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Crosscutting Technology Research Sensors and Controls Project Portfolio

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U.S. DEPARTMENT OF ENERGY

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NATIONAL ENERGY TECHNOLOGY LABORATORY

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Contents

Introduction

The Crosscutting Technology 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 Crosscutting Technology Research Program executes the R&D efforts by partnering and collaborating with research institutions and the power generation industry throughout the United States and in select international collaborations. The Crosscutting Technology 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 Program comprises three technology areas: Coal Utilization Sciences, Plant Optimization Technologies, and University Training and Research. A general description of each of these technology areas is detailed below:

Coal Utilization Sciences: The Coal Utilization Sciences technology area research effort is conducted to develop modeling and simulation technologies leading 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. These products are based on validated models and highly detailed representations of equipment and processes. Multinational laboratory efforts are being coordinated through the National Risk Assessment Partnership (NRAP) and Carbon Capture Simulation Initiative (CCSI) to focus on post-combustion capture of carbon, risk assessment, and integrated multiscale physics-based simulations.

Plant Optimization Technologies: The Plant Optimization Technologies technology area exists to develop advanced sensors and controls, materials, and water- and emissions-related technologies. Projects within this funding area enable novel control systems to optimize operations where harsh environmental conditions are present in both current and future applications in power plants and industrial facilities.

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 Office of Fossil Energy and the Crosscutting Technology Research Program. UTR is the umbrella program under which the University Coal Research (UCR) and Historical 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.

In addition to the Crosscutting Technology Research funding programs listed above, 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 the small business and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and it 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 to 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 Technology Research program comprises 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. Controls research centers around self-organizing information networks and distributed intelligence for process control and decision making.

High Performance Materials: Materials development under the Crosscutting Technology Research Program focuses on structural materials that will lower the cost and improve the performance of fossil-based power-generation systems. Computational tools in predictive performance, failure mechanisms, and molecular design of materials are also under development to support highly focused efforts in material development.

Simulation-based Engineering: This technology area represents a vast amount of 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 under this technology area.

Innovative Energy Concepts: Innovative Energy Concepts is concerned with the development of novel cost-effective technologies that promote efficiency, environmental performance, availability of advanced energy systems, and the development of computational tools that shorten development timelines of advanced energy systems. This area provides for fundamental and applied research in innovative concepts with a 10-25 year horizon that offers the potential for technical breakthroughs and step-change improvements in power generation and the removal of any environmental impacts from fossil energy-based power system.

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. 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 understanding of the intimate relationship between energy and water resources.

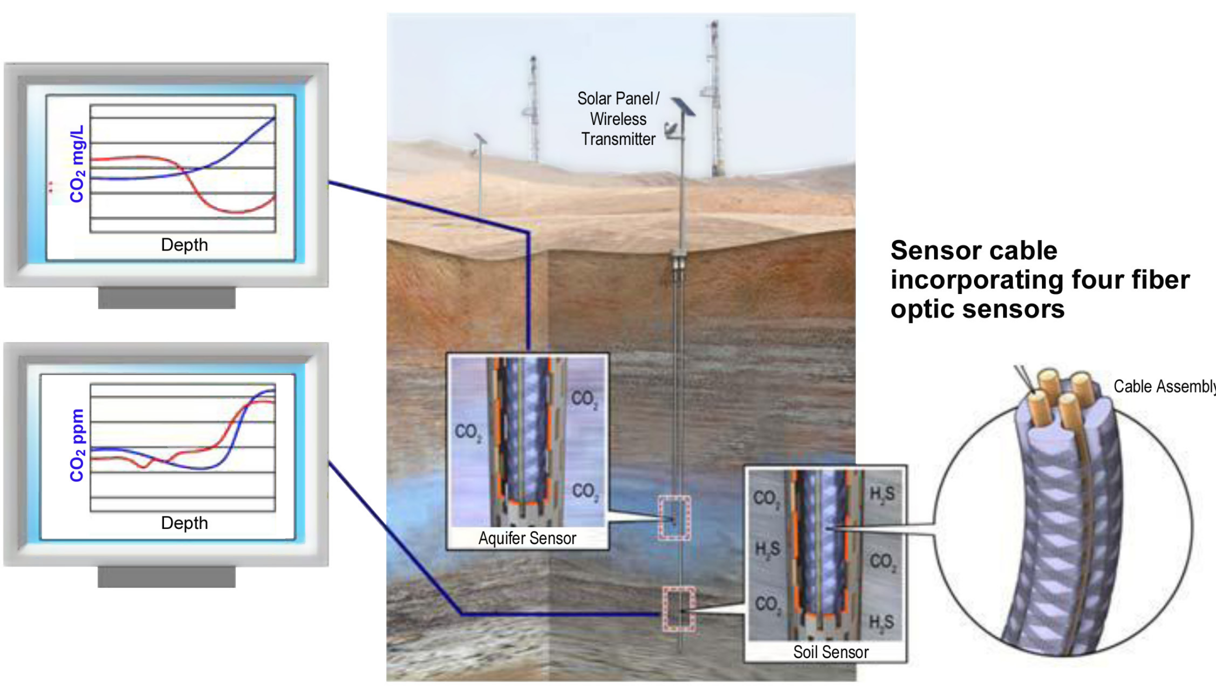
Sensors and Controls

The aim 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 around 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
  - Microsensors
  - Novel Sensor Concepts
- Distributed Intelligent Controls
  - Advanced Process Control
  - Sensor Placement & Networks

These new technologies are designed to benefit both existing and advanced power systems such that meaningful improvements can be made with respect to their efficiency and availability. As generational and transformational systems mature, sensors and controls will serve as an essential and enabling technology to operate these systems under conditions where optimal performance is balanced with reliability. Alongside the sensors and controls efforts, users need the ability to make and implement decisions and derived optimizations in real time. This capability will be attained by means of new computational tools capable of matching sensor data and analytical inputs to decision-making assistance and controls actuation resulting in desired outcomes.

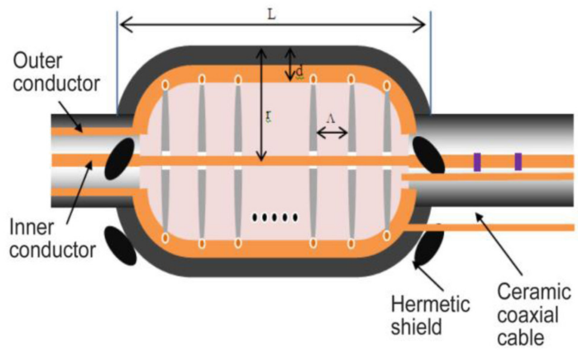


Projects by Component Technologies

Advanced Sensors

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 under extreme environments, designs for multiplexing and distributed measurements, approaches for low-cost devices, materials for fiber coatings, optically active smart coatings, and packaging of the sensors to enable commercial application. The use of fiber optics has made a significant impact on the viability of sensors in harsh environments because of its immunity to electromagnetic interference (EMI), the inherently drift-free sensor designs it enables, and the availability of a range of materials suitable for high-temperature applications.



Multi-Point Pressure and Temperature Sensing Fiber Optic Cable for Monitoring CO_2 Sequestration

Performer: General Electric Global Research

Collaborator(s): None

Award Number: FE0010116

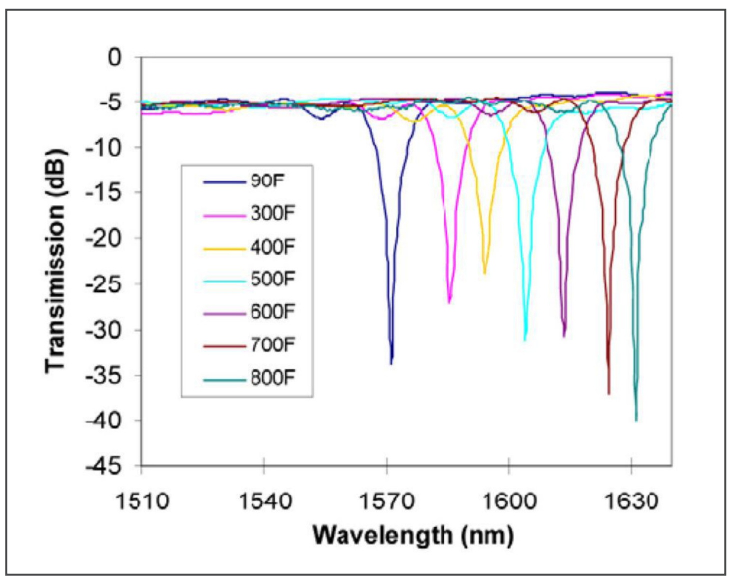
Project Duration: 1/1/2013 – 12/31/2014

Total Project Value: $1,248,733

Funding Source: Coal Utilization Sciences

GE Global Research was to develop and demonstrate a multi-point fiber optic sensor cable for in situ monitoring of pressure and temperature in the harsh environment of CO_2 sequestration wells. The research performed includes the design of a multi-point pressure/temperature sensor cable and package for operation up to 250 °C and 10,000 psi; a simplified, multiplexed readout method; fabrication of the multi-point pressure/temperature sensing cable with multiple spliced temperature and pressure sensors; and incorporation of remote wireless activation and operation of the sensors in a simulated environment.

Specific objectives and tasks to accomplish them included: Standard modeling and fabrication processes will be employed to design the new sensor die. Sensor splicing techniques will be developed from experience obtained with the single-point sensor splicing. An optical readout system will be constructed in the laboratory for testing the system response and accuracy, and accelerated environmental testing of the entire cable will be performed according to standard practices to determine the long-term survivability of the sensor system. Wireless communication systems and protocols developed by GE for remote monitoring will also be demonstrated for operation of the sensor.



Thermal long-period fiber grating (TLPFG) transmission spectrum at various.

Intrinsic Fiber Optic Chemical Sensors for Subsurface Detection of CO_2

Performer: Intelligent Optical Systems, Inc.

Collaborator(s): Terralog Technologies, Stanford University - Panama St.

Award Number: FE0010318

Project Duration: 10/1/2012 – 9/30/2015

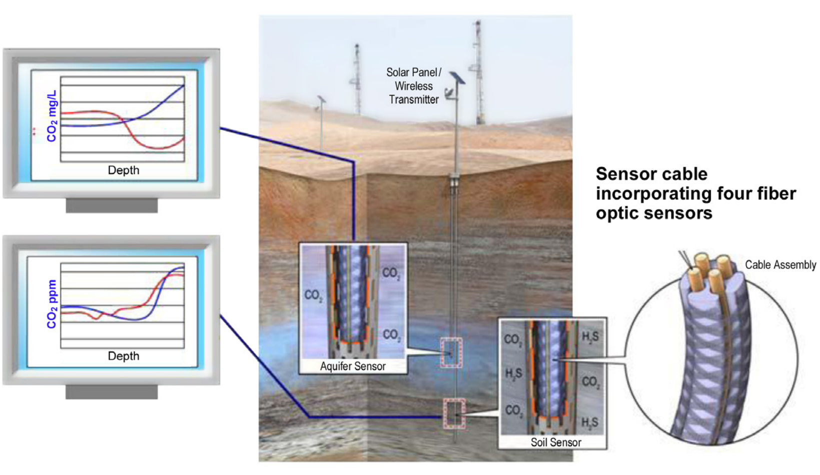
Total Project Value: $1,632,470

Funding Source: Plant Optimization Technologies

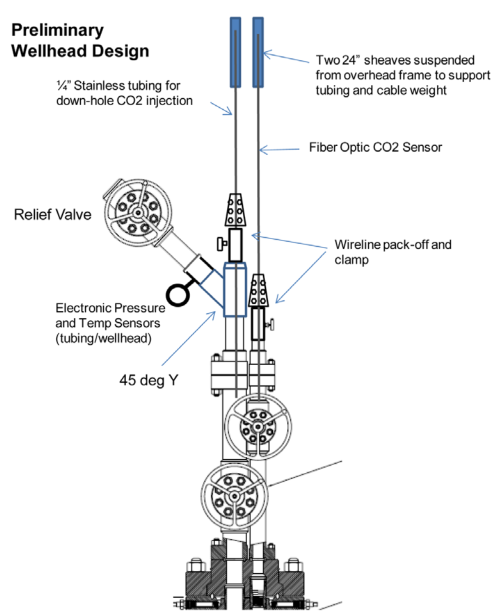
This project will focus on the design of a field-ready sensor based on an intrinsic fiber optic system for subsurface CO_2 plume migration monitoring and above-zone leak detection. The work will include approaches to enable the sensor to be deployed into the subsurface, employing materials and designs such that installation through monitoring wells can be pursued.

The project will demonstrate fiber optic sensor prototypes (20 to 100 m long) for gas-phase and/or dissolved CO_2 monitoring capable of withstanding corrosive liquids (with traces of NO_x or SO_x, with pH near 4 and salinity up to 250,000 ppm) and elevated temperatures. After concept demonstration, fiber optic sensors will be manufactured at lengths ranging from 2,500 to 12,000 feet. Deployable sensor designs will include a stand-alone multichannel read-out unit for distributed intrinsic fiber optic sensors with wireless communication capability, and will be included as part of this project work.

Sensor designs will focus on coating materials applied to the exterior of optical fiber. The coatings will be sensitive to CO_2 concentration. Materials development concerns include the ability to selectively sense CO_2, but to also withstand challenging subsurface conditions. Targeted sensor performance includes sensitivity (better than 0.1% CO_2), measurement range (0 to 100%), and response time (in the minutes range) adequate for monitoring plume migration and above-zone leak detection of CO_2. Additional research areas include the ability to resolve concentration of CO_2 while in varying conditions of temperature and pressure that impact accuracy of the measurement and impose requirements on the signal processing to enable sensing to depths of up to 5,200 feet and hydrostatic pressures up to 2,000 psi.



Sensor cable incorporating four fiber optic sensors.



Preliminary wellhead design for sensor deployment.

Micro-Structured Sapphire Fiber Sensors for Simultaneous Measurements of High Temperature and Dynamic Gas Pressure in Harsh Environments

Performer: Missouri University of Science and Technology

Collaborator(s): University of Cincinnati, AmerenUE Corporate

Award Number: FE0001127

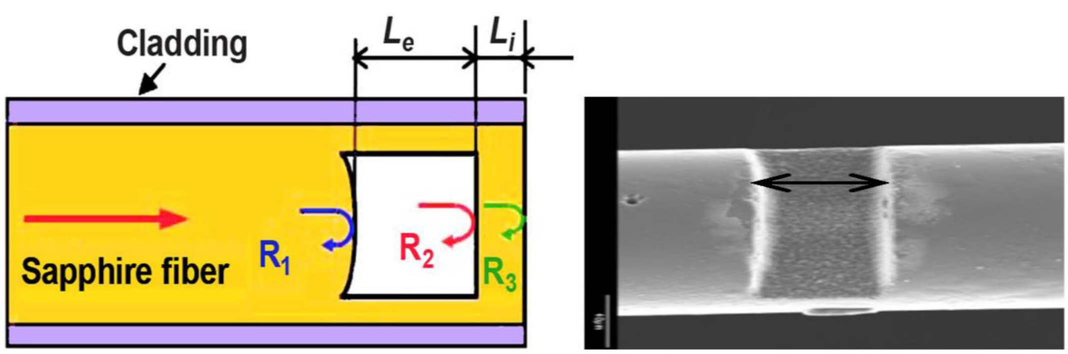
Project Duration: 10/1/2009 – 9/30/2014

Total Project Value: $1,278,007

Funding Source: Plant Optimization Technologies

The focus of this project was to conduct fundamental and applied research leading to successful development and demonstration of robust, multiplexed, micro-structured sensors using single-crystal sapphire fibers. At the core of the technology are the hybrid extrinsic/intrinsic Fabry-Perot interferometer sensors directly micro-machined on a sapphire fiber using an ultrafast laser. These sensors can be deployed into the hot zones of advanced power and fuel systems (inside a coal gasifier or gas turbine system) to simultaneously measure high temperature (up to 1600 °C) and dynamic gas pressure.

The primary goal of this program is to develop and demonstrate multiplexed, micro-structured, single-crystal sapphire fiber sensors for temperature and gas pressure measurement in harsh environments. The project had three main objectives: (1) to incorporate sapphire fibers into sensors that are fully operational at high temperatures in a simulated harsh environment; (2) to develop and demonstrate novel sensors to simultaneously measure temperature and gas pressure in harsh environments; and (3) to develop and demonstrate novel sapphire fiber cladding and excitation techniques to assure high signal integrity and sensor robustness. The sapphire sensors being developed can help to produce affordable and clean energy from coal and other fossil fuels in an effort to secure a sustainable energy economy.



Conceptual design of micro-machined sapphire fiber for Fabry-Perot interferometer sensor for the measurement of temperature and pressure (left) and micro-machined silica fiber for conceptual evaluation (right). (Figure and Photo provided courtesy of Missouri University of Science and Technology and University of Cincinnati).

Innovative Process Technologies–Growth of Ultra High Temperature Optical Fibers

Performers: National Energy Technology Laboratory - ORD

Award Number: FWP-2012.04.01.2

Project Duration: 10/1/2014 – 9/30/2015

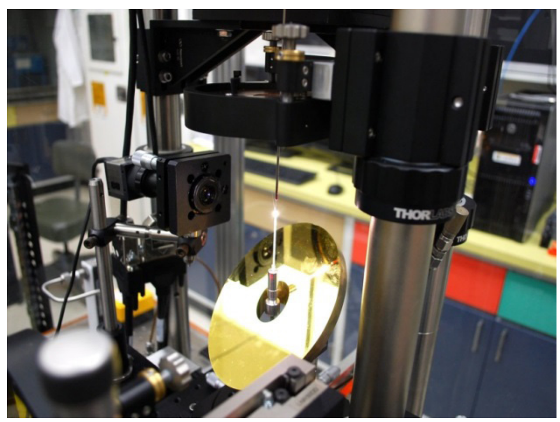
Total Project Value: $599,952

Technology Area: Plant Optimization Technologies

The purpose of this project is to improve the fabrication process and develop cladding materials for specialty non-silica high temperature fibers, which will then enable new sensing applications in harsh environments.

Complementing the advanced functional sensing material effort, the laser heated pedestal growth (LHPG) system will initiate the Office of Research and Development (ORD) research in specialty fiber development for harsh environments. NETL's experience with silica fibers has indicated a useful temperature limit of about 700–850 °C, depending upon the gas environment. Initial testing and literature review have pointed toward alternative, single-crystal fiber materials (such as sapphire), for superior temperature and chemical stability. However, in 2014, single-crystal optical fibers are difficult to manufacture, expensive, and limited in availability. Furthermore, single-crystal fibers are commercially supplied without a cladding, making them inherently high-loss devices. Both of these factors have limited the fibers performance and industrial application.

This effort will apply the laser heated pedestal growth (LHPG) system and implement improvements to the system to improve the growth of sapphire optical fiber, develop cladding materials and fabrication process for sapphire optical fiber, and grow optical fibers from other high-temperature stable materials, such as yttrium aluminum garnet (YAG). The fibers fabricated through these efforts will be used in conjunction with the novel high-temperature functional materials to create more robust and cost effective harsh environment optical fiber sensors.



Laser heated pedestal growth system.

Innovative Process Technologies–Fabrication of Specialized Capillaries for Advanced Optical Sensors and Diagnostics

Performers: National Energy Technology Laboratory - ORD

Award Number: FWP-2012.04.01.2

Project Duration: 10/1/2014 – 9/30/2015

Total Project Value: $599,952

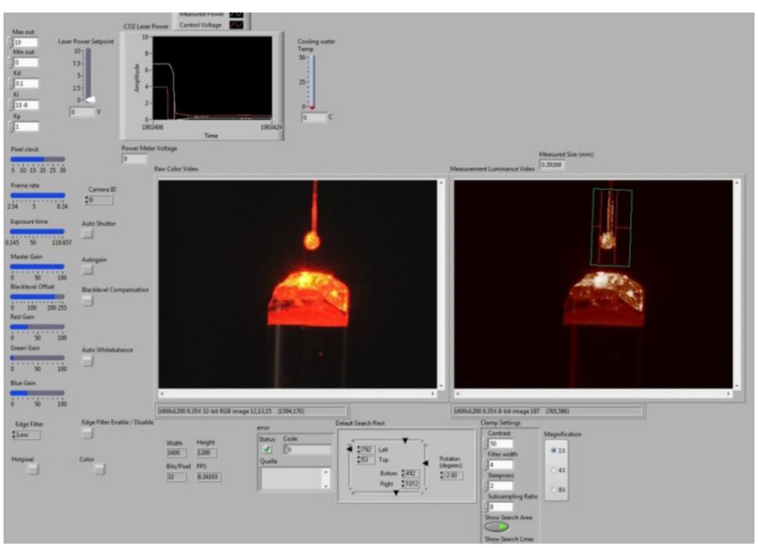
Technology Area: Plant Optimization Technologies

The purpose of this project is to advance foundational science for optical waveguide-based sensor systems, particularly for lower-concentration species. The scope of the capillary development research is improving the performance of optical capillary sensors and instruments.

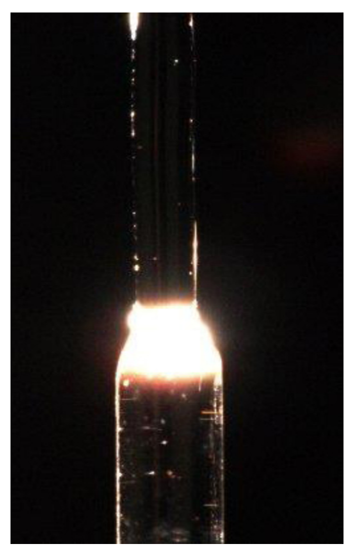
Optical waveguides, or reflectively lined capillaries, are a key component in the NETL Raman Gas Composition Analyzer, which uses laser light scattering within a reflectively-lined capillary waveguide to increase signal from gases by 10,000 times over conventional technology. NETL is the world leader in research in this area. Continued research on optical waveguides for gas sensing will improve their performance and durability.

The protective coating development is to improve signal and also resistance to corrosive species such as hydrogen sulfide. Combination of capillaries with other optical diagnostics, such as Coherent Anti-Stokes Raman Spectroscopy (CARS), will be examined to improve detection of low concentration species.

The research will also allow evaluation of surfaced enhanced Raman, CARS within a capillary, and other techniques for measurement of low-concentration species which may benefit from the optical behavior of the capillary waveguide.



Sapphire seed (125 µm) is measured using the real-time video-based system.



1mm fused silica test-draw.

Laser-Based Detection of Trace Level Contaminants

Performers: Sandia National Laboratory

Award Number: FWP-10-014451

Project Duration: 2/1/2009 – 9/30/2014

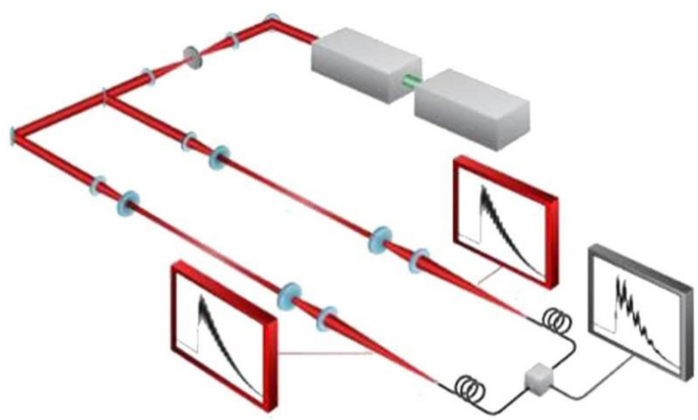
Total Project Value: $350,000

Technology Area: Plant Optimization Technologies

The primary goal of this research program was the development of an instrument for high-sensitivity, real-time detection of elemental selenium (Se[0]) and selenium dioxide (SeO_2). This instrument will employ laser-induced fluorescence (LIF) detection schemes selective for the species of interest, thereby enabling in situ monitoring of selenium compounds in the flue gas.

This project was developing instrumentation for high-sensitivity, simultaneous real-time detection of multiple trace-level components of fossil fuel combustion. Previous efforts have focused on methods for detection of elemental and oxidized selenium (Se) and mercury (Hg), while the current effort has focused on hydrochloric acid (HCl) detection at sub-ppm levels in the presence of high water vapor content and other relevant species such as CO_2, NO_2, CH_4, and SO_2. Sandia National Laboratory plans to develop proof-of-concept demonstration of the dual-etalon, frequency-comb cavity ring-down spectrometer. This spectrometer will need quantified and analysis quality will be scrutinized. Through this spectrometer, the optimization of detecting HCl in situ will be greatly enhanced though higher sensitivity and specificity and faster response time.

The impact of this technology will be to lower operating costs by allowing accurate and rapid measurement of the combustion flue gases of a boiler in order to better control its operation. Specifically, this project employs laser-excitation detection schemes applicable to many chemical species, thereby enabling in situ and extractive monitoring of multiple compounds in flue gas. The sensor under development has the potential for greater real-time emissions control in any exhaust gas byproduct waste stream.



Dual-etalon, frequency-comb cavity ring-down spectrometer: a broad-bandwidth laser beam is directed through two etalon cavities, and the combined ring-down signals are collected on a single detector, yielding a high-resolution absorption spectrum spanning the bandwidth of the laser pulse.

Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High-Temperature Coal Gasifiers

Performer: Stanford University

Collaborator(s): University of Utah

Award Number: FE0001180

Project Duration: 10/1/2009 – 9/30/2013

Total Project Value: $1,409,821

Funding Source: Plant Optimization Technologies

Stanford University and the University of Utah combined efforts to design, build, and test a tunable diode laser (TDL) sensor capable of measuring gas concentrations and temperature in a gasification system. The laser sensor was to be tested in laboratory and pilot-scale facilities to determine the conditions and locations in the gasification system in which the sensor can operate. Test data enabled Stanford to better understand the sensor performance in full-scale gasification systems. Two crucial sensor needs for the production and utilization of syngas were identified: (1) to control the temperature of the gasifier by adjusting feed rates of fuel and oxygen to the gasifier, and (2) to control the air dilution at the intake to the gas turbine. To address these needs, the laser-based sensor measures H_2O, CO, CO_2, and CH_4 concentrations in the high-temperature, high-pressure gasifier environment. CO and CO_2 concentrations have the potential to be used as control variables for the gasifier as well as for the subsequent utilization of the syngas (e.g., in a gas turbine). The CH_4 concentration in the output syngas stream often serves as a surrogate monitor of gasifier temperature. However, the TDL sensor measures in situ the real-time gas temperature from the ratio of absorption of selected H_2O absorption transitions.

The project's first phase—Sensor Development—focused on developing the laser sensor and fabricating optical access downstream of the gasifier reactor. The second phase—Sensor Testing—evaluated sensor performance in the main reaction section of the gasifier. Lessons learned from the first phase were used to make improvements to the laser and optical access design. The ability to scale sensor performance from the pilot-sized reactor at the University of Utah to various potential commercial designs requires understanding sensor performance as a function of particulate loading and gasifier pressure. The researchers developed scaling rules needed to estimate sensor performance in other environments (e.g., different gasifier designs or operating conditions).

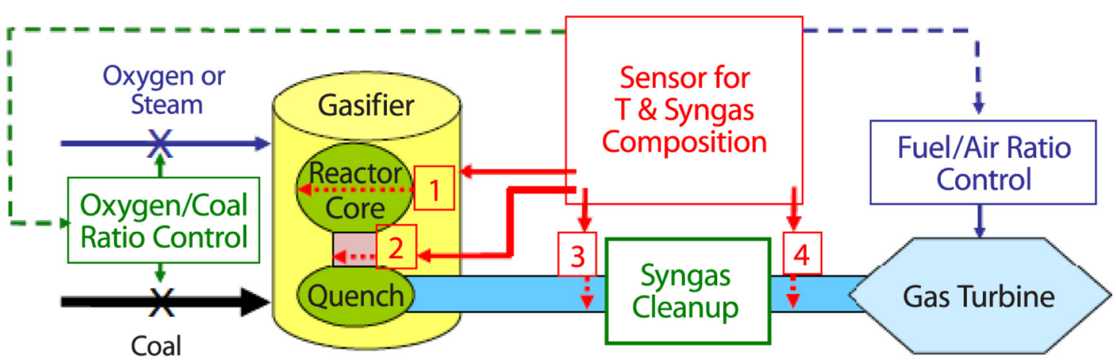


Illustration of the potential locations of gas sensors for control of a combined cycle power plant.

Heat Activated Plasmonics Based Harsh Environment Chemical Sensors

Performer: The Research Foundation of State University of New York

Collaborator(s): University of Minnesota, Goodrich Corporation

Award Number: FE0007190

Project Duration: 10/1/2011 – 9/30/2015

Total Project Value: $530,777

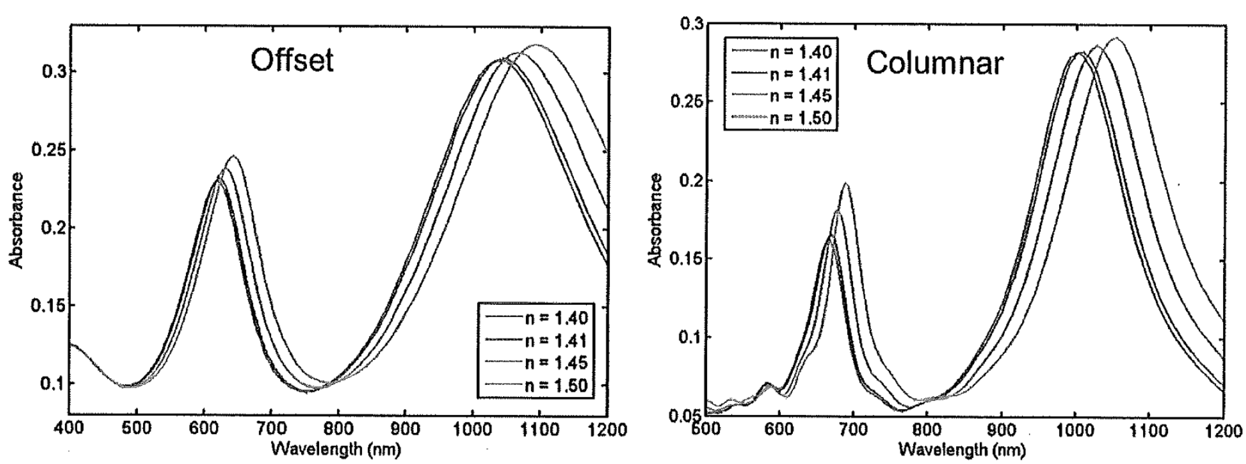
Technology Area: University Training and Research

The development of zero-emissions power systems and active emission-control systems are significant challenges for the DOE and require improved monitoring capability to support optimum performance. In accomplishing these objectives, there are critical needs to develop cost-effective sensing technologies that can function inside the harsh, high-temperature operating environments envisioned. Capitalizing on nano technology will tackle these challenges by developing robust nanorod chemical sensors at the University at Albany (UA) and a heat-activated plasmonic source at the University of Minnesota. Goodrich is serving as technical consultants as well as developing methods for packaging the finished device.

This project includes: (1) optical modeling of both nanorod and energy harvesting plasmonic devices; (2) development of ebeam patterned arrays of Au nanorods embedded in metal-oxide matrices with optical responses in the 600 nm to 1200 nm range; (3) design and development of a plasmonic energy-harvesting light source; (4) stability and selectivity testing for detection of the target gases in the presence of interfering species (principle component analysis will be used to analyze the statistically relevant selectivity characteristics of the sensing array); (5) development of a single-wavelength sensor testing station; and (6) design of packaging details for the integrated device.

The targeted product from this project will be a passive light source with sufficient energy in the selected wavelength to be sensed by a photodetector; the project will also demonstrate a chemical sensor for specific emissions.

This novel sensing approach will provide an indication of the presence and concentration of the emissions of interest. Integration methods will be aimed at implementation within existing engine and combustion platforms.



Comparison of simulation absorbance spectra shift using an offset layout vs. columnar layout of the nanorod array as the index of refraction of the surrounding layer is varied.

High Temperature Sapphire Pressure Sensors for Harsh Environments

Performer: University of Florida

Collaborator(s): Florida State University

Award Number: FE0012370

Project Duration: 1/1/2014 – 12/31/2016

Total Project Value: $1,098,191

Technology Area: Plant Optimization Technologies

The University of Florida, in collaboration with Florida State University, began work focused on the development of sapphire manufacturing technologies for high-temperature sensor fabrication and packaging by combining ultra-short pulse laser micromachining (LM) and spark plasma sintering (SPS). Specifically, the primary objective of this project is to develop sensor materials and designs to achieve the manufacture of sensors that enable physical parameters to be measured in situ and on line under extreme conditions such as high temperature and pressure and corrosive environments.

The proposed research will implement a multi-faceted approach to develop and quantify manufacturing technologies for the fabrication of 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 enable the creation of 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 such as pressure, temperature, stress/strain, etc., although for the purposes of this proposal the primary application will be an optical pressure sensor capable of operation in environments in excess of 1000 °C and pressures up to 1000 psi. The proposed research is applied in nature and will result in the establishment of critical functions regarding LM and SPS materials synthesis as well as a packaged and experimentally characterized pressure sensor.

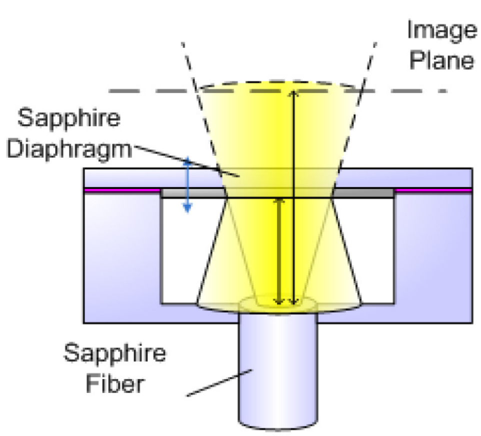
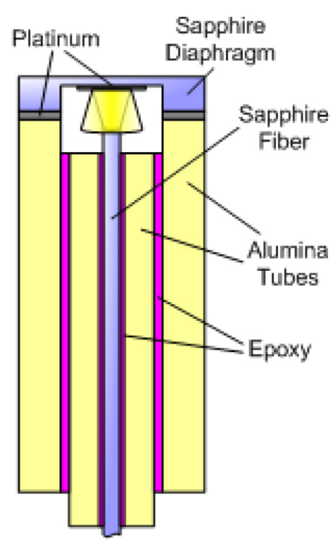


Illustration of the fiber-optic lever transduction scheme implemented in the pressure sensor design.



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

Robust Metal-Ceramic Coaxial Cable Sensors for Distributed Temperature Monitoring in Harsh Environments of Fossil Energy Power Systems

Performer: University of Cincinnati

Award Number: FE0022993

Project Duration: 7/1/2014 – 6/30/2017

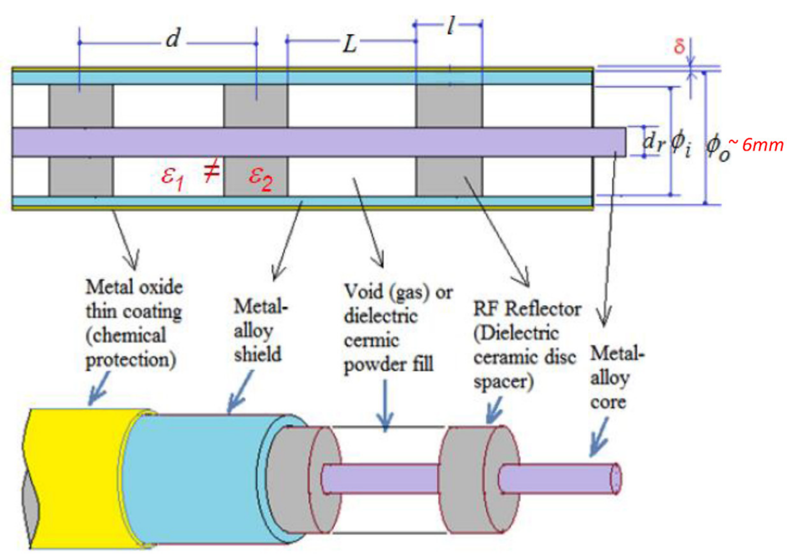
Total Project Value: $399,666

Technology Area: University Training and Research

Key Technology: Sensors and Controls

This project will develop a new metal-ceramic coaxial cable (MCCC) Fabry-Perot interferometer (FPI) sensor and demonstrate its ability for real-time, distributed monitoring of temperatures up to 1000 degrees Celsius. The project will also identify and optimize sensor materials with desired electrical and dielectric properties as well as thermochemical and structural stability. A MCCC-FPI sensor will be constructed and its stability will be tested in high-temperature gases relevant to fossil energy power system. Instrumentation for signal processing and algorithms for operating the sensor and distributed sensing systems will be developed.

Research activities undertaken under this project will address the fundamental issues associated with sensor material design, synthesis, and integration of the instrumentation and algorithms for sensor devices and measurement system. This project will provide reliable, highly sensitive, low-cost distributed sensing over large distances.



MCCC-FPI distributed sensor concept.

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

Performers: University of Massachusetts

Collaborator(s): University of Connecticut; and Alstom

Award Number: FE0023031

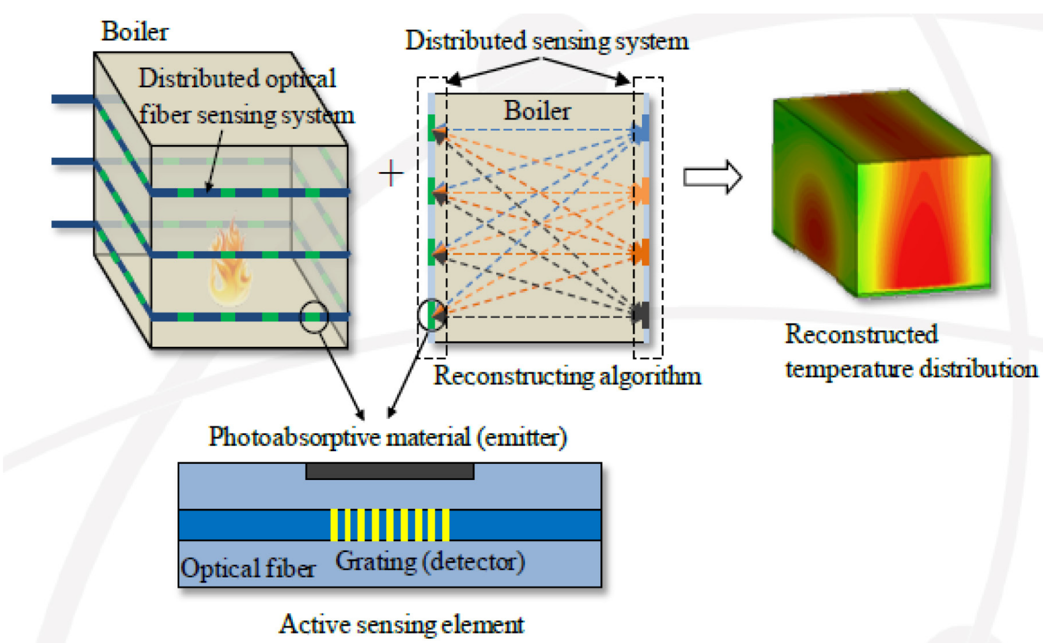
Project Duration: 9/1/2014 – 8/31/2017

Total Project Value: $400,000

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 °C). The reconstructed 3D temperature profile will provide critical input for the control mechanisms to optimize the combustion process thus achieving higher efficiency and fewer pollutant emissions.

In order to accomplish this, the project will first develop 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; (3) Develop the distributed sensing system to integrate multiple active sensing elements on a single optical fiber. The entire sensing system, when fully integrated and tested in the university labs, will be tested on Alstom's combustion test facility. The novel distributed sensor can have broader applications including measurements of strain, flow, velocity, crack growth, and corrosion for structural health monitoring.



Methodology to reconstruct the 3D high temperature distribution within a boiler via a novel fiberoptic distributed temperature sensing system using optically generated acoustic waves.

Robust Ceramic Coaxial Cable Down-Hole Sensors for Long-Term In Situ Monitoring of Geologic CO_2 Injection and Storage

Performer: University of Missouri System

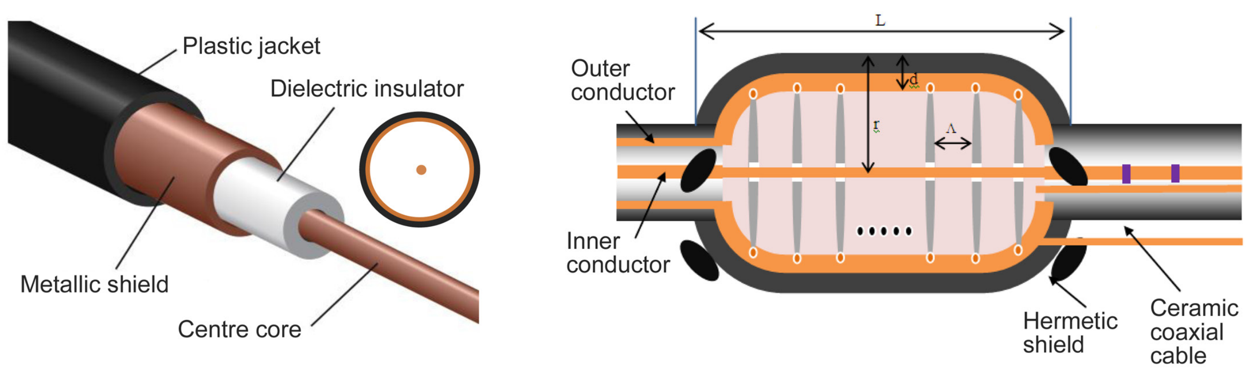
Award Number: FE0009843

Project Duration: 10/1/2012 – 3/31/2016

Total Project Value: $1,447,193

Technology Area: Plant Optimization Technologies

The project will develop a low-cost, distributed, and robust ceramic coaxial cable sensor platform for in situ down-hole monitoring of geologic CO_2 injection and storage with high spatial and temporal resolutions. The novel sensors are based on a recent invention of coaxial cable Bragg gratings (CCBGs) and coaxial cable Fabry-Perot interferometers (CCFPIs) in conjunction with the latest available high-temperature, ultralow-loss ceramic coaxial cables. Robust sensors will be created by forming CCBGs and CCFPIs into ceramic coaxial cables for in situ long-term measurement of temperature, pressure, and strain, which are critical to CO_2 injection and storage. Additionally, a novel signal processing scheme will be developed to achieve dense multiplexing of the sensors for low-cost distributed sensing with high spatial resolution. The interrelations between the sensor data and the geological models will be investigated in detail for the purposes of model validation, guiding sensor installation/placement, enhancement of model prediction capability, and optimization of CO_2 injection processes.



Multi-point strain and temperature coaxial cable sensor concept for monitoring CO_2 sequestration.

Development of Metal-Oxide Nanostructure-Based Optical Sensors for Fossil Fuel Derived Gas Measurement at High Temperature

Performer: University of Pittsburgh

Award Number: FE0003859

Project Duration: 9/1/2010 – 8/31/2014

Total Project Value: $298,395

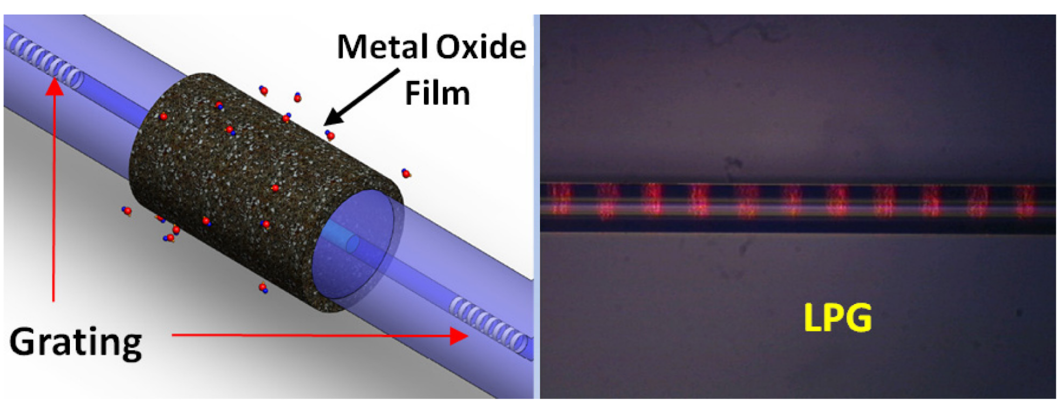
Funding Source: University Training and Research

Real-time gas composition analysis has multiple critical applications for the energy industry. The precise knowledge of fuel gas composition and its key post combustion derivatives play important roles in improving energy production efficiency and reducing pollution. The goal of this project was to perform nano-engineering to produce functional metal-oxide sensing materials and integrate them with high-temperature optical sensor platforms for real-time fossil fuel gas composition analysis.

The objectives of this project are twofold. The first task focuses on the design, fabrication, and three-dimensional (3-D) testing of macro-porous photonic crystals using functional metal oxides. Porous metal-oxide 3-D photonic crystals will be fabricated using a holographic lithography. The surface-chemistry-derived refractive index change or spectroscopic changes will be enhanced by 3-D optical confinement and the large surface area of the porous structure, which can be readily measured remotely through transmission and reflection spectroscopy.

To perform multi-species fuel-gas composition analysis, metal-oxide nanostructures can be integrated with high-temperature stable fiber grating devices fabricated by femtosecond ultrafast lasers; this is the second objective. The surface chemical-induced refractive index change or structural change can then be measured by the high-temperature stable in-fiber grating sensors. The coating technique can also be developed to synthesize functional metal-oxide films on the inner wall of hollow-core optical fibers. The surface adsorption of fuel gas can then be measured using either Raman spectroscopy or photoluminescent spectroscopy enhanced by the hollow waveguide. The application of hollow-core optical fiber as both the sample gas cell and signal optical collection components can dramatically amplify the sensing signal, leading to orders-of-magnitude enhancements of the signal.

The expected outcome is high-sensitivity optical sensors that can rapidly measure a wide array of fossil-fuel gas species in real time for automatic control of large combustors and fuel cells. The precise and real-time knowledge of fuel gas composition and its key post-combustion derivatives will provide data to allow engineers to increase efficiency and lower emissions in energy production from fossil fuels.



Conceptual drawing of coated fiber Bragg grating and photo of Long Period gratings (LPG) on fiber.

Novel Modified Optical Fibers for High-Temperature In Situ Miniaturized Gas Sensors in Advanced Fossil Energy Systems

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Award Number: FC26-05NT42441

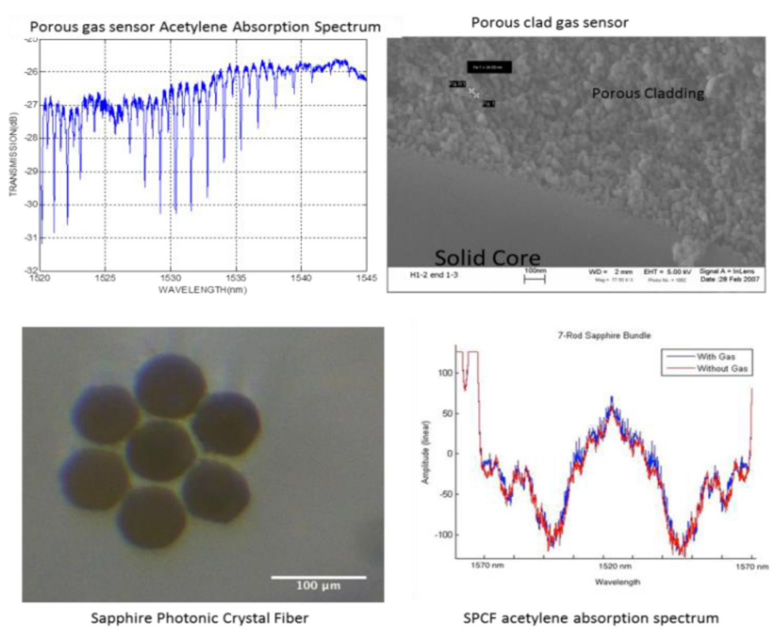
Project Duration: 7/1/2005 – 6/30/2014

Total Project Value: $2,446,104

Funding Source: Coal Utilization Science

Accurate and reliable detection of various gases is necessary for emissions monitoring and advanced process control in coal-fired power plants. Ideal gas sensors in these processes would operate in situ, exposed to high temperatures and harsh environments, where many conventional sensors cannot operate. Very few sensors are commercially available for high-temperature (1000 °C) and harsh-environment monitoring of gases such as nitrogen oxides, sulfur oxides, carbon monoxide, hydrogen, oxygen, methane, and ammonia, which are present in coal and coal-derived syngas applications. Such sensors suffer from a number of major limitations including limited accuracy, extremely short lifetimes, unexpected failure, and intensive maintenance.

Virginia Tech was to develop novel modified fiber materials for high-temperature gas sensors based on evanescent wave absorption in standing hole optical fibers. In order to overcome the response-time limitation of current available holey fibers (due to gas phase diffusion constraints), a novel process is being developed to produce holes perpendicular to the fiber axis. This process uses the glass phase separation by spinodal decomposition to form three-dimensionally connected standing hole optical fibers. The presence of the gas molecules in the holes of the fiber appears as a loss of wavelengths characteristic to the particular gas species. Using a broadband source or spectral tuning of a laser source across key wavelengths permits the detection of multiple gases as well as establishing self-calibrating measurement capability. Researchers will investigate the feasibility of upgrading the technology to single-crystal sapphire by using sol-gel processing and performing laser backside photochemical etching, thereby advancing the temperature capability of the gas sensor.



Stochastically porous glass and sapphire photonic crystal fiber (SPCF) gas sensors and associated gas detection absorption spectrum.

Distributed Fiber Optic Sensor for On-Line Monitoring of Coal Gasifier Refractory Health

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Collaborator(s): None

Award Number: FE0005703

Project Duration: 10/1/2010 – 10/31/2014

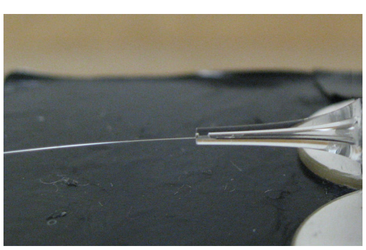
Total Project Value: $1,835,148

Funding Source: Coal Utilization Science

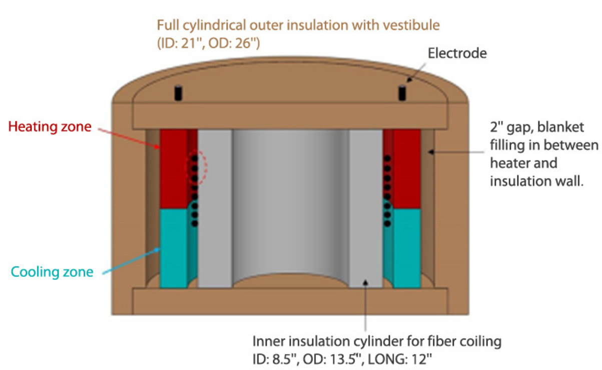
Recent advances in fossil fuel energy production technologies have shown tremendous potential to efficiently create clean, sustainable electricity using a variety of carbon rich fuels. Approaches such as coal gasification combined cycle have been demonstrated as feasible next-generation energy sources, but commercial operation of these facilities poses significant challenges. Foremost among these difficulties is the issue of refractory wear. The high-temperature reducing environment in the gasifier causes rapid corrosion of even the toughest refractory materials, limiting typical useful lifetime. Furthermore, the complexity and uncertainty of the gasification process makes remaining refractory life difficult to predict in working gasifiers.To address this concern, this project will develop an advanced distributed sensing technology capable of monitoring refractory wear in an operating coal gasifier. The Virginia Tech Center for Photonics Technology (CPT) will develop a prototype sensing system and evaluate it in a laboratory test environment for operation at temperatures over 1000 °C.

The project's objective will be met through development of a basic numerical model of the thermal effects of refractory degradation. The model will then be used to guide the design of the sensor and simulated test environment. CPT will develop a basic computational model to describe the thermal properties of specific refractory breakdown phenomena, from which the high-temperature distributed sensor technology can be used to pinpoint weak spots in the refractory liner and evaluate remaining lifetime. Numerical output will be compared to the laboratory test results and used to confirm the sensor's ability to monitor refractory health.

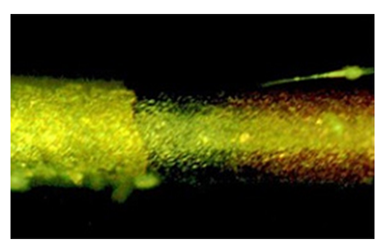
By providing the capability for comprehensive on-line monitoring of refractory health, the proposed technology will ultimately improve gasifier availability and reduce the frequency of refractory maintenance through condition-based assessment. The direct measurement technology will enable early detection of hot spots in the refractory wall and measurement of its remaining lifetime, leading to improved performance, longevity, and cost savings. Use of the distributed sensor will allow gasifier operators to adopt a conditions-based maintenance model, reducing the need for frequent shut-downs.



Concept validation setup.



Cutaway view of prototype sensing system.



Microscope image of the darkened segment of gold coated fiber after 1000 °C annealing in Inconel alloy tube.

Reduced Mode Sapphire Optical Fiber and Sensing System

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Award Number: FE0012274

Project Duration: 1/1/2014 – 12/31/2016

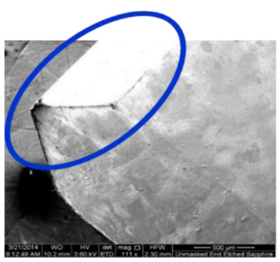
Total Project Value: $1,875,000

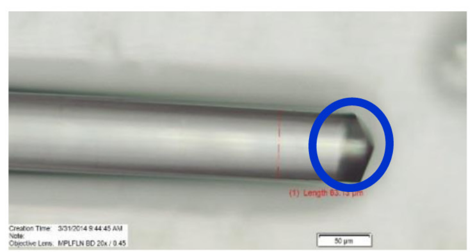
Funding Source: Plant Optimization Technologies

Real-time, accurate and reliable monitoring of temperatures at distributed locations will enable attempts to further revolutionize technologies such as the integrated gasification combined cycle configuration of turbines and ultrasupercritical steam cycle designs. A new modal reduction waveguide design will take advantage of the high-temperature stability and corrosion resistance of sapphire and result in a paradigm shift in ultra-high-temperature sensing. A novel and precise etching technique will significantly reduce (>50%) the mode volume in a novel robust sapphire fiber.

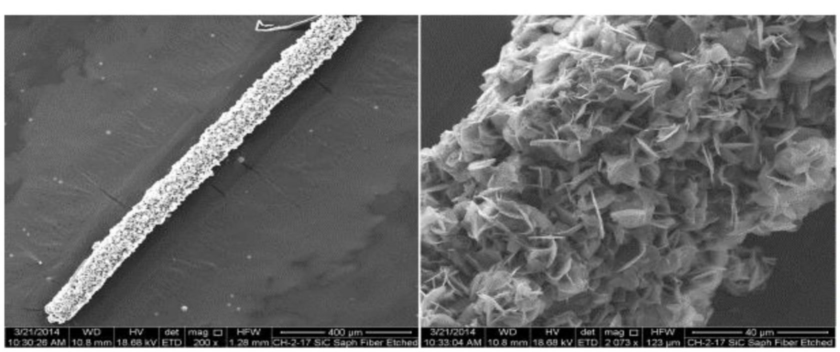
The proposed sapphire fiber waveguide design will overcome the harsh environment challenges that severely limit the integration of mature optical fiber sensing technologies in new power plant control systems. Overall, this technology is expected to lower operating costs by allowing more accurate measurement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

Angled Edge on Single Crystal Sapphire Wafer via VT Etching Process





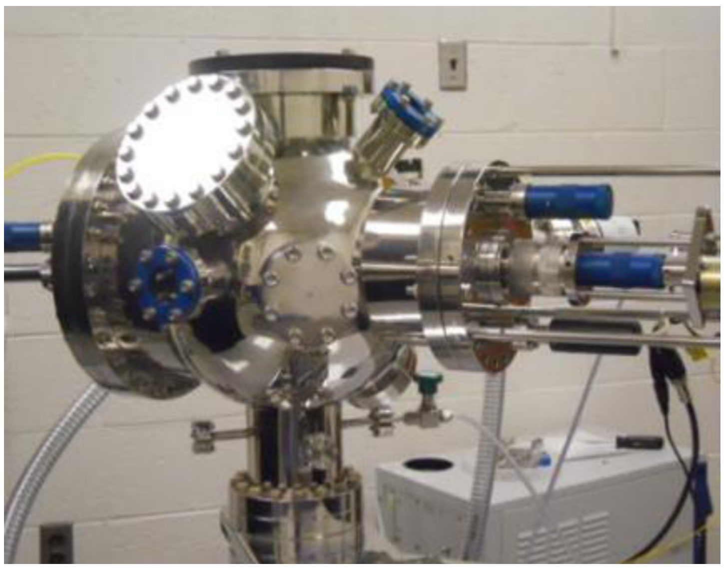
Angled Edge on the End of a Single Crystal Sapphire Fiber and Fiber Size Reduction via VT Etching Process



Conversion of single crystal sapphire fiber to mullite via VT SiC masking technique (for creating features in fiber).

Microsensors

The microsensor technology area encompasses a significant research effort to develop materials and structures to enable sensing at elevated temperatures (>500 °C). Measurements targeted for the microsensors include detection of a suite of gases, as well as temperature, pressure, strain/stress, corrosion, and other component condition assessments. Primary challenges with microsensors center on the selectivity and accuracy of devices with respect to a specific parameter (e.g., concentration of a particular gas) or suite of simultaneous measurements. This area includes sensing devices that can be made wireless, integrated with self-powering capability, and/or embedded within a component. Recent efforts in this area include the development of sensors that are low cost and can be rapidly prototyped with advanced manufacturing techniques. The culmination of this work will be robust, low-cost sensors that can be rapidly produced for wide distribution within an industrial environment.



Wireless, Passive Ceramic Strain Sensors for Turbine Engine Applications

Performer: University of Central Florida

Award Number: FE0007004

Project Duration: 10/1/2011 – 9/30/2014

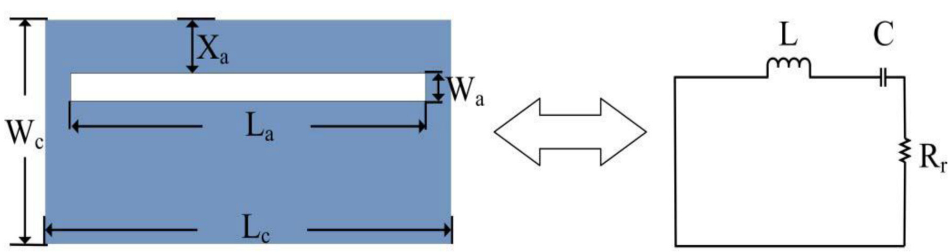
Total Project Value: $299,162

Funding Source: University Training and Research

The UCF research team will develop a sensor based on recently developed piezo-dielectric polymer-derived ceramics (p-PDCs) which in turn are based on a cavity radio frequency resonator that exhibits a strong strain/stress-dependent dielectric constant. This research is expected to provide a solid foundation for the development of commercially viable advanced sensor technologies for in situ, real-time monitoring of power generation systems, resulting in higher efficiency, increased reliability, and better pollution control.

The goal of this project is to develop wireless, passive, high-temperature (up to 1300 °C), polymer-derived ceramic strain/stress sensors based on a cavity radio frequency resonator for in situ measurement of strain inside turbine engines used in coal-based power generation systems. Several important technical objectives must be met to develop the necessary knowledge base to meet this goal. These objectives include (1) development of piezo-dielectric polymer-derived ceramics to obtain materials with optimal piezo-dielectric effects and dielectric loss, as well as thermal-mechanical properties; (2) design and fabrication of a prototype of the proposed strain sensors; and (3) characterization of the sensors under various conditions (e.g., temperature, corrosive environments, and strain) to demonstrate the proposed sensor, determine the possible degradation mechanisms and kinetics of the sensor under different conditions, and build a model for predicting the lifespan of the sensor.

The need for wireless sensors for turbine engine applications has resulted in extensive research activity in the past few years. UCF plans to develop sensor technology beyond the current state of the art by significantly advancing high-temperature sensing technology, promoting the use of new and advanced materials in turbine technology, and effectively combining wireless technology with new developments in materials science. Strain/stress sensors developed for in situ, on-line monitoring can help predict the failure of turbine engine parts by providing useful information on their condition. The sensors can also help reduce unnecessary out-of-service examination and replacement of engine parts, thereby reducing operating costs.



Schematic geometry of the proposed sensor. Where WC: the width of the SiAlCN rectangular; LC: the length of the SiAlCN rectangular; Wc = 1/2 "Lc " ; H: the thickness of the SiAlCN rectangular. The dominant model for this rectangular is TE101.

Metal Oxide/Nitride Heterostructured Nanowire Arrays for Ultra-Sensitive and Selective Multi-Mode High Temperature Gas Detection

Performer: University of Connecticut

Award Number: FE0011577

Project Duration: 7/18/2013 – 6/30/2016

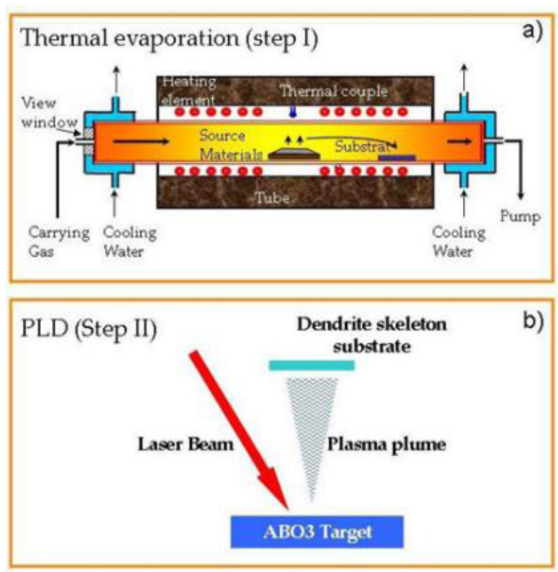
Total Project Value: $300,000

Funding Source: University Training and Research

The focus of this project is to design and fabricate a new class of well-defined (size, geometry, interface, and orientation) metal oxide/nitride-based heterostructured nanowire array sensing platforms that can run under multiple sensing modes, including electrical (resistance and impedance) and optical (photocurrent) modes at high temperature (600–1000 °C). The new sensing nanostructures will be assembled as either vertical or tilted arrays of single-crystal or polycrystalline metal oxide nanowires [i.e., cerium oxide and zinc oxide decorated by perovskite nanoparticle shells (i.e., [lanthanum (La), strontium (Sr)] MO_3, M=cobalt (Co) and iron (Fe)). An aluminum-gallium-nitrogen ($Al_xGa_{1-x}N$) (x=0, 0.25, and 0.5) epitaxial layer on sapphire (aluminum oxide) substrate will be used to grow metal oxide nanowire arrays with different epitaxial orientations and form the coherent hetero-interfaced nanowire arrays needed to enable multi-mode sensor operation.

The research team will design, fabricate, and control the metal oxide/nitride heterostructure arrays using different orientation alignments (vertical and tilt configurations) through the epitaxial nanostructure growth control and heterostructure layering in a two-step solution- and vapor-phase-based synthesis process. Hydrothermal synthesis or thermal evaporation will be employed to synthesize metal oxide nanowire cores, while a pulsed laser deposition, magnetron sputtering, or sol-gel wash-coating process will be used to produce conformal or mesoporous perovskite nanoparticle shells. The team will enable the multi-mode sensing capability of the sensors using these heterostructured nanowires, and make them easily adaptable into wireless and remote sensor systems. The team will also design and fabricate a novel miniaturized multi-mode sensing platform that has parallel, combinatory, and multiplexed arrays of integrated electrical and photocurrent-based nanosensors on the same $Al_xGa_{1-x}N$ epi-substrates. The simultaneous measurements of electrical resistance, impedance, and optically excited current (photocurrent) provide three independent but intrinsically correlated sensing parameters and will greatly enhance the information output and accuracy of the enabled gas sensors.

The metal oxide nanowire arrays developed through this project will be more robust and provide more information than sensors currently available for use under high-temperature harsh conditions. These nanosensors can achieve good selectivity, fast response, and enhanced sensitivity for high-temperature gas detection due to the diversity of the nanomaterials, inherent large specific surface area of nanostructures, and minimized gas diffusion resistance. Potential applications for this technology include combustion monitoring in industry and power plants and high-temperature gas sensing for vehicle and aircraft engines.



Schematic of a typical experimental set-up for synthesis of perovskite nanoparticle decorated nanowire arrays on Al_xGaN epi-substrates.

Gallium Oxide Nanostructures for High-Temperature Sensors

Performer: University of Texas at El Paso (UTEP)

Award Number: FE0007225

Project Duration: 10/1/2011 – 1/31/15

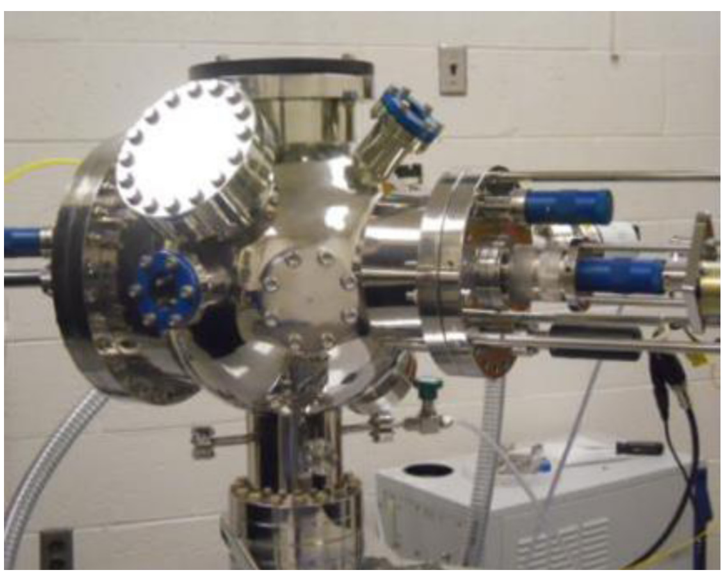
Total Project Value: $200,000

Funding Source: University Training and Research

This project was focused on the design of gallium oxide (Ga_2O_3)-based nanostructured materials capable of operating with demonstrated reliability and stability, and without significant interference from other pollutants or emissions, under the extreme conditions within fossil fuel energy systems. The experimental approaches and methods will address issues and technical barriers related to the growth, microstructure-property relationship, and ability to evaluate the performance of Ga_2O_3-based oxygen sensors.

The goal of this project was to develop high-temperature O_2 sensors, based on pure and doped Ga_2O_3 nanostructures, capable of operating at 800 °C and above in corrosive atmospheres. The specific objectives are (1) to fabricate high-quality pure and doped Ga_2O_3-based materials and optimizing conditions to produce unique architectures and morphology at the nanoscale; (2) to derive the structure-property relationships at nanoscale dimensions and demonstrate enhanced high-temperature oxygen sensing and stability; and (3) to promote research and education in the area of sensors and controls.

This project fostered the development of high-temperature O_2 sensors with enhanced selectivity, sensitivity, and long-term stability when compared to their conventional counterparts. Improved O_2 sensors will contribute to cleaner and more efficient coal-fired power generating plants.



Sputter deposition system developed by the researchers.

High-Temperature Nano-Derived Micro-H_2 and H_2S Sensors

Performer: West Virginia University Research Corporation

Award Number: FE0003872

Project Duration: 7/8/2010 – 5/15/2014

Total Project Value: $299,950

Funding Source: University Training and Research

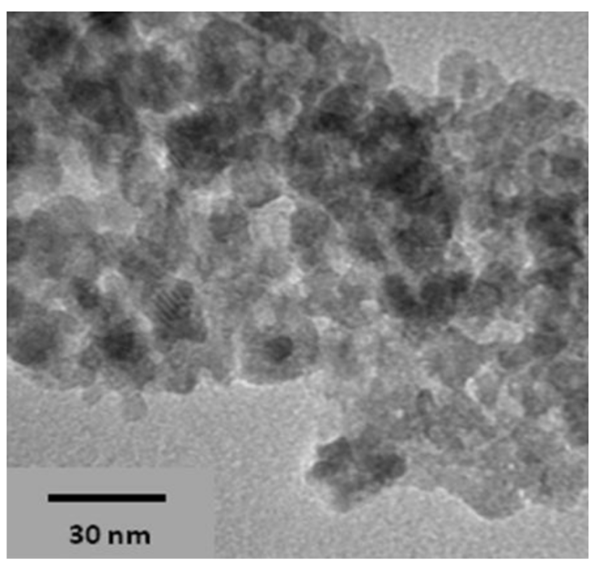
The goal of this project was to develop micro-scale chemical sensors and sensor arrays to detect gases such as H_2 and H_2S within high-temperature environments. The project directly aligns with the long-term goal of the Advanced Research Program to demonstrate sensor materials and processing strategies that can also be used on sensor arrays that monitor other chemicals.

Currently, micro-patterned semiconductor based chemical sensors are created using thin film deposition and wet/dry etching processes. This project will demonstrate an innovative microcasting process for forming chemiresistive sensors with 20–100 micrometer feature size of various geometries composed of nano-composite electrodes that display high-temperature microstructural and morphological stability. In order to achieve this goal, the work will concurrently address issues relating to electrode stability, selectivity, and sensor miniaturization.

To achieve this goal, the project pursued the following objectives:

- Investigate methods for stabilizing the microstructure of nanocomposite H_2 and H_2S selective electrodes for high-temperature chemiresistive sensing applications.
- Investigate the effect of sensor electrode poisoning due to typical impurities in coal syngas at high temperature.
- Define a lost-mold microcasting process to produce micron-scale three-dimensional sensor structures (with feature sizes less than 100 micrometers) composed of nano-composite selective electrode nanopowders.
- Demonstrate and test H_2 and H_2S micro-sensor arrays utilizing the nano-composite selective electrode materials.

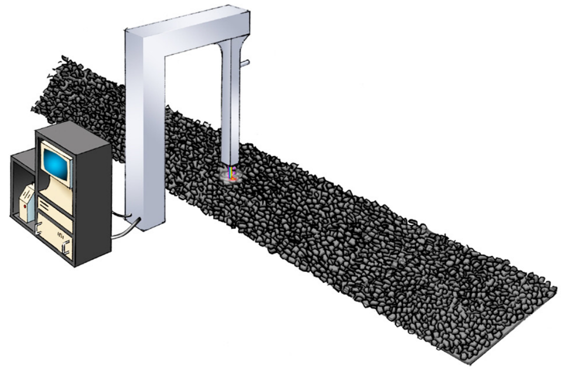
The performance of advanced power systems is limited by the lack of sensors and controls capable of withstanding high-temperature and high-pressure conditions. Harsh environments are inherent to new systems that aim to achieve high efficiency with low emissions. In addition, these systems are complex, with operational constraints and system integration challenges that push the limits of traditional process controls. Chemiresistive electrode sensors such as those being developed in this project will be able to withstand the high temperatures and pressures present in power generation systems; concurrently address issues relating to electrode stability, selectivity, and sensor miniaturization; and represent the next step in monitoring and control technology.



TEM micrograph of refractory nanomaterials (<10nm in size) for H_2 and H_2S sensing at temperatures >500 °C. (Source: Edward Sabolsky).

Novel Sensor Concepts

New approaches not only to sensing technologies but also to manufacturing (e.g., of smart parts) and utilization of sensor data (e.g., imaging/visualization) have the potential to be transformative. This includes functional sensor materials, chemical sensors for subsurface monitoring, thermionic sensors, sensor packaging, 2-D and 3-D mapping of system components, Advanced manufacturing techniques for sensor design and fabrication, self-powered and wireless capbility, and smart part fabrication.



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Innovative Process Technologies–Functional Sensor Materials & Characterization Research

Performers: National Energy Technology Laboratory - ORD

Award Number: FWP-2012.04.01.2

Project Duration: 10/1/2014 – 9/30/2015

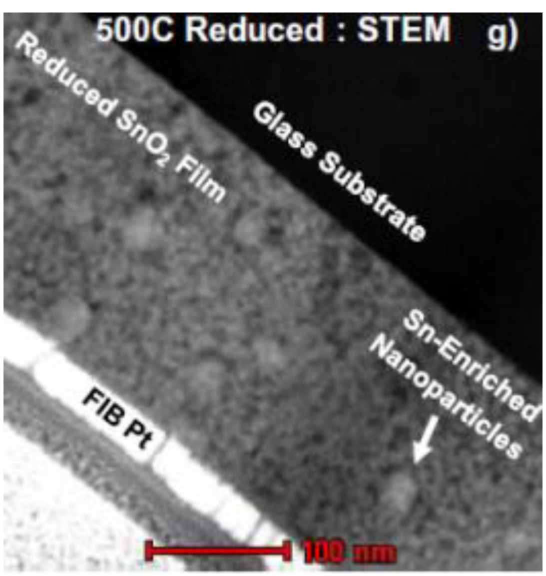
Total Project Value: $599,952

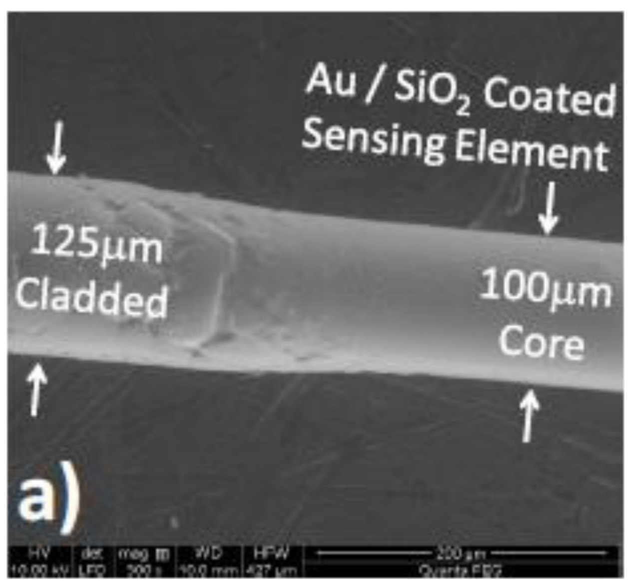
Technology Area: Plant Optimization Technologies

This effort will develop functional sensor materials and new sensor laboratory facilities relevant for the aggressive harsh environment conditions in advanced FE applications. Emphasis will be placed on evanescent wave absorption spectroscopy-based sensing but the developed systems will also be relevant to other optical sensor platforms and many will also be relevant for electronic sensing platforms.

The capabilities and expertise established through these efforts can also be leveraged in designing novel thin films for other energy-related applications. The short-term end product will be novel sensors capable of measurements of important parameters of interest with an emphasis on gas composition in the harsh environments of advanced power plants or carbon capture and storage processes. The long-term goals include the creation of new functional sensing materials approaches relevant for gas turbine and potentially even gasification applications, as well as new laboratory facilities capable of measuring sensor devices and materials under relevant high temperature and high pressure conditions.

The task will also provide support by the materials analysis and microscopy laboratories, including scanning electron microscopy (SEM) and x-ray diffraction (XRD) at the Pittsburgh, Pennsylvania and Morgantown, West Virginia sites for sensor research activities under IPT.





Scanning Electron Microscope (SEM) images of thin film material characterization.

Innovative Process Technologies–Advanced Sensors Testing in the National Energy Technology Laboratory Combustion Facilities

Performers: National Energy Technology Laboratory - ORD

Award Number: FWP-2012.04.01.2

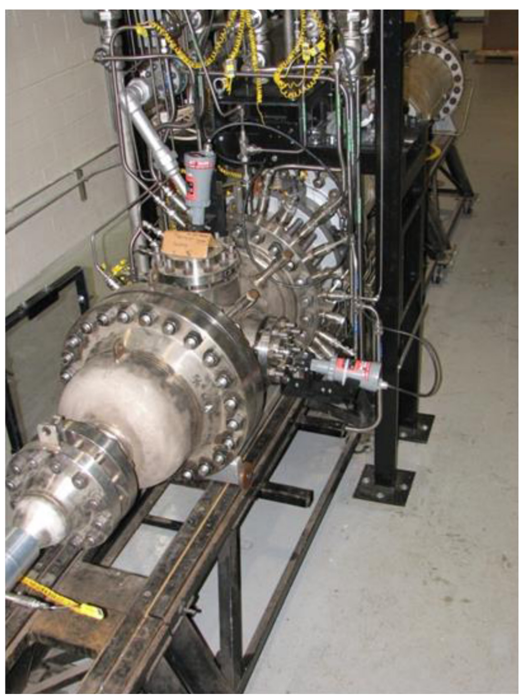
Project Duration: 10/1/2014 – 9/30/2015

Total Project Value: $599,952

Technology Area: Plant Optimization Technologies

The objective of this project is to support the efforts of the Department of Energy (DOE) to help extramural projects to increase the Technology Readiness Level (TRL) of their sensors, and to screen and test the applicability of nontraditional control approaches to advanced power generation systems. The purpose of both of these efforts is to help make the steps to commercialization for advanced sensors and controls technologies more rapid and cost efficient by leveraging of existing DOE laboratory facilities.

A significant barrier with broad impact for development of advanced sensor and control technologies is the cost of realistic power plant experimental platforms to test the effectiveness of novel sensors and control strategies. Dedicated or piggy-back testing of new sensors at NETL's High Pressure Combustion Facility often provides a cost-effective approach to testing sensors in a real, high-pressure, high-temperature environment. Screening and testing of nontraditional control approaches may be accomplished at NETL's Hybrid Performance Facility (HYPER), which captures several difficult control challenges for advanced power generation in a well-instrumented system.



Aerothermal test rig in the B6
High Pressure Combustion Facility.

Development of a CO_2 Chemical Sensor for Downhole CO_2 Monitoring in Carbon Sequestration

Performer: New Mexico Institute of Mining and Technology

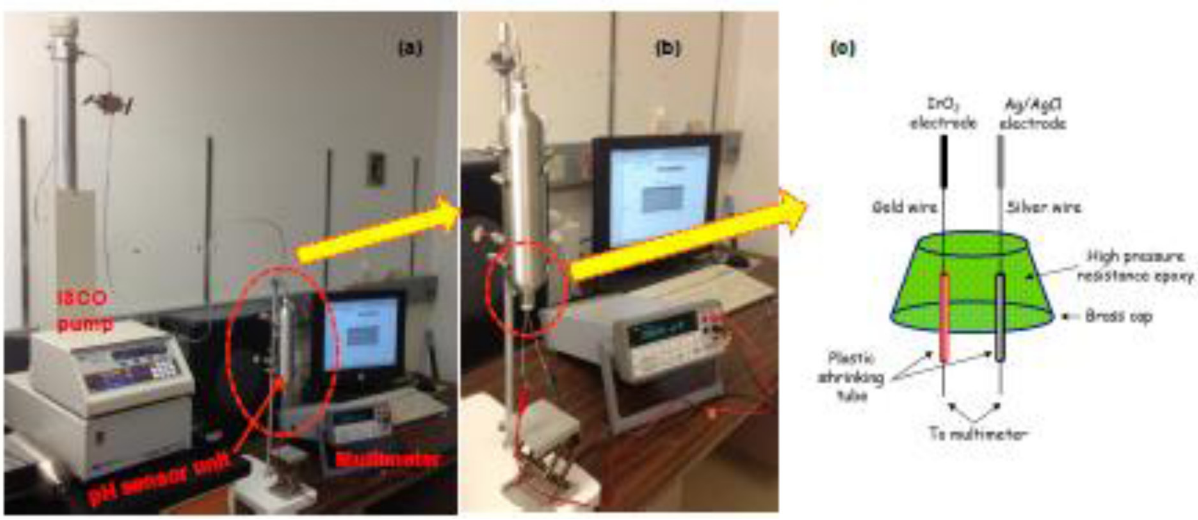
Award Number: FE0009878

Project Duration: 10/1/2012 – 9/30/2015

Total Project Value: $1,345,414

Funding Source: Plant Optimization Technologies

The proposed work targets the development of a robust pH sensor for in situ monitoring of subsurface waters. The pH of the water will reflect dissolved CO_2 and can thus indicate CO_2 plume migration. The downhole pH/CO_2 sensor will be developed to resist high pressures, high temperatures, and high salinity. Materials development work includes the use of a metal-oxide pH electrode with good stability and the understanding of different factors' effects on the performance of the electrode, after which sensor performance under high pressures, temperatures, and salinity conditions will be evaluated. Additional performance evaluations of the sensor will be carried out using CO_2/brine core flooding tests, and a data acquisition system will be developed to enable measurement of pH and CO_2.



The apparatus for pH potential measurement at high pressure (a) apparatus overview; (b) pH sensor unit connected with multimeter and data acquisition system; (c) details of pH sensor unit.

Heat Sensor-Harsh Environment Adaptable Thermionic Sensor

Performer: Palo Alto Research Center Incorporated

Collaborator(s): SEI and ESL are to construct the sensor

Award Number: FE0013062

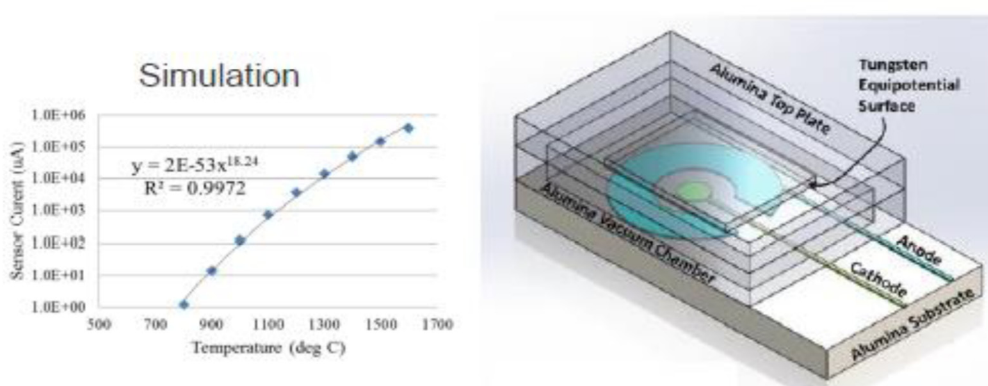
Project Duration: 10/1/2013 – 2/29/2016

Total Project Value: $1,822,037

Technology Area: Plant Optimization Technologies

The objectives of this project are to first develop and demonstrate the operation of the thermionic element; second, to develop and validate the performance of a functional Generation 1 temperature and pressure sensor; third, to develop and demonstrate the pathway to a Generation 2 multi-parameter wireless sensor; and finally, to achieve sufficient design and performance maturity to support the commercialization of the HEAT sensor technology. The thermionic element is the basic building block of the Harsh Environment Adaptable Thermionic (HEAT) platform, requiring architecture design, materials selection, and fabrication process development. The HEAT sensors will be designed for operation in environments with temperatures of 750 °C to 1600 °C, pressures up to 1000 psi, and gaseous environments consisting of hydrocarbons, oxygen, water vapor, carbon dioxide, carbon monoxide, SO_x, and NO_x. The Generation 1 HEAT sensor will integrate thermionic elements into a functional package capable of measuring temperature and pressure over the target range of environmental conditions, and amplifying the resulting signals for data transmission over wire. The Generation 2 HEAT sensor will expand the capability to measure additional process parameters such as strain, flux, and flow rate, as well as incorporating energy harvesting, wireless data transmission, and complete vacuum sealing for a fully wireless configuration. Concept designs and experimental validation of the key enablers for these additional capabilities will be completed, with a stretch goal to advance as far as possible towards demonstration of a fully integrated Generation 2 HEAT sensor package.

The project team will pursue technology transfer through the transition of the HEAT sensor technology first to Fossil Energy systems and then to the general commercial market for applications that require sensing in similar harsh environments. The team will leverage this joint investment to develop the high-quality technical and economic data package necessary to execute the process of working with leading market partners to transition the technology.



HEAT temperature sensor design.

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

Performers: Sporian Microsystems Inc.

Award Number: SC0008269

Project Duration: 6/28/12 – 8/13/2015

Total Project Value: $1,159,954

Technology Area: Plant Optimization Technologies

This novel concept attempts to develop ultra-high temperature "smart" sensors from silicon carbon nitride (SiCN) materials for energy generation and aerospace systems. The sensors will be developed from innovative fabrication processes and contain internal compensation, health check and data bus support to the interface.

In order to do this, the project will build 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 °C. Secondly, the project will construct and fabricate designs for multiple sensors to produce bench-pilot scale operable demonstration ready sensing.

By continuous condition monitoring of high temperature surrounding using these sensors, one can expect to lower failure rates, improved contact and reduced moisture collection with sensing at the source and an overall lower cost associated with life and system failures.

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

Performers: Tech4Imaging

Award Number: SC0010228

Project Duration: 6/11/2013 – 7/27/2016

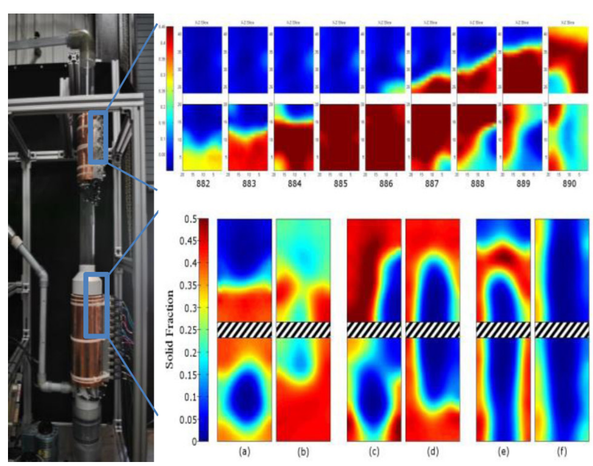
Total Project Value: $1,149,686

Technology Area: Plant Optimization Technologies

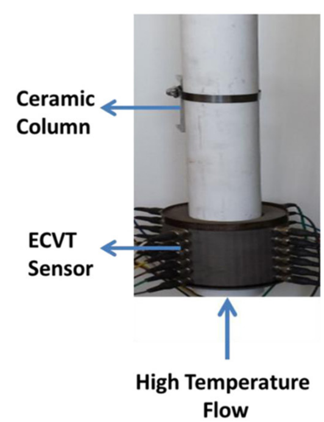
Controlling emissions and increasing efficiencies are essential requirements in future advanced power plants. Herein, next generation power systems require greater flexibility in their operations for meeting the higher efficiency and lower emissions conditions that are geared toward meeting consumer demand and adhering to increased regulatory standards, simultaneously. Those requirements can be met by developing non-invasive imaging systems that can reveal details of combustion and power generation flow systems toward their optimization.

In this phase II effort, Tech4Imaging will develop a system based on capacitance sensors. Capacitance sensors were successfully used to image flow variables in cold flow systems. An Electrical Capacitance Volume Tomography (ECVT) system was successfully developed for that objective. Capacitance sensors exhibit favorable features of safety, flexibility, and suitability for scale-up applications that make them a favorable solution for industrial applications. In Phase I, a feasibility of using capacitance sensors for imaging flow variables in harsh conditions; typical in power generations systems; was established. 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 utilized for testing ECVT sensors. A mass-Gauging method was also devised to measure mass-flows of process variables, in real-time. Results from tasks conducted in Phase I will be used to develop a full ECVT system for power generation systems at high temperatures. Phase II tasks will focus on optimizing sensors, electronic hardware, and feature extraction software for hot flow applications.

Successful completion of this project will result in significant public benefit due to the potential of this technology in helping the energy industry increase efficiencies and lower emissions. The proposed system would also advance multi-phase flow research of hot systems by providing access to obscure locations of a flow system. It also has a very high potential of attracting commercial interests as the need for advanced instrumentation is imminent to address the increased sophistication of advanced power plants. This would also benefit the public by spurring economic growth.



NETL CLC Demo Unit, ECVT Sensors.



4in & 2in Sensors, CLC Demo.

Additive Topology Optimized Manufacturing with Embedded Sensing

Performer: United Technologies Corporation

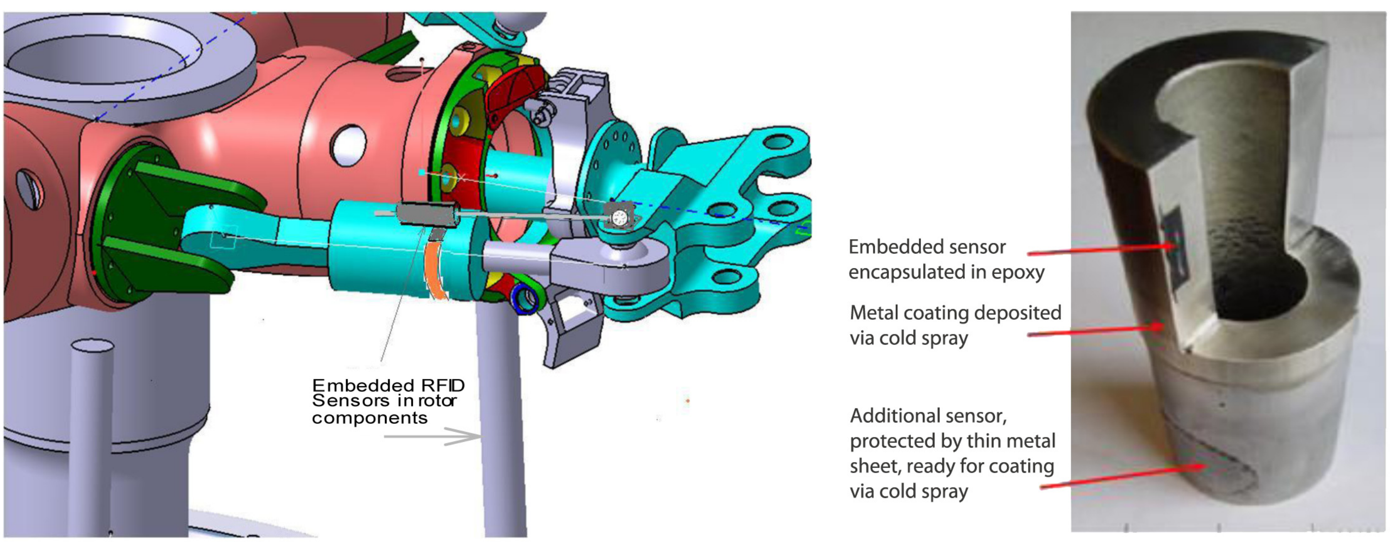
Award Number: FE0012299

Project Duration: 10/1/2013 – 9/30/2016

Total Project Value: $1,482,700

Funding Source: Plant Optimization Technologies

United Technologies Research Center (UTRC) will seamlessly embed a suite of sensors into the industrial gas turbine airfoil to demonstrate additive manufacturing as a relevant process (when guided by physics-based models) for next-generation gas turbines. The resulting "smart part" will: be remotely powered and sensed, maintain its structural integrity, and provide real-time diagnostics when coupled to a Health-Utilization-Monitoring System (HUMS). UTRC will use physics-based models to predict the impact of placing the sensing element into a highly demanding structural component such as an INGT airfoil. The structural and process models will be used to minimize structural impact, while positioning the sensor suite for maximum information content subject to the structural constraint. Electromagnetic modeling will be used to concomitantly predict transfer of RF power and signal level as a result of embedding the sensors in a metal housing. A cold spray process will be used to actually embed the sensors into the airfoil, followed by extensive structural and electromagnetic testing. Finally, a wireless communication transponder and high-bandwidth uplink will be used to demonstrate real-time data analysis of the sensor suite using a health and utilization monitoring system.



Embedded sensor locations.

High-Temperature Wireless Sensor for Harsh Environment Condition Monitoring

Performer: University of Maine System

Collaborator(s): Environetix Technologies Corporation

Award Number: FE0007379

Project Duration: 1/1/2012 – 12/31/2015

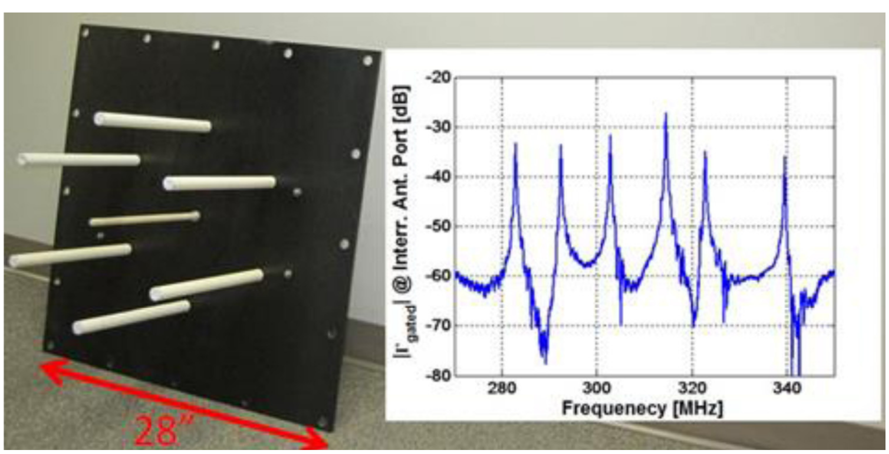
Total Project Value: $1,513,675

Funding Area: Plant Optimization Technologies

The University of Maine will develop novel high-temperature, harsh-environment, thin-film electrodes; piezoelectric smart microwave acoustic sensing elements; sensor encapsulation materials that are engineered to function reliably over an acceptable time frame at high temperature; and a radio-frequency (RF) wireless interrogation electronics unit.

The goal of the project is to develop and demonstrate the performance of small battery-free wireless microwave acoustic sensors for temperature and pressure measurement in environments up to 1200 °C and 750 psi. Specific objectives include development of thin-film electrodes, microwave acoustic sensing elements, and sensor arrays with the ultimate goal of demonstrating use of novel wireless microwave acoustic temperature and pressure sensors embedded into equipment and structures within fossil-fuel power plants to monitor the condition of components such as steam headers, reheat lines, water walls, burner tubes, and power turbines to acquire reliable real-time sensing information under harsh temperature/pressure power plant conditions.

This wireless microwave acoustic sensor technology offers several significant advantages including wireless, battery-free, maintenance-free operation. The small size and configuration of the sensors allow for flexible sensor placement and the ability to embed multiple sensor arrays into a variety of components that can be interrogated by a single RF unit. These sensing and control technologies will aid in the development of efficient and advanced near-zero-emission power systems and improve operations at existing fossil energy power plants.



Assembled sensor array test fixture and measured wireless response of array at interrogation antenna port.

Wireless sensor array viewed from interior of furnace at Penobscot Energy Recovery Company (PERC) in Orrington, Maine.

Additive Manufacture of Smart Parts with Embedded Sensors for In Situ Monitoring in Advanced Energy Systems

Performer: Missouri University of Science and Technology

Award Number: FE0012272

Project Duration: 10/1/2013 – 9/30/2016

Total Project Value: $1,879,427

Funding Source: Plant Optimization Technologies

The main objective of this three-year program is to conduct fundamental and applied research that will lead to successful development and demonstration of "smart parts" with embedded sensors for in situ monitoring of multiple parameters. Such measurements are imperative to the realization of safe operation and optimal control of advanced energy systems for enhanced reliability, improved efficiency and reduced emissions.

The proposed research focuses on solving the fundamental and engineering challenges involved in design, fabrication, integration, and application of the proposed novel "smart liner block" and "smart pipes". Innovative research will be conducted in the following subjects: (a) robust, embeddable OCMI sensors for in situ measurement of temperature (up to 1600 degrees Celsius), pressure and refractory wall cracking and thinning; (b) novel signal processing and instrumentation for distributed sensing; (c) comprehensive thermal and mechanical models of the sensor-integrated "smart parts" for optimal sensor embedment and rational interpretation of the sensor outputs; (d) multifunctional protective layers between optical carrier-based microwave interferometry (OCMI) sensor and the host materials for thermal, mechanical and chemical protection of the sensors; and (e) additive manufacturing of the smart parts with embedded sensors.

The research will be carried out in two phases. Phase I will focus on the proof of the smart part concept through the development and characterization of the individual components including the OMCI sensors, instrumentation, thermal and mechanical models, protective layers and additive manufacturing techniques/processes. In Phase II, these components will be integrated and optimized to construct smart blocks and pipes for systematic technology evaluation and demonstration under simulated conditions using test facilities in the laboratory.

Dual-laser additive manufacturing (AM) system for fabrication of "smart parts."

Laboratory test equipment.

Investigation on Pyroelectric Ceramic Temperature Sensors for Energy System Applications

Performer: University of Texas at El Paso (UTEP)

Award Number: FE0011235

Project Duration: 7/1/2013 – 6/30/2016

Total Project Value: $200,000

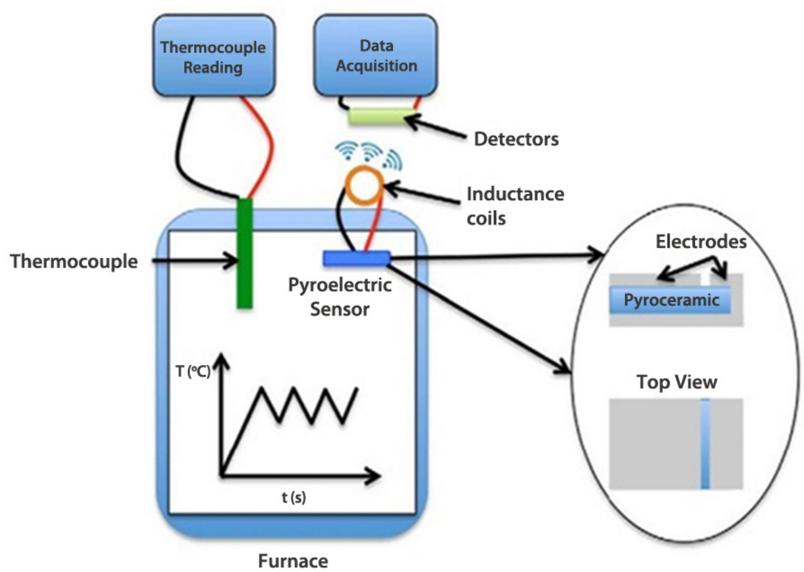
Funding Source: University Training and Research

The research team will fabricate pyroelectric ceramic films using an electrophoretic deposition process and characterize their material properties such as microstructure, morphology, and crystal structure. Pyroelectric materials generate an electric charge upon a change in temperature, and it is this effect upon which the sensor is based. Deposition by electrophoresis—the motion of dispersed particles in a fluid under uniform electric charge—has many advantages and may be achieved by a number of methods.

The wireless sensor system will be constructed using a pyroceramic and inductive coupling technique, where the current generated by the pyroceramic will, upon a change in temperature, be converted to magnetic flux that is wirelessly detected by an inductance coil. Before applying this wireless sensor system to energy systems, it will be calibrated using a commercial thermocouple as a reference. Finally, the research team will conduct torch and combustor rig testing to determine the sensor's ability to function in the energy system. A full report of the sensor's design, fabrication process, and characterization method will be delivered upon completion of the project.

The goal of the project is to develop a self-powered, low-cost wireless temperature sensor capable of withstanding harsh environments. The objectives are fabrication and characterization of pyroelectric ceramic temperature sensor materials, construction of a wireless sensing system and demonstration of its temperature sensing capability, and demonstration of wireless temperature sensing and other requisite capabilities, including data transmission and durability, at the high temperatures and harsh environmental conditions of coal-based power systems.

The proposed work may result in the development of a low-cost, reliable, extremely sensitive, high-temperature, harsh environment sensor that will help increase the affordability and efficiency and reduce emissions of advanced power plants. Additionally, participating students will receive training in the development of pyroelectric ceramic temperature sensor materials under this Historically Black Colleges and Universities research program.



Calibration and Demonstration of wireless temperature sensing.

Investigation of "Smart Parts" with Embedded Sensors for Energy System Applications

Performer: University of Texas at El Paso (UTEP)

Award Number: FE0012321

Project Duration: 10/1/2013 – 9/30/2016

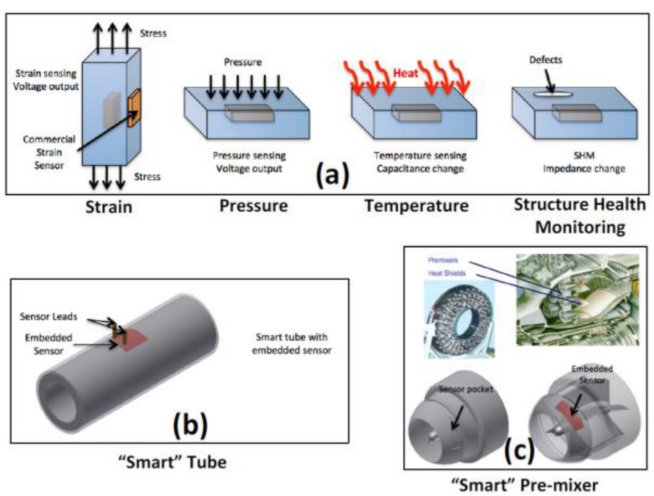
Total Project Value: $1,150,894

Funding Source: Plant Optimization Technologies

A need for laboratory-scale experiments for fabrication, testing, and characterization of "smart parts" and their relevance to fossil energy systems has been established. This work proposes to develop smart parts with embedded strain, pressure, temperature, and structural health monitoring sensors. A high Curie temperature piezoceramic and titanium will be used to fabricate the smart parts and they will be tested in three case studies simulating realistic energy system components. Expected deliverables include design, fabrication, and characterization of the smart parts, validation of the sensing capabilities, and documentation of the sensor performance in a harsh energy system environment.

This research project aims to optimize advanced three-dimensional manufacturing processes for embedded sensors in energy system components, characterize the performance and properties of these smart parts, and assess the feasibility of applying these parts in harsh energy system environments. Specific project objectives are to (1) fabricate energy system related components with embedded sensors, (2) evaluate the mechanical properties and sensing functionalities of the smart parts with embedded piezoceramic sensors, and (3) assess the in situ sensing capability of such energy system parts. This research effort will not only contribute to designing and fabricating parts, but also to determining the smart part's durability, repeatability, and stability by testing them in realistic energy environs.

The benefit of this project will be the development of advanced technologies to reduce the cost and increase the efficiency of power-generation facilities with carbon capture in eight specific pathways: sensors, controls, and novel concepts; dynamic modeling; high-performance materials and modeling; water-emissions management and controls; carbon capture simulation; carbon storage risk assessment; innovative energy concepts; and systems analyses and product integration.



Calibration and Demonstration of wireless temperature sensing.

In Situ Acoustic Measurements of Temperature Profile in Extreme Environments

Performer: University of Utah

Award Number: FE0006947

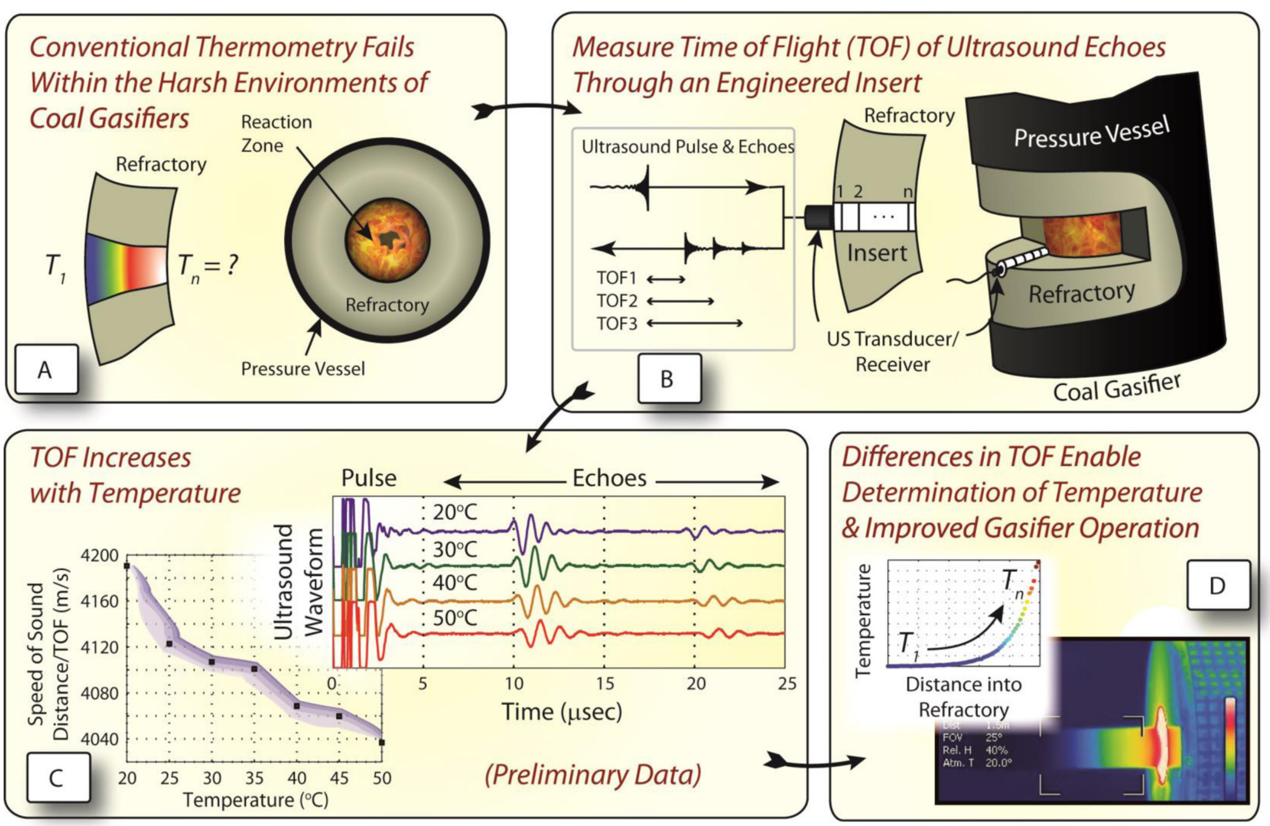
Project Duration: 10/1/2011 – 3/31/2015

Total Project Value: $300,000

Funding Source: University Training and Research

The University of Utah team is developing an ultrasound measurement technology that will provide valuable information about refractory temperature and thickness. This information will be used along with heat transfer models (one- or three-dimensional, as necessary) to characterize changes in the heat conductivity of the refractory material as a function of its degradation. A second effort tests the proposed approach in characterizing its benefits and limitations. Overall, the project aims to bring the ultrasound measurements technology to a state of readiness appropriate for subsequent industrial testing.

The project's objective was to develop in situ sensors and measurement systems for coal gasification refractory monitoring based on noninvasive and nondestructive ultrasound measurements. By improving avoidance of costly repairs caused by refractory failure, more economical and efficient gasifier operations will ensue resulting in reduced power plant emissions and lower-cost electricity generation.



The ultrasound pulse is generated by a transducer located outside the harsh environment. The pulse propagates through an engineered material which produces multiple partial echoes (panel B). The time of flight of each echo is measured and used to calculate the speed of sound which changes with the temperature (panel C) of the corresponding segment of the refractory. By sequentially estimating the temperature of each segment, the temperature distribution along the entire path of ultrasound propagation is obtained (panel D).

Embedded Active Fiber Optic Sensing Network for Structural Health Monitoring in Harsh Environments

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Award Number: FE0007405

Project Duration: 10/1/2011 – 9/30/2016

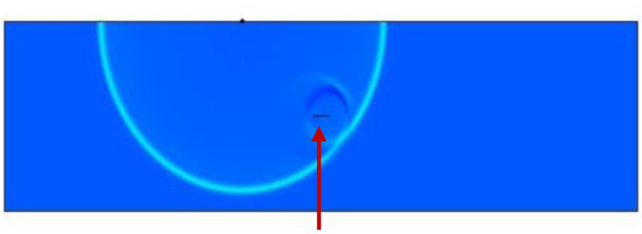
Total Project Value: $1,493,117

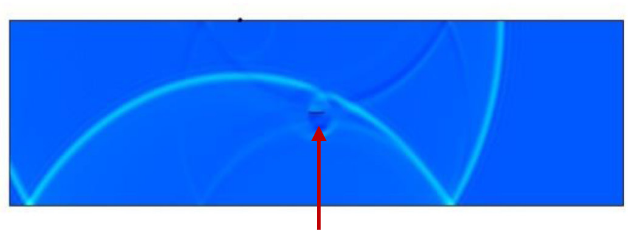
Funding Source: Plant Optimization Technologies

The Center for Photonics Technology (CPT) at Virginia Polytechnic Institute will design and construct a novel sensing network for structural health monitoring under harsh environmental conditions. The fiber-optic active sensing is based on an in-line acoustic generator and receiver created by erbium doped fiber (EDF) and fiber Bragg grating (FBG) respectively. An EDF acoustic generator will be paired with a single or multiple FBG receivers to form a basic sensing node, and a sensing network will be constructed of many such elements using wavelength division multiplexing and optical fiber switching. Each sensing element is capable of providing information from which multiple parameters (temperature, strain, corrosion and cracks) can be recovered through advanced signal processing. This technology also has the potential to multiplex a large number of integrated acoustic generator and detector pairs along a single fiber cable for long-span distributed structural health monitoring.

CPT will also develop a computational model to describe how the sensor signal is affected by the multiple environmental factors in order to guide the sensor design and provide a theoretical comparison. A sensing element will be constructed and tested to achieve performance optimization, forming the basis on which the sensor network will be designed and constructed. At the end of the project, an effort will be made to perform embedment and construct a laboratory test apparatus with which a bench-scale demonstration of multi-parametric sensing will be performed.

The goal of this three-year project is to develop a first-of-a-kind technology for remote fiber optic generation and detection of acoustic waves for structural health monitoring in advanced power systems. Specific objectives include designing the fiber optic element for non-destructive evaluation (FO-NDE), demonstrating the FO-NDE element, and testing the sensor in a simulated environment. The technology requires no electric power supply at the monitoring site and the detected acoustic signal as well as the additional returned optical signal will allow extraction of information about multiple material conditions including temperature, strain, corrosion, and cracking.





Simulated first order (left) and second order (right) echos of a short acoustic pulse on a small crack in the middle of a metal plate. The crack positions are marked by the red arrows.

Development of Self-Powered Wireless-Ready High Temperature Electrochemical Sensors of In Situ Corrosion Monitoring for Boiler Tubes in Next Generation Coal-Based Power Generation Systems

Performer: West Virginia University Research Corporation

Collaborator(s): International Lead Zinc Research Organization, Western Research Institute, Special Metals Corp.

Award Number: FE0005717

Project Duration: 10/1/2010 – 6/30/2015

Total Project Value: $1,175,827

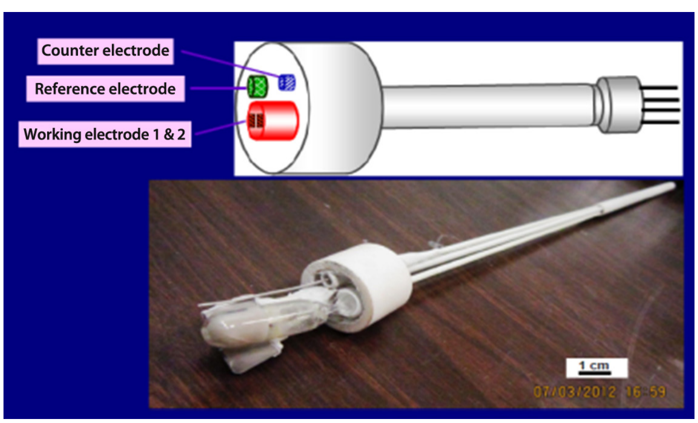
Funding Area: Plant Optimization Technologies

In this project, West Virginia University (WVU), the International Lead Zinc Research Organization, Special Metals Corporation (SMC), and Western Research Institute (WRI) have partnered to develop in-situ corrosion monitoring sensors for fireside corrosion of ultra-supercritical (USC) boiler tubes in next-generation pulverized coal-fired power plants. Through analysis of the currently available data, the project team believes the shortcoming of current sensors is the lack of a reliable high-temperature reference electrode, which provides the reference point for all the electrochemical readings and analysis.

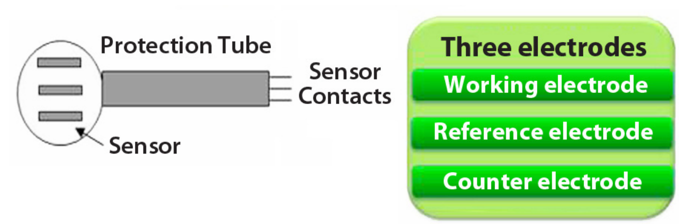
To address this issue, the project team will experiment with different materials for the reference electrode components, including the glass ceramic tube, electrode wire, and electrolyte solution, that are resistant to oxidation and chemical attack at high temperatures. In particular, the research team is investigating the use of beta alumina, which is considered a high quality high-temperature sodium ion conductor, for the electrode's internal wire reference membrane. Other materials being considered by the researchers include alpha alumina and other ceramics for the tube.

In-situ corrosion monitoring validation will be conducted for several key alloys with conditions closely simulating USC boiler tubes operating conditions. Advanced condition-monitoring networks will play an essential role in meeting these challenges by helping to enhance the overall reliability and performance of advanced fossil-energy power plants.

The project will enhance the ability for real-time corrosion monitoring, enabling the reduction of the number of forced outages and the avoidance of unplanned events in ultrasupercritical boilers. This research will also be leveraged to other applications where corrosion in high temperature processes is a concern.



High temperature electrochemical corrosion rate probe sensor developed on the project.



Coupled Multielectrode Sensor (CMS) probes.

Graphene-Based Composite Sensors for Energy Applications

Performer: West Virginia University Research Corporation

Award Number: FE0011300

Project Duration: 7/17/2013 – 7/16/2016

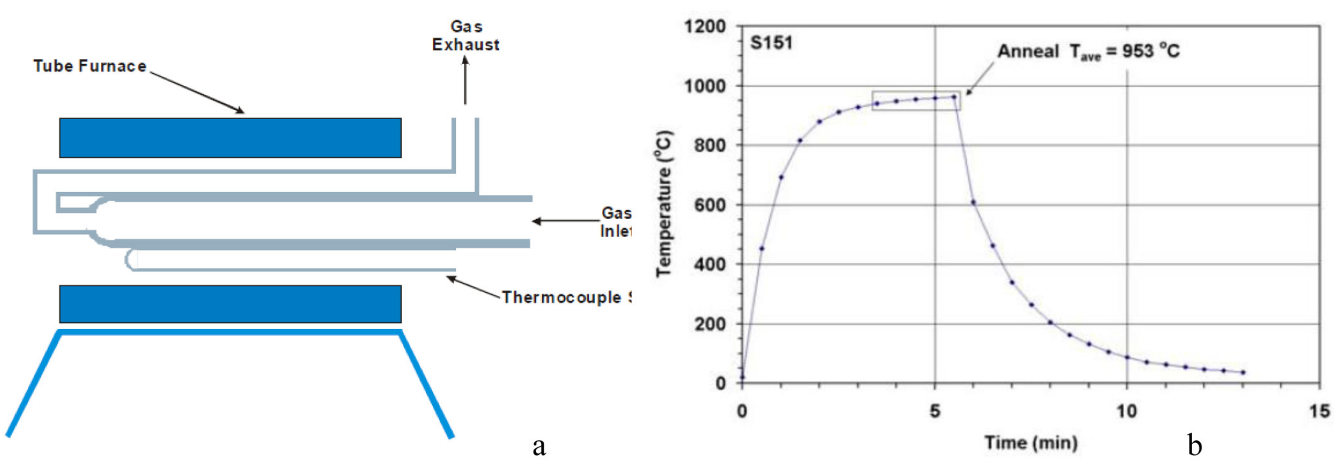
Total Project Value: $300,000

Funding Source: University Training and Research

The objectives of this research are to develop and demonstrate the use of graphene-based composites as a high sensitivity, rapid response electronic nose for sensing gas species in energy applications. Graphene-based materials that support sensing structures in the temperature range of 600 °C–1000 °C will be targeted. The scope of work includes (a) establishing procedures for controllable nucleation and growth of nanoparticles on graphene surface defects as a basis for selective gas sensing, (b) fabrication of graphene-based composite sensors, (c) fabrication of ruggedized deployable graphene-based composite sensors, (d) establishment of the electrical properties of graphene-based composites, (e) establishment of the characteristics of graphene-based composite sensors in simple mixtures, (f) establishment of the characteristics of graphene-based composite sensors in simulated environments, and (g) testing of the graphene-based sensors in representative environments and applications.

This work will focus on deriving, implementing, and testing agent-objective functions that promote coordinated behavior in large heterogeneous sensor networks. The long-term objective of the proposed work is to provide a comprehensive solution to the scalable and reliable sensor coordination problem to lead to safe and robust operation of advanced energy systems.

The objectives support this goal by first ensuring that the information collected by the heterogeneous sensors provides the greatest added value to the full network, and then by ensuring that that information can be effectively used to improve advanced power system performance. The method will be tested to ensure robust network operation and good response to system changes.



(a) Experimental setup for rapid thermal annealing; (b) Typical annealing profile for RTA samples.

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: 10/1/2013 – 9/30/2016

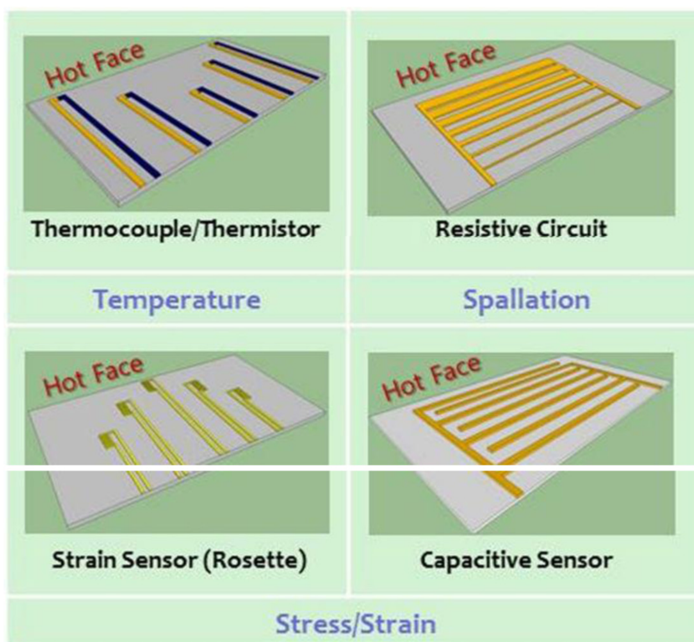
Total Project Value: $1,617,113

Funding Source: Plant Optimization Technologies

The United States Department of Energy (DOE) National Energy Technology Laboratory (NETL) has partnered with West Virginia University 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 West Virginia University (WVU), in collaboration with ANH Refractories Company (ANH), 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.

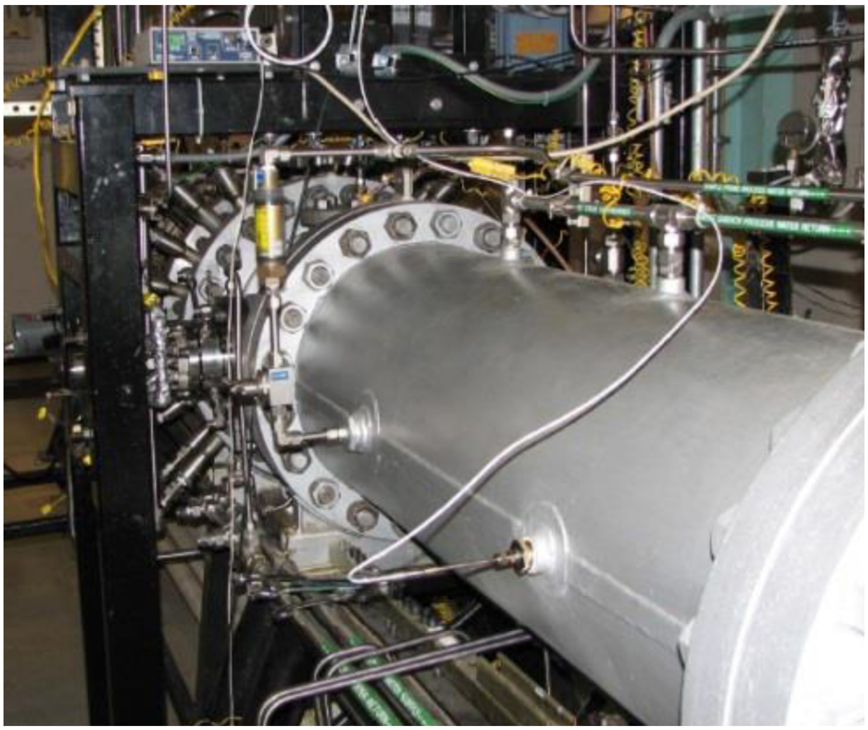


Schematics depicting possible embedded sensor designs. (Source: West Virginia University Project Narratives).

Distributed Intelligent Controls

Advanced Process Control

Dynamic process modeling encompasses computational efforts to represent physical systems and processes by developing and using 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 fast 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 these approaches but incorporates new approaches that have the ability to develop control systems with fast dynamics for nonsteady- state and incorporate controls that are capable of handling systems that are inherently nonlinear. Accomplishing these developments, with real system validation, provides significantly increased control compared with that of traditional proportional-integral-derivative (PID) control and is more robust than linear model predictive control algorithms.



Merged Environment for Simulation and Analysis (MESA)

Performer: Ames National Laboratory

Award Number: FWP-AL-12-470-009

Project Duration: 5/1/2012 – 9/30/2015

Total Project Value: $1,425,000

Funding Source: Plant Optimization Technologies

Advanced power plants that utilize fossil fuel require higher efficiencies and lower emissions than have been attained in order to provide for future power consumption needs while meeting higher regulatory standards. Current control strategies involve a hierarchical framework that utilizes large numbers of sensors to collect data to operate a small number of actuators, which can limit power plant efficiency. Advanced control strategies are needed that use embedded intelligence at the sensor and component level to make faster decisions based on local information.

The goal of this project was to develop a merged environment for simulation and analysis (MESA) at NETL's hybrid fuel cell turbine laboratory. The research under MESA provided a development platform for investigating: (1) advanced sensors with control strategies; (2) testing and development of sensor hardware; (3) various modeling in the loop algorithms; and (4) other advanced computational algorithms for improved plant performance using sensors, real-time models, and complex systems tools. The first step in the development of this facility was to integrate the graphic and computational representation of the HYPER facility with the physical facility. This created a dynamic integrated computational environment capable of supporting a broad range of control and operations algorithms based on the merged physical and computational environment using smart sensors and other components. Data gathered from NETL's facility will be used to model advanced power system software in an all-encompassing integrated computational environment (ICE); under separate construction) in order to test advanced sensors and controls and other complexity-based strategies in the NETL ICE lab. The data gathering was also used to determine potential sensor locations and plant actuations while implementing novel (or advanced) control and smart-sensing capabilities, including the use of biomimetic methodologies. The advanced control methods were then tested in the ICE and demonstrated to have the ability to control the experimental facility. The project concluded with a demonstration of various sensor and control strategies on an advanced power system and a comparison between conventional control strategies and novel and advanced sensor and control strategies. Ames Laboratory worked closely with key technical personnel within NETL to ensure that capabilities developed in this project are extensible to other systems and applications.

Rendition of hyper facility in both real and virtual space.

Innovative Process Technologies–Advanced Controls Testing and Development

Performers: National Energy Technology Laboratory – ORD

Award Number: FWP-2012.04.01.2

Project Duration: 10/1/2014 – 9/30/2015

Total Project Value: $599,952

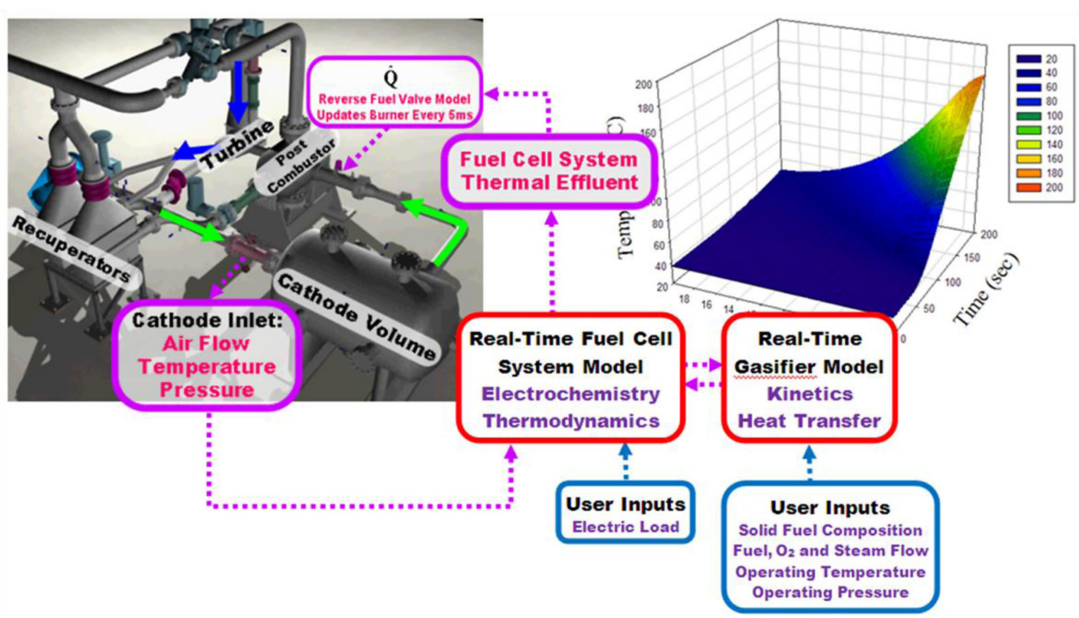
Technology Area: Plant Optimization Technologies

The purpose of this advanced controls research project is to develop and test control approaches to overcome the barriers associated with the coupling of highly disparate power generation technologies, enhancing energy security though expanding operating flexibility and improved overall energy conversion efficiency.

The scope of this research is to develop advanced controls strategies for advanced power plants, and to perform screening or testing of extramurally developed advanced controls, identified in collaboration with Strategic Center for Coal (SCC). The development and testing of advanced controls for power generation systems will include modeling and analysis of components in advanced power generation systems with nonlinear coupled elements, as well as the development of corresponding transfer functions for fully coupled hardware simulations.

Novel controllers will be developed using transfer functions and evaluated against standard methods of control (proportional integral derivative [PID]). Experimental testing will use the HYPER Facility which provides a mid-scale test facility for the control of advanced power systems. The facility's primary configuration is set up to address the component integration of high-efficiency hybrid power systems making use of a recuperated turbine cycle for heat recovery.

The focus of recent work has been in the area of integrated gasifier-fuel cell-turbine (IGFCT) hybrid power systems control. Progress has been made on several issues for control of the system, including safe and rapid shutdown, load following, startup, fuel flexibility, nonlinear actuator coupling, and component degradation. However, these pre-commercial research issues still remain as the main technical barriers for IGFCT and any other highly coupled advanced power systems.



HYPER facility technical operations illustration.

Evolving Robust and Reconfigurable Multi-Objective Controllers for Advanced Power Systems

Performer: Oregon State University

Award Number: FE0012302

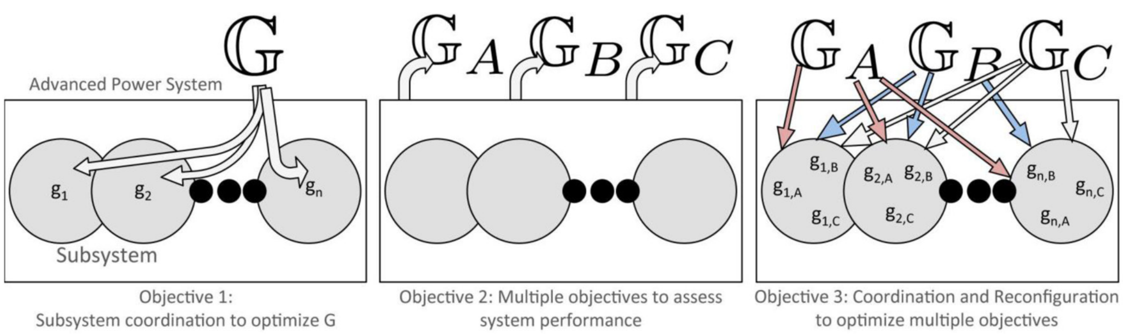
Project Duration: 10/1/2013 – 9/30/2016

Total Project Value: $1,401,192

Funding Source: Coal Utilization Science

This work will focus on deriving, implementing, and testing biomimetic control and multi-objective optimization algorithms that promote robust and reconfigurable performance in an advanced power system. The long-term objective of the proposed work is to provide a comprehensive solution to the scalable and robust multi-objective control of an advanced power system where no detailed system model is required for real-time control. To achieve this long-term objective, the control algorithms can account for multiple, possible dynamic objectives in a safe and reliable manner. Work will be done to evaluate the effectiveness of the biomimetic control algorithm as well as the multi-objective control algorithm. The algorithms will then be tested to ensure robust, scalable, and reconfigurable performance in an advanced power system.

The first impact of this work is to provide an implicit model of the system interactions through the derivation of the subsystem objectives, and to enable the use of biomimetic control approaches. The second impact is the extension of those results to multi-objective settings which directly enables the control of advanced power systems. Finally, the third impact is to derive coordination mechanisms that allow the system to be reconfigured in response to changing needs (e.g., sudden external events requiring new responses) or changing power plant characteristics (e.g., sudden changes to plant condition).



High level description of the objective decomposition.

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

Performer: West Virginia University Research Corporation

Collaborator(s): Vishwamitra Research Institute

Award Number: FE0012451

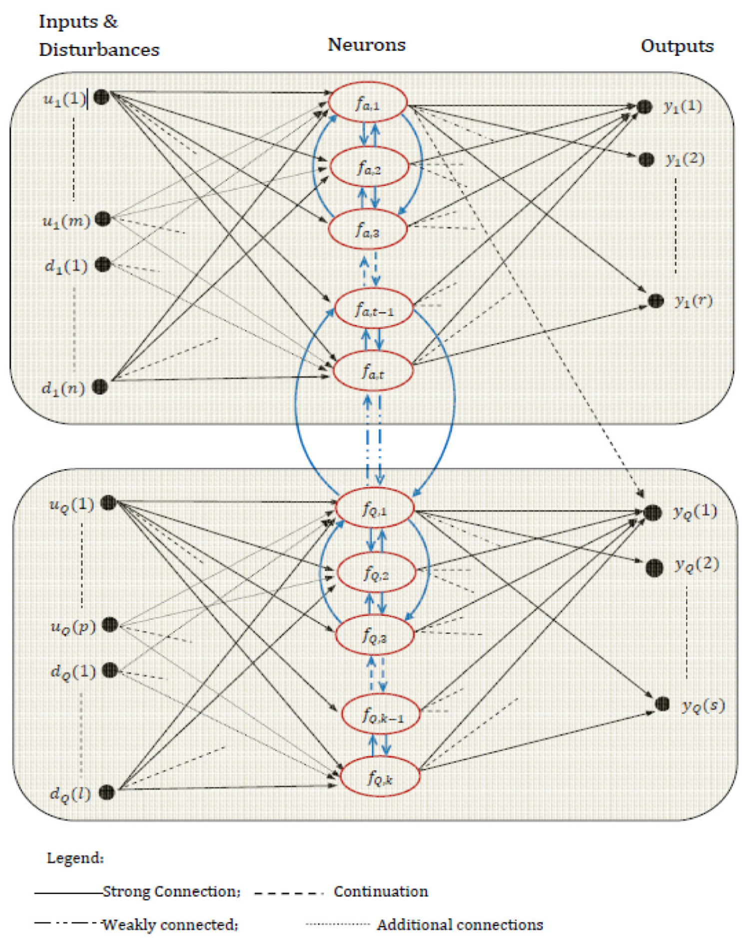
Project Duration: 1/15/2014 – 1/14/2017

Total Project Value: $1,403,611

Funding Source: Plant Optimization Technologies

The objective of this proposed research is to develop algorithms and methodologies for designing biomimetic control systems that utilize distributed intelligence for optimal control of advanced energy plants. The algorithms developed will be applicable to other processes and power plants for which plant models are available.

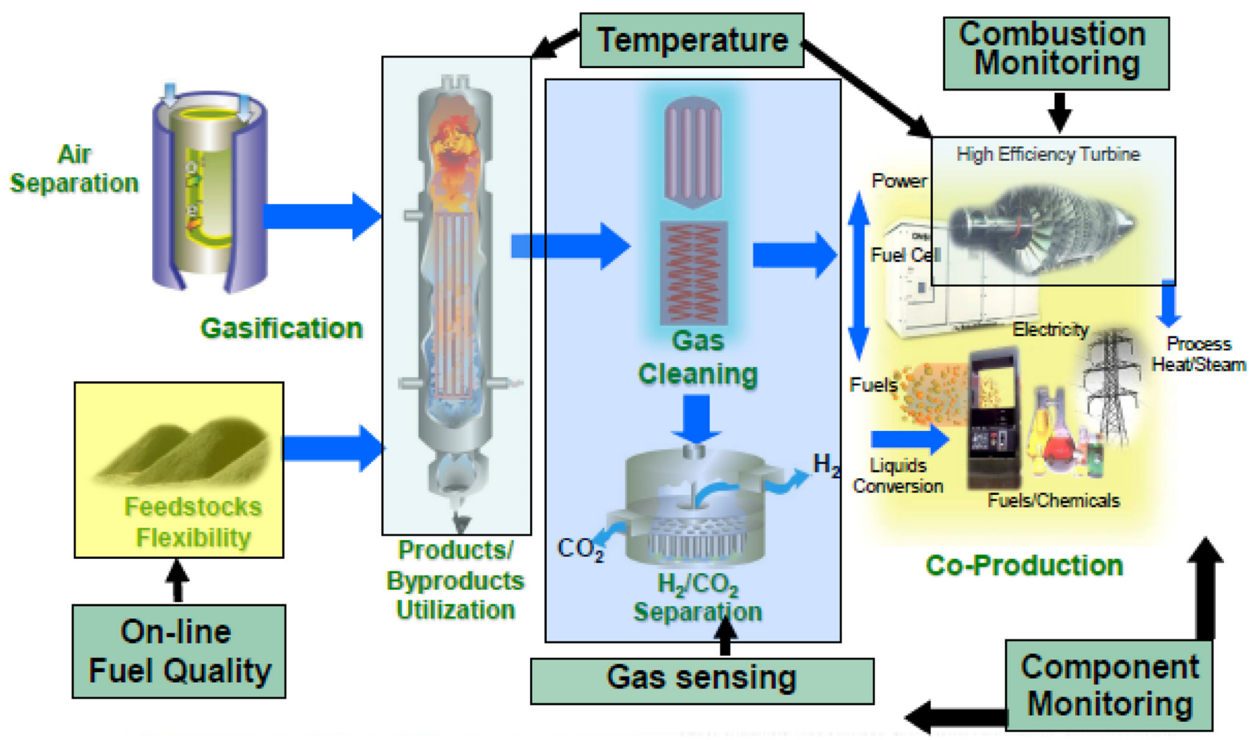
West Virginia University Research Corporation will develop and implement biomimetic-based control methodologies for the control system in general, including deterministic, stochastic and adaptive components.



Self-organizing, biometric control structure selection.

Sensor Placement and Networks

This research focus is a transformational effort that attempts to unify and apply a wide range of novel computational and measurement approaches to derive value and improve operation and control of complex systems. This research focus area encompasses novel computational approaches to optimize sensor placement for various objectives (e.g., performance, fault management, cost) and to enable cognitive capability within sensing and actuation components such that intelligence can be distributed within a control architecture. This distribution of intelligence, coupled with self-organization of actuation and sensing devices, is anticipated to offer a robust approach to managing fast dynamics and large amounts of data/information; and it addresses the need to make many decisions in millisecond time scales for a large and highly integrated power system with carbon capture. Measures for this area include the correct identification of algorithms and architecture to permit novel approaches to be combined and operated as a unified system. NETL has developed simulation tools and a hardware-based test bed to evaluate concepts and to provide a platform to assess the value of these breakthrough concepts.



Performer	Project Title	Page
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Case Western Reserve University	An Information Theoretic Framework and Self-Organizing Agent-Based Sensor Network Architecture for Power Plant Condition Monitoring	58
Oregon State University	Intelligent Coordination of Heterogeneous Sensors in Advanced Power Systems	59
Texas Tech University System	Model-Based Sensor Placement for Component Condition Monitoring and Fault Diagnosis in Fossil Energy System	60
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High-Density Sensor Network Development

Performer: Ames National Laboratory

Award Number: FWP-AL-06-205-020

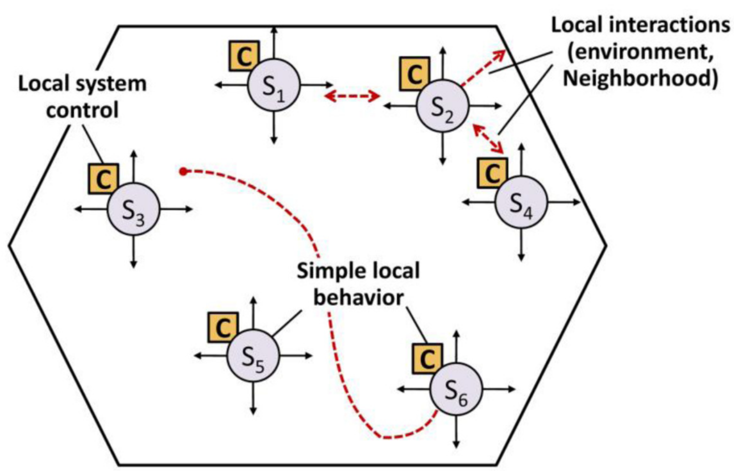
Project Duration: 2/20/2006 – 9/30/2014

Total Project Value: $2,213,000

Funding Source: Plant Optimization Technologies

The cost of various sensors is dramatically dropping, the capability of sensors is increasing, and the demands for control and sensing in advanced power plants are significant. Based on this, future sensor development should consider implementation of large-scale, high-density sensor networks. These networks may include a large variety of sensors ranging from simple temperature and pressure measurement with little on-board processing capability, to those with advanced lab-on-a-chip capabilities. Due to the size and complexity of such sensor networks, the sensors will need to be synchronized and orchestrated to provide useable information to significantly improve power plant control and engineering capability necessary to achieve high efficiency and near-zero emissions.

The goal of this project was to develop the understanding, algorithms, and synchronization strategies needed to utilize large-scale, high-density sensor networks in advanced power plants. If the low-cost sensing is to be realized, then microsensors will need to have enhanced capabilities and be able to measure more and different kinds of information. In addition, because they will be smaller and significantly less expensive, they will have the potential to be widely utilized and provide many more times the amount of useable information gathered by current systems. They will preprocess the data on the chip and will, in some cases, be able to respond to requests for new types of data. A first reaction to this revolution in sensing technology is that more data is more beneficial. However, there are significant challenges to interaction with these microsensors and control of a new-generation power plant. The coming flood of data will challenge current data handling and processing strategies and change how sensors are used. This project is a basis to support this new paradigm in sensing and is based on managing and working with sensors as smart, self-organizing devices that can perform tasks as a group. Central to this strategy is the task of the synchronization of heterogeneous sensors with widely varying capabilities using strategies based on self-organization.



Management and control in self-organizing systems.

An Information Theoretic Framework and Self-Organizing Agent-Based Sensor Network Architecture for Power Plant Condition Monitoring

Performer: Case Western Reserve University

Collaborator(s): The Charles Stark Draper Laboratory and Alstom

Award Number: FE0007270

Project Duration: 11/1/2011 – 10/31/2015

Total Project Value: $1,934,017

Technology Area: Coal Utilization Sciences

Advanced combustion, gasification, turbine, carbon capture, and gas cleaning and separation technologies are used in highly efficient, low-emissions power systems. This requires sensor, communications, and control systems capable of operating in high-temperature and -pressure environments with highly reactive and corrosive process conditions. These systems are complex, with operational constraints and system integration challenges that push the limits of traditional process controls. Robust sensing technologies, including durable materials and highly automated process controls, are needed to optimize the operation and performance of these advanced systems.

The goal of this project is to develop an information-theoretical sensing and control framework and companion computational algorithms that maximize the collection, transmission, aggregation, and conversion of data to information. This integrative framework will use relationships among control, estimation, signal processing, and communication theory to provide five key innovations: (1) exploiting the deep connection between information theory and the thermodynamic formalism; (2) enriching the information content of available observations by addressing the intrinsic relationship between estimation and control within an information-theoretic context; (3) using virtual sensors to discover the correlative structure of the available observations and fuse information from disparate sources; (4) using compressive sensing algorithms in a networked setting; and (5) deploying, testing, and validating distributed intelligent agents in a hardware-in-the-loop simulation environment.

Specific project objectives include: (1) developing an intelligent agent-based information-theoretic architecture for advanced power plant applications; (2) developing computational algorithms to be employed by intelligent agents that maximize the collection, transmission, aggregation, and conversion of data to actionable information for monitoring and controlling power plants; and (3) evaluating the effectiveness of these algorithms in organizing agents to maximize information content from power plant data through an integrated hardware-in-the-loop simulation test bed.

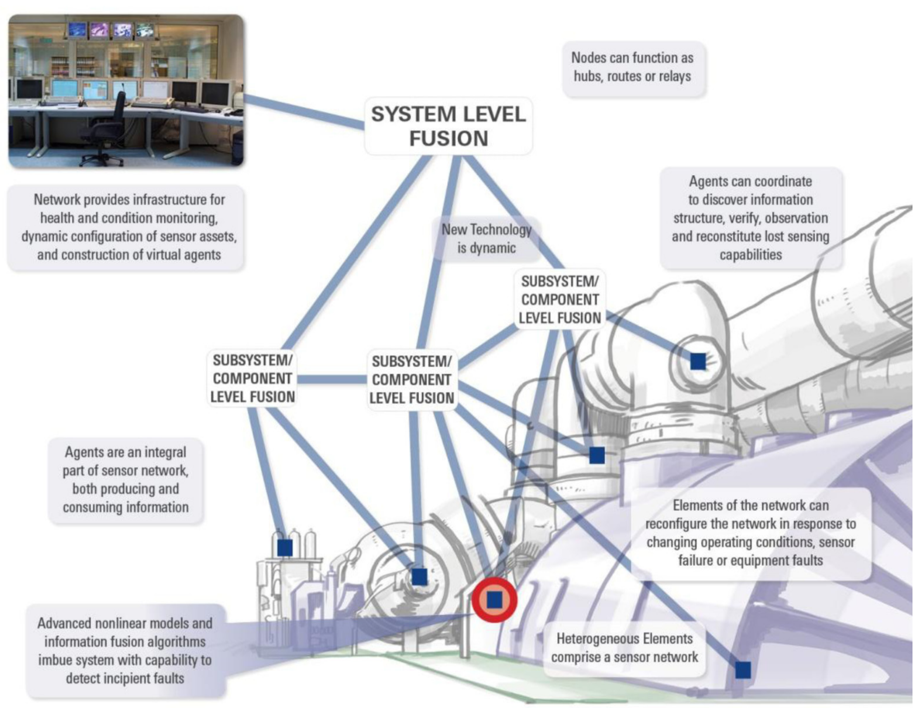


Diagram of system level fusion of sensor.

Intelligent Coordination of Heterogeneous Sensors in Advanced Power Systems

Performer: Oregon State University

Award Number: FE0011403

Project Duration: 9/13/2013 – 3/12/2015

Total Project Value: $299,991

Funding Source: University Training and Research

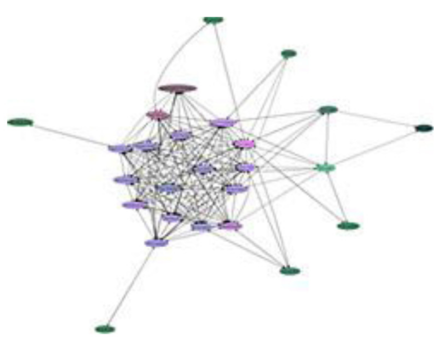
This work focused on deriving, implementing, and testing agent objective functions coupled with algorithms that promote coordinated behavior in large networks of heterogeneous sensors with embedded intelligence. The long-term objective of this work is to provide sensor deployment, coordination, and networking algorithms for large numbers of sensors to ensure the safe, reliable, and robust operation of advanced energy systems. Two specific objectives are to:

1. Derive sensor performance metrics for heterogeneous sensor networks.

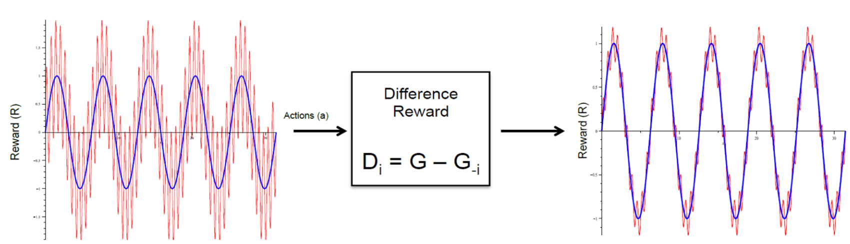
2. Demonstrate effectiveness, scalability and reconfigurability of heterogeneous sensor network in advanced power systems.

The two objectives support this goal by first ensuring that the information collected by the heterogeneous sensors has the greatest added value to the full network, and then by ensuring that that information can be effectively used to improve advanced power system performance. The method will then be tested to ensure robust network operation and good response to system changes.

The key technical contribution of this work is to push the coordination step to the design of the objective functions of the sensors, allowing networks of heterogeneous sensors to be controlled. By ensuring that the control and coordination is not specific to particular sensor hardware, this approach enables the design and operation of large heterogeneous sensor networks. In addition to the coordination mechanism, this approach allows the system to be reconfigured in response to changing needs (e.g., sudden external events requiring new responses) or changing sensor network characteristics (e.g., sudden changes to plant condition).



Distributed sensor network.



Demonstration of cleaned up sensor signal.

Model-Based Sensor Placement for Component Condition Monitoring and Fault Diagnosis in Fossil Energy System

Performer: Texas Tech University

Collaborator(s): West Virginia University

Award Number: FE0005749

Project Duration: 1/1/2010 – 12/31/2015

Total Project Value: $981,909

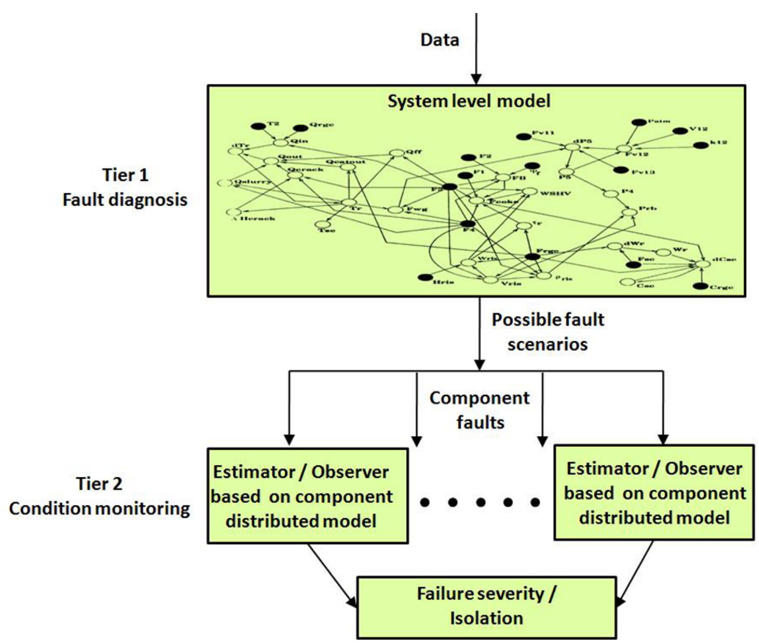
Funding Source: Plant Optimization Technologies

Fossil fuel power plants generate about two-thirds of the world's total electricity and are expected to continue to play an important role in the future. Increasing global energy demands, coupled with the issues of aging, inefficient power plants, and increasingly strict emission requirements, will require high levels of performance, capacity, efficiency, and environmental controls from energy generation facilities. Advanced condition-monitoring networks will play an essential role in enabling power plants to meet these challenges by enhancing the overall reliability, performance optimization, and availability of emerging near-zero emissions power production systems.

In this project, Texas Tech University (TTU) and West Virginia University (WVU) will develop model-based sensor placement algorithms for maximizing the robustness and effectiveness of the sensor network to monitor the plant health both at the unit level and at the systems level. This will be achieved by developing a two-tier sensor network algorithm capable of performing component condition monitoring and system-level fault diagnosis. The algorithms will be implemented on a plant-wide simulation of a coal-based integrated gasification combined cycle (IGCC) plant with a rigorous gasifier model.

To meet the objective, a comprehensive list of faults in a typical IGCC plant will be identified. Structural changes to the Aspen Dynamics™ (Aspen Technology, Inc.) model will be performed to incorporate simulation models for the identified faults. Sensor placement algorithms for condition monitoring and fault diagnosis will be developed and tested on the plant-wide dynamic IGCC model.

The result of this project will be model-based sensor placement algorithms that will increase the efficiency and effectiveness of fossil energy systems sensor networks. More specifically, the sensors will monitor the status of equipment, materials degradation, and process conditions that impact the overall health of a component or system in the harsh high-temperature, highly corrosive environments of advanced power plants.



Model-based sensor placement algorithms.

Multi-Objective Optimal Sensor Deployment under Uncertainty for Advanced Power Systems

Performer: University of Illinois

Award Number: FE0011227

Project Duration: 9/1/2013 – 8/31/2016

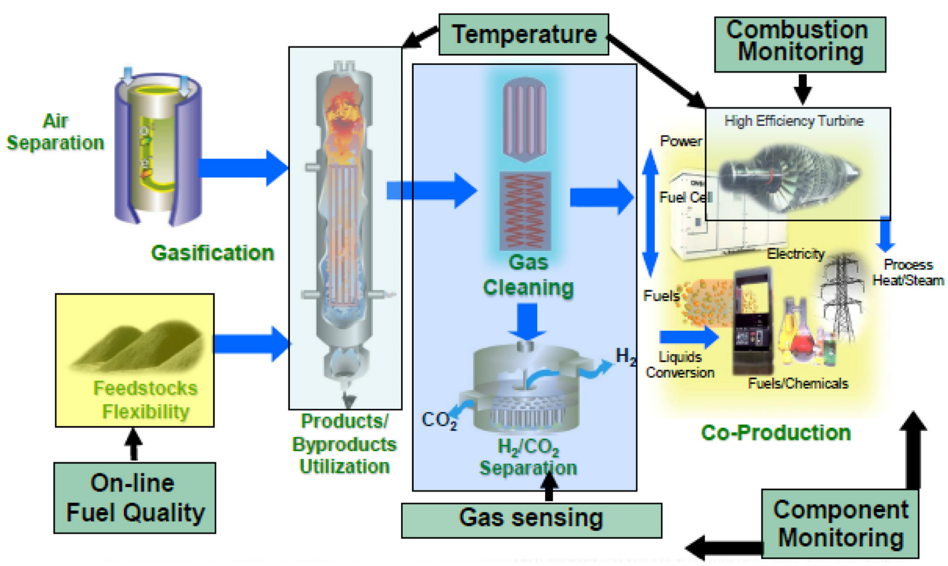
Total Project Value: $300,000

Funding Source: University Training and Research

The proposed work will focus on a virtual sensing framework developed by considering a suite of physical models consisting of computational modeling, reduced order modeling, and system-level modeling. In addition to developing a virtual sensing framework, process models will be used to obtain a relationship between type, number, and location of sensors in the plant to achieve the following objectives: observability, cost effectiveness, efficiency, and low environmental impact. The problem of sensor placement will be formulated as a multi-objective stochastic programming problem to obtain the optimal sensor locations for a specific advanced power system in the face of uncertainty in performance, costs, and power demand.

The goal of the project is to develop a virtual sensing capability and multi-objective stochastic programming capability for optimal sensor placement under uncertainty conditions for advanced power systems that comply with Computer Aided Process Engineering –OPEN (CAPE-OPEN) standards for interfacing components for chemical processes. Other programming objectives include the attainment of efficiency, maximum information collection, and cost-effectiveness. In order to solve this large-scale optimization under uncertainty conditions, a new algorithmic framework will be developed. The virtual sensing capability and the algorithmic framework will be integrated into one CAPE-OPEN-compliant capability and will be tested on various virtual case scenarios.

Potential benefits include development of advanced technologies to reduce the cost and increase the efficiency of power-generation facilities with carbon capture in eight specific pathways: sensors, controls, and novel concepts; dynamic modeling; high-performance materials and modeling; water-emissions management and controls; carbon capture simulation; carbon storage risk assessment; innovative energy concepts; and systems analysis and product integration.



Prioritized sensing needs in advanced power systems.

Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Performers: University of Texas at Arlington

Collaborator(s): UC San Diego

Award Number: FE0023118

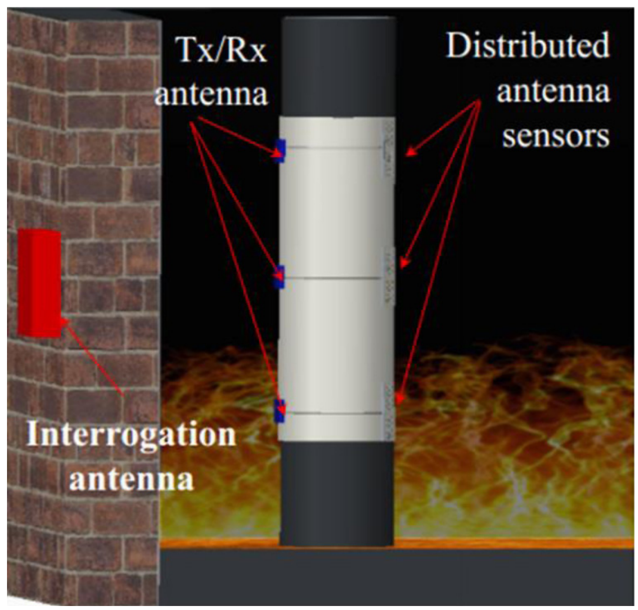
Project Duration: 1/1/2015 – 12/31/2017

Total Project Value: $434,079

Technology Area: University Training and Research

University of Texas Arlington (UTA) and UC San Diego will develop wireless antenna sensors to provide distributed sensing of temperature, strain, and soot accumulation inside a coal-fired boiler. The objectives for 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 distance 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 when the optimal planned soot cleaning should take place as well as by safeguarding from overly high temperatures in a high-pressure corrosive environment. The benefit of this project includes distributed sensing for in-process control, real-time health assessment of structural components, and improved heat transfer efficiency of boilers.



Distributed condition monitoring of steam pipes.

Abbreviations

3-D . . . . three-dimensional

AI. . . . artificial intelligence

$Al_xGa_{1-x}N$ . . . . aluminum-gallium-nitrogen

C . . . . Celsius

CCBG . . . . coaxial cable Bragg gratings

CCFPI. . . . coaxial cable Fabry-Perot interferometers

CCSI . . . . Carbon Capture Simulation Initiative

CO. . . . carbon monoxide

Co . . . . cobalt

CO_2 . . . . carbon dioxide

CPT. . . . Center for Photonics Technology

CUS . . . . Coal Utilization Sciences

DOE . . . . Department of Energy

ECVT . . . . Electrical Capacitance Volume Tomography

EDF. . . . erbium doped fiber

EMI . . . . electromagnetic interference

EPA. . . . Environmental Protection Agency

FBG. . . . fiber Bragg grating

Fe . . . . iron

FPI. . . . Fabry-Perot Interferometer

Ga_2O_3 . . . . gallium oxide

GE. . . . General Electric

GHG . . . . greenhouse gasses

GTI . . . . Gas Technology Institute

H_2 . . . . hydrogen

H_20 . . . . Water

H_2S . . . . hydrogen sulfide

HAP . . . . hazardous air pollutants

HBCU. . . . Historic Black Colleges and Universities

HCl . . . . hydrogen chloride

HEAT . . . . harsh environment adaptable thermionic

H_g . . . . Mercury

HUMS . . . . health-utilization-monitoring system

HYPER . . . . Hybrid Fuel Cell Turbine Laboratory

ICE . . . . integrated computational environment

IGCC. . . . integrated gasification combined cycle

K . . . . kelvin

La . . . . lanthanum

LASST . . . . Laboratory for Surface Science & Technology

LBCO . . . . $LnBaCo_2O_{5+d}$, where Ln=Pr or La

LIF. . . . Laser-induced fluorescence

LM . . . . laser micromachining

MESA . . . . merged environment for simulation and analysis

NO_x . . . . nitrogen oxide

NRAP . . . . National Risk Assessment Partnership

O_2 . . . . oxygen

OCMI . . . . optical carrier-based microwave interferometry

OEM . . . . original equipment manufacturer

OMI . . . . Other Minority Institutions

PDC . . . . polymer-derived ceramics

pH . . . . power of hydrogen

PID . . . . proportional-integrated-derivative

POT . . . . Plant Optimization Technologies

ppm . . . . parts per million

p-PDC . . . . piezo-dielectric polymer-derived ceramics

R&D . . . . research and development

RF . . . . radio frequency

RFID . . . . radio frequency identification

RUL . . . . remaining useful life

SAW . . . . surface acoustic wave

SBIR . . . . Small Business Innovative Research

SeO . . . . selenium

SeO_2 . . . . selenium dioxide

SiCN . . . . silicon carbon nitride

SMC . . . . Special Metals Corporation

SO_x . . . . sulfur oxide

SPCF . . . . stochastically porous glass and sapphire photonic crystal fiber

SPS . . . . spark plasma sintering

Sr . . . . strontium

SUNY . . . . State University of New York

TDL . . . . tunable diode laser

TTU . . . . Texas Tech University

UA . . . . University at Albany

UCF . . . . University of Central Florida

UMaine . . . . University of Maine

USC . . . . ultrasupercritical

UCR . . . . University Coal Research

UTA . . . . University of Texas Arlington

UTAS . . . . UTC Aerospace Systems

UTEP . . . . University of Texas - El Paso

UTR . . . . University Training and Research

UTRC . . . . United Technologies Research Center

VTAG . . . . Virginia Tech Antenna Group

WO_3 . . . . tungsten oxide

WRI . . . . Western Research Institute

WVU . . . . West Virginia University

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http://energy.gov/fe/coal-utilization-science

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

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