Driving Innovation ♦ Delivering Results

Department of Energy Office of Fossil Energy's Solid Oxide Fuel Cell (SOFC) Program

17th Annual SOFC Workshop

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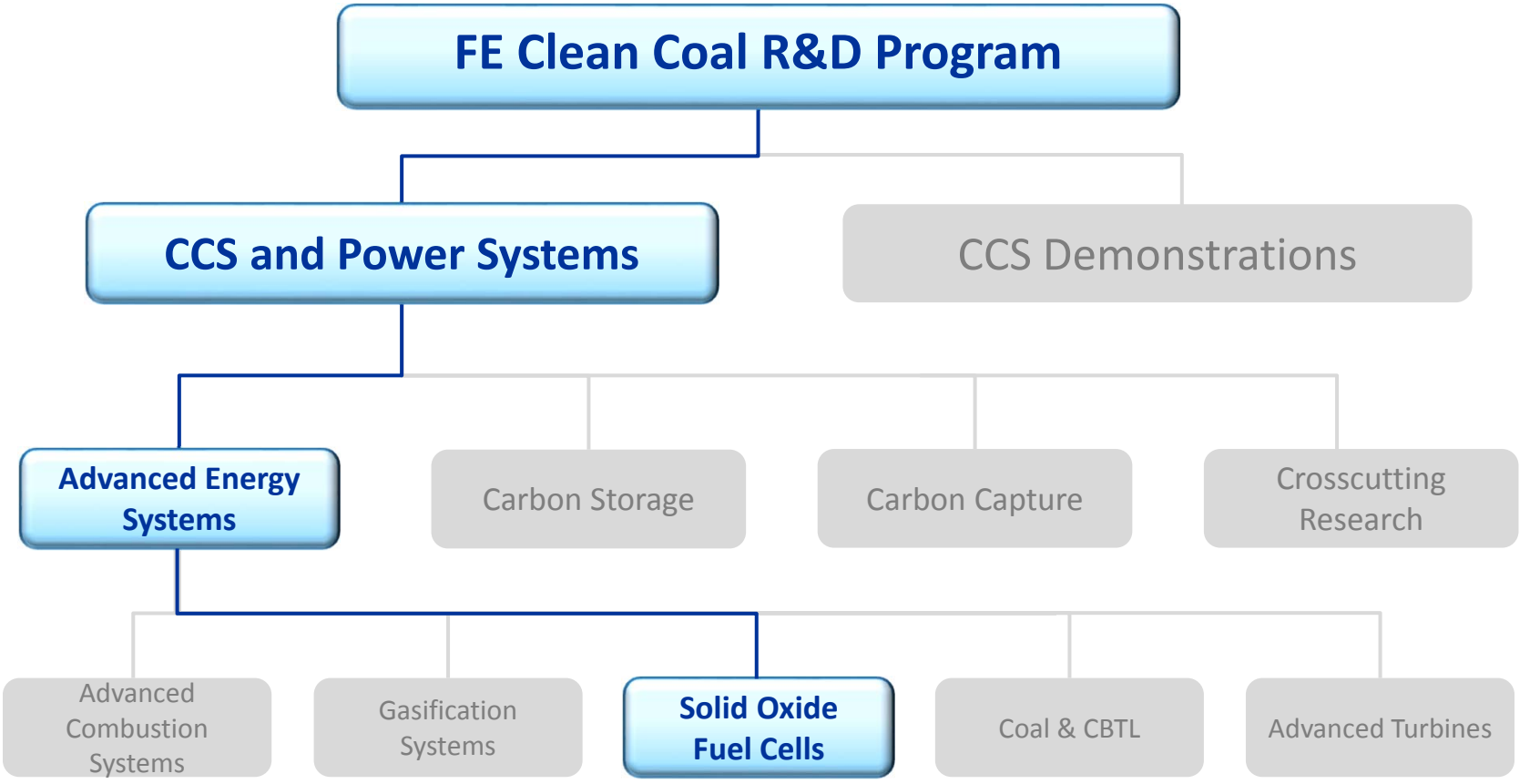
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

DOE Office of Fossil Energy (FE)
Solid Oxide Fuel Cell (SOFC) Program



DOE's Clean Coal R&D Program is focused on developing and demonstrating advanced power generation and Carbon Capture and Storage (CCS) technologies

SOFC Program Mission

- **Enable the generation of efficient, low-cost electricity from domestic coal and natural gas with near-zero emissions of CO_2 and air pollutants and minimal use of water in central power generation applications.**
- **Increase reliability, robustness, and durability of solid oxide fuel cell and stack technology.**
- **Provide the technology base to permit natural gas fueled distributed generation (DG) applications.**

60% Efficiency (Coal HHV)	*≥ 97% CO2 Capture*	*<0.5ppm NOx, low H2O use*	*Low Cost, similar footprint to IGCC*	*Modular Technology*	*Fuel-Flexible*

SOFC Program Overview

Metric	Current	2020 Target	2025 Target
System Cost	>$12,000/kWe	$6,000/kWe	$900/kWe
System Degradation Rate	~1.0% per 1,000 hrs	0.5 - 1.0% per 1,000 hrs	0.2% per 1,000 hrs
Cell Manufacturing Approach	Batch	Semi- Continuous	Continuous
Demonstration Scale	50 kWe Integrated System 400 kWe Prototype	1-5 MWe DG Integrated Systems	10 – 50 MWe Integrated Power System

APPROACH

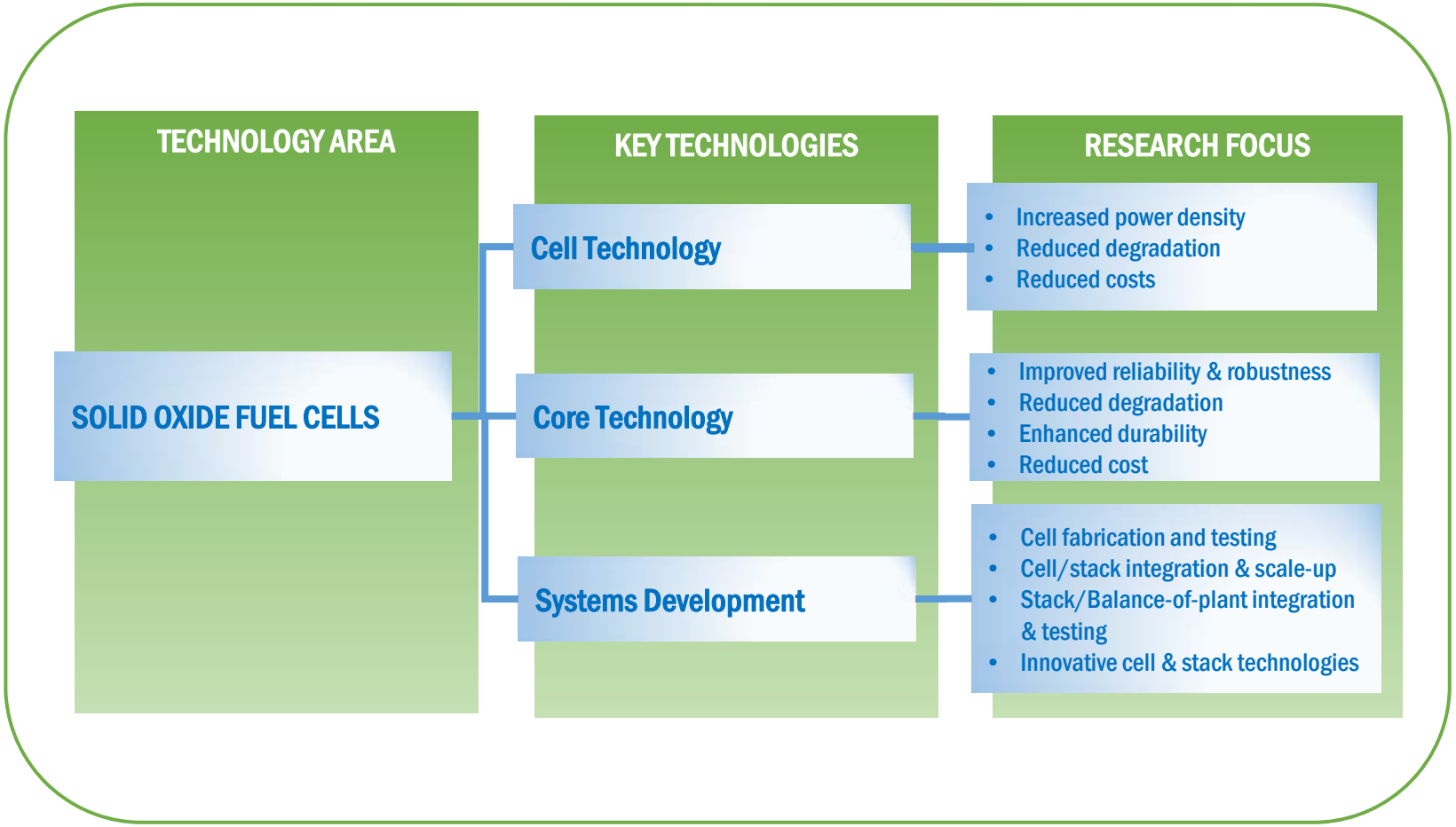
- Early Applied (TRL* 2-4): R&D is focused on cell, stack and BOP related technologies critical to commercialization. NETL, academia, industry and National Labs conduct lab and bench-scale testing to improve performance and reliability and lower cost; identify and mitigate stack related degradation; and develop computational tools and models.
- Development (TRL 5-7) is focused on testing progressively larger stacks and integrated power systems. Multiple SOFC developers provide technology diversification and reduce program dependency on a single developer.

KEY MILESTONES

- FY16/17: Demonstrate 100 kWe-class Proof-of-Concept systems
- FY17/18: Demonstrate integrated 400 kW prototype system field test(s)
- FY20: Demonstrate First of a kind 1 MW pilot (natural gas)
- FY25: Demonstrate 10-50 MWe FOAK IGFC/NGFC large pilot(s)

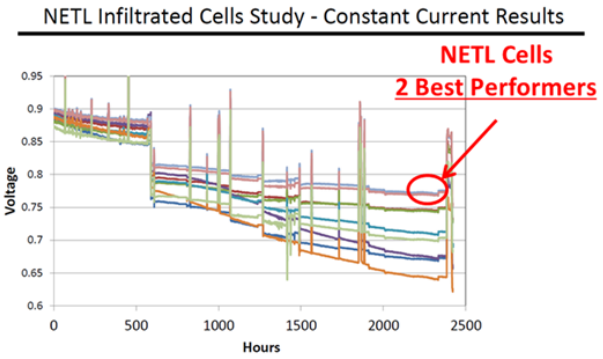
** TRL – Technology Readiness Level, systematic measurement system that supports assessments of the maturity of a particular technology on a scale of 1-9*

SOFC Program Structure



Cell Technology

- R&D emphasis on anode, cathode, electrolyte and interconnect
- Electrochemical performance, durability and reliability
- Advanced materials development
- Advanced manufacturing processes
- Contaminant testing
- Failure analysis
- R&D portfolio consists of ~20 projects



Cell Technology Research is focused on the cell-related technologies critical to the commercialization of SOFC technology.

Core Technology

- Applied R&D on stack technology issues (exclusive of the cell components)
- Laboratory & bench-scale testing to improve stack reliability and lower cost
- Identify and mitigate stack-related degradation
- Develop computational tools and models
- Improve reliability and lower cost of BOP components
- R&D portfolio consists of ~15 Projects

Core Technology Research is focused on technology issues – exclusive of the cell components – that are critical to the commercialization of SOFC technology.

Systems Development

State-of-the-Art (SOA)

- Two developers
  - Near term natural gas, long term coal-derived syngas
- Proof-of-Concept (POC) systems
  - Fully integrated fuel cells power systems
  - Current Status : 50 kW - 200 kW
- Prototype system field test(s)
  - One award for a 400 kWe system (FuelCell Energy)

Innovative Concepts (IC)

- Next generation cell and/or stack technology
- Four developers with unique concepts
- 5 – 10 kW stack tests

SOA Developers are validating their technology and acquiring operational experience for large-scale, integrated systems; IC developers are breaking ground on the next generation of SOFC technology

SOFC Project Portfolio – FY16

Systems Development

FuelCell Energy*
LG Fuel Cell Systems*
General Electric
Redox Power Systems

Cell Development

Argonne National Laboratory
Boston University*
Case Western Reserve University
Georgia Tech*
Kettering University
Montana State University
National Energy Technology Lab.
Oak Ridge National Laboratory
Pacific Northwest National Lab.
Pneumaticoat
PolarOnyx
Sonata
SMI
Stanford University
Tennessee Technological Univ.
University of Connecticut
University of Maryland
University of Pennsylvania
University of South Carolina*
West Virginia University*

Core Technology (Stack & BOP)

Interconnects
NexTech
Pacific Northwest Natl. Lab.
Sonata

Seals
Michigan State University
Pacific Northwest Natl. Lab.

Modeling & Simulation
Natl. Renewable Energy Lab.
Pacific Northwest Natl. Lab.

Balance-0f-Plant
HiFunda
InnoSense
Mohawk
Pacific Northwest Natl. Lab.

Stack Reliability & Testing
Acumentrics*
U.S. Department of the Navy
Natl. Renewable Energy Lab.
Oak Ridge Natl. Laboratory

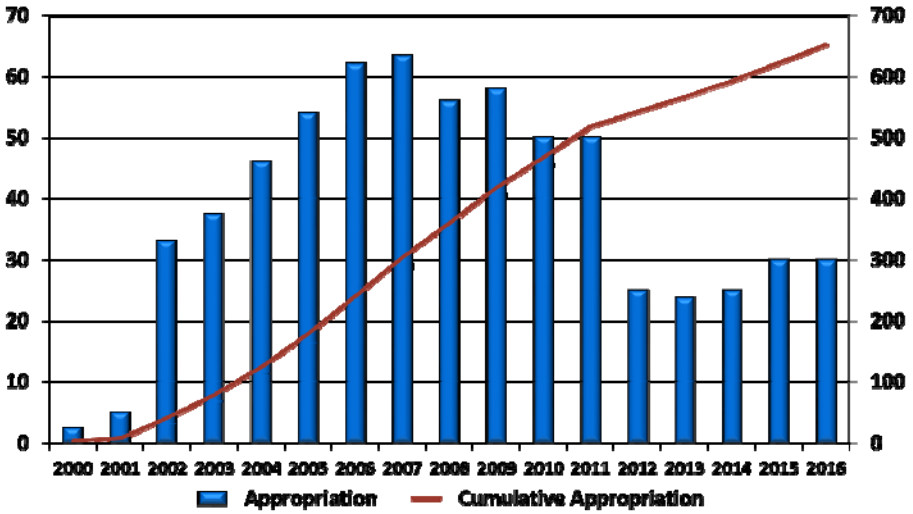
*** Multiple awards**

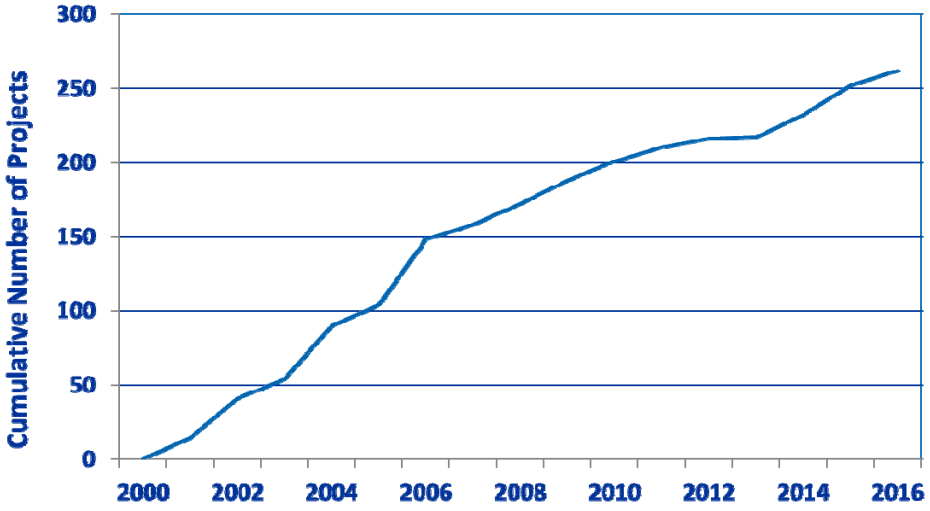
The SOFC Program has a portfolio of ~40 projects, ranging from bench-scale R&D to system-scale testing

SOFC Program Metrics
FY00 – FY16

Total DOE Funding: **~$652M**

Total Cost Share: **~$250M**





Total Number of Awards: **>260**

Total Number of Participants: **115**

Industry	65
Academia	40
Nat'l Labs	10 (includes gov't agencies)

Since the last Workshop…..

- Testing progressively larger stacks/systems
- Continuing R&D to reduce cost, enhance performance and improve reliability
- Hosted workshop to identify critical reliability issues

Current Reliability Challenges

Technology	Topic	Issue
Cells	Manufacturing/QC	• Manufacturing reliability/quality control issues. • Non- destructive tests • Cell –to-cell variability
	Chemical Instability	• Long-term microstructural/chemical changes in cell • Phase separation
Stacks	Manufacturing/QC	• Dimensional tolerances
	Contacts	• Electrode-Interconnect contact variability and degradation
	Seals	• Seal failure • Corrosion of brazes/welds • Delta T effects
Systems	Electrode Contamination	• Cathode poisoning (e.g., Cr)
	Anode Redox	• Anode redox expansion/contraction
	Commissioning	• BOP components • Thermal management

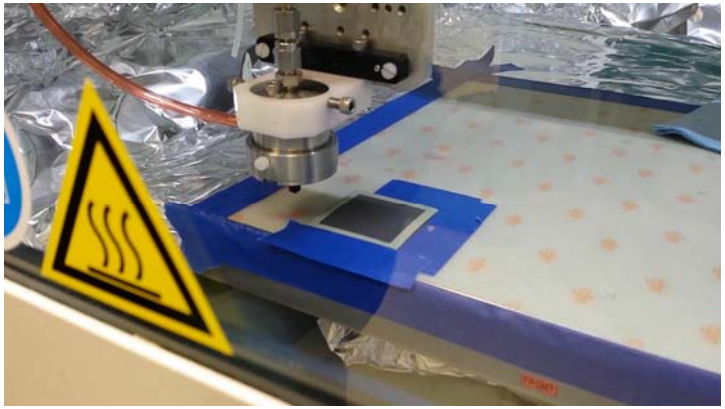
SOFC Reliability – Cr Poisoning

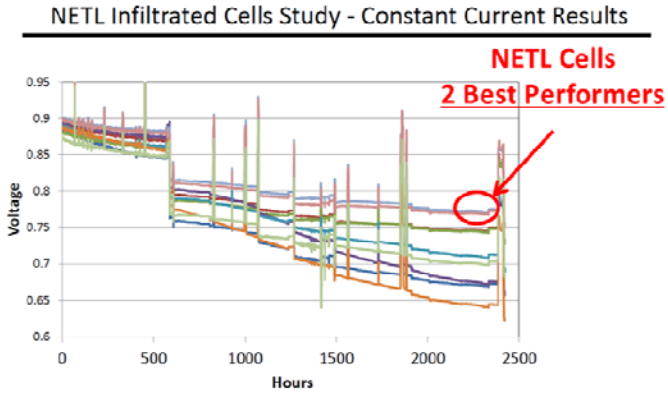
- **Surface Coating of interconnects and BOP components**
  - PNNL, Nexcersis, BU and Tennessee Tech
- **Cr Getter**
  - U Conn
- **Modified Cathode Materials**
  - Georgia Tech, U Conn, BU

Multiple Approaches to Mitigate Cr Poisoning Being Pursued

SOFC Reliability – NETL Research & Innovation Center

- **Electrode Engineering - Nano-catalyst Infiltration Improves Reliability on the Cell Level**
  - Efficient oxygen reduction / Degradation reduction
  - Industrial scale-up to stack level
    - Tested on various commercial cells (at 100% scale) from FY14-FY16
  - Infiltration cost of less than $0.006/cm² via advanced manufacturing
- **Modeling, analysis, and visualization tools created to evaluate and predict long-term performance degradation of relevant SOFC components**
  - Accurately identify a specific mechanism of degradation and initiate a tailored real-time mitigation strategy to improve long-term performance reliability

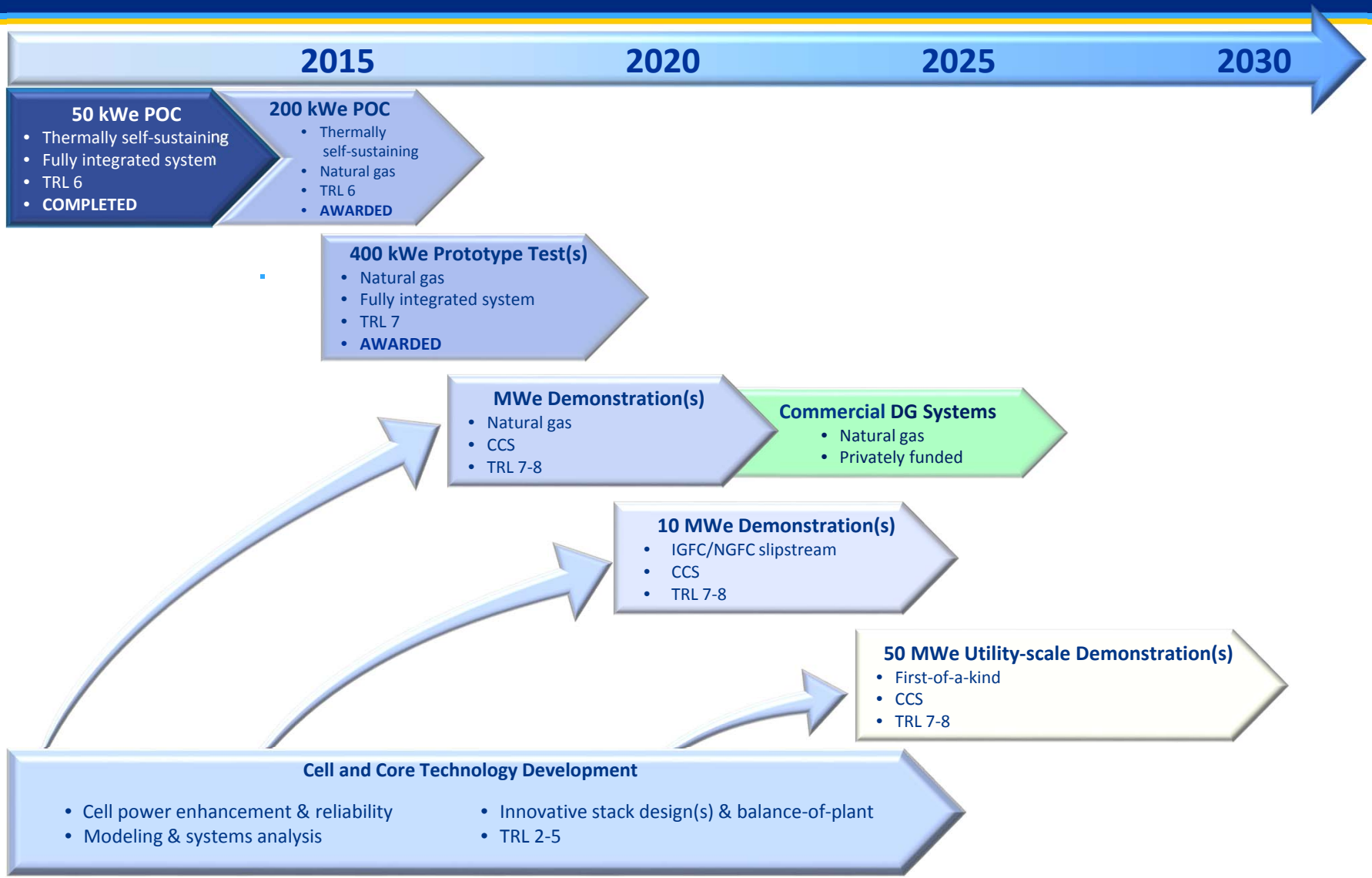




Result: ↑10% peak power, 33% ↓relative degradation, > 200% ↑ lifetime

U.S. Provisional Patent Application 62/191,548 filed July 13, 2015 "Method of forming catalyst layer by single step infiltration"
U.S. Provisional Patent Application 62/026,876 filed July 21, 2014 "Functional Grading of Cathode Infiltration for Spatial Control of Activity"
Shiwoo Lee and Kirk Gerdes, "Functional nanostructure engineering of SOFC cathode by solution infiltration," ECS Electrochem. Lett. 2015 volume 4, issue 3, F17-F20.

Technology Development Schedule



FY16 SOFC Program Update

- **One competitive solicitation**
  - **FOA-0001469: SOFC Core Technology and Innovative Concepts**
    - Topic Area 1: SOFC Core Technology
      - Lab or bench scale R&D that improves the cost robustness, reliability and endurance of SOFC stack or BOP technology (excludes cell R&D; anode, cathode, electrolyte)
      - Propose solution to a specific stack, mechanical BOP, or operational issue
      - Partnership with an SOFC manufacturer/developer encouraged
      - Two phases, with competitive down-select for Phase II
      - **Five awards, ~$0.5M per award, 20% Participant Cost Share (Phase I)**
    - Topic Area 2: Innovative Concepts
      - R&D of SOFC technology that has the potential to surpass current SOFC technology in terms of cost, robustness, reliability, or endurance
      - Novel architectures or materials sets preferred over conventional planar designs
      - **Four awards, ~$3.0M per award, 20% Participant Cost Share**
- **One new SBIR project**
- **Peer Review of six projects**
- **Closer collaboration with ARPA-E**

SOFC Program – FY16 Awards

FOA-0001469: SOFC Core Technology and Innovative Concepts	
Topic Area 1 – SOFC Core Technology	
Auburn University	Chromium Vapor Sensor for Monitoring SOFC Systems
General Electric	Highly Selective and Stable Multivariable Gas Sensors for Enhanced Robustness and Reliability of SOFC Operation
Mohawk Innovative Technology	High Temperature Anode Recycle Blower for SOFC
University of Connecticut	Development of Chromium and Sulfur Getter for SOFC Systems
West Virginia University	Minimizing CR-Evaporation From Balance of Plant Components by Utilizing Cost-Effective Alumina-Forming Austenitic Steels
Topic Area 2 – Innovative Concepts	
Acumentrics	Performance and Reliability Advancements in a Durable Low Temperature Tubular SOFC
Cummins Power Generation	Metal-Supported Ceria Electrolyte-Based SOFC Stack for Scalable, Low Cost, High Efficiency and Robust Stationary Power Systems
FuelCell Energy	Transformational SOFC Technology
Redox Power Systems	Robust SOFC Stacks for Affordable and Reliable Distributed Generation Power Systems

SOFC Program - Key Takeaways

- **Acquiring experience on fabricating and testing integrated SOFC systems**
  - First fully integrated, thermally self-sustaining 50 kWe stack test - completed
  - 200 kWe POC – underway
  - 400 kWe prototype field test – awarded
- **Initiated second generation cell and stack R&D (Innovative Concepts)**
  - Four projects underway
  - Four projects recently awarded
- **Identified critical reliability issues**
  - Nine projects addressing Cr poisoning mitigation. Four additional projects awarded in FY 2016

Cell development and Core research well-aligned with industry needs

Websites and Contact 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 FY16 Project Portfolio
- SOFC Technology Program Plan
- Technology Readiness Assessment
- Past Workshop Proceedings
- Systems Analysis
- Fuel Cell Handbook

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