Crosscutting Research & Analysis Program Sensors and Controls Project Portfolio

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

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Introduction

The Crosscutting Research and Analysis 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 Research and Analysis Program executes R&D efforts by partnering and collaborating with research institutions and the power generation industry throughout the United States and in select international locations. The 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 Research and Analysis Program. UTR is the umbrella program under which the University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) and Other Minority Institutions (OMI) initiatives operate. These grant programs address the scientific and technical issues key to achieving Fossil Energy's goals, and build our nation's capabilities in energy science and engineering by providing hands-on research experience to future generations of scientists and engineers.

In addition to the Crosscutting Research and Analysis Program 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 small businesses and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and encourages the commercialization of the technology, product, or service, which, in turn, stimulates the U.S. economy. Since its inception in 1982 as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses compete for Federal research and development awards. These contributions have enhanced the nation's defense, protected the environment, advanced health care, and improved our ability to manage information and manipulate data.

The Crosscutting Research and Analysis 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 on self-organizing information networks and distributed intelligence for process control and decision making.

High Performance Materials: Materials development under the Crosscutting Research and Analysis 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

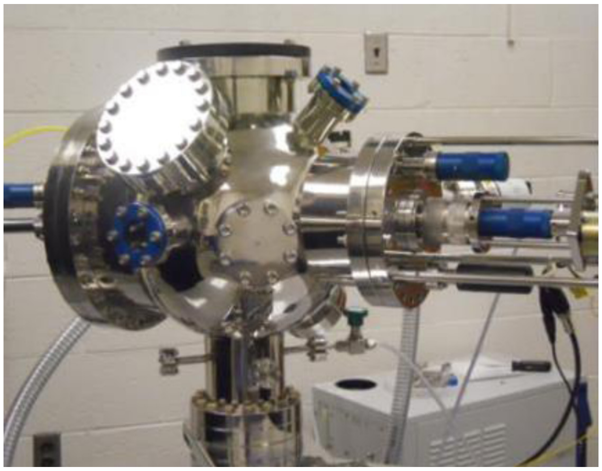
The aim of the sensors and controls research area is to make available new classes of sensors and measurement tools that manage complexity, permit low cost, perform robust monitoring, and enable real-time optimization of fully integrated, highly efficient power generation systems. Research is focused 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.

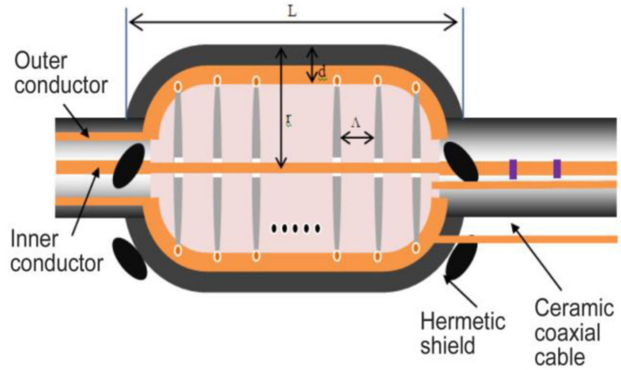
The Sensors and Controls project portfolio is categorized into these component technology areas:

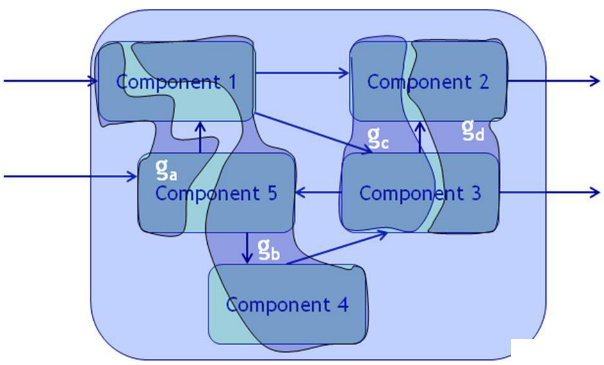
- **Advanced Sensors**
  - Optical Sensors
  - Microsensors
  - Wireless Sensors
  - Embedded Sensors
  - Novel Sensor Concepts
- **Distributed Intelligent Controls**
  - Advanced Process Control
  - Sensor Placement & Networks

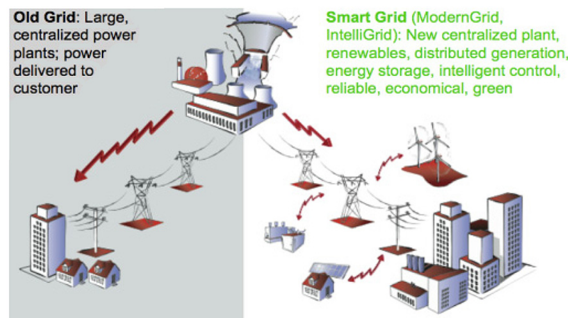
These new technologies are designed to benefit both existing and advanced power systems such that meaningful improvements can be made with respect to their efficiency and availability. As generational and transformational systems mature, sensors and controls will serve as an essential and enabling technology 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 that can match sensor data and analytical inputs to decision-making assistance and controls actuation, resulting in desired outcomes.

Projects by Component Technologies

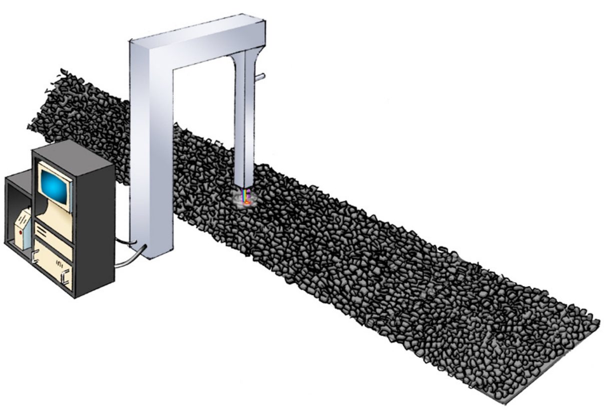


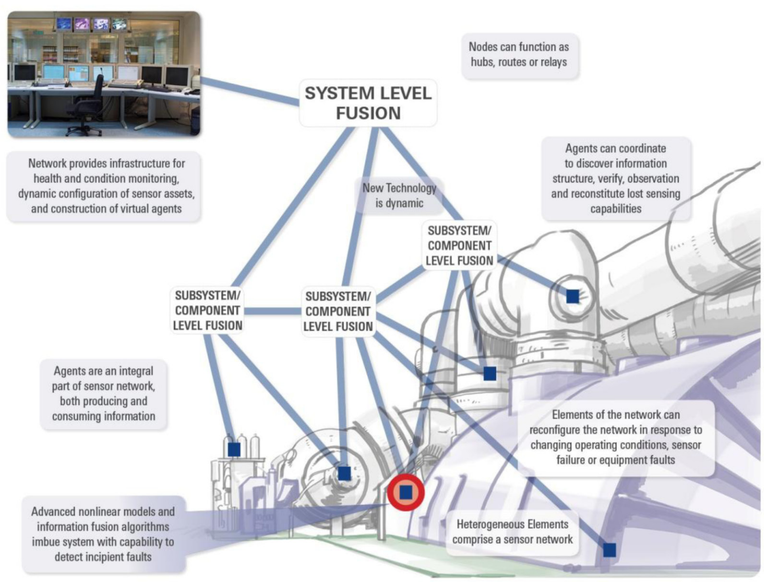




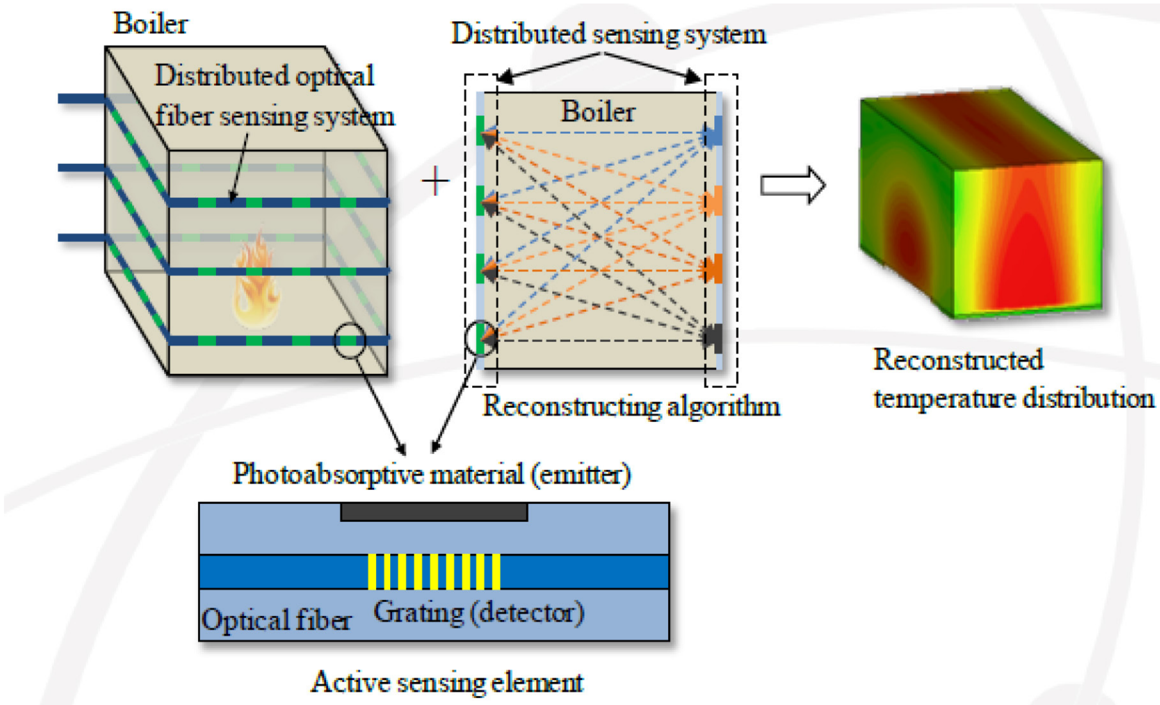


National Energy Technology Laboratory (NETL), 2007





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, the inherently drift-free sensor designs it enables, and the availability of a range of materials suitable for high-temperature applications.

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: 10/01/2012-10/31/2015

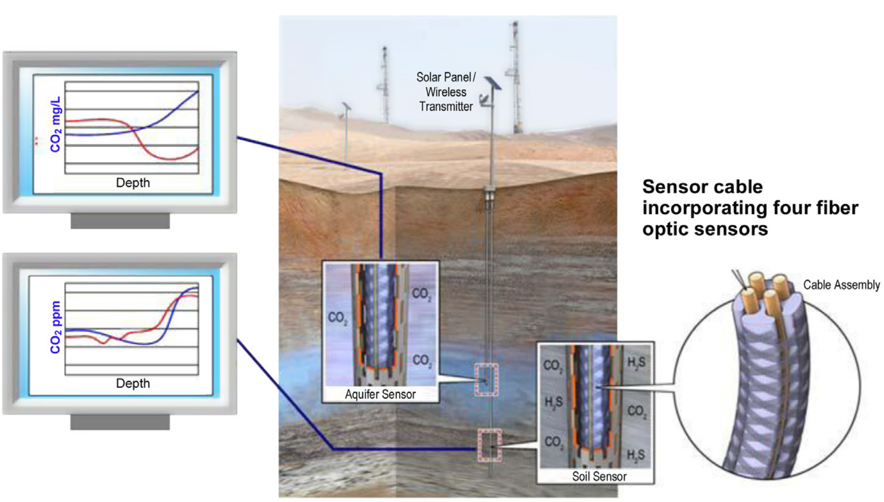
Total Project Value: $1,632,470

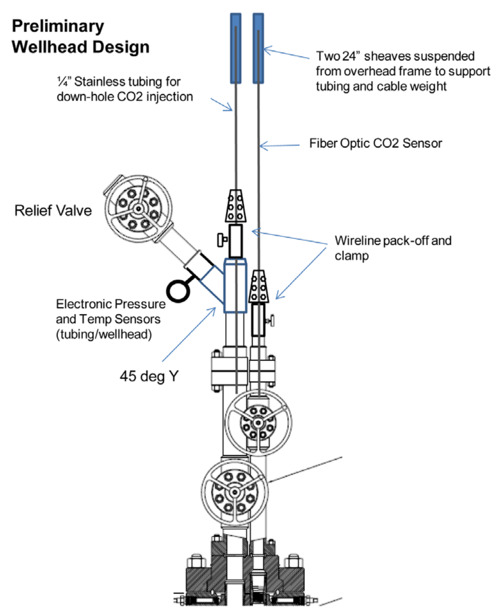
Technology Area: Plant Optimization Technologies

This project focused 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 included approaches to enable the sensor to be deployed into the subsurface, employing materials and designs such that installation through monitoring wells could be pursued.

Sensor designs focused on coating materials applied to the exterior of optical fiber that are 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 included 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.

The project demonstrated fiber optic sensor prototypes for gas-phase and/or dissolved CO_2 monitoring capable of withstanding corrosive liquids and elevated temperatures. Deployable sensor designs included a stand-alone multichannel read-out unit for distributed intrinsic fiber optic sensors with wireless communication capability. After concept demonstration, fiber optic sensors were manufactured and tested in a 5,200 ft well with multiple releases of CO_2. For the first time, low levels of dissolved CO_2 were monitored, in situ and in real time, at multiple depths, in a deep monitoring well, at elevated pressure and temperature.





Preliminary wellhead design for sensor deployment.

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: 10/01/2011 - 09/30/2015

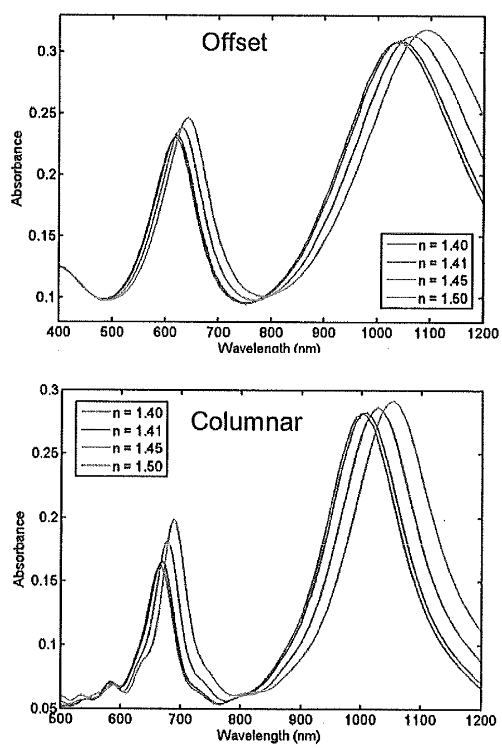
Total Project Value: $530,777

Technology Area: University Training and Research

A passive plasmonics based chemical sensing system to be used in harsh operating environments was investigated and developed within this program. The initial proposed technology was based on combining technologies developed at the SUNY Polytechnic Institute Colleges of Nanoscale Science and Engineering (CNSE) and at the University of Minnesota (UM). Specifically, a passive wireless technique developed at UM was to utilize a heat-activated plasmonic design to passively harvest the thermal energy from within a combustion emission stream and convert this into a narrowly focused light source. This plasmonic device was based on a bullseye design patterned into a gold film using focused ion beam methods (FIB). Critical to the design was the use of thermal stabilizing under and overlayers surrounding the gold film. These stabilizing layers were based on both atomic layer deposited films as well as metal laminate layers developed by United Technologies Aerospace Systems (UTAS).

While the bullseye design was never able to be thermally stabilized for operating temperatures of 500ºC or higher, an alternative energy harvesting design was developed by CNSE within this program. With this new development, plasmonic sensing results were presented where thermal energy is harvested using lithographically patterned Au nanorods, replacing the need for an external incident light source. Gas sensing results using the harvested thermal energy are in good agreement with sensing experiments which used an external incident light source. Principal component analysis (PCA) was used to reduce the wavelength parameter space from 665 variables down to 4 variables with similar levels of demonstrated selectivity. The method was further improved by patterning rods which harvested energy in the near infrared, which led to a factor of 10 decrease in data acquisition times as well as demonstrated selectivity with a reduced wavelength data set. The combination of a plasmonic-based energy harvesting sensing paradigm with PCA analysis and wavelength downselection offers a novel path towards simplification and integration of plasmonic-based sensing methods using selected wavelengths rather than a full spectral analysis.

Integration efforts were designed and modeled for thermal and mass transport considerations by UTAS which led to the 3D printing of scaled models that would serve as the housing for the alternative energy harvesting plasmonic chemical sensor design developed by CNSE.



Comparison of simulated 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: The University of Florida

Collaborator(s): Florida State University

Award Number: FE0012370

Project Duration: 01/01/2014 - 08/31/2017

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.

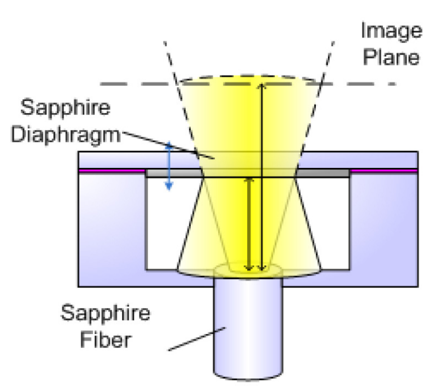
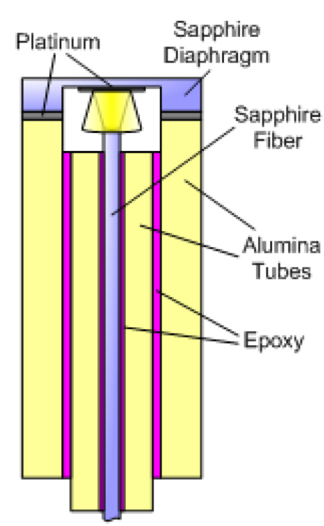


Illustration of the fiber-optic lever transduction scheme implemented in the pressure sensor design.



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: 07/01/2014 - 06/30/2017

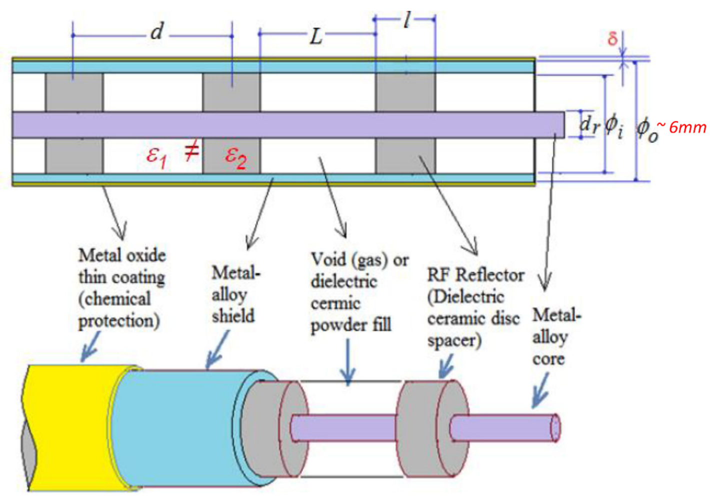
Total Project Value: $399,666

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 °C. 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 systems. 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

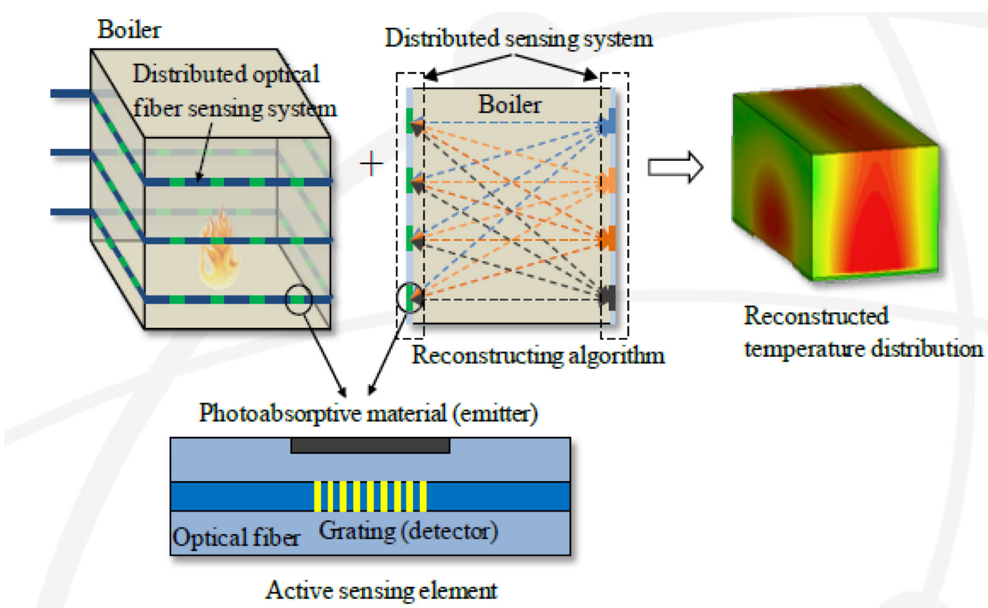
Project Duration: 09/01/2014 - 08/31/2017

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

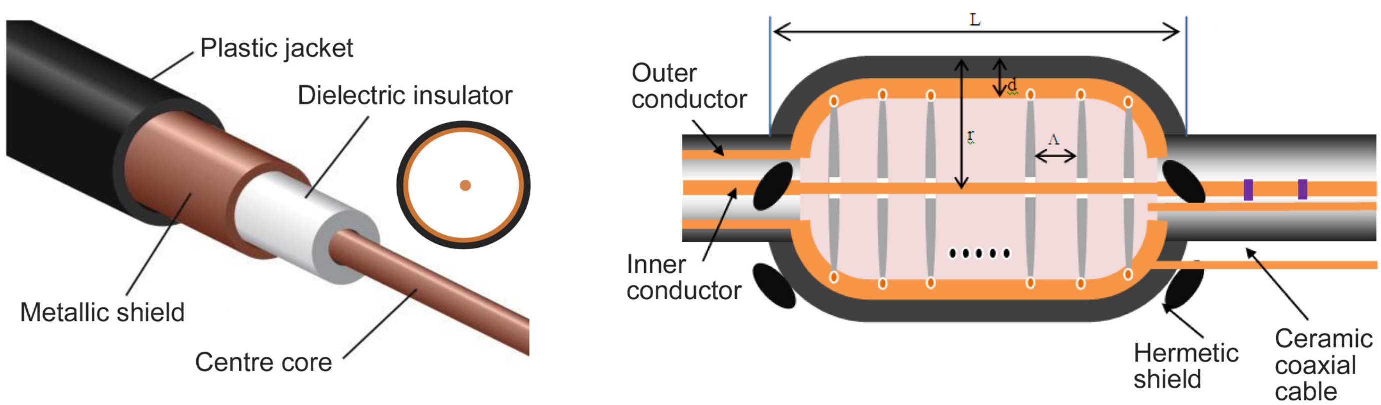
Award Number: FE0009843

Project Duration: 10/01/2012 - 06/30/2016

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 downhole 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.

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

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

Award Number: FE0005703

Project Duration: 10/01/2010 - 10/31/2015

Total Project Value: $1,835,148

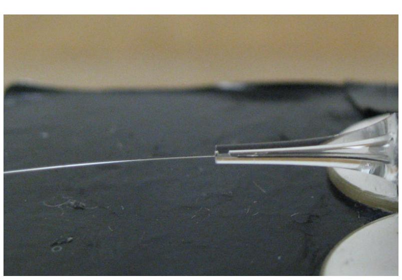
Technology Area: Coal Utilization Sciences

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.

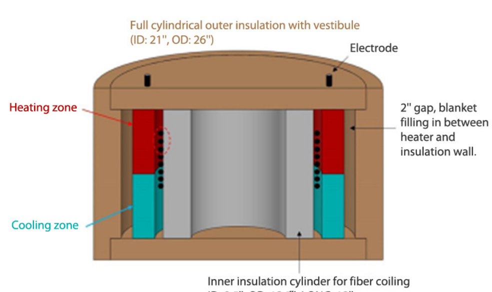
This project developed an advanced distributed sensing technology to monitor refractory wear in an operating coal gasifier. The Virginia Tech Center for Photonics Technology (CPT) developed a prototype sensing system and evaluated it in a laboratory test environment for operation at high temperatures. A basic numerical model of the thermal effects of refractory degradation was constructed, then was used to guide the design of the sensor and simulated test environment. Numerical output was compared to the laboratory test results and used to confirm the sensor's ability to monitor refractory health.

Testing at temperatures up to 850 °C showed good performance and survivability, but annealing tests at 1,000 °C resulted in transmission losses indicating fiber breaking during the cooldown. This failure was analyzed and an alternative fiber deployment strategy was proposed that may mitigate the problem and enable the sensing system to be used in the high-temperature gasifiers environment.

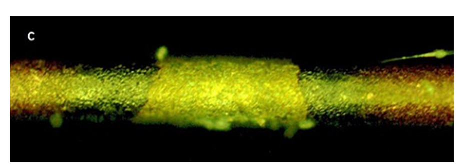
Direct measurement technology will enable early detection of hot spots in the refractory wall and measurement of its remaining lifetime, leading to improved performance, longevity, and cost savings. Use of distributed sensing will allow gasifier operators to adopt a conditions-based maintenance model, reducing the need for frequent shutdowns.



Concept validation setup.



Cutaway view of prototype sensing system (above).



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

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: 10/01/2011 - 09/30/2016

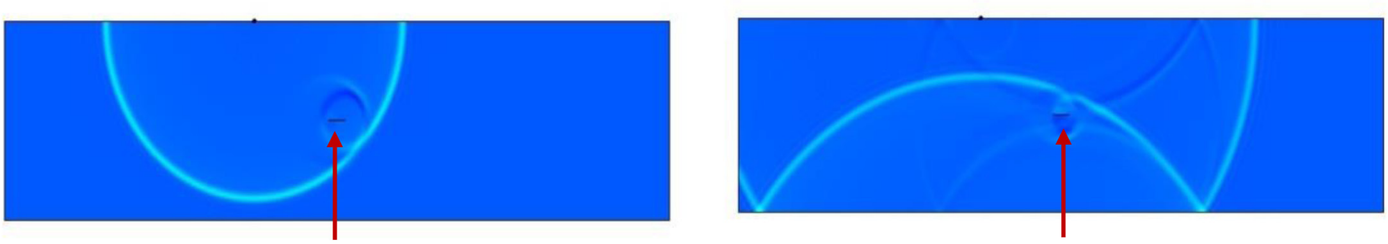
Total Project Value: $1,493,117

Technology Area: 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.

Reduced Mode Sapphire Optical Fiber and Sensing System

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

Award Number: FE0012274

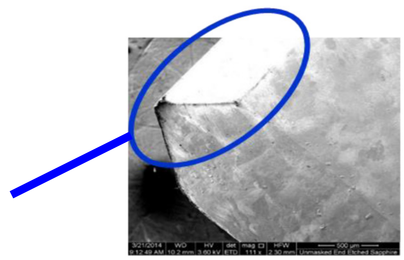
Project Duration: 01/01/2014 - 12/31/2016

Total Project Value: $1,875,000

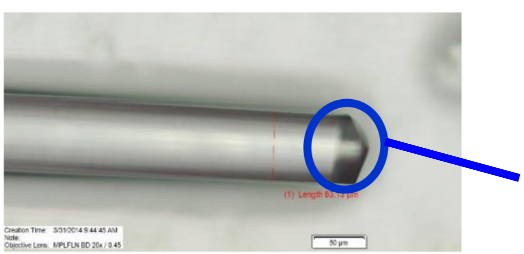
Technology Area: Plant Optimization Technologies

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.

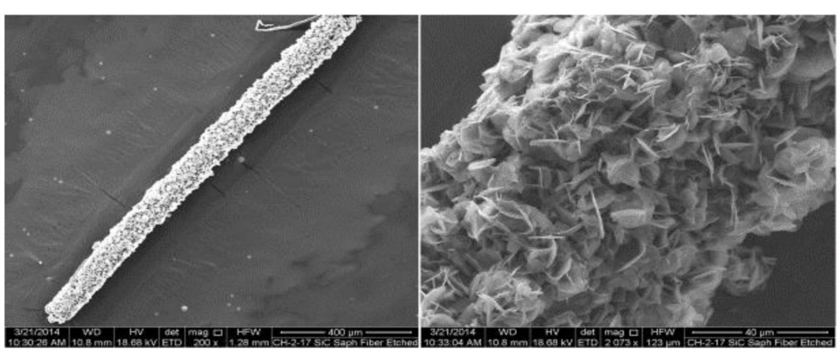
The proposed sapphire fiber waveguide design will overcome the harsh environment challenges that severely limit the integration of mature optical fiber sensing technologies in new power plant control systems. Overall, this technology is expected to lower operating costs by allowing more accurate measurement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



Angled Edge on Single Crystal Sapphire Wafer via VT Etching Process.



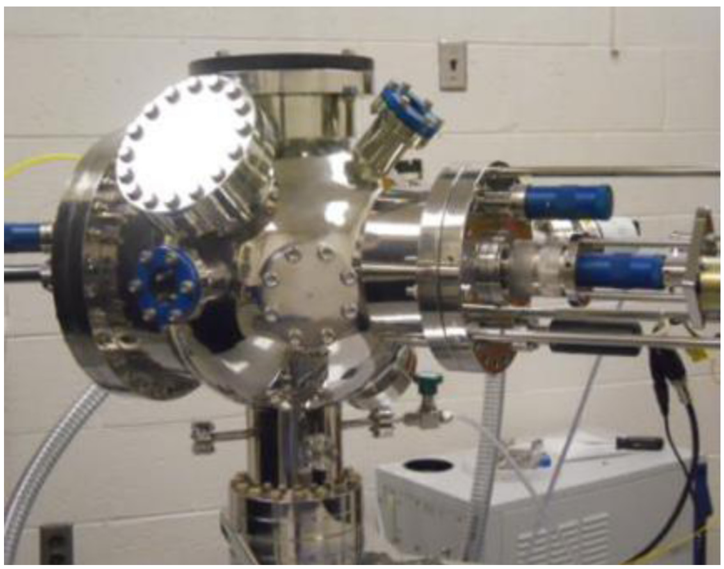
Angled Edge on the End of a Single Crystal Sapphire Fiber and Fiber Size Reduction via VT Etching Process.



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.



Performer	Agreement Name	Page
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University of Texas at El Paso	Gallium Oxide Nanostructures for High-Temperature Sensors	26

Wireless, Passive Ceramic Strain Sensors for Turbine Engine Applications

Performer: University of Central Florida

Award Number: FE0007004

Project Duration: 10/01/2011 - 03/31/2015

Total Project Value: $299,162

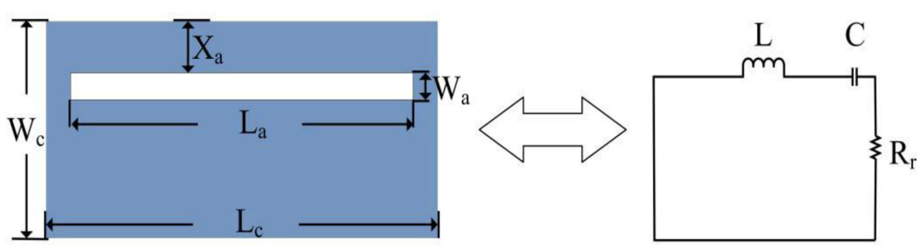
Technology Area: University Training and Research

The UCF research team worked toward 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 was 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 was 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. Project objectives included (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 first two objectives were achieved, but the need to develop facilities to test the strain sensor in realistic conditions has postponed attainment of the third objective. The team is now collaborating with the turbomachinery group at UCF to perform testing.

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 mode 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: 07/18/2013 - 06/30/2016

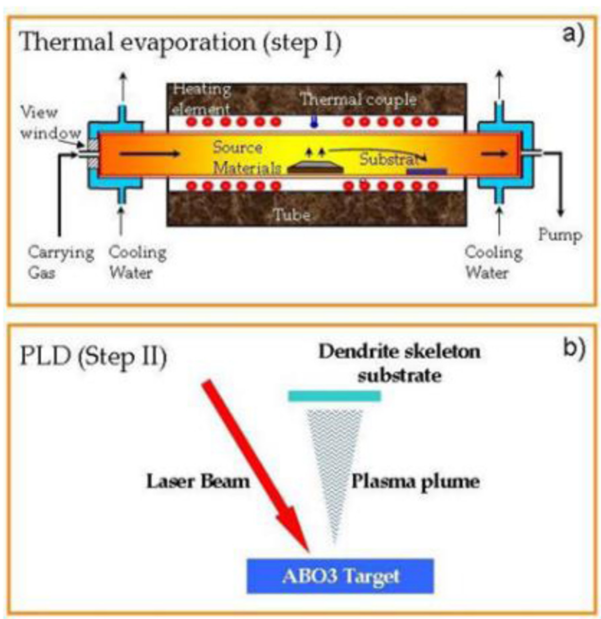
Total Project Value: $300,000

Technology Area: 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 meso-porous 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 AlxGaN epi-substrates.

Gallium Oxide Nanostructures for High-Temperature Sensors

Performer: University of Texas at El Paso

Award Number: FE0007225

Project Duration: 10/01/2011 - 01/31/2015

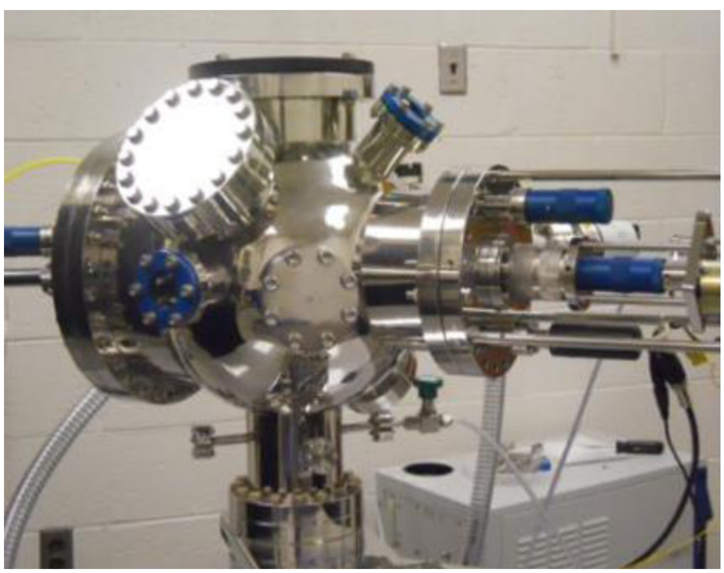
Total Project Value: $200,000

Technology Area: 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 were (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.

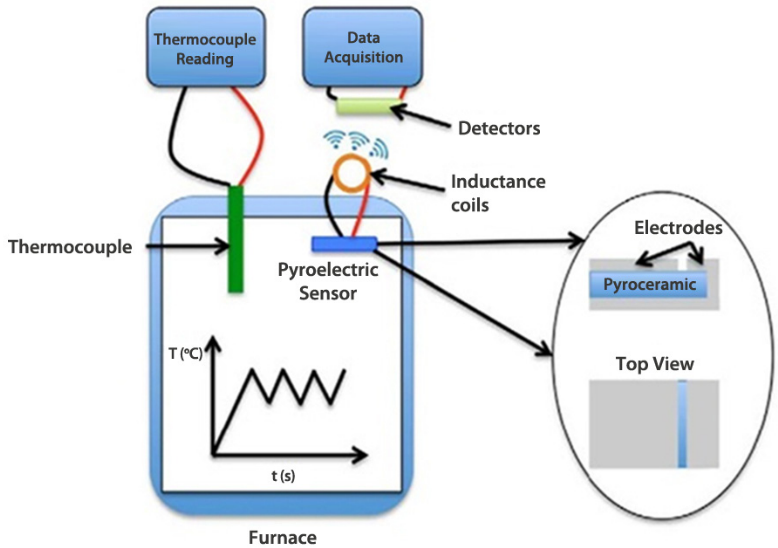
This project fostered the development of high-temperature O_2 sensors with enhanced selectivity, sensitivity, and long-term stability when compared to their conventional counterparts. Improved O_2 sensors will contribute to cleaner and more efficient coal-fired power generating plants.



Sputter Deposition System Developed by the Researchers.

Wireless Sensors

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



Performer	Agreement Name	Page
University of Connecticut	Wireless 3D Nanorod Composite Arrays-Based High-Temperature Surface Acoustic Wave Sensors for Selective Gas Detection Through Machine Learning Algorithms	27
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Washington State University	Low-Cost Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems	32
West Virginia University	Passive Wireless Sensors Fabricated by Direct-Writing for Temperature and Health Monitoring of Energy Systems in Harsh-Environments	33
West Virginia University Research Corporation	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	34

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

Performers: University of Connecticut

Award Number: FE0026219

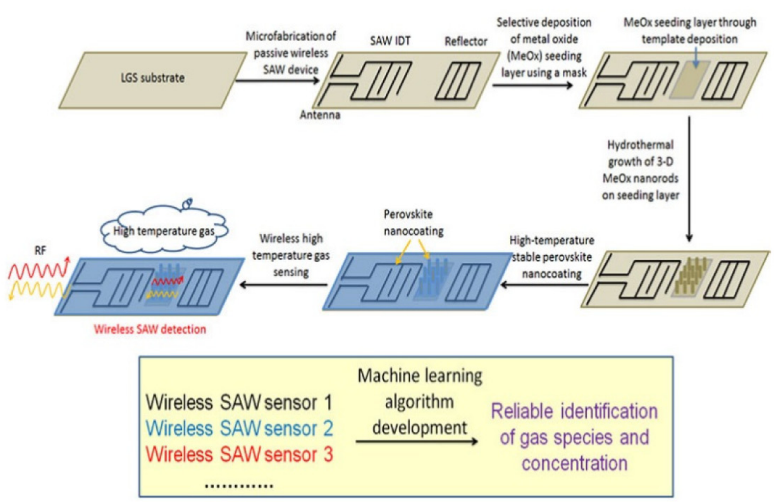
Project Duration: 09/01/2015 - 08/31/2018

Total Project Value: $400,000

Technology Area: University Training and Research

This project aims at developing a wireless integrated gas/temperature microwave acoustic sensor capable of passive operation (no batteries) over the range of 350 °C to 1,000 °C in harsh environments relevant to fossil energy technology, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems. The proposed wireless sensor system is based on a surface-acoustic-wave sensor platform that is configured using a langasite piezoelectric crystal with Pt/Pd interdigital electrodes and yttria-stabilized zirconia films doped with Pd, Pt, or Au nanocatalysts to detect H_2, O_2, and NO_X gases and to also monitor the gas temperature in the harsh environment. Fully packaged prototype sensors will be designed, fabricated, and tested under gas flows of H_2 (< 5 percent), O_2, and NO_X in laboratory furnaces, and the sensor response will be characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

This project could advance development of high temperature stable sensing materials by developing a novel high-temperature sensing strategy to realize fast, sensitive, selective, rugged, and cost-effective high-temperature gas sensors for power and fuel systems. The sensing technique developed could be suitable for various fossil energy end-use applications ranging from ultra-supercritical boilers (up to 760 °C) to solid oxide fuel cells (650-1000 °C) and automotive engines (up to 1000 °C).



The wireless high-temperature surface-acoustic-wave gas sensor arrays with machine learning algorithm development.

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

Performers: University of Maine System

Award Number: FE0026217

Project Duration: 09/01/2015 - 08/31/2018

Total Project Value: $399,999

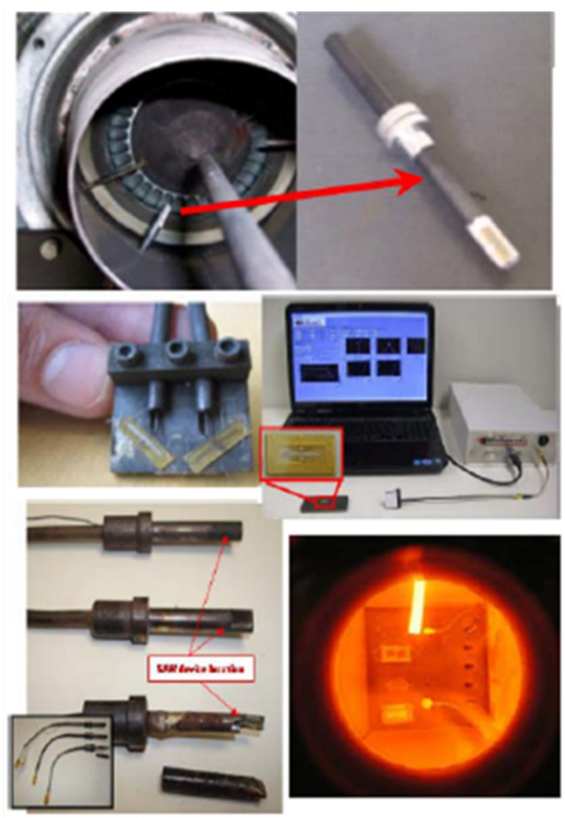
Technology Area:

This project aims to develop a wireless integrated gas/temperature microwave acoustic sensor capable of passive operation (no batteries) over the range 350 - 1000 °C in harsh environments relevant to fossil energy technology, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems.

The proposed wireless sensor system is based on a surface acoustic wave (SAW) sensor platform that could be used to detect H_2, O_2, and NO_X gases and monitor the gas temperature in the harsh environment. Fully packaged prototype sensors will be designed, fabricated, and tested under gas flows of H_2 (< 5%), O_2, and NO_X in laboratory furnaces, and the sensor response characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

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

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



Examples of Umaine harsh environment wireless LGS SAW sensors.

High-Temperature Wireless Sensor for Harsh Environment Condition Monitoring

Performer: University of Maine System

Collaborator(s): Environetix Technologies Corporation

Award Number: FE0007379

Project Duration: 01/01/2012 - 12/31/2016

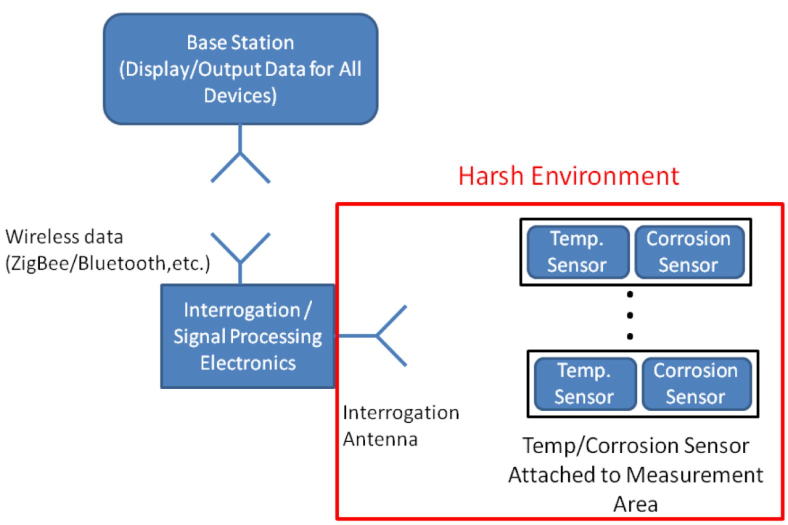
Total Project Value: $1,657,677

Funding Area: Plant Optimization Technologies

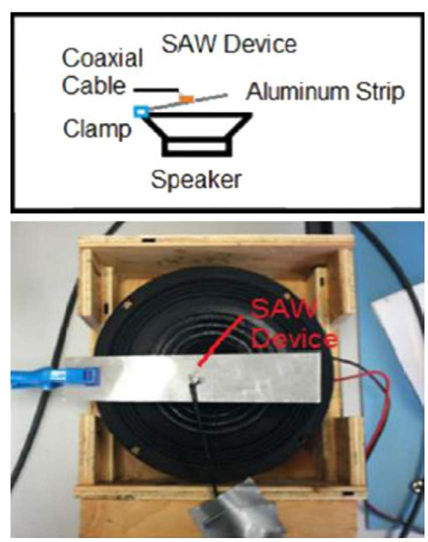
The University of Maine will develop novel high-temperature, harsh-environment, thin-film electrodes; piezoelectric smart microwave acoustic sensing elements; sensor encapsulation materials that are engineered to function reliably over an acceptable time frame at high temperature; and a radio-frequency (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 near-zero-emission power systems and improve operations at existing fossil energy power plants.



Block diagram of Environetix's prototype wireless sensor system .



Schematic and photograph of test setup for interrogation of LGS SAW resonator under dynamic stress conditions.

Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Performers: University of Texas at Arlington

Collaborator(s): UC San Diego

Award Number: FE0023118

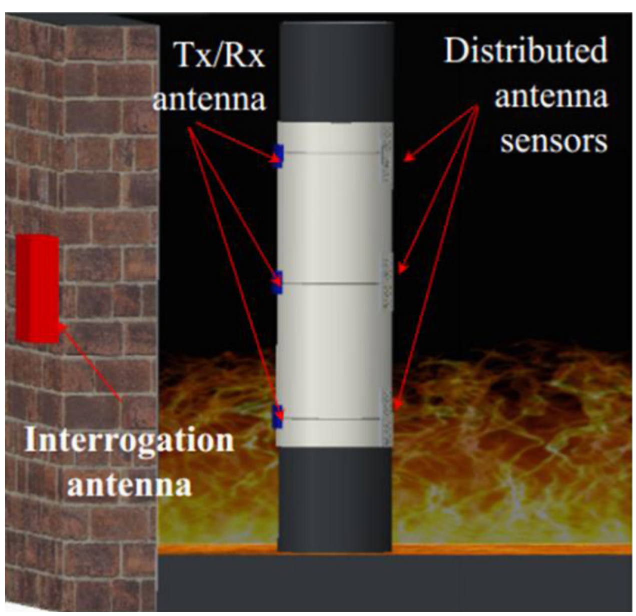
Project Duration: 01/01/2015 - 12/31/2017

Total Project Value: $434,079

Technology Area: University Training and Research

University of Texas Arlington and University of California, 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.

Investigation of Pyroelectric Ceramic Temperature Sensors for Energy System Applications

Performer: University of Texas at El Paso

Award Number: FE0011235

Project Duration: 07/01/2013 - 06/30/2016

Total Project Value: $200,000

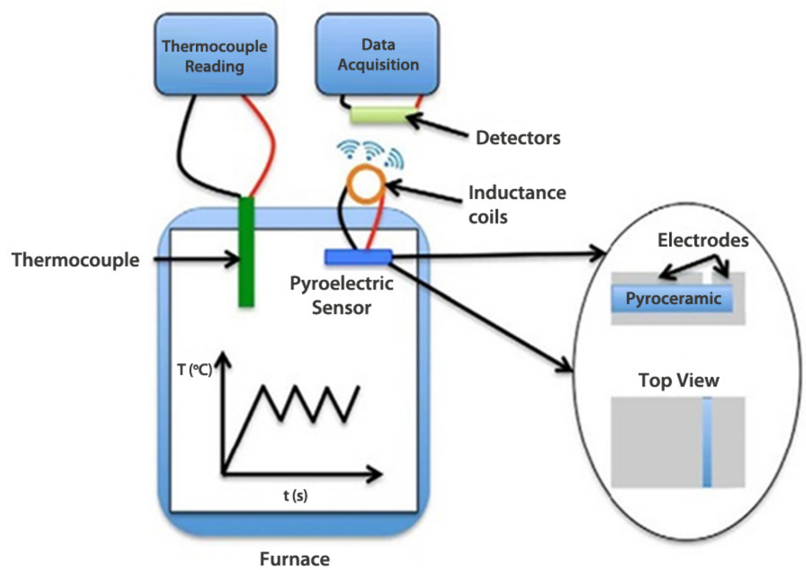
Technology Area: University Training and Research

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.

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

Performers: Washington State University

Award Number: FE0026170

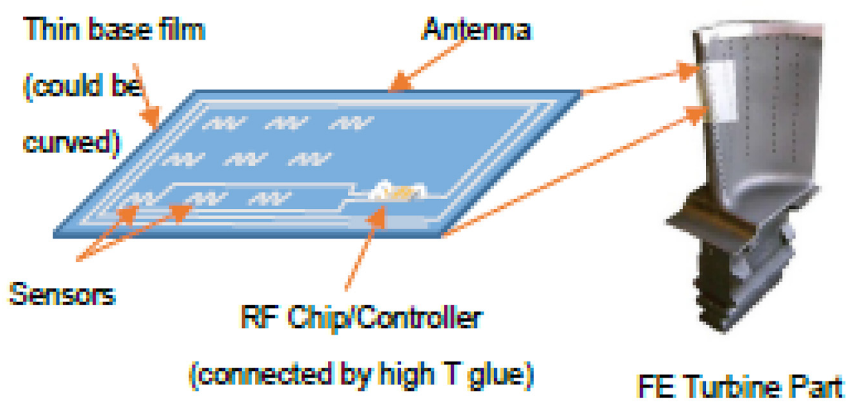
Project Duration: 10/01/2015 - 09/30/2018

Total Project Value: $488,738

Technology Area: University Training and Research

This project will design, characterize, and demonstrate wireless, conformal strain and pressure sensors manufactured using low-cost, direct write additive methods for application in fossil energy (FE) systems. The goal is to demonstrate the feasibility of 'low-cost aerosol jet manufacturing' for FE systems and to develop next-generation sensors and controls, which can sustain high temperatures up to 500 °C. Specifically, this project will advance the current state of the art by developing novel materials and devices for wireless circuits that surpass 350 °C, the operating temperature limits of traditional silicon-based electronics; integrating electronic circuitry on curved 3-D surfaces such as those observed in gas turbine engines, demonstrating capabilities that surpass that of traditional (2-D) lithographic techniques; and improving reliability issues for wireless sensors that arise from the demanding FE environments.

It is anticipated that this reseach could improve the in-situ monitoring and thus the performance of the FE devices and systems.



Schematic of a fully integrated high temperature wireless sensor system.

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

Performers: West Virginia University

Collaborator(s): NexTech Materials, Ltd.

Award Number: FE0026171

Project Duration: 10/01/2015 - 09/30/2018

Total Project Value: $399,965

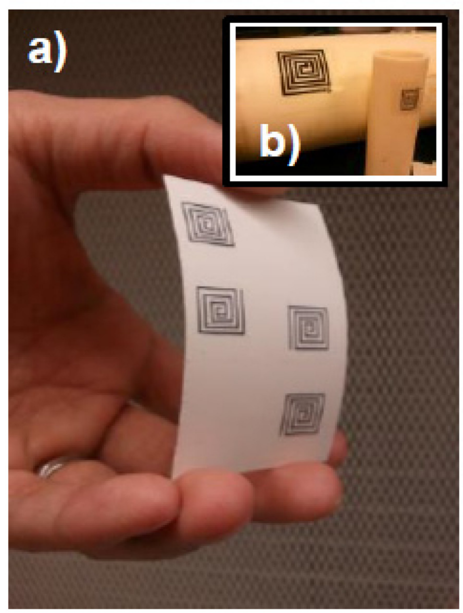
Technology Area: University Training and Research

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

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

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

The sensor system developed may find application in solid oxide fuel cells, chemical reactors, furnaces, engines, boilers, and gas turbines (for both energy and aerospace applications) systems.



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

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: 10/01/2010 – 06/30/2015

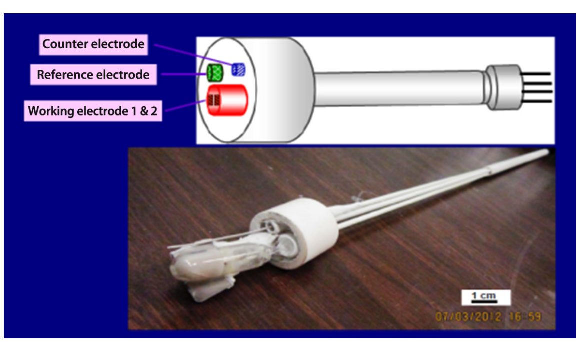
Total Project Value: $1,175,312

Funding Area: Plant Optimization Technologies

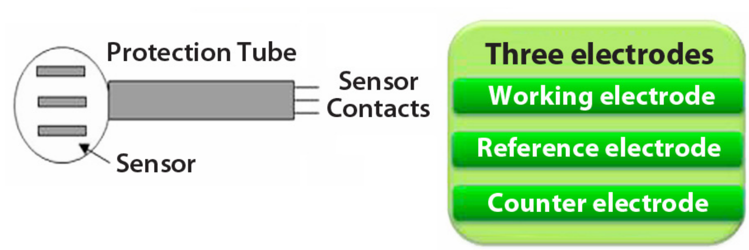
In this project, West Virginia University (WVU), the International Lead Zinc Research Organization, Special Metals Corporation (SMC), and Western Research Institute (WRI) partnered to develop in-situ corrosion monitoring sensors for fireside corrosion of ultra-supercritical (USC) boiler tubes in next-generation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

To address this issue, the project team experimented with different materials for the reference electrode components, including glass ceramic tube, electrode wire, and electrolyte solution, that are resistant to oxidation and chemical attack at high temperatures. In particular, the research team investigated the use of beta alumina, which is considered a high-quality high-temperature sodium ion conductor, for the electrode's internal wire reference membrane. An existing five-electrode sensor design was adapted and reduced to four electrodes (two identical sensing electrodes, a counter electrode, and the reference electrode, for effective measurement of electrochemical potential, current, and impedance. In-situ corrosion monitoring validation was conducted for Inconel 740 under conditions closely simulating USC boiler tube operating conditions. Two electrochemical noise patterns were found to correlate with the oxidation and sulfidation stages in the hot coal ash corrosion process, and two characteristic current noise patterns indicate the extent of corrosion.

The project has enhanced 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.



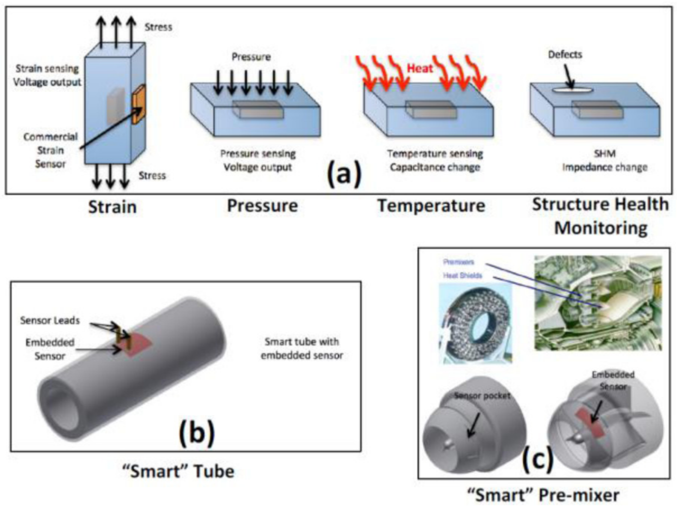
High temperature electrochemical corrosion rate probe sensor.



Coupled Multielectrode Sensor (CMS) probes.

Embedded Sensors

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



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West Virginia University Research Corporation	Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health and Degradation of Slagging Gasifiers	39

Additive Topology Optimized Manufacturing with Embedded Sensing

Performer: United Technologies Corporation

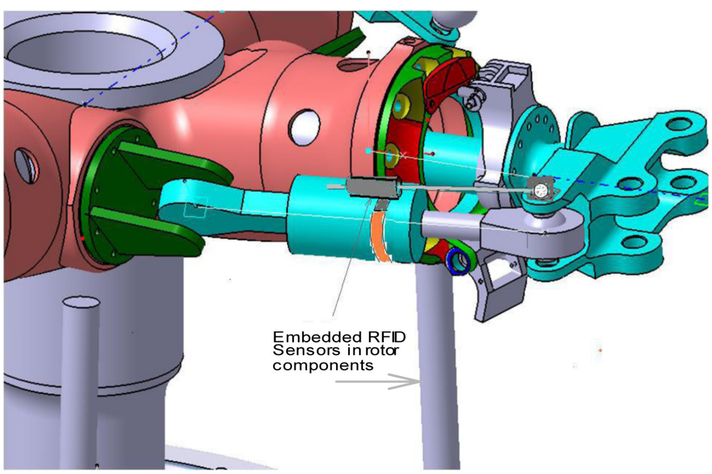
Award Number: FE0012299

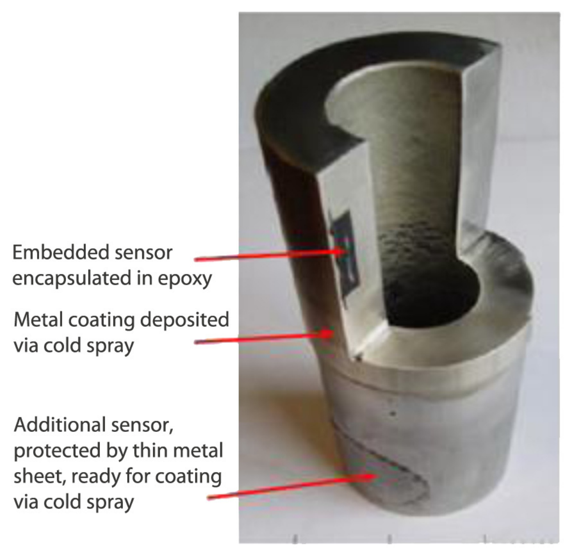
Project Duration: 10/01/2013 - 09/30/2016

Total Project Value: $1,482,700

Technology Area: 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 predict transfer of radio-frequency 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.

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

Performer: University of Missouri System

Award Number: FE0012272

Project Duration: 10/01/2013 - 09/30/2016

Total Project Value: $1,879,427

Technology Area: 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 emission.

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 °C), 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 of "Smart Parts" with Embedded Sensors for Energy System Applications

Performer: University of Texas at El Paso

Award Number: FE0012321

Project Duration: 10/01/2013 - 09/30/2016

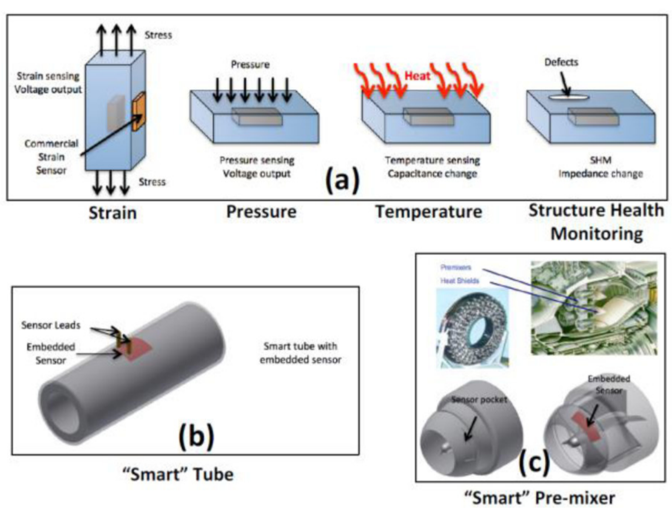
Total Project Value: $1,150,894

Technology Area: 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 parts' 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.



"Smart Parts" with embedded sensors, (a) sensing capabilities showcase; (b) case study 1, "smart" tube; (c) case study 2, "smart" pre-mixer.

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

Performer: West Virginia University Research Corporation

Award Number: FE0012383

Project Duration: 10/01/2013 - 09/30/2016

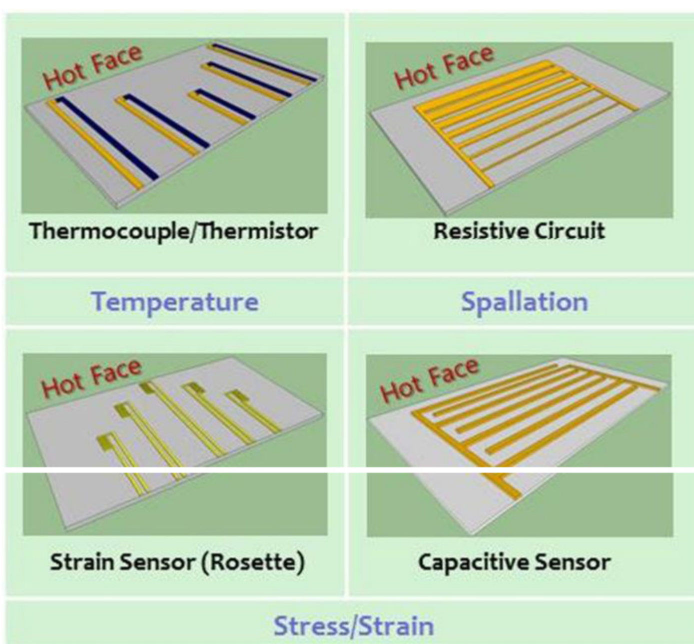
Total Project Value: $1,617,113

Technology Area: Plant Optimization Technologies

The United States Department of Energy (DOE) National Energy Technology Laboratory (NETL) has partnered with West Virginia University (WVU) to develop in situ and online sensing capability for advanced energy systems operating at high temperature and pressure, in the harsh environments of advanced power generation systems. Researchers at WVU, 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.

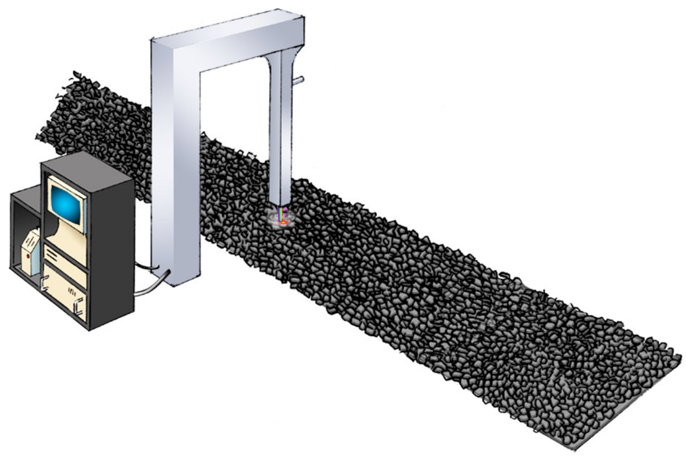
The anticipated benefit of this project would be the development of a more reliable and non-intrusive method of monitoring gasifier temperature and refractory health than is possible with current methods. Such improvements are expected to result in lower operating and maintenance costs of slagging gasifiers. 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.

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.



Innovative Process Technologies-Advanced Sensors Research & Development

Performers: National Energy Technology Laboratory – Research and Innovation Center (RIC)

Award Number: FWP-2012.04.01.2.1 and FWP-2012.04.01.2.2

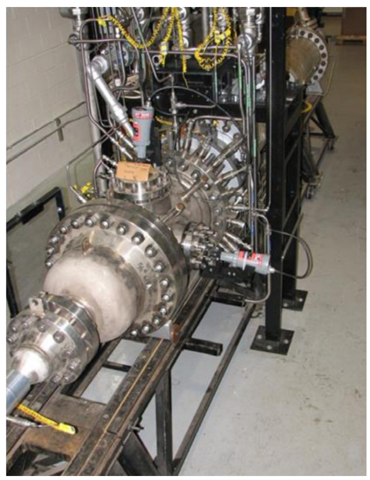
Project Duration: 10/01/2015 - 09/30/2016

Total Project Value: $1,440,670

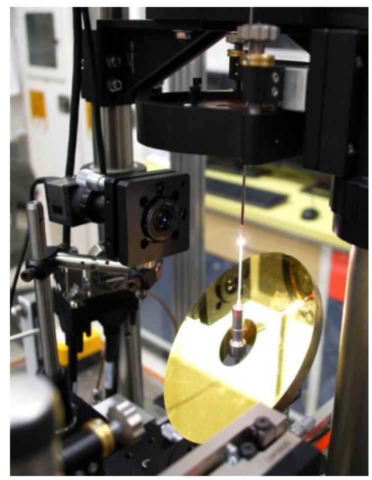
Technology Area: Plant Optimization Technologies

Research and development on this task aims to advance the state-of-the-art for sensors with application to advanced fossil power generation and Carbon Capture Utilization and Storage (CCUS). Work to be performed under this task includes:

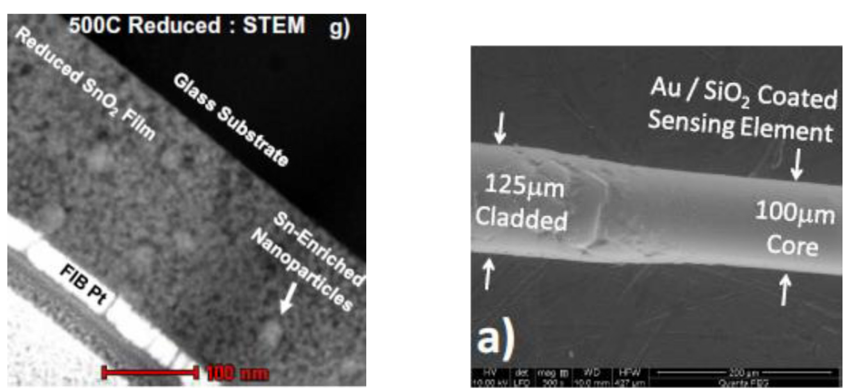
- Fabrication and testing of novel functional sensor materials, and sensors using those materials, for high-temperature power generation process applications.
- Growth of sapphire optical fiber (and other high temperature materials) using laser heated pedestal growth (LHPG) technique, and development of an optical cladding.
- Maintenance, improvement, and application of the Raman gas analyzer (RGA); and maintenance and enhancement of optical diagnostics capabilities for use in RIC experimental facilities.
- Continued development of the subterranean laser induced breakdown spectroscopy (LIBS) system, including performance of temperature and pressure controlled experiments with carbonated brines and real rocks and casing cements; and review of subterranean optical fiber sensor and wireless technology.
- Coordination of testing in NETL facilities (e.g., the High Pressure Combustion Facility) to advance the technology readiness levels (TRLs) of advanced sensors being developed with FE support.



Aerothermal test rig in the B6 High Pressure Combustion.



Laser heated pedestal growth.



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

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

Performer: New Mexico Institute of Mining and Technology

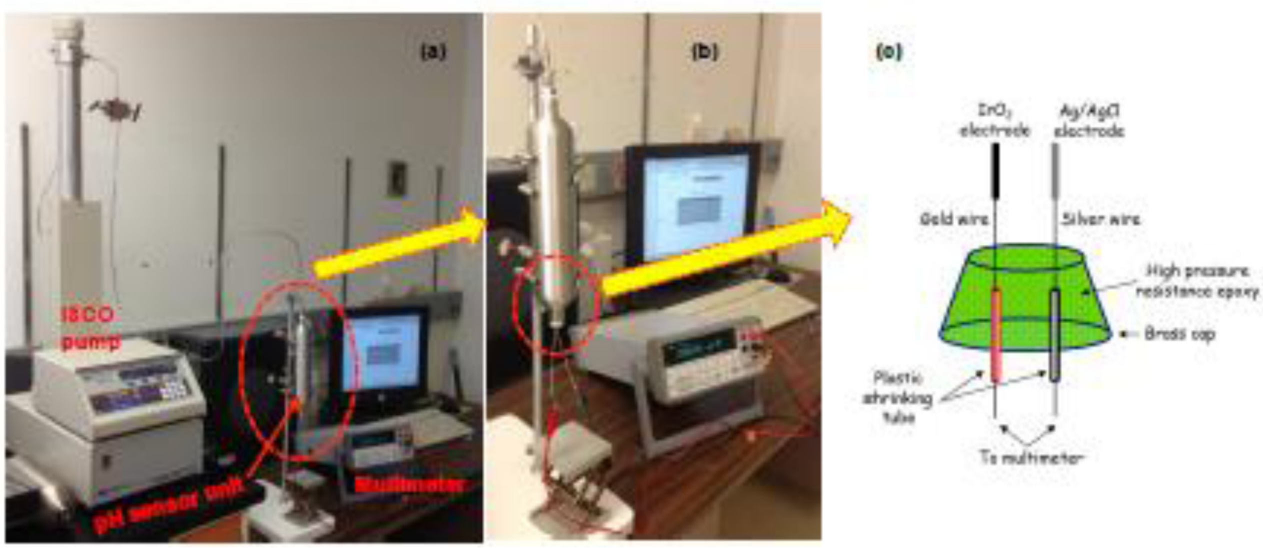
Award Number: FE0009878

Project Duration: 10/01/2012 – 09/30/2016

Total Project Value: $1,345,414

Technology Area: 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

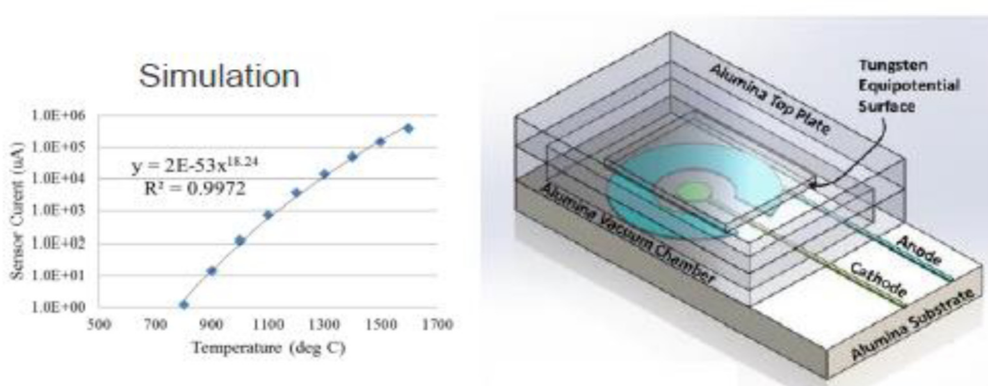
Project Duration: 10/01/2013 - 05/31/2016

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 Harsh Environment Adaptable Thermionic (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.

Collaborator(s): Honeywell, Pratt & Whitney, Boeing, Rolls-Royce, Siemens, Lockheed Martin, NavAir, Williams International, Ohio Aerospace Institute, and Propulsion Instrumentation Working Group

Award Number: SC0008269

Project Duration: 06/28/12 – 08/13/2017

Total Project Value: $2,159,100

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 have 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 team will construct and fabricate designs for multiple sensors to produce bench- and pilot-scale operable demonstration-ready sensing.

By continuous condition monitoring of high temperatures surrounding using these sensors, one can expect to lower failure rates, improve contact and reduce moisture collection with sensing at the source and an overall lower cost associated with system lifespan.

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

Performer: Tech4Imaging, LLC

Collaborator(s): The Ohio State University

Award Number: SC0011936

Project Duration: 06/09/2014-07/27/2017

Total Project Value: $1,160,000

Technology Area: Plant Optimization Technologies

Tech4Imaging LLC will build a functional prototype of an Adaptive Electrical Capacitance Volume Tomography (AECVT) system for mass-flow gauging of solids circulating in high-temperature (> 750 °C) environments. Adaptive Electrical Capacitance Volume Tomography (AECVT) is a newly developed technology that can provide 3-D imaging of multiphase flow behavior in real time. Devices that can accurately measure the solid flow rate of an operating gas-solid system would be of great aid for optimizing and controlling the combustion processes in advanced reactors. Presently, the availability of such devices, particularly at high temperatures, is very limited. In this Phase II effort, a functional prototype of an Adaptive Electrical Capacitance Volume Tomography (AECVT) system for mass-flow gauging of solids circulating at high temperatures will be built. The intrinsic high measuring speed of capacitance measuring technology and high resolution capability of AECVT technology will enable such mass flow measurements at 5% spatial resolution and 1 Hz temporal resolution. Simulation and preliminary measurement results verified feasibility of the AECVT architecture during Phase I. Capacitance sensors exhibit favorable features of safety, flexibility, and suitability for scale-up applications that make them a favorable solution for industrial applications. Tasks in this Phase II will focus on optimizing sensors, electronic hardware, and feature extraction software for hot flow applications based on AECVT technology. Tasks are based on logical progressions from past experience of developing imaging systems.

Successful completion of this Phase II will provide a prototype of an AECVT system for hot temperature applications in harsh conditions reactors that can be extended to many energy-related applications. A logical progression from Phase I to Phase II is established in which Phase II efforts are focused on implementing designs developed in Phase I that proved feasible. The proposed system would also advance multiphase 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.

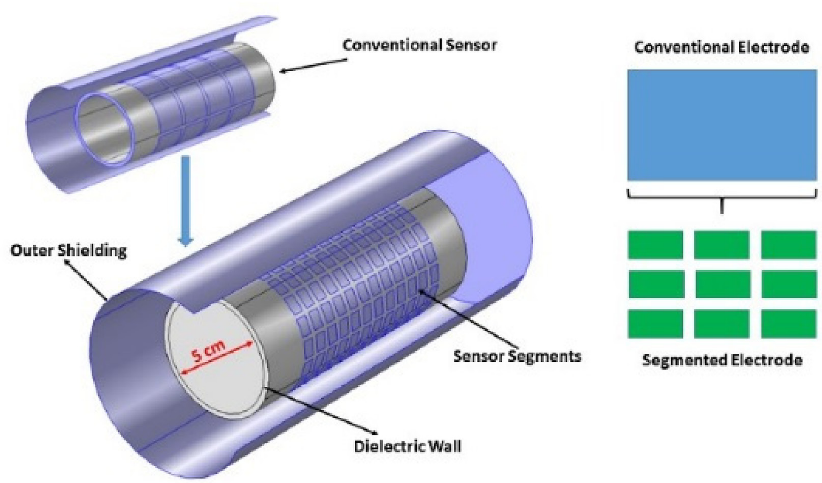


Illustration of Adaptive Electrical Capacitance Volume Tomography System.

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 LLC

Award Number: SC0010228

Project Duration: 06/11/2013 - 07/27/2016

Total Project Value: $1,149,686

Technology Area: Plant Optimization Technologies

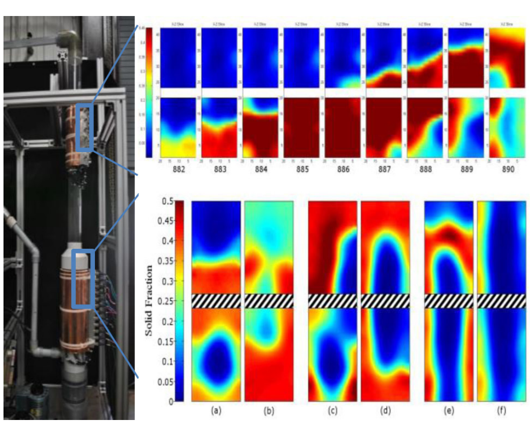
Controlling emissions and increasing efficiencies are essential requirements in future advanced power plants. Next-generation power systems require greater flexibility in their operations for simultaneously meeting the higher efficiency and lower emissions conditions that are geared toward meeting consumer 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 that are useful to their optimization.

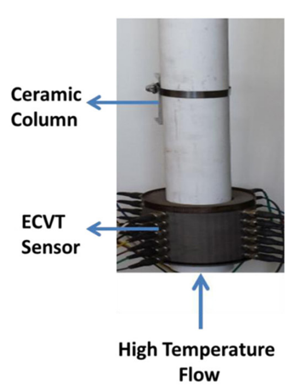
In this Phase II effort, Tech4Imaging is developing such a system based on capacitance sensors. An Electrical Capacitance Volume Tomography (ECVT) system was successfully developed to image flow variables in cold flow systems. Capacitance sensors exhibit favorable features of safety, flexibility, and suitability for scale-up applications that make them a favorable solution for industrial applications. In Phase I, the 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. Tasks under Phase II will focus on optimizing sensors, electronic hardware, and feature extraction software for hot flow applications.

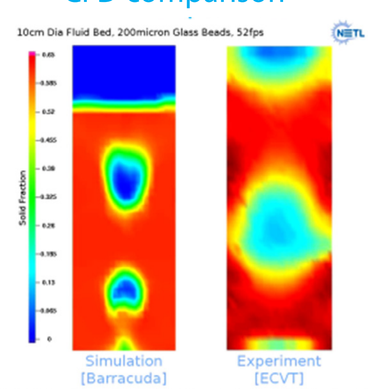
Successful completion of this project will result in significant public benefit due to the potential of this technology in helping the energy industry increase efficiencies and lower emissions. The proposed system would also advance multi-phase flow research of hot systems by providing access to obscure locations of a flow system. It also has a very high potential of attracting commercial interest 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.

4 in. & 2 in. Sensors, CLC Demo





CFD comparison



Justin M. Weber, Ky Layfield, Dirk VanEssendelft, Joseph S. Mei, Fluid Bed Characterization Using Electrical Capacitance Volume Tomography (ECVT), Compared to Computational Particle Fluid Dynamics's (CPFD) Barracuda, Powder Technology, Submitted

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

Performers: University of Texas at El Paso

Award Number: FE0026330

Project Duration: 10/01/2015 - 09/30/2018

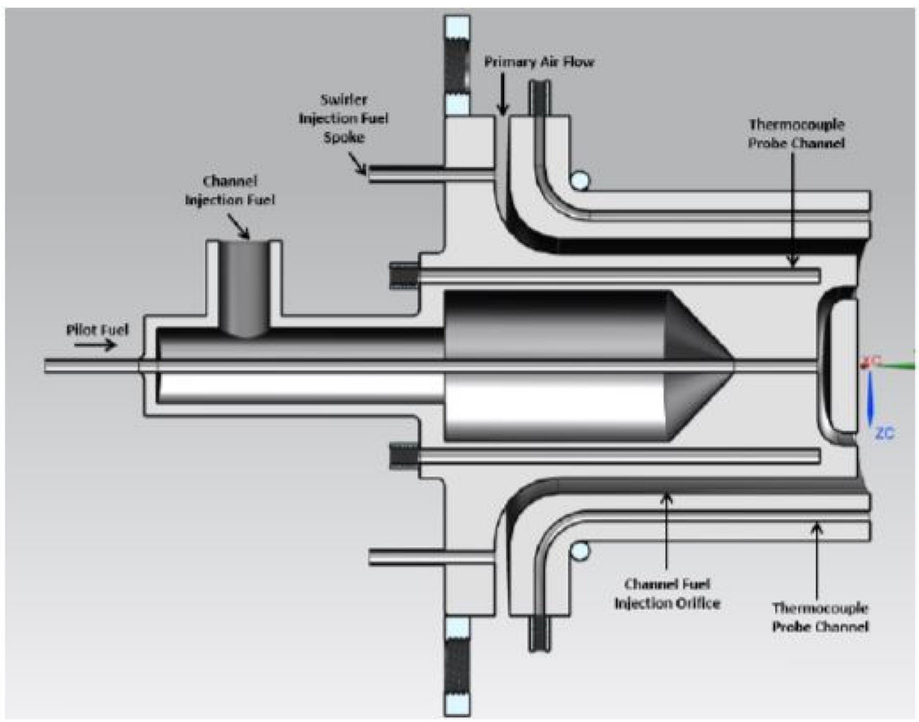
Total Project Value: $250,000

Technology Area: University Training and Research

This work necessitates the exploration of design and prototyping of a Dry Low-NO_X (DLN) fuel injector with integrated temperature sensing capabilities using the electron beam melting (EBM) additive manufacturing (AM) process. Low-NO_X natural gas fuel injectors, commonly used in Dry Low NOx (DLN) gas turbine combustors, have complex internal cavities and passages to ensure tailored mixing of air and fuel to achieve ultra-low levels of NO_X emission. Since the current design methodology of these injectors is based on conventional fabrication techniques (e.g. multi-step machining and welding processes), a new paradigm of design methodology needs to be developed for their adaptation to the EBM fabrication process.

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

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



Test Article to be Designed and Fabricated: DLN Fuel Injector with integrated Ceramic Insulated High Temperature Thermocouples.

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

Performers: Siemens Corporation

Award Number: FE0026348

Project Duration: 09/16/2015 - 02/28/2017

Total Project Value: $937,500

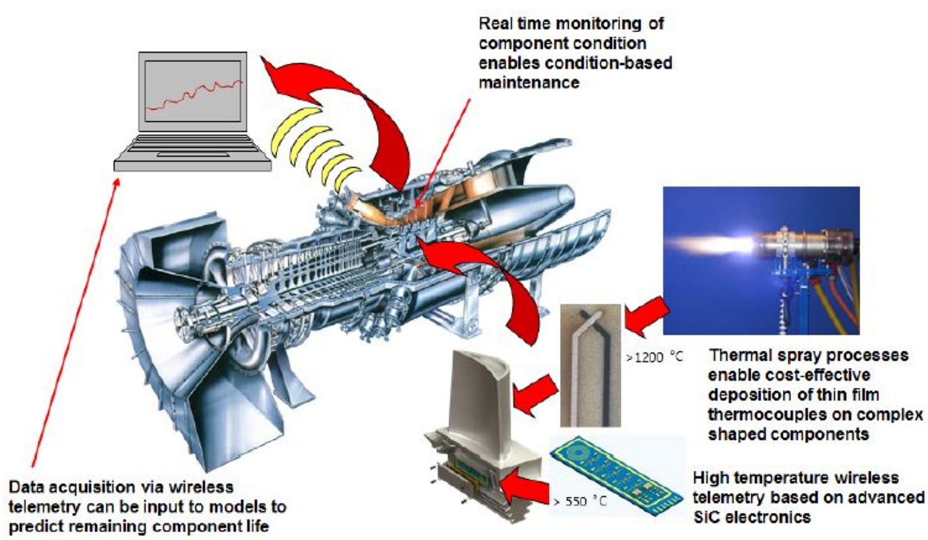
Technology Area: Plant Optimization Technologies

As advanced fossil energy systems progress towards higher efficiencies and ultra-low emissions, the conditions under which fuel is converted to power are becoming increasingly harsh (i.e. pressure, temperature, and corrosivity increases) leading to accelerated rates of degradation and failure of materials and components. A reliable and long-term monitoring capability will contribute to the overall reliability of the combustion turbine; however, real-time component condition monitoring in an industrial gas turbine presents significant technical challenges in several key technology development areas.

To meet the need for continuous monitoring, Siemens and its key partner Arkansas Power Electronics will develop an innovative, real-time sensor integrated component monitoring concept in the combustion turbine for long-term engine operation.

The objective of the program is to integrate durable, non-intrusive, ultra-high-temperature thermocouples (> 1200 °C) with high temperature wireless telemetry to enable materials prognostics and active condition monitoring in the hot gas path (HGP) of industrial gas turbines. The specific objectives are (1) to fabricate and install Smart Turbine Blades with thermally sprayed sensors and high temperature wireless telemetry systems in an H-Class engine, and (2) to integrate the component engine test data with remaining useful life (RUL) models and develop an approach for networking the component RUL data with Siemens' Power Diagnostics engine monitoring system. Phase 1 involves scaling up the thermal spray process to develop high temperature ceramic thermocouples with development of wireless telemetry system components, and demonstration of integrated sensor/wireless telemetry approach on stationary lab test rig.

The proposed system will transmit real-time blade-specific data from the turbine blade, enabling a transition to lower-cost, condition-based maintenance programs.



The smart turbine component, consisting of integrated embedded sensors with wireless telemetry, operational in the harsh environments of the gas turbine.

In-Situ Acoustic Measurements of Temperature Profile in Extreme Environments

Performer: University of Utah

Award Number: FE0006947

Project Duration: 10/01/2011 - 03/31/2015

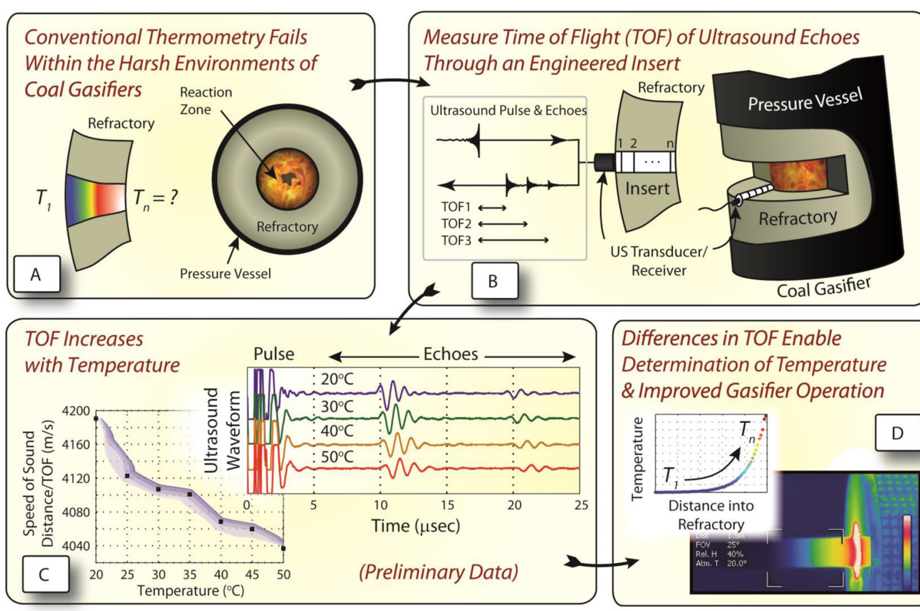
Total Project Value: $300,000

Technology Area: University Training and Research

This research proposed, demonstrated, and validated a novel approach using a noninvasive ultrasound method that provides real-time temperature distribution monitoring across the refractory, especially the hot face temperature of the refractory. The essential idea of ultrasound measurements of segmental temperature distribution is to use an ultrasound propagation waveguide across a refractory that has been engineered to contain multiple internal partial reflectors at known locations. When an ultrasound excitation pulse is introduced on the cold side of the refractory, it will be partially reflected from each scatterer in the propagation path in the refractory wall and returned to the receiver as a train of partial echoes. The temperature in the corresponding segment can be determined based on the recorded ultrasonic waveform and the experimentally defined relationship between the speed of sound and temperature.

This ultrasound system consists of an engineered waveguide, transducer/receiver, and data acquisition, logging, interpretation, and online display system which is simple to install with minimal modification on existing units or for use in new construction. The system was successfully tested with a 100 kW pilot-scale downflow oxyfuel combustor, capturing in real time temperature changes during all relevant combustion process changes. Measurements have excellent agreement with thermocouple measurements, and appear to be more immediately sensitive to temperature changes. This is believed to be the first demonstration of ultrasound measurements of segmental temperature distribution across refractories.

The ultrasound measurement method offers a powerful solution to provide continuous real-time temperature monitoring for circumstances in which conventional thermal, optical, and other sensors are infeasible due to the impossibility of insertion of a probe, harsh environment, unavailable optical path, and causes.



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).

Graphene-Based Composite Sensors for Energy Applications

Performer: West Virginia University Research Corporation

Award Number: FE0011300

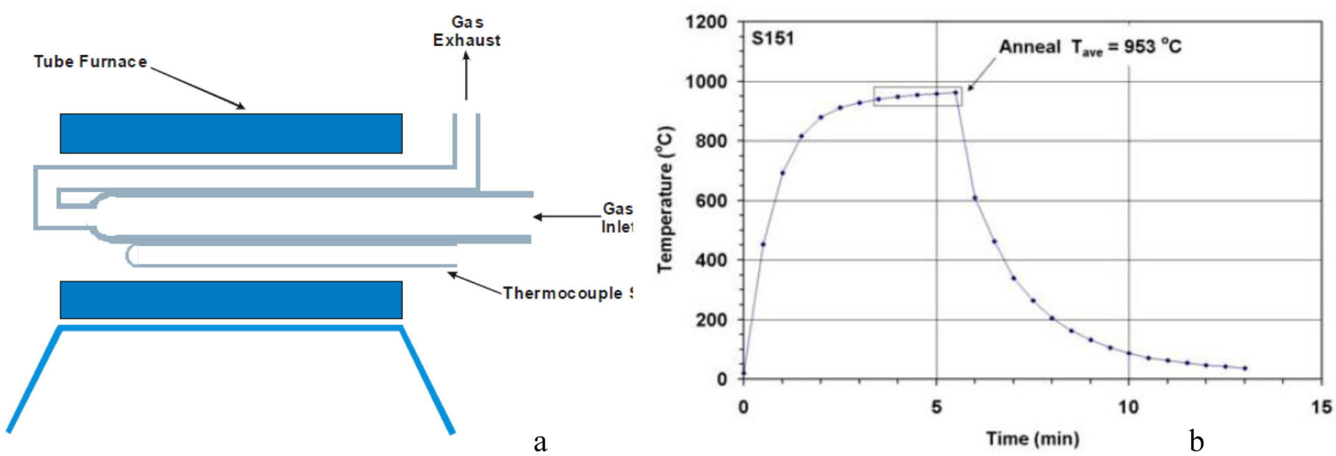
Project Duration: 07/17/2013 - 07/16/2016

Total Project Value: $300,000

Technology Area: University Training and Research

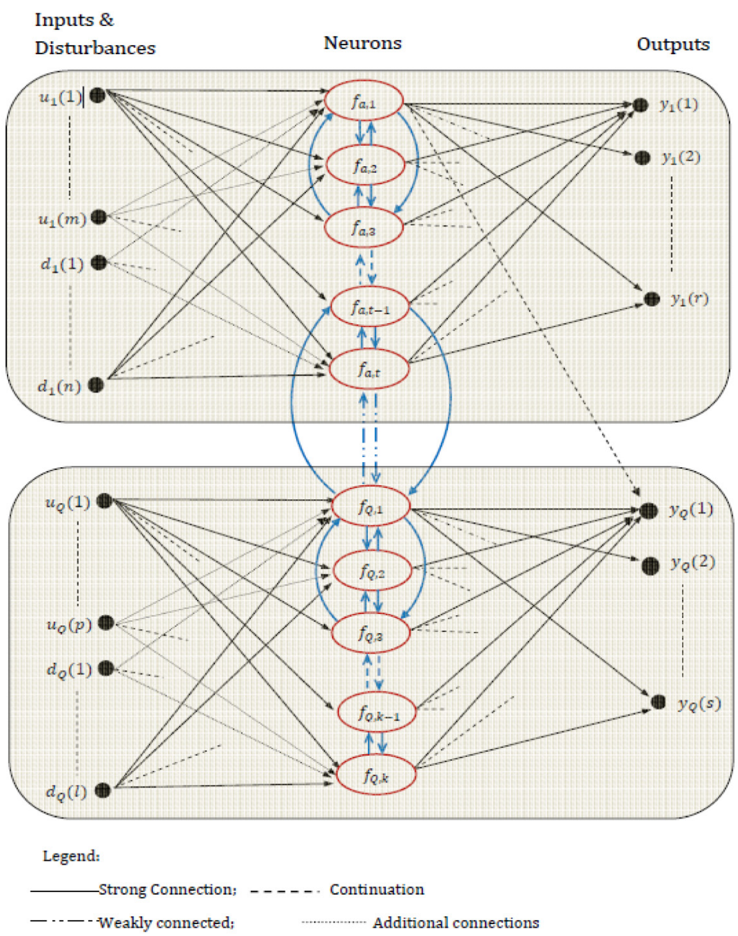
The objectives of this research are to develop and demonstrate the use of graphene-based composites as a high-sensitivity rapid-response electronic nose for sensing gas species in energy applications. Graphene-based materials that support sensing structures in the temperature range of 600 °C - 1000 °C 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.

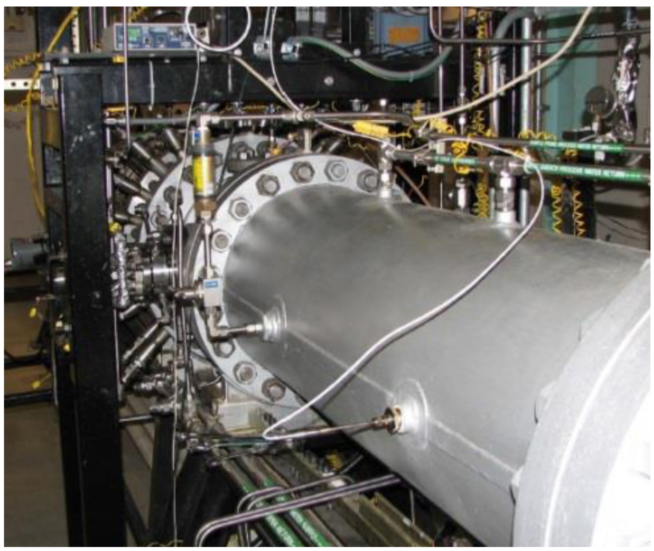
Distributed Intelligent Controls



Self-organizing, biometric control structure selection.

Advanced Process Control

Dynamic process modeling encompasses computational efforts to represent physical systems and processes by developing and implementing high-fidelity models using real-time data as input. For the purposes of control, these high-fidelity models are reduced and configured to run in real time (second time scales) to represent the dynamics of the operating system. Using reduced and speedy models in conjunction with estimation algorithms and other types of predictive algorithms, an overall control solution can be derived to enable model-based control to be used for real-time process control. This general approach is well understood for linear and steady-state systems. Research within the Sensors & Controls key technology area adopts 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.



Performer	Project Title	Page
Ames National Laboratory	Merged Environment for Simulation and Analysis (MESA)	53
National Energy Technology Laboratory Research and Innovation Center	Innovative Process Technologies-Advanced Controls Testing and Development	54
Ohio State University	Advanced Control Architecture and Sensor Information Development for Process Automation, Optimization, and Imaging of Chemical Looping Systems	55
Oregon State University	Evolving Robust and Reconfigurable Multi-Objective Controllers for Advanced Power Systems	56
West Virginia University Research Corporation	Development of Integrated Biomimetic Framework with Intelligent Monitoring, Cognition and Decision Capabilities for Control of Advanced Energy Plants	57

Merged Environment for Simulation and Analysis (MESA)

Performer: Ames National Laboratory

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

Project Duration: 05/01/2012 – 09/30/2016

Total Project Value: $1,925,000

Technology Area: 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 is 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 gathered will also be 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 will conclude 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 – Research and Innovation Center (RIC)

Award Number: FWP-2012.04.01.2.3

Project Duration: 10/01/2015 - 09/30/2016

Total Project Value: $285,000

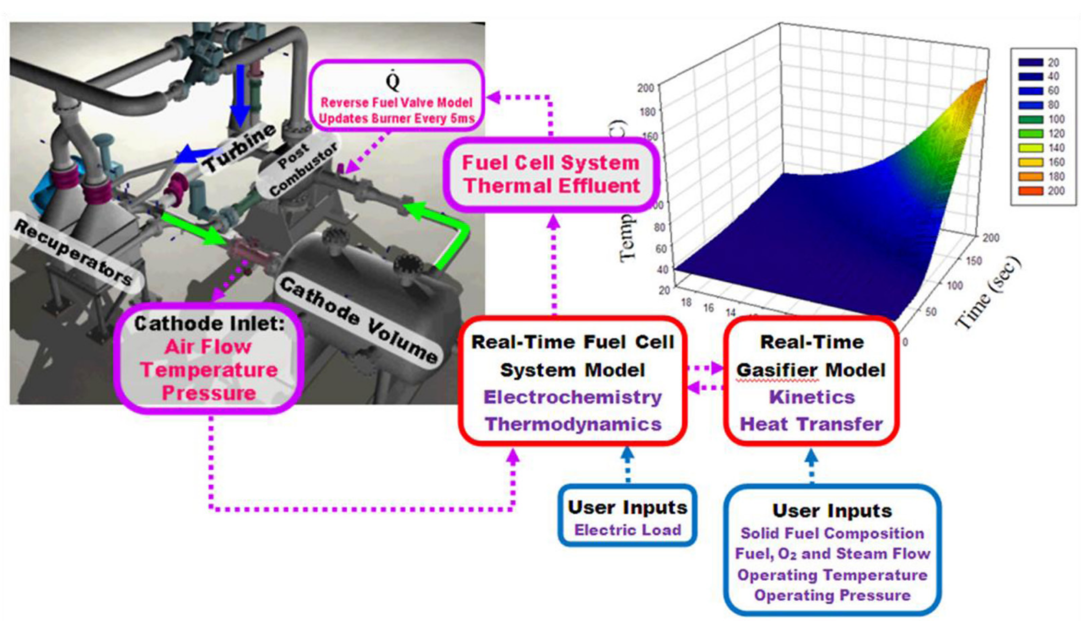
Technology Area: Plant Optimization Technologies

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 Technology Development and Integration Center (TDIC). 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.

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

Performers: Ohio State University

Collaborator(s): Tech4Imaging LLC

Award Number: FE0026334

Project Duration: 09/11/2015 - 02/28/2017

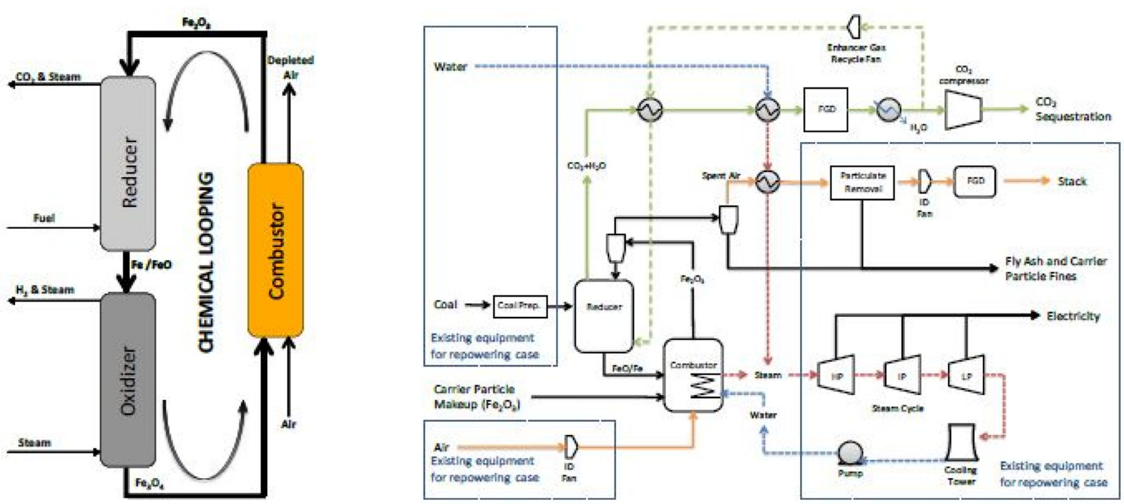
Total Project Value: $1,400,000

Technology Area: Coal Utilization Science

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

The intelligent process automation controller and optimization software will be tested in OSU's existing sub-pilot chemical looping test unit for Phase I, and ultimately integrated with the pressurized syngas chemical looping (SCL) pilot test unit constructed at the National Carbon Capture Center (NCCC) for Phase II. Additionally, electrical capacitance volume tomography (ECVT) sensor software will be developed to image a packed moving bed of oxygen carriers at the operating temperatures of the reducer reactor. The successful development of the imaging sensor software will be tested and verified in an existing bench test apparatus and incorporated into the chemical looping sub-pilot test unit for Phase I.

Chemical looping is considered a near-term technology with the potential to simplify CO_2 capture both efficiently and economically for power and chemical plant applications. The OSU coal direct chemical looping (CDCL) and SCL processes represent advanced energy systems for the conversion of solid and gaseous fuels, respectively, to H_2 and heat with in-situ CO_2 capture. The success of the proposed project will increase the operational reliability and efficiency of the chemical looping technologies. The work is scalable for larger demonstration units and will impact both the CDCL and SCL processes as the control scheme and sensor measurements used on both systems are nearly identical. Therefore, the developed automation concept and process optimization and imaging software for the SCL process can be directly applied to the CDCL system.



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

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

Performer: Oregon State University

Award Number: FE0012302

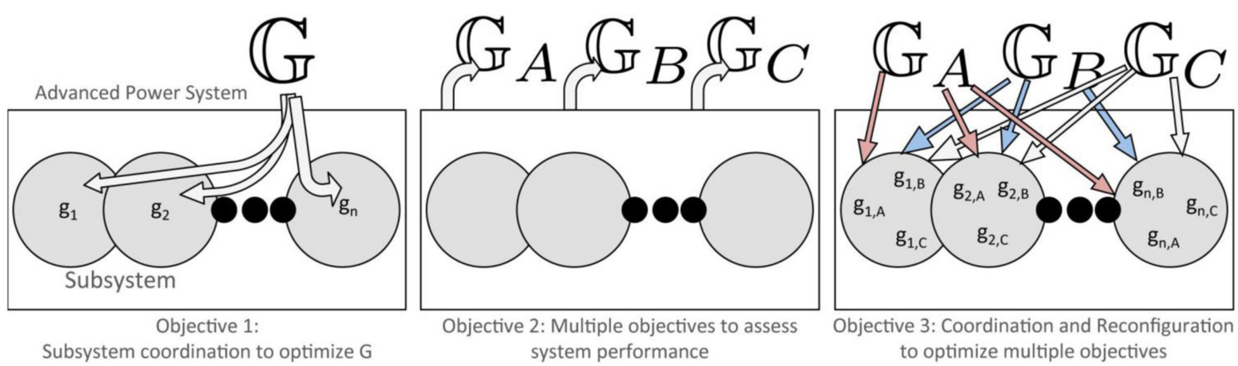
Project Duration: 10/01/2013 - 09/30/2017

Total Project Value: $1,401,192

Technology Area: Coal Utilization Sciences

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

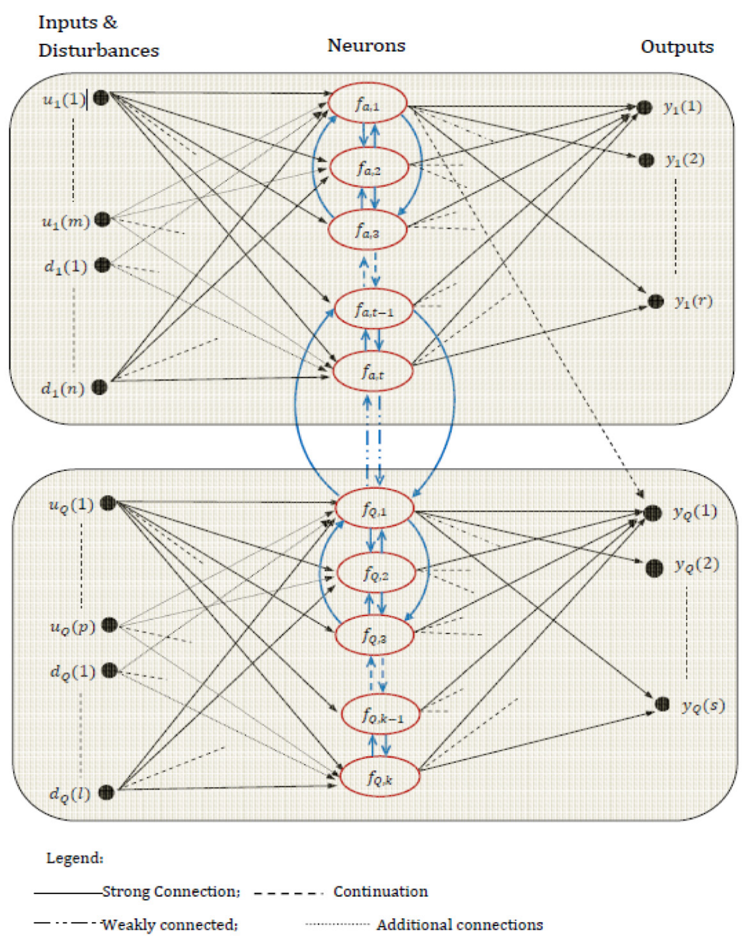
Project Duration: 01/15/2014 - 01/14/2017

Total Project Value: $1,403,611

Technology Area: 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.

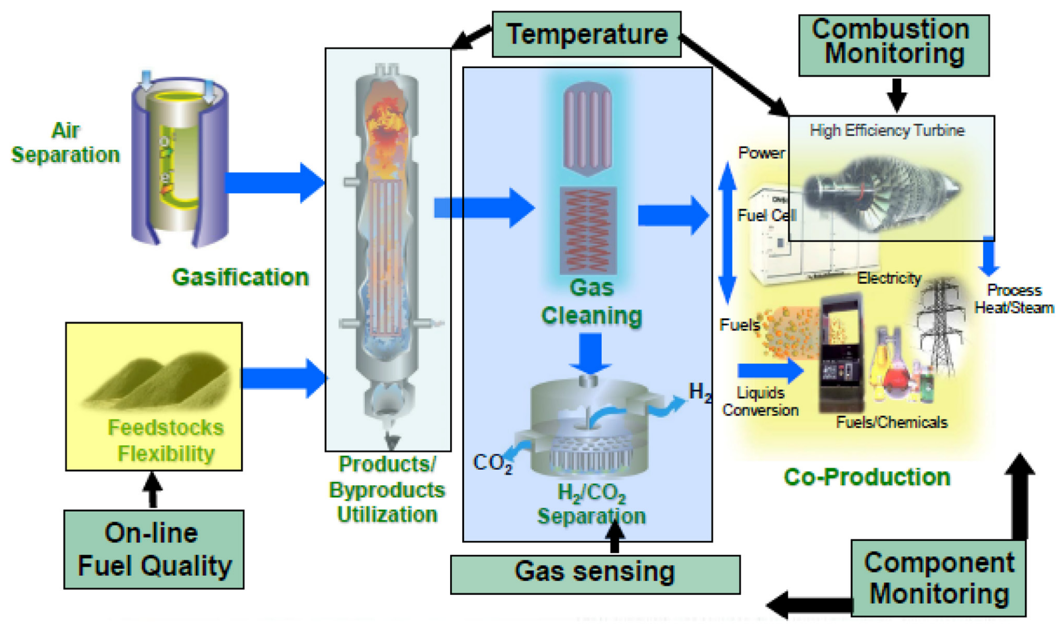
West Virginia University Research Corporation will develop and implement biomimetic-based control methodologies for the control system in general, including deterministic, stochastic and adaptive components.



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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Oregon State University	Intelligent Coordination of Heterogeneous Sensors in Advanced Power Systems	60
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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: 11/01/2011 - 10/31/2016

Total Project Value: $2,344,332

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.

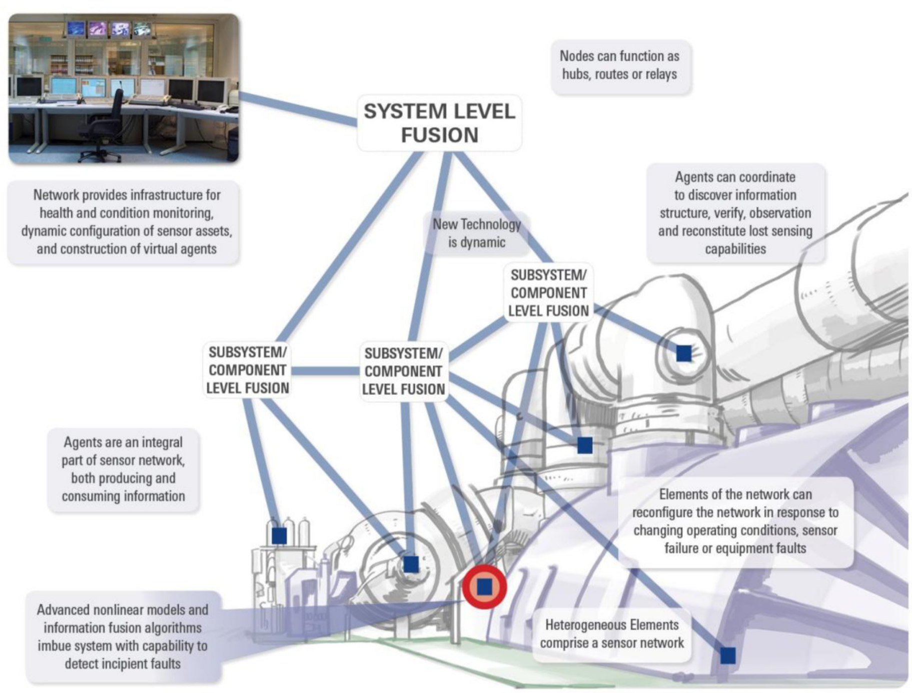


Diagram of System Level Fusion of Sensor.

Intelligent Coordination of Heterogeneous Sensors in Advanced Power Systems

Performer: Oregon State University

Award Number: FE0011403

Project Duration: 09/13/2013 - 03/12/2015

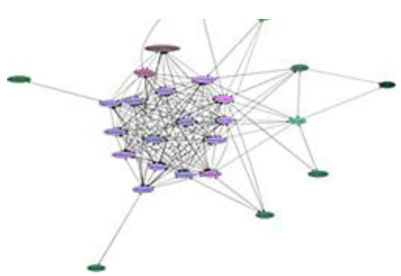
Total Project Value: $299,991

Technology Area: University Training and Research

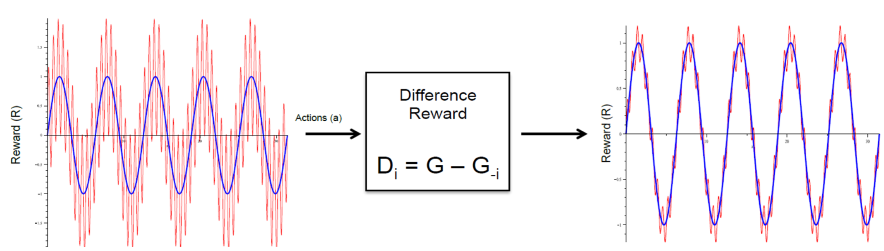
This work focused on deriving, implementing, and testing agent objective functions coupled with algorithms that promote coordinated behavior in large networks of heterogeneous sensors with embedded intelligence. The long-term objective of this work was to provide sensor deployment, coordination, and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

1. Derive sensor performance metrics for heterogeneous sensor networks.
2. Demonstrate effectiveness, scalability and reconfigurability of heterogeneous sensor networks in advanced power systems.

Results demonstrated that by properly shaping agent objective functions, large (up to 10,000 devices) heterogeneous sensor networks with key desirable properties may be developed. Achievement of the first milestone shows that properly choosing agent-specific objective functions increases system performance by up to 99.9% compared to global evaluations. The second milestone shows evolutionary algorithms learn excellent sensor network coordination policies prior to network deployment, and these policies can be refined online once the network is deployed. The third milestone shows the resulting sensor networks are extremely robust to sensor noise, where networks with up to 25% sensor noise are capable of providing measurements with errors on the order of 10^{-3}. The fourth milestone shows the resulting sensor networks are extremely robust to sensor failure, with 25% of the sensors in the system failing resulting in no significant performance losses after system reconfiguration. Because of the massive scale of the coordination this research allows, its impact goes beyond sensing in power plants. It is also applicable to energy problems from power distribution to managing smart grids to designing micro-grids.



Distributed sensor network.



Demonstration of cleaned up sensor signal.

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

Performer: Texas Tech University

Collaborator(s): West Virginia University

Award Number: FE0005749

Project Duration: 01/01/2010 – 12/31/2015

Total Project Value: $981,909

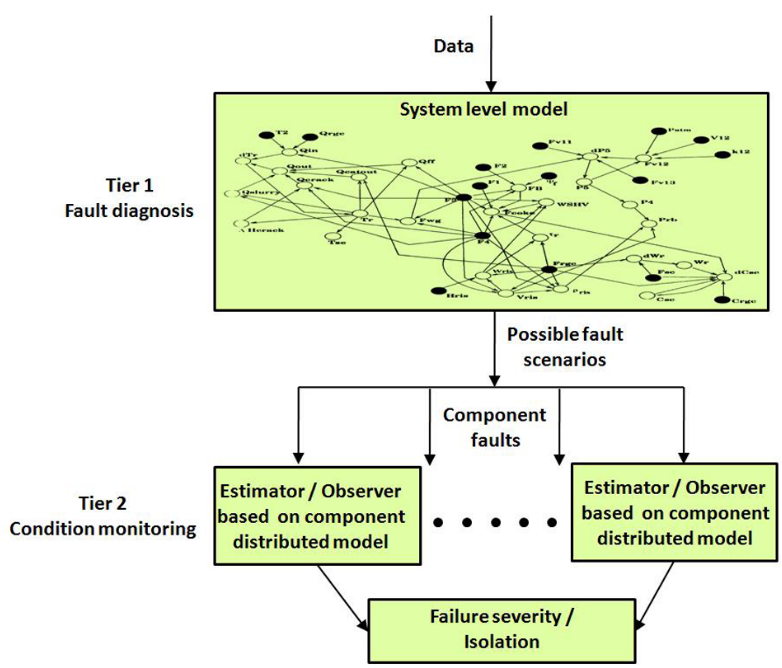
Technology Area: Plant Optimization Technologies

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) developed 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 was achieved by developing a two-tier sensor network algorithm capable of performing component condition monitoring and system-level fault diagnosis. The algorithms were 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 had to be identified. Structural changes to the gasifier model were implemented to incorporate simulation models for the identified faults. Sensor placement algorithms for condition monitoring and fault diagnosis were developed and tested on the plant-wide dynamic IGCC model.

The result of this project was model-based sensor placement algorithms that will increase the efficiency and effectiveness of fossil energy systems sensor networks. More specifically, the sensors 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: 09/01/2013 - 08/31/2016

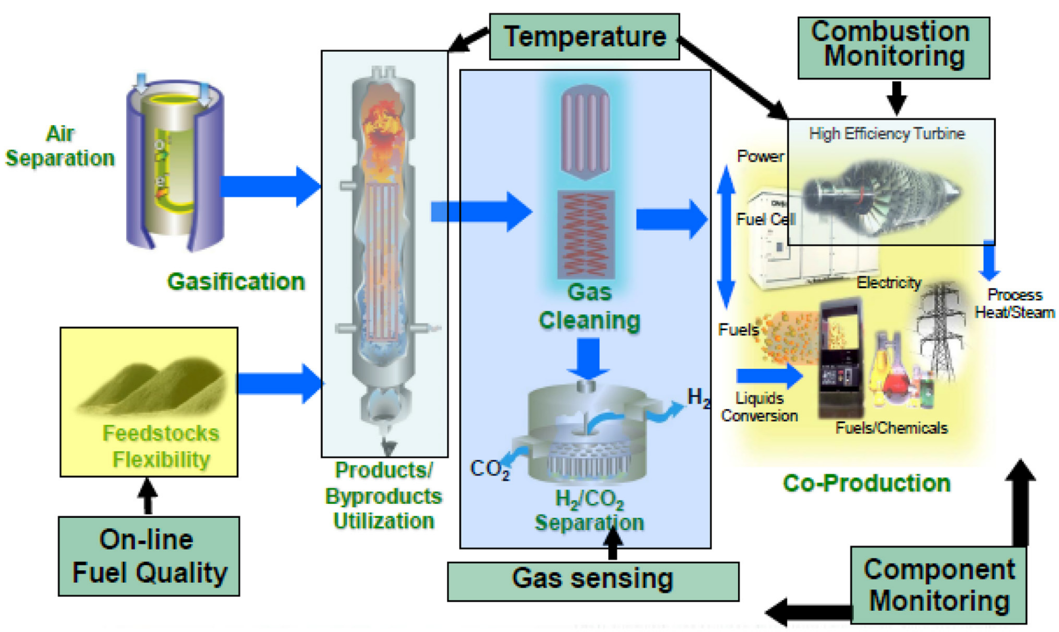
Total Project Value: $300,000

Technology Area: 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.

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 (NETL program)

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_2S . . . hydrogen sulfide

HAP . . . hazardous air pollutants

HBCU . . . Historically Black Colleges and Universities

HCl . . . hydrogen chloride

HEAT . . . harsh environment adaptable thermionic

Hg . . . 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

Abbreviations

RFID .... radio frequency identification
RUL .... remaining useful life
SAW .... surface acoustic wave
SBIR .... Small Business Innovative Research (U.S. Department of Commerce program)
SeO .... selenium
SeO_2 .... selenium dioxide
SiCN .... silicon carbon nitride
SMC .... Special Metals Corporation
SOx .... 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 (NETL program)
UTA .... University of Texas Arlington
UTAS .... UTC Aerospace Systems
UTEP .... University of Texas - El Paso
UTR .... University Training and Research (NETL program)
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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Websites:

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

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

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