI as a result of user feedback, most notably an initial guess generation tool, which has been very effective in reducing simulation time and improving numerical stability in challenging applications.

PROJECT TITLE: Improved Flow-Field Structures for Direct Methanol Fuel Cells
PARTICIPANT: NuVant Systems, Inc.
PROJECT NO.: FE0000982

A unique direct methanol fuel cell design has been developed by NuVant that enables use of highly concentrated fuel streams while mitigating, in large part, fuel crossover within the cell. Reduced methanol crossover significantly improves fuel efficiency and power generation per unit volume of fuel solution, also known as gross fuel energy density (GFED). The new configuration required design of a porous graphite barrier plate that would regulate the delivery of methanol fuel (which can be synthesized from gasified coal) to the cell electrodes, while also normalizing the fuel concentration across the surface of the electrode. The patterned plate, or integrated flowfield diffusion layer (IFDL), was evaluated and optimized using Fluent computational fluid dynamics modeling software. In order to correlate the model to experimental data, one side of the IFDL plate must be treated with a hydrophobic coating to allow for the products to readily exit the fuel cell and to optimally direct the flow of the liquid feed methanol. A Teflon® coating/impregnation method is being developed to evenly coat the single side of the IFDL plate. Fuel cell testing was performed with the non-treated IFDL plates, and GFED reached a maximum of 781 watt hours per liter with fuel utilizations up to 79.4 percent for cells that have operated up to 80 hours in duration. Mathematical modeling of the entire fuel cell is being employed to rapidly optimize the GFED and fuel utilization by varying fuel cell parameters. These results will be correlated with experiment and can help predict the appropriate configurations to improve the GFED to 1,000 watt hours per liter or greater without significant losses in fuel utilization. A small stack, consisting of two fuel cells connected in series, has been constructed and evaluated. Work is underway to minimize the fluctuations in cell performance. A furnace has been purchased to enable rapid prototyping of IFDL plates and to thermally flow Teflon® modified IFDL plate.

Mathematical modeling of the entire IFDL-based direct-methanol fuel cell (DMFC) was performed and the modeling and experimental results agree very well. A hydrophobic diffusion layer production facility was built to manufacture the cathodic diffusion layer. The production facility is flexible enough to produce diffusion media and diffusion electrodes for a vast range of electrochemical industries.

PROJECT TITLE: Solid Oxide Fuel Cells Operating on Alternative and Renewable Fuels
PARTICIPANT: Pennsylvania State University
PROJECT NO.: NT0004396

Research at Pennsylvania State University's Earth and Mineral Sciences Energy Institute has advanced the development of some new adsorbents with high adsorption performance. A Cu-Ti-Ce mixed oxide adsorbent has been developed and thoroughly studied, showing that the combination with the certain molar ratio of Cu:Ti:Ce gives a superior capacity for H_2S and the Cu addition plays a critical role. Its capacity for H_2S is approximately 3.2 wt %, 30 percent higher than that for the TDA Research SulfaTrap™ R7 adsorbent. More importantly, the adsorbent is air regenerable. As for the other contaminants in anaerobic digester gas (ADG) including ammonia and siloxanes, a new type of molecular basket sorbent (MBS) adsorbents has been developed by loading a polymer with numerous acidic functional groups onto higher surface area silica support. The adsorbent showed high affinity to ammonia. It can remove ammonia to below 1 ppmv and the adsorption capacity can reach about 6 wt %. In addition, the adsorbent can be regenerated by temperature swing adsorption. The removal of siloxanes was explored and conducted over silica-based adsorbents including silica gels, using an online GC-ICP-MS (an integrated system that combines three analytical tools: gas chromatography, inductively coupled plasma, and mass spectrometry) to monitor solixanes in the gas stream. The adsorbent exhibited excellent performance for siloxanes, reducing siloxanes down to below approximately 10 parts per billion with a capacity of about 22 wt % (for D4 siloxane). These adsorbents developed in this project are promising for deep clean of biogas streams for SOFC applications.

There have been several accomplishments collaborating with a new industrial partner, Delphi. Both the debug stack and the first "real" stack were tested and the compatibility of the electrochemical electronics equipments and gas flow system with the stack testing setup was verified. The initial individual cell performance, as well as that of the entire stack, was checked. Electrochemical equivalent circuit models were also developed to model the button cell and stack EIS data. All the aforementioned work provided a solid platform to check the consistency between the results obtained at Pennsylvania State University and Delphi and will serve as baseline information for the main experimental part on the project.

PROJECT TITLE: Techno-Economic Analysis of Scalable Coal-Based Fuel Cells
PARTICIPANT: University of Akron
PROJECT NO.: FE0000528

The University of Akron designed and fabricated a fuel cell stack by integration of three and five Ni/YSZ anode-supported fuel cells in series. The series configuration was achieved with low cost metal alloy connecting the anode of each cell to the cathode of the adjacent cell. The metal alloy interconnects and current collectors were tailored by coating with a highly conductive paste to improve the durability and decrease the resistance. Low resistance of the interconnects and current collector allows the three- and five-cell stacks to produce open circuit voltages of 3.0 V and 4.6 V, respectively, which are close to the expected fuel cell Nernst potential. The result from this study provides an insight into the fabrication process and operating conditions of the coal-based fuel cell. The addition of less 3 percent H_2 to the anode chamber keeps the Ni anode in a reduced state, prolonging coal fuel cell operation. The Cu-Ni alloy anode was found to be highly resistant to coking.

SECTION 3: ATMOSPHERIC PRESSURE SYSTEMS

the ENERGY lab

PROJECT FACTS

Fuel Cells

SECA Coal-Based Systems – FuelCell Energy

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

FuelCell Energy, Inc. (FCE), in cooperation with the SOFC technology developer Versa Power Systems (VPS), is one of multiple SECA Industry Teams developing SOFC technology for Integrated Gasification Fuel Cell (IGFC) systems. VPS became a wholly owned subsidiary of FCE in late 2012. FCE is currently engaged in the third phase of the project subsequent to meeting the fuel cell test and system cost metrics in the prior phases.

Earlier project phases focused on cell and stack research and development with emphasis on SOFC performance enhancement (power density, fuel utilization, and degradation), cost reduction, and scaling the cells and stacks to larger sizes. Conceptual and preliminary Baseline IGFC System (>100 megawatts [MW]) designs were developed and analyzed, and FCE completed a conceptual design of the 250-1000 kilowatt (kW) proof of concept (POC) fuel cell module system. Such modules may serve as market-entry commercial products as well as the building blocks of larger systems. Stack tests conducted in accordance with DOE guidance culminated each phase, and data from these tests were used to estimate the performance and cost of the SOFC stacks and Baseline IGFC System. In 2010, FCE met the SECA high-volume cost targets for the SOFC stack and IGFC power block of \$175/kW and \$700/kW, respectively (2007 dollars [\$]).

Project Description

In Phase III, the work is focused on the continued development of cell and stack technology via design and materials development with emphasis on performance, reliability, cost, and manufacturing enhancement. This development is supported through the fabrication, testing, and post-test analyses of the fuel cells and fuel cell stacks, culminating in the test of a ≥ 30 kW stack tower for 3000 hours or more. The stack tower test shall meet DOE cost goals (≤ \$700/kW power block, ≤ \$175/kW stack, 2007 \$) and endurance goals (≤ 1.5%/1000 hours steady-state degradation). With a successful stack tower test, FCE will complete detailed design of a SOFC-based small-scale proof-of-concept module system, including the SOFC stacks, mechanical balance of plant (BOP), and electrical BOP. Cost and IGFC system performance analyses will be updated as the work progresses.

FCE relies upon state-of-the-art planar SOFC technology provided by VPS. A cell, with an electrochemically active area of 550cm^2, is composed of a nickel yttria-stabilized

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Versa Power Systems, Inc. (VPS)

PROJECT DURATION

Start Date	End Date
02/27/2004	09/30/2013

COST

Total Project Value
\$102,383,489

DOE/Non-DOE Share
\$68,543,167 / \$33,840,322

AWARD NUMBER

NT41837

U.S. DEPARTMENT OF ENERGY

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zirconia (Ni-YSZ) anode, YSZ electrolyte, and a proprietary perovskite cathode. Cells are manufactured by tape casting, screen printing, and co-sintering (TSC). The repeat-unit building blocks of the fuel cell stack consist of a cell and coated low-cost stainless steel interconnects. The repeat units are assembled into stacks, which are in turn aggregated into modules of the desired power rating.

Goals and Objectives

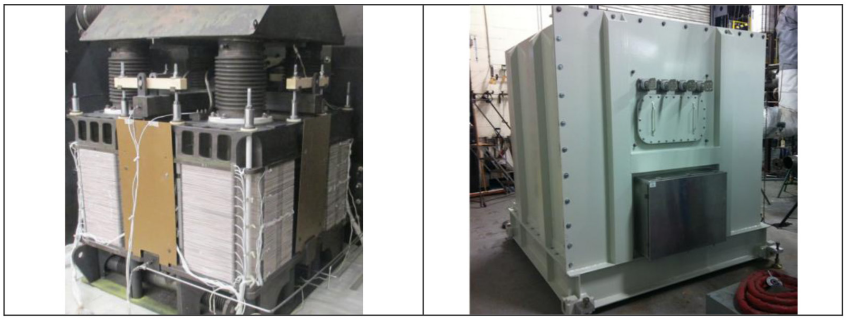
The overall goal of this project is the development of SOFC cell and stack technology suitable for use in highly-efficient, economically-competitive central generation power plant facilities fueled by coal synthesis gas (syngas). The supporting objective in Phase III is the validation of the performance and robustness of stacks and scaled stack arrays suitable for use in large-scale power generation systems such as IGFC systems, where reliable, fail-safe operation is of paramount importance.

Accomplishments

- New cell materials have reduced the performance degradation rate to <0.4%/1000 hours in a 28-cell stack tested for over 18,000 hours.
- Thin anode substrate cells with increased mechanical strength have resulted in more than a 25% cell material cost reduction and higher performance at higher fuel utilization.
- Third generation manufacturing processes (TSC-3) were developed for scaled-up 550 cm^2 active area (25 cm x 25 cm) cells based on high-performance thin cell technology.
- Over 5000 cells of 25 cm x 25 cm cell size (550 cm^2 active area) have been fabricated in the pilot manufacturing facility, with >95% product yield.
- A 120-cell stack metric test successfully met DOE's requirement of completing 1500 hours of testing before the end of Phase II, demonstrating a peak power of 25.2 kW and achieving a steady state average power degradation rate of 0.9%/1000 hours (well below the Phase II DOE requirement of 2%/1000 hours).
- A Baseline IGFC System (~670 MW nominal), utilizing catalytic gasification and capturing > 99% of carbon (as CO_2) in the syngas, was developed with an electrical efficiency of 58.7% (high heating value of coal), surpassing the DOE target for an atmospheric pressure SOFC plant. This system consumes 75% less water compared to pulverized coal plants utilizing scrubbing technology for carbon capture. The plant footprint is comparable to that of an Integrated Gasification Combined Cycle (IGCC) power plant.
- The Baseline IGFC System Factory Cost Estimate, audited by an independent party, achieved a cost of $635/kW (2007 $) for the SOFC power island including the stack module cost of $147/kW (2007 $), meeting the SECA goal of <$700/kW.
- Demonstrated a portfolio of technologies to mitigate chromium poisoning effect on cathode performance under highly humid air (10% relative humidity), achieving performance degradation rate of <0.5% / 1000 hours in single cell tests.
- Fabricated and successfully factory tested 15 stack blocks (each with 96 cells of 550 cm2 area) towards standardization of the stack manufacturing process and implementation of a quality control program.
- Demonstrated operation of a 96-cell stack block in the laboratory environment for >5000 hours.
- Completed >3000 hours test of a 30 kW SOFC stack tower consisting of two standard 96-cell stack blocks, as a demonstration of technology scale-up to larger power plants.
- Conducted >1500-hour grid connected operation of a 4-stack quad-base 60 kW proof-of-concept module (PCM) in a power plant facility, achieving 60.6 kW peak power and a gross dc efficiency surpassing 67% based on lower heating value of natural gas.
- Completed system performance analysis for a 60 kW system for combined heat and power (CHP) applications with electrical efficiency of >61% and overall thermal efficiency of >83%.

Benefits

The SOFCs program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and capable of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achievement of this goal will have significant impact for the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology, accompanied by risks higher than the private sector initially can accept. In parallel, SECA Industry Teams will take advantage of the inherent scalability and fuel flexibility of SOFCs in seeking nearer-term, smaller-scale commercial applications for this efficient, environmentally-friendly technology, which has less risk than a first-of-a-kind full-scale IGFC system. Success in these spin-off applications (e.g., distributed generation, military, etc.) will further SOFC technology advancement and widespread commercial deployment through the resultant manufacturing and operational experience.



60 kW Stack Module

NT41837, May 2013

SECA Coal-Based Systems—UTC Power

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

UTC Power, in cooperation with the SOFC technology developer Delphi, United Technologies Research Center, and Battelle, is one of multiple SECA Industry Teams developing SOFC technology for integrated gasification fuel cell (IGFC) systems.

A key element is cost reduction, with cost targets of $175 per kilowatt (kW) for fuel cell modules and $700/kW for the IGFC power block (2007 dollars [$]; 250 megawatts [MW] per year). Analysis has shown that IGFC systems are well suited to achieving the DOE Office of Fossil Energy's Advanced (Coal) Power Systems goals. In early 2013, ClearEdge Power acquired UTC Power and has decided to end its participation in the project.

Project Description

UTC Power's approach consisted of integrating Delphi-produced SOFC stacks into larger systems with a focus on durability, reliability, cost, and high volume manufacturability. Phase II work included testing stacks and stack modules, performing system modeling and analysis, and integrating stacks into a thermally self-sustaining stack fixture to validate scaled-up operability and performance of the system. Ultimately this work will facilitate the development of economical SOFC systems, which will eventually yield large-scale SOFC-based centralized power generation.

Goals and Objectives

The overall goal of this project was to advance the development of SOFC technology to significantly advance the nation's energy security and independence while simultaneously addressing environmental concerns, including greenhouse gas emissions and water usage.

Accomplishments

- A Gen 3 stack successfully completed durability testing to 9,700 hours with a degradation rate of 2.2 percent per 1000 hours.
- A Gen 3 stack completed 200 deep thermal cycles from 750 degrees Celsius (°C operating temperature to under 100 °C with a total power degradation of less than five percent.
- A 40-cell Gen 4 stack demonstrated a gross power of 6.4 kW at an average power density of 398 milliwatts per square centimeter (mW/cm^2) and average cell voltage of 0.7 volts, utilizing the SECA simulated coal gas blend.

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PROJECT FACTS
Fuel Cells

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PARTNERS

Delphi
United Technologies Research Center
Battelle

PROJECT DURATION

Start Date	End Date
10/01/2008	04/04/2013

COST

Total Project Value
$52,860,053

Base
DOE/Non-DOE Share
$38,887,767 / $13,972,286

AWARD NUMBER

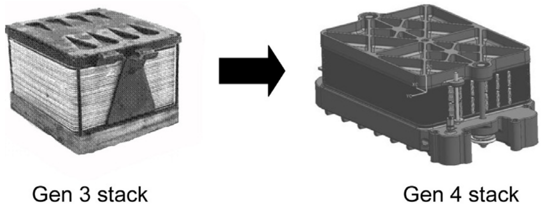
DE-NT0003894

U.S. DEPARTMENT OF ENERGY

- Demonstrated a maximum initial power on 50-cell Gen 4 stack of 9.3 kW at a power density of 463 mW/cm^2 and a mean cell voltage of 0.78 V on a 48.5% H_2 – 48.5% N_2 – 3% H_2O fuel.
- A Gen 4 stack has completed a durability test of approximately 3,500 hours at a constant current density of 155 milliamps (mA)/cm^2 and has a degradation rate of about 4 percent in the first 300 hours and no measurable power degradation thereafter. The successful stack results are highly encouraging for the ensuing phases of the program.
- A 30-cell Gen 4 stack was built with several interfacial control concepts and was tested for 5,000 hours with the best treatment combinations exhibiting an average degradation of 0.64 percent per 500 hours.
- A Gen 4 stack has successfully completed over 90 deep thermal cycles from 750 °C operating temperature to under 100 °C with a total power degradation of less than one percent. The successful stack test results provide confidence that the stacks will survive periods of maintenance and shutdowns in larger power plants.
- At a normal operating condition, the cathode pressure drop on the Gen 4 cathode interconnect (from Gen 3) has been reduced by about 20 percent.
- Developed low cost, high volume manufacturable processes for Gen 4 stack components. Fabricated and tested multiple Gen 4 stacks at a variety of test conditions.
- Preliminary cost analysis of the power block hardware for the IGFC power plant shows a cost of $566/kW in 2007$ with a 90 percent confidence interval, which meets the SECA cost requirement of ≤$700/kW.
- Completed the design, development, and installation of a test stand at UTC Power capable of testing a 50 kW SOFC stack.
- Developed three IGFC designs that produce greater than 100 MW net AC power at efficiency greater than 50 percent HHV and capture greater than 90 percent carbon. Sensitivity analyses were carried out demonstrating that the designs maintained their key performance requirements over a wide range of key operating variables.
- Down-selected three power module concepts after detailed investigation of several competing designs. All three systems were designed for 400 kW net AC and achieved efficiency in excess of 60 percent based on fuel lower heating value. Heat-up and power ramp studies were performed on all systems to define internal and external characteristics.
- Completed design and development of the SOFC breadboard power plant that is thermally self-sustaining while operating at 25 kW using natural gas as fuel. The breadboard power plant includes a hydrodesulfurizer, pre-reformer, a low-cost turbocharger, a novel catalyzed wall heat exchanger, and a network of heat exchangers to support thermal self-sufficiency.
- Completed test stand modifications at UTC Power to support natural gas operation of the breadboard power plant.
- Identified high-risk components in the breadboard power plant and demonstrated durability testing of the same as part of risk mitigation.
- Successfully completed integration of the breadboard power plant and Gen 4 stack assembly in the test stand facility at UTC Power.
- Demonstrated successful startups of the breadboard power plant and stack assemblies. Achieved steady state operation at 6.5 kW using natural gas.

Benefits

The SOFCs program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept. In parallel, SECA Industry Teams will take advantage of the inherent scalability and fuel flexibility of SOFCs in seeking nearer-term, smaller-scale commercial applications for this efficient, environmentally-friendly technology, which has less risk than a first-of-a-kind full-scale IGFC system. Success in these spin-off applications (e.g., distributed generation, military, etc.) will further SOFC technology advancement and widespread commercial deployment through the resultant manufacturing and operational experience.



Scaled-up cells from 105 cm^2 (active area) to 403 cm^2 for Gen 4 stacks.

Test room with SOFC Breadboard for Four Stack Assembly.

NT0003894, May 2013

SECA Coal-Based Systems—LG Fuel Cell Systems Inc.

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

LG Fuel Cell Systems (LGFCS), along with Rolls-Royce Fuel Cell Systems, three universities, and two national labs, is one of multiple SECA Industry Teams developing SOFC technology for integrated gasification fuel cell (IGFC) systems. A key element is cost reduction, with cost targets of $175 per kilowatt (kW) for fuel cell modules and $700/kW for the IGFC power block (in 2007 dollars [$], 250 megawatts [MW] per year). Analysis has shown that IGFC systems are well-suited to achieving the DOE Office of Fossil Energy's Advanced (Coal) Power Systems goals.

Project Description

The Phase I effort was focused on cell and stack research and development, specifically performance enhancement (power density, fuel utilization, and degradation), cost, and scaling. LGFCS utilized its integrated planar segmented-in-series SOFCs at pressures up to seven atmospheres, as pressurized operation achieves higher volumetric power densities. The Phase I effort also commissioned the requisite cell and stack manufacturing scale and capacity to support follow-on SECA phases. The Phase I deliverable was a ~15 kW SOFC stack comprised of commercially scaled cells and stacks, to be tested for 5,000 hours in accordance with the program minimum requirements (degradation of less than two percent per 1,000 hours [<2%/1,000 h], operating on simulated synthesis gas). Data from this test were used to estimate the performance and cost of the Baseline System.

The current Phase II effort is to deliver a greater than (>) 15 kW SOFC stack incorporating the cumulative technology advancements and developments of the Phase I and II programs. The stack shall be tested in accordance with the guidance provided in the DOE-approved test plan and the SECA Minimum Requirements, and the performance and cost evaluated with respect to the metrics specified therein. The stack deliverable shall be technically and economically viable for aggregation into a greater than or equal to (≥) 250 kW fuel cell power module, which in turn would serve as a building block for a >100 MW IGFC system.

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PROJECT FACTS

Fuel Cells

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PROJECT DURATION

Start Date	End Date
09/01/2009	09/30/2013

COST

Total Project Value
$27,902,987

DOE/Non-DOE Share
$20,274,432/$7,628,555

AWARD NUMBER

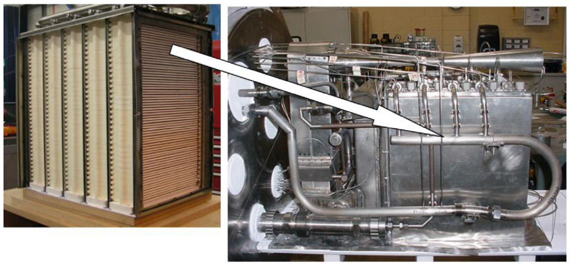
FE0000303

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The ultimate goal of this project is to develop SOFC technology suitable for use in >100 MW IGFC systems. Primary objectives of the project are as follows:

- Reduce SOFC-based electrical power generation system cost to ≤ $700/kW (2007$) for a >100 MW IGFC power plant, exclusive of coal gasification and CO_2 separation subsystem costs and with the associated stack cost at <$175/kW.
- Achieve an overall IGFC power plant efficiency of ≥50 percent, from coal (higher heating value, or HHV) to alternating current power (inclusive of coal gasification and carbon separation processes).
- Reduce the release of CO_2 to the environment in an IGFC power plant to ≤10 percent of the carbon in the coal feedstock.
- Increase SOFC stack reliability to achieve a design life of >40,000 hours.



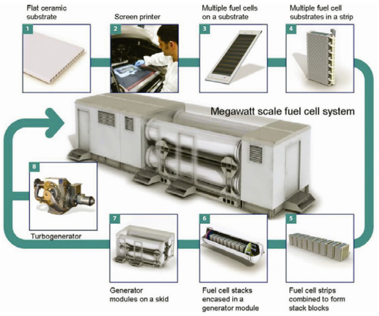
Assembly of 5 LGFCS SOFC strips into a block configuration (left) having a nominal power output of 19 kW and inclusion within the pressurized test rig (right) that incorporates product-level system technology and operates at conditions representative of future commercial systems.

Accomplishments

- A next-generation cell technology having an area specific resistance of 0.29 ohm per square centimeter was selected for the ~10 kW to ~20 kW block-scale durability and reliability metric tests. The cumulative power density improvement has been 73 percent since the beginning of the program.
- Durability testing of the selected cell technology under system relevant conditions has shown an average power degradation rate of <1%/1,000 h in testing out to 16,000 hours. Key degradation mechanisms have been identified with candidate optimized cell layers being screened for further reduction in the degradation rate to work towards meeting the longer-term goal of 40,000-hour life
- A next-generation stack technology utilizing redesigned manifold components for improved fuel distribution and substrates with increased permeability characteristics has been demonstrated. Combined these changes are enabling stack testing at the 80 percent fuel utilization target.
- A new pressurized block test rig in Canton, OH, has been commissioned and a second rig in the United Kingdom has been modified to accommodate the next-generation stack technology for the metric tests.
- A Phase 1 Factory Cost Report incorporating all the subsystems for the 100 MW power modules of the IGFC power plant was submitted showing costs at under $700/kW.
- A metric test consisting of 2 strips with total output of 7.6 kW demonstrated a power degradation of 0.54%/1,000 h through 2,100 hours of testing. A second metric test of 5 strips with output of ~19 kW is demonstrating a similar degradation rate through 1,400 hours of test time, with testing scheduled for 5,000 hours.
- Optimized LSM-based cathodes show improved phase uniformity and microstructure stability through an accelerated testing protocol, providing resolution to a key degradation mechanism identified in tests that have extended beyond 8,000 hours. These cathodes will be a further screened under the fully representative system and product conditions available in the block test rigs used for metric tests.
- Detailed mechanical property characterization and analysis of the porous substrate support structure by ORNL has revealed promising slow crack behavior that can provide for high structural reliability over the required lifetimes. Extension of the mechanical property database for all the ceramic components of the strip continues.

Benefits

The SOFCs program will ultimately enable fuel cell-based, near-zero emission coal plants with greatly reduced water requirements and capable of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achievement of this goal will have significant impact for the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology, accompanied by risks higher than the private sector initially can accept. In parallel, SECA Industry Teams will take advantage of the inherent scalability and fuel flexibility of SOFCs in seeking nearer-term, smaller-scale commercial applications for this efficient, environmentally-friendly technology, which has less risk than a first-of-a-kind full-scale IGFC system. Success in these spin-off applications (e.g., distributed generation, military, etc.) will further SOFC technology advancement and widespread commercial deployment through the resultant manufacturing and operational experience.



Schematic of the pressurized 1 MW LGFCS distributed power generation. SOFC system being investigated for adoption into an IGFC power plant.

FE0000303 May 2013

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PROJECT FACTS

Fuel Cells

Synchrotron X-Ray Studies of SOFC Cathodes—Argonne National Laboratory

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Argonne National Laboratory's (ANL) project was selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

The performance of SOFCs is strongly influenced by the nanoscale structure and chemistry of electrode materials under operating conditions. SOFCs are operated at elevated temperatures and at near atmospheric pressure, which makes the utilization of traditional surface science techniques, typically requiring vacuum conditions, difficult. ANL is advancing the state of the art in high-pressure, high-temperature surface science by employing X-ray scattering and spectroscopy techniques to characterize the surface chemistry and structure of SOFC cathode materials at elevated temperatures (up to 900 degrees Celsius [°C]), in controlled oxygen partial pressures (including air), and under electrochemical loads.

Project Description

ANL will expose model cathode thin films to synchrotron X-rays to better understand the role of cathode surface chemistry, crystallography, and electronic structure. Researchers will examine the dynamic structural and chemical changes that occur at the cathode side of a fuel cell under conditions that simulate actual operating conditions. The studies being performed in this project provide the needed understanding of in situ-ex situ correlations. The results also enable the development of molecular-level models for stimulating the rational design and development of high-performance cathode materials.

Goals and Objectives

The goal of this project is to improve the performance of SOFCs by measuring the atomic and chemical state of cathode materials under typical operating conditions, by correlating those measurements with other ex situ results, and by developing cathode modifications that will accelerate the oxidation reduction reaction and oxygen transport to the fuel cell electrolyte.

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PARTNERS

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PERIOD OF PERFORMANCE

Start Date	End Date
10/01/1995	09/30/2013

(annual continuations)

COST

Total Project Value
$10,780,000

DOE/Non-DOE Share
$10,780,000 / $0

AWARD NUMBER

FWP49071

U.S. DEPARTMENT OF ENERGY

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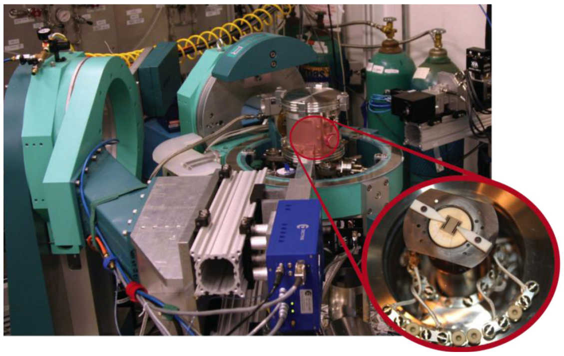
In Fiscal Year 2013, ANL's objectives are as follows:

- Perform in situ X-ray characterizations of cathode materials at the Advanced Photon Source including:
    - studies of surface structure with a focus on the effect of atmospheric impurity components such as CO_2 and H_2O,
    - studies of the cathode/electrolyte interface that is not accessible to standard surface techniques,
- Integrate electrochemical data from in situ X-ray measurements with NETL SOFC modeling efforts,
- Examine the synthesis, atomic level stability, and activity of model infiltrants, and
- Monitor cation migration during cathode aging studies.

Accomplishments

- Determined trends for strontium surface segregation in lanthanum strontium manganite ($La_{1-x}Sr_xMn_{O3}$; LSM), lanthanum strontium cobaltite (La_1-$_xSr_xCoO_3$; LSC), and lanthanum strontium cobalt ferrite (La_1-$_xSr_xCo_1$-yFe_{O3}; LSCF) as a function of temperature and oxygen partial pressure. In doing so, equilibrium, high-temperature results were compared with room temperature non-equilibrium measurements.
- Demonstrated the utility of resonant X-ray scattering techniques and inelastic X-ray measurements for probing the chemical state of materials under conditions approximating those of operating SOFCs.
- Completed X-ray scattering and spectroscopy experiments comparing LSM (011) on yttria-stabilized zirconia (YSZ) (111) that were electrochemically conditioned in situ and ex situ. Ex situ conditioned samples were found to be more electrochemically stable when subject to the same applied potential for further experiments.
- Demonstrated that surface strontium (Sr) segregation on LSM (011) on YSZ (111) is dependent on the distance from the contact wires under cathodic potential. Strontium was found to segregate in areas of the LSM thin film that is less active under potential.
- Found that LSC (011) without a gadolinium-doped ceria (GDC) buffer layer reacts with YSZ (111) forming a resistive layer. LSC (001) on a GDC (001) buffer film was found to decompose if the GDC film is less than 60 nanometers thick.



The environmental chamber mounted on the 12ID-D diffractometer at the Advanced Photon Source. The inset shows the sample that is within the beryllium windowed chamber.

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- Discovered that the LSCF (001) surface has a different crystal structure than bulk LSCF, and determined the sensitivity of the surface reconstruction to temperature and oxygen partial pressure (pO_2).
- Developed a detailed model of the surface polarization and position-dependent current for thin-film cathodes with wire electrodes. This included measuring and modeling the lateral potential drops from an LSCF on YSZ thin film when using a series of wires as current collector.
- Found that, upon high temperature annealing, Sr segregates to the surface, new phases form, and there are chemical shifts on the surfaces of LSCF films grown on YSZ (111) or GDC/YSZ (001) with a strong dependence on the distance from the electrode contact.
- Demonstrated that a thin LSM overlayer increases stability of LSCF films compared to bare LSCF films without the overlayer under similar annealing conditions.
- Determined the lattice parameter and electrical conductance of thin LSCF films as functions of temperature, pO_2, and electrochemical potential.
- The effects of long-term applied electrochemical potential on the surface structure and chemical state of pulse laser deposited thin-film cathodes were measured.
- A symmetric SOFC cell for ultra-small angle X-ray scattering studies was designed and constructed. The cell was used to determine the baseline porosity of sintered cathodes in preparation for atomic layer deposition infiltration studies.
- Determined oxygen exchange rates in LSCF films based on conductivity and lattice parameter relaxation rates when cathodic/anodic potentials are applied.
- Observed that Co and Sr segregate to the surface of LSCF film while Fe and La desegregate at operating temperature at open circuit potential (OCP).
- Observed that only Co segregates and desegregates under electrochemical biases; Co remains segregated under OCP and anodic electrochemical biases while it desegregates under cathodic bias (decreased oxygen vacancies).
- In situ ultra-small angle X-ray scattering measurements show that the average size of the porous cathodes increases rapidly above 900 °C and, albeit slowly, increases even at 800 °C implicating a slow degradation of active surface area during extended operations.

Benefits

The ANL project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology accompanied by risks higher than the private sector initially can accept.

FWP49071, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Solid Oxide Fuel Cell Cathodes: Unraveling the Relationship among Structure, Surface Chemistry, and Oxygen Reduction—Boston University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture

The Boston University (BU) project was competitively selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Many of the specific details of the oxygen reduction reaction in a SOFC cathode are not completely understood. Surface chemistry directly influences the nature of oxygen reduction reaction pathways and the rates at which the individual processes proceed. This project will attempt to clarify the cause and effect relationships in oxygen reduction processes through correlations between the chemistry and structure of oxide surfaces to provide valuable guidance in improving cathode performance.

Project Description

In this cathode surface science project, BU will study deposition of epitaxial thin-film cathodes, heteroepitaxial thin film layers of selected cathode materials, and polycrystalline thin-film cathodes. The chemical, crystallographic, and electronic structure of cathode surface materials will be characterized. Epitaxial methods grow one layer of crystals on another of the same structure. Heteroepitaxial technology is a single-crystal layer grown on a different material and is often used to grow crystalline films of materials for which crystals cannot otherwise be obtained and to fabricate integrated crystalline layers of different materials.

BU will acquire surface-specific chemical and structural data on heteroepitaxial thin films of lanthanum strontium manganite (LSM) and lanthanum strontium cobalt ferrite (LSCF) cathodes on single crystals of yttria-stabilized zirconia (YSZ) and YSZ coated with a barrier layer of rare-earth doped ceria such as yttrium oxide (Y_2O_3)-doped cerium dioxide (CeO_2) (YDC) electrolytes. This is being accomplished using a combination of analytical spectroscopic techniques and transmission electron microscopy (TEM). BU will also employ soft X-ray spectroscopies (X-ray emission spectroscopy [XES]/ X-ray

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PARTNERS

None

PROJECT DURATION

Start Date	**End Date**
10/01/2008	03/31/2013

COST

Total Project Value
$856,014

DOE/Non-DOE Share
$675,001/$181,013

AWARD NUMBER

NT0004104

U.S. DEPARTMENT OF ENERGY

absorption spectroscopy [XAS]) to correlate the surface chemical composition and the charge state of the manganese ion to changes in the thin film polarization resistance. The overall goal is to understand the role of surface atomic and electronic structure in the oxygen reduction reaction.

Goals and Objectives

The goal of this project is to understand the role of surface atomic and electronic structure in the oxygen reduction reaction of SOFC cathodes. Project objectives are as follows:

- Continue deposition of high quality epitaxial and polycrystalline cathodic thin films.
- Use in situ x ray chamber to obtain high-temperature surface structure and composition analysis.
- Obtain kinetics data on oxygen exchange on cathode thin films using impedance spectroscopy.

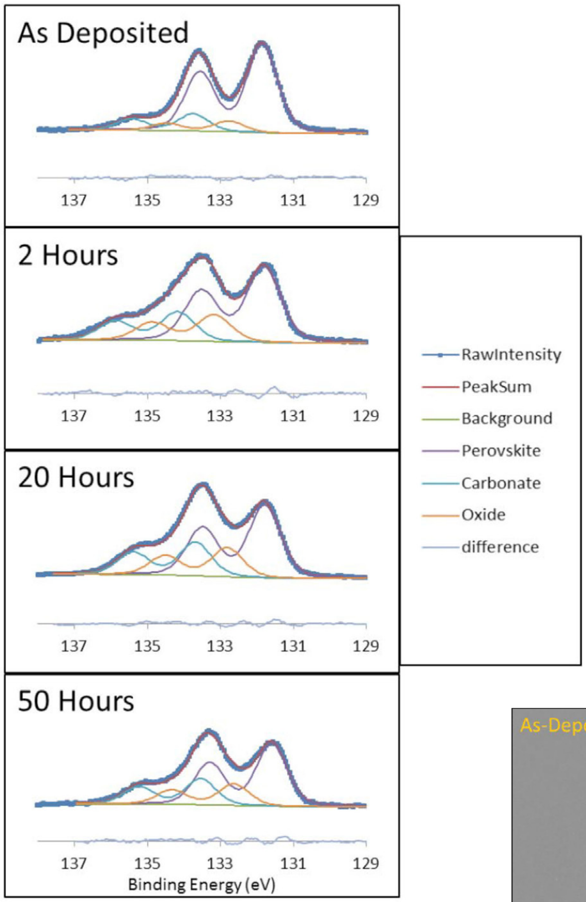


Figure 1. *Curve fitted Sr 3D regions of the HAXPES spectra of LSCF 7328.*

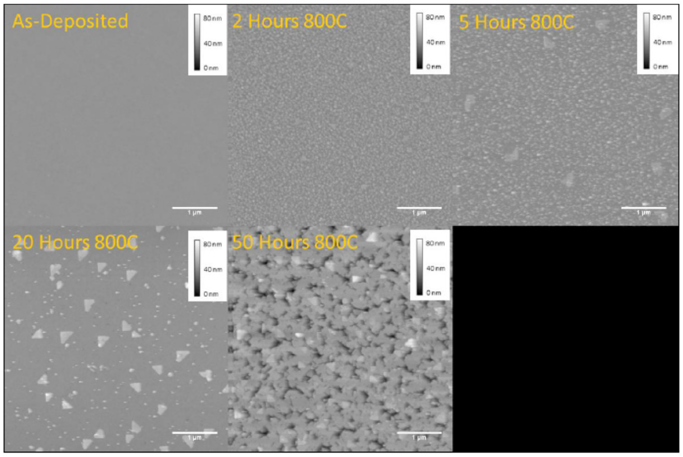
Accomplishments

- Total reflection X-ray fluorescence data clearly show diminished A/B ratios at the surface of LSM thin films.
- Oxygen adsorption, surface diffusivity, and incorporation reaction rate coefficients have been measured for polycrystalline thin films.
- Hard X-ray photoelectron spectroscopy (HAXPES) technique was employed to clarify the cation segregation and surface evolutions effects in LSCF including the formation of surface strontium carbonate.
- Impedance spectroscopy has been used to separate the relative importance of surface and bulk diffusion in LSCF cathodes.

Benefits

The BU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

Figure 2. *Atomic force microscopy images of LSCF 7328 thin films.*



NT0004104 May 2013

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PROJECT FACTS

Fuel Cells

Unraveling the Role of Transport, Electrocatalysis, and Surface Science in the SOFC Cathode Oxygen Reduction Reaction—Boston University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture

The electrochemical performance of SOFCs can be substantially influenced by mass and charge transport of reaction species at cell interfaces. Unfortunately, the interplay among the structural, chemical, and electronic properties of interfaces, transport phenomena, and catalytic activity is unclear, particularly in SOFC cathodes.

Boston University's (BU) project was competitively selected to acquire the fundamental knowledge and understanding of cell interfaces to facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

BU will build on prior SECA support by employing a combination of experimental and computational tools to develop newer cathode and electrocatalyst materials employed in increasing levels of complexity:

- Fabrication of micropatterned cathode thin films and heteroepitaxial thin films (crystalline films grown by deposition on differing crystalline material) of various cathode materials on suitably chosen electrolyte substrates.
- Use total reflection X-ray fluorescence and hard X-ray photoelectron spectroscopy to probe the surface composition and oxidation states and the chemical environment of the surface cations and anions.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2012	09/30/2014

COST

Total Project Value
$632,354

DOE/Non-DOE Share
$499,999 / $132,355

AWARD NUMBER

FE0009656

U.S. DEPARTMENT OF ENERGY

- Use point defect models to relate compositional changes to changes in oxygen vacancy concentrations and distribution of oxidation states for multivalent elements such as manganese.
- Experimentally measure surface exchange and diffusion coefficients using the oxygen isotope ^{18}O.
- Use AC impedance spectroscopy on micropatterned electrodes of selected cathode materials, with transport phenomena modeling using MATLAB-SIMULINK and/or COMSOL.
- Use transmission electron microscopy to probe the buried interfaces between the cathode and electrolyte before and after polarizing the interface.
- Use density functional theory to calculate the most facile pathways for the oxygen reduction reaction (ORR) on several cathode material surfaces, while also exploring the rates of the ORR under various experimental conditions.
- Use experimental and theoretical research on thin film cathodes to narrow choice of cathode material and composition.
- Fabricate and test single cells using selected cathode materials. The power density and performance degradation metrics will be used to evaluate cathode material and composition.
- Use polarization loss modeling to deconvolve (i.e., disentangle mixed information) the cathodic concentration and activation polarization values.

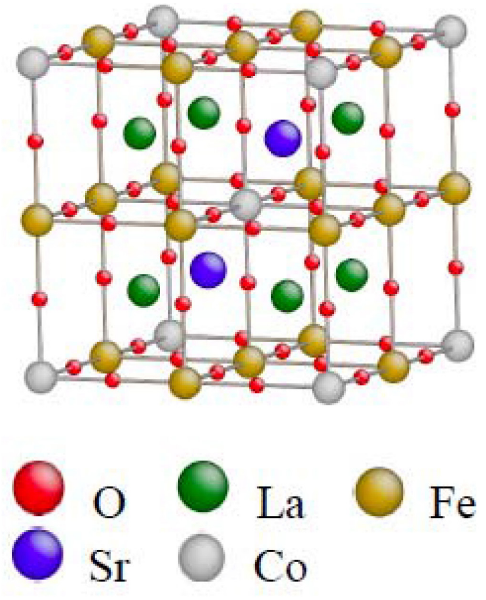

Figure 1. *Basic LSCF structure for DFT calculations.*

- Characterize porous microstructure of the cells to quantify the effective surface area and triple phase boundary length.
- Optimize materials choice and cathode microstructure to demonstrate a 50 percent improvement in performance.

Goals and Objectives

The goal of this work is to deepen the fundamental knowledge and understanding of SOFC interfaces to greatly improve electrochemical performance while meeting SECA cost, stability, and lifetime targets at the cell level. Specific objectives are as follows:

- Separating and identifying the influence of oxygen surface adsorption, transport pathways, electron transfer reaction, and incorporation into the electrolyte on the overall ORR.
- Identifying the role and time evolution of the cathode surface and buried layer interface structure, surface electronic properties, surface composition, and the oxidation state of the transition metal ions during the oxygen reduction process.
- Using new materials combinations and architectures based on the knowledge gained from the above objectives to demonstrate a 50 percent improvement in performance in maximum power densities of cells compared to baseline cells employing state-of-the-art materials and cell stability that shows 0.1 percent or less degradation in cell performance per 1,000 hours of use.

Accomplishments

- Fabricated three different target compositions of lanthanum strontium cobalt ferrite (LSCF).
- Performed preliminary calculations of cation segregation effects in LSCF and stability calculations using density functional theory (DFT).

Benefits

The BU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

FE0009656, May 2013

SOFC Cathode Surface Chemistry and Optimization Studies—Carnegie Mellon University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Carnegie Mellon University's (CMU) project was selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

There is relatively little known about the relationships between the fundamental chemistry and structure of oxide surfaces and their electrochemical performance on SOFC cathodes. This project will probe the nature of atomic-scale surface chemistry and microstructure on ideal thin film cathodes and determine key correlations between the chemical, structural, and electronic structure to kinetic mass transfer parameters indicative of the electrocatalytic activity for oxygen (O_2) reduction reactions.

Project Description

The cathode in SOFCs is responsible for the reduction of O2 gas and its incorporation into the electrolyte. When SOFCs are operated at specific current densities, the O2 incorporation or uptake process can contribute significantly to limiting the performance of the system. Two major options exist for improving the cathode performance by specifically targeting the O2 incorporation process: changing the base component material or adding a catalyst to the existing framework. This work will use both approaches by (1) developing an experimental program that allows probing the nature of atomic-scale surface chemistry and its role in oxygen incorporation in lanthanum strontium manganese oxide (LSM), lanthanum strontium cobalt oxide (LSC), lanthanum strontium iron oxide (LSF), lanthanum strontium cobalt iron oxide (LSCF), and related cathode materials; and (2) determining the optimal catalyst chemistry from both an activity and stability perspective.

CMU is providing high quality surface engineered thin films to collaborators working on identifying surface chemistries and properties that will lead to improved electrocatalytic performance.

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PARTNERS

Argonne National Laboratory
Massachusetts Institute of Technology
University of Nevada, Las Vegas

PROJECT DURATION

Start Date	**End Date**
09/30/2008	03/29/2013

COST

Total Project Value
$1,100,783

DOE/Non-DOE Share
$888,588/$212,195

AWARD NUMBER

NT0004105

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The goal of this project is to understand the role of cathode surface properties on SOFC performance.

Current project objectives are:

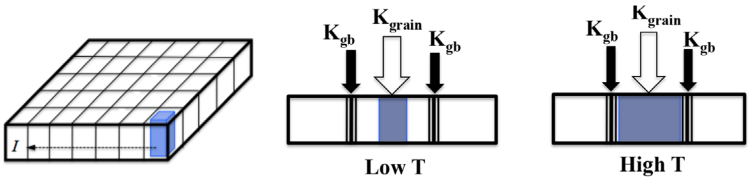
- Develop samples of cathode materials having specific surface structures and chemistries using thin film preparation methods, as requested by collaborators.
- Provide LSM, LSC, and LSCF samples for surface characterization to collaborators at Argonne National Laboratory's Advanced Photon Source (APS), Massachusetts Institute of Technology (MIT), and University of Nevada, Las Vegas (UNLV).
- Determine the activation energy of the chemical surface exchange coefficient (k_{chem}) for LSM (100), (110), and (111) at different thicknesses and on different substrates. The (100), (110), and (111) refer to a crystal's orientation, which determines the crystalline material's surface properties and therefore determines how it reacts with other materials.
- Refine investigations into the O_2 uptake kinetics in thin film samples. Specifically, make correlations between the extended defect populations and O_2 exchange for (110) textured LSM films on yttria-stabilized zirconia (111).
- Determine the O_2 exchange kinetics for high index samples such as (621) LSM.

Accomplishments

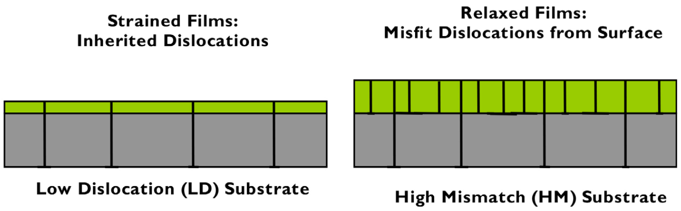
- Developed single-crystal, epitaxial, textured, and polycrystalline thin films of LSM, LSC, and LSCF with low roughness values on both insulating and electrolytic substrates of various geometries that were used in both in-house and collaborators' experimental facilities to understand the nature of the surface chemistry/reactivity of cathode materials.
- Characterized thin film samples at the APS as a function of temperature (T), pressure (P), and electrochemistry for their surface compositions, structures, and charge states; at MIT for their local electronic properties using scanning tunneling spectroscopy and electrochemical properties with electrochemical impedance spectroscopy; at UNLV with Auger electron spectroscopy and x ray photoelectron spectroscopy, and at CMU with x ray diffraction (XRD), atomic force microscopy (AFM), electrical conductivity relaxation (ECR), and Kelvin probe spectroscopy.
- Demonstrated that the activation energy of 600 nanometer (nm) thick LSM films was between ≈0.8 and ≈1.2, depending on the orientation of the crystal.
- Demonstrated that relaxed films of the (110) orientation had the largest k_{chem} value in SOFC operating conditions owing to their high activation energy (and their large high-temperature intercept value on an Arrhenius plot).
- Demonstrated that the activation energy of 600 nm thick LSM films was between ≈0.75 and ≈1.5, depending on the crystal quality and strain state of the film, as well as the temperature itself.
- Established that the strained (100) films had the highest exchange rate of all measured (100) films, indicating strain can be an important enhancing factor in SOFCs. Strained films had significantly different and greater activation energies than relaxed films.
- Used two surface exchange values to fit the response of textured (110) films, with the area each contributed to being a function of temperature, and with the large activation energy contributing the most to the high temperature SOFC response.
- Established that extended defects play a major role in the O_2 exchange at intermediate temperatures.

Benefits

The CMU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Left: Schematic of grain boundaries inside textured film. The centered grain is filled in the lower right. The dashed line indicates in-plane current direction, indicating the parallel paths.
Below: Schematic of two possible oxygen flux pathways on the surface: one through intrinsic surface/grain, the other through variant/grain boundaries.



NT0004105, May 2013

Phase III Xlerator Program: Electro-deposited Mn-Co Alloy Coating for Solid Oxide Fuel Cell Interconnects—Faraday Technology

Background

Based on preliminary cost analysis estimates, Faraday Technology has shown that its FARADAYIC™ electrodeposition process for coating interconnects is cost competitive. Funding from the American Recovery and Reinvestment Act (ARRA) under the Small Business Innovation Research (SBIR) Phase III Xlerator Program will be directed toward developing, optimizing, and validating the FARADAYIC process as an effective and economical manufacturing method for coating interconnect materials with a manganese-cobalt (Mn-Co) alloy for use in solid oxide fuel cell (SOFC) stacks.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) whose mission is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

Electrodeposition is widely considered an inexpensive, scalable, non-line-of-sight industrial manufacturing process, and the addition of FARADAYIC's pulse/pulse-reverse processing further enhances the electrodeposition process through the control of grain size, morphology, stress, and composition of the deposits. In addition to reducing SOFC component manufacturing costs, this technology will mitigate SOFC performance losses by minimizing SOFC performance degradation mechanisms due to chromium diffusion from the interconnect, increase the lifetimes of SOFC systems, and enable more flexibility in the flow field designs, bringing SOFCs one step closer to being a commercially viable alternative energy source. Therefore, the anticipated outcome of this Phase III Xlerator program is the development of an inexpensive manufacturing process for coating interconnect materials used in SOFC stacks with a Mn-Co alloy that is subsequently converted to a conductive spinel coating. The intent of the process development is to prepare as-plated Mn-Co interconnects that can be directly inserted into the SOFC stack without post deposition annealing steps to produce the $(Mn,Co)_3O_4$ spinel coating, thus minimizing the number of production steps and the total manufacturing cost. On-cell tests with button cells will be performed by subcontractor West Virginia University (WVU) to determine the coating electrical properties and their effect on cell performance.

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Fuel Cells

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PARTNERS

West Virginia University

PERFORMANCE PERIOD

Start Date	**End Date**
10/01/2010	09/30/2013

COST

ARRA Funded

Total ARRA Project Value
$992,392

DOE/Non-DOE Share
$992,392 / $0

Government funding for this project is provided in whole or in part through the American Recovery and Reinvestment Act.

AWARD NUMBER

FE0006165

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The specific objectives of the Phase III Xlerator program are as follows:

- Continued development, optimization, and validation of the FARADAYIC electrodeposition process for 4"x4" single and dual sided grooved interconnect materials;
- Development of a layered coating structure of Co and MnO_x that could reduce T441 stainless steel surface exposure to oxygen and prevent chromium (Cr) from diffusing to the coating surface where it could potentially poison the SOFC;
- Mitigation of Cr diffusion by determining the controlling mechanism through in situ high-temperature, X-ray diffraction (XRD) measurements and X-ray photoelectron spectroscopy (XPS) depth profiling;
- Development of a more comprehensive economic assessment of the electrodeposition coating process as it relates to interconnect manufacturing; and
- Enhancement of the program's commercialization plan through close collaboration with SECA SOFC developers.

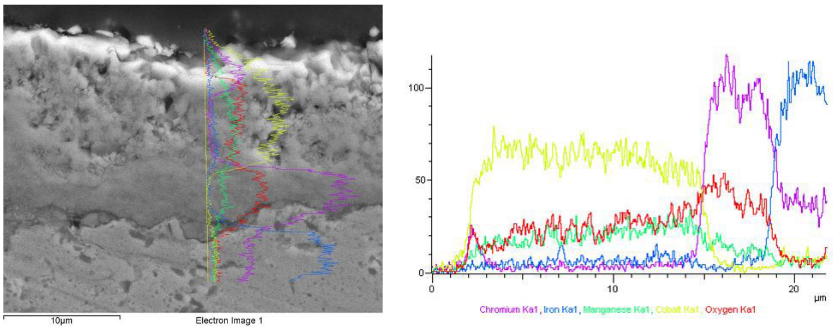
Photograph of pilot-scale electrodeposition cell for coating industrial scale SOFC interconnects.

Accomplishments

- Completed fabrication of a small FARADAYIC electrodeposition cell similar to the one used for the SBIR Phase I program work (a prior agreement with the DOE) for Mn-Co alloy deposition onto 2"x2" and 1"x1" planar T441 stainless steel interconnect substrates for West Virginia University.
- Commissioned the tube furnace located on-site in Faraday's pilot-scale facility for use in long term, high temperature thermal evaluation
- Completed program milestone 1, installation of a pilot-scale electrodeposition cell for coating industrial scale interconnects.
- Completed program milestone 2, long-term, high-temperature thermal evaluation of coatings, in which Mn-Co spinel coated samples exhibited minimal chromia scale growth, good scale adhesion and low area specific resistance values.
- Completed program milestone 3, process development of 100 cm^2 planar interconnects in which coated samples exhibited thickness and chemical compositional uniformity.
- Initiated program milestone 4, process development for 100 cm^2 interconnects containing gas flow field features by performing coating activities and evaluating coated samples by scanning electron microscope / energy dispersive spectroscopy.
- Initiated program milestone 5, long-term on-cell performance evaluation by coating 16 cm^2 button cells for insertion into test equipment.

Benefits

The SBIR program is positioned to leverage the agility and innovative competencies of small businesses. It is through this program that a small company, Faraday Technology, in Clayton, Ohio has developed a breakthrough technology for the electrodeposition process of coating interconnects. ARRA investment in this small business will likely result in more U.S. jobs, and a successful coating process that would help reduce SOFC stack manufacturing costs would help enable an economically viable alternative energy option for the commercial energy sector. The technical success of this project is dependent upon scaling the process up to full-size interconnects for testing under ideal SOFC operating conditions by potential commercial partners.



SEM image (left) and EDS line scan data (right) for Mn-Co coated T441 stainless steel sample exposed to an air atmosphere at 800 °C for 2000 hours. Image shows the good adhesion etween the 4 µm chromia scale and T441 stainless steel.

FE0006165, May 2013

Fundamental Investigations and Rational Design of Durable High-Performance SOFC Cathodes—Georgia Institute of Technology

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of solid SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Cathode durability is critical to long-term SOFC performance for commercial deployment. Current state-of-the-art SOFC cathode materials are subject to degradation mechanisms and various contaminants under realistic operating conditions (ROC) that affect their stability.

The Georgia Institute of Technology (Georgia Tech) fuel cell project was competitively selected to study the durability of cathode materials under a diversified portfolio for anode-electrolyte-cathode development. Georgia Tech will characterize new materials and electrode structures required to mitigate the stability issues. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

Georgia Tech will use specially-designed electrodes and cells, such as electrodes of thin films and patterned electrodes, to study the electrochemical response of lanthanum strontium cobalt ferrite (LSCF) cathodes under ROC, to probe and map contaminants on the LSCF, and to characterize the correlation between electrochemical performance and microstructure/morphology of LSCF cathodes as well as their evolution over time. A range of characterization tools will be used to study the chemical and structural changes during fuel cell operation. Electrochemical techniques, such as impedance and DC polarization, will be intensively applied to characterize the cathode performance, which will be correlated with the structural and compositional evolution of the LSCF cathode under ROC. Proper characterization, modeling techniques, and prediction tools will be used to help in formulating an effective strategy to mitigate the stability issues and predict new catalyst materials that can enhance the stability of LSCF. Finally, the performance and stability of the modified LSCF cathode will be validated in commercially available cells under ROC.

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PARTNERS

None

PERFORMANCE PERIOD

Start Date	End Date
09/20/2012	09/19/2015

COST

Total Project Value
$625,000

DOE/Non-DOE Share
$500,000 / $125,000

AWARD NUMBER

FE0009652

U.S. DEPARTMENT OF ENERGY

The microstructure, morphology, and chemistry of LSCF cathodes will be carefully characterized and correlated with their electrochemical behavior under ROC to unravel the degradation mechanism. In particular, in situ and ex situ characterization of surface morphology and topography via atomic force microscopy, surface species via Raman spectroscopy, and surface phases via X-ray diffraction and Raman spectroscopy will be performed as a function of time. The well-defined cathode configuration will provide a unique platform for morphology observation, composition analysis, and in situ characterization. The resulting mechanistic understanding will guide the formulation of an effective strategy to mitigate the stability issues. Then multi-scale modeling and simulation will be used to suggest new cathode materials for experimental verification.

Goals and Objectives

The goal of this work is to systematically characterize the degradation mechanisms of LSCF cathodes and to establish the scientific basis for rational design of new materials and electrode structures to mitigate the stability issues caused by the contaminants commonly encountered under realistic operating conditions. Specific objectives are as follows:

- Unravel the degradation mechanism of LSCF cathodes exposed to different types of contaminants under ROC by performing in situ and ex situ measurements on specially designed cathodes.

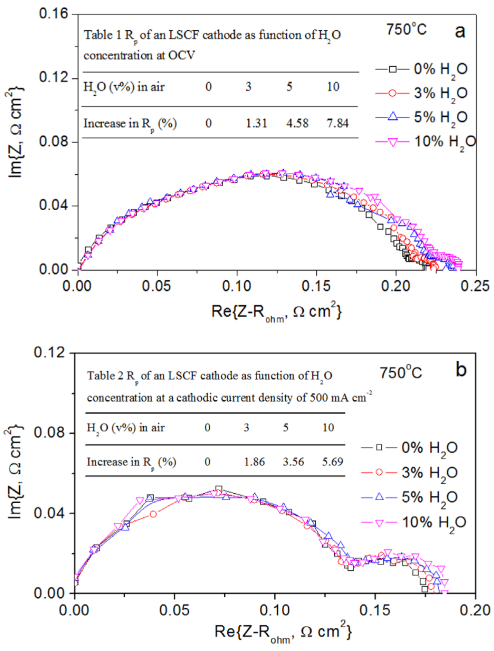

Figure 1. Impedance spectra of an LSCF cathode in humidified air with different concentrations of water vapor (0, 3, 5, and 10%): (a) under open circuit voltage (OCV) and (b) at a constant cathodic current density of 500 mA cm^{-2}. A symmetrical cell with a three-electrode configuration was used for the impedance measurements at 750 °C. The bulk resistance of the cell (from the electrolyte and the lead wire) was removed from the spectra for clarity in comparison. The change in R_p with the concentration of water vapor is summarized in the inserted Tables 1 and 2.

- Examine the microstructural and compositional evolution of the LSCF cathodes as well as the cathode/electrolyte interfaces under ROC.
- Correlate the fuel cell performance instability/degradation with the microstructural/morphological evolution and surface chemistry change of the cathode under ROC.
- Explore new catalyst materials/electrode structures to enhance the stability of the LSCF cathode under ROC.
- Validate the long term stability of the modified LSCF cathode in commercially available cells under ROC.

Accomplishments

- Established a new testing procedure for cells with porous electrodes, thin film electrodes, and pattern electrodes upon exposure to different contaminants including water (H_2O), CO_2, and chromium.
- Characterized the electrochemical behavior of porous LSCF cathodes exposed to H_2O or CO_2, and investigated the effect of contaminant concentration and polarization condition on performance of the LSCF cathodes.
- Quantified the performance change of the porous LSCF cathode as the cathode gas was switched from dry air to the air containing H_2O or CO_2, eliminating the effect of the performance variation from cell to cell, and the effect of degradation caused by other time-dependent degradation mechanisms.
- Fabricated the LSCF thin film cells with desired thickness and composition using a radio frequency sputtering technique, which will be used for further electrochemical characterization.

Benefits

The Georgia Tech project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability to capture 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

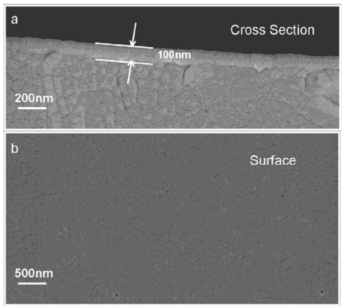

Figure 2.
(a) A cross-sectional and (b) a surface view of the LSCF thin film deposited on a gadolinia-doped ceria substrate by a radio frequency sputtering technique after annealing at 800°C for 1 hour.

FE0009682, May 2013

Chemistry of SOFC Cathode Surfaces: Fundamental Investigation and Tailoring of Electronic Behavior—Massachusetts Institute of Technology

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The Massachusetts Institute of Technology (MIT) project was competitively selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

The relation of surface cation chemistry and surface electronic structure to oxygen reduction reaction kinetics remains unanswered in the search for highly active cathodes for SOFCs. In this project, the surface properties of some catalytic cathode materials are characterized with a variety of advanced analytical techniques and the results are compared with the known reactivity of these materials to understand how and why some materials work better than others as SOFC cathodes.

Project Description

This project will demonstrate the role of cathode surface properties in SOFC performance. The surface properties of some catalytic cathode materials will be characterized with a variety of advanced analytical techniques and the results will be compared with the known reactivity of these materials to understand how and why some SOFC cathode materials work better than others. A multidisciplinary effort will be employed integrating advanced fabrication and surface-sensitive characterization techniques. Dense thin-film, multi-component, cathode structures with atomic-level control of the surfaces will be formed using the pulsed laser deposition technique provided by Carnegie Mellon University under a separate Cooperative Agreement. The structural and compositional nature of the model cathodes will be characterized with advanced analytical characterization methods, including high-temperature scanning tunneling microscopy and spectroscopy and high resolution auger electron spectroscopy at MIT. The University of Nevada–Las Vegas will study the laterally averaged surface chemistry and electronic structure using soft X-ray and electron spectroscopy. The results from the project will be used to propose improved SOFC cathode surfaces with enhanced electrochemical performance and low degradation.

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Fuel Cells

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PARTNERS

University of Nevada – Las Vegas

PROJECT DURATION

Start Date	End Date
10/01/2008	03/31/2013

COST

Total Project Value
$1,000,000

DOE/Non-DOE Share
$800,000/$200,000

AWARD NUMBER

NT0004117

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The overall goal of this project is to understand the role of cathode surface properties in SOFC performance. Project objectives are as follows:

- Observe local electronic structure, electron tunneling properties, and chemical characteristics of lanthanum strontium manganite (LSM) dense thin-film model cathodes at conditions of elevated temperature and reactive gas environment with oxygen.
- Identify correlations between surface chemical state and electron transfer characteristics on LSM as a function of temperature and thin film strain state that are of relevance to infiltrated cathode microstructure.
- Identify the mechanisms that lead to cation segregation on the surface which degrades the surface reactivity, and propose compositions and conditions that minimize this aging mode.

Accomplishments

- MIT demonstrated the effects of epitaxial strain on the surface cation chemistry and the surface electronic structure of LSM as a model system, both at room temperature and at elevated temperatures. This is important for determining the activity of the cathode surface to oxygen reduction, particularly the electron transfer reactions.

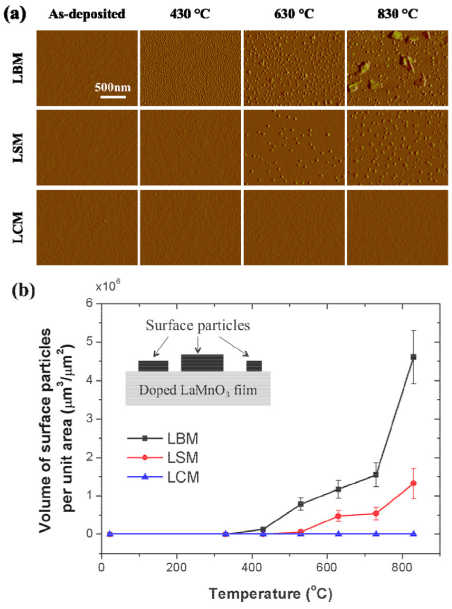

Figure 1. *(a) AFM amplitude images of the Ba-, Sr- and Ca-doped LaMnO$_3$ thin film surfaces as a function of annealing temperature. Each column represents the surface morphology after annealing in air for 1 hour at the temperatures stated on the top. Each row represents the surface morphology of LBM, LSM, and LCM. (b) The volume per unit area of the surface particles, calculated from the AFM images, as a function of annealing temperature for LCM, LSM and LBM.*

- X-ray photoelectron spectroscopy results showed that a greater tendency for strontium enrichment and oxygen vacancy formation is prevalent for tensile-strained LSM surfaces. In particular, the latter is expected to have a role to accelerate the oxygen reduction kinetics on the cathode.
- Scanning tunneling spectroscopy results showed that the tensile strained LSM exhibits a more active state for electron transfer, beneficial for the oxygen reduction process on LSM at high temperature. On the other hand, at room temperature the electronic structure exhibits the presence of an energy gap between the occupied and unoccupied states, favoring a smaller band gap for compressively strained LSM at room temperature. This contrast between the room-temperature and high-temperature data signifies the importance of in situ measurements.
- MIT quantitatively assessed and demonstrated that the mechanism of dopant segregation on perovskite oxides includes both the elastic and electrostatic energy contributions, shown explicitly on the model perovskite compounds, LnMnO$_3$ (host cation Ln = La, Sm, and dopants Ca, Sr and Ba). A smaller size mismatch between the host and dopant cations and a chemically expanded lattice were found to reduce the segregation level of the dopant and to enable more stable cathode surfaces. Ca-doped LaMnO$_3$ was found to have the most stable surface composition with the least cation segregation among the compositions surveyed. Lastly, scanning probe image-contrast showed that the surface chemical heterogeneities made of dopant oxides upon segregation were electronically insulating.

Benefits

The MIT project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

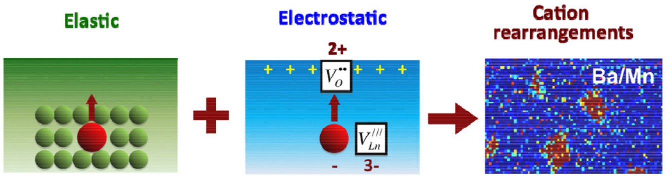

Figure 2. *The mechanism of dopant segregation on perovskite oxides includes both the elastic and electrostatic energy contributions. A smaller size mismatch between the host and dopant cations and a chemically expanded lattice were found to reduce the segregation level of the dopant and to enable more stable and chemically uniform cathode surfaces.*

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PROJECT FACTS

Fuel Cells

Synchrotron Investigations of SOFC Cathode Degradation—Montana State University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture

Montana State University's (MSU) project was selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

SOFC cathodes are responsible for the reaction in which oxygen from the air in a fuel cell is converted into ions that migrate across a solid membrane to react with a fuel to form water or CO_2. A lack of understanding of cathode material degradation under SOFC operational conditions remains a barrier to broad implementation, particularly when the material is lanthanum strontium cobalt iron oxide (LSCF). This project proposes to eliminate that barrier by identifying the causes of cathode degradation and identifying strategies to mitigate cathode degradation.

Project Description

This project will investigate and characterize multiple-scale variations and modifications of the SOFC cathode/electrolyte interface region. These modifications will be correlated to the effects of current, gaseous environment, and possible synergistic effects between them. Correlations will be established between the operating conditions, the degradation, and the observed chemical or structural modifications that are fundamentally responsible for the degradation. Once identified, methods to mitigate or prevent degradation can be proposed and investigated.

In order to reach the objectives, a systematic study of several samples representative of the lanthanum-doped strontium (LSTM)/ yttria-stabilized zirconia (YSZ) and LSTM/gadolinia-doped ceria (GDC) interfaces of SOFCs will be carried out, where TM represents a transition metal. In order to eliminate extraneous effects and to focus on specific parameters, pulse laser deposited (PLD) samples will be used providing consistent characteristics that

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
09/03/2008	09/30/2013

COST

Total Project Value
$656,311

DOE/Non-DOE Share
$525,000/$131,311

AWARD NUMBER

NT0004115

U.S. DEPARTMENT OF ENERGY

should give unambiguous results. The samples will undergo area-specific resistance (ASR) measurements while exposed to a specific combination of current, temperature, and gaseous environment over time. The samples will then undergo careful characterization, first by in-house techniques such as X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), and/or field emission microscopy (FEM). The first characterization steps will serve to quickly and easy implement preliminary investigations to direct future sample experiments and prepare for more advanced characterization by synchrotron-based experiments. The synchrotron experiments will consist of X-ray absorption spectroscopy (XAS) and X-ray resonant scattering (XRS), allowing the examination of LSTM/YSZ or LSTM/GDC interfacial regions in a non-destructive manner.

Goals and Objectives

The goal of this project is to identify degradation mechanisms in SOFC cathode materials.

- Characterize atomic variations and modifications occurring in the nanometer to millimeter range, in the cathode/electrolyte interface region of SOFCs.
- Correlate these modifications to electric potential, ion current, gaseous environment, and characterize any synergistic effects between them.
- Identify the mechanism for strontium segregation in LSCF materials.

Accomplishments

- Determined the cobalt (Co) valence dependence on operational environment for LSCF/GDC sandwich structures. These measurements confirm that in situ valence can be frozen-in during cool down.

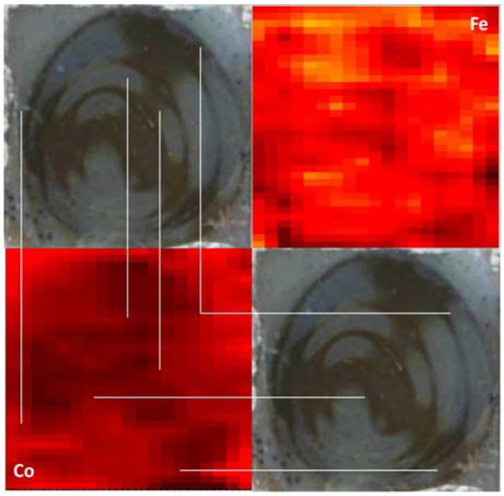

Figure 1: *Comparison of the Co (bottom left) and Fe (top right) mapping with an actual picture (top left, bottom right) of the sample surface of the positive side of sample (with GDC interlayer, 500 mV applied bias during heat treatment). White lines as guide to the eye point out prominent structures in the picture and their counterpart in the map.*

- Determined the spatial variation of the Co valence across the surface of the SOFC and attribute the large variation to the availability of oxygen from the air flow.
- Outlined a mitigation strategy by increasing and stabilizing oxygen vacancy concentrations through co-doping in the near surface region or matching oxygen vacancy concentrations.
- Demonstrated that periodic reverse SOFC operation serves to prolong SOFC lifetimes.
- Demonstrated elemental surface valence determination with a field of view of 10 mm x 10 mm and a spatial resolution of 100 µm x 100 µm.
- Identified large surface Co valence variation between Co^{3+} and Co^{2+} across an LSCF cathode operated over 100 hours at 850 °C and +450 mV bias potential at 75% humidity.
- Developed a method to significantly reduce spatial valence variation with the inclusion of laminar flow across the cathode surface.

Benefits

The MSU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

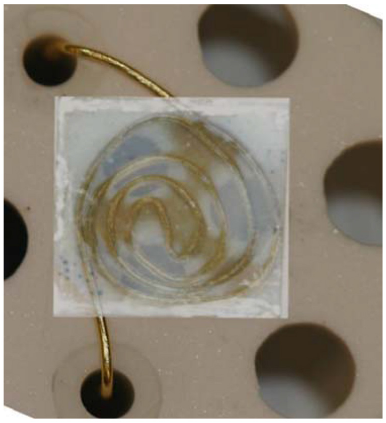

Figure 2: *Overlay of a picture of the sample (positive side, same used in Figure 1) with the positive side of the sample holder. The gold spiral hinders the access of ambient air to parts of the sample, making them appear dark in the picture.*

NT0004115 May 2013

NETL-RUA Fuel Cells Initiative

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The NETL-Regional University Alliance (RUA) Fuel Cell Team performs fundamental SOFC technology evaluation, enhances existing SOFC technology, and develops advanced SOFC concepts in support of the SOFCs program. Research projects are designed to meet critical technology development needs that can be uniquely addressed by NETL-RUA and are broadly focused on investigation of the degradation processes of anode-electrolyte-cathode (AEC) components and cathode materials and microstructural engineering. The research approach for each component task is targeted to address program technology development goals, especially with regard to reducing stack costs, increasing cell efficiency, and increasing stack longevity. The ultimate goal of these research and development efforts is to transfer technology that facilitates commercial acceptance of SOFC technology.

Project Description

Cell and Stack Degradation: Among stack components, the AEC degradation rate is potentially the most influential over the total stack degradation rate. It is also perhaps the most complex in terms of the unique degradative modes, and is also the most susceptible to degradation owing to its central role in the electrochemical process. The AEC is therefore a key component targeted for degradation investigation. Comprehensive models predicting SOFC stack degradation do not exist, or are not sufficiently descriptive to consider all of the primary degradative modes. Due to the complexity and sheer number of degradation processes occurring in the SOFC stack, the present effort to evaluate degradation is initially confined to the AEC structures and materials under commercial consideration. Results of the degradation mode investigation will be incorporated into a computational model that will include only the most prominent degradation modes. Individual degradation modes will be examined with specialized techniques and constituted as mathematical expressions relating dependent AEC parameters (e.g., electrode porosity) to independent operating parameters including operating temperature and local overpotential. This model will provide evolving AEC performance parameter updates on a 40 plus kilohour timescale. Model predictions will be confirmed by comparison to samples prepared in-house and also from samples obtained from industry teams.

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Fuel Cells

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NETL-RUA PARTNERS

Carnegie Mellon University
Penn State
University of Pittsburgh
URS Corporation
Virginia Tech
West Virginia University

PERFORMANCE PERIOD

Start Date	End Date
10/01/2012	09/30/2014

(annual continuations)

COST

Total Project Value
$4,000,000

DOE/Non-DOE Share
$4,000,000 / $0

AWARD NUMBER

FWP-2012.03.04

U.S. DEPARTMENT OF ENERGY

A detailed investigation of the degradation modes in the AEC will facilitate targeted efforts to improve fuel cell longevity, ultimately resulting in decreased system costs. Development of a world-class modeling tool will accelerate AEC materials and structure innovation leading to more commercially relevant SOFC technology.

Cathode Materials and Microstructural Engineering: Cathodes are a primary source of the inefficiency observed in a state-of-the-art anode-supported cell operating at temperatures from 750–800 °C. Owing to the relatively high contribution of cathode overpotential to total cell inefficiency, SOFC research to improve cathode performance can help meet critical program targets for cell cost and efficiency. Conventional cathode microstructural engineering is accomplished through careful control of precursor cathode materials. Using conventional methods, limited variability is available in the final cathode structures. New approaches focus on generation of advanced microstructures that are more conducive to species transport, or methods to apply an engineered cathode at lower cost. These research projects will result in full characterization of performance and durability of the proposed technologies at an intermediate scale. Results will be shared with SECA industry teams, and the most promising technologies will be selected for further scale-up. Methods developed will generate more functional cathode structures to facilitate enhanced cathode performance, and will potentially allow greater tuning of the final cathode architecture. These research efforts will improve cathode performance, thereby resulting in increased cell efficiency and, ultimately, a diminished system cost. Cathode material and structure innovations developed through these projects should be readily transferable to industry.

Accomplishments

- Completed short stack demonstration of infiltration technology in two independent tests with industry teams. Cells were operated for 500 to 1000 hours under industrially relevant conditions.
- Demonstrated two integrated SOFC technology concepts to industrial SOFC manufacturers.
  - Concept 1: Modeled impact of infiltration on cell performance
  - Concept 2: Correlated long-duration structural evolution to performance degradation
- New tools were developed for examination of SOFC performance based on deconvolution of electrochemical impedance spectroscopy.
- Published and submitted more than 10 peer reviewed journal articles and delivered or submitted more than 10 conference presentations.

Benefits

The NETL-RUA project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

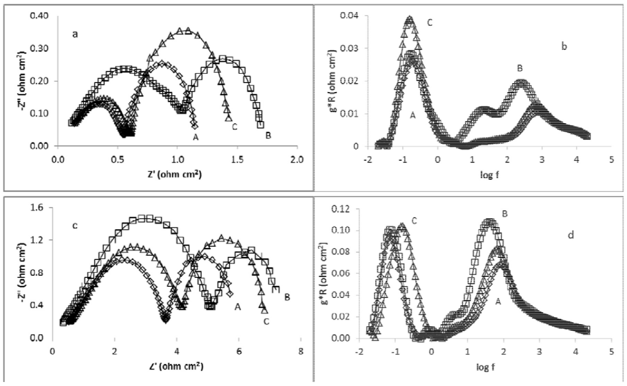
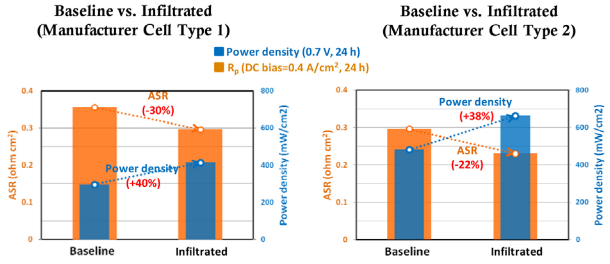


Figure 1: Nyquist plots and deconvolution spectra for Cell 2 at two temperatures and three flows: (A) Normal, (B) low air, (C) low fuel. (a) Nyquist plots at 800 °C. (b) Deconvolution spectra at 800 °C. (c) Nyquist plots at 700 °C. (d) Deconvolution spectra at 700 °C. Nyquists plots are corrected for ohmic resistance and inductance. Deconvolution ordinates are the product of the deconvolution values and the polarization resistance.



ALL CELLS AVERAGE →

	24 h	382 h
ASR	- 24 %	- 28 %
Power density	+ 19 %	+ 36 %

Figure 2: Infiltration of manufacturer's cells resulted in Area Specific Resistance (ASR) decrease of more than 20% and power density increase of more than 30%. Tests on the manufacturer's cells were consistent or better than the average results obtained on all cells tested at NETL using the infiltration technology.

FWP-2012.03.04, May 2013

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PROJECT FACTS

Fuel Cells

Understanding of Solid Oxide Fuel Cell Stack in Pressurized Conditions—Naval Undersea Warfare Center

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The Naval Undersea Warfare Center (NUWC) Division Newport is developing SOFC-based power sources for unmanned undersea vehicles (UUVs) intended to operate in an air-independent environment and at depth pressure. SOFC technology has the potential to greatly increase UUV mission time compared with current rechargeable battery technology. Under an Interagency Agreement, NUWC will acquire and install a SOFC stack being developed by Delphi Corporation as part of the SECA program in order to explore operation in pure oxygen and at elevated pressure up to 3 atmospheres (atm).

The NUWC project provides vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems. Future coal gasification plants using oxygen-blown coal gasifiers could be designed to provide pure oxygen feed to a SOFC power plant block.

Project Description

NUWC will procure a SECA SOFC stack and install it into a test platform capable of producing pressurized and air-independent operating conditions. Pure oxygen usage at the cathode will simulate the air-independent performance needed for UUV operations. Reliable methods for pressure control and stack operation will be refined in order to test the SECA SOFC stack at elevated pressure.

NUWC will construct a test cell that includes pressure controls, gas analysis, and data acquisition. While the SOFC stack will be the main item under test, NUWC will also be testing its own control algorithms and back pressure regulators that equalize the pressures at the cathode, anode, and ambient zones (external to the SOFC stack). Minimizing the pressure differentials between any two zones limits the amount of gas leakage while also increasing efficiency and reliability.

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PARTNERS

Delphi Corporation

PROJECT DURATION

Start Date	End Date
10/01/2012	12/31/2013

COST

Total Project Value
$100,000

DOE/Non-DOE Share
$100,000 / $0
($300,000 to date from ONR)

AWARD NUMBER

FE0005652

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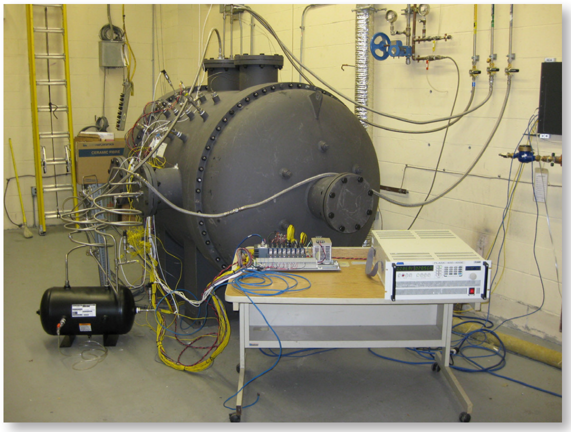
U.S. DEPARTMENT OF ENERGY

NUWC will assemble the system and will use (and purchase if necessary) appropriate heaters and insulation to ensure the proper operating temperature of the SOFC stack. A mass spectrometer will be used to monitor gas compositions at various locations in the system, and a condenser will collect water at the anode exhaust.



Fifty-inch Inside Diameter Vessel for Pressurized SOFC Stack and System Demonstrations. Nitrogen/argon gas is supplied to the pressure vessel to balance the ambient stack pressure to the anode and cathode pressures. Algorithms will be used to simultaneously raise all zone pressures as well as continuously monitor and control all three pressures using a single set point.

Goals and Objectives

The goal of this project is to explore operation of SOFC stacks in pure oxygen and at elevated pressure. Project objectives are as follows:

- Procure a new 10-cell Delphi Generation 4 (Gen 4) SOFC stack for pressurized testing.
- Construct a test cell that includes pressure controls, gas analysis, and data acquisition.
- Assemble a system with appropriate heaters and insulation to ensure proper operating temperature.

Accomplishments

- Test cell has been constructed for testing up to 45 psia (3 atm) SOFC stack and related system components.
- Procurement is underway for 10-cell Delphi Gen 4 SOFC stack for pressurized testing.
- Test plans and procedures have been drafted for running the pressurized Delphi stack tests.

Test capability has been established for evaluating SOFC planar stacks and related systems under elevated pressure. The Office of Naval Research (ONR) has funded the construction of the pressurized test vessel and testing of a 60-cell SOFC stack fabricated by Materials and Systems Research, Inc. (MSRI). Much of the hardware and control methods developed in this ONR program can now be applied to the testing of a Delphi Gen 4 SOFC stack in the DOE research program.

Benefits

This NUWC project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

FE0005652, April 2013

Reliability and Durability of Materials and Components for SOFCs – Oak Ridge National Laboratory

Background

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has a mission to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Oak Ridge National Laboratory's (ORNL) project was selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

ORNL has provided multi-year project support by conducting research on testing for reliability and durability of materials for SOFCs. The current focus of the project is thermal-mechanical property characterization of SOFC materials under conditions representative of SOFC operation (temperatures and environments). This project supports modeling efforts by developing material property characterization techniques, the collection and analysis of associated experimental data, and the development of failure criteria.

Project Description

ORNL will experimentally characterize SOFC cell and stack materials and interfaces, provide data on thermal and mechanical properties under typical operating conditions, and establish the experimental techniques required to collect this data. This information is then used to produce high-fidelity models to assess and predict SOFC cell and stack behavior.

ORNL will also identify the mechanisms that are responsible for the failure of SOFC components, in particular multilayer anode/electrolyte/cathode assemblies which constitute the building blocks of these systems. They will then develop and implement a probabilistic design methodology for predicting the life and reliability of SOFCs. In addition, ORNL will characterize the thermo-mechanical properties of these materials for incorporation into state-of-the-art computer-based modeling tools. ORNL will also develop and evaluate engineered glass-based composite seals characterizing self-healing SOFC seal designs (glass seals that flow at high temperatures to heal cracks formed during thermal cycling) incorporating crystallization-resistant glasses.

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PROJECT FACTS

Fuel Cells

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
10/01/2000	09/30/2013

(annual continuations)

COST

Total Project Value
$6,075,000

DOE/Non-DOE Share
$6,075,000 / $0

AWARD NUMBER

FC-FEAA066

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The primary goal of this project is to identify and characterize the mechanisms that are responsible for the failure of SOFC materials, components, and stacks, and in particular the multilayer anode/electrolyte/cathode/interconnect assemblies that constitute the building blocks of these systems. A second goal of this effort is to develop engineered self-healing seal systems, which includes the characterization of selected glasses after long term exposure in SOFC environments. Project objectives include the following:

- Characterization of the various interfaces within the SOFC assembly, in particular the interfaces between metallic interconnects, their thermally-grown oxide layer, and protective coatings applied to metallic interconnects.
- Characterization of specific commercial glasses in the SECA Core Technology Program for potential use as SOFC seal materials.
- Development and design of engineered glass sealing concepts.
- Conducting experiments characterizing SOFC interfaces (cathode-interconnect and interconnect-thermally grown oxide-coating). The results are being utilized by Pacific Northwest National Laboratory (PNNL) in the modeling effort to guide stack design and interconnect coating/cathode contact aid material development aimed at reducing interfacial resistance and increasing stack robustness.
- Developing, characterizing, and testing self-healing SOFC seal systems in collaboration with PNNL.
- Development of the American Society of Mechanical Engineer (ASME) SOFC Design Basis Document.

Accomplishments

- Successfully characterized the micro-structural changes in candidate glass seals that have been exposed to SOFC environments (800 degrees Celsius in air and gas mixtures of steam, hydrogen and nitrogen) in excess of 15,000 hours.
- Developed concepts for glass sealing that will allow dimensional tolerances in the SOFC stack to be accommodated. Several concepts of engineered glass seal designs have been developed.

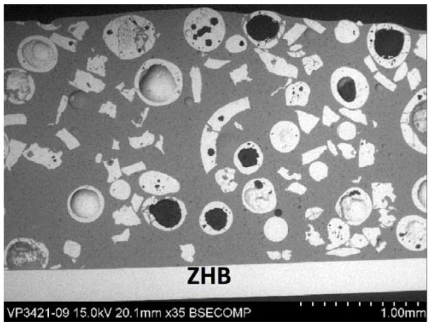

Figure 1: Scanning electron micrograph of a composite glass seal consisting of SEM-COM's crystallization-resistant multi-component silicate glass, SCN-1, and frangible hollow calcia-stabilized zirconia particles. The fracture of the hollow spheres under the application of a compressive load gives the composite glass seal the ability of filling uneven spaces, for example, when sealing surfaces that are not parallel or flat.

- Determined the uncertainty associated with the quantitative chemical compositional analysis of glass seal materials.
- Developed a test methodology based on the Brazilian disk geometry to characterize the adhesion of oxide scales on metallic interconnects.
- Supported the SECA Industry and Core Teams in the characterization of potential glass seal materials. Cooperative development projects have been executed with Delphi Corporation and LG Fuel Cell Systems. The ORNL team closely partners with PNNL in various areas such as seal leakage testing.
- Finalized, in cooperation with PNNL and ASME, the initial ASME Design Basis document. This document serves as a repository for SOFC mechanical design based upon the efforts of the SECA Core Technology Program since its inception.
- Used in-situ synchrotron x ray diffraction (XRD) to monitor phase evolution of the oxide scale on ferritic stainless steel interconnects. The growth stresses and residual stresses of the oxide scales were also evaluated
- Established data bases of thermomechanical properties of fuel cell materials and components (e.g., anode, electrolyte, cathode)
- Characterized the effect of adding ceramic particles and ceramic fibers on the mechanical and physical properties (e.g., viscosity) of multi-component barium silicate glasses.

Benefits

This project assists the SOFCs program in meeting its cost and life targets by understanding the mechanisms that limit the reliability and durability of SOFC materials. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achievement of this goal will have significant impact for the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology, accompanied by risks higher than the private sector can accept.

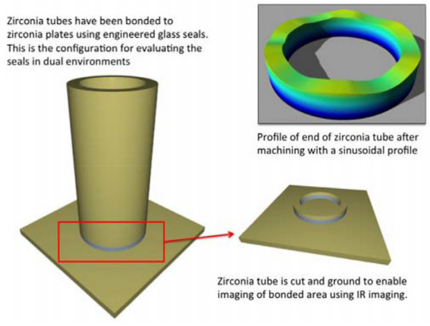

Figure 2. Experimental procedure used to demonstrate the ability of engineered glass seals to seal surfaces that are not flat and/or parallel. The inset shows the end of the zirconia tube that had been machined with a sinusoidal profile with an amplitude of 75 µm. The integrity of the joint was examined by infrared imaging and its hermeticity was evaluated using a dual environmental test set-up.

FC-FEAA066, May 2013

Low Cost Modular SOFC Development—Pacific Northwest National Laboratory

Background

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has a mission to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for coal-fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Pacific Northwest National Laboratory's (PNNL) project was selected to acquire the fundamental knowledge and understanding that will facilitate research and development to enhance electrochemical performance under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

PNNL has provided multi-year project support to develop advanced SOFC component materials and computational tools. In particular, interconnection components for both atmospheric and pressurized operation are being developed. Emphasis is placed on evaluation and development of materials and manufacturing processes for various SOFC components such as electrolytes, anodes, cathodes, cell-to-cell interconnections, and seals.

Project Description

This project will accelerate the development of reliable, low-cost SOFC power generation systems capable of operation on coal derived fuels by developing advanced SOFC component materials and computational tools. Interconnection components for both atmospheric and pressurized operation will be developed. Important to this work is the evaluation and development of materials and manufacturing processes for various SOFC components (electrolyte, anode, cathode, cell-to-cell interconnections, and seals) to support higher performance and robustness, less degradation, and lower cost. In addition, this project will address the effects of coal contaminants on SOFCs and how to mitigate any deleterious effects through upstream clean-up and modification of SOFC components.

This project will also identify, develop, test, validate, and optimize cost-effective cell and stack components, materials, and fabrication techniques; develop advanced computational tools and capabilities for cell and stack design analysis and optimization; test cells exposed to coal contaminants and complete analysis of the results, both post-test and using thermodynamic software; and develop and evaluate new interconnect compositions appropriate for pressurized SOFCs.

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Fuel Cells

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PARTNERS

Oak Ridge National Laboratory
University of Connecticut

PROJECT DURATION

Start Date	End Date
10/01/1999	09/30/2013

(annual continuations)

COST

Total Project Value
$52,889,667

DOE/Non-DOE Share
$52,889,667 / $0

AWARD NUMBER

FWP40552

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The primary goal of this project is to develop, manufacture, and evaluate advanced SOFC component materials and computational tools.

Objectives are as follows:

- Develop, test, and optimize high-performance, reliable cell and stack component materials and fabrication techniques for low-cost, reliable SOFC stacks. Develop a SOFC stack test fixture for use by PNNL and other participants.
- Develop and utilize computational techniques to assist in the development and optimization of modular SOFC systems. The electrochemical aspect of the modeling capability will be enhanced by the incorporation of instrumented stack data provided by an Industry Team. Model predictions of thermal profiles will be compared with other independent models and used to guide stack development. The American Society of Mechanical Engineers (ASME) SOFC design basis document will be updated as needed.
- Collaborate with Oak Ridge National Laboratory (ORNL) to obtain necessary material properties to support SOFC modeling. Develop materials and fabrication techniques for low-cost modular SOFC stacks. This task focuses on the testing and analyses of various materials under development (viscous and refractory seals, interconnect alloys and coatings, and cathode contact aids) in a stack environment. PNNL and ORNL will collaborate to design, experimentally evaluate, and develop seals based on viscous glass.
- Research and development on fuel related technical topics of importance to operating SOFCs on gasified coal, such as the effects of impurities in gasified coal on SOFC anodes.
- Identify, prioritize, and coordinate SECA technical activities. The management of the program involves interactions with universities, national laboratories, and SECA Industry Team members to identify, prioritize, and coordinate technical activities and to disseminate results.

Accomplishments

- Commissioned second generation stack test fixture.
- Successfully assembled and tested 3-cell stack fixture for long-term (approximately 6,000 hours) evaluation/validation of manganese-cobalt (M-C) spinel and alumina coated interconnects.
- Demonstrated excellent electrical performance of M-C spinel-coated AISI 441 for over two years (20,000 hours).
- Evaluated performance of coatings with reduced (or zero) cobalt content.
- Optimized ultrasonic spray process for interconnect coatings. An ultrasonic spray process was evaluated and successfully developed for the application of cerium oxide-modified M-C coatings aluminization on metallic interconnects.
- Conducted a microscopic study which included evaluation of interconnect coatings using composition and phase analysis. It was determined after one year that the oxide scale under the coating consisted of a continuous matrix of titanium-doped chromium oxide with dispersed grains of manganese-chromium oxide. No evidence of impending degradation was found using high-resolution transmission electron microscopy provided by Carnegie Mellon.
- Completed the ASME SOFC design basis document. This living document, modeled after those published by the ASME, acts as a repository for the current best practices in the design of structurally-sound SOFC stacks. The baseline version of the design guide covers all major aspects of stack design and is supported by five appendices of technical reference material. The document will be reviewed every six months and updated on an as-needed basis to continually reflect the state-of-the-art in SOFC stack design.
- Demonstrated that sodium volatility from soda lime glass and potassium volatility from potassium silicate had no discernible effect on performance of lanthanum strontium manganite/yttria-stabilized zirconia (LSM/YSZ) composite cathodes and lanthanum strontium cobalt ferite (LSCF) cathodes.
- Identified new coal gas contaminant absorber materials. It was found that an absorber bed containing potassium carbonate completely captures phosphorus at temperatures of 350 degrees Celsius (ºC) and above, and completely captures arsenic at temperatures of 600 ºC and above. This represents a possible inexpensive option for removing these contaminants from coal gas.
- Investigated the role of cell voltage on contaminant attack. A parametric study of cell voltage and coal contaminants phosphorus, arsenic, sulfur, selenium, and hydrogen chloride on anode degradation was completed. No changes in the cell degradation rate at different operating voltages were observed in the presence of phosphorus, arsenic, and hydrogen chloride; however, distinctly different responses to sulfur and selenium were observed at different voltages.
- Transferred stack test fixture capability to NETL. Single-cell stack fixtures were delivered to and commissioned at NETL. This establishes the capability at NETL for independent parallel evaluation of materials and concepts for cells and stacks.
- Devitrifying “refractory” sealing glasses were optimized in terms of softening temperature, wetting behavior, and coefficient of thermal expansion.
- Evaluated a new sealing approach incorporating a glass which is compliant at SOFC operating temperatures through single and dual atmosphere testing. Compliant seals improve mechanical robustness of SOFC stacks by reducing residual stresses during stack operation and thermal cycling. Process optimization studies were performed to control pore size and volume fraction porosity. Additions of zirconia fillers to form a glass/zirconia composite can improve dimensional stability at operating temperature. Collaborative development efforts at PNNL and ORNL involving glass only and glass/zirconia particle or fiber composites were continued.

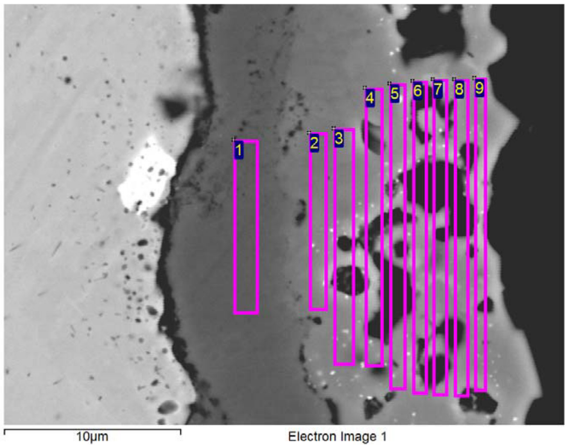
- Continued a long-term (>20,000 hours) study evaluating the effects of applying surface modifications to ferritic stainless steel interconnect materials prior to application of protective spinel coatings. Substantial improvement in scale adhesion and spallation resistance (compared to unmodified surfaces) can be achieved, particularly through surface blasting or grinding.

- Provided topical report to SECA industry teams summarizing benefits of select surface modifications on scale adhesion / spallation resistance of steel-based interconnects.

- Effects of humidity in air on LSM- and LSCF-based cathodes were quantified as a function of operating temperature and time.

- Performed high temp XRD analyses on working LSCF cathodes as a function of operating time, voltage, and temperature. Changes in the perovskite structure and overall phase assemblage were quantified.

- Developed and implemented a continuum damage-healing modeling framework to simulate the thermal-viscoelastic behavior of compliant glass seals in SOFC stacks using finite element analysis. Sensitivity studies on the seal design parameters were performed to evaluate the effects of material properties and operating conditions on seal mechanical behavior for the seal design engineering effort.



Spectrum	O	Si	Ti	**Cr**	Mn	Fe	Co	Ce
1	63.90	0.27	0.27	**35.38**		0.17		
2	61.16		0.27	**13.42**	11.65	1.90	11.59	
3	60.33	0.30	0.43	**7.72**	15.94	2.78	12.22	0.28
4	59.42		0.50	**5.52**	18.42	2.99	13.15	
5	57.68	0.60	0.51	**5.25**	19.30	3.09	13.28	0.29
6	58.89	0.68	0.44	**5.07**	18.84	2.81	12.78	0.48
7	57.05	0.75	0.48	**5.28**	19.79	2.87	13.21	0.56
8	57.30	0.41	0.49	**5.37**	19.59	2.96	13.53	0.36
9	61.84	0.42	0.43	**4.61**	17.30	2.67	12.50	0.24

SEM image and results from cross-sectional EDS analysis of M-C spinel-coated surface-blasted AISI 441 after oxidation at 800 °C for 20,000 hours (element concentrations in atomic %). Note excellent scale adhesion and limited transport of Cr into the coating (right side of image).

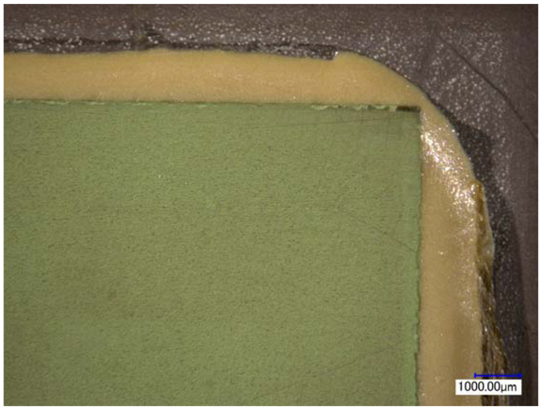
- Developed a modeling framework that automatically creates reduced order models (ROMs) for SOFC stacks. The framework interface guides the user through the analysis procedure, samples and interrogates the multi-parameter operating space using the detailed stack model, performs regression to generate the response surfaces, and implements the response surfaces into a ROM submodel for general use within system modeling software.

- Developed a user-friendly interface for the 2D SOFC-MP software to perform pre-processing and post-processing for SOFC stack evaluations. The pre-processing capability enables users to enter and modify SOFC model geometry, stack operating conditions, and simulation control parameters, while the post-processing capability helps users to visualize the solution results for various physical quantities across the stack model domain.

- Benchmarked the 2D SOFC-MP modeling tool against experimental data. Model simulations for ten cases with different fuel compositions and temperature boundary conditions were successfully verified with experimental thermocouple data from a state-of-the-art stack for H_2 and reforming fuel compositions.

- Developed models to investigate humidity effects on cathode performance. Micro-scale modeling is used to understand competition of water with LSM activity and kinetics of possible reactions, while meso-scale modeling is used to quantify the corresponding electrochemical degradation within the electrode microstructure.

- Modified the interconnect lifetime prediction methdology to be informed from interfacial indentation data of oxide scale-substrate interfaces with different surface modifications.



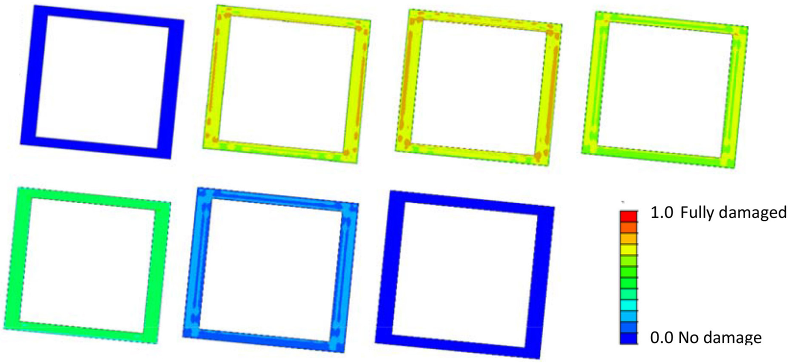
Post-test image of SCN-1 compliant glass sealed between aluminized AISI441 and an anode/electrolyte bilayer . No evidence of damage or leakage was observed after 12 thermal cycles between RT and 800 °C.

Benefits

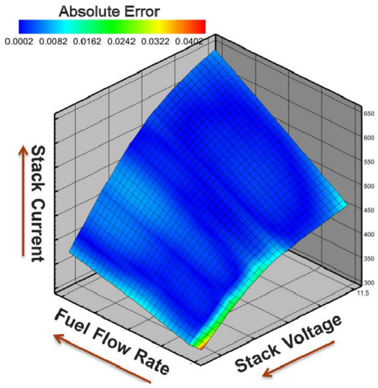
The PNNL project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

Interconnect research and development will improve low-cost metallic interconnects, coatings, and interfacial materials operating in the temperature range of 650 to 850 °C. This will minimize leading contributors to lifetime degradation and will address oxide growth, spallation, good electrical contact, and impact of volatile species on electrode performance. Electrode studies will improve the understanding of effects of humidity and contaminants on electrode microstructure, polarization, and resistance to support efforts to improve electrode stability and reliability during long term operation. Development of seals based on compliant glass will improve robustness of SOFC stacks towards thermal cycling and thermal gradients during operation.

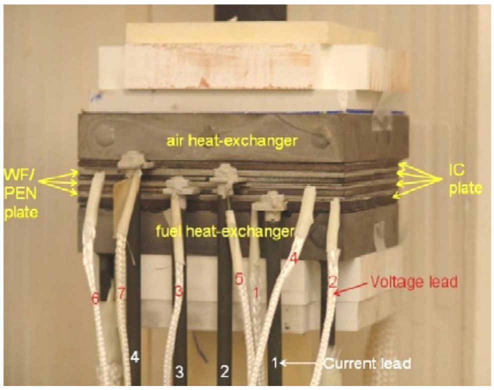
Modeling and Simulation R&D will create multi-physics models for fuel cell, stack, and system performance in order to define the optimal operating condition space, guide manufacturing, and lower costs. This will address fuel cell integrity over the required lifetime under all possible non-steady state conditions. Providing this necessary level of assurance experimentally is not cost-effective. Modeling of electrode, seal, and interconnect behavior will improve mechanistic understanding of causes of performance degradation and predict component lifetime.



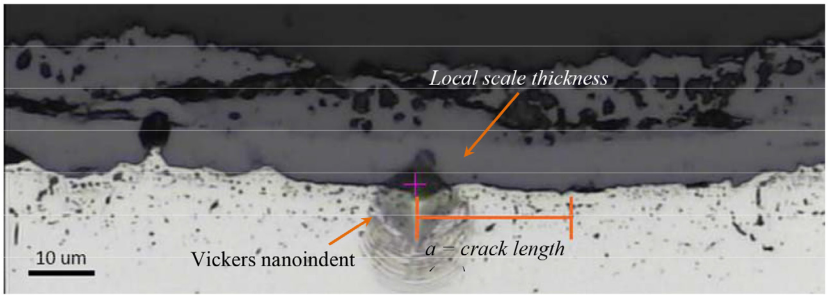
Progression of damage and healing of a viscous glass sealant during thermal-mechanical loading of an SOFC stack.



Response surface prediction and associated error for use in reduced order models (ROMs) of SOFC stack performance.



Stack test fixture used for evaluation/validation of new cell and stack materials under realistic stack environment conditions.



Use of pyramidal micro-indentation tests to characterize interfacial toughness for the interconnect scale.

FWP40552, May 2013

Surface-Modified Electrodes: Enhancing Performance Guided by In-Situ Spectroscopy and Microscopy—Stanford University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The electrochemical performance of SOFCs can be substantially influenced by mass and charge transport of reaction species at cell interfaces. Unfortunately, the interplay among the structural, chemical, and electronic properties of interfaces, transport phenomena, and catalytic activity is unclear, particularly in SOFC cathodes.

Stanford University's project was competitively selected to acquire the fundamental knowledge and understanding of cell interfaces to facilitate research and development in studying electrochemical performance enhancement under a diversified portfolio for anode-electrolyte-cathode development. Sandia National Laboratories is providing collaborator support for this project under a Support Field Work Proposal. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

Stanford will identify correlations between performance and the microscopic surface properties of oxygen reduction reaction (ORR) active sites in state-of-the-art SOFC cathodes, quantified using novel in situ spectroscopy, scattering, and microscopy techniques, while the electrochemical reactions take place under SOFC operating conditions. In particular, the characteristics of active sites that display high electrochemical activity will be identified. This fundamental knowledge will be used to rationally engineer electrode surfaces in both idealized and, later, porous lanthanum strontium cobalt ferrite (LSCF) and similar cathodes. Finally, the effort will optimize and validate the electrode modification strategies using button-cell SOFCs.

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Fuel Cells

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PARTNERS

Sandia National Laboratories

PROJECT DURATION

Start Date	End Date
10/01/2012	09/30/2015

COST

Total Project Value

$500,000

DOE/Non-DOE Share

$375,000 / $125,000

AWARD NUMBER

FE0009620

U.S. DEPARTMENT OF ENERGY

This project relies on using three new approaches to measure cathode surface characteristics in situ: (1) X-ray spectroscopy, (2) X-ray diffraction, and (3) transmission electron microscopy (TEM). The team will utilize two DOE Office of Science user facilities: the Advanced Light Source (ALS) facility at Lawrence Berkeley National Laboratory and the Stanford Synchrotron Radiation Lightsource (SSRL) facility (a directorate of SLAC National Accelerator Laboratory operated by Stanford University) to carry out in situ X-ray experiments.

Goals and Objectives

The goal of this project is to improve SOFC performance by modifying the surfaces of state-of-the-art cathode materials. The project will consist of three main technical tasks:

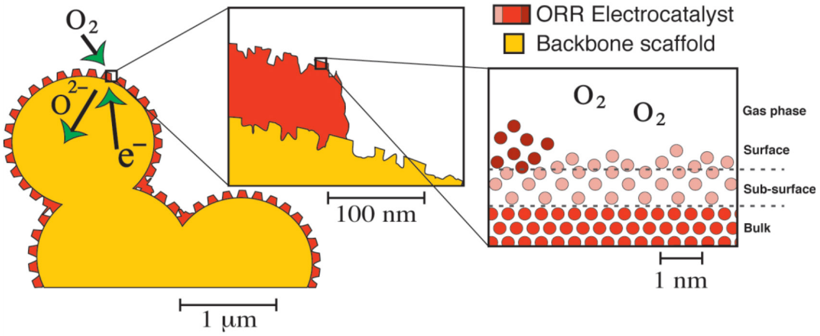
- Fabricating ideal thin-film cathodes on single crystal electrolyte substrates and characterizing their ORR activities using current-voltage and impedance spectroscopy measurements.
- Probing the microscopic behavior of cathode thin films using in situ X-ray spectroscopy, scattering, and environmental TEM under SOFC-relevant conditions, and correlating them to the ORR activity.
- Developing surface modification strategies for ideal and commercial LSCF and similar cathodes to dramatically improve the electrochemical activity.

Accomplishments

- Observed the electronic structure of thin-film perovskite cathodes during fuel cell operation in near-ambient pressure of oxygen.
- Identified the crucial electronic species that participate in the ORR.
- Directly monitored the surface composition of ferrite-perovskite cathodes during fuel cell operation.
- Designed a new in situ cell to measure the surface structure of thin-film cathodes during fuel cell operation.

Benefits

Stanford's project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



A schematic drawing of a heterostructured SOFC cathode depicting the variation in chemistry and structure going from the micro- to the nanoscale. At the nanometer length scale, the solid-gas interface is very different from the bulk in terms of structure, composition, and electronic structure. The backbone scaffold conducts oxygen ions and electrons to and from the electrolyte and external circuit respectively, and the electrocatalyst facilitates the surface reaction.

FE0009620, May 2013

Study of the Durability of Doped Lanthanum Manganite and Cobaltite Based Cathode Materials under "Real World" Air Exposure Atmospheres—University of Connecticut

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Cathode durability is critical to long-term SOFC performance for commercial deployment. Cathode exposure to air, moisture, CO_2, chromium vapor, and particulates results in long-term performance degradation and is a problem that needs to be solved.

The University of Connecticut (UConn) project (with support from Alfred University and the University of California, San Diego) was competitively selected to study the durability of cathode materials under real world operating conditions. The team's research will contribute to a better understanding of the cathode degradation mechanism, identify resistant cathodes, and identify air chemistries that will not degrade cathodes. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

The UConn team will perform an evaluation and analysis—using experimentation and computational simulation—of degradation phenomena in lanthanum manganite- and cobaltite-based cathode electrodes when exposed to air atmosphere conditions during SOFC operation. Specific study interests are product formation and interactions with air contaminants; dopant segregation and oxide exolution (i.e., release) at free surfaces; cation inter-diffusion and reaction product formation at the buried interfaces; interface morphology changes; lattice transformation and the development of interfacial

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Fuel Cells

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PARTNERS

Alfred University
University of California, San Diego

PROJECT DURATION

Start Date	**End Date**
10/01/2012	09/30/2014

COST

Total Project Value
$624,215

DOE/Non-DOE Share
$499,372 / $124,843

AWARD NUMBER

FE0009682

U.S. DEPARTMENT OF ENERGY

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porosity and micro-cracking; and delamination from the stack repeat units. The feasibility of the mitigation approaches will also be tested under accelerated conditions. Reaction processes will be studied via electrochemical and high temperature material compatibility tests followed by structural and chemical characterization. Degradation hypotheses will be proposed and validated through further experimentation and computational simulation of equilibrium interface atomic configurations at various processing conditions using first-principles thermodynamics, zero-temperature density functional theory with statistical mechanics, and high-accuracy measurements of lattice constants, rapid evaluation of the cation transport, and gas-solid phase interactions.

This project will examine the role of dopants, electric polarization, gas phase contaminants, oxygen stoichiometry (proportions), and A: B ratio on the long-term bulk and interfacial stability of lanthanum manganite and cobaltite cathodes. Cathode materials will be characterized to develop both initiation and propagation processes responsible for chemical and morphological changes. The role of electrode poisoning in the presence of chromium vapor will be examined using existing test facilities capable of generating a wide range of vapor pressures in humidified air.

Goals and Objectives

The goal of this project is to develop and validate mechanisms responsible for the overall structural and chemical degradation of lanthanum manganite and cobaltite based cathode materials when exposed to real world air atmosphere conditions experienced during SOFC systems operation. The following are specific objectives:

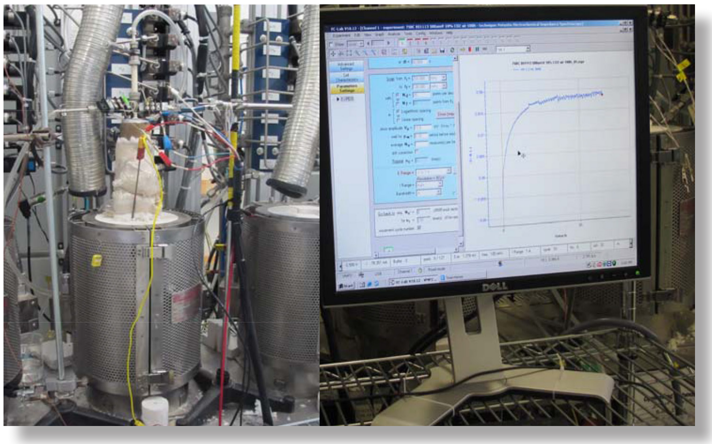
- Identification of critical types and amounts of impurities in cathodes and measurement of cathode degradation during electrochemical testing/operation.
- In situ investigation of phase evolution, crystal structure and chemistry changes, and surface segregation.
- Simulation and tailoring of cathode interface chemistry.
- Determination of changes/modifications/evolutions in SOFC cathodes and cathode/interconnect interfaces under real world operating conditions.
- Identification and documentation of mitigation approaches.

Accomplishments

- Customized experimental set up for electrochemical testing has been completed.
- Contribution of humidity in real world atmosphere on strontium doped lanthanum manganite (LSM) air electrode degradation has been examined under nominal and simulated accelerated conditions.
- Mechanistic understanding of LSM air electrode degradation is being developed from experimental observations and complementary computational study.

Benefits

The UConn project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability to capture 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Electrochemical test facility capable of testing under "real world" air exposure conditions.

FE0009682, May 2013

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PROJECT FACTS

Fuel Cells

Mechanistic Enhancement of SOFC Cathode Durability—University of Maryland

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of solid oxide fuel cells (SOFCs) for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Cathode durability is critical to long-term SOFC performance for commercial deployment. Cathode exposure to moisture, CO_2, chromium vapor (from interconnects and the balance of plant equipment), and particulates results in long-term performance degradation and is a problem that needs to be solved.

The University of Maryland (UMD) project was competitively selected to study the durability of cathode materials under real world operating conditions. UMD's project will contribute to a fundamental understanding of cathode degradation mechanisms and facilitate validated approaches to mitigate them under a diversified portfolio for anode-electrolyte-cathode development. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

The UMD project is a multi-faceted fundamental investigation of the effects of contaminants on cathode degradation mechanisms in order to establish cathode composition/structures and operational conditions to enhance cathode durability. Using a dual focused ion beam/scanning electron microscope approach, UMD will quantify in three dimensions (3-D) the microstructural changes of cathode samples, both standardized and from each of the SECA Industry Teams. This includes changes in triple-phase boundary density, phase connectivity, and tortuosity (a metric related to diffusivity). UMD will also use heterogeneous catalysis methods to elucidate the cathode oxygen reduction reaction (ORR) mechanism and determine how contaminants affect the ORR as a function of temperature, time, and composition, and will use an integrated in situ system that allows simultaneous ^{18}O-isotope exchange and electroanalytical characterization of button cells under applied current/voltage conditions.

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PARTNERS

None

PERFORMANCE PERIOD

Start Date	**End Date**
09/01/2012	08/31/2015

COST

Total Project Value
$625,000

DOE/Non-DOE Share
$500,000 / $125,000

AWARD NUMBER

FE0009084

U.S. DEPARTMENT OF ENERGY

The results will be used to develop hypotheses that explain the microstructural and compositional cathode performance degradation mechanisms and mitigation strategies. Phenomenological models will be developed concurrently to describe the role of architectural and operational variables on cathode performance and stability. These will result in the formation of design criteria that will be validated experimentally in terms of electrochemical performance stability in the targeted contaminant containing air in long-term tests.

Goals and Objectives

The goal of this lab-scale research effort is to characterize the effect of air composition on SOFC cathodes, as well as to propose and test degradation mitigation strategies. Specific objectives are as follows:

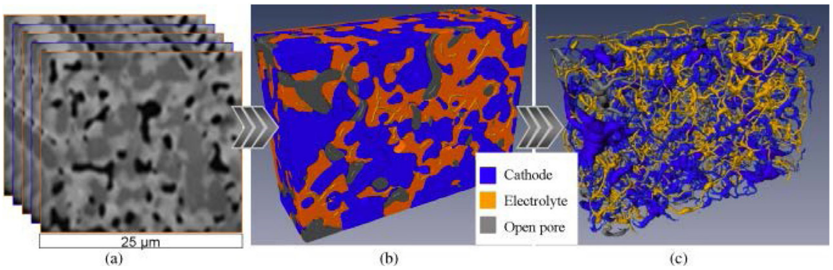
- Determine mechanistic effects of contaminants on cathode durability.
- Quantify 3-D microstructural and compositional changes using various types of electron microscopy and spectroscopy.
- Determine surface exchange mechanisms and coefficients using in situ ^{18}O-isotope exchange of labeled contaminants with lanthanum strontium manganite (LSM) and lanthanum strontium cobalt ferrite (LSCF) powders and their composites with yttria-stabilized zirconia (YSZ).
- Extend in situ oxygen-isotope exchange to button cells and determine surface exchange mechanisms and coefficients of oxygen vs. contaminant compositions under applied current/voltage conditions and how they relate to cell polarization.
- Integrate results and propose cathode composition structures and operational conditions to enhance durability.

Accomplishments

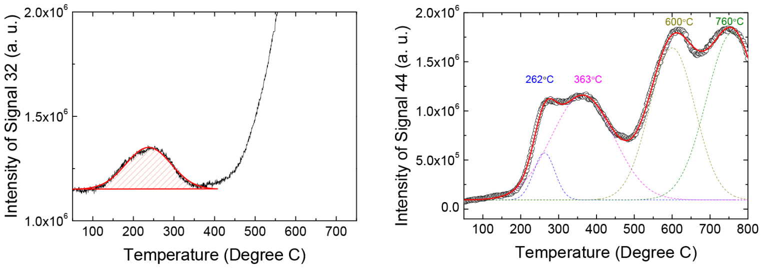
- Finalized setup of in situ isotope exchange system and initiated O_2 and CO_2 exchange experiments with LSCF and LSM cathode powders. Included setup of mass spectrometer, all gas lines and manifolding, and flow and system calibrations. This will allow determination of fundamental cathode ORR rates and the influence of contaminant gasses on ORR.
- Fabricated LSM-YSZ/YSZ/LSM-YSZ and LSCF-GDC/GDC/LSCF-GDC (gadolinia-doped ceria) symmetric button cells for degradation studies and developed 3-D focused ion beam-scanning electron microscopy reconstruction capabilities using National Institute of Standards and Technology facilities. This will allow determination of effect of contaminants on microstructural and compositional cathode degradation mechanisms.

Benefits

The UMD project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Schematic showing the transition from scanning electron image stack (a), which is used to generate a three-dimensional (3-D) reconstruction (b), which is then reduced to a mass centroid 3-D skeleton (c).



Temperature programmed desorption (linear thermal ramp with in-situ mass spectrometer analysis of desorbed gaseous species) of LSCF powder: (a) oxygen (mass 32) desorption as a function of temperature showing 240 °C surface "α-peak" and bulk oxygen "β-peak" above 500 °C; and (b) CO_2 (mass 44) desorption de-convoluted into four different peaks demonstrating ability to identify and quantify individual binding energy surface states.

FE0009084, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Enhancement of SOFC Cathode Electrochemical Performance Using Multi-Phase Interfaces— University of Wisconsin

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The electrochemical performance of SOFCs can be substantially influenced by mass and charge transport of reaction species at cell interfaces. Unfortunately, the interplay among the structural, chemical, and electronic properties of interfaces, transport phenomena, and catalytic activity is unclear, particularly in SOFC cathodes.

The University of Wisconsin's (UW) project was competitively selected to acquire the fundamental knowledge and understanding of cell interfaces to facilitate research and development in studying electrochemical performance enhancement under a diversified portfolio for anode-electrolyte-cathode development. Subcontract support will be provided by the Massachusetts Institute of Technology and the University of Washington. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

The UW team will focus initially on patterned thin films of lanthanum strontium cobalt ferrite (LSCF)-113 with varying levels of LSC-214 decoration. Patterned films have controlled orientations, interfacial relationships, and surface geometry, making them far better suited for extracting quantitative electrochemical properties and catalytic mechanisms than standard sintered electrode structures. These films will be studied with a combination of linear-and non-linear electrochemical impedance spectroscopy to establish the magnitude of their oxygen reduction reaction (ORR) activity and the underlying mechanisms. These data will be interpreted through both standard equivalent circuit analysis and modeling of the elemental kinetic processes. Molecular-scale ab-initio methods will be used to provide qualitative guidance on local composition, defect chemistry, reaction mechanisms, and reaction rate barriers at surfaces and interfaces. The work will extend beyond the thin-film studies to realize the interfacial enhancement under realistic SOFC conditions and

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PARTNERS

Massachusetts Institute of Technology
University of Washington

PROJECT DURATION

Start Date	End Date
10/01/2012	09/30/2015

COST

Total Project Value

$625,162

DOE/Non-DOE Share

$499,926 / $125,236

AWARD NUMBER

FE0009435

U.S. DEPARTMENT OF ENERGY

will be accomplished through studying realistic LSCF-113 porous electrodes decorated with LSC-214 and tested in SOFC button cells. The results will be interpreted to determine the operating mechanisms and identify new material architectures enabling improved fuel cell performance.

Porous SOFC cathodes with enhanced performance and durability will be developed based on a proven LSCF material platform, which could enable SOFC operation at lower temperatures. As this enhancement requires elements and structures that are very similar to those of pure LSCF, it has the potential to be achieved at no significant detriment to metrics of cost, stability, or lifetime of the cathode. Lowering operating temperatures of SOFCs will reduce component degradation, extend life, and reduce working cost.

Goals and Objectives

The goal of this work is to improve SOFC performance by developing LSCF-113-based cathodes with enhanced oxygen reduction activity through decoration with LSC-214 phase materials and to understand how this enhancement occurs. The following are specific objectives:

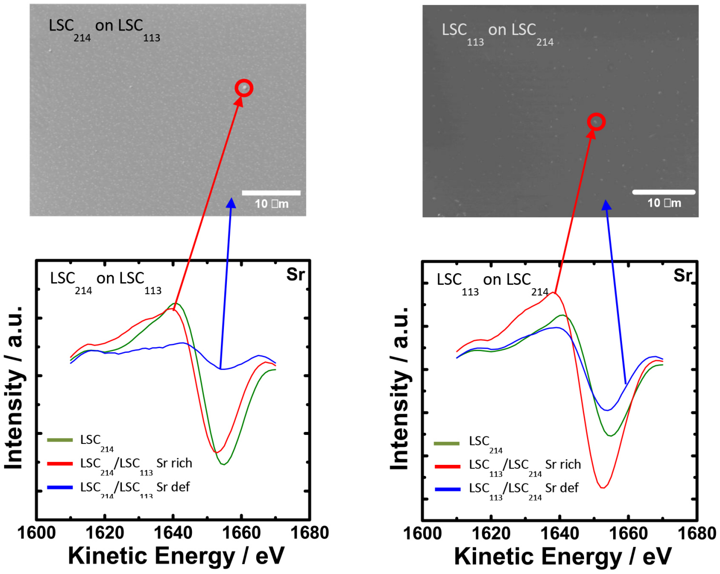
- Grow physically well-characterized thin film electrodes with controlled LSC-214/LSCF-113 interfaces of varying length and under varying synthesis conditions.
- Measure the electrochemical characteristics of these films with linear and non-linear impedance spectroscopy, both to determine catalytic performance as well as probe the origin of electrocatalytic enhancement.
- Model the oxygen reduction process at macroscopic and molecular length scales with continuum and ab-initio methods as a means to test hypotheses about the enhancement mechanisms.
- Fabricate and measure the performance of cathodes consisting of LSCF-113 porous electrodes decorated with LSC-214 in a SOFC button cell.

Accomplishments

- Performed a comparative investigation on patterned LSC-214/LSC-113 films versus the LSC-113/LSC-214 films that showed greatly enhanced ORR activity on the former while the later did not show any ORR activity enhancement. Auger electron spectroscopy results suggest distinction on surface chemistry associated with surface Sr segregation between the two cases.
- Developed an ab-initio based LSC-214 defect model to understand relative role of interstitials and vacancies in material's activity and be able to predict these defect concentration versus temperature, partial pressure of O_2, and Sr doping.
- Developed a one-dimensional model of O_2 reduction within a porous p-type perovskite, which can be used to predict the electrochemical impedance spectroscopy (EIS) and nonlinear EIS response of a porous electrode with large utilization length. This model will be used to test various hypotheses regarding the surface chemistry and reaction mechanism on LSCF.

Benefits

The UW project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



A comparative investigation on patterned LSC$_{214}$/LSC$_{113}$ films (left panel) vs. LSC$_{113}$/LSC$_{214}$ films (right panel). The upper pictures are the SEM images and the lower plots are the Sr signals from Auger electron spectroscopy. Electrochemical impedance spectroscopy (EIS) measurements suggest the LSC$_{214}$/LSC$_{113}$ films exhibit greatly enhanced ORR activity while LSC$_{113}$/LSC$_{214}$ films did not show clear activity enhancement. The Sr intensity results from Auger electron spectroscopy reveal differences of surface phases on LSC$_{214}$/LSC$_{113}$ vs. LSC$_{113}$/LSC$_{214}$ films.

FE0009435, May 2013

Fundamental Understanding of Oxygen Reduction and Reaction Behavior and Developing High Performance and Stable Cathodes—West Virginia University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

The electrochemical performance of SOFCs can be substantially influenced by mass and charge transport of reaction species at cell interfaces. Unfortunately, the interplay among the structural, chemical, and electronic properties of interfaces, transport phenomena, and catalytic activity is unclear, particularly in SOFC cathodes.

West Virginia University's (WVU) project was competitively selected to acquire the fundamental knowledge and understanding of cell interfaces to facilitate research and development in studying electrochemical performance enhancement under a diversified portfolio for anode-electrolyte-cathode development. WVU will develop a pathway for the creation of next-generation cathodes with both high performance and stability. This project is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

WVU will study the fundamental mechanisms of oxygen reduction and reaction (ORR) behavior in heterostructured cathodes through both experimental investigation and theoretical modeling. The focus is on the heterostructured surface of the cathode by infiltration, and its effect on oxygen exchange behavior between the surface and bulk of the lanthanum strontium cobaltite ferrite (LSCF) cathode. The infiltrated phase will be used in a novel combination to tailor the surfaces of LSCF-based cathode backbones. Electrical conductivity relaxation (ECR) will serve as the main experimental method to characterize oxygen transport behavior in the cathode, especially at the infiltrated/

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Fuel Cells

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
08/31/2012	09/30/2015

COST

Total Project Value
$634,839

DOE/Non-DOE Share
$499,953 / $134,886

AWARD NUMBER

FE0009675

U.S. DEPARTMENT OF ENERGY

cathode backbone interface. Isotope exchange will also be utilized to verify the results. Chemical composition and lattice strain variation at the heterointerface formed by infiltration will be detected. A physical model will then be built up and the corresponding simulation results will provide insight into improving cathode performance.

High-performance and stable SOFC cathodes with heterostructured surfaces will be developed and process parameters such as infiltration solution composition, sintering temperature, and loading amount will be optimized to achieve the best cathode performance. Performance will be evaluated by electrochemical testing of both half and full cells. Long-term on-cell testing will also be done to check the optimized infiltrated cathode stability. Furthermore, steady-state electrochemical performance degradation of the infiltrated cathode will be quantitatively characterized by techniques such as ECR.

Goals and Objectives

The goal of this project is to develop highly active and stable intermediate temperature SOFC cathodes by improving ORR kinetics and enhancing cation segregation tolerance through introduction of a heterostructured oxygen reactive interface on the bulk cathode surface. The primary objectives are to (1) develop a fundamental understanding of the ORR mechanisms, especially the oxygen exchange behavior between the heterostructured surface and bulk of the cathode through systematic experimental investigations and theoretical modeling; and (2) develop—via a low-cost infiltration method—a cathode with a heterostructured surface that possesses high performance and stability.

Accomplishments

- Fabrication, microstructure characterization, and impedance analysis of LSCF backbone
- Preparation and characterization of catalyst infiltrating into LSCF
- Study of temperature dependence of polarization resistance for both LSCF scaffold and catalyst infiltrated LSCF

Benefits

The WVU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

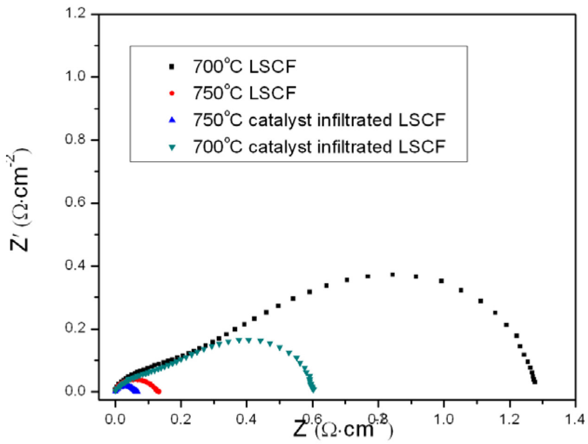

Figure 1. Nyquist plots of LSCF backbone and catalyst infiltrated LSCF cathode measured at 700 and 750 °C in air showing the decreased polarization resistance by infiltration.

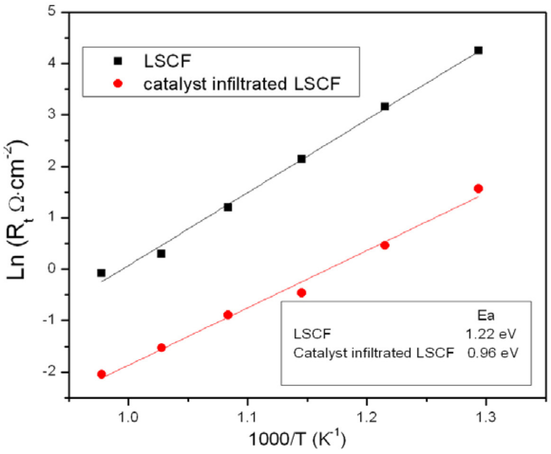

Figure 2. Polarization resistance as a function of inverse temperature. The performance of a noninfiltrated cell is provided for comparison. The activation energy of LSCF cathode is reduced by infiltration.

FE0009675, May 2013

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PROJECT FACTS

Fuel Cells

Direct Utilization of Coal Syngas in High Temperature Fuel Cells—West Virginia University

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

West Virginia University's (WVU) project will establish the tolerance limits of contaminant levels in coal-derived synthesis gas (syngas) for SOFCs and predict the lifetime of the cells for given contaminant levels. This fuel cell project was selected under the Experimental Program to Stimulate Competitive Research (EPSCoR), augments a diversified portfolio for anode-electrolyte-cathode development, and is providing vital support that addresses applied technological issues common to multiple SECA Industry Teams developing SOFC systems.

Project Description

This project is based on a multi-scale, multi-disciplinary approach and comprises three integrated tasks: (1) characterization of contaminant effects, (2) multi-scale continuum modeling, and (3) anode material development. The knowledge base gained from experiments (Tasks 1 and 3) will be used in multi-scale computational models (Task 2) to establish the tolerance limits for the impurities and to predict the life of SOFCs operating on coal syngas that contains impurities.

- Conduct long-term anode exposure tests to phosphine (PH_3) and measure out-of-plane surface deformations at specified time intervals to quantify the PH_3 effects on structural properties. The test results will facilitate the development of long-term anode structural durability and electrochemical degradation models under coal syngas utilization. Kinetics of the PH_3/nickel (Ni) reaction will be measured using thermogravimetric analysis. Investigations of the phosphorus penetration rate into the Ni yttria-stabilized zirconia (YSZ) anode.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
09/05/2006	07/31/2013

COST

Total Project Value
$6,631,048

DOE/Non-DOE Share
$3,450,000/$3,181,048

AWARD NUMBER

ER46299

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- Build a model based on the experimental data to determine the influence of the electrical current and water content on the degradation rate and Ni migration. This model will be used to predict the lifetime of the anode operated on coal syngas that contains PH_3. The Ni patterned electrode will be used to study the influence of the PH_3 on the triple phase boundary (TPB) sites. The data will be integrated with the electrochemical measurements to verify TPB length change during PH_3 attack.

- Connect a mass spectrometer to the point at which contaminant gases are mixed with the fuel stream to confirm the composition of gases entering the hot zone of the tube furnace. A sampling tube will be constructed at a point just above the anode surface for sampling and analyses of gasses. These gas analyses will be correlated to determine the fate of contaminants (phosphine, hydrogen sulfide, etc.) inside the furnace as a function of the initial fuel composition, temperature, and current flow through the SOFC.

- Design and develop alternative ceramic anode components for operation in sulfur- and phosphor-containing coal syngas using contaminant tolerant materials. The materials of interest are ionically and electronically conductive ceramic oxides with perovskite structure. This type of anode material has been proven to tolerate higher concentrations of sulfur. Previous research indicated that PH_3, even at parts per million (ppm) levels, can degrade the perovskite anode. The challenge is to design and synthesize anode materials capable of mitigating both sulfur and phosphorus poisoning. WVU's research experience in SOFC manufacturing and mixed oxides impregnation, together with an atmospheric high-temperature instrument, will be utilized to overcome these technical barriers.

Goals and Objectives

The overall goal of this project is to support the direct utilization of coal syngas in SOFCs. The specific focus is on studying the effects of trace contaminants found in syngas on SOFCs using experimental, theoretical, and modeling techniques.

Project objectives are as follows:

- Implement new characterization methods.
- Develop remedies for impurity effects.
- Identify the tolerance limits of the SOFC anode for specific impurities.
- Predict the lifetime of the anode for a given impurity level.

Accomplishments

- It was found that hydrogen fuel mixed with steam containing 10 ppm PH_3 will degrade more rapidly than it will at dry fuel conditions.
- Phosphine impurities were successfully removed from the coal syngas before it reached the cell by using nickel and iron-based filters.
- Transmission electron microscopy (TEM) characterization revealed nano-scale phenomena in SOFC anodes that were exposed to impurities.
- A mass spectrometer was acquired and used to monitor in situ forms of impurity species and their concentrations, before and after passing through the cell.
- Cell lifetimes and tolerance limits for impurities were estimated using the new degradation model.
- The synergistic effects of multiple impurities were simulated including hydrogen sulfide, arsine, and PH_3, and it was found that a mixture of impurities results in faster degradation than does a single impurity.
- In-house modeling code was used to simulate button cells operating on biogas with both dry and wet reforming.
- Modeling results show that at low PH_3 concentrations the anode structural degradation may be as significant as electrochemical degradation.
- The mechanism responsible for sulfur tolerance of lanthanum-doped ceria impregnated anodes was studied.
- Ni-YSZ with gadolinium-doped ceria barrier layer on an anode showed suitable resistance to syngas contaminated with 100 ppm hydrogen sulfide.
- New strontium-magnesium-molybdenum-oxide anodes with a gadolinium-doped ceria barrier layer were prepared in-house and were shown to be tolerant to syngas that contained PH_3.
- Monitored the microstructure evolution of SOFC anodes exposed to impurities in a unique experiment using Environmental Scanning Electron Microscope (ESEM); no evidence was found for softening or melting of secondary phases in the anode at SOFC operating temperatures.
- Assessed the elementary mechanisms responsible for impurity induced anode performance degradation through experiments on patterned anodes fabricated in-house using photo lithography and wet etching.

- Simulated the degradation of large planar SOFCs exposed to fuel contaminants by incorporating a phenomenological degradation model into a three-dimensional computational model for planar SOFCs, both developed in-house. Significant spatial and temporal variations are observed in the local degradation rates inside planar SOFCs.
- Investigation of the nano structure of the anode using high-resolution TEM revealed that, in addition to Ni, YSZ crystalline structure is also affected by PH_3 in the fuel and Yttrium forms secondary phases with P.
- Investigated a sulfur tolerant anode made of calcium-doped yttrium chromate (YCC) and identified the factors affecting the conductivity, electrochemical activity and overall performance of the alternative material.
- Perfected sulfur tolerant anode materials with refined manufacturing techniques and utilizing various ceramic composites.

Benefits

The WVU project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based, near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology, accompanied by risks higher than the private sector initially can accept.

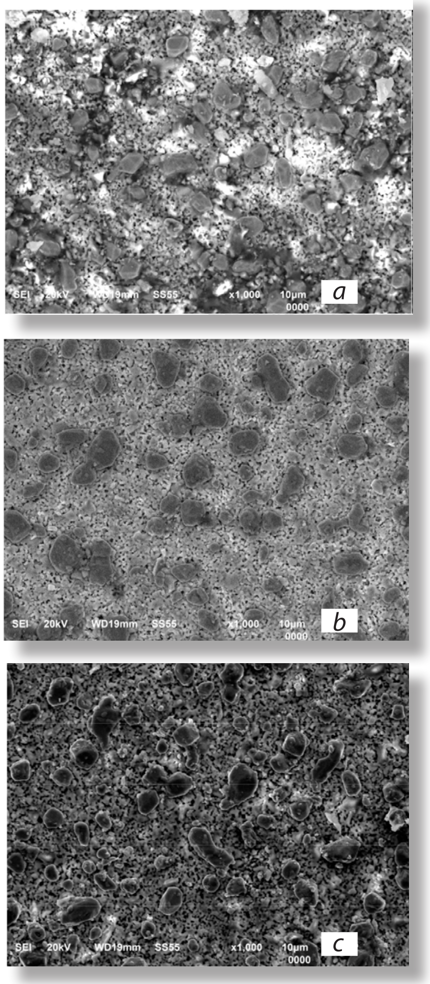

Figure 1: Microstructure images of anode aged in dry H_2 with 10 ppm PH_3 obtained using Environmental Scanning Electron Microscope (ESEM): (a) Initial at 25 °C (b) after 6 hours at 800 °C (c) final at 25 °C

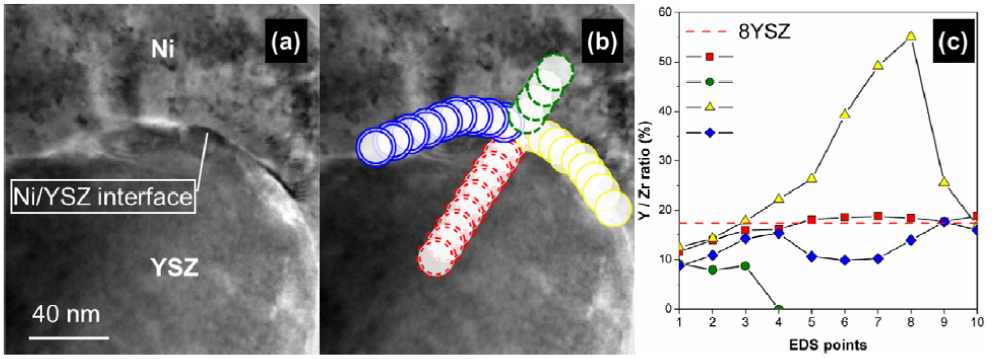

Figure 2: Yttrium migration along the Ni/YSZ interface in anode operated in syngas with 10 ppm PH_3 (a) nano structure of Ni/YSZ interface (a) location of sampling points: tetragonal YSZ domain (blue), cubic YSZ domain (yellow) (c) Profiles of Y/Zr ratio.

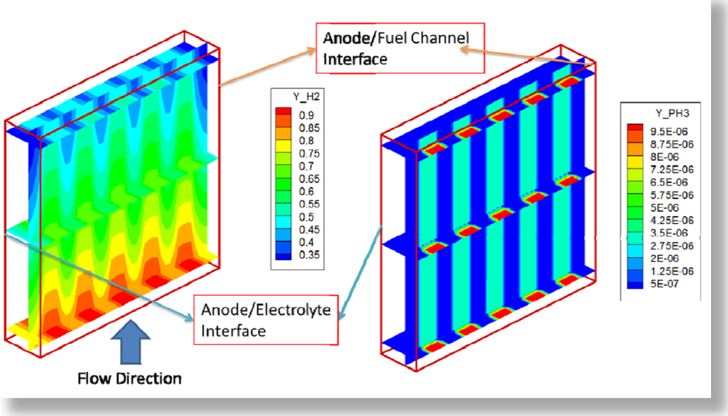

Figure 3: Results for mole fraction inside the anode from the degradation model after 2.5 hours of exposure to 10 ppm phosphine in 3% steam, 97% hydrogen fuel at about 850 °C.

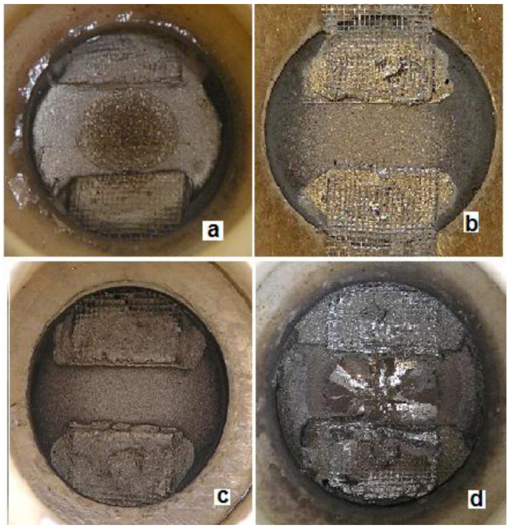

Figure 4: Post-mortem PH_3 poisoned cell anodes (2 cm diameter). (a) syngas at 750 °C, (b) syngas at 850 °C, (c) dry H_2 fuel at 800 °C and (d) dry H_2 fuel without load at 800 °C.

ER46299 May 2013

SECTION 6: ALTERNATIVE AEC DEVELOPMENT

Performance Degradation of LSCF Cathodes—GE Global Research

Background

The mission of the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

GE Global Research (GEGR) will focus on the investigation of SOFC degradation mechanisms and the development and implementation of mitigation strategies, as well as the research and development (R&D) of alternative cell manufacturing techniques. The scope of the effort focuses on fundamental cell R&D issues—primarily power density enhancement and materials stability (degradation) under a portfolio for alternative anode-electrolyte-cathode development.

Project Description

The project will investigate, characterize, and develop mitigation strategies for SOFC degradation mechanisms. This effort encompasses cell and test fixture design, fabrication, and testing to characterize performance, and substantial microanalysis to investigate fundamental degradation mechanisms. It is focused on cathode side materials stability and degradation mechanisms. These mechanisms may include area specific resistance (ASR) increases due to interconnect oxidation; fundamental material instability as a function of time at temperature; and/or chemical and electrochemical solid state interactions between interconnects, interconnect coatings, contact aids, cathodes, and cathode interlayers. The project also includes an investigation of alternative cell manufacturing techniques, applying a thermal spray manufacturing approach to overcome the high costs of producing SOFCs at lower volumes.

Goals and Objectives

The primary project goal is to reduce power density degradation rates to less than one percent per 1,000 hours (<1%/1,000 h), while maintaining high initial power densities (greater than 0.75 watt per square centimeter [$>0.75 W/cm^2$]). To support this goal, the dominant degradation mechanisms must be identified and cost-effective mitigation strategies developed and implemented. The focus is to retain high electrochemical activity in lanthanum strontium cobalt ferrite (LSCF)-based cathodes over the operational lifetime of an SOFC stack (>40,000 h). LSCF-based cathodes have sufficient activity to produce increased power densities in cells at higher operating voltages, which is important for system efficiency and stack and system cost. Primary project objectives are:

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PROJECT FACTS
Fuel Cells

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PARTNERS

None

PROJECT DURATION

Start Date	**End Date**
10/01/2008	09/30/2013

COST

Total Project Value
$9,066,707

DOE/Non-DOE Share
$6,800,030 / $2,266,677

AWARD NUMBER

NT0004109

U.S. DEPARTMENT OF ENERGY

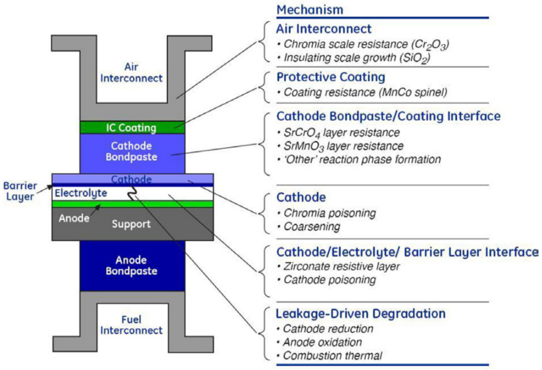
- Identify fundamental cathode degradation mechanisms and validate cost-effective mitigation strategies.
- Evaluate operational condition-specific (temperature, voltage, current) performance degradation.
- Investigate interconnect chromium evaporation to optimize coating structure to mitigate chromium transport.
- Validate degradation mitigation strategies on planar cells.
- Develop kinetic oxidation models for GE-13L and 441SS at relevant operating temperatures.
- Determine the effect of interconnect contact geometry on contact resistance.
- Develop processing method to increase cathode interconnect coating density to minimize chromium volatilization.
- Identify and mitigate potential anode degradation mechanisms.
- Evaluate alternative cell manufacturing approaches.
- Apply alternative manufacturing approaches to produce larger area planar cells.
- Build a three cell stack using larger area planar cells.

Accomplishments

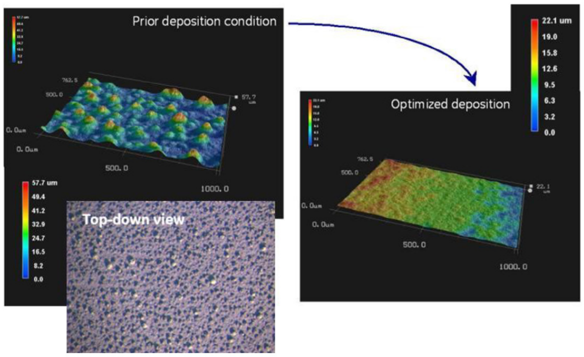
- Identified high-impact fundamental degradation mechanisms and developed cost-effective mitigation solutions.
- Demonstrated stable high performance of LSCF-based cathode SOFCs with gold current collectors.
- Demonstrated parabolic power density degradation behavior with ferritic stainless steel current collectors, which is indicative of chromia scale growth.
- Validated 441HP stainless steel as a viable, low-cost current collector alloy during a 1,500 h electrochemical test.
- Designed, constructed, and validated a novel approach to real-time measurements of chromium volatilization from interconnect alloys using solution conductivity.
- Demonstrated that interconnect geometry does not influence contact resistance degradation.
- Validated that the power density degradation behavior using AL441 stainless steel current collectors decreases with time from approximately (~) 3%/1,000 h for the initial 1,000 h and ~0.5%/1.000 h for subsequent testing (~600 h).
- Identified the anode contact layer as a degradation mechanism responsible for ASR increases of 5–15 milliohms (mΩ)-cm^2/1,000 h and developed mitigation strategy.
- Optimized processing to create a dense current collector chromium barrier coating to prevent chromium volatilization in support of 40,000 h fuel cell interconnect life.
- Developed thermal spray conditions to produce a smooth fuel electrode (anode) on a porous metal support.
- Developed thermal spray conditions to produce a dense, crack-free and hermetic electrolyte (>95% open circuit voltage theoretical sufficient to enable high-efficiency commercially feasible SOFC stacks).
- Achieved repeatable SOFC performances of 0.25 W/cm^2 at 0.7V on 25 cm^2 thermal spray manufactured cells operating at 800 °C at high fuel utilizations (>90%).

Accomplishments

The GEGR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Schematic of a SOFC highlighting potential degradation mechanisms.



Development of a smooth thermal sprayed anode to enable thin thermal sprayed electrolytes.

NT0004109, May 2013

High Temperature Viscous Sealing Glasses for Solid Oxide Fuel Cells—Mo-Sci Corporation

Background

Solid oxide fuel cells (SOFCs) require robust seals that can prevent intermixing of air and fuel, remain inert in reducing and oxidizing environments while in contact with SOFC materials, and maintain their effectiveness through repeated thermal cycles. One potential technology that can meet these constraints is viscous seals that are capable of healing themselves if they fracture during a thermal cycle.

In this project, Mo-Sci Corporation (Mo-Sci) will facilitate the development of viscous glass-based seals for SOFCs. Viscous seals are a new class of SOFC seal that is capable of healing-in situ-leaks that may form during operation. The challenge lies in developing a glass composition that maintains its viscous character over the 40,000 hour lifetime of a SOFC. In addition, the seal must be electrically insulating, thermo-mechanically stable from room temperature to 800 degrees Celsius (°C), and chemically compatible with adjacent cell components.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program and augments a diversified portfolio for anode-electrolyte-cathode development. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

In Phase I of this work, Mo-Sci developed a prototype viscous glass SOFC seal. Mo-Sci has identified new glass compositions that have the appropriate viscosity and stability for this application. In Phase II, the compositions will be optimized and tested under more stringent conditions. Candidate glasses will be tested to ensure they do not adversely react with other SOFC components and that desired viscous properties are retained over long periods of time (SOFC target lifetime is 40,000 hours). Down-selected candidate glasses will be used to construct prototype seals that will undergo thermal cycle testing. A successful glass seal will make SOFCs more robust devices, expanding the number of applications that SOFCs can fulfill.

Goals and Objectives

The overall goal of this project is to facilitate the development of viscous glass-based seals for SOFCs.

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PROJECT FACTS

Fuel Cells

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
09/22/2009	08/14/2013

COST

Total Project Value
$1,086,954

DOE/Non-DOE Share
$1,086,954/$0

AWARD NUMBER

SC0002491

U.S. DEPARTMENT OF ENERGY

Project objectives are as follows:

- Develop glass compositions that exhibit stable thermo-mechanical properties, including viscosity and thermal expansion characteristics, for use as seals for SOFCs.
- Characterize the thermochemical reactions that occur at the seal/cell material interface, and characterize the volatilization of glass components under SOFC relevant operating conditions (temperature and atmosphere).
- Conduct leak tests and analyze the self-healing performance of candidate viscous glass seals at operational temperatures.

Accomplishments

- Identified new alkali-free borosilicate viscous glass compositions that exhibited promising sealing behavior for SOFCs.
- Determined that the dilatometric softening points (Ts) and the glass transition temperatures (Tg) of the new glasses are below the lower bound of the SOFC operating temperature (650 °C).
- Determined that insignificant weight loss (volatility) occurs in the glasses when they are held at 650 °C or 750 °C in ambient air or wet forming gas for 2,000 hours.
- Demonstrated stability against crystallization in heat treatment tests for 1,000 hours in ambient air at 800 °C.
- Measured viscosities of the new viscous sealing glasses and determined that 'self-healing' behavior, which is expected around a viscosity of 105 Pascal-seconds (Pa-s), should occur at temperatures above 725–750 °C.
- Demonstrated that the isokom temperatures (i.e., temperatures corresponding to the same viscosity) for certain glasses do not change after heat treatments for 1,000 hours at 650–850 °C, indicating that these glasses are thermo-rheologically stable at SOFC operating temperatures.
- Demonstrated that the new glasses wet both aluminized stainless steel 441 and nickel oxide/yttria stabilized zirconia (NiO/YSZ) substrates.
- Demonstrated re-sealing (self-healing) of glass seals that were cracked by thermal shock at temperatures as low as 700-725 °C for hermetic test coupons.
- Demonstrated a new glass seal that survived 103 thermal cycles (room temperature to 750 °C) over the course of 3,555 hours without failure of the hermetic seal at constant pressure of 0.5 pounds per square inch differential (psid).

Benefits

This SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFC seals can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications Federal funding support of this research is appropriate given the game changing nature of the technology accompanied by risks higher than the private sector initially can accept.

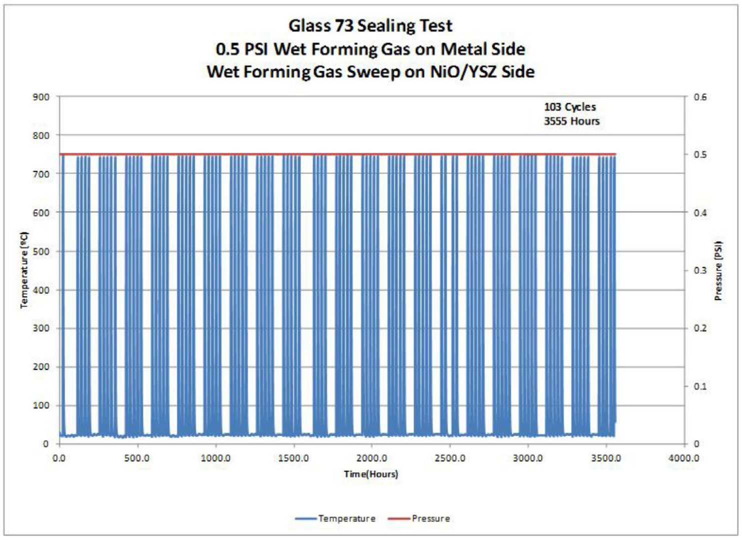

Figure 1. Demonstration of a hermetic seal made from SS441/Glass 73/NiO-YSZ bilayer. This seal survived 103 thermal cycles (room temperature to 750 °C) in wet forming gas at a differential pressure of 0.5 psi (26 torr) for more than 3,500 hours.

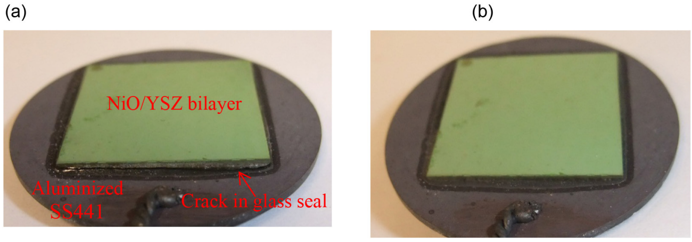

Figure 2. Demonstration of re-sealing of a glass seal. Sandwich coupon (a) crack caused by high cooling rate quench (b) crack healing after re-heating to 725 °C for 2 hours.

SC0002491 July 2013

Solid Oxide Fuel Cell Cathode Enhancement Through a Vacuum-assisted Infiltration—Materials and Systems Research, Inc.

Background

Solid oxide fuel cell (SOFC) technology promises to provide an efficient method to generate electricity from coal-derived synthesis gas (syngas), biofuels, and natural gas. The typical SOFC composite cathode (current source) possesses excellent performance characteristics but is subject to chemical stability issues at elevated temperatures both during manufacturing and power generation. Costs attributed to the cathode and its long-term stability issues are a current limitation of SOFC technologies. These must be addressed before commercial SOFC power generation can be realized.

Materials and Systems Research, Inc. (MSRI) will develop a vacuum-assisted infiltration technique to improve SOFC cathode performance and longevity through the impregnation of an inexpensive electro-catalyst precursor into a preformed cathode backbone.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program and augments a diversified portfolio for anode-electrolyte-cathode development. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

Currently, composite cathodes are formed by directly mixing the active cathode material with electrolyte at different ratios, followed by deposition and sintering into graded functional layers. Since the effectiveness of the composite cathode (the cathode is the electrode at which oxygen ions are removed from the air supply) greatly depends on the composite microstructure and intrinsic material properties, SOFC cell fabrication processes must be engineered to ensure the electrode micro-structural characteristics have continuous phases, open and continuous pores, well-linked (sintered) cathode particles, and a long triple phase boundary.

This project will develop a cost-effective vacuum-pressure infiltration thermal treatment (VPIT) technique to improve SOFC cathode performance and longevity through the impregnation of an inexpensive electro-catalyst precursor into a cathode backbone. Upon calcination (a thermal treatment process) at reduced temperatures, a thin but continuous network of nano-sized catalysts is formed, covering the cathode backbone with enlarged catalytic surface area and heterogeneous microstructure. This enhances both the oxygen exchange rate and oxygen ion transport rate on the cathode surface.

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PARTNERS

None

PROJECT DURATION

Start Date	**End Date**
07/08/2011	08/07/2014

COST

Total Project Value
$1,150,000

DOE/Non-DOE Share
$1,150,000/$0

AWARD NUMBER

SC0006374

U.S. DEPARTMENT OF ENERGY

The reduced temperature calcination will greatly improve the stability of the cathode.

In Phase I, the vacuum-assisted infiltration apparatus and the infiltration protocol will be developed and validated using two sizes of cell test apparatus: button cells and short stacks with 100 square centimeters per-cell active areas. Catalyst distribution and morphology will be investigated via advanced X-ray diffraction and radiographic techniques. Phase II will support manufacturing scale-up to meet cost goals, and will include kilowatt-scale stack validation.

Goals and Objectives

The goal of this project is to develop a vacuum infiltration process for adding catalysts to SOFC cathodes. Current Phase II project objectives are as follows:

- Perfect the VPIT process via:
  - optimization of catalyst loading level,
  - construction of catalyst optimal structure,
  - implementation of degradation mitigation strategies, and
  - refinement of the single-step infiltration apparatus for large cell application.
- Characterize performance enhancement resulting from infiltration treatment.
- Conduct techno-economic evaluation of the single-step VPIT process.

Accomplishments

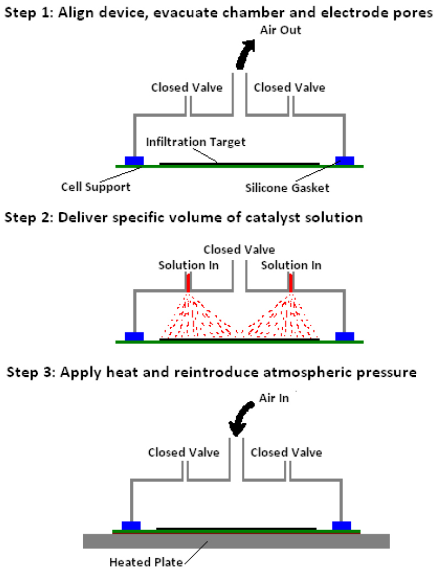
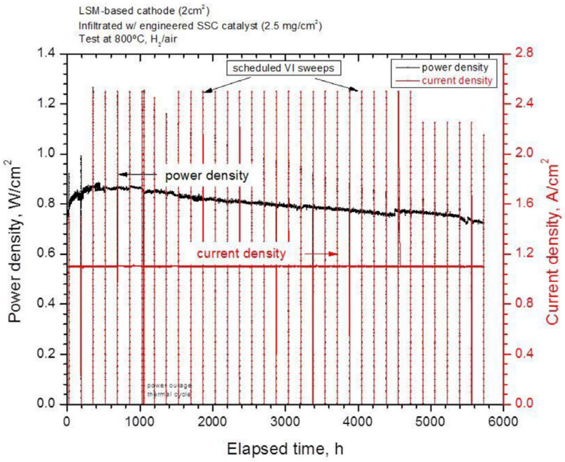


Diagram of the single-step VPIT technique, involving the precipitation of a nitrate solution into the porous cathode backbones (with engineered electrode morphology), followed by gelation at a proper rate, and decomposition.

- Engineered cathode backbone microstructures for an efficient infiltration.
- Developed a single-step VPIT process for infiltrating a nano sized catalyst into the pre-established cathode backbones.
- Investigated key parameters determining the infiltration efficiency.
- Successfully increased the catalyst loading level to 2.5 mg cm^2 on both button-sized cells and 10 cm x 10 cm cells via the single-step VPIT process.
- Improved cell performance more than 60 percent after catalyst infiltration.
- Successfully demonstrated a cell degradation rate less than 3 percent per 1,000 hours over 5,000 hour tests.
- Precisely controlled activation polarization losses via the investigation and evaluation of cell degradation mechanisms.

Benefits

This SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal plants with greatly reduced water requirements and the capability of capturing 97 or greater percent of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding in support of this research is appropriate given the game changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Long-term degradation test of a button cell infiltrated with an engineered SSC (strontium-doped samarium cobaltite) catalyst via the single-step VPIT process.

SC0006374, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

SOFC Protection Coatings Based on a Cost-Effective Aluminization Process—NexTech Materials

Background

To make solid oxide fuel cell (SOFC) systems easier to manufacture and reduce costs, less expensive stainless steels have been substituted into the stack design as alternatives to ceramic interconnects. Stainless has also been substituted for high-cost, nickel-based superalloys in balance of plant (BOP) components. For successful implementation of these steels, protective coatings are necessary to protect the air-facing metal surfaces from high-temperature corrosion/oxidation and chromium (Cr) volatilization.

NexTech Materials Ltd. (NexTech) will develop an aluminide diffusion coating as a low-cost alternative to conventional aluminization processes and evaluate the ability of the coating to mitigate high-temperature corrosion/oxidation and Cr volatilization. This work leverages NexTech's process technology for applying conductive oxide protective coatings to ferritic steels. This process has already been translated from the laboratory to pilot-scale manufacturing.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems co-ordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

To demonstrate the applicability of NexTech's aluminization process to SOFC applications, two commercially important systems will be investigated. (1) Compatibility of aluminide coating with SOFC stack components will be evaluated, including interactions with sealant materials and other cell components. A complete interconnect coating solution will be demonstrated by integrating the aluminide coating with the existing manganese cobalt oxide (MCO) active layer coating. The performance of these dual MCO/aluminide coated interconnects will be validated through three-cell stack tests. (2) The high-temperature corrosion protection and Cr volatilization mitigation of aluminide coated BOP components will be evaluated. The commercial potential of the aluminization process for providing protective aluminide coatings for both the non-active seal area of metallic interconnects and BOP components will be quantified based on an analysis of cost and performance.

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PARTNERS

None

PERFORMANCE PERIOD

Start Date	**End Date**
06/28/2012	03/27/2013

COST

Total Project Value
$150,000

DOE/Non-DOE Share
$150,000 / $0

AWARD NUMBER

SC0008203

U.S. DEPARTMENT OF ENERGY

Goals and Objectives

The goal of this work is to evaluate the feasibility of a spray-based, low-cost aluminization coating process for applying corrosion protection diffusion coatings onto a range of SOFC alloys. The applicability of the coating for non-active areas of the metallic interconnect and BOP applications will be investigated.

Objectives for metallic interconnect work.

- Demonstrate aerosol spray deposition (ASD) aluminization process that is compatible with existing MCO coating process.
- Reduce detrimental interconnect/seal interactions.
- Demonstrate a ten-fold improvement in oxidation resistance of aluminide and dual MCO/aluminide coated ferritic steel substrates over uncoated ferritic steel in humidified air at 800 and 900 °C.
- Achieve a significant reduction in Cr volatilization for aluminide coated ferritic steel versus uncoated ferritic steel.
- Validate the performance of dual MCO/aluminide coated interconnect in a three-cell stack test using NexTech's 160-cm^2 active area stack platform.
- Refine the existing cost model and manufacturing analysis to integrate the aluminization process into the current interconnect coating (IC) process and identify a cost reduction roadmap for achieving less than $2/IC in high-volume manufacturing.

Objectives for BOP work.

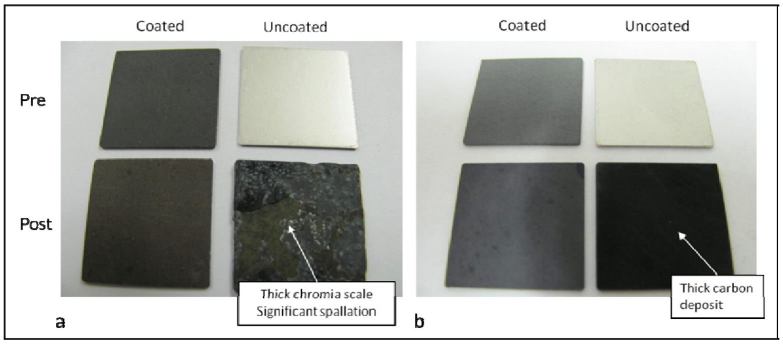
- Demonstrate aluminide coating utility on a range of commercially important BOP alloys.
- Demonstrate a dip-coating process for applying aluminide coating to non-planar, tubular BOP components with matched performance to the ASD based process (greater than 10 times improvement in oxidation resistance and Cr volatilization mitigation over uncoated components).
- Recommend candidate alloy and coating combinations for BOP subsystems based on cost/performance analysis coupled with feedback from SOFC developers.
- Identify and demonstrate the feasibility of strategies (coating first, coating last) to address joinability and formability of coated BOP components.

Accomplishments

- Developed a modified ASD coating process for metallic interconnects to achieve dual-coated MCO active area and aluminide non-active seal area coating process. Stable electrical performance of the MCO active area coating derived from modified process demonstrated for greater than 5,000 hours at 800 °C.
- Demonstrated the critical functionality of the aluminide coating for non-active areas of metallic interconnects: high-temperature oxidation/chromium volatilization resistance and excellent thermal cycle leak rate performance due to reduction in detrimental seal/substrate interactions.
- Demonstrated fidelity of the coating for commercially important BOP alloys and established significant improvement in high temperature corrosion (oxidation/coking) resistance.
- Successfully scaled the coating process from small planar coupons to uniformly coating interior and exterior surfaces of large components with complex geometries and developed a process for uniformly coating welded areas.
- Cost modeling indicated the cost for dual coated parts to be less than $3/part for a 15 cm by 15 cm part at 1 million parts/year volume production.

Benefits

NexTech's SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology, accompanied by risks higher than the private sector initially can accept.



Appearance of coated and uncoated 304 austenitic stainless steel after (a) 500 hours in an oxidizing atmosphere at 900 °C; and (b) 24 hours in a coking atmosphere at 600 °C.

SC0008203, May 2013

Low Cost Spray-On Coatings for Protection of SOFC Interconnects and BOP Components—nGimat Company

Background

The use of ferritic steels in solid oxide fuel cells (SOFCs) can decrease cost, but degradation of these materials due to elevated temperatures (600 to 1000 degrees Celsius), dual reducing and oxidizing atmospheres, and water vapor present during operation necessitates the development of innovative solutions to provide durable oxidation protection and mitigation of chromium (Cr) volatilization. Current solutions involve the use of specialty alloys or coatings that are often expensive, ineffective, or impractical for SOFC components.

nGimat Company proposes the use of NanoSpray^{SM} Combustion Chemical Vapor Deposition (CCVD) for the flame spray application of coatings intended to protect SOFC stainless steel interconnects and balance of plant (BOP) components against oxidation, corrosion, and metal loss that leads to increased cost as well as decreased SOFC lifetime and performance. Test results show that CCVD-formed nanolaminate technology does increase the lifetime and durability of stainless steels used for SOFC components as well as other metals in high-temperature environments while costing less than other thin film coating processes.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

This project will apply and test the use of NanoSpray^{SM} CCVD for the flame spray application of coatings from liquid precursors. nGimat will develop alumina-based nanolaminate coatings for BOP components as well as manganese cobaltite spinel $[(Mn,Co)_3O_4]$ coatings specifically designed for SOFC interconnects. Alumina coatings (Al_2O_3) present a cost effective method for mitigating oxidation of most metal SOFC components; however, electrical conductivity must be considered for interconnect coatings, and $(Mn,Co)_3O_4$ has been shown to be an effective oxidation barrier while also mitigating Cr evaporation and maintaining the necessary high electrical conductivity.

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PROJECT FACTS

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PARTNERS

None

PERFORMANCE PERIOD

Start Date	**End Date**
06/28/2012	03/27/2013

COST

Total Project Value
$149,641

DOE/Non-DOE Share
$149,641 / $0

AWARD NUMBER

SC0008267

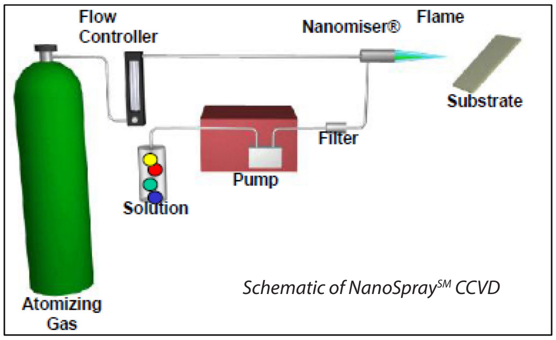
U.S. DEPARTMENT OF ENERGY

NanoSpray^{SM} CCVD technology enables the fabrication of layers similar to high vacuum vapor deposited coatings but with a low cost and open atmosphere process that does not require post deposition heat treatment. Other advantages of this unique technology include the ability to easily tailor or alter composition to form nanolaminates through a one-step process that can be readily integrated into a production line and adapted for roll-to-roll (R2R) fabrication. R2R is the preferred method for continuous production of metal for SOFC interconnects, and the ability to incorporate a coating process into such a processing line will be necessary to make it viable and practical.

Goals and Objectives

The ultimate goal of this work is to decrease the cost of SOFCs by increasing SOFC life and performance, using NanoSpray^{SM} CCVD for the flame spray application of coatings to protect SOFC stainless steel interconnects and BOP components against oxidation, corrosion, and metal loss. Specific objectives include the following:

- Synthesize $(Mn,Co)_3O_4$ precursor.
- Define Al_2O_3 and $(Mn,Co)_3O_4$ coating deposition process.
- Conduct high-temperature testing and analyze NanoSprayed coated samples.
- Develop partnerships utilizing license agreements to advance the commercialization of the technology.



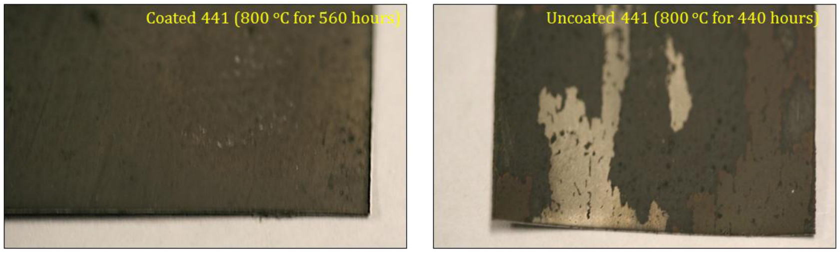
Schematic of NanoSpray^{SM} CCVD

Accomplishments

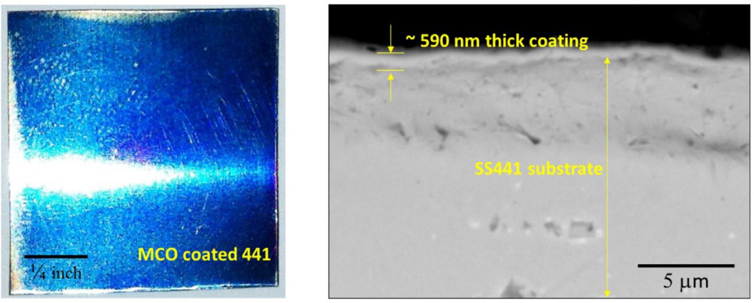
- Successfully adapted the low cost and one step NanoSpray^{SM} CCVD for the deposition of Al_2O_3- and $(Mn,Co)_3O_4$-based coatings on SOFC-relevant ferritic stainless steels (441 and 430 SS).
- Reduced oxidation rate at 800 °C by >80% for both 441 and 430 SS.
- Significantly improved scale adhesion compared to uncoated and demonstrated coating/scale durability through thermal cycling.
- Drew the interest of a major SOFC manufacturer and specialty SOFC metals producer.

Benefits

nGimat's SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Images of ~1"x1" coupons of $(Mn,Co)_3O_4$ coated and uncoated 441 SS following oxidation in ambient air at 800 °C. The coated scale remains adhered while large portions of the uncoated scale have spalled.



Dense and adherent $(Mn,Co)_3O_4$ coating on 441 SS (left), and scanning electron micrograph of as-coated $(Mn,Co)_3O_4$ on 441 SS (right).

SC0008267, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Low-Cost Alloys for High-Temperature SOFC Systems Components — QuesTek Innovations

Background

One of the key opportunities for cost reduction in a solid oxide fuel cell (SOFC) system is the set of balance of plant (BOP) components supporting the fuel cell itself, including the heat exchanger and air/fuel piping. These represent about half of the overall cost of the system. A major enabling technological breakthrough is to replace incumbent nickel-based superalloys in high-temperature BOP components with low-cost ferritic stainless steel. However, the ferritic alloys are unsuitable for SOFC application without additional coatings due to the inherent volatile nature of the alloy's chromium oxide (Cr_2O_3) element, which tends to poison the fuel cell's cathode and leads to per-formance degradation.

QuesTek Innovations LLC (QuesTek) will apply its computational alloy design methodology and experience with high-Cr stainless ferritic alloy and oxidation modeling to create a novel low-cost alloy for SOFC BOP applications. QuesTek will evaluate various approaches to develop weldable alloys with low Cr volatility and high oxidation resistance under typical SOFC high-temperature (700 to 900 degrees Celsius), oxygen-rich operating conditions.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

QuesTek is uniquely positioned to design a new material for SOFC BOP components using its advanced *Materials by Design*® stage-gate alloy development process. The process is based on computationally-implemented mechanistic models to predict process-structure and structure property relationships at length-scales ranging from inter-atomic bonding to macro-segregation during ingot solidification.

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PARTNERS

None

PROJECT DURATION

Start Date	End Date
06/28/2012	03/27/2013

COST

Total Project Value
$149,768

DOE/Non-DOE Share
$149,768 / $0

AWARD NUMBER

SC0008236

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

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QuesTek has generated two unique alloy micro-structural concepts to achieve cost effectiveness, oxidation resistance and low Cr volatility in its new alloys. One is an alumia-forming ferritic alloy that develops a thermally grown oxide layer with slow growth kinetics that serves as a Cr diffusion barrier on the alloy substrate and provides additional oxidation resistance. One of the concerns of this approach is the reduced room-temperature toughness due to high aluminum content. The other is an in situ spinel-forming ferritic alloy (similar to custom alloys such as Crofer 22) that grows a spinel oxide layer on top of Cr_2O_3 to reduce the Cr vaporization rate. Spinel systems with minimal Cr solubility and diffusivity will be incorporated into the alloy designs.

Goals and Objectives

The goal of this project is to design prototype alloys using an integrated suite of material design models and demonstrate the feasibility of the initial design by producing and proto-typing ingots and evaluating them against program goals including low Cr volatility, oxidation resistance, creep resistance, weldability, and cost. Specific objectives are as follows:

- Extend existing thermodynamic databases and refine and validate mechanistic computational alloy design models to enable computational design.
- Investigate the potential of two well-defined microstructural concepts to achieve performance criteria required for cost effective oxidation resistant and non Cr-volatile alloys for SOFCs with a particular focus on the BOP components.
- Design and produce a series of sub-scale prototype alloys that explore different aspects of microstructural concept space. These prototypes will be tested to demonstrate concept feasibility.
- Refine the present models with data from the micro-structural and property characterization.

Accomplishments

QuesTek has demonstrated the feasibility of applying its *Materials by Design*® approach to computationally design new alloys to address the technical challenges related to SOFC components. During the Phase I SBIR, QuesTek designed and fabricated prototype austenitic stainless steels that exhibited:

- Stable, continuous aluminum oxide layer with suppressed aluminum nitride formation.
- Good high temperature moist-air oxidation resistance.
- Low Cr volatility at high temperature and under moist conditions.
- Improved high temperature strength over 310 stainless.

Image of a 30 lb prototype steel ingot designed and produced by QuesTek

The performance of these prototype alloys approaches that of much more costly nickel-based alloys, and they exceed the performance of existing steels considered leading candidate materials.

Benefits

QuesTek's SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.

NETL

SC0008236, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Stable Glass-Ceramic Nanocomposites as Compliant Seals for SOFCs—SEM-COM Company

Background

The challenge in developing a high-temperature seal material for solid oxide fuel cells (SOFCs) results from the dissimilarities between the seal and the components to be joined, in particular, their physical and chemical properties. A criterion that severely limits the use of inorganic, non-metallic sealing materials for SOFCs is their poorly matching coefficients of thermal expansion (CTE) within the operating temperatures (700 to 850 degrees Celsius [°C]) of SOFC stacks.

SEM-COM Company, Inc (SEM-COM) will develop a novel high-CTE hexacelsian glass that will be especially useful in glass-to-metal applications in the SOFC structure. Hexacelsian is a polymorph of celsian, a barium aluminosilicate feldspar. Nanoparticles will be dispersed between the matrix glass and hexacelsian glass particles to prevent the matrix glass from dissolving the filler glass as either a sacrificial coating or a barrier coating. Nanotechnology materials are ideal for this application because their high surface area characteristics will minimize the amount needed to isolate the primary composite glasses.

This fuel cell project was competitively selected under the Small Business Innovative Research (SBIR) Program. It is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance (SECA), DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

SEM-COM will develop a composite sealing system with appropriate thermal and mechanical properties to which nanoscale materials have been introduced to inhibit or prevent the dissolution of a hexacelsian phase into the matrix glass, thereby eliminating the CTE drift in the composite system in the 700 to 850 °C temperature range. A two-phase mixture or composite will be developed that is stable. One of the phases is a crystalline (devitrified) phase whose composition has been selected to provide a thermal expansion match of the composite to the SOFC system (in the room temperature to glass transition temperature range), and the equilibrium second phase is a vitreous phase to provide the much-needed compliance at the operating temperature.

There are three innovations involved: (1) an inorganic, non-metallic, composite sealing material that at elevated temperatures is compliant so as to provide hermetically sealed materials with dissimilar (non-matching) CTE properties; (2) a glass-ceramic material with a CTE as high as 18 ppm/°C that can be predictably controlled and tailored by varying the heat treatment of the material; and (3) the use of nanoscale materials as barriers in inorganic composite systems to keep various components separate and distinct. The

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Ceramatec, Inc.

PROJECT DURATION

Start Date	End Date
03/04/2012	05/19/2013

COST

Total Project Value
$149,550

DOE/Non-DOE Share
$149,550 / $0

AWARD NUMBER

SC0007608

U.S. DEPARTMENT OF ENERGY

high-CTE hexacelsian glass, especially with the addition of the nanoscale materials, will allow the development of a new family of high-CTE sealing glasses that currently do not exist.

Goals and Objectives

The goal of this project is to develop the materials and processes for a hermetic seal system for SOFCs with the ability to withstand the rigors of normal use over an extended period of time (i.e., 40,000 hours) including dozens of thermal cycles. The objectives are as follows:

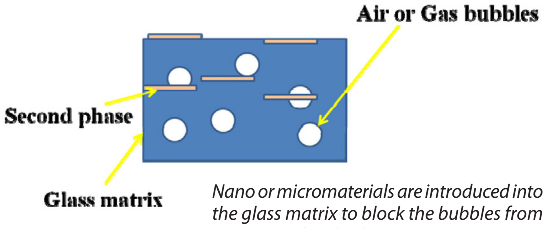
- Identify and prepare the appropriate materials.
- Develop the best process to coat and adhere the filler or matrix particles with the nanoparticles.
- Develop a process to mix the system components.
- Measure the properties of the composites (flow, CTE, etc.).
- Develop appropriate thermal cycles.
- Study the microstructure of the glass to confirm dispersion of the nanoparticles.
- Measure CTE stability (e.g., at 8 hours, 96 hours, 300 hours) and crystallization characteristics.
- Evaluate basic compatibility with other SOFC materials including flow and wetting.

Accomplishments

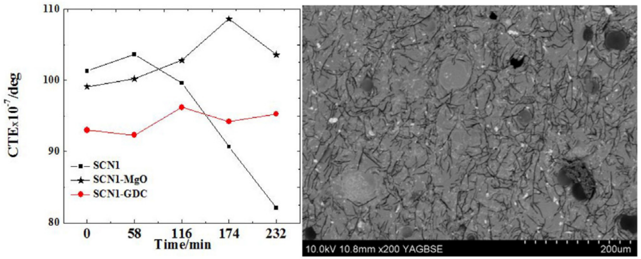
- Early on in this project it was found that the high CTE characteristic of the hexacelsian composite was due to the formation of a high CTE crystal phase in the matrix glass and the CTE instability was due to the high CTE phase re-dissolving into the matrix glass. Additions of nanoscale materials offered little hope of remedying that situation, so the project focus shifted to the use of nano and microscale materials to inhibit the movement and coalescing of air bubbles in the well-researched SCN-1 sealing glass
- Appropriate materials as second phase to be dispersed within SCN-1 were identified. These consisted of nano and microscale particles and fibers.
- Coating materials for the second phase were identified and added to the system to stabilize the CTE.
- Processes to mix the system components were developed.
- CTE stability of the glass composite was achieved (232 hours at 850 °C) as well as mitigation of air bubble movement and coalescence.

Benefits

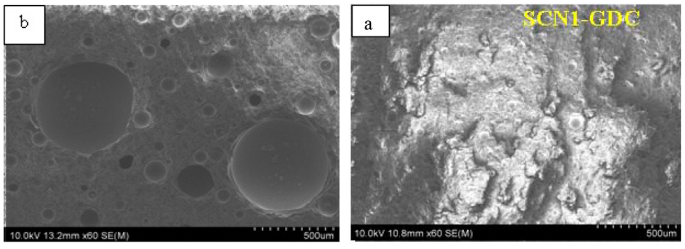
SEM-COM's SBIR project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability to capture 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to permit grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.



Nano or micromaterials are introduced into the glass matrix to block the bubbles from moving and make the structure stronger. As result the CTE of the glass composite will be stable over many operating hours.



Comparing CTEs of SCN1 glass and glass composites contains magnesium oxide (MgO) or gadolinium doped ceria (GDC) particles as second phase T: 850 °C (left). Observing the second phase lodged (GDC) within the glass matrix by using a backscatter electron (BSE) imaging technique. The second phase is differentiated from glass by higher difference in the contrast (right).



SCN-1 (232 hrs @850°C)

SCN-1 + gadolinium doped ceria (232 hrs @850°C)

SEM show the reduction in void density with the second phase additives.

SC0007608, May 2013

SOFC Model Development—LG Fuel Cell Systems

Background

In this congressionally directed project, LG Fuel Cell Systems Inc. (LGFCS), formerly known as Rolls-Royce Fuel Cell Systems (US) Inc., is developing a solid oxide fuel cell (SOFC) multi-physics code (MPC) for performance calculations of their fuel cell structure to support product design and development. The MPC is based in the computational fluid dynamics software package STAR-CCM+ (from CD-adapco) which has been enhanced with new models that allow for coupled simulations of fluid flow, porous flow, heat transfer, chemical, electrochemical and current flow processes in SOFCs. Simulations of single cell, five-cell, substrate and bundle models have been successfully validated against experimental data obtained by LGFCS. The MPC is being used to support Solid State Energy Conversion Alliance (SECA) activities within LGFCS by providing invaluable performance information to the design and improvement of cell components, substrates, bundles, and peripheral stack components.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) whose mission is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the SOFCs program and systems coordination from SECA, DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

LGFCS developed a multi-physics SOFC model(s) for performance calculations of their fuel cell in support of design and product development with work completed in March, 2013. LGFCS requires computational performance evaluation and prediction tools to integrate into all of its SOFC design activities, from single-cell components to system-level analysis. The LGFCS fuel cell includes the integrated planar cell, cell assemblies that form bundles, bundle assemblies that form strips, and multiple strips that define the fuel cell block. The fuel cell block is the fundamental repeat unit, and when replicated, defines a one megawatt fuel cell module.

The scope of this effort included a review of LGFCS's existing models and state-of-the-art technology, a review of commercially-available multi-physics platforms, down selection of a specific code, and the establishment of functional specifications and code modification and development. Validation was performed by comparing benchmark testing to actual performance data.

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PROJECT FACTS

Fuel Cells

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PARTNERS

NONE

PROJECT DURATION

Start Date	End Date
10/01/2009	03/13/2013

COST

Total Project Value
$1,542,100

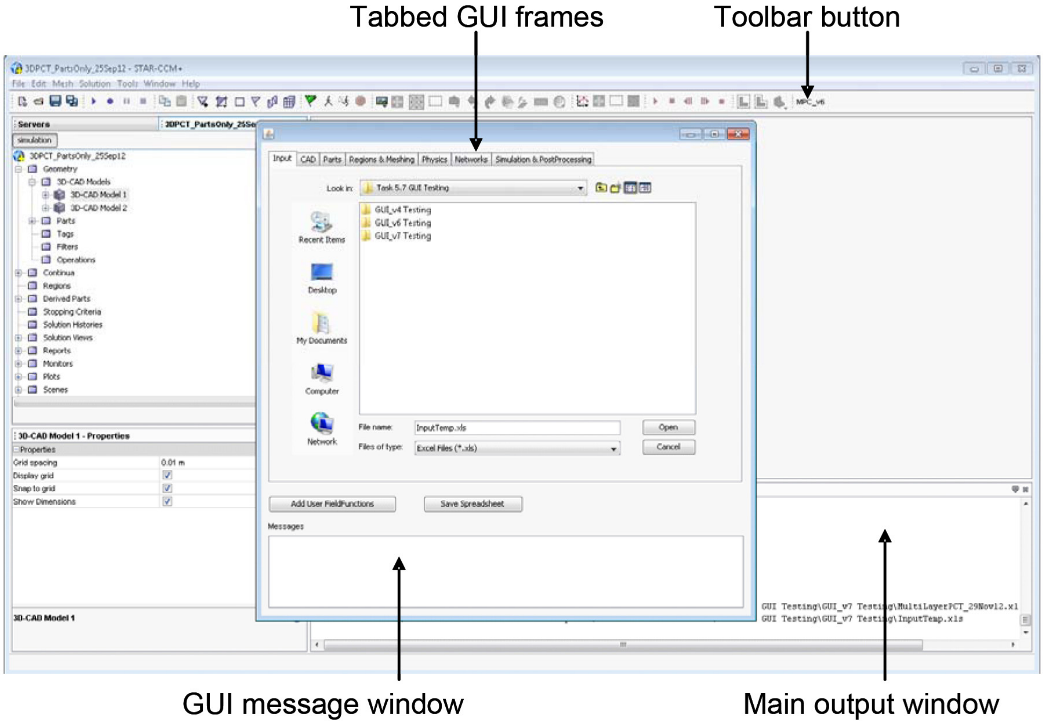
Base
DOE/Non-DOE Share
$1,233,680 / $308,420

AWARD NUMBER

DE-FE0000773

Fuel cell model development proceeded using multiple and independent approaches developed within LGFCS in conjunction with various universities (e.g., Imperial College, Genoa University and University of Cambridge). Each approach focused on different computational aspects of the LGFCS fuel cell models and modeling capabilities. Further developments were needed to leverage the performance and flexibility of a commercial multi-physics platform with capabilities to integrate the important features of the latest models and provide a flexible platform for future model upgrades.

The chosen commercial MPC was adapted to include the capabilities of existing LGFCS fuel cell models as well as new models. This development activity progressed concurrently with code evaluation to ensure that performance, usability, and reliability were not compromised. The code was validated against experimental measurements made by LGFCS on single integrated planar cell segments, complete fuel cell assemblies, and bundles.



Look in: Task 5.7 GUI Testing

File name: InputTemp.xls

Files of type: Excel Files (*.xls)

Grid spacing	0.01 m
Display grid	☑
Snap to grid	☑
Show Dimensions	☑

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GUI Testing\GUI_v7 Testing\MultiLayerPCT_29Nov12.xl
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Figure 1. A typical view of the MPC GUI installed into STAR-CCM+.

Goals and Objectives

The overall goal of this project was to develop a SOFC MPC for performance calculations of the LGFCS fuel cell structure in support of product design and development. This work consolidated years of LGFCS investment and research throughout the world as part of its business objective to develop an SOFC product for stationary power generation. The primary project objectives were as follows:

- Enhance MPC to install and configure the following models: integrated current flow and electrochemistry; empirical and kinetic degradation models; chemical reactions; fluid (laminar and turbulent) and porous flows; plug fluid flow; heat transfer by convection, conduction, and radiation.
- Enhance MPC to model transient behavior of cells, substrates and bundles over a range of relevant time scales.
- Establish and validate one- and two-dimensional models of a single cell, two- and three-dimensional models of a five-cell structure, and three-dimensional models of a substrate and bundle.
- Develop degradation models and validate against available experimental data.
- Validate transient predictions of MPC cell/substrate/bundle current-voltage measurements during anticipated operational transients.

- Establish external supercomputing capability for running large simulations.
- Interface with lifetime and reliability modeling project to supply required variables from substrate and bundle models.
- Interface with larger-scale lower resolution model to obtain boundary conditions for in situ bundle operation within a block.
- Develop new model applications to demonstrate MPC predictive capabilities to the LGFCS team.
- Prepare MPC for use by LGFCS engineers outside of the project team.

Accomplishments

- Completion of MPC enhancements as set out in the project objectives.
- Successful development and validation of: one- and two-dimensional models of a single cell; two- and three-dimensional models of a five-cell structure; and three-dimensional models of a substrate and bundle.
- Development of empirical degradation models from five-cell test results obtained from over 6,000 hours of operation (experiments are ongoing).
- Establishment of external supercomputing capability for running large simulations. Substrate and bundle models were run successfully.
- Creation of interface between MPC and other simulation activities including lifetime and reliability modeling and larger-scale lower resolution models.
- Demonstration of MPC predictive capabilities in a variety of advanced engineering applications including analysis of tube electrical connections, strip flow distribution, ejector performance, in-situ bundle temperature distribution, and ripple current input signals.
- Further enhancement of an acceleration algorithm to generate initial guesses for SOFC and non-SOFC applications.
- Integration of MPC capabilities into a Graphical User Interface (GUI) that provides an interactive environment to perform automated simulation tasks.
- Successful testing of the GUI with six engineering staff outside of the MPC project team – GUI is being used to perform engineering analysis of a number of LGFCS SOFC system components.

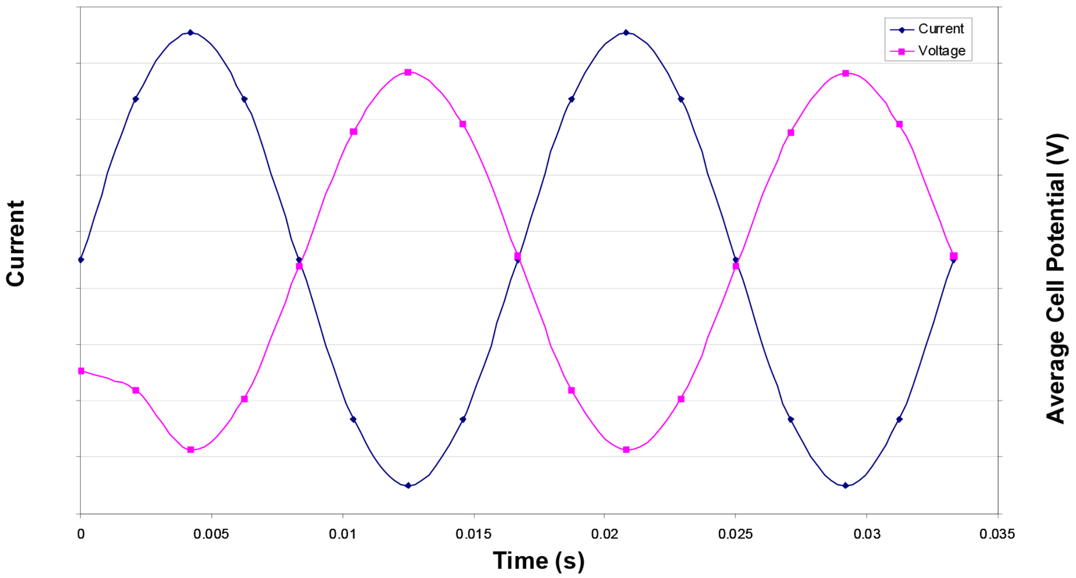

Figure 2. Voltage response of cells to sinusoidal input current signal.

This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FE0000773.

Benefits

The final product, a computational design tool, provides improved accuracy of steady-state behavior predictions and detailed examination of transient behavior. Transient analysis capabilities directly contribute to the credibility of failure mode and reliability analyses and also ensure safe system operation during start-up, shut-down, and off-design transients. This code will ultimately be integrated into the LGFCS design process and provide a platform for future model enhancement with state-of-the-art research.

FE0000773, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Improved Flow-field Structures for Direct Methanol Fuel Cells—NuVant Systems, Inc.

Background

In this congressionally directed project, NuVant Systems, Inc. (NuVant) will improve the performance of direct methanol fuel cells (DMFCs) by designing anode flow-fields specifically for the delivery of liquid methanol. The goal is to deliver concentrated methanol to the DMFC anode in an even and controllable manner such that the phenomenon known as crossover is avoided. Crossover occurs in a DMFC when unutilized methanol passes from the anode to the cathode through the permeable Nafion electrolyte. Traditionally, crossover has been avoided by pre-diluting methanol (with water) to decrease the methanol concentration gradient across the Nafion electrolyte. This operating strategy is undesirable for portable power applications because it reduces the specific energy content (watt-hours per kilogram) of the fuel (diluted methanol) that must be carried. NuVant's technology to deliver concentrated methanol to the DMFC anode could increase the specific energy content of DMFC fuel, potentially pushing the performance beyond the current state-of-the-art in portable power (lithium-ion batteries).

The project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), whose mission is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance, DOE/NETL is leading the research, development, and demonstration of solid oxide fuel cells (SOFCs) for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

NuVant will contend with the problem of methanol crossover by employing highly porous structures at the DMFC anode which will allow for controlled delivery of highly concentrated or "neat" methanol to the anode side. The methanol delivery to the anode side will be adjusted in concert with the back-diffusion of water from the cathode side such that diluted methanol will be created in situ at the anode. In this way crossover will be minimized and high gross fuel energy density will be achieved. The basis for success is the tightly controlled structure of the porous material and the fuel delivery mode. The pore diameter and total porosity play a very important role in how (and how much) the highly concentrated methanol arrives at the anode. Various hydrophilic and/or hydrophobic treatments of the porous substrate impact the way methanol distributes over the entire geometric area of the electrode. These treatments also impact the way reaction products are being exhausted.

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PARTNERS

None

PROJECT DURATION

Start Date	**End Date**
08/01/2009	05/31/2013

COST

Total Project Value
$1,142,481

DOE/Non-DOE Share
$913,985 / $228,496

AWARD NUMBER

FE0000982

U.S. DEPARTMENT OF ENERGY

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In order to best build these porous structures, a thorough understanding of flow and diffusion through porous media is required. A computer model will be developed that utilizes the relevant physical and chemical properties of methanol to model the flow of liquid fuel through the porous graphite plates that compose the anode flow-fields. The modeling effort will begin with a literature review to identify the physical and chemical properties necessary to accurately model the flow of methanol through porous graphite media. These parameters will enable the development of a mathematical model to predict how various flow-fields affect fuel distribution across the DMFC anode. A down-selection will identify flow-fields exhibiting the best-demonstrated performance according to the mathematical model. Physical prototypes of the down-selected flow-fields will be created. The prototypes will be evaluated for hundreds of hours in a bench scale DMFC stack test. This test will serve as validation that improved DMFC performance can be achieved via improved flow-fields.

Goals and Objectives

The primary goal of this project is to develop improved flow-fields for DMFCs. This will be achieved by modeling the transport of methanol through anode flow-fields (porous graphite structures), creating prototypes of the best demonstrated flow-fields, and validating the down-selected flow-fields in a DMFC stack. Project objectives are as follows:

- Produce computational fluid dynamic models of various flow-field geometries and material porosities using FLUENT software package (Ansys, Inc.).
- Fabricate porous plates according to modeling results.
- Maximize fuel energy density by optimizing membrane electrode assembly (MEA) structure and operating scheme.
- Perform extended life tests of optimized MEAs.
- Construct one or more short stacks consisting of three to four cells.
- Optimize the short stack(s) in terms of operating parameters.

Accomplishments

- FLUENT modeling of the porous plate structure was performed and determined that a square-grid flow-field on both sides of the porous plate would provide the most uniform flow distribution.
- Flow-field plates were successfully fabricated from porous graphite using a table-top end mill machine.
- DMFC single cells were evaluated using the porous graphite flow-field plates and resulted in gross fuel energy densities of over 781 watt-hours per liter with fuel utilizations of over 79.4 percent.
- Single cells have been operated using the porous flow-field plate configuration for over 80 hours with no significant decrease in power output.
- A short stack has been constructed consisting of two cells; initial performance testing has begun.
- The entire integrated flowfield diffusion layer (IFDL)-based DMFC has been modeled, and the modeling results agree very well with the experimental data.
- A brand new factory for casting conducting ultra-hydrophobic water-repellent and gas-permeable cathodic diffusion layers has been built at NuVant (the company that used to provide hydrophobic diffusion layers no longer offers the product, nor does any other company in the world).
- Characterization of the product is ongoing.

Benefits

The principal benefit of this project is the improved performance of DMFCs due to the design and validation of porous graphite plates specifically for the delivery of liquid methanol.

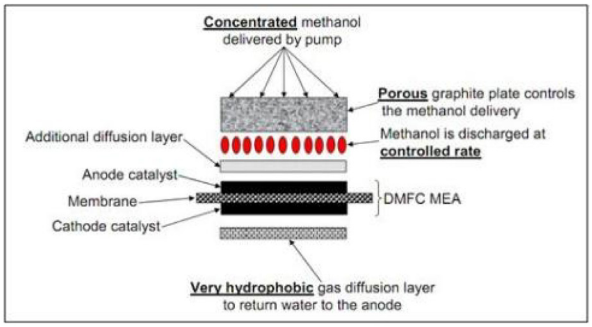

Figure 1. *Schematic of the construction of an IFDL-based DMFC.*

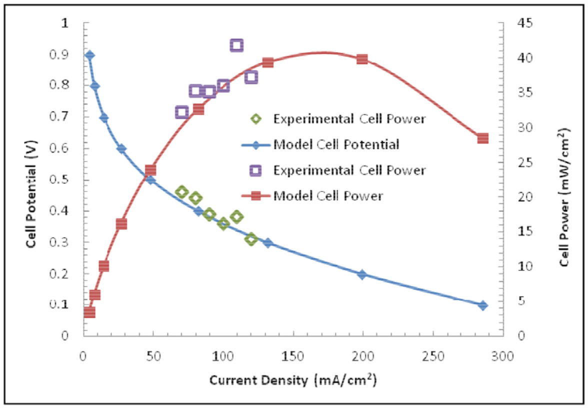

Figure 2. *Polarization and power curves for DMFC model and experimental Data.*

FE0000982, May 2013

Solid Oxide Fuel Cells Operating on Alternative and Renewable Fuels—Pennsylvania State University

Background

In this congressionally directed project, the Earth and Mineral Science (EMS) Energy Institute at Pennsylvania State University (PSU) focuses on the development of fuel processors, reforming catalysts, and chemical sorbents to support the production of electricity from anaerobic digester gas (ADG) and ultra-low sulfur diesel (ULSD) via solid-oxide fuel cells (SOFCs). PSU will use the fuel processors, reforming catalysts, and chemical sorbents developed under this work to transform and clean ADG and ULSD into a syngas stream suitable as a feedstock for SOFCs.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), whose mission is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the SOFCs program and systems coordination from the Solid State Energy Conversion Alliance, DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Originally, this project included a subcontract for Siemens Energy to provide SOFC stacks and cell samples to PSU for testing. Siemens eliminated their Stationary Fuel Cell Division, which led to the cancellation of the Siemens subcontract under this PSU research effort. Since that time PSU has signed a new subcontract with Delphi Automotive Systems, under which Delphi will complete the scope of work originally intended for Siemens.

Project Description

PSU will develop fuel processors for ADG and commercial diesel fuels. These fuel processors will transform ADG and diesel fuel into syngas fuel, which can be utilized in SOFCs. The trace contaminants present in the ADG and diesel-derived syngas fuel are expected to overlap coal syngas contaminants with respect to level and variety of contaminants. Therefore this work will also include the development of adsorbents suitable for trace contaminant removal. Data from the operation of SOFCs on reformed diesel fuel will be applicable to early market SOFC spin-off applications, e.g., truck auxiliary power units (APUs).

The major work of this project is focused on the 1) preparation and evaluation of novel sorbents including molecular basket sorbent (MBS) and mixed metal oxides adsorbents for ADG cleanup; 2) improvement of the adsorption performance of mesoporous molecular sieve supported Nickel (Ni) adsorbents and mixed Titanium-Cerium-Oxygen (Ti-Ce-O) based adsorbents for adsorptive desulfurization of ULSD; 3) evaluation and characterization of Ni-based catalysts for steam reforming of commercial diesel fuel; and 4) the testing of SOFC stack delivered to PSU by Delphi, and 5) the continued

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Fuel Cells

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Delphi Automotive Systems

PERIOD OF PERFORMANCE

Start Date	**End Date**
08/1/2009	08/31/2013

COST

Total Project Value
$4,767,783

DOE/Non-DOE Share
$3,734,954 / $1,032,829

AWARD NUMBER

NT0004396

U.S. DEPARTMENT OF ENERGY

operation of a Ni-yttria-stabilized zirconia (YSZ) single cell SOFC on both a model ADG and also a commercial diesel reformate.

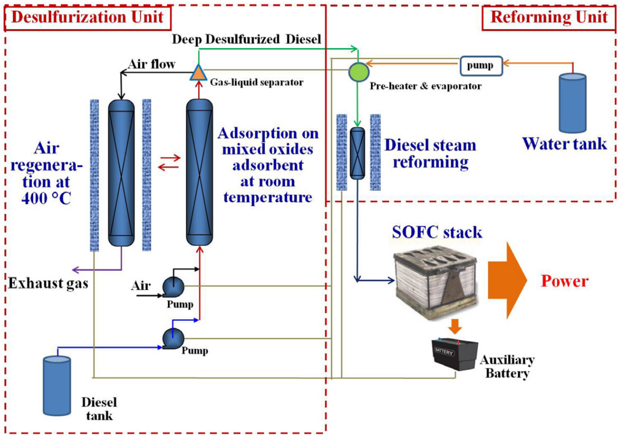
Goals and Objectives

The primary goal of this project is to develop new fuel processing approaches for using selected alternative and renewable fuels such as ADG and commercial diesel fuel (with 15 parts per million sulfur) in SOFC power generation systems. Project objectives are as follows:

- To develop new fuel processing approaches for using selected alternative and renewable fuels, ADG and commercial diesel fuel, in SOFC power generation systems.
- To develop and evaluate effective sorbents for ADG cleanup.
- To improve the performance of the Ni-based and metal oxide-based adsorbents for adsorptive desulfurization (ADS) of ULSD.
- To develop Ni-based catalysts for steam reforming of commercial diesel fuel with fundamental understanding the sulfur-tolerance and carbon-resistance of the developed catalysts via various characterization techniques.

Accomplishments

- Developed a novel MBS sorbent that is able to remove both CO_2 and H_2S for ADG cleanup simultaneously.
- Explored mixed metal oxide-based adsorbents for ADG cleanup; a highly efficient Cu-Ti-Ce-O adsorbent has been developed, which is air regenerable. The promotion effect of Cu addition has been studied.
- Developed new type of MBS adsorbents for deep removal of ammonia to below 1 ppmv for ADG cleanup.
- Explored silica based adsorbents for deep removal of siloxanes from ADG monitored on-line by GC-ICP-MS, which can reduce siloxanes below ten parts per billion.
- Supported Ni adsorbents were found highly effective for sulfur removal from ULSD.
- Studied and clarified the effects of Ti-Ce loading and support on the performance of mesoporous silica supported Ti-Ce-O adsorbent for adsorptive desulfurization of ULSD, which is air regenerable at elevated temperatures (e.g., 400 °C).
- Prepared and studied low-cost iron modified Ni catalysts with and without K modification for the steam reforming of a commercial diesel. The developed catalyst can work for 100+ hours of diesel steam reforming without any deactivation in a lab test.
- A conceptual design has been proposed for diesel fuel processor utilizing the developed air-regenerable Ti-Ce mixed oxide adsorbents for deep desulfurization and the low-cost, highly carbon-resistant and sulfur-tolerant Fe-Ni bimetallic catalyst for diesel steam reforming for SOFCs.
- Developed and tested a combined steam reforming, Ni-YSZ anode SOFC test system for a period of 200+ hours running on a simulated ADG and reformed commercial diesel.
- Used electrochemical impedance spectroscopy (EIS) and equivalent circuit modeling to track the degradation of SOFC performance operating on ADG over a period of 200+ hours.
- Evaluated the effects of SOFC poisoning by H_2S impurities in ADG fuel using EIS.
- Developed and tested a SOFC stack testing setup which could be operated simultaneously with miniature SOFC button cells operating on hydrogen, diesel reformate, and bio-gas reformate.
- Tested and evaluated the degradation effects of various levels of concentrations of inorganic impurities (Sulfur, Chlorine, Silicon and Ammonia) present in fuel reformate streams on SOFC button cell performance by EIS.
- Operated the SOFC stack under operating conditions mutually discussed by PSU and Delphi with pure hydrogen and simulated reformate streams and then carried out its initial characterization by EIS and other performance tests.
- Established a protocol for testing of the SOFC stacks operating on hydrogen, simulated diesel reformate, simulated bio-gas reformate and also different concentrations of impurities in the fuel stream.



The Conceptual Design for Diesel Fuel Processor using the Deep Desulfurization Adsorbent and the Low-cost Fe-Ni Bimetallic Steam Reforming Catalyst Developed in this Project for SOFC.

Benefits

This project will provide valuable operational experience with SOFC cells on pseudo-coal syngas and new and novel contaminant removal materials and processes for large coal-fueled integrated gasification fuel cell systems. The fuel processors to be developed and tested within this project will produce reformate gases having compositions similar to coal syngas, and the contaminant removal adsorbent and processes may have applications with respect to particular contaminants of interest found in coal (e.g., phosphorus).

NT0004396, May 2013

the ENERGY lab

PROJECT FACTS

Fuel Cells

Techno-Economic Analysis of Scalable Coal-Based Fuel Cells—University of Akron

Background

In this congressionally directed project, the University of Akron (UA) will develop a scalable coal fuel cell manufacturing process to a megawatt scale. UA has demonstrated the technical feasibility of a laboratory coal fuel cell that can economically convert high sulfur coal into electricity with little negative environmental impact.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), whose mission is to advance energy options to fuel our economy, strengthen our security, and improve our environment. With the Solid Oxide Fuel Cells (SOFCs) program and systems coordination from the Solid State Energy Conversion Alliance, DOE/NETL is leading the research, development, and demonstration of SOFCs for both domestic coal and natural gas fueled central generation power systems that will enable low cost, high efficiency, near-zero emissions and water usage, and carbon dioxide (CO_2) capture.

Project Description

This project will demonstrate the technical and economic feasibility of building a 250 kilowatt (kW) direct coal fuel cell (DCFC) pilot plant. Researchers at the UA have demonstrated the technical feasibility of a laboratory coal fuel cell that can economically convert high sulfur coal into electricity with near-zero negative environmental impact. Scaling up this coal fuel cell technology to a megawatt scale requires two key elements: (1) developing the manufacturing technology for the components of the coal-based fuel cell and (2) long-term testing of a kW-scale fuel cell pilot plant. This novel coal fuel cell technology is expected to be a highly efficient, super clean, multi-use electric generation technology, which promises to provide low cost electricity by expanding the utilization of U.S. coal supplies and relieving our dependence on foreign oil.

A DCFC stack consists of multiple fuel cells that are interconnected electrically to one another. The performance of the stack will be simulated on the basis of preliminary design and the single cell performance. The simulations and test data will be used to further refine the design.

Goals and Objectives

The ultimate goal of this project is to demonstrate the technical and economic feasibility of building a 250 kW pilot plant coal fuel cell. This project will address initial development, scaling, and manufacturing of the core technology as follows:

- Design a kW-scale fuel cell system and simulate its performance.

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PARTNERS

None

PROJECT DURATION

Start Date	**End Date**
09/01/2009	08/31/2013

COST

Total Project Value

$1,713,961

DOE/Non-DOE Share

$1,370,977/$342,984

AWARD NUMBER

FE0000528

U.S. DEPARTMENT OF ENERGY

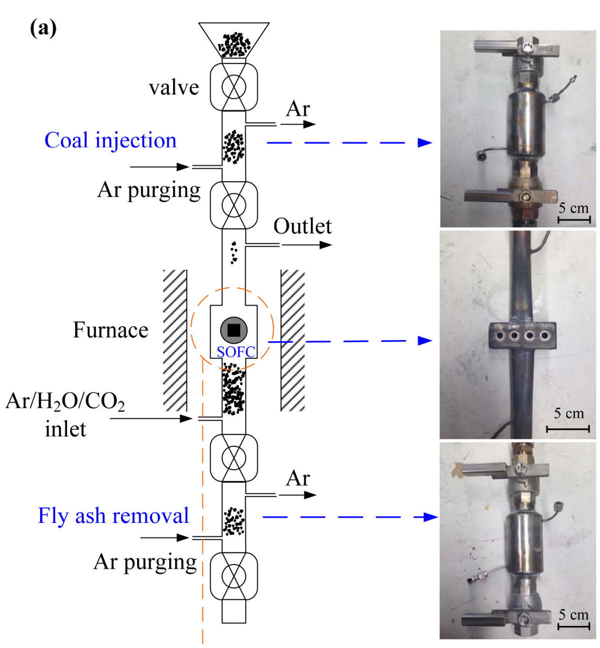
- Develop a kW-scale fuel cell manufacturing technology.
- Evaluate the durability of the kW fuel cell components.
- Develop low cost interconnect and the cathode current collector materials.
- Design a coal injection and flyash withdraw system.
- Design a 250 kW fuel cell pilot plant.

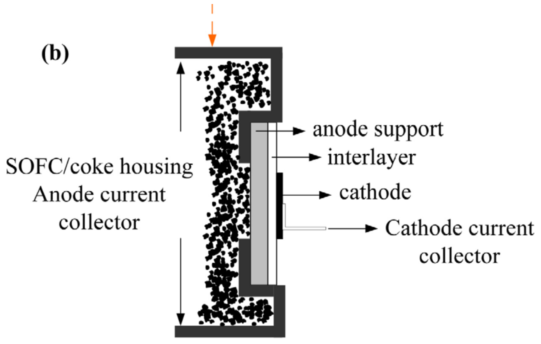
Accomplishments

- Synthesized and characterized a copper-nickel-yttria-stabilized zirconia (Ni/YSZ) anode that exhibits high catalytic activity for electrochemical oxidation of carbon and hydrocarbons, and resistance to deactivation.
- Developed a tape casting formulation that facilitates the fabrication of fuel cells with variable anode porosity and high mechanical strength.
- Simulated the steady-state operation of a 250 kW coal-based system determining mass/energy balances and energy efficiencies.
- Identified and tested suitable ceramic and glass-ceramic sealant materials for the operation of a coal-based fuel cell, demonstrating leakage rates as low as 0.17 standard cubic centimeters per minute per centimeter, and matching the performance of alternative compression seals.
- Designed and tested a coal injection and fly ash removal reactor.
- Flowing trace amount (2% or less) of H_2, CO_2, and H_2O improves the performance of coke fuel cell.
- Exposure of coke to 3 mol% H_2 keeps the anode in reduced state and promotes formation of CO and CH_4.
- Exposure of coke to 7 mol% H_2O (steam) improves the performance of the SOFC with coke as the feed. This improvement is due to the H_2 and CO_2 generation via water gas shift reaction and coke gasification.
- Assembled and successfully tested five Ni/YSZ anode-supported fuel cells in series, generating 4.6 open circuit voltage.

Benefits

The UA project assists the SOFCs program in meeting its cost and performance targets by ensuring that SOFCs can achieve reliable operation over an extended operating life. The program will ultimately enable fuel cell-based near-zero emission coal and natural gas power plants with greatly reduced water requirements and the capability of capturing 97 percent or greater of carbon at costs not exceeding the typical cost of electricity available today. Achieving this goal will significantly impact the nation given the size of the market, the expected growth in energy demand, and the age of the existing power plant fleet. It will also provide the technology base to enable grid-independent distributed generation applications. Federal funding support of this research is appropriate given the game-changing nature of the technology accompanied by risks higher than the private sector initially can accept.





(a) Schematic of the coal injection and fly ash withdraw system

(b) Side view of the coal SOFC compartment

FE0000528, May 2013

SECTION 9: ABBREVIATIONS

2-D	two dimensional
3-D	three dimensional
AC	alternating current
ADG	anaerobic digester gas
AES	Advanced Energy Systems
Al	aluminium
ANL	Argonne National Laboratory
ASR	area-specific resistance
atm	atmosphere
Ba	barium
BOP	balance-of-plant
°C	degrees Celsius
Ca	calcium
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CCVD	combustion chemical vapor deposition
Ce	cerium
cm	centimeter
Co	cobalt
CO_2	carbon dioxide
COE	cost of electricity
CTE	coefficient of thermal expansion
Cu	copper
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DG	distributed generation
DMFC	direct-methanol fuel cell
DOE	Department of Energy
EDS	energy-dispersive spectrometry
EIS	electrochemical impedance spectroscopy
FCE/VPS	FuelCell Energy/Versa Power Systems
Fe	iron
FE	Office of Fossil Energy
FIB	focused ion beam
FY	fiscal year
GDC	gadolinium-doped ceria
GFED	gross fuel energy density
GUI	graphical user interface
GW	gigawatt
H_2	hydrogen
H_2S	hydrogen sulfide
HAXPES	hard X-ray photoelectron spectroscopy
HHV	higher heating value
IFDL	integrated flowfield diffusion layer
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell
kW	kilowatt
La	lanthanum
LGFCS	LG Fuel Cell Systems
LHV	lower heating value
Ln	lanthanide chemical elements
LSC	lanthanum strontium cobalt
LSCF	lanthanum strontium cobalt ferrite
LSM	lanthanum strontium manganite
MBS	molecular basket sorbent
MC	(Mn,Co)304
MCFC	molten carbonate fuel cell
mg	milligram
Mn	manganese
mol %	mole percent
MPC	multi-physics computer code
MW	megawatt
N	nitrogen
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NGFC	natural gas fuel cell
Ni	nickel
NIFT	National Institute for Fuel Cell Technology
NiO	nickel oxide
NIST	National Institute of Standards and Technology
nm	nanometer
NO_x	nitrogen oxides
NUWC	Naval Undersea Warfare Center
O	oxygen
O&M	operating and maintenance
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
ORR	oxygen-reduction reaction
OSD	Office of the Secretary of Defense

P	phosphorus
PCM	proof-of-concept module
PNNL	Pacific Northwest National Laboratory
pO_2	oxygen partial pressure
ppmv	parts per million by volume
psi	pounds per square inch
psia	pounds per square inch absolute
R&D	research and development
RD&D	research, development, and demonstration
RF	radio frequency
ROM	reduced order model
RT	room temperature
RUA	Regional University Alliance
SBIR	Small Business Innovation Research
SCC	Strategic Center for Coal
SECA	Solid State Energy Conversion Alliance
SEM	scanning electron microscopy
Sm	samarium
SOFC	solid oxide fuel cell
Sr	strontium
$SrCO_3$	strontium carbonate
SSC	strontium-doped samarium cobaltite
Tg	glass-transition temperature
Ti	titanium
Ts	dilatometric softening point
TXRF	total X-ray fluorescence
UAV	unmanned aerial vehicle (drone)
UUV	unmanned undersea vehicle
V	volt
VPIT	vacuum-pressure-infiltration thermal-treatment
W	watt
wt %	weight percent
XAS	X-ray absorption spectroscopy
XPS	X-ray photoelectron
XRD	X-ray diffraction
YSZ	yttria-stabilized zirconia
µm	micrometre

SECTION 10: DOE POINTS OF CONTACT

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SECTION 11: INDEX OF PREVIOUS PROJECTS

Table 5. Projects Discontinued in FY 2012

Contract Number	Performer	Project Topic
ER46497	Auburn University	Effect of SOFC Interconnect-Coating Interactions on Coating Properties and Performance
FE0005132	Technology Management Inc.	Small-Scale SOFC Demonstration Using Bio-Based and Fossil Fuels
MSD-NETL-01	Lawrence Berkeley National Laboratory	Cathode Contact Materials for Anode-Support Cell Development
NT0005177	Alfred University	Viscous Glass/Composite SOFC Sealants
NT0006557	Georgia Institute of Technology	Theory, Investigation, and Stability of Cathode Electro-Catalytic Activity
NT43247	Naval Underwater	Testing and Evaluation of Solid Oxide Fuel Cells in Extreme Conditions
SC0001208	NexTech Materials	Manufacturing Analysis of SOFC Interconnect Coating Processes
SC0006282	FuelCell Energy, Inc.	High-Performance Catalytic Heat Exchanger for SOFC Systems

Table 6. Projects Discontinued in FY 2011

Contract Number	Performer	Project Topic
ER85006	CellTech Power LLC	Liquid Tin Anode Direct Coal Fuel Cell
ER85020	R&D Dynamics Corporation	Foil Gas Bearing Supported High-Temperature Cathode Recycle Blower (Large-Size Cathode/Anode Recycle Blower)
ER85202	Materials and Systems Research, Inc.	Glass Composite to Coated Interconnect Seals for Long-Term Chemical Stability
FE0001390	University of Cincinnati	Innovative Self-Healing Seals for Solid Oxide Fuel Cells
NT0004111	CellTech Power LLC	Liquid Tin Anode Direct Coal Fuel Cell
NT0004113	NexTech Materials	Validation of Novel Planar Cell Design for Megawatt-Scale SOFC Power Systems
NT41246	Delphi Automotive Systems LLC	Solid State Energy Conversion Alliance Delphi SOFC
NT42513	Allegheny Technologies, Inc.	Evaluation of a Functional Interconnect System for SOFCs
PPM 300.02.08	Walt Harrison/Stanford University	Electronic Structure of Cathode Materials
SC0004380	TDA Research	Post-SOFC Residual Fuel Oxidizer for CO_2 Capture
SC0004582	CellTech Power LLC	Liquid Tin Anode Direct Coal Fuel Cell
SC0004845	NexTech Materials	Manufacturing System Design Analysis of SOFC Stacks

Table 7. Projects Discontinued in FY 2010

Contract Number	Performer	Project Topic
ER84394	Eltron Research and Development Inc.	Reformer for Conversion of Diesel Fuel into CO and Hydrogen
ER84590	Acumentrics Corporation	Hybrid Ceramic/Metallic Recuperator for SOFC Generator
ER84595	Ceramatec, Inc.	Proton Conducting Solid Oxide Fuel Cell
ER84616	R&D Dynamics Corporation	Foil-Bearing Supported High-Speed Centrifugal Cathode Air Blower
NT0006343	Treadstone Technologies, Inc.	Investigation of Modified Ni-YSZ-Based Anode for High Impurities Containing Syngas Fuels
NT43042	National Institute of Standards and Technologies	Advanced Power Conditioning System Technologies for High-Megawatt Fuel Cell Power Plants
SC0000871	Eltron Research and Development Inc.	Perovskite Adsorbents for Warm-Gas Arsenic and Phosphorus Removal
SC0000872	Eltron Research and Development Inc.	First Principles Identification of New Cathode Electrocatalysts for Fuel Cells

Table 7. Projects Discontinued in FY 2010

Contract Number	Performer	Project Topic
SC0001492	TDA Research, Inc.	Sorbents for Warm Temperature Removal of Arsenic and Phosphorous from Coal-Derived Synthesis Gas
SC0001659	Materials and Systems Research, Inc.	Novel SOFC Anodes with Enhanced Tolerance to Coal Contaminants
SC0002491	Mo-Sci Corporation	High-Temperature Viscous Sealing Glasses for Solid Oxide Fuel Cells

Table 8. Projects Discontinued in FY 2009

Contract Number	Performer	Project Topic
41567	Virginia Polytechnic Institute and State University	A Low-Cost Soft-Switched DC-DC Converter for Solid Oxide Fuel Cells
41817	American Society of Mechanical Engineers	SOFC Design Basis Development Project
41817	Carnegie Mellon University	TEM Investigations of SOFCs: Stability of LSCF-Based Cathodes
41817	University of California	High-Efficiency Coal Gasification-Based SOFC Power Plants
42219	Georgia Institute of Technology	Novel Sulfur-Tolerant Anodes for Solid Oxide Fuel Cells
42533	Tennessee Technological University	Novel Composite Materials for SOFC Cathode-Interconnect Contact
42613	Siemens Energy, Inc.	Coal Gas-Fueled SOFC Hybrid Power Systems with CO_2 Separation
42735	Georgia Institute of Technology	Characterization of Atomic and Electronic Structure of Electrochemically Active SOFC Cathode Surfaces
43063	University of Texas at San Antonio	Novel Low-Temperature Solid State Fuel Cells
44036	Montana State University	SECA Coal-Based Systems Core Research—Montana State University
84209	Phoenix Analysis & Design Technologies	Anode and Cathode Blower Systems for SOFC
84210	R&D Dynamics Corporation	Foil Gas Bearing Supported High-Speed Centrifugal Anode Gas Recycle Blower

Table 9. Projects Discontinued in FY 2008

Contract Number	Performer	Project Topic
5690	American Society of Mechanical Engineers	SOFC Design Basis Development Project (project transferred to RDS41817.3130105-036)
08-220692	National Energy Technology Laboratory	Materials Development for the Solid Oxide Fuel Cell Environment
41572	Georgia Institute of Technology	Functionally Graded Cathodes for Solid Oxide Fuel Cells
42221	Missouri University of Science & Technology	Thermochemically Stable Sealing Materials for Solid Oxide Fuel Cells
42223	Tennessee Technological University	Development of Low-Cr Fe-Ni-Based Alloys for Intermediate Temperature SOFC Interconnect Application
42225	Arcomac Surface Engineering, LLC	Oxidation Resistant, Cr Retaining, Electrically Conductive Coatings on Metallic Alloys for SOFC Interconnects
42227	University of Cincinnati	Innovative Seals for Solid Oxide Fuel Cells
42229	Delavan d.b.a. Goodrich Turbine Fuel Technologies	An Innovative Injection and Mixing System for Diesel Fuel Reforming
42471	Ceramatec, Inc.	Intermediate Temperature Solid Oxide Fuel Cell Development
42516	University of Michigan	Carbon Tolerant Steam Reforming and SOFC Anode Catalysts
42527	Ohio University	Combined Theoretical and Experimental Investigation and Design of H_2S Tolerant Anode for Solid Oxide Fuel Cells
42614	GE Global Research	Solid Oxide Fuel Cell Coal-Based Power Systems
42623	University of Utah	A High Temperature Electrochemical Energy Storage System Based on Sodium Beta Alumina Solid Electrolyte (BASE)
42627	SRI International	Effect of Coal Contaminants on Solid Oxide Fuel Cell System Performance and Service Life
44036	University of Florida	SECA Coal-Based Systems Core Research—University of Florida
49071	Massachusetts Institute of Technology	Local Electronic Structure and Surface Chemistry of SOFC Cathodes

Table 9. Projects Discontinued in FY 2008

Contract Number	Performer	Project Topic
68250	Sandia National Laboratories	Reliable Seals for Solid Oxide Fuel Cells
84662	Aspen Products Group, Inc.	Waterless 5-kWe Diesel Reformer
84663	Ceramatec, Inc.	SOFC Integrated Multi-Mode Diesel Reformer
84673	Lynntech, Inc.	Low Cost, Compact Plasma Fuel Reformer for APUs
84881	NexTech Materials	Intermediate Temperature Solid Oxide Fuel Cell Cathode Enhancement Through Infiltration Fabrication Techniques

Table 10. Projects Discontinued in FY 2007

Contract Number	Performer	Project Topic
41838	Acumentrics Corporation	Development of a Low-Cost 10-kW Tubular SOFC Power System
41245	GE Global Research	Solid State Energy Conversion Alliance (SECA) Solid Oxide Fuel Cells Program
42175	University of Missouri-Rolla	Resilient Sealing Materials for Solid Oxide Fuel Cells
41247	Siemens Power Generation	Small-Scale Low Cost Solid Oxide Fuel Cell Power Systems
42220	University of Utah	Electrically Conductive, Corrosion-Resistant Coatings Through Defect Chemistry for Metallic Interconnects
42741	Virginia Polytechnic Institute and State University	Digital Manufacturing of Gradient Meshed SOFC Sealing Composites with Self-Healing Capabilities
84611	Mesta Electronics Inc.	DC-AC Inverter with Reactive-Power-Management Functionality
84616	R&D Dynamics Corporation	Foil-Bearing Supported High-Speed Centrifugal Cathode Air Blower
84624	TIAX LLC	Low-Cost, High-Temperature Recuperators for SOFC Fabricated from Titanium Aluminum Carbide (Ti_2AlC)
83795	TDA Research, Inc.	Sorbents for Desulfurization of Natural Gas and LPG
84608	Materials and Systems Research, Inc.	A Thin Film, Anode-Supported Solid Oxide Fuel Cell Based on High Temperature Proton Conducting Membrane for Operation at 400–700 °C
86280	Materials and Systems Research, Inc.	A High-Temperature (400– 650 °C) Secondary Storage Battery Based on Liquid Sodium and Potassium Anodes
86140	FuelCell Energy, Inc.	Advanced Control Modules for Hybrid Fuel Cell/Gas Turbine Power Plants
86283	NexTech Materials	Component Manufacturing and Optimization of Protonic SOFCs
41244	Cummins Power Generation	10-kW Solid Oxide Fuel Cell Power System Commercialization
42184	University at Albany – SUNY	Feasibility of an SOFC Stack Integrated Optical Chemical Sensor
42624	Massachusetts Institute of Technology	Photo-Activated Low Temperature, Micro Fuel Cell Power Source
42625	Northwest University	High Temperature Fuel Cells for Co-Generation of Chemicals and Electricity
42626	United Technologies Research Center	Techno-Economic Feasibility of Highly Efficient Cost Effective Thermoelectric-SOFC Hybrid Power Generation Systems

Table 11. Projects Discontinued in FY 2006

Contract Number	Performer	Project Topic
FEAA067	Oak Ridge National Laboratory	Power Electronics for Solid Oxide Fuel Cells
FWP49100	Argonne National Laboratory	Technology Development in Support of SECA
34139	Siemens Power Generation	High Temperature Solid Oxide Fuel Cell Development
40798	FuelCell Energy, Inc.	Direct Fuel Cell/Turbine Power Plant
41562	University of Florida	Determination of Electrochemical Performance and Thermo-Mechanical-Chemical Stability of SOFCs from Defect Modeling

Table 11. Projects Discontinued in FY 2006

Contract Number	Performer	Project Topic
41566	University of Washington	Advanced Measurement and Modeling Techniques for Improved SOFC Cathodes
41569	Ceramatec, Inc.	Metal Interconnect for Solid Oxide Fuel Cell Power Systems
41571	Georgia Institute of Technology	An Integrated Approach to Modeling and Mitigating SOFC Failure
41574	University of Illinois at Chicago, Ceramatec Inc., Virginia Tech, Oak Ridge National Laboratory, Pacific Northwest National Laboratory	An Investigation of Resolve the Interaction between Fuel Cell, Power Conditioning System, and Application Load
41575	NexTech Materials	Continuous Process for Low-Cost, High-Quality YSZ Powder
41578	University of Pittsburgh	Fundamental Studies of the Durability of Materials for Interconnects in Solid Oxide Fuel Cells
41915	Southern University and A&M College	Dense Membranes for Anode Supported All-Perovskite IT-SOFCs
41959	University of Florida	Electrocatalytically Active High Surface Area Cathodes for Low-Temperature SOFCs
41960	University of Houston	New Cathode Materials for Intermediate Temperature Solid Oxide Fuel Cells
42222	Chevron Energy Research and Technology Company	Development of Ni-Based Sulfur-Resistant Catalyst for Diesel Reforming
42228	Connecticut Global Fuel Cell Center University of Connecticut	Low-Cost Integrated Composite Seal for SOFC: Materials and Design Methodologies
42514	Franklin Fuel Cells, Inc.	Novel Cathodes Prepared by Impregnation Procedures
42515	Georgia Institute of Technology Center for Innovative Fuel Cell and Battery Technologies	Quantitative Characterization of Chromium Poisoning of Cathode Activity
42517	University of Michigan	Desulfurization of High-Sulfur Jet Fuels by Adsorption and Ultrasound-Assisted Sorbent Regeneration
73138	Ceramatec, Inc.	Advanced Net-Shape Insulation for Solid Oxide Fuel Cells
83528	NexTech Materials	Highly Textured Glass Composite Seals for Intermediate-Temperature SOFCs
84387	FuelCell Energy, Inc.	Diesel Plasma Reformer
84212	Spinworks, LLC	Low-Cost/High-Temperature Heat Exchanger for SOFCs Using Near-Net-Shape Ceramic Powder Forming Process

Table 12. Projects Discontinued in FY 2005

Contract Number	Performer	Project Topic
FE09	Los Alamos National Laboratory	Diesel Reforming for Solid Oxide Fuel Cell Auxiliary Power Units
40779	General Electric	SOFC Hybrid System for Distributed Power Generation
41539	Boston University	Materials System for Intermediate-Temperature SOFC
41602	University of Utah	Active Cathodes for Super-High Power Density SOFC Through Space Change Effects
41631	California Institute of Technology	Enhanced Power Stability for Proton-Conducting Solid Oxide Fuel Cells
41801	Virginia Polytechnic Institute and State University	Modeling and Design for a Direct Carbon Fuel Cell with Entrained Fuel and Oxidizer
41803	University of Akron	Carbon-Based Fuel Cell
41804	Duke University	Carbon Ionic Conductors for Use in Novel Carbon-Ion Fuel Cells
83212	Ceramatec, Inc.	Lanthanum Gallate Electrolyte Based Intermediate-Temperature Solid Oxide Fuel Cell Development

SECTION 12: RESOURCES

To ensure the Solid Oxide Fuel Cells program continually addresses current and future needs, NETL relies on outreach activities, such as publications, workshops, a comprehensive website, and participation in open forums. These outreach efforts help foster wider awareness and understanding of the benefits of SOFC technology. The following resources provide information on the *Solid Oxide Fuel Cells Program Plan*, *Technology Readiness Assessment*, SOFC technology, and an array of other information.

- **U.S. Department of Energy:** http://energy.gov/
- **U.S. Department of Energy, Office of Fossil Energy:** http://energy.gov/fe/office-fossil-energy
- **National Energy Technology Laboratory:** http://www.netl.doe.gov/
- **U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy:** http://www.eere.energy.gov/
- **The SOFC program website:** http://www.netl.doe.gov/technologies/coalpower/fuelcells
- **The SECA program homepage:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/
- **Proceedings from past SECA workshops and peer reviews:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/workshop.html
- **A primer on SOFC technology:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/primer/index.html
- **The Solid Oxide Fuel Cells Program Plan:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/pdf/Program-Plan-Solid-Oxide-Fuel-Cells-2013.pdf
- **The 2012 Solid Oxide Fuel Cells Program Portfolio:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/publications/Fuel-Cell-Annual-Report-2012.pdf
- **NETL 2012 Technology Readiness Assessment:** http://www.netl.doe.gov/technologies/coalpower/refshelf/TRL%20Comprehensive%20Report_121112_FINAL_1.pdf
- **The Fuel Cell Handbook:** http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/pubs/FCHandbook7.pdf
- **The National Fuel Cell Research Center:** http://www.nfcrc.uci.edu/2/default.aspx
- **The Fuel Cell and Hydrogen Energy Association:** http://www.fchea.org/

National Energy Technology Laboratory

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1450 Queen Avenue SW
Albany, OR 97321-2198
541.967.5892

Anchorage Location:
420 L Street
Suite 305
Anchorage, AK 99501
907.271.3618

Morgantown Location:
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304.285.4764

Pittsburgh Location:
626 Cochrans Mill Road
Pittsburgh, PA 15236-0940
412.386.4687

Sugar Land Location:
13131 Dairy Ashford Road
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Sugar Land, TX 77478
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JULY 2013