U.S. DOE Office of Fossil Energy's Solid Oxide Fuel Cell Program

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DOE Office of Fossil Energy (FE)

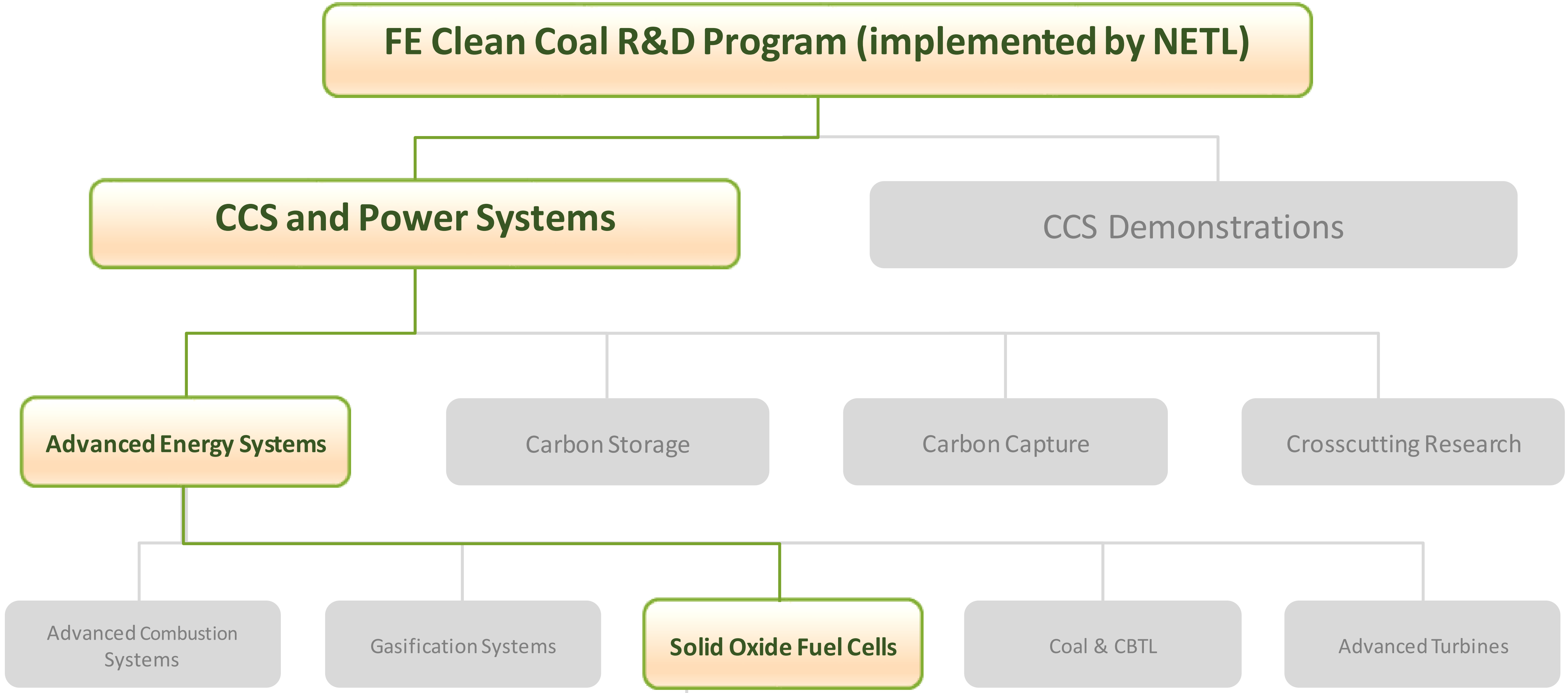
- **Lead office for coal, natural gas and oil exploration and development**
- **Mission: Clean, secure, affordable energy, enhancing environmental protection**
- **Made up of about 750 federal employees- scientists, engineers, technicians, administrative staff**
- **Oversees R&D projects- development of energy facilities that efficiently transform coal, biomass, other fuels into commercial products**
- **Responsible for federal RD&D on advanced power generation, power plant efficiency, CCUS technologies, R&D on oil and gas**
- **HQ offices in downtown Washington, D.C. and Germantown, MD**
- **National Energy Technology Laboratory (NETL) is included in FE**
  - 5 offices (MGN-WV, PGH-PA, Albany-OR, Sugar Land-TX, Anchorage-AK)

National Energy Technology Laboratory (NETL)

- Supports the DOE mission
- Expertise in coal, NG and oil technologies, contract and project management, analysis of energy systems and international energy issues.
- The only one of the DOE's 17 NLs that is both government owned and operated.
- In a unique position to accelerate the development of technology through strategic partnerships (Science and Technology Strategic Plans and Programs: TDIC and RIC)
- The only NL dedicated to fossil energy R&D

DOE Office of Fossil Energy (FE)

Solid Oxide Fuel Cell (SOFC) Program



AES: developing a new generation of clean fossil fuel based power systems (affordable power, reduce CO2 emission)

SOFC (DOE FE) Program Focus

- Supports mission and goals of CCRP: developing SOFC power systems and R&D that address technical challenges to deploy SOFC power systems
- To enable the generation of efficient, low-cost electricity from natural gas or coal for:
  - ➢ Near term: Natural gas-based distributed generation
    - 100 kWe – 1 MWe
  - ➢ Long term: Coal and natural gas utility-scale applications with Carbon Capture and Sequestration (CCS)
    - 10 MWe – 50 MWe

SOFC (DOE FE) Program Structure

Key Technologies

TECHNOLOGY AREA	KEY TECHNOLOGIES
SOLID OXIDE FUEL CELLS	Cell Development
	Core Technology
	Systems Development

Figure courtesy NETL

Figure courtesy LG Fuel Cell Systems

Figure courtesy FuelCell Energy

SOFC Program Project Portfolio

FY19 Participants

SOFC Program Metrics

Metric	Current	Near Term	Long Term
System Cost (100 kW- 1MW)	>$12,000/kWe	$6,000/kWe	$900/kWe
Single Cell Degradation	0.2 - 0.5% per 1,000 hrs		
Cell Manufacturing Approach	Batch	Semi- Continuous	Continuous
System Degradation	1 – 1.5% per 1,000 hrs	0.5 - 1.0% per 1,000 hrs	<0.2% per 1,000 hrs
Fuel Reformation	Primarily external natural gas conditioning/reforming	100% integrated natural gas reformation inside cell stack	
Durability	<2,000 hrs	5,000 hrs	5 years
Platform	Proof-of-Concept	Prototype/Pilot	DG: Commercial Utility-scale: Pilot
Configuration	Breadboard/Integrated systems	Fully packaged	Fully packaged
Fuel	Natural gas	Natural gas Simulated syngas	Natural gas Coal-derived syngas
Demonstration Scale	50 kWe – 200 kWe	200 kWe – 1 MWe	DG: MWe-class Utility-scale: 10 – 50 MWe

Single-cell performance and degradation are acceptable; stack and system performance, reliability and endurance need to be demonstrated

SOFC Program: *Technology-specific Challenges*

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Technology	Topic	Challenges
Cells	Manufacturing/QC	• Manufacturing reliability/quality control issues. • Non-destructive tests • Cell–to-cell variability
	Chemical Instability	• Microstructural/chemical changes in cell due to high temperature
Stacks	Manufacturing/QC	• Dimensional tolerances
	Contacts	• Electrode-Interconnect contact variability and degradation
	Seals	• Seal failure • Corrosion of brazes/welds • Thermal gradients/management
Systems	Electrode Contamination	• Cathode poisoning (e.g. Cr)
	Anode Redox	• Anode redox expansion/contraction
	Commissioning	• Integration and reliability of first-of-a-kind system • Purpose-specific BOP components • Unplanned shutdowns

SOFC Program: Partners and their roles

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- **Cell Technology**
  - National Labs, academia, small businesses, research institutions
  - Applied research on individual cell components
- **Core Technology**
  - National Labs, government agencies, academia, small businesses, research institutions, industry
  - Applied research on stack technology issues
- **Systems Development**
  - Industry
  - Develop unique and proprietary technology
  - Identify Cell and Core Technology R&D focus
  - Bring the technology to market

SOFC Program
Key Takeaways

- The Program continues to support cell and stack R&D … however …
- Program emphasis is shifting to the resolution of design, operation, and performance considerations at the system level
- Identified critical reliability issues and put into place R&D projects to resolve these issues
- Demonstrated Proof-of-Concept systems at ratings up to 200 kWe
- Acquiring fabricating and operational experience on integrated, prototype field tests
- Initiated RD&D into the next generation of cell and stack architectures

Improving the Cell Performance

- **Most improvements have been on the cathode side**
  - Cathode infiltration
  - Cathode capping layers – blocks strontium segregations and precipitation
  - Additional development of mixed ionic electronic conductors
  - Optimizations in processing (firing temp, particle size distributions, etc…)

- **Why focus on the cathode?**
  - Appreciation for YSZ's amazing properties
  - Anodes are fairly stable and have worked "well-enough"
  - At the time, cathodes were the performance bottle neck
  - Most degradation occurred on the cathode side

New Cathode Materials

- **There are still opportunities for improving the cathode**
  - Additional development on MIECs
    - Nickelate cathodes
    - Potential for higher performance and innate resistance to chrome poisoning
  - Engineered cathodes with tri-layer structures
    - Further separates electrochemical functions for additional optimization
    - Potential for more optimized cathode structures
  - Thin layers offer possibilities for new materials
    - Insulators aren’t bad conductors if they are thin enough

Anode Materials

- **Work at NETL to improve the anode through infiltration**
  - More difficult than infiltrating the cathode due to density and thickness, but possible.
  - Improve electrochemical performance, coking resistance, and possibly redox tolerance
- **Work at Montana State University to add anchoring phases to anode**
  - Increase strength by up to 50% (allows for 33% thinner anode)
    - Thinner anodes allow for higher fuel utilizations
    - Reduces steam concentration in the active area
    - Significant reduction in material cost
  - Increases in redox tolerance
- **Work at UES and University of Connecticut**
  - HEA as an internal reforming anode materials

Enhancing reliability, robustness and endurance of SOFC stacks and/or BOP components

Ways to mitigate Cr assisted degradation

- Surface coating for Interconnects or BOP components
  - Aluminization of BOP components
    - PNNL
    - Nexercise
      - Alumi-Lok™
  - Spinel coated interconnect materials
    - Boston U, Tennessee Tech U, PNNL
- Cr getter
  - Cr getter for BOP components consisting of non-noble low cost metal oxides getters
    - UConn successfully demonstrated a Cr getter for BOP components consisting of non-noble low cost metal oxides getters, tested at 850C, 3% H2O, 500 hrs
    - Currently: Scaling up the chrome getter fabrication process and validating the getter operation at SOFC stack and system levels

Ways to mitigate Cr assisted degradation

- Modified cathode materials
  - Cr tolerant cathodes
    - Georgia Tech (Infiltrated cathodes, catalyst-coated cathodes)
    - University of South Carolina
  - Cathodes and contact paste consisting of chromium getter to minimize cathode degradation
    - Uconn
    - Tennessee Technological University
  - Understand mechanisms of Cr effects on cathodes and propose ways to mitigate
    - Boston U, UConn
- Acceleration tests on cathodes in the presence of chromium contamination
  - Various approaches to minimizing the presence of Cr in the system environment

Ways to mitigate Cr assisted degradation

- **Alloy chemistry of BOP components**
  - **Fe and Ni based chromia and alumina forming alloys**
  - **Block and reduce Cr evaporation rates from BOP components**
  - **West Virginia University**
- **Cr sensor**
  - **Monitoring the chromium vapor produced during SOFC operation**
  - **GE, Auburn Universities**

ALD unique characteristics

- Thickness control
- Uniformity and conformality
- Tailor compositions in precise manner
- Low temperature
- Almost anything from the periodic table can be deposited by ALD
  - pure components, mixed oxides
- Best suited for depositing multicomponent materials because of its stepwise approach.
- Adding catalytic materials to the electrode surface without changing the electrode morphology
  - performance can be more clearly linked to surface coverage.
- Typical ALD materials
  - Oxides, nitrides, carbides
  - Pure element (metal)

ALD related SOFC Projects

- **Currently there are 10 projects under SOFC portfolio**
  - West Virginia University, University of Pennsylvania, University of South Carolina, Georgia Tech, Michigan State University, Sonata
- **Most of them focus on using ALD to enhance cathode performance**
  - Catalysts: single materials, multi-components
  - Multifunctional
    - Resistance to impurities/contaminations
    - Prevent grain coarsening
  - Long term stability of cathode
  - Surface modification layer on cathode powders (drop-in process).
- **One project using ALD to enhance anode capability**
  - Direct hydrocarbon (methane) SOFC applications
- **One project using ALD for barrier layer of the interconnect**

ALD related SOFC Projects

- **Testing**
  - Most test done in half-cells/symmetrical cells/button cells.
  - Need to be tested in full size cells and short stack to bridge the gap between the academic research and industrial scale up.
  - Need more longer-term test
- **Technology transfer**
  - FCE and Atrex
  - Test at Industry team facility
    - Stack level
    - Real SOFC environments.
  - Perform ALD coating on the Industry team's cells

Challenges in ALD

- The properties of ALD-modified materials depend highly on the procedures and conditions used to carry out the ALD growth
    - ALD equipment/reactor (in house or commercial)
    - Inconsistencies of growth rates
    - Dense or porous ALD layers
    - One project to understand ALD mechanisms and what causes a challenge
- Scale-up
- Cost Analysis

SOFC R&D at NETL

Cell and Stack Degradation Modeling	Electrode Engineering	Systems Engineering and Analysis	High Temp Optical Sensors
• Development of comprehensive predictive modeling tool • Atoms to system scale bridging • Validated through experiment	• Mitigation of prominent degradation modes • Successful transfer of technology to industry	• Public dissemination of SOFC market potential, performance, and cost advantages • Hybrid configuration assessment • Tie to R&D goals and objectives	• Multi-application technology under development for high temperature sensing • Demonstrated in SOFC • In-situ sensing of temperature distribution and gas composition

SOFC R&D at Pacific Northwest National Lab (PNNL)

Materials	Modeling	Small-Scale SOFC Test Platform
• Quantitative understanding of Cr poisoning • Validation of Cr capture materials • Enhanced reliability of cathode/contact material interfaces • Cobalt-free protective coatings for metallic interconnects	• Advanced Reduced Order Models (ROM) for accurate simulation of stack performance in system models • Modeling to mitigate stack degradation and increase reliability	• Designed and fabricated SOFC test platform (1-10 kW) • Used for evaluation of performance and reliability of emerging stack technologies • First technology to be tested: Ceres Power stack module (~4 kW)

SOFC R&D at Oak Ridge National Lab (ORNL)

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Degradation Mechanisms and Reliability of SOFCs	Measurement Techniques To Predict Reliability of SOFC Components	Long-term Exposure to SOFC-Relevant Environments	Advanced manufacturing of SOFCs

• Creep deformation in anode materials
  • Stress and temperature dependence
• Residual stress in SOFC
• With PNNL: alternative SOFC geometries to increase reliability
	• Residual Stress
	  • X-ray diffraction
	  • Raman Spectroscopy and photo-stimulated luminescence
	  • Digital Image Correlation
	• Test methods for the determination of the state of residual stresses in cells and structural joints in stacks
		• Quantify changes in the microstructure and physical and mechanical properties of 8YSZ
		• 40,000 hrs barium alkali silicate glasses
			• Develop technologies to enable to deposition of multiple materials in multilayered configurations, that in the future, could lead to the fabrication of SOFCs using advanced manufacturing techniques.

SOFC R&D at Argonne National Lab (ANL)

ORR Surface Study	Cr Poisoning Mitigation	Electrochemical performance and material properties of ceramic powders
• Model surfaces under operando conditions • Perturbation of surface conditions and composition • Determine relative rate of oxygen transport	• Collaboration with CMU and PNNL • Identify source, mechanism, and mitigation strategy of volatile Cr • Proposed mechanism of LSM microstructural degradation	• Establishing protocol for baseline performance and statistical comparison • Analyzing feedstock cathode powder characteristics and tolerances for reliable electrochemical performance • Developing rapid and simple powder diagnostic approaches

SOFC Program: Systems Development
Fuel Cell Energy 200 kW SOFC prototype

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- March 2019 to end of October 2019
- High electrical efficiency (greater than 50%)
- Low environmental impact (ultra-low SOx, NOx, and PM emissions due to no combustion)
- No water consumption during power generation mode
- Available heat for Combined Heat and Power (CHP) applications
- Fully automatic with turnkey operation (unattended operation)
- Quiet operation
- Truck transportable

and easily installed





LG Prototype System Testing

Fuel Cell Systems

Features

Figure courtesy LGFCS

- Fully integrated system
- Fuel: Pipeline natural gas
- Unmanned operation

Accomplishments

- >1800 Hours on Load
- Power to Grid
  - 250 KW-AC
- Efficiency
  - 61% DC / 55% AC
- Power Degradation
  - 0.3% per 1000 hours
- Emissions
  - Meets NOx standards

Work performed under DOE agreement DE-FE0031180

21st Annual Solid Fuel Cell (SOFC) Project Review Meeting

NATIONAL ENERGY TECHNOLOGY LABORATORY

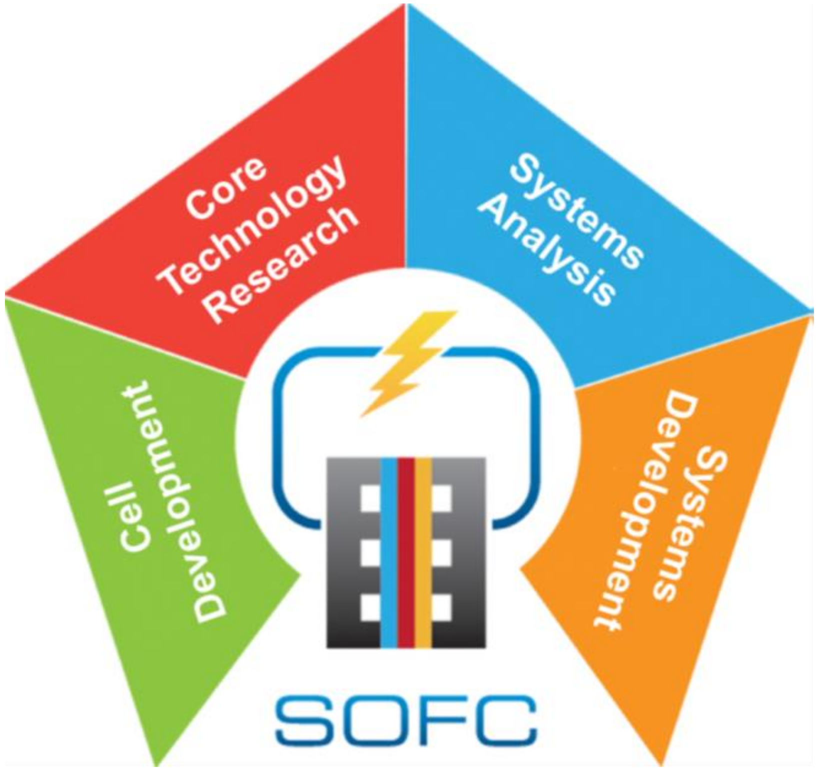
To be held on July 21-23, 2020

Pittsburgh Airport Marriott Hotel, Pittsburgh, Pennsylvania.

For Additional Information

Office of Fossil Energy: www.energy.gov/fe/office-fossil-energy
NETL Website: www.netl.doe.gov/
SOFC Program website: www.netl.doe.gov/coal/research/energy-systems/fuel-cells
Reference Shelf:

- SOFC Program FY19 Project Portfolio
- SOFC Technology Program Plan
- Technology Readiness Assessment
- Past Workshop Proceedings
- Systems Analysis
- Fuel Cell Handbook



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