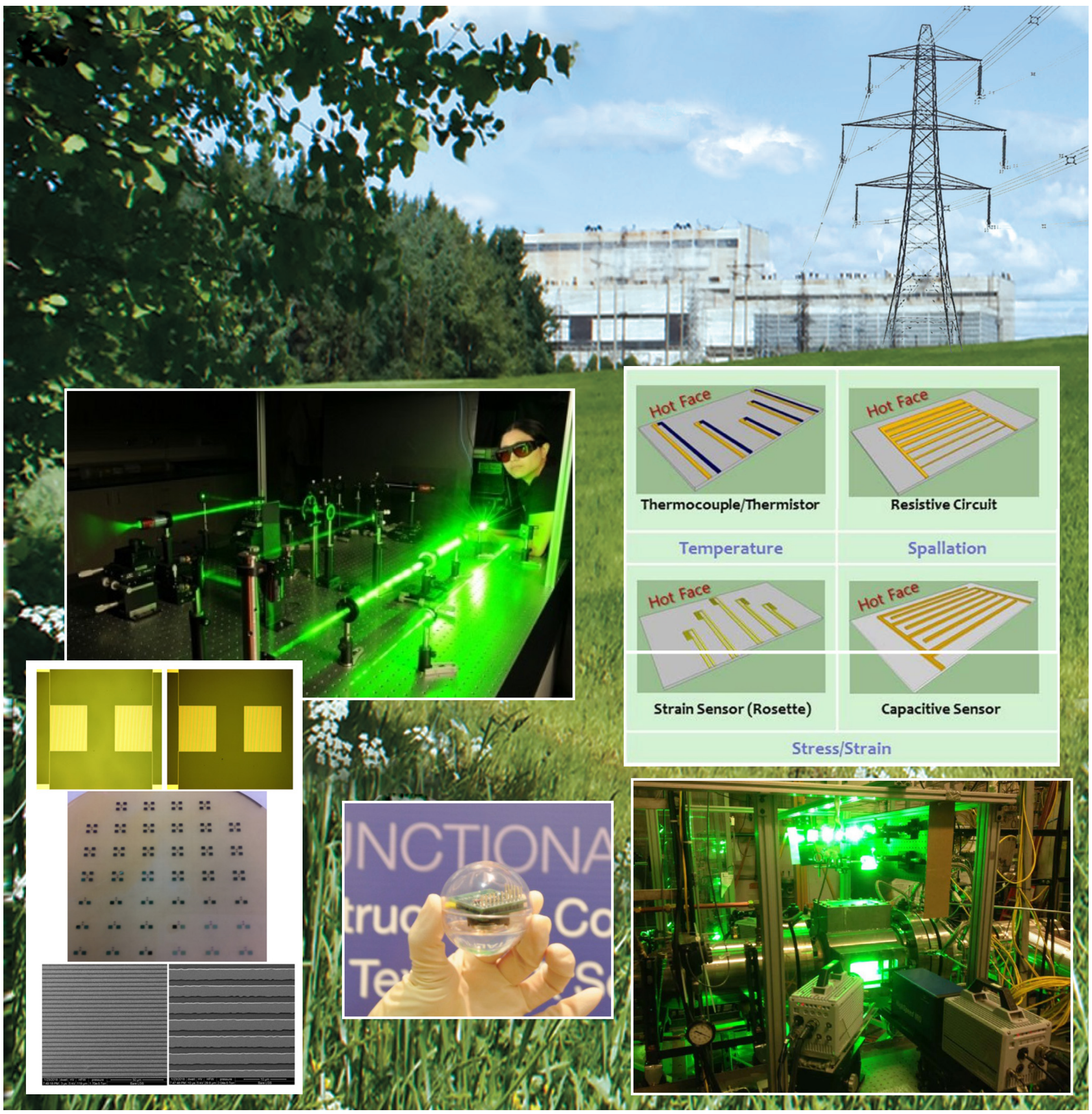
NATIONAL ENERGY TECHNOLOGY LABORATORY

CROSSCUTTING RESEARCH PROGRAM
SENSORS AND CONTROLS PROJECT PORTFOLIO



April 2018

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

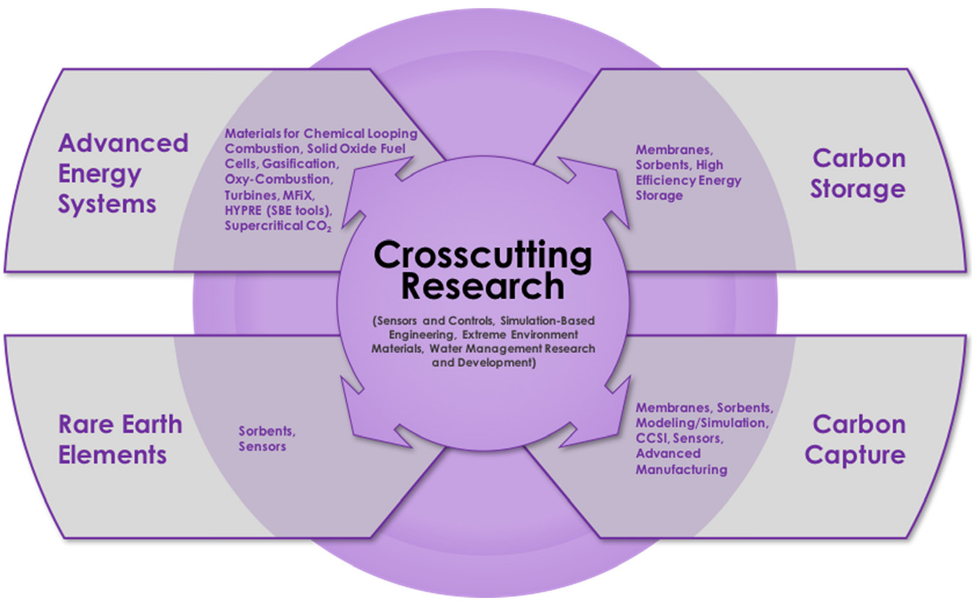
DISCLAIMER

CONTENTS

INTRODUCTION

The Crosscutting Research Program develops a range of innovative and enabling technologies that are key to improving existing power systems and essential for accelerating the development of a new generation of highly efficient, environmentally benign fossil fuel-based power systems. The mission space is focused on bridging the gap between fundamental and applied research and development (R&D) efforts. Technologies that successfully bridge this gap are intended to offer viable step-change improvements in power system efficiency, reliability, costs, and environmental impacts.

The research fundamental to the Crosscutting Research Program overlaps and benefits other Office of Fossil Energy (FE) program areas—rare earth elements, carbon capture, carbon storage, and advanced energy systems—as shown in the figure below.



Crosscutting Research technology overlaps with other Fossil Energy Program Areas.

The Crosscutting Research Program executes R&D efforts by partnering and collaborating with research institutions and the power generation industry throughout the United States and in select international locations. The Crosscutting Research Program also sponsors one of the longest running and most important university training and research programs to reinforce the research-based education of students at U.S. universities and colleges with emphasis on fossil energy science. The major objective for this program is to produce tools, techniques, and technologies that map to the Clean Coal Research Program efforts.

The Crosscutting Research Program is comprised of three focus areas: Coal Utilization Sciences, Plant Optimization Technologies, and University Training and Research. A description of each area follows.

Coal Utilization Sciences: The Coal Utilization Sciences technology area research effort is focused on modeling and simulation technologies that lead to a suite of products capable of designing and simulating the operation of next-generation, near-zero-emissions power systems such as gasification and oxy-combustion. Models can also solve current plant operational and lifetime issues. These products are based on validated models and highly detailed representations of equipment and processes.

Plant Optimization Technologies: The Plant Optimization Technologies technology area exists to improve availability, efficiency and environmental performance of coal-based fossil energy power generation plants. Research is focused on sensors and control systems, materials, and water management as the basis for successful implementation of advanced power generation systems in the harsh coal-fired environment. This area also explores novel concepts such as direct power extraction and the application of additive manufacturing towards constructing complex components (e.g., turbine blades with embedded sensing capabilities).

University Training and Research: The University Training and Research (UTR) program awards research-based educational grants to U.S. universities and colleges in areas that benefit the FE and the Crosscutting Research Program. UTR is the umbrella program under which the University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) and Other Minority Institutions (OMI) initiatives operate. These grant programs address the scientific and technical issues key to achieving Fossil Energy's goals and build our nation's capabilities in energy science and engineering by providing hands-on research experience to future generations of scientists and engineers. The program also coordinates with and seeks opportunities to partner with State and Tribal governments and engage industry, universities, and non-governmental organizations (NGOs) on the responsible use of fossil fuels nationally and internationally.

In addition to the Crosscutting Research Program listed above, the National Energy Technology Laboratory (NETL) uses its participation in the U.S. Department of Energy's (DOE) Office of Science **Small Business Innovation Research (SBIR) Program** to leverage funding, enhance the research portfolio, and, most importantly, facilitate a pathway to commercialization. SBIR is a highly competitive program that encourages small businesses to explore technological potential and provides the incentive to profit from commercialization. By including qualified small businesses in the nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit to meet specific research and development needs. SBIR targets the entrepreneurial sector because that is where most innovation and innovators thrive. By reserving a specific percentage of Federal R&D funds for small business, SBIR protects small businesses and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and encourages the commercialization of the technology, product, or service which, in turn, stimulates the U.S. economy. Since its inception in 1982 as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses compete for Federal research and development awards. These contributions have enhanced the nation's defense, protected the environment, advanced health care, and improved our ability to manage information and manipulate data.

The Crosscutting Research Program fosters the development of innovative power systems by conducting research in these key technology areas:

Sensors and Controls: The basis for this research area is to make available new classes of sensors and measurement tools that manage complexity; permit low cost, robust monitoring; and enable real-time optimization of fully integrated, highly efficient power-generation systems. Sensor development focuses on measurements to be made in high temperature, high pressure, and/or corrosive environments of a power system or underground injection system. Harsh environment sensing concepts and approaches focus on low cost, dense distribution of sensors; exploration of sensor networking using passive and active wireless communication; and thermoelectric and vibration energy harvesting approaches. Advanced manufacturing techniques focus on how to lower cost and improve fabrication of sensors. Controls research centers on self-organizing information networks and distributed intelligence for process control and decision making.

High Performance Materials: Materials development under the Crosscutting Research Program focuses on structural materials that will lower the cost and improve the performance of fossil-based power-generation systems and on functional materials, which are designed to perform specified non-structural tasks (e.g., shape memory materials or barrier coatings). Computational tools in predictive performance, failure mechanisms, and molecular design of materials are also being developed to support highly-focused efforts in materials development and reduce the time and cost to develop new materials. Advanced manufacturing development is represented under High Performance Materials in two capacities: first, the need for advancements in feedstocks such as metal powders for superalloys and second, as a set of methods for producing high-performance materials.

Simulation-Based Engineering: This key technology area comprises the expertise and capability to computationally represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant. Science-based models of the physical phenomena occurring in fossil fuel conversion processes and development of multiscale, multi-physics simulation capabilities are just some of the tools and capabilities in Simulation-Based Engineering. This key technology area enables the development of innovative, advanced energy systems by developing and utilizing advanced process systems, engineering tools and approaches, and the transformation of computationally intensive models into reduced order, fast, user-enabled models for the purposes of study, development, and validation. These tools will be used to optimize data handling and exploit information technology in the design of advanced energy systems with carbon capture.

Water Management Research and Development: Water research encompasses the need to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality. Research in effluent treatment and water quality sensing, field testing of technologies and processes for treating water produced by injection of carbon dioxide into deep saline aquifers, and exploration of water-limited cooling and innovative multi-stage filtration technologies are being conducted. Data modeling and analysis is being employed to examine existing water availability data on a regional basis. The vision for this program area is to develop a 21st-century America that can count on abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential for continued security and economic health. To accomplish this, Crosscutting Research is needed to lead a critical national effort directed at removing barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing our understanding of the intimate relationship between energy and water resources.

SENSORS AND CONTROLS

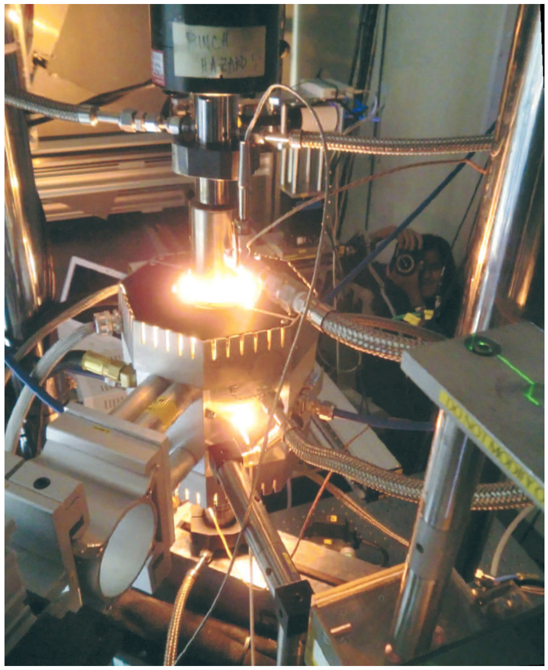
The objective of the sensors and controls research area is to make available new classes of sensors and measurement tools that manage complexity, permit low cost, perform robust monitoring, and enable real-time optimization of fully integrated, highly efficient power generation systems. Research is focused on sensors capable of monitoring key parameters (temperature, pressure, and gas compositions) while operating in harsh environments, and analytical sensors capable of on-line, real-time evaluation and measurement. Controls development centers on self-organizing information networks and distributed intelligence for process control and decision making.

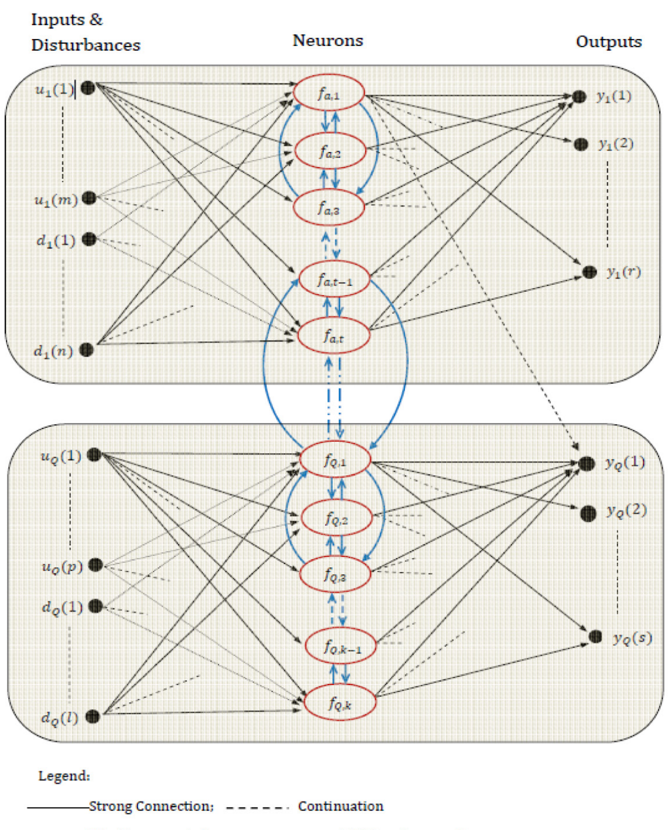
The Sensors and Controls project portfolio is categorized into these component technology areas:

- Advanced Sensors
  - Optical Sensors
  - Wireless Sensors
  - Embedded Sensors
  - Novel Sensor Concepts
- Distributed Intelligent Controls
  - Advanced Process Control

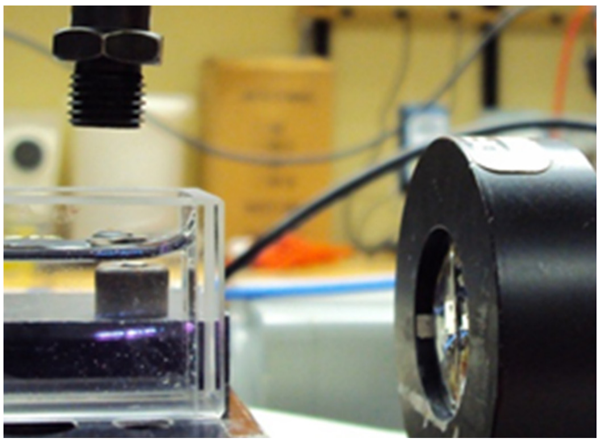
These new technologies are designed to improve the availability and efficiency of both existing and advanced power systems. As generational and transformational systems mature, sensors and controls will serve as an essential and enabling technology to operate these systems under conditions in which optimal performance is balanced with reliability. In addition to sensing and control, users must be able to make and implement decisions and derived optimizations in real time. This capability will be attained via new computational tools that can match sensor data and analytical inputs to decision-making assistance and controls actuation, resulting in desired outcomes.The Water Management Research and Development project portfolio is categorized into three core technologies:

PROJECTS BY COMPONENT TECHNOLOGIES



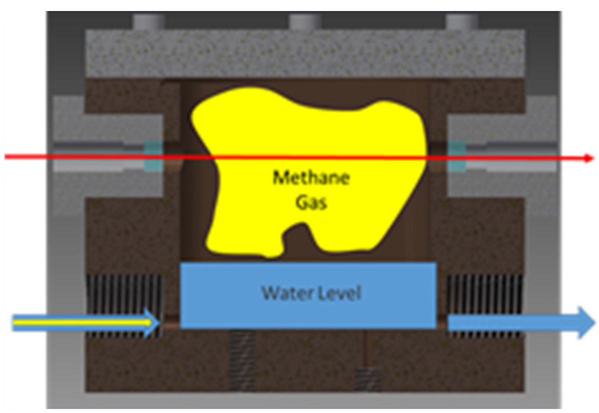


ADVANCED SENSORS



Laser induced breakdown spectroscopy.

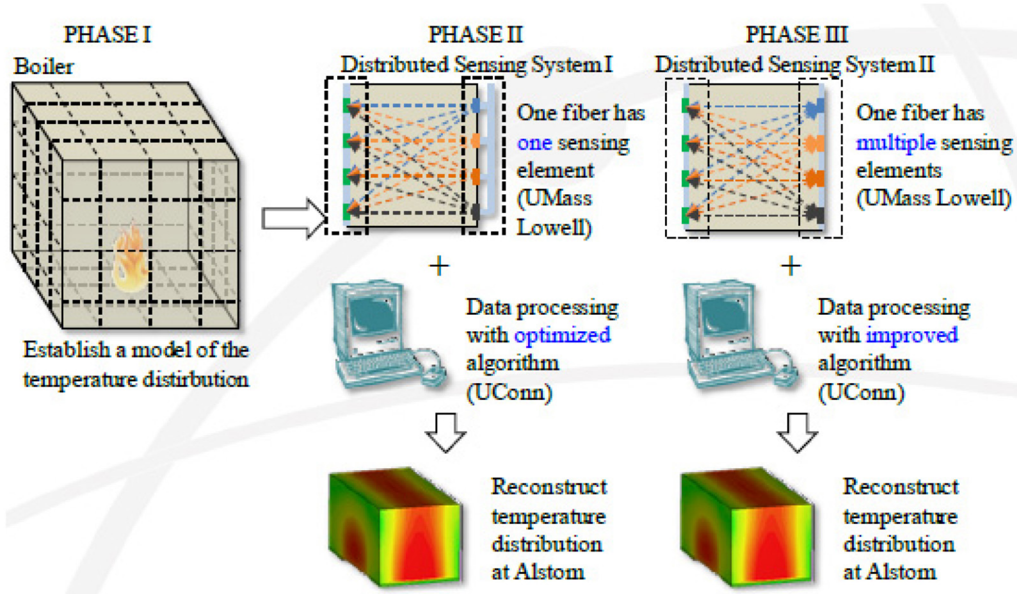
Raman gas analyzer.



Tunable diode laser absorption spectroscopy applied to methane production measurement.

OPTICAL SENSORS

The optical sensing area addresses a range of sensing devices to enable real-time measurement of temperature, pressure, strain/stress, and gas species. Approaches range from non-contact laser-based techniques to novel fiber optic sensor designs. Development efforts within this area include promoting the ability to function in extreme environments, designs for multiplexing and distributed measurements, approaches for low-cost devices, materials for fiber coatings, optically active smart coatings, and packaging of sensors to enable commercial application. Fiber optics have made a significant impact on the viability of sensors in harsh environments because of their immunity to electromagnetic interference, the inherently drift-free sensor designs they enable, and the availability of a range of materials suitable for high-temperature applications.



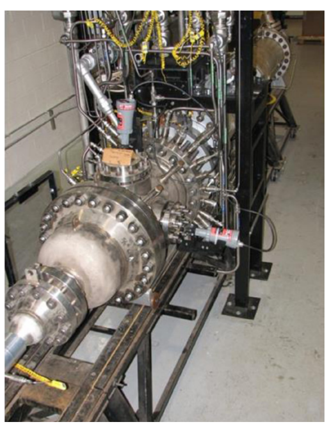
PERFORMER	PROJECT TITLE	PAGE
National Energy Technology Laboratory	Development of Fiber Optic Sensing for Future Fossil Energy Applications	13
Opto-Knowledge Systems, Inc.	Mid IR Laser Sensor for Continuous SO_3 Monitoring to Improve Coal-Fired Power Plant Performance during Flexible Operations	14
University of Central Florida	In-Situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments	15
University of Florida	High-Temperature Sapphire Pressure Sensors for Harsh Environments	16
University of Massachusetts Lowell	Distributed Fiber Sensing Systems for 3D Combustion Temperature Field Monitoring in Coal-Fired Boilers Using Optically Generated Acoustic Waves	17
University of Pittsburgh	Engineering Metal Oxide Nanomaterials for Fiber Optical Sensor Platforms	18
Virginia Polytechnic Institute and State University	Investigation of High Temperature Silica Based Fiber Optic Materials	19
Virginia Polytechnic Institute and State University	Reduced Mode Sapphire Optical Fiber and Sensing System	20
Washington State University	Raman Spectroscopy for the On-Line Analysis of Oxidation States of Oxygen Carrier Particles	21

Development of Fiber Optic Sensing for Future Fossil Energy Applications

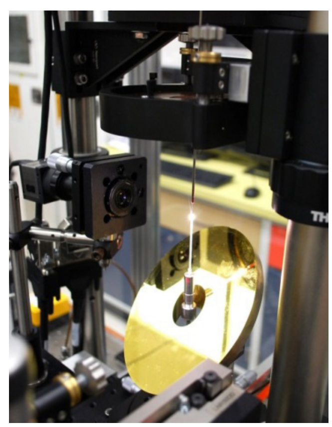
Performer	National Energy Technology Laboratory
Award Number	FWP 1022427 Task 2
Project Duration	01/01/2017 – 03/31/2018
Total Project Value	$ 914,629
Technology Area	Plant Optimization Technologies

The National Energy Technology Laboratory will research materials and sensing approaches to develop a fiber-based sensing concept that can provide spatially resolved species and temperature measurements from a fiber at more than 800 degrees Celsius (°C). The effort will include developing very-high-temperature optical fibers, functional material coatings for sensing, and interrogation methods for temperature and chemical species. The capability to create higher-temperature optical-quality fibers that can operate at temperatures beyond those of silica fibers is needed to maximize the technology benefit. The recently constructed laser-heated pedestal growth system will be utilized to refine the techniques needed to make high-temperature crystalline optical fibers (from materials such as sapphire or garnet) and to develop a durable optical cladding. The goal of this project is to measure chemistry and temperature in radically engineered modular systems as well as spinoffs to shorter-term applications such as measurements within a fuel cell stack.

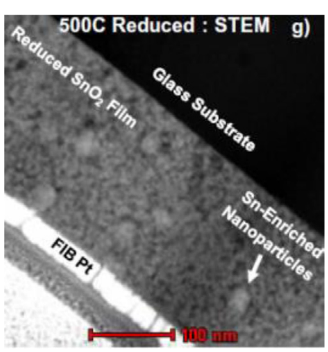
Advances in sensing technology will provide a new tool for developing fossil energy technologies, moving from an array of discrete sensors (e.g., thermocouples) to an array of measurements along an optical fiber, with a single port and readout for the fiber.

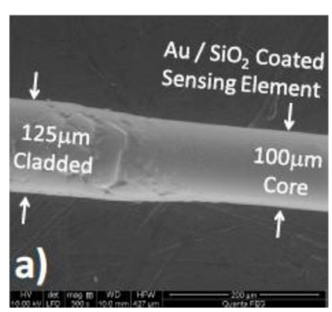


Aerothermal test rig in the High-Pressure Combustion Facility



Laser heated pedestal growth system.





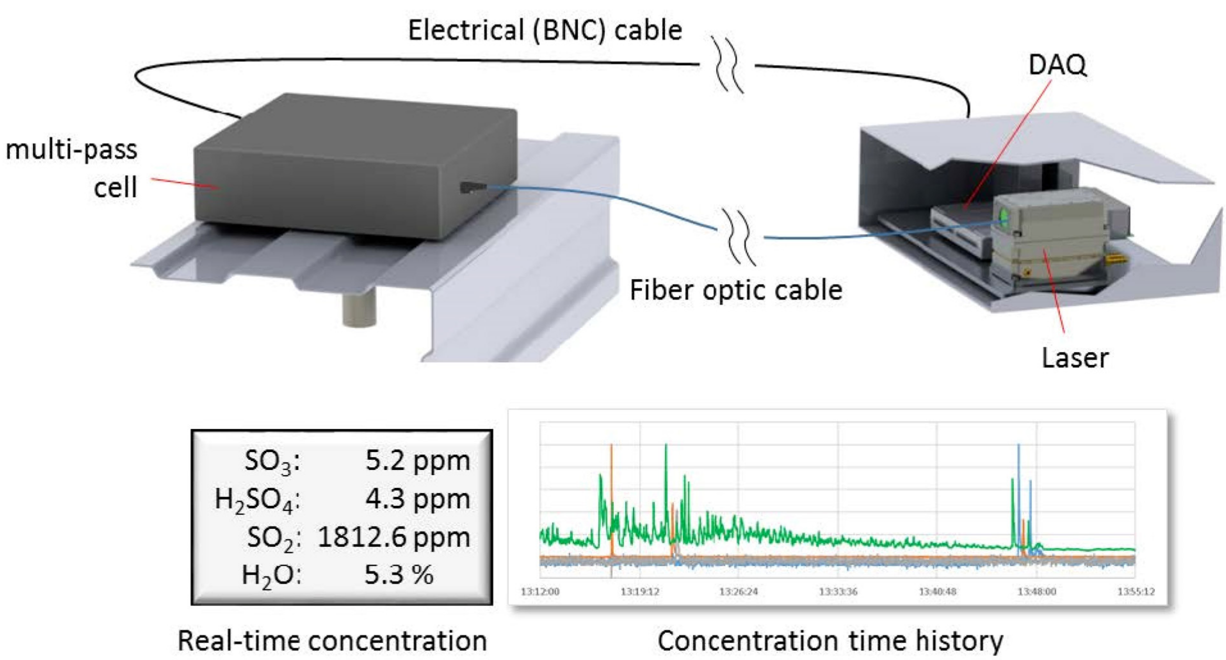
Scanning electron microscope images of thin film material characterization.

Mid IR Laser Sensor for Continuous SO_3 Monitoring to Improve Coal-Fired Power Plant Performance during Flexible Operations

Performer	Opto-Knowledge Systems, Inc.
Award Number	FE0031560
Project Duration	03/29/2018 – 01/31/2021
Total Project Value	$ 625,000
Technology Area	Plant Optimization Technologies

The primary objective of this project is to develop and demonstrate a continuous SO_3 monitoring system for coal-fired power plants, which will provide real-time, actionable information to enable control of additive injection, and minimize catalyst deactivation. The system to be developed will utilize the sensitivity, specificity, and real-time capabilities of mid-infrared laser-based sensor technology, along with a close-coupled cell mounted directly to the pollution control duct of a coal-fired power plant. The effort will consist of two rounds of prototype development and field testing at an operating coal-fired power plant.

A sensor that can provide continuous, accurate measurements of SO_3 in coal-fired power plants will provide relevant information that would allow better control of the alkali injection systems used to mitigate SO_3. Currently, without a reliable SO_3 measurement, utilities over-inject alkali to insure mitigation of a blue plume. A reliable SO_3 measurement will result in better control, leading to cost savings. In addition, low-load operation would benefit from an online SO_3 measurement, which will allow the region of ammonium bisulfate formation to be more accurately predicted, thereby minimizing catalyst deactivation and improving plant capability for flexible operation.

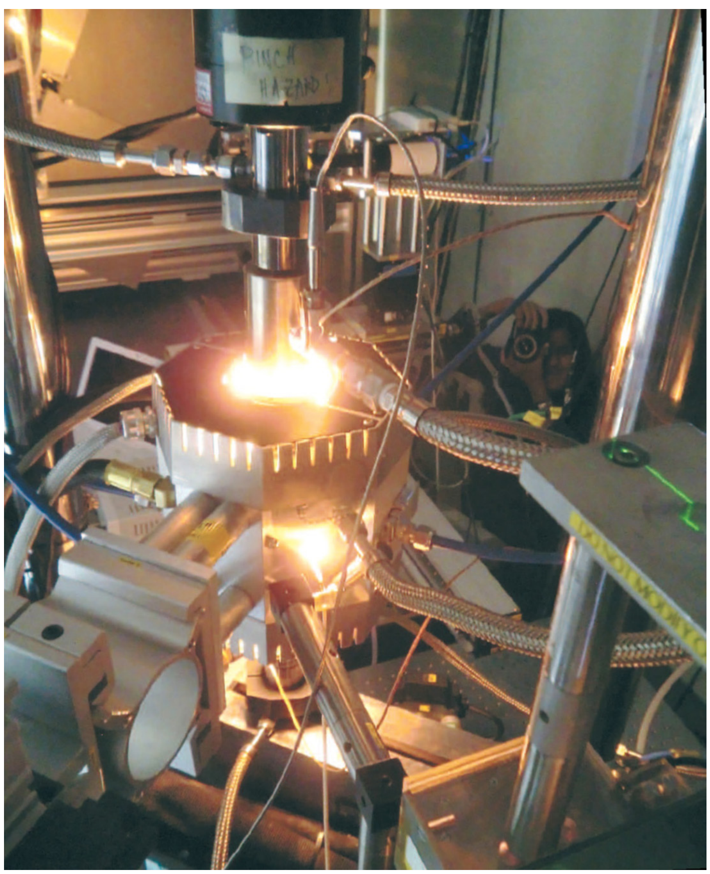


Simple diagram illustrating concept.

In-Situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments

Performer	University of Central Florida
Award Number	FE0031282
Project Duration	10/01/2017 – 09/30/2020
Total Project Value	$ 879,488
Technology Area	Advanced Turbines

With engine temperatures exceeding the limits that metallic blades and vanes can endure, advanced monitoring techniques that ensure the integrity and durability of thermal barrier coatings are paramount to continuous and safe operation. The University of Central Florida will use key properties of optical radiation—including temporal, spectral, and spectral intensity response modes, coupled with active sensing from coating properties—to gain diagnostic information on high-temperature thermal barrier coatings (TBCs). Materials design incorporating rare earth elements within TBCs to create the self-indicating property will be accompanied by research efforts to correlate optical measurements to TBC diagnostic parameters. The methods will be developed and demonstrated at the laboratory scale with the goal of future implementation in gas turbine conditions.



Prototype laboratory-scale test rig for the demonstration of in-situ luminescence sensing under extreme thermal and/or thermo-mechanical conditions.

High Temperature Sapphire Pressure Sensors for Harsh Environments

Performer	University of Florida
Award Number	FE0012370
Project Duration	01/01/2014 – 08/31/2018
Total Project Value	$ 1,098,191
Collaborator	Florida State University
Technology Area	Plant Optimization Technologies

The University of Florida, in collaboration with Florida State University, began an effort to develop sapphire manufacturing technologies for fabricating and packaging high-temperature sensors by combining ultra-short pulse laser micromachining (LM) and spark plasma sintering (SPS). The primary objective of this project is to develop sensor materials and manufacturing designs for measuring physical parameters in situ and on line under extreme conditions (i.e., high temperatures and pressures and corrosive environments).

The proposed research will employ a multi-faceted approach to develop and quantify manufacturing technologies for fabricating sapphire high-temperature sensors. Laser micromachining processes will be developed using an Oxford Laser J-355PS picosecond laser micromachining workstation. SPS will be used to develop processes for joining sapphire and alumina substrates. These two technologies will help create three-dimensional microscale sapphire structures by bonding planar laser micromachined substrates via SPS. Performance of the machined components will be simulated and experimentally quantified via fracture and dislocation mechanics methods.

These technologies will enable the manufacture of miniature sapphire sensors for a variety of applications of interest (pressure, temperature, stress/strain, etc.); however, for the purpose of this proposal, the primary application will be an optical pressure sensor capable of operating in environments in excess of 1000 degrees Celsius and up to 1000 pounds per square inch. The proposed applied research will help establish critical functions regarding LM and SPS materials synthesis as well as a packaged and experimentally characterized pressure sensor.

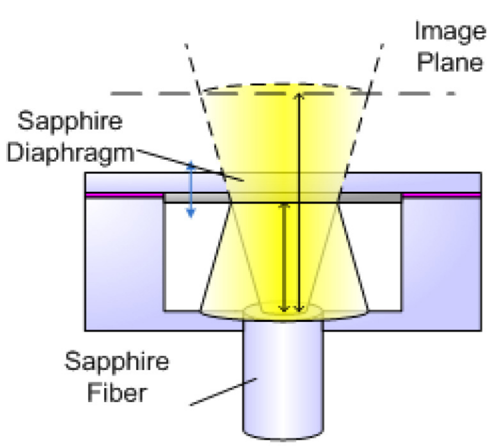
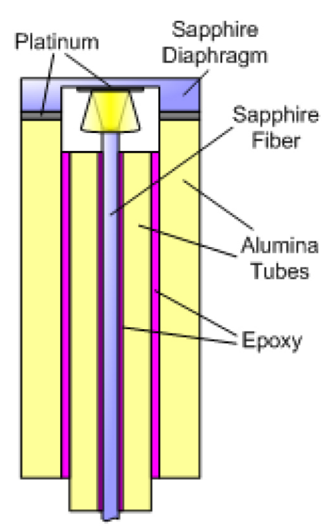


Illustration of the fiber-optic lever transduction scheme implemented in the pressure sensor design.



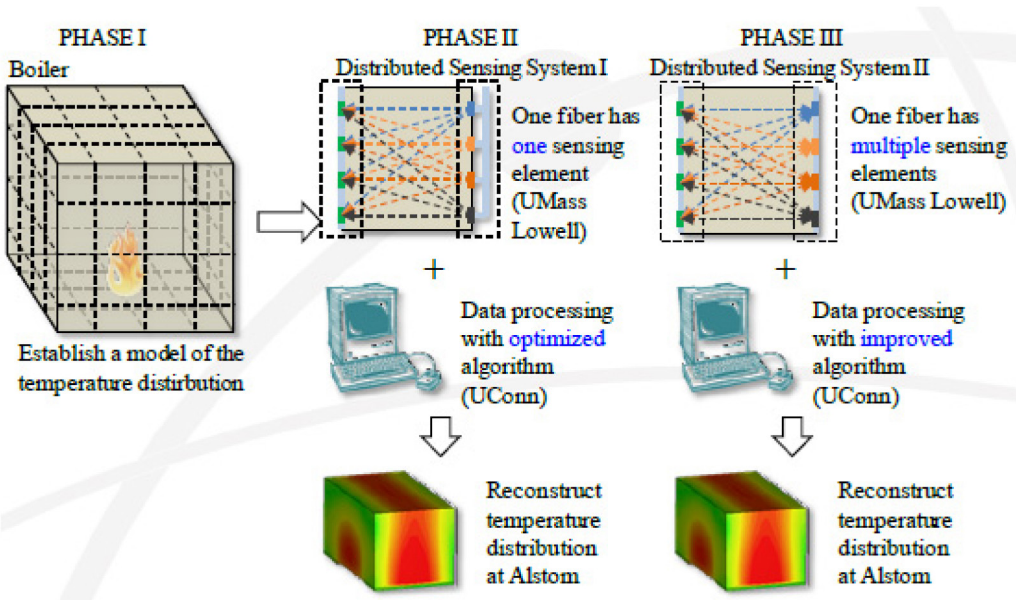
Schematic of sensor and packaging for the high-temperature pressure sensor.

Distributed Fiber Sensing Systems for 3D Combustion Temperature Field Monitoring in Coal-Fired Boilers Using Optically Generated Acoustic Waves

Performer	University of Massachusetts Lowell
Award Number	FE0023031
Project Duration	09/01/2014 – 08/31/2018
Total Project Value	$ 400,000
Collaborators	Alstom Power, Inc. and University of Connecticut
Technology Area	University Training and Research

The University of Massachusetts will attempt to monitor and optimize real-time spatial and temporal distributions of high-temperature profiles in a fossil fuel power plant boiler system. Distributed optical fiber sensing has the potential to measure high temperatures while the optically generated acoustic signals can measure regions where the fibers cannot survive (e.g., 2000 degrees Celsius). The reconstructed three-dimensional temperature profile will provide critical input for the control mechanisms to optimize the combustion process, thus achieving higher efficiency and fewer pollutant emissions.

To accomplish this, project personnel will first develop a methodology to (1) establish a boiler furnace temperature distribution model and guide the design of the sensing system; (2) develop the sensors with one active sensing element on each fiber as well as a temperature distribution reconstruction algorithm for proof of concept; and (3) develop the distributed sensing system to integrate multiple active sensing elements into a single optical fiber. The entire sensing system, after achieving full integration and testing in the university labs, will be tested in Alstom's combustion test facility. This novel distributed sensor can have broader applications including measurement of strain, flow, velocity, crack growth, and corrosion for monitoring structural health.



Phases of project objectives.

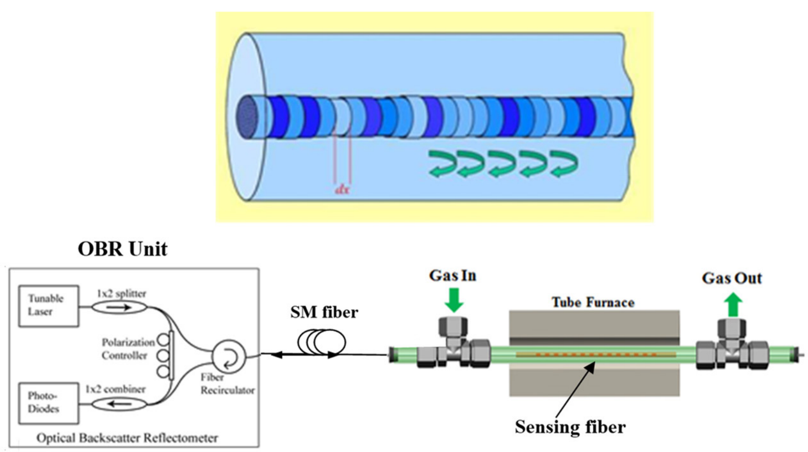
Engineering Metal Oxide Nanomaterials for Fiber Optical Sensor Platforms

Performer	University of Pittsburgh
Award Number	FE0028992
Project Duration	10/01/2016 – 09/30/2019
Total Project Value	$ 400,000
Technology Area	University Training and Research

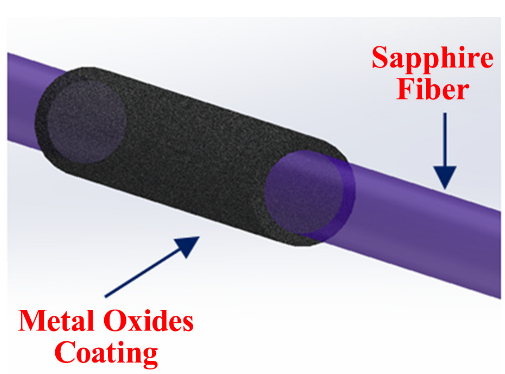
The University of Pittsburgh will explore nano-engineered metal oxides—a class of important sensor materials—for fiber optic chemical sensing for high-temperature energy applications using both silica and sapphire fibers as sensing platforms.

This project will develop an integrated sensor solution for performing direct and simultaneous measurements of chemical reactions and temperature in a solid oxide fuel cell (SOFC) with 5-millimeter (mm) spatial resolution. This project will measure the internal hydrogen consumption rate at very high temperatures (600 to 800 degrees Celsius [°C]), test hydrogen sensors in an SOFC in the High-temperature Fuel Cell Testing Facility, and determine the range and continuity of the refractive index tenability with Pluronic F-127.

This project will develop a highly stable physical-based sensor for use in highly reactive gas streams for fossil-based power plant applications and will demonstrate real-time multi-species flue gas measurements at high temperatures (400 to 900 °C) using a single fiber.



Distributed Rayleigh scattering.



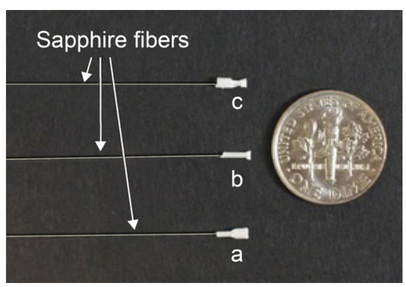
Sapphire fibers.

Investigation of High Temperature Silica Based Fiber Optic Materials

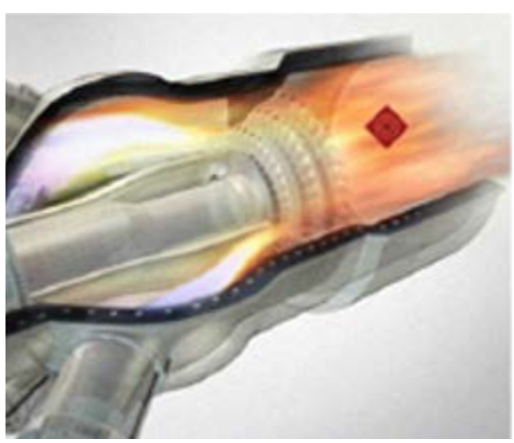
Performer	Virginia Polytechnic Institute and State University
Award Number	FE0027891
Project Duration	10/01/2016 – 09/30/2018
Total Project Value	$ 400,000
Technology Area	University Training and Research

Virginia Polytechnic Institute and State University will develop a comprehensive and complete understanding of the optical and mechanical stability of fused silica optical fibers at high temperatures under various gaseous species conditions, and employ this knowledge to properly select optical fibers that can be readily integrated into sensing technologies. This project will include comprehensive testing and analysis of the interactions of fuel gas stream species with state-of-the-art optical fibers to understand the induced devitrification, chemical reactions, and the diffusion of chemical species on mechanical and optical performance, and to evaluate novel and traditional fused silica fibers that will be drawn under various process conditions to fully understand the fundamental mechanisms that govern performance.

The optical performance of the fibers will be evaluated during exposure to selected chemical constituents and elevated temperatures, and induced attenuation phenomena will be analyzed to evaluate time and temperature dependencies.



Single crystal sapphire fibers.



Fiber optic sensing system.

Reduced Mode Sapphire Optical Fiber and Sensing System

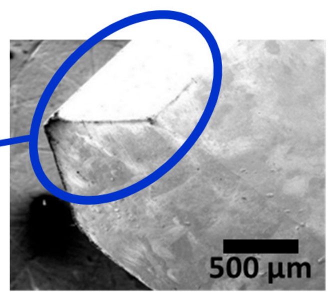
Performer	Virginia Polytechnic Institute and State University
Award Number	FE0012274
Project Duration	01/01/2014 – 12/31/2018
Total Project Value	$ 2,625,000
Technology Area	Plant Optimization Technologies

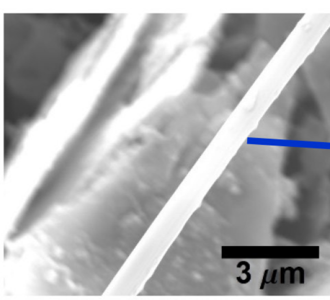
Virginia Polytechnic Institute and State University is developing distributed temperature sensing systems based on Raman backscatter and fiber Bragg grating sensors that utilize a micro-structured single crystal sapphire fiber with reduced modal volume. Real-time, accurate, and reliable temperature monitoring at distributed locations will help further revolutionize technologies such as the integrated gasification combined cycle configuration of turbines and ultra-supercritical steam cycle designs.

A new modal reduction waveguide design will take advantage of the high-temperature stability and corrosion resistance of sapphire, resulting in a paradigm shift in ultra-high-temperature sensing. A novel and precise etching technique will be optimized to create a unique and robust sapphire fiber that significantly reduces the modal volume by greater than 95 percent. The distributed temperature sensing systems will be demonstrated to temperatures in excess of 1400 degrees Celsius and deployed, with harsh environment sensor packaging, in an operating power plant.

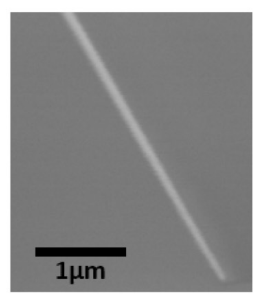
The sapphire fiber waveguide design will overcome the harsh environment challenges that severely limit the integration of mature optical fiber sensing technologies into new power plant control systems. Overall, this technology is expected to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control its operation.

Angled edge on single crystal sapphire wafer via etching process.

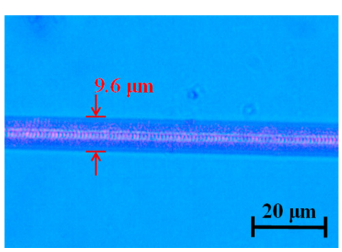




Submicron single crystal sapphire fiber.



Nano single crystal sapphire fiber (less than 5 nanometers).



Bragg grating sensor fabricated in a low modal volume single crystal sapphire fiber.

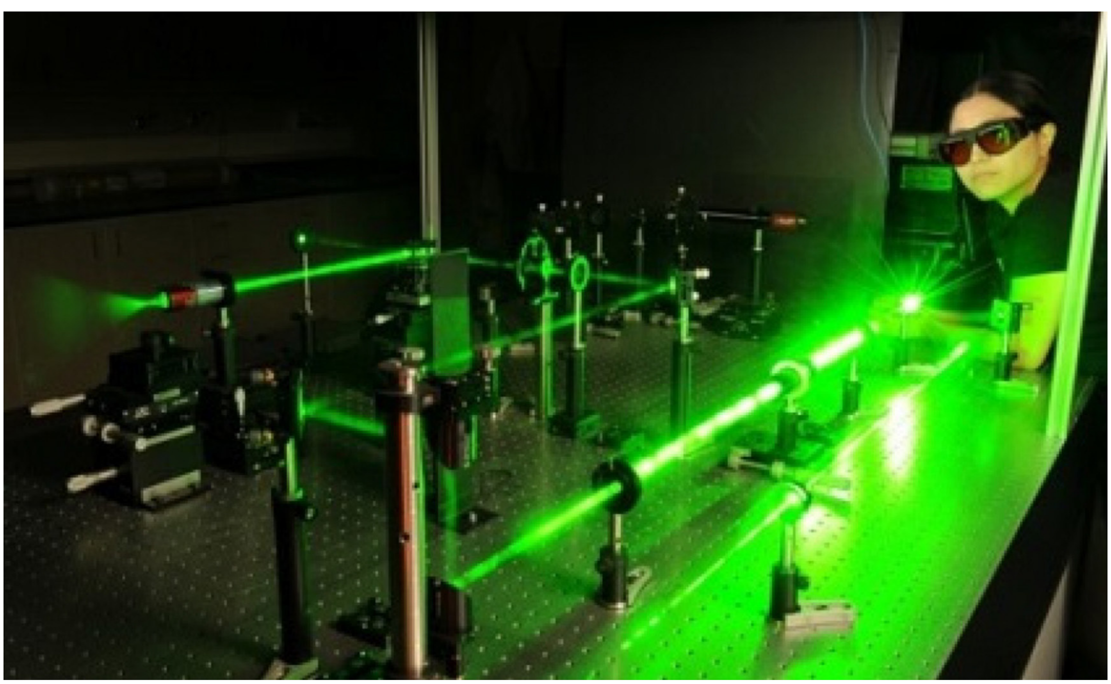
Raman Spectroscopy for the On-Line Analysis of Oxidation States of Oxygen Carrier Particles

Performer	Washington State University
Award Number	FE0027840
Project Duration	10/1/2016 – 09/30/2018
Total Project Value	$ 400,000
Technology Area	University Training and Research

Researchers at Washington State University will develop and demonstrate the feasibility of an online optical sensor for optimizing future power-generation technologies such as chemical looping reactors. These reactors rely on oxygen-carrier particles, for example iron oxides, copper oxides, and calcium sulfates, to provide oxygen for the combustion process. In order to optimize the overall process performance, it is critical that the properties of the oxygen carriers are well-defined and maintained for their specific purpose during the different stages of the chemical looping process.

The expected operating conditions of the sensor include oxygen-carrier particle temperatures in the range of 800 to 1000 degrees Celsius and about 10 atmospheric pressures. One of the critical properties of the oxygen carrier particles is their oxidation state (e.g., prevalence of Fe_2O_3 vs. Fe_3O_4) as it affects the fundamental operation of the chemical looping process. Measurements of the oxidation state will have to be evaluated using pulsed and continuous-wave (CW) lasers, and the expected results are to be of a statistical nature, providing relative concentrations of the different oxidation states.

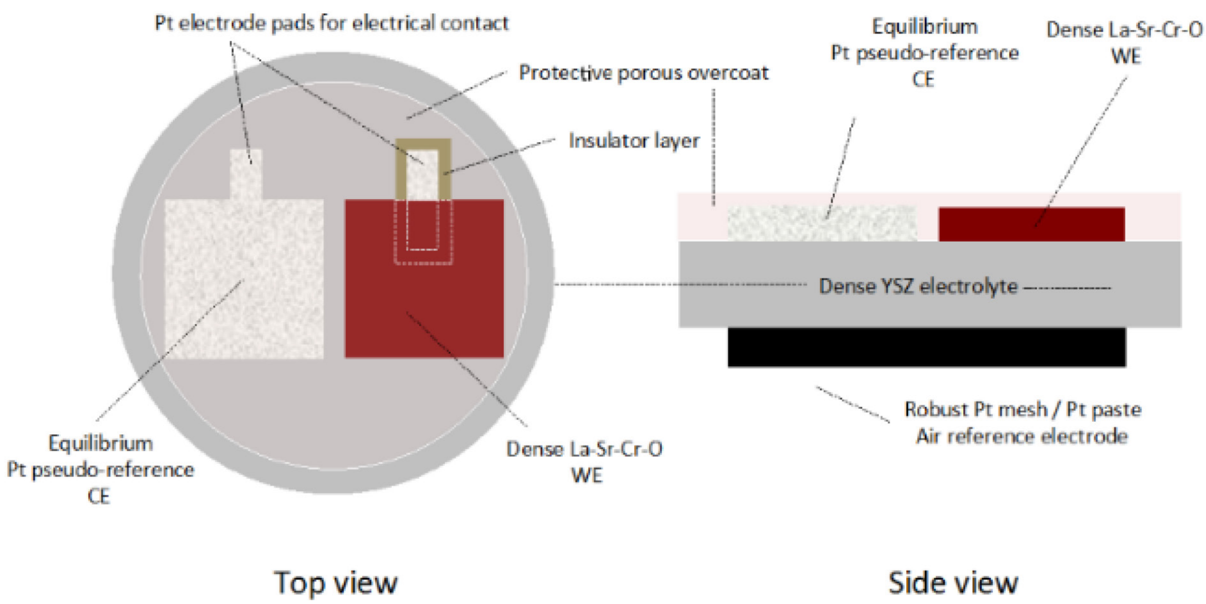
This project will develop and test a pulsed/time-gated and CW Raman spectroscopy system in combination with a pressurized high-temperature sample chamber; optimize the operating parameters of the Raman spectroscopy system and measure the high-temperature spectra of oxygen carriers; and develop an analysis procedure, including statistical modeling and multivariate calibration, for interpreting the Raman spectra.



Raman setup.

WIRELESS SENSORS

Components and machinery for fossil-energy-based energy systems require meaningful measurements and data from locations where wired technologies are not feasible and/or practical. Technologies currently under development include methodologies for wireless signal transfer at stand-off distances under various harsh environment conditions as observed in boilers, gas turbines, and other fossil energy applications.



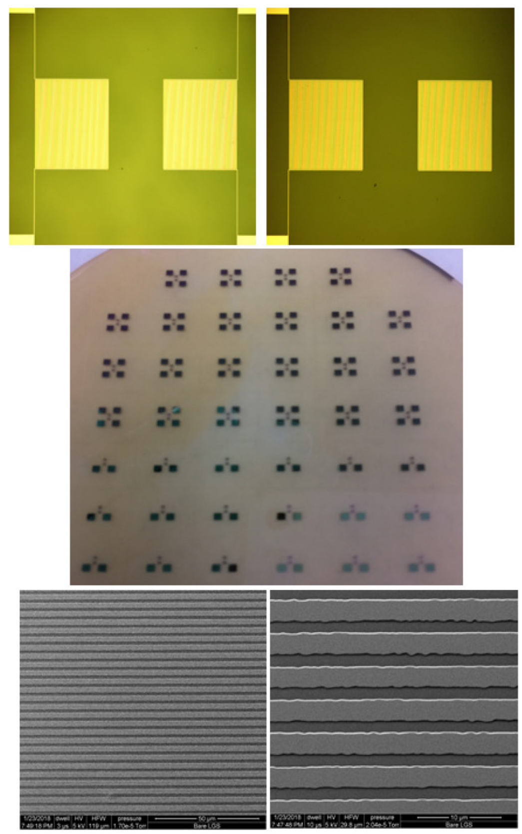
PERFORMER	PROJECT TITLE	PAGE
University of Connecticut	Wireless 3D Nanorod Composite Arrays-Based High-Temperature Surface Acoustic Wave Sensors for Selective Gas Detection Through Machine Learning Algorithms	23
University of Maine System	High Temperature Integrated Gas and Temperature Wireless Microwave Acoustic Sensor System for Fossil Energy Applications	24
University of Maine System	Technology Maturation of Wireless Harsh-Environment Sensors for Improved Condition-Based Monitoring of Coal-Fired Power Generation	25
University of Texas at Arlington	Distributed Wireless Antenna Sensors for Boiler Condition Monitoring	26
Washington State University	Low-Cost Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems	27
West Virginia University	Passive Wireless Sensors Fabricated by Direct-Writing for Temperature and Health Monitoring of Energy Systems in Harsh-Environments	28
West Virginia University Research Corporation	High Temperature Electrochemical Sensors for In-Situ Corrosion Monitoring in Coal-Based Power Generation Boilers	29
West Virginia University Research Corporation	High Temperature Gas Sensor for Coal Combustion System	30

Wireless 3D Nanorod Composite Arrays-Based High-Temperature Surface Acoustic Wave Sensors for Selective Gas Detection Through Machine Learning Algorithms

Performer	University of Connecticut
Award Number	FE0026219
Project Duration	09/01/2015 – 08/31/2018
Total Project Value	$ 400,000
Technology Area	University Training and Research

The University of Connecticut intends to develop a wireless gas sensor capable of passive operation (no batteries) from 600 to 1000 degrees Celsius (°C) in harsh environments relevant to fossil energy technologies, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems. The proposed wireless sensor system is based on a surface-acoustic-wave (SAW) sensor platform that is configured using a langasite (LGS) piezoelectric crystal with platinum/titanium interdigital electrodes and three-dimensional (3D) nanorod composites to detect oxygen, nitrogen oxides, ammonia, and hydrocarbon gases in the harsh environment. In conjunction with machine learning techniques, selective, reliable and wireless detection of targeted gases in high-temperature mixed gas environments can be realized.

This project could advance the fundamental understanding of gas-responsive high-temperature sensing materials and machine-learning based high-temperature wireless SAW gas detection with high sensitivity, enhanced selectivity, and high temperature stability. The project will also provide unique perspectives and understanding in high temperature nanomaterials science and SAW sensing mechanisms on 3D nanostructures. The sensing technique could be suitable for various fossil energy end-use applications ranging from ultra-supercritical boilers (up to 760 °C) to solid oxide fuel cells (650–1000 °C) and automotive engines (up to 1000 °C).



SAW circuit (platinum/titanium) deposited on a LGS wafer.

High Temperature Integrated Gas and Temperature Wireless Microwave Acoustic Sensor System for Fossil Energy Applications

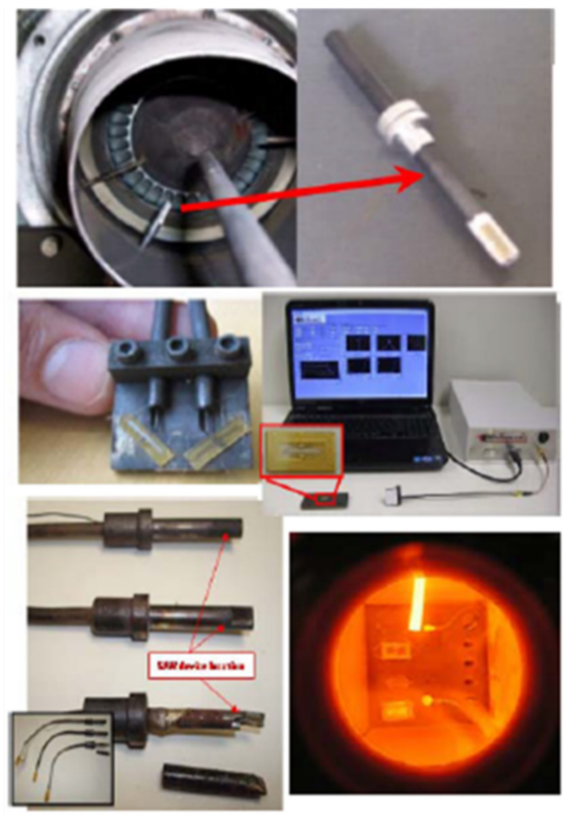
Performer	University of Maine System
Award Number	FE0026217
Project Duration	09/01/2015 – 08/31/2018
Total Project Value	$ 399,999
Technology Area	University Training and Research

The University of Maine System intends to develop a wireless integrated gas/temperature microwave acoustic sensor capable of passive operation (no batteries) from 350 to 1000 degrees Celsius in harsh environments relevant to fossil energy technologies, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems.

The sensor system is based on a surface acoustic wave (SAW) sensor platform that could be used to detect hydrogen (H_2), oxygen (O_2), and nitrogen oxides (NO_x) and monitor gas temperatures in harsh environments. Fully packaged prototype sensors will be designed, fabricated, and tested under H_2 (less than 5 percent), O_2, and NO_x gas flows in laboratory furnaces, and the sensor response will be characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

The SAW sensors have the advantage of being potentially readily scalable for rapid manufacturing using photolithography/ metallization fabrication steps, followed by integrating each sensor into a stand-alone wireless harsh environment sensor package. The SAW gas sensor technology will be targeted for implementation and demonstration in a power plant environment.

Acquiring temperature and gas composition data from wireless sensors in diverse harsh environment locations in power plants will help increase fuel burning efficiency, reduce gaseous emissions, and reduce maintenance costs through condition-based monitoring.



Examples of harsh environment wireless langasite SAW sensors.

Technology Maturation of Wireless Harsh-Environment Sensors for Improved Condition-Based Monitoring of Coal-Fired Power Generation

Performer	University of Maine System
Award Number	FE0031550
Project Duration	01/11/2018 – 01/10/2021
Total Project Value	$ 2,504,425
Technology Area	Plant Optimization Technologies

The University of Maine will develop, adapt, implement, test, and transition wireless harsh-environment surface acoustic wave (SAW) sensor technology in coal-fired power plants. The technology offers several potential advantages for inline monitoring of coal-based power generation systems including accurate, battery-free, maintenance-free wireless operation. The small footprint will potentially allow flexible sensor placement and embedding of multiple sensor arrays into a variety of components that can be sampled with a near-by interrogating antenna and radio frequency signal processing unit. The temperature and/or strain measurements acquired from wireless SAW sensors represent critical data for actively monitoring the health condition and detecting failures in boiler tubes, headers, and piping at several key locations in coal-based power generation facilities.

Expected outcomes include a matured technology; advancements in the packaging of SAW sensors and antennas to allow long-term robust operation; refined wireless communications protocols and signal processing; improved thin films and sensor packaging; and prototype static and dynamic strain SAW sensors. The University of Maine will install and test their resulting prototype wireless sensor systems at a solid-waste-to-energy plant and a coal-fired power plant.

SAW sensors (white rectangles) installed on boiler tubes at waste-to-energy facility.

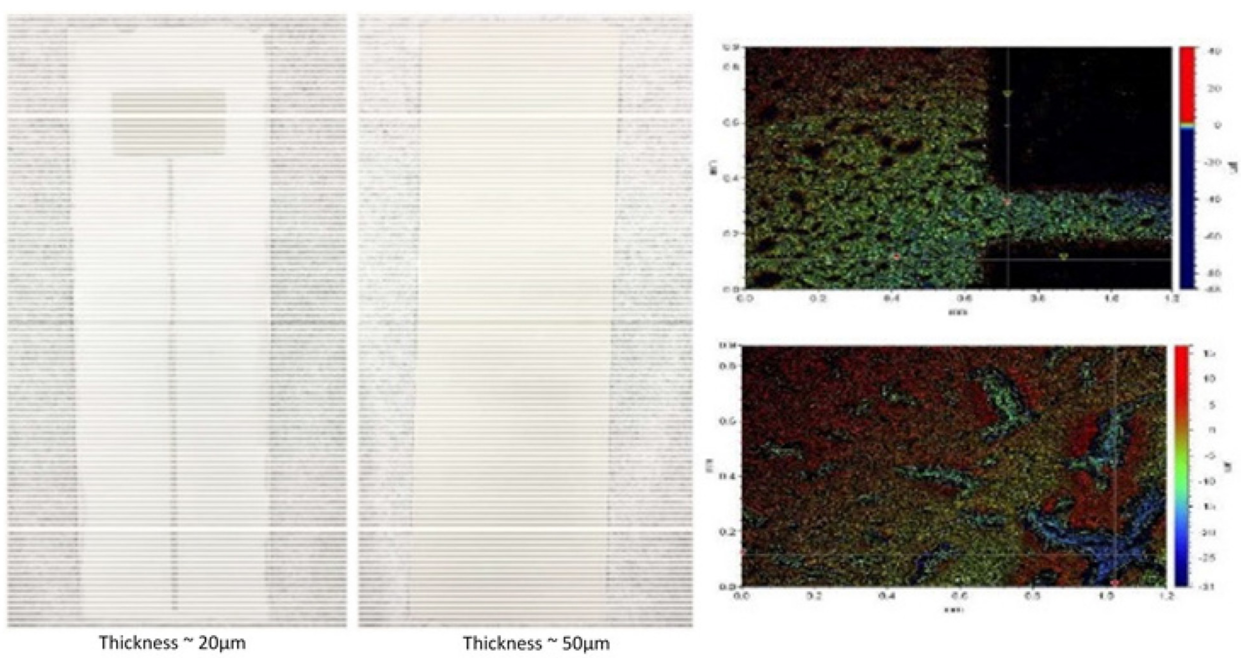
Access door to economizer area of trash burning boiler with array of six SAW sensors surrounding interrogation antenna in center.

Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Performer	University of Texas at Arlington
Award Number	FE0023118
Project Duration	01/01/2015 - 12/31/2018
Total Project Value	$ 434,079
Collaborator	University of California, San Diego
Technology Area	University Training and Research

University of Texas at Arlington and University of California, San Diego will develop wireless antenna sensors for distributed sensing of temperature, strain, and soot accumulation inside a coal-fired boiler. The objectives of the project include (1) a methodology to realize low-cost antenna sensor arrays that can withstand high-temperature and high-pressure environments; (2) a wireless interrogation technique that can remotely interrogate the sensors at long distances with high resolution; and (3) material and fabrication recipes for synthesizing flexible dielectric substrates with controlled dielectric properties.

By continuous condition monitoring of industry steam pipes, power plants can expect to enhance safety by determining an optimal soot cleaning schedule as well as by safeguarding against overly high temperatures in high-pressure corrosive environments. The benefits of this project include distributed sensing for in-process control, real-time health assessment of structural components, and improved heat transfer efficiency of boilers.



Laser machined antenna sensor.

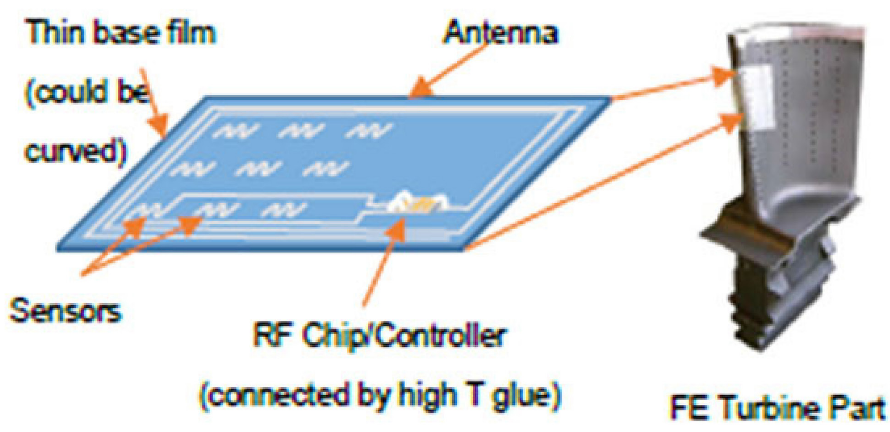
Low-Cost Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems

Performer	Washington State University
Award Number	FE0026170
Project Duration	10/01/2015 – 09/30/2018
Total Project Value	$ 488,738
Collaborator	University of Texas at El Paso
Technology Area	University Training and Research

Washington State University will design, characterize, and demonstrate wireless, conformal strain and pressure sensors manufactured using low-cost, direct write additive methods for application in fossil energy (FE) systems. The goal is to demonstrate the feasibility of low-cost aerosol jet manufacturing for FE systems and to develop next-generation sensors and controls that can sustain temperatures up to 500 degrees Celsius (°C).

Specifically, this project will advance the current state of the art by developing novel materials and devices for wireless circuits that surpass 350 °C—the operating temperature limit of traditional silicon-based electronics—integrating electronic circuitry on curved three-dimensional surfaces such as those observed in gas turbine engines, demonstrating capabilities that surpass those of traditional (two-dimensional) lithographic techniques; and improving reliability issues for wireless sensors that arise from the demanding FE environments.

It is anticipated that this research will improve in-situ monitoring and the performance of FE devices and systems.



Schematic of a fully integrated high-temperature wireless sensor system.

Passive Wireless Sensors Fabricated by Direct-Writing for Temperature and Health Monitoring of Energy Systems in Harsh-Environments

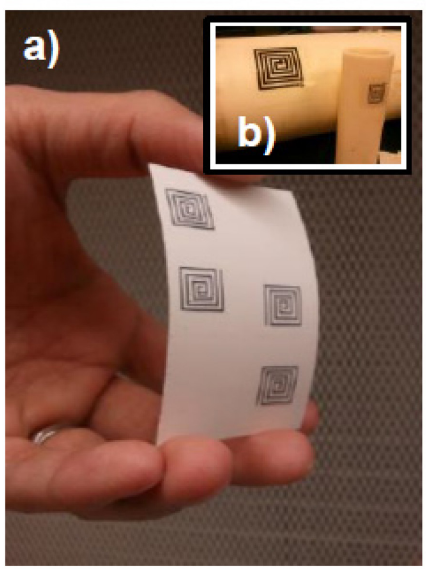
Performer	West Virginia University
Award Number	FE0026171
Project Duration	10/01/2015 – 09/30/2018
Total Project Value	$ 399,965
Collaborator	NexTech Materials, Ltd.
Technology Area	University Training and Research

West Virginia University will demonstrate a wireless high-temperature sensor system for monitoring the temperature and health of energy-system components. The active sensor and electronics for passive wireless communication will be composed entirely of electroceramic materials (conductive ceramics), which can withstand the harsh environments associated with advanced fossil-energy-based technologies.

The project will focus primarily on fabricating and testing thermocouples and thermistors (temperature) and strain/stress and crack propagation sensors (health monitoring) that function at extreme temperatures (from 500 to 1700 degrees Celsius). A passive wireless communications circuit to accompany the high-temperature sensor that will enable transmission of the data (based on electromagnetic coupling) to a nearby reader antenna will be developed along with a peel-and-stick-like transfer process to deposit the entire sensor circuit to various energy-system components.

The results of this research could reduce the need for interconnect wires near the active—and possibly rotating—energy-system component. The results may also permit economical and precise placement of the sensor circuit onto components of various shapes and locations, without altering the geometry and active features of the manufactured component, or necessitating the removal (or decommissioning) of the component for installation.

The sensor system could be applied to solid oxide fuel cells, chemical reactors, furnaces, engines, boilers, and gas turbine systems for both energy and aerospace applications.

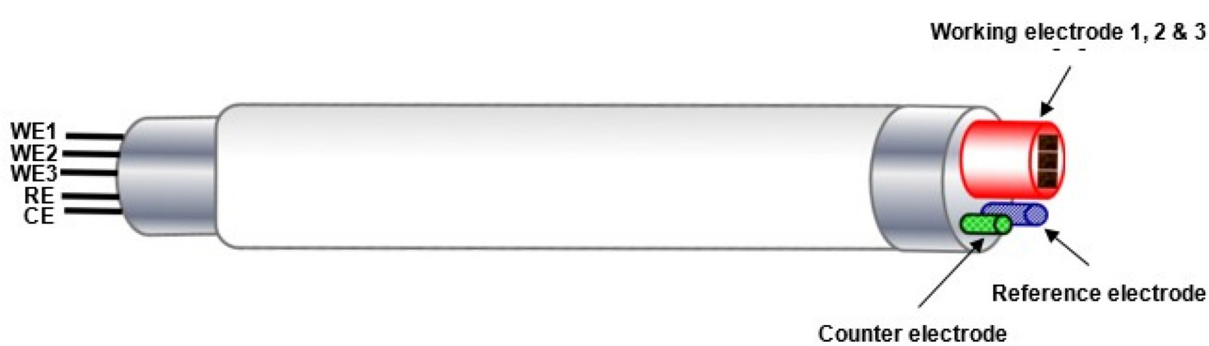


a) Picture of spiral inductor pattern ink-jet printed of ceramic ink onto fugitive carrier film, and b) picture of two patterns transferred to alumina tubes by West Virginia University's "peel & stick" process.

High Temperature Electrochemical Sensors for In-Situ Corrosion Monitoring in Coal-Based Power Generation Boilers

Performer	West Virginia University Research Corporation
Award Number	FE0031548
Project Duration	01/01/2018 – 12/31/2020
Total Project Value	$ 1,676,687
Technology Area	Advanced Combustion Systems

West Virginia University Research Corporation will refine and validate the effectiveness of their previous electrochemical sensor for high temperature (HT) corrosion in coal-based power generation boilers; optimize the HT sensor; and develop a pathway toward commercialization. Sensors will be tested at two scales: (1) commercial-scale sensors will be optimized specifically for a net 700 megawatt Amec Foster Wheeler once-through, low-mass flux, vertical tube, advanced ultrasupercritical boiler and (2) bench-scale sensors will be tested under a range of operating conditions that would serve a variety of coal-fired combustion boilers. A software system and a corrosion database will also be developed, enabling operators to interpret sensor data into actionable information.



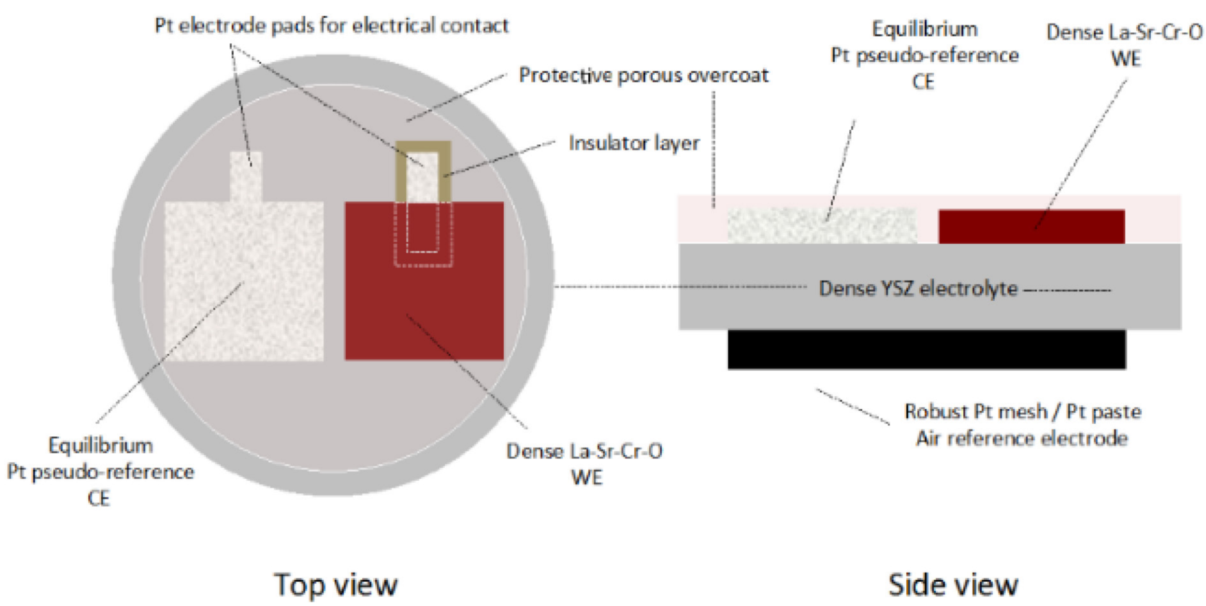
High-temperature corrosion sensor design.

High Temperature Gas Sensor for Coal Combustion System

Performer	West Virginia University Research Corporation
Award Number	FE0031564
Project Duration	03/01/2018 – 02/29/2020
Total Project Value	$ 635,414
Technology Area	Plant Optimization Technologies

The objectives of this project are to (1) develop an accurate, robust, high temperature oxygen sensor based on refractory, reliable, catalytically inactive $La_{1-X}Sr_XCrO_3$ materials capable of monitoring combustion in a coal-fired plant in real time to improve combustion performance; (2) investigate the feasibility and sensitivity of a new catalytic/non-catalytic sensor design to detect "oxidizable" target gases at high temperatures where other electrochemical sensors have failed; and (3) integrate and test the basic components of the proposed sensor in an operating commercial 700 megawatt power plant.

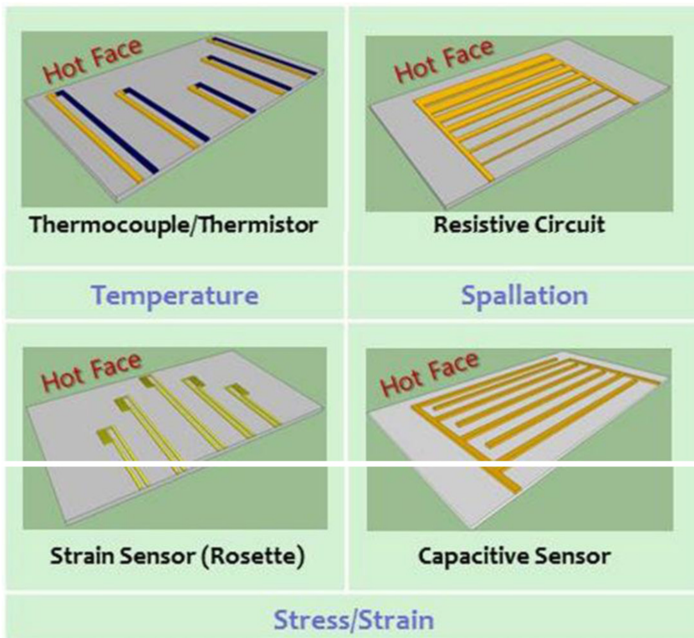
If the sensor is tested and found to be commercially viable, power plants will be inclined to adopt the technology with a full sensor grid to allow for optimized combustion. The sensor will be a benefit over existing continuous emissions monitoring systems because being an in-situ measurement, extraction of the flue gas or gas filters or traps is not required, and with faster measurement times, real-time data will be acquired thereby allowing better control of the dynamic combustion process. The advantage will be optimal combustion monitoring and intelligent control of fuel and air components. Ultimately, power plants could be more efficient without increasing nitrogen oxides emissions.



Schematic of the proposed high temperature gas sensor.

EMBEDDED SENSORS

Embedded sensors enable increased durability and reliability by removing sensor elements from direct exposure to the harsh operating environments encountered within FE-based energy systems. Projects in this section feature advanced manufacturing and fabrication techniques to embed sensor elements into components. Embedded sensors allow for advanced structural health monitoring over component lifetime and process control to increase system efficiency.



PERFORMER	PROJECT TITLE	PAGE
West Virginia University Research Corporation	Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health and Degradation of Slagging Gasifiers	32

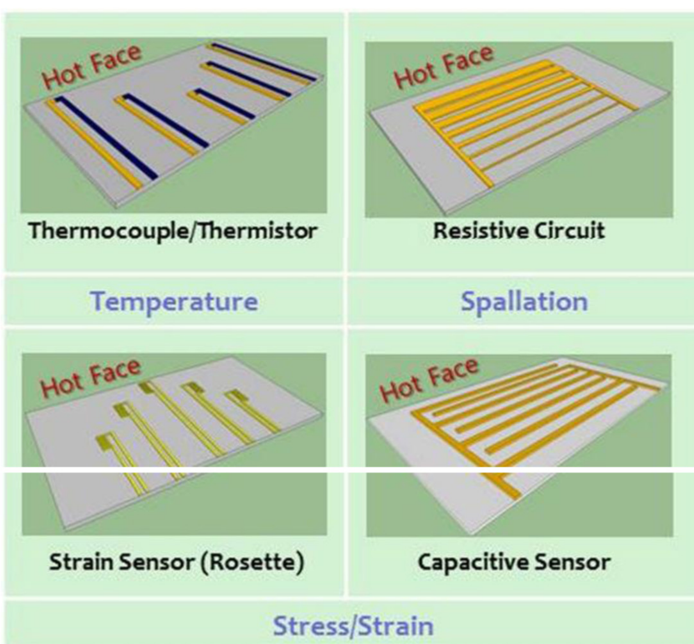
Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health and Degradation of Slagging Gasifiers

Performer	West Virginia University Research Corporation
Award Number	FE0012383
Project Duration	10/01/2013 - 03/31/2018
Total Project Value	$ 1,617,113
Technology Area	Plant Optimization Technologies

The United States Department of Energy National Energy Technology Laboratory has partnered with West Virginia University (WVU) to develop in situ and online sensing capability for advanced energy systems operating at high temperature and pressure in the harsh environments of advanced power generation systems. Researchers at WVU will demonstrate a high-temperature sensor concept for monitoring reaction conditions and health within slagging coal gasifiers. The technology will include the development of smart refractory gasifier brick. The new sensors will monitor the status of equipment, materials degradation, and process conditions that impact the overall health of a refractory lining in the high-temperature, highly corrosive environments of coal gasifiers.

The key aspect of the proposed technology is that these sensors will be incorporated and interconnected throughout the volume of the refractory brick and will not negatively impact the intrinsic properties of the refractory, thereby circumventing the need to insert a sensor into the refractory via an access port. This will ensure the integrity of the sensor within the harsh environment and will not introduce flaws or slag penetration pathways within the refractory, as is typically the issue with inserting sensors through access ports.

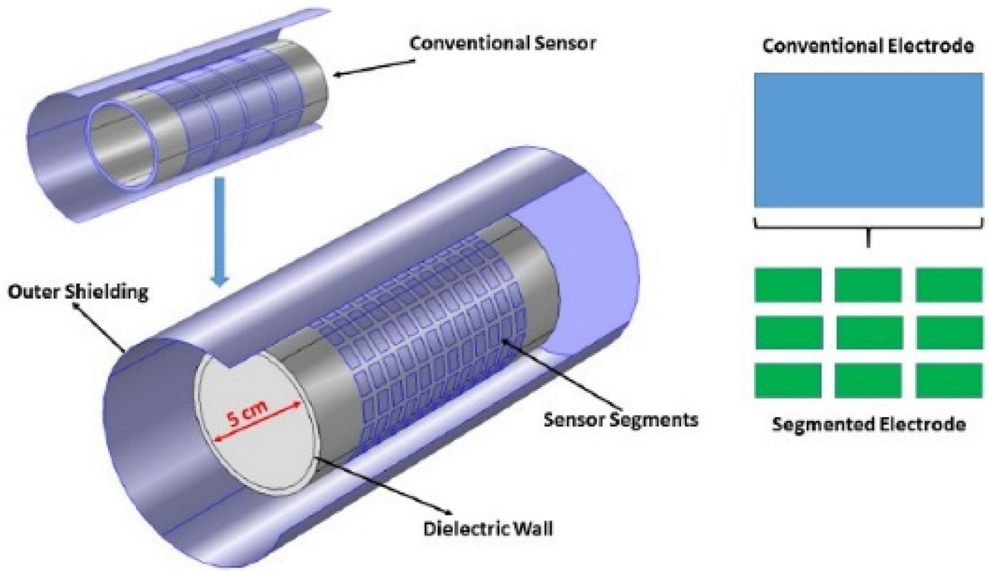
The anticipated benefit of this project would be the development of a more reliable and non-intrusive method of monitoring gasifier temperature and refractory health than is possible with current methods. Such improvements are expected to result in lower operating and maintenance costs of slagging gasifiers. The development of the proposed smart refractory and refractory sensor system concept could be applied to other applications, such as conventional coal-fired boiler technology, biomass gasification, and steel and glass manufacturing.



Schematics depicting possible embedded sensor designs.

NOVEL SENSOR CONCEPTS

New approaches to both sensing technologies and manufacturing (e.g., of smart parts) and utilization of sensor data (e.g., imaging/visualization) have the potential to be transformative.

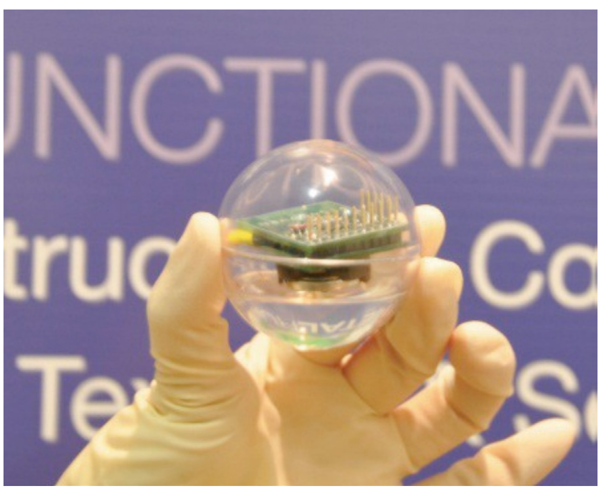


Wireless Networked Sensors in Water for Heavy Metal Detection

Performer	NanoSonic, Inc.
Award Number	SC0013811
Project Duration	06/08/2015 – 07/31/2018
Total Project Value	$ 1,150,000
Technology Area	Plant Optimization Technologies

NanoSonic, Inc. will develop wireless sensors for use in analyzing heavy metal chemistry for power generation facilities and, more broadly, for commercial use. The company will develop wireless networked sensors using conformal nanomembrane-based chemical field effect transistors (ChemFETs) to detect heavy metals in water. NanoSonic will fabricate prototype nanomembrane ChemFET sensor elements, design and synthesize chemical-specific ionophores for selectively detecting targeted heavy metal elements, and demonstrate the performance of prototype sensor devices. NanoSonic will work with a local environmental monitoring company to produce a wireless sensor network for in-situ environmental monitoring.

Project success will enable efficient monitoring of heavy metals in water for environmental surveillance, location of pollution sources using analysis from concentration gradients, and detection and mapping of chemical concentrations that are potentially harmful to people and/or destructive to agriculture.



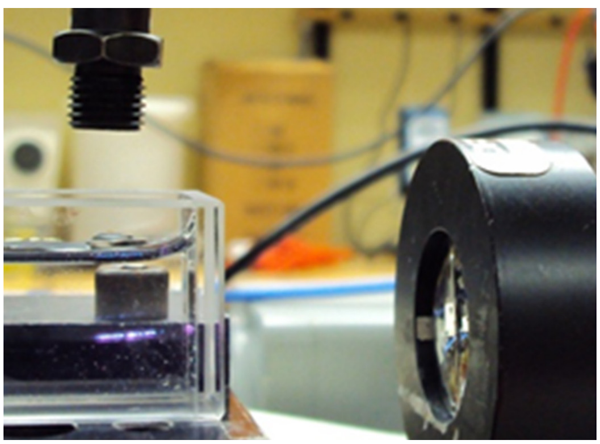
Wireless sensor node.

Wireless sensor probe.

Diagnostics and Sensor Applications

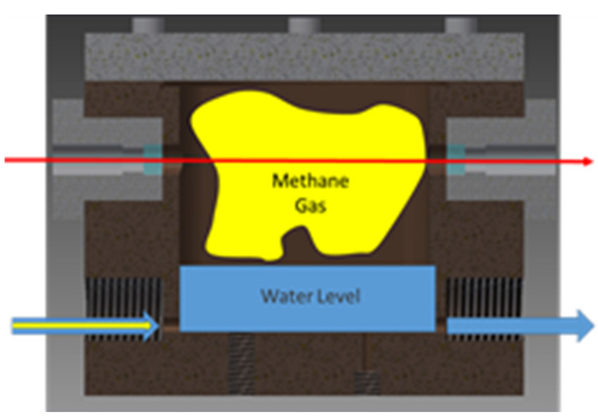
Performer	National Energy Technology Laboratory
Award Number	FWP 1022427 Task 3
Project Duration	01/01/2017 – 03/31/2018
Total Project Value	$ 660,000
Technology Area	Plant Optimization Technologies

The National Energy Technology Laboratory (NETL) will focus on applying recently developed, usually pre-commercial sensor systems, and developing and applying advanced diagnostics to fossil energy research. This project will include building the capability to apply tunable diode laser absorption spectroscopy in experimental research at NETL, with a short-term objective of applying the technique to measure bio-enhancement of methane production in a laboratory bench experiment simulating coal bed conditions. Also in this project, the NETL-developed Raman gas analyzer (RGA) will be used to support research in various NETL laboratories with the goal of gaining near-commercial application experience, thus helping to improve the RGA and support technology transfer. This project also includes development of laser induced breakdown spectroscopy for specialty fossil energy applications, including in-situ subterranean sensing. The task will help to strengthen NETL's core capabilities in diagnostics.



Laser induced breakdown spectroscopy.

Raman gas analyzer.



Tunable diode laser absorption spectroscopy applied to methane production measurement.

Systems Engineering & Analysis (SEA) Support for Sensors and Controls

Performer	National Energy Technology Laboratory
Award Number	FWP 1022427 Task 5
Project Duration	01/01/2017 – 03/31/2018
Total Project Value	$ 239,500
Technology Area	Plant Optimization Technologies

The National Energy Technology Laboratory will improve understanding of thermodynamic and environmental performance and economics of fossil energy power system technologies in order to guide R&D, reduce technical risks, and inform key stakeholders. This task includes model development and analyses of advanced fossil energy power system technologies focused on sensors and controls issues with respect to thermodynamic and environmental performance and economics. The work will entail modeling and simulation at the process-through-system-analysis scale, including both steady-state and dynamic approaches, as appropriate. Both commercial and advanced process technologies may be evaluated.

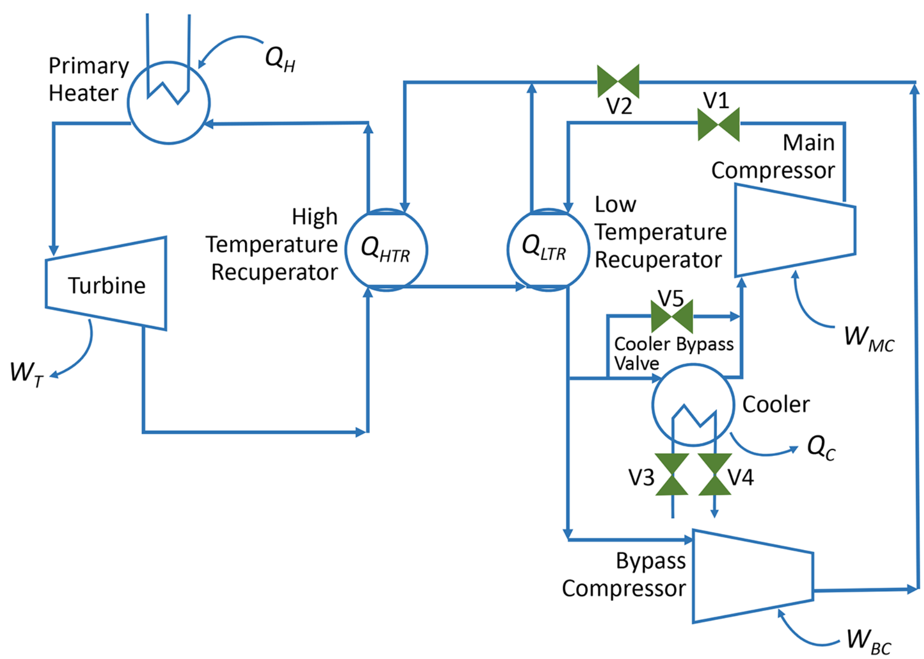


Diagram of an energy power system.

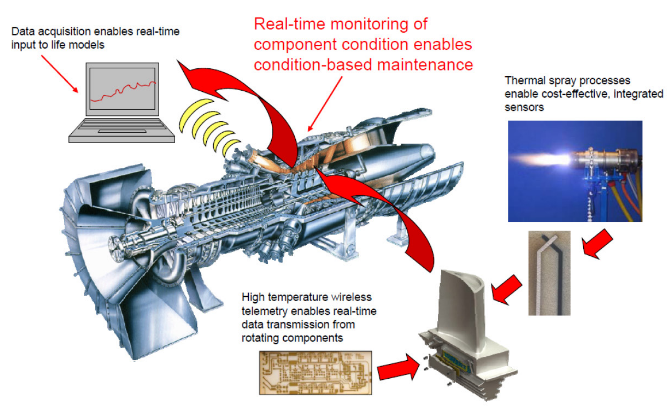
Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines

Performer	Siemens Corporation
Award Number	FE0026348
Project Duration	09/16/2015 – 08/31/2020
Total Project Value	$ 4,687,500
Collaborators	Arkansas Power Electronics International, Inc. and Siemens Energy, Inc.
Technology Area	Plant Optimization Technologies

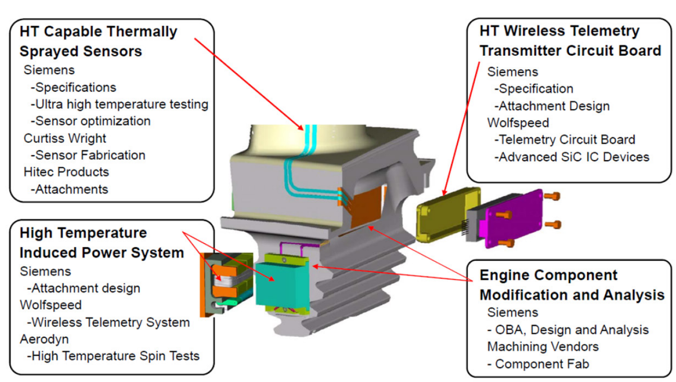
The objective of the program is to develop and engine-test hardware and software technologies that will enable active condition monitoring to be implemented on hot gas path turbine blades in large industrial gas turbines. The specific objectives are (1) to fabricate and install smart turbine blades with thermally sprayed sensors and high-temperature wireless telemetry systems in an H-class engine, (2) to integrate the component engine test data with remaining useful life (RUL) models and develop an approach for networking the component RUL data with Siemens' Power Diagnostics® engine monitoring system.

Phase 1 has focused on down-selection of novel chemistries for ceramic thermocouples with capability to withstand 1400 degrees Celsius (°C) up to 4000 hours, development of wireless telemetry system components, and demonstration of integrated sensor/wireless telemetry approach on a stationary lab test rig. Key successes from the Phase 1 effort include: (a) demonstration of ceramic thermocouples that showed ten-fold improvement in voltage output compared to metallic thermocouples (25 millivolts (mV) to 2.5 mV at 1200 °C), (b) development of a cutting-edge silicon carbide (SiC) integrated circuits operational amplifier-based system to perform analog signal conditioning of the sensor signal, which utilizes a closed-loop architecture to enable large, stable signal amplification across the range of operating temperatures, compared to previous open-loop architectures based around discrete SiC junction field effect transistors, which suffered from low gain that varied over temperature, (c) development of a new induced-power driver and receiver geometry capable of transferring 5 watts (W) of power over 17 millimeters, which constitutes an order-of-magnitude increase in power as compared to 0.5-1 W obtained from original designs, (d) improved wire-bond design capable of withstanding high centrifugal loading, and (e) successful lab test of the integrated sensor-wireless telemetry package on a gas turbine blade.

The advances in high-temperature wide-bandgap telemetry combine with the new geometry for an induced power driver and receiver to transmit digital data wirelessly. The current Phase 2 program will focus on validation testing of the sensor-wireless telemetry package in a spin rig and advanced operation-based assessment model utilizing artificial intelligence. Significant efforts will be expended on the application of the technology to components to be tested in an actual gas turbine engine for active condition monitoring using smart turbine blades.



Anatomy of a Smart Component.



Novel sensor's wireless telemetry system.

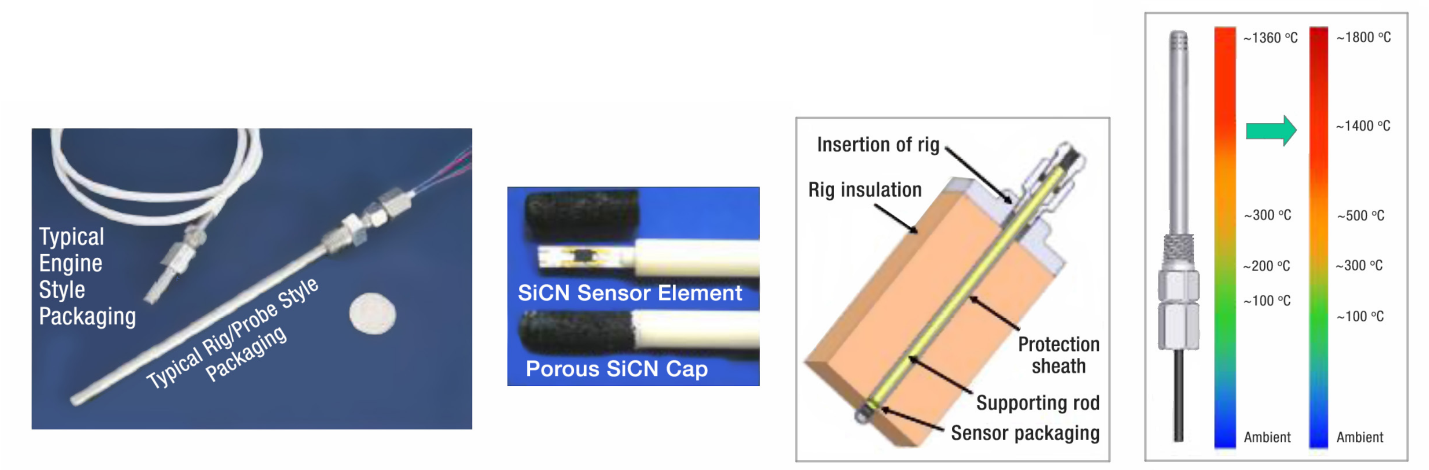
Advanced Ceramic Materials and Packaging Technologies for Realizing Sensors Operable in Advanced Energy Generation Systems

Performer	Sporian Microsystems, Inc.
Award Number	SC0008269
Project Duration	06/28/2012 – 08/13/2018
Total Project Value	$ 2,159,100
Technology Area	Plant Optimization Technologies

Sporian Microsystems, Inc. is developing ultra-high temperature smart sensors from silicon carbon nitride (SiCN) materials for use in energy generating and aerospace systems. The sensors will be developed via innovative fabrication processes and contain internal compensation, health check, and data bus support to the interface.

The project will be accomplished by building a sensor utilizing a class of high-temperature ceramic materials synthesized by thermal decomposition of polymeric precursors, which possess excellent mechanical properties up to 1800 degrees Celsius. In addition, the team will construct and fabricate designs for multiple sensors capable of bench- and pilot-scale operable demonstration-ready sensing.

Use of these sensors to continually monitor high-temperature systems should reduce system failure rates, improve contact, and reduce moisture collection with sensing at the source, resulting in an overall lower cost associated with system lifespan.



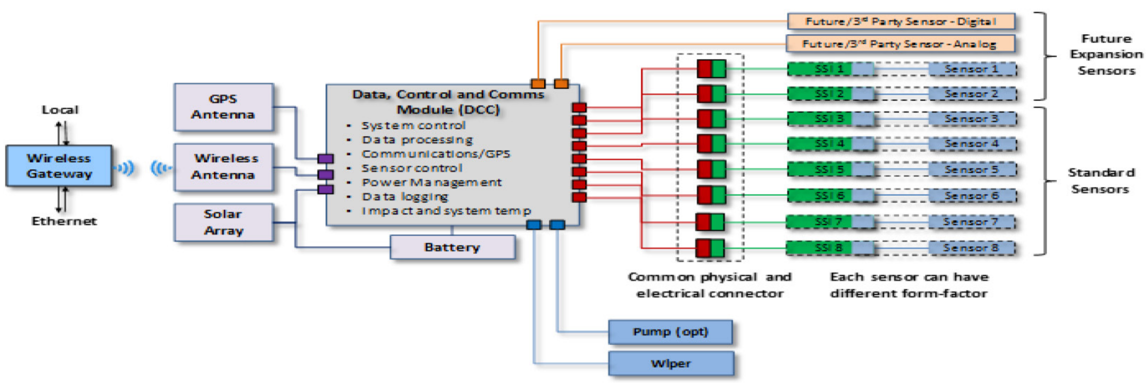
High temperature harsh environment packaging.

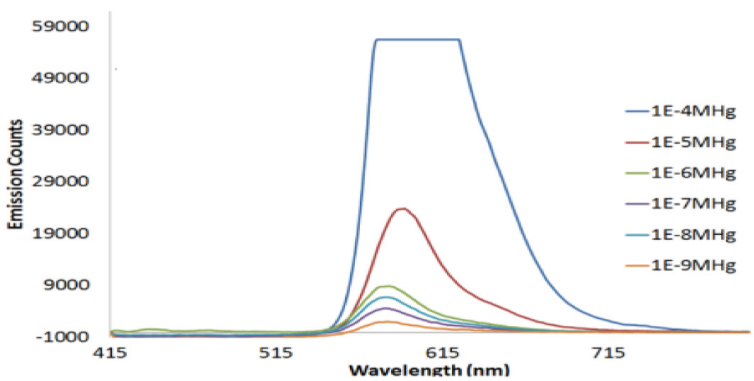
Integrated Sensors for Water Quality

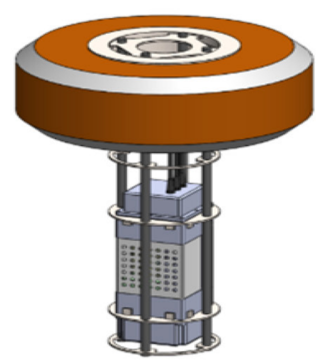
Performer	Sporian Microsystems, Inc.
Award Number	SC0013863
Project Duration	06/08/2015 – 07/31/2018
Total Project Value	$ 1,164,896
Technology Area	Plant Optimization Technologies

This Sporian Microsystems, Inc. project involves preparing, optimizing, and characterizing imprinted polymer (IP) systems, evaluating IP film fabrication methodologies, and experimentally evaluating/demonstrating IP sensing performance with Sporian's existing sensor system hardware. Sporian Microsystems will develop an integrated water sensor package that is low-cost, rapidly deployable, wireless, self-powered, and capable of relaying relevant in-situ water measurements in real-time.

This technology could support reducing or maintaining the water-use footprint in the energy sector, provide highly reliable real-time measurement-based data for water management, and be deployed at low cost. In addition, this technology could be highly attractive for monitoring sanitary water for consumption or processes that affect water use and require sensors for ensuring proper contamination monitoring and abatement, especially in the energy, industrial/agricultural, municipal drinking water, and wastewater monitoring sectors.







Top: System architecture.

Bottom left: Molecularly imprinted polymer signaling versus mercury concentration.

Bottom right: Buoy hardware design concept.

Adaptive Electrical Capacitance Volume Tomography for Real-Time Measurement of Solids Circulation Rate at High Temperatures

Performer	Tech4Imaging LLC
Award Number	SC0011936
Project Duration	06/09/2014 – 07/30/2019
Total Project Value	$ 2,159,964
Collaborator	Ohio State University
Technology Area	Plant Optimization Technologies

Tech4Imaging LLC will build a functional prototype of an adaptive electrical capacitance volume tomography (AECVT) system for gauging the mass flow of solids circulating in high-temperature (greater than 750 degrees Celsius) environments. AECVT is a newly developed technology that can provide three-dimensional imaging of multiphase flow behavior in real time. Devices that can accurately measure the solids flow rate of an operating gas-solid system would be of great value for optimizing and controlling combustion processes in advanced reactors. Presently, the availability of such devices, particularly at high temperatures, is very limited. This Phase II effort will result in a functional prototype of an AECVT system for gauging the mass flow of solids circulating at high temperatures. The intrinsic high speed of the capacitance measuring technology and high-resolution capability of AECVT technology will enable mass-flow measurements at 5 percent spatial and 1 hertz temporal resolutions. Simulation and preliminary measurement results verified the feasibility of the AECVT architecture during Phase I. Capacitance sensors exhibit good safety, flexibility, and suitability for scale-up that make them advantageous for industrial applications. Phase II tasks will focus on optimizing sensors, electronic hardware, and feature extraction software for hot-flow applications based on AECVT technology. Tasks are based on logical progressions from past experience of developing imaging systems.

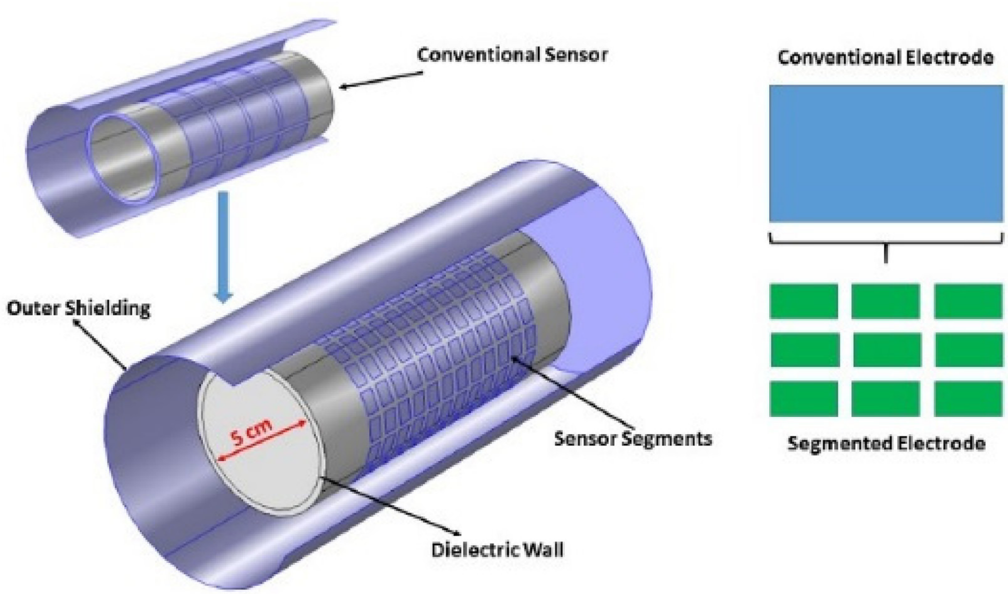


Illustration of AECVT system.

Successful completion of Phase II will provide a prototype of an AECVT system for high-temperature applications in the harsh conditions of reactors that can be extended to many energy-related applications. A logical progression from Phase I to Phase II has been established in which Phase II efforts are focused on implementing Phase I designs that proved feasible. The proposed system would also advance multi-phase flow research of hot systems by providing access to obscure locations within a flow system. The system has a very high potential of attracting commercial interest as the need for advanced instrumentation to address the greater sophistication of advanced power plants becomes critical. This technology would benefit the public by spurring economic growth.

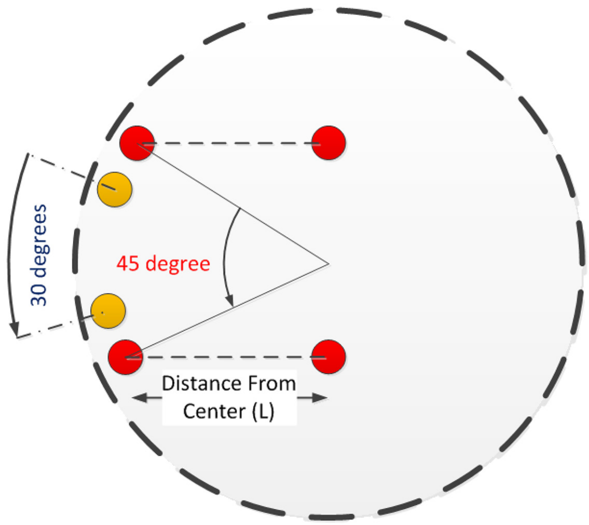


Illustration of simulation setup for AECVT enhanced resolution.

A demonstration of the AECVT advantages over conventional electrical capacitance volume tomography (ECVT) technology is illustrated in a set of simulations of objects at different locations inside the imaging domain.

The imaging resolution for the conventional 12 electrode ECVT sensor and the adaptive sensor is compared in the following:

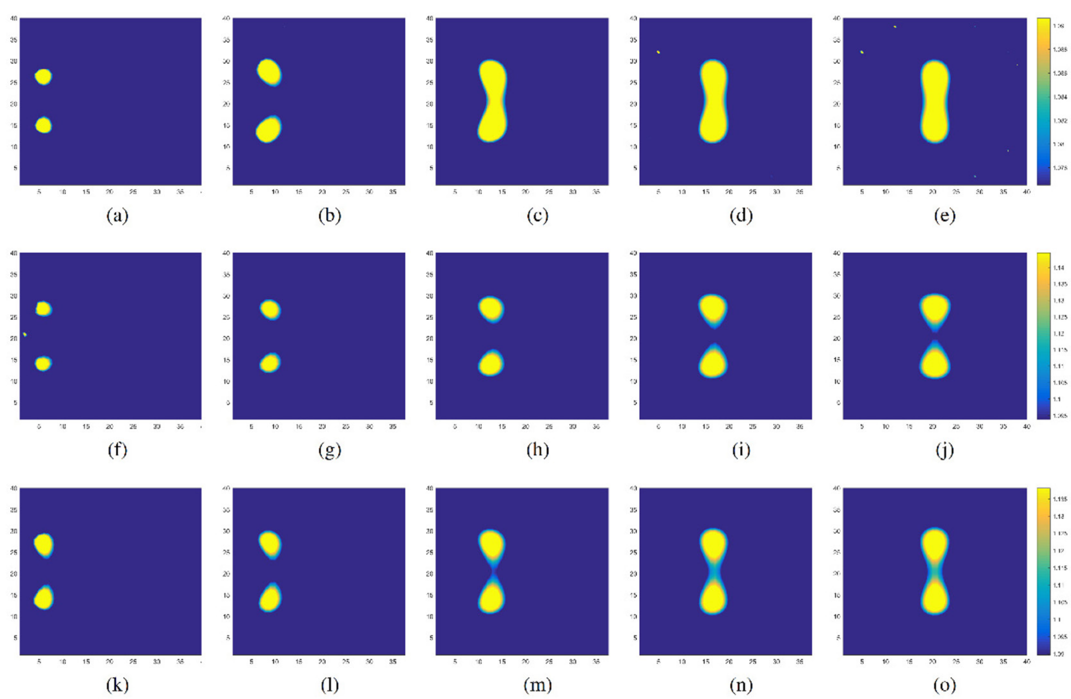


Image reconstruction results for two nearby spherical dielectric objects, placed at different locations inside the imaging domain with initial subtended angle equal to 45 degrees as depicted in figure above. (a-e) Results using conventional ECVT with 12 fixed electrodes (no electronic scanning). (f-j) show AECVT results with synthetic electrode scanning by combining 3 segments. (k-o) AECVT results with synthetic electrode scanning by combining 4 segments.

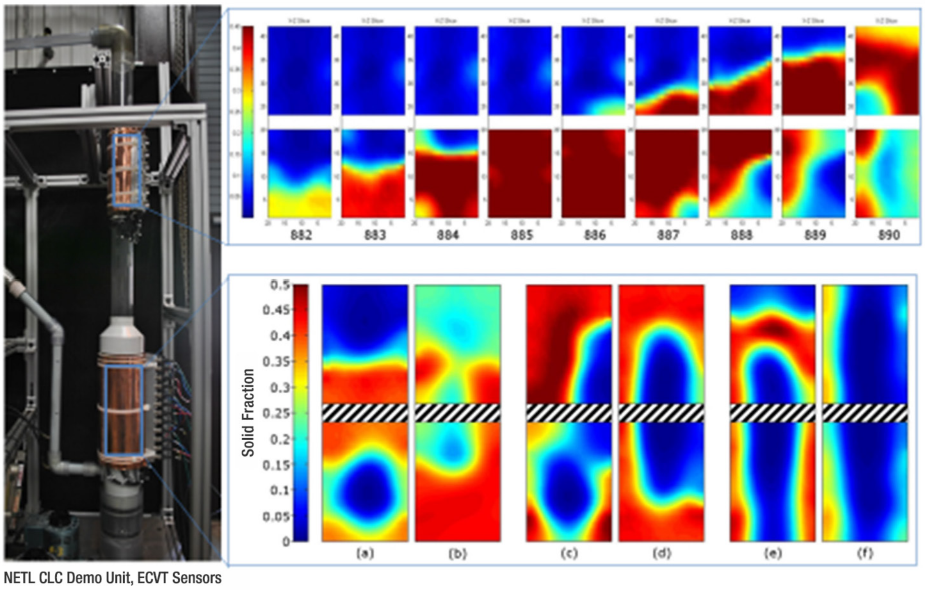
Real-Time 3D Volume Imaging and Mass-Gauging of High Temperature Flows and Power System Components in a Fossil Fuel Reactor Using Electrical Capacitance Volume Tomography

Performer	Tech4Imaging LLC
Award Number	SC0010228
Project Duration	06/10/2013 – 07/30/2019
Total Project Value	$ 2,149,686
Collaborator	Ohio State University
Technology Area	Plant Optimization Technologies

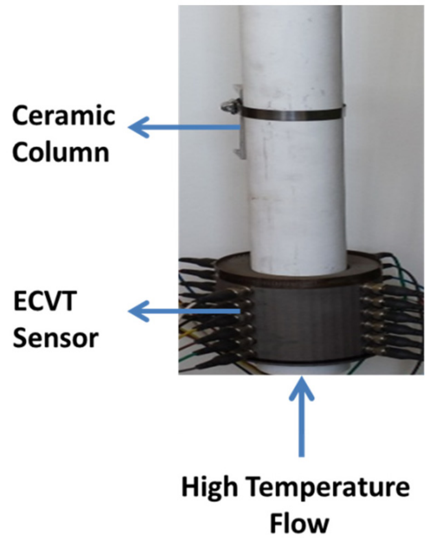
Controlling emissions and increasing efficiencies are essential requirements of future advanced power plants. Next-generation power systems require greater operating flexibility to simultaneously achieve the higher efficiency and lower emissions requirements geared toward meeting consumer demand and increased regulatory standards. These requirements can be met by developing non-invasive imaging systems that can reveal details of combustion and power-generation flow systems that are useful to their optimization.

In this Phase II effort, Tech4Imaging is developing an electrical capacitance volume tomography (ECVT) system to image flow variables in flow systems. Capacitance sensors exhibit good safety, flexibility, and suitability for scale-up that make them advantageous for industrial applications. The Phase I effort established the feasibility of using capacitance sensors for imaging flow variables under the harsh conditions typical in power-generation systems. Capacitance sensors were tested at high temperatures, and materials for designing ECVT sensors for harsh environments were devised. Chambers for imaging flames and combustion particles were constructed and used for testing ECVT sensors. A mass-gauging method to measure mass flows of process variables in real time was also devised. Phase I results were used to develop a full ECVT system for use in power-generation systems operating at high temperature. Phase II efforts are focused on optimizing sensors, electronic hardware, and feature extraction software for hot flow applications.

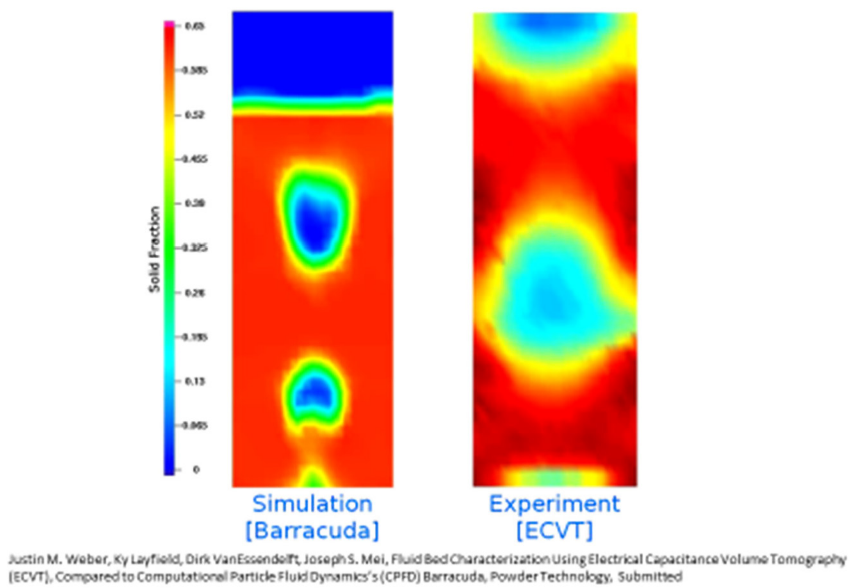
This project could provide significant public benefit due to the potential of this technology for helping the energy industry increase efficiencies and reduce emissions. The proposed system would also advance multi-phase flow research of hot systems by providing access to obscure locations within a flow system.



Four- and two-inch sensors chemical looping combustion demo.



ECVT sensor.



Computational fluid dynamics comparison (10-centimeter diameter fluid bed, 200-micron glass beads, 52 frames per second).

Continuous Water Quality Sensing for Flue Gas Desulfurization Wastewater

Performer	University of Alabama at Birmingham
Award Number	FE0027778
Project Duration	08/01/2016 – 01/31/2018
Total Project Value	$ 439,986
Collaborator	Southern Research
Technology Area	University Training and Research

The overall goal of this project is to develop an integrated water sensor package for continuous water quality monitoring of flue gas desulfurization (FGD) wastewaters to include concentration measurements of multiple contaminants (e.g., trace metals: selenium, arsenic, and mercury) and measurement of common water quality indicators (e.g., pH, total dissolved solids).

The proof-of-concept prototype will successfully demonstrate the key features of the technology through on-site processing of FGD wastewater including reliable in-field automated operation for extended periods (i.e., one week); accurate trace metal detection (i.e., selenium, arsenic, and mercury) using a proprietary FGD sample preparation technique; low cost, small footprint detection with a commercial off-the-shelf (COTS) voltammetry device, parts per trillion (ppt) limit of detection/qualification; continuous monitoring with high sampling frequency (more than one measurement per hour for trace metals); integration of COTS water quality indicators (pH, total dissolved solids); and wireless transmission of measurements to an on-site control room.

The project comprises three phases: Phase I Development of Sample Preparation Batch Process; Phase II Design and Development of Continuous Sample Preparation Prototype; and Phase III Demonstration Unit Integration and Field Testing. The resulting demonstration unit will be used for extended in-field testing at a coal-fired power plant at a partner's site and will be validated for accuracy and reliability through comparison with the gold-standard analysis method provided by onsite inductively coupled plasma mass spectrometry analysis.

Anticipated project benefits include (1) ability to monitor and detect contaminant concentration levels in FGD wastewater discharge in coal-fired power plants; (2) reduction in recurring operating and off-site laboratory analysis costs by minimizing required FGD wastewater treatment reagents and equipment; and (3) closed-loop control of contaminant concentrations in effluent discharge resulting in a high level of confidence of compliance with Environmental Protection Agency discharge guidelines.

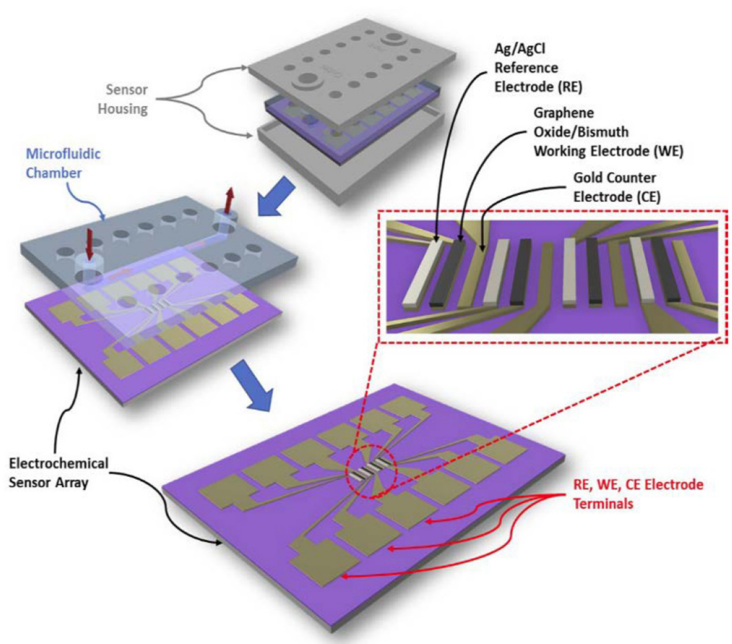
Multi-phase approach.

Applying Anodic Stripping Voltammetry to Complex Wastewater Streams for Rapid Metal Detection

Performer	University of California at Los Angeles
Award Number	FE0030456
Project Duration	08/01/2017 – 07/31/2020
Total Project Value	$ 400,000
Collaborator	Regents of the University of California at Riverside
Technology Area	University Training and Research

This project's objective is to develop a lab-on-a-chip (LOC) electrochemical sensor capable of accurately measuring heavy metal concentrations, including lead (Pb), cadmium (Cd), and arsenic (As), in complex aqueous streams such as wastewater. The sensor technology relies on anodic stripping voltammetry (ASV), which has been demonstrated to detect extremely low (sub parts-per-million) concentrations of these metals. The technology will be capable of autonomously conducting metal measurements and report the findings remotely via cellular technology. Furthermore, using open-source hardware and software tools, the project team will construct sensor technology that operates with minimal human intervention and is capable of autonomously performing all of the pre-treatment steps needed to perform metal measurement activities. To accomplish this objective, the project team will concentrate on characterizing metal speciation in wastewater, develop appropriate pre-treatment methods that will allow analysis of this complex matrix on an LOC device, fabricate a range of electrodes specifically tailored to enhance the detection of the target metals, and finally, construct and test an autonomous LOC device that incorporates the pre-treatment steps and specialized electrodes for the detection of heavy metals in wastewater.

All pre-treatment steps will be integrated into the fully automated LOC device, which will conduct the metal analysis without the need for human intervention beyond periodically re-filling reagent reservoirs. Current heavy metal measuring methods are time-consuming and rely on grab sampling and expensive analytical instruments. Thus, the proposed technology would decrease costs and increase the frequency of measurements, enabling heavy metal contamination to be detected in near real time.



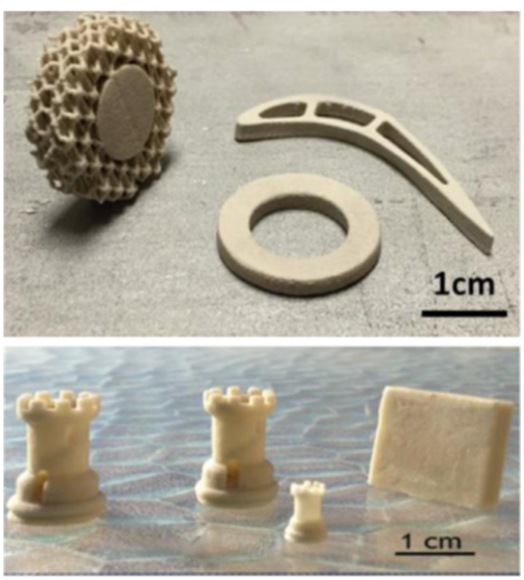
Schematic of electrochemical sensor arrays microanalyzer system.

Additive Manufacturing of Energy Harvesting Material System for Active Wireless Microelectromechanical Systems (MEMS) Sensors

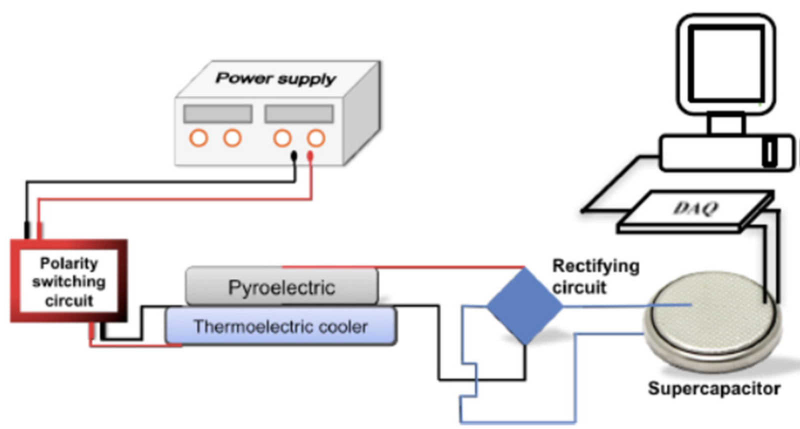
Performer	University of Texas at El Paso
Award Number	FE0027502
Project Duration	09/01/2016 – 08/31/2019
Total Project Value	$ 250,000
Technology Area	University Training and Research

University of Texas at El Paso will design, fabricate, and evaluate an energy harvesting material system capable of working at up to 1200 degrees Celsius to harvest both vibrational and thermal energy for powering high-temperature wireless MEMS sensors. This project will establish theoretical models to predict the effective material property, fabricate ceramic-graphene composites using the binder jetting three-dimensional (3D) printing technique, and determine mechanical, thermal, and simultaneous energy harvesting properties at high temperatures.

This project will provide a full knowledge set of graphene/lithium niobate crystal modeling, 3D printing fabrication, characterization, and energy harvesting potential. Findings could lead to a new energy harvesting material design paradigm for powering wireless harsh environment MEMS sensors.



Fabrication of complex shapes.



Thermal energy harvesting setup.

Conceptual diagram of the proposed supercritical extracted water desalination and energy generation system.

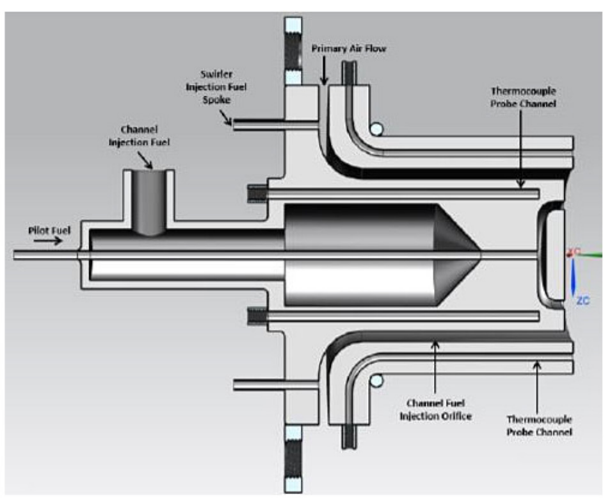
Metal Three Dimensional (3D) Printing of Low-Nitrous Oxide (NO_X) Fuel Injectors with Integrated Temperature Sensors

Performer	University of Texas at El Paso
Award Number	FE0026330
Project Duration	10/01/2015 - 09/30/2018
Total Project Value	$ 250,000
Technology Area	University Training and Research

This project explores design and prototyping of a dry low-nitrogen-oxides (low-NO_X; DLN) fuel injector with integrated temperature sensing capabilities using the electron beam melting (EBM) additive manufacturing (AM) process. Low-NO_X natural gas fuel injectors, commonly used in DLN gas turbine combustors, have complex internal cavities and passages to ensure tailored mixing of air and fuel to achieve ultra-low levels of NO_x emissions. Since the current design methodology of these injectors is based on conventional fabrication techniques (i.e., multi-step machining and welding processes), a new design methodology paradigm must be developed to adapt them to the electron beam melting (EBM) fabrication process.

The proposed effort has three specific objectives: (1) development of design methodologies for low-NO_x fuel injectors with embedded temperature sensing capabilities for EBM-based three-dimensional manufacturing; (2) development of optimum EBM process parameters and powder removal techniques to remove sintered powder from internal cavities and channels of low-NO_x fuel injectors with embedded temperature sensors; and (3) testing of the EBM fabricated low-NO_x fuel injector with integrated temperature measurement capabilities in a high-pressure laboratory turbine combustor.

Metal AM processes enable embedding or integrating sensors into complex energy system components without post-production modification of the component. Conventional manufacturing processes generally require more than five steps of fabrication, assembly, and finishing to develop energy system components such as fuel injectors with complex internal geometries. In contrast, the same part can be fabricated in a single metal AM step with the option of sensor integration and more complex internal geometries.



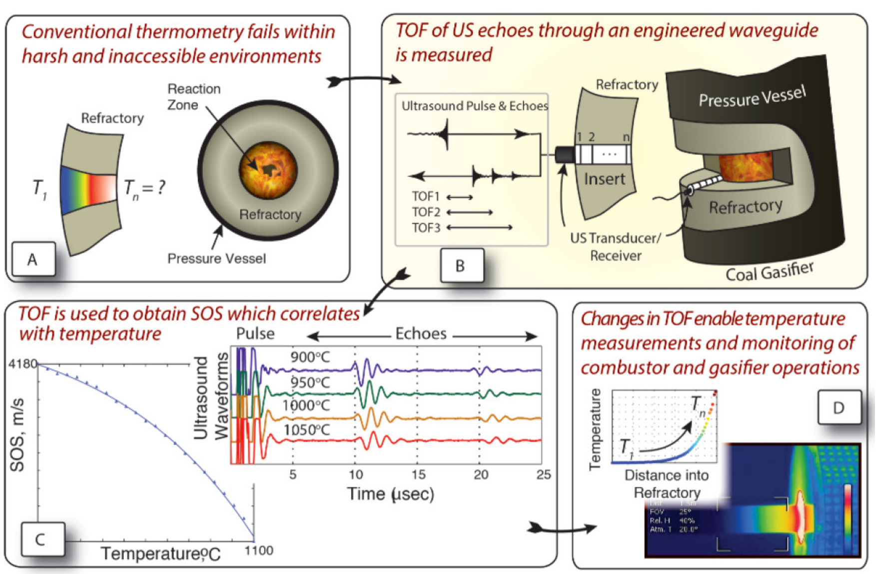
Test article to be designed and fabricated: DLN fuel injector with integrated ceramic insulated high temperature thermocouples.

Ultrasonic Measurements of Temperature Profile and Heat Fluxes in Coal-Fired Power Plants

Performer	University of Utah
Award Number	FE0031559
Project Duration	01/01/2018 – 12/31/2020
Total Project Value	$ 625,000
Technology Area	Plant Optimization Technologies

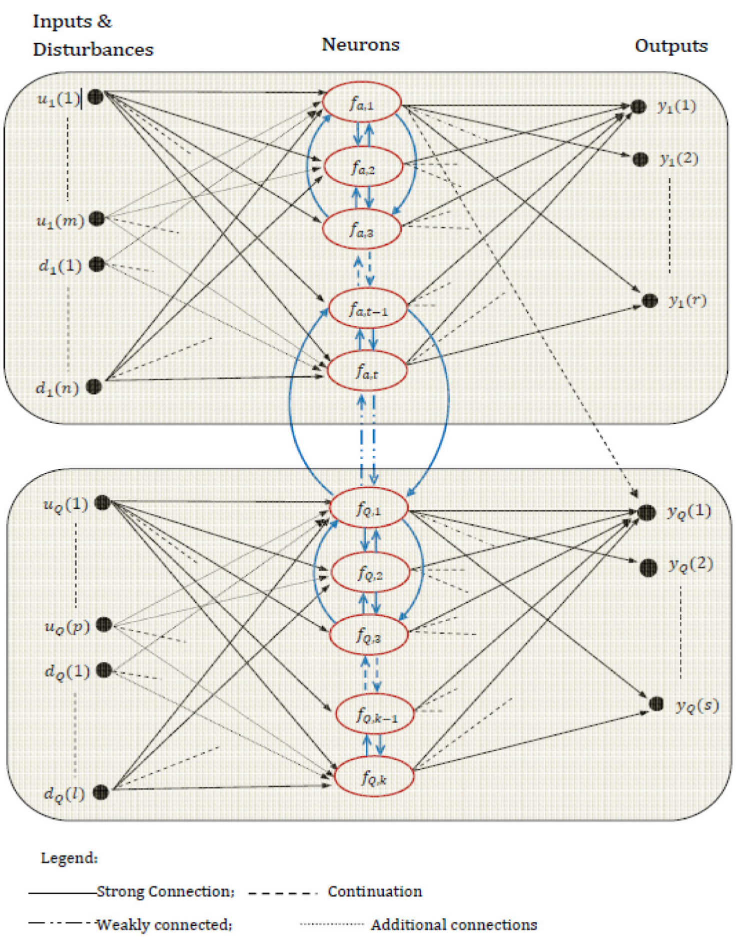
The objective of this project is to develop a prototype multipoint ultrasound measurements of segmental temperature distribution (US-MSTD) method by refining the existing implementation and evolving its capabilities to measurements at multiple locations, across several zones, and the characterization of soot and other deposits. The implementation of the US-MSTD method with metal waveguides is particularly appealing as a step towards the applications in measuring temperature distribution along steam tubes and other metal components of utility and industrial boilers. Refinements of the prototype US-MSTD system with its new features and capabilities will be validated through multiple tests in an iterative progression from laboratory experiments to testing at the pilot scale and with large utility boilers at the Hunter Power Plant.

Measurement of temperature profiles in different combustion zones and components of utility boilers with high accuracy (within 1 to 10 degrees Celsius, comparable to high-velocity thermocouple measurements) and sampling rates (100 hertz); lower uncertainty than infrared and acoustic pyrometry measurements; robust continuous availability; scalability to multiple measurement locations; and lower cost are achieved by multiplexing instrumentation across a large number of measurement locations. By overcoming limitations of currently available alternatives, the US-MSTD will present an economic and scalable option for management and control to optimize the efficiency of current and future fossil power systems. An improved real-time characterization of temperatures is particularly important in controlling load following in operating power plants, efficiency optimization during flexible operation (startup, shut-down, cycling), and proper management and protection of the boiler and entire steam circuit.



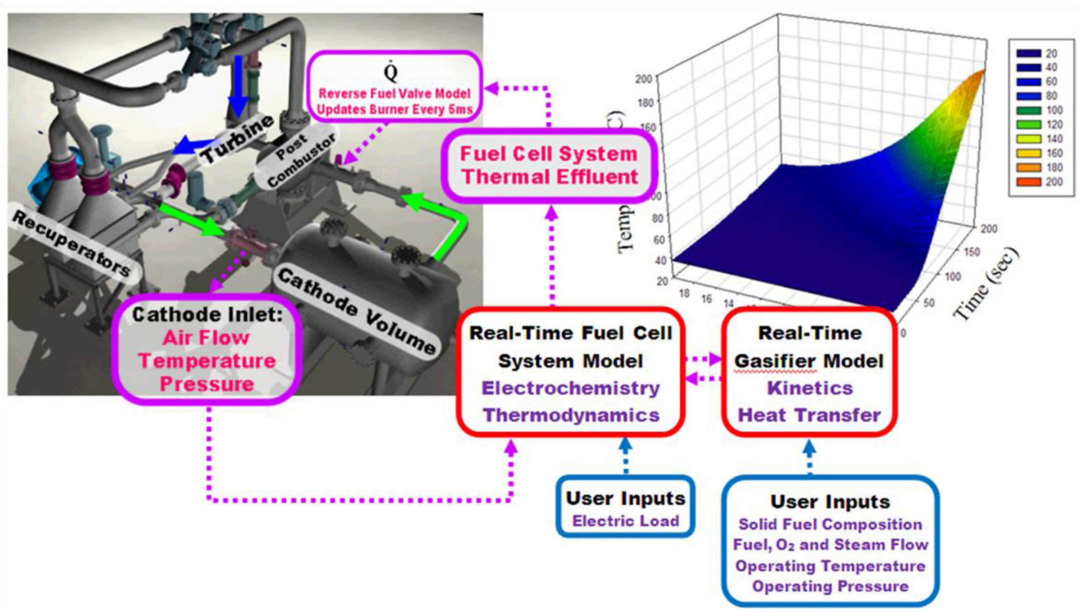
Changes in time of flight (TOF) and temperature measurements and monitoring of combustor and gasifier operations.

DISTRIBUTED INTELLIGENT CONTROLS



ADVANCED PROCESS CONTROL

Dynamic process modeling encompasses computational efforts to represent physical systems and processes by developing and implementing high-fidelity models using real-time data as input. For the purposes of control, these high-fidelity models are reduced and configured to run in real time (second time scales) to represent the dynamics of the operating system. Using reduced and speedy models in conjunction with estimation algorithms and other types of predictive algorithms, an overall control solution can be derived to enable model-based control to be used for real-time process control. This general approach is well understood for linear and steady-state systems. Research within the Sensors & Controls key technology area adopts this approach but augments it with new ones for developing control systems with fast dynamics for nonsteady states and incorporates controls that are capable of handling systems that are inherently nonlinear. These developments, with real system validation, provide significantly better control compared with that of traditional proportional-integral-derivative control and are more robust than linear model predictive control algorithms.



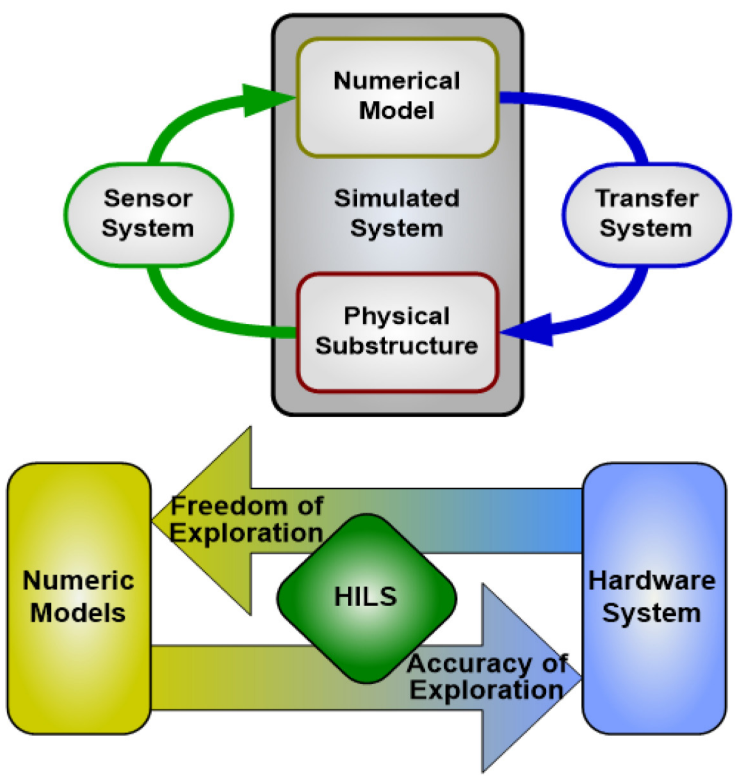
PERFORMER	PROJECT TITLE	PAGE
Georgia Tech Research Corporation	Expedited Real Time Processing for the NETL Hyper Cyber-Physical System	51
Georgia Tech Research Corporation	Real-Time Health Monitoring for Gas Turbine Components Using Online Learning and High Dimensional Data	52
Microbeam Technologies, Inc.	Improving Coal Fired Plant Performance Through Integrated Predictive and Condition-Based Monitoring Tools	53
National Energy Technology Laboratory	Advanced Controls Development	54
Ohio State University	Advanced Control Architecture and Sensor Information Development for Process Automation, Optimization, and Imaging of Chemical Looping Systems	55
West Virginia University Research Corporation	Development of Integrated Biomimetic Framework with Intelligent Monitoring, Cognition and Decision Capabilities for Control of Advanced Energy Plants	56

Expedited Real Time Processing for the NETL Hyper Cyber-Physical System

Performer	Georgia Tech Research Corporation
Award Number	FE0030600
Project Duration	08/01/2017 – 07/31/2020
Total Project Value	$ 504,130
Technology Area	Plant Optimization Technologies

The primary objective of the proposed project is to provide the National Energy Technology Laboratory's Hybrid Performance (Hyper) Facility the needed numerical methods algorithm(s), software development and implementation support to enact real time cyber-physical systems that simulate process dynamics on the order of five milliseconds or smaller. The proposed paths forward comprise three distinct approaches to faster transient simulations. They fall under the numerical methods categories of (1) optimizing key parameters within the facility's present real-time processing scheme; (2) introducing an "informed" processing approach wherein a priori computations expedite real-time attempts; and (3) implementing alternatives to the presently employed explicit-implicit blended finite difference (spatio-temporal) approach. Although each of these three classes will be attempted independently as options for improvement, in some cases one may complement another.

The three approaches provide individual paths that will expedite critical computational steps. They are also anticipated to have points of compatibility to synergistically speed processing. Achieving the five-millisecond time-step threshold for the pioneering Hyper cyber-physical system would afford dynamic operability studies that capture higher-time-resolution phenomena (e.g., electrochemical-fluidic dynamics) at the full response capability of the Hyper system.

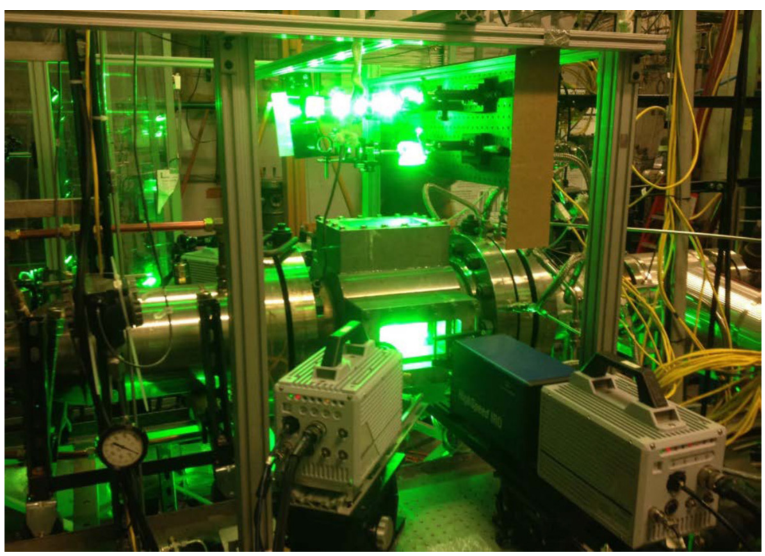


Cyber-physical simulation.

Real-Time Health Monitoring for Gas Turbine Components Using Online Learning and High Dimensional Data

Performer	Georgia Tech Research Corporation
Award Number	FE0031288
Project Duration	10/01/2017 – 09/30/2020
Total Project Value	$ 750,297
Technology Area	Advanced Turbines

The Georgia Tech Research Corporation will use two industry-class gas turbine component test rigs to generate first-of-its-kind data for critical gas turbine faults with varying severity levels. These gas turbine test facilities will be examined using instrumentation techniques to build an open data collection that will support predictive algorithm development for combustors and turbines. The test conditions in the two test facilities will include common critical events that occur in the operation of power plants. The data will be correlated with physics-based models and first-principle relationships to improve component life predictions. Additionally, a comprehensive big data analytics methodology will be developed, guided by the generated experimental data, industrial data from collaborators, and physics-based models with engineering domain knowledge. The effort will leverage existing research facilities that will generate the first publicly available data with simulated combustor and turbine faults.



Over-instrumented blowout experiment in optically accessible combustion test rig at Georgia Tech.

Improving Coal Fired Plant Performance Through Integrated Predictive and Condition-Based Monitoring Tools

Performer	Microbeam Technologies, Inc.
Award Number	FE0031547
Project Duration	01/01/2018 – 12/31/2020
Total Project Value	$ 1,822,490
Technology Area	Advanced Combustion Systems

Microbeam Technologies Inc. aims to demonstrate coal-fired power plant boiler performance and reliability improvements using condition-based monitoring. The approach develops a tool that includes Combustion System Performance Indices (CSPI) and CoalTracker (CT) programs, which alert plant operators and engineers about poor boiler conditions. The goal is to integrate the operations of the CSPI-CT into plant control systems and plant operating parameters. These improvements will potentially allow automation of coal selection and blending, and improve the efficiency and long-term reliability of coal plants. Project tasks include: CSPI-CT and sensor installation and shakedown; database development and software training; neural network correlation integration; field testing; and validation of performance improvements. The effort will culminate with installing and testing a beta version of the CSPI-CT program in a coal plant.

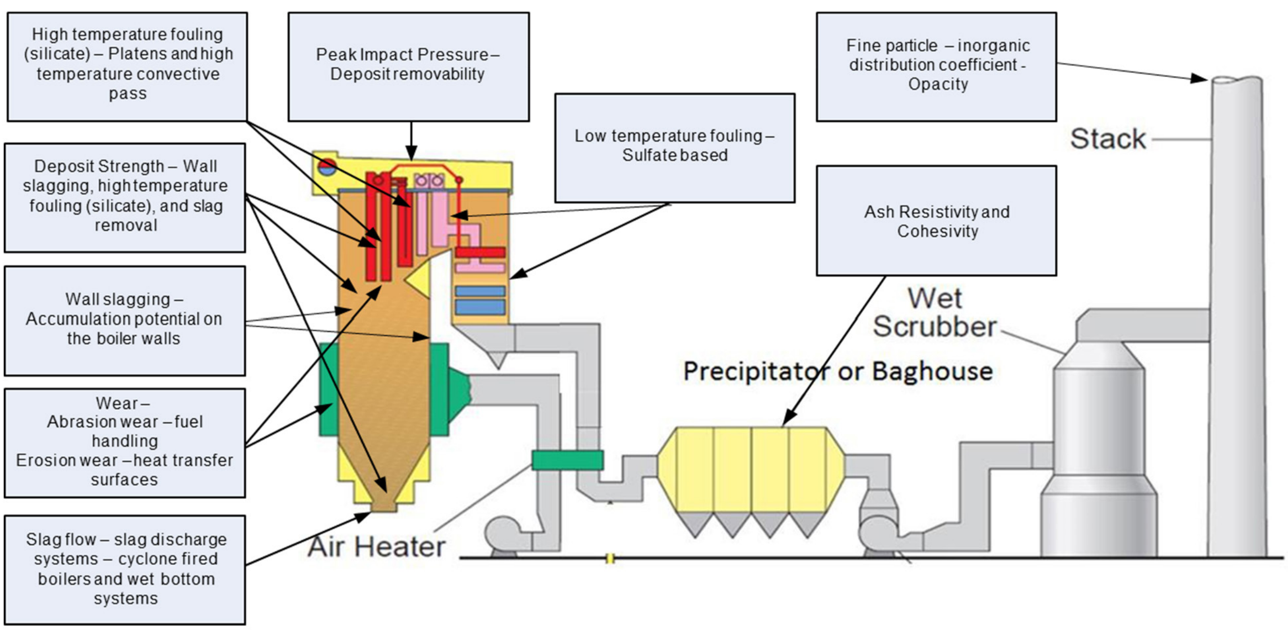
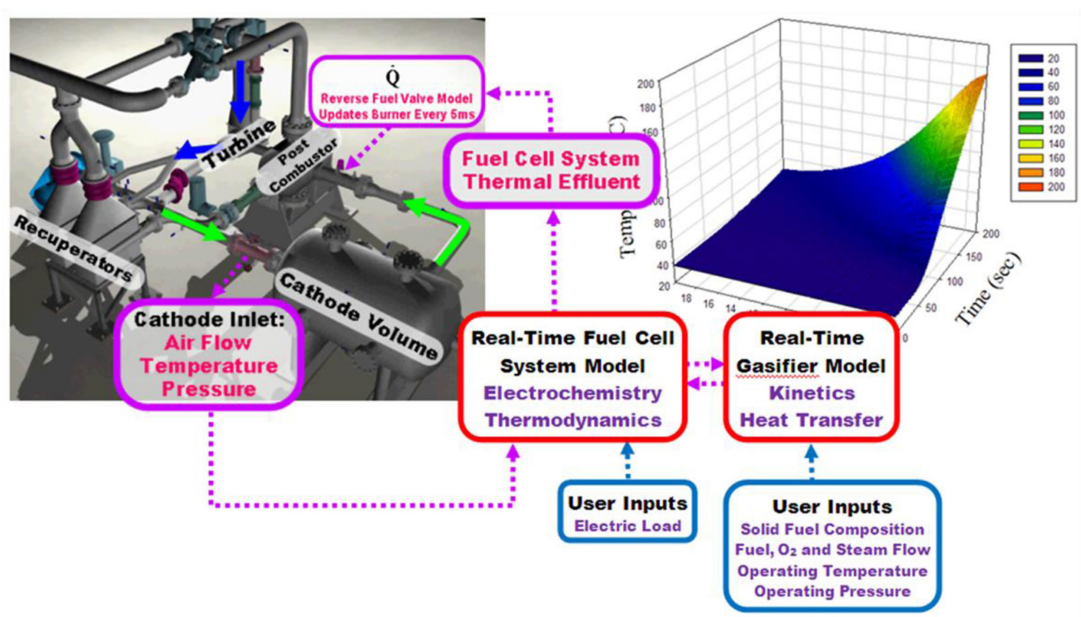


Illustration of coal quality management system fireside performance indices.

Advanced Controls Development

Performer	National Energy Technology Laboratory
Award Number	FWP 1022427 Task 4
Project Duration	01/01/2017 – 03/31/2018
Total Project Value	$ 305,376
Technology Area	Plant Optimization Technologies

The objective of this National Energy Technology Laboratory effort is to develop and test advanced controls for highly-coupled advanced power generation systems, which are often plagued with non-linear actuator response. This project will include the evaluation of novel control strategies and development of system identification methods through cyber-physical simulation. The more general concept of cyber-physical simulation of power systems applied to technology development and control applications will be explored longer term.



Hybrid Performance Facility technical operations illustration.

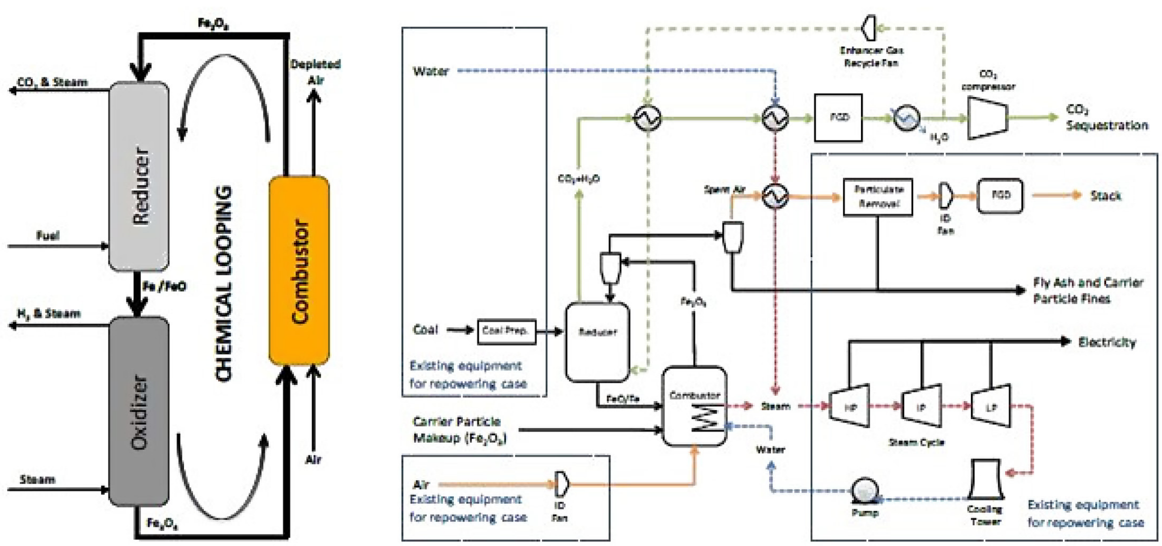
Advanced Control Architecture and Sensor Information Development for Process Automation, Optimization, and Imaging of Chemical Looping Systems

Performer	Ohio State University (OSU)
Award Number	FE0026334
Project Duration	09/11/2015 – 02/28/2018
Total Project Value	$ 1,400,000
Collaborators	Tech4Imaging LLC and The Babcock and Wilcox Company
Technology Area	Coal Utilization Sciences

The goal of this project is to develop advanced autonomous control architecture and imaging and optimization sensor information for the Ohio State University chemical looping processes. To automate these dynamic, nonlinear systems, a hybrid controller consisting of decision making and controller-selection logic (high-level controller) integrated with sliding mode controllers will be used to develop a distributed intelligence automation scheme for the chemical looping process startup and shutdown.

The intelligent process automation controller and optimization software will be tested in OSU's existing sub-pilot chemical looping test unit, and potentially integrated with the pressurized syngas chemical looping (SCL) pilot test unit constructed at the National Carbon Capture Center. In addition, electrical capacitance volume tomography sensor software will be developed to image oxygen carriers in the riser section and dense moving bed standpipe at operating temperature (greater than 900 degrees Celsius). The imaging sensor software will be tested and verified in an existing bench test apparatus.

Chemical looping is considered a near-term technology with the potential to efficiently and economically capture carbon dioxide (CO_2) for power and chemical plant applications. The OSU coal direct chemical looping (CDCL) and SCL processes represent advanced energy systems for converting solid and gaseous fuels, respectively, to hydrogen and heat with in-situ CO_2 capture. The successful development will increase the operational reliability and efficiency of the chemical looping technologies. The work is scalable for larger demonstration units and will impact both the CDCL and SCL processes as the control scheme and sensor measurements used on each system is nearly identical. Therefore, the developed automation concept and process optimization and imaging software for the SCL process can be directly applied to the CDCL system.

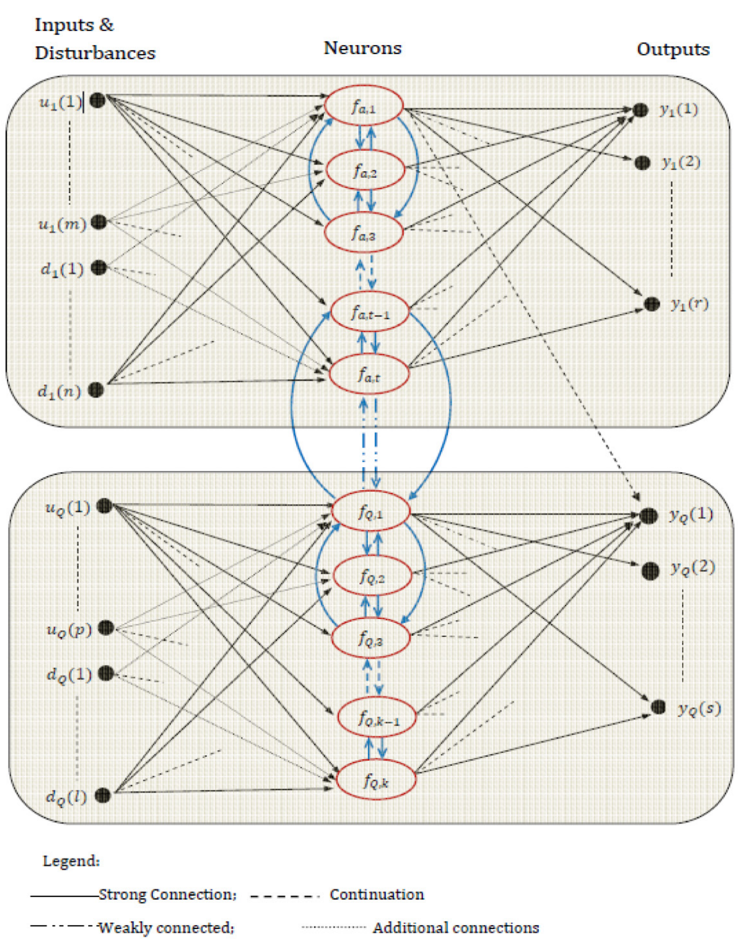


OSU chemical looping process concept (left) and the commercial-scale CDCL process flow diagram concept for power generation (right).

Development of Integrated Biomimetic Framework with Intelligent Monitoring, Cognition and Decision Capabilities for Control of Advanced Energy Plants

Performer	West Virginia University Research Corporation
Award Number	FE0012451
Project Duration	01/15/2014 – 01/14/2018
Total Project Value	$ 1,403,611
Collaborator	Vishwamitra Research Institute
Technology Area	Plant Optimization Technologies

The objective of this research is to develop algorithms and methodologies for designing biomimetic control systems that utilize distributed intelligence for optimal control of advanced energy plants. Through a transformative biomimetic framework, West Virginia University Research Corporation in collaboration with Vishwamitra Research Institute will develop computational techniques to accomplish: (i) self-organization of control structure, (ii) distributed, adaptive, and intelligent control with cognition and decision capabilities, and (iii) seamless coordination and integration among different components of the control system by leveraging a highly interacting, multi-agent framework.



Self-organizing, biometric control structure selection.

ABBREVIATIONS

°C . . . . degrees Celsius

3D . . . . three-dimensional

AECVT . . . . adaptive electrical capacitance volume tomography

AM . . . . additive manufacturing

ASV . . . . anodic stripping voltammetry

CDCL . . . . coal direct chemical looping

ChemFET . . . . chemical field effect transistor

CO_2 . . . . carbon dioxide

COTS . . . . commercial off-the-shelf

CSPI . . . . combustion system performance indices

CT . . . . CoalTracker

CW . . . . continuous-wave

DLN . . . . dry low-nitrogen-oxides

DOE . . . . Department of Energy

EBM . . . . electron beam melting

ECVT . . . . electrical capacitance volume tomography

FE . . . . fossil energy

FGD . . . . flue gas desulfurization

H_2 . . . . hydrogen

HBCU . . . . Historically Black Colleges and Universities

HT . . . . high temperature

Hyper . . . . Hybrid Performance Facility

IP . . . . imprinted polymer

LGS . . . . langasite

LM . . . . laser micromachining

LOC . . . . lab-on-a-chip

MEMS . . . . microelectromechanical systems

mm . . . . millimeter

mV . . . . millivolts

NETL . . . . National Energy Technology Laboratory

ABBREVIATIONS

NGO . . . . . non-governmental organizations

NO_x . . . . . nitrogen oxides

O_2 . . . . . oxygen

OMI . . . . . Other Minority Institutions

OSU . . . . . Ohio State University

pH . . . . . power of hydrogen (measure of acidity)

ppt . . . . . parts per trillion

R&D . . . . . research and development

RGA . . . . . Raman gas analyzer

RUL . . . . . remaining useful life

SAW . . . . . surface acoustic wave

SBIR . . . . . Small Business Innovative Research (program)

SCL . . . . . syngas chemical looping

SEA . . . . . Systems Engineering & Analysis (NETL program)

SiC . . . . . silicon carbide

SiCN . . . . . silicon carbon nitride

SOFC . . . . . solid oxide fuel cells

SPS . . . . . spark plasma sintering

TBC . . . . . thermal barrier coating

TOF . . . . . time of flight

U.S. . . . . . United States

UCR . . . . . University Coal Research (NETL program)

US-MSTD . . . . . ultrasound measurements of segmental temperature distribution

UTR . . . . . University Training and Research (NETL program)

W . . . . . watt

WVU . . . . . West Virginia University

CONTACTS

Briggs White

Technology Manager

412-386-7546

Briggs.White@netl.doe.gov

Patricia Rawls

Supervisor

Enabling Technologies and Partnerships Team

412-386-5882

Patricia.Rawls@netl.doe.gov

WEBSITES:

https://www.netl.doe.gov/research/coal/crosscutting/sensors-controls

https://energy.gov/fe/plant-optimization-technologies

https://www.netl.doe.gov/research/coal/crosscutting

ACKNOWLEDGEMENTS

The Sensors and Controls Portfolio was developed with the support of many individuals. Principal Investigators, Federal Project Managers, Technology Managers, Supervisors, and National Energy Technology Laboratory site-support contractors involved with the preparation of Sensors and Controls Portfolio played key roles..

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

Program staff are also located in **Houston, TX**
and **Anchorage, AK**.

Visit us: **www.NETL.DOE.gov**

@NationalEnergyTechnologyLaboratory

@NETL_DOE

@NETL_DOE

April 2018