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

FE Clean Coal R&D Program (implemented by NETL)

CCS and Power Systems

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
## SOFC Program Metrics

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

Single-cell performance and degradation are acceptable; stack and system performance, reliability and endurance need to be demonstrated.
## SOFC Program: *Technology-specific Challenges*

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

- **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
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

<table>
<thead>
<tr>
<th>Cell and Stack Degradation Modeling</th>
<th>Electrode Engineering</th>
<th>Systems Engineering and Analysis</th>
<th>High Temp Optical Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Development of comprehensive predictive modeling tool</td>
<td>• Mitigation of prominent degradation modes</td>
<td>• Public dissemination of SOFC market potential, performance, and cost advantages</td>
<td>• Multi-application technology under development for high temperature sensing</td>
</tr>
<tr>
<td>• Atoms to system scale bridging</td>
<td>• Successful transfer of technology to industry</td>
<td>• Hybrid configuration assessment</td>
<td>• Demonstrated in SOFC</td>
</tr>
<tr>
<td>• Validated through experiment</td>
<td></td>
<td>• Tie to R&amp;D goals and objectives</td>
<td>• In-situ sensing of temperature distribution and gas composition</td>
</tr>
</tbody>
</table>
SOFC R&D at Pacific Northwest National Lab (PNNL)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Modeling</th>
<th>Small-Scale SOFC Test Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quantitative understanding of Cr poisoning</td>
<td>• Advanced Reduced Order Models (ROM) for accurate simulation of stack performance in system models</td>
<td>• Designed and fabricated SOFC test platform (1-10 kW)</td>
</tr>
<tr>
<td>• Validation of Cr capture materials</td>
<td>• Modeling to mitigate stack degradation and increase reliability</td>
<td>• Used for evaluation of performance and reliability of emerging stack technologies</td>
</tr>
<tr>
<td>• Enhanced reliability of cathode/contact material interfaces</td>
<td></td>
<td>• First technology to be tested: Ceres Power stack module (~4 kW)</td>
</tr>
<tr>
<td>• Cobalt-free protective coatings for metallic interconnects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Degradation Mechanisms and Reliability of SOFCs
- Creep deformation in anode materials
  - Stress and temperature dependence
- Residual stress in SOFC
- With PNNL: alternative SOFC geometries to increase reliability

### Measurement Techniques To Predict Reliability of SOFC Components
- 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

### Long-term Exposure to SOFC-Relevant Environments
- Quantify changes in the microstructure and physical and mechanical properties of 8YSZ
- 40,000 hrs barium alkali silicate glasses

### Advanced manufacturing of SOFCs
- 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.
### ORR Surface Study
- Model surfaces under operando conditions
- Perturbation of surface conditions and composition
- Determine relative rate of oxygen transport

### Cr Poisoning Mitigation
- Collaboration with CMU and PNNL
- Identify source, mechanism, and mitigation strategy of volatile Cr
- Proposed mechanism of LSM microstructural degradation

### Electrochemical performance and material properties of ceramic powders
- 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

- 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
Prototype System Testing

Features

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

Figure courtesy LGFCS

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
To be held on July 21-23, 2020

Pittsburgh Airport Marriott Hotel, Pittsburgh, Pennsylvania.
For Additional Information

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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