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Crosscutting Research Sensors and Controls Project Portfolio

Crosscutting Research Program

The National Energy Technology Laboratory (NETL) Crosscutting Research Program is an applied research effort with a multi-disciplinary approach aimed at addressing barriers to clean fossil energy-based power generation and fosters breakthrough concepts that offer the potential to result in a step change improvement over current technology. Crosscutting Research's mission space is bound by investments in innovative sensor and control technology, advanced materials, revolutionary modeling and simulation tools, and university training and research that promote the education of students at U.S. universities and colleges.

U.S. DEPARTMENT OF ENERGY

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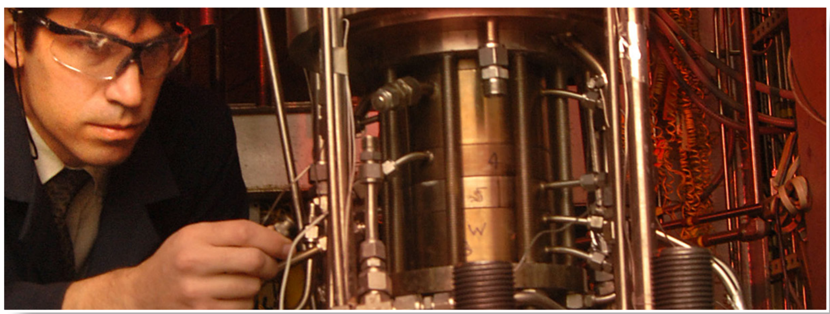
Crosscutting Research Program

The National Energy Technology Laboratory (NETL) Crosscutting Research Program is an applied research effort with a multi-disciplinary approach aimed at addressing barriers to clean fossil energy-based power generation and fosters breakthrough concepts that offer the potential to result in a step change improvement over current technology. Crosscutting Research's mission space is bound by investments in innovative sensor and control technology, advanced materials, revolutionary modeling and simulation tools, and university training and research that promote the education of students at U.S. universities and colleges.



The Sensors and Controls project portfolio is categorized into several technology areas. Projects from these technology areas are funded by the Crosscutting Research programs listed below:

1. **Plant Optimization Technologies (POT)** has research efforts aimed at developing new classes of sensors and measurement technology to enable low-cost, robust monitoring of advanced power plants and employing novel control strategies. These strategies will manage complexity and enable real-time optimization of fully integrated, highly efficient power generation systems, including large-scale environmental and carbon control systems, and support fundamental advanced materials research applicable to a full range of power generation technologies.

2. **Coal Utilization Sciences (CUS)** targets computational system dynamics and energy science through the development of simulation and modeling tools aimed at the optimization of plant design and shortening of developmental timelines. This work encompasses development of science-based models of the physical phenomenon occurring in fossil fuel conversion processes and multi-scale, multi-physics simulation capabilities that couple fluid flow, heat and mass transfer, and complex chemical reactions for optimizing the design and operation of critical unit processes in advanced power generation systems.

3. **University Training and Research (UTR)** supports science and engineering education at major universities and in minority colleges to improve the understanding of chemical and physical processes involved in the conversion and utilization of coal in an environmentally acceptable manner, maintains and upgrades the coal research capabilities and facilities of U.S. colleges and universities, and promotes the education of students in the area of coal science through grants to U.S. colleges and universities.

In addition to the Crosscutting Research funding programs listed above, NETL uses its participation in the U.S. Department of Energy's (DOE) Office of Science Small Business Innovative 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 their technological potential and provides the incentive to profit from commercialization. By including qualified small businesses in the Nation's research and development (R&D) arena, high-tech innovation is stimulated and the United States benefits from entrepreneurial spirit while meeting specific R&D needs.

This project portfolio for Sensors and Controls explores the efforts across the Crosscutting Research program. The basis for this research 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. 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. The controls development centers around self-organizing information networks and distributed intelligence for process control and decision making, and includes investigating fundamental combustion and gasification chemistry to discern rates and mechanisms affecting emissions behavior under combustion and gasification conditions.

These new technologies are designed to benefit both existing and advanced power systems such that meaningful improvements can be made to 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. Along with the sensors and control efforts, the need for new computational design tools support the goal to enable real time decision making to occur in the plant so that the optimized performance of advanced power systems can be realized in practice.

Technology Areas

Optical Sensing

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 and novel fiber optic sensor designs. Development efforts within this area include 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 optical fibers has made a significant impact on the viability to sense in harsh environments because of the immunity to Electromagnetic Interference (EMI), the inherent drift-free approach for select sensor designs, and a range of materials suitable for high-temperature applications.

Microsensors

The microsensor area encompasses a significant research effort to develop materials and structures to enable sensing at elevated temperatures (>500 °C). Targeted measurements for the microsensors include 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 the device to a specific parameter (e.g., gas) or suite of simultaneous measurements. This area can include sensing devices that can be made wireless, integrated with self-powering capability, and/or be embedded within a component. Recent efforts in this area include the desire to produce sensors that are low cost and can be rapidly prototyped with advanced manufacturing techniques. The culmination of this work targets robust, low-cost sensors that can be rapidly produced for wide distribution within an industrial environment.

Novel Control Architectures and Communication Frameworks

Process control is essential to any system or plant today and plays a key role in automating and coordinating sequences of events in which to achieve the desired performance. Many process control systems used today are built on sound mathematical relationships that utilize proportional integrated derivative (PID) control and a hierarchical relationship that was established in the mid-20th century. As plants become more complex and computational capabilities explode, the opportunities to enable optimized plant operation using emerging technology are both unique and timely. R&D opportunities include those that explore novel control for core processes (e.g., gasifier), as well as transformational control algorithms that represent the foundations for new types of control architectures that take advantage of networked sensors; distributed intelligence; and real-time, model-based optimization. In large power systems, insights from complex system theory may apply, including biomimetic approaches.

Device Integration for Distributed Sensing

Complimentary to the areas described above for the Sensor and Control Program, there are other enabling technologies needed to achieve the goals of improved sensing and advanced control. Included in this area are efforts to develop self-powering capability, wireless communication, and approaches to distribute sensors within an information and control network.

The use of wireless technology can minimize the cost of adopting new sensor devices in existing power plants by reducing installation costs. There are many ongoing efforts focused on wireless communication. However, this research is primarily focused on obtaining sensor data from a harsh environment wirelessly rather than the communication protocol used to deliver data on a wireless network. This effort targets different challenges and therefore different types of research in an attempt to extract real-time meaningful and accurate information.

Alongside wireless signal transmission, another interest to support the adoption of new sensor technology is self-powering capability of the sensor devices. Self-powered devices avoid the expense and effort associated with power supply, either wired to a power main or provided by batteries requiring periodic replacement. Harvesting waste energy to power sensor devices could simplify device installation and maintenance. Harvesting power requires a nearby power source, and in a large-MW fossil fuel plant, the sources of heat and vibration are numerous. Near-term applications of harvested energy are to power sensors and wireless communication devices that monitor the condition of the plant, thus enabling plant operators to improve reliability and performance at a much reduced cost relative to running wiring throughout the plant.

While some development efforts are focused on a specific type of technology (e.g., energy harvesting), other projects are addressing the challenge of integrating a sensor device with energy harvesting devices and wireless communication capability. The challenges associated cited with device integration are important to address alongside fundamentals so that the barriers to commercial application can be addressed in a timely fashion.

Imaging and Other Novel Approaches

The Crosscutting Research Program also explores new and innovative technologies that have potential across many segments of commercial power plants. The following are a few of the research opportunities being developed:

- Images are created when sensors are able to gather and save information about an extended object. High-resolution images can be obtained by scanning or sectioning methods. The information received does not need to be optical, but can be based on electrical, magnetic, or other physical properties of the sampling volume. R&D in this area seeks to enhance visualization capability.

- The emergence of advanced manufacturing has opened the opportunity to explore the application of embeddable sensors within the structure of components or subsystems used in power plant applications. Advanced manufacturing also opens up new realms of possibility for sensor manufacturing, including the ability to rapidly produce custom devices at low cost.

- Other novel sensors are under study to develop and demonstrate the performance of wireless microwave acoustic temperature and pressure sensors that are embedded in equipment and structures located in fossil fuel power plant environments to monitor the condition of components.

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Technology Area:
Optical Sensing
Plastic jacket
Metallic shield
Centre core
Metal Oxide Film
Grating

Development of Prototype Commercial Gasifier Sensor

Performer: Gas Technology Institute (GTI), North Carolina State University, and Phillips 66 Company

Date: 8/1/2012 – 7/31/2014

Cost: $626,423

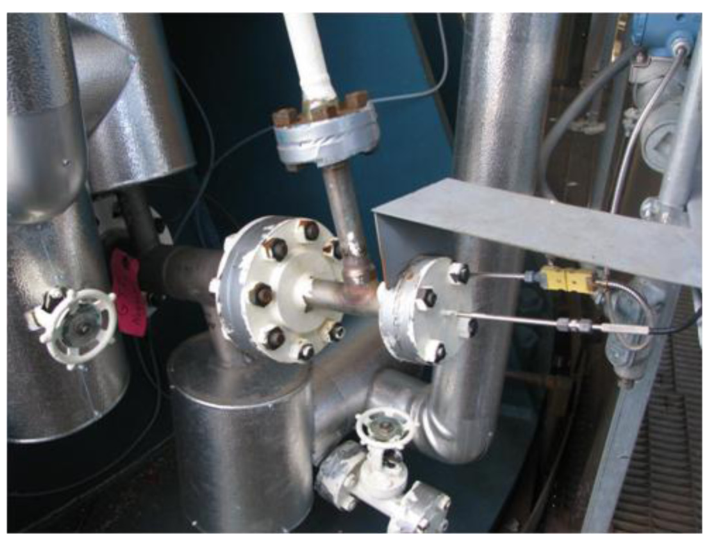
Technology Area: Optical Sensing

Program Area: Advanced Systems – Integrated Gasification Combined Cycle

GTI, North Carolina State, and Phillips 66 Company continue their collaboration to make ultra-clean gasification commercially competitive. This project will further develop and demonstrate of the sensor technology developed under the "Real Time Flame Monitoring of Gasifier Burner and Injectors". During sensor testing at CANMET's vertical Combustor, the project team has already demonstrated that the sensor technology can be utilized to identify and characterize processes which occur during coal combustion such as devolatilization, char heating and burning. Spectral data was obtained and successfully translated into flame temperature measurements. It was also demonstrated that the reduced spectral data could be well correlated with very important gasification process parameters such as the air/fuel and water/fuel ratio. Any one of these parameters (temperature, air/fuel, and water/fuel) is sufficient to assess burner wear; however, the tested sensor was capable of monitoring all three of them plus the flame shape as functions of burner wear. This will likely be a very powerful tool which should enable significant improvements in gasifier efficiency, reliability, and availability.

Finally the sensor was tested in the PWR (Pratt & Whitney Rocketdyne) gasification plant located at GTI's research campus and at the ConocoPhillips industrial scale gasifier at Wabash River Indiana. The field trials of the GTI Gasifier sensor modified to withstand high temperature and pressure corrosive atmosphere of the industrial entrain flow gasifier. The project team successfully demonstrated the Gasifier Sensor system's ability to monitor gasifier interior temperature while maintaining unobstructed optical access in excess of six weeks without any maintenance. Upon completion of the trial, sensor examination revealed that the system did not sustain any damage and required minor cleanup of the optics.

The "Development of Prototype Commercial Gasifier Sensor" project began with modification of the sensor software to enable real time temperature data acquisition, processing and providing the obtained gasifier temperature information to the gasifier operators. The second project task will focus on the sensor hardware modifications needed to improve reliability of the sensor system. The modified gasifier sensor will be installed at the Wabash River commercial gasifier and tested over a six month period to evaluate sensor accuracy and durability. Finally, the project will evaluate the commercial viability of the sensor system.



Sensor Installed at Wabash River Gasifier.

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

Performer: General Electric

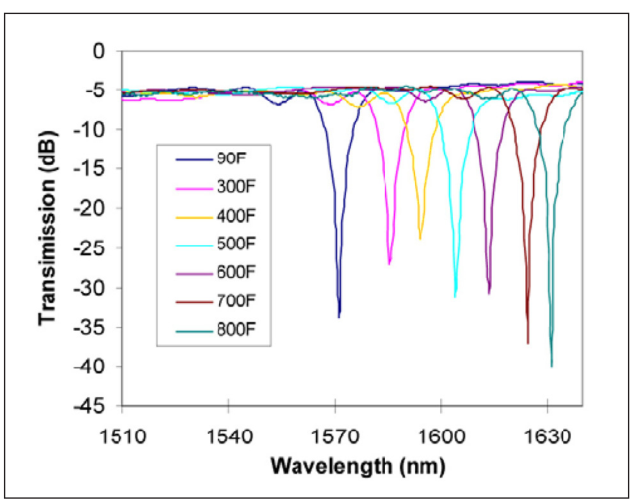
Date: 10/1/2012 – 9/30/2014

Cost: $1,248,733

Technology Area: Optical Sensing

Program Area: Plant Optimization Technologies

GE Global Research will develop and demonstrate a multi-point fiber optic sensor cable for in situ monitoring of pressure and temperature in the harsh environment of CO_2 sequestration wells. The research includes the design of a multi-point pressure/temperature sensor cable and package for operation up to 250 °C and 10,000 psi; a simplified, multiplexed readout method; fabrication of the multi-point pressure/temperature sensing cable with multiple spliced temperature and pressure sensors; and incorporation of remote wireless activation and operation of the sensors in a simulated environment. Standard modeling and fabrication processes will be employed to design the new sensor die. Sensor splicing techniques will be developed from experience obtained with the single point sensor splicing. An optical readout system will be constructed in the laboratory for testing the system response and accuracy, and accelerated environmental testing of the entire cable will be performed according to standard practices to determine the long term survivability of the sensor system. Wireless communication systems and protocols developed by GE for remote monitoring will also be demonstrated for operation of the sensor.



Thermal long-period fiber grating (TLPFG) transmission spectrum at various temperatures (fabricated by CO_2 laser irradiations). (Figure provided courtesy of Missouri University of Science and Technology)

Intrinsic Fiber Optic Chemical Sensors for Subsurface Detection of CO_2

Performer: Intelligent Optical Systems, Inc.

Date: 10/1/2012 – 9/30/2015

Total Award Value (Dollars): $1,632,426

Cost Share (% and Dollars): Recipient 20.4% ($333,000); DOE 79.6% ($1,299,426)

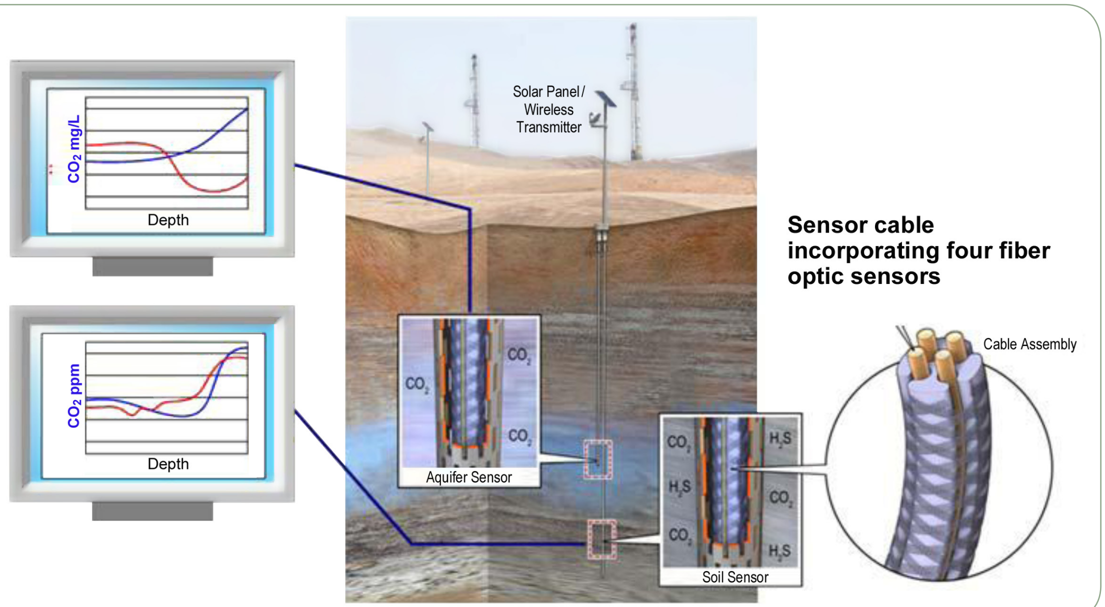
Technology Area: Optical Sensing

Program Area: Plant Optimization Technologies

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

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

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



Coated fiber concept for continuous monitoring of subsurface CO_2 concentration. (Figure provided courtesy of Intelligent Optical Systems)

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

Performer: Missouri University of Science and Technology, University of Cincinnati, and AmerenUE Corporate

Date: 10/01/2009 – 9/30/2013

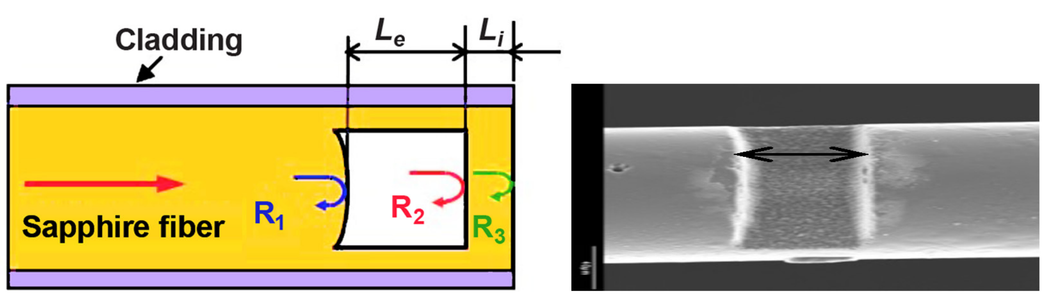
Cost: $1,131,799

Technology Area: Optical Sensing

Program Area: Coal Utilization Science

The focus of this project is to conduct fundamental and applied research leading to successful development and demonstration of robust, multiplexed, micro-structured sensors using single-crystal sapphire fibers. At the core of the technology are the hybrid extrinsic/intrinsic Fabry-Perot interferometer sensors directly micro-machined on a sapphire fiber using an ultrafast laser. This hair-thin, cylindrical filament made of single-crystal sapphire (glass) is able to transmit light by confining it within regions of different optical indices of refraction. These sensors can be deployed into the hot zones of advanced power and fuel systems (inside a coal gasifier or gas turbine system) to simultaneously measure high temperature (up to 1600 °C) and dynamic gas pressure.

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



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

Raman Gas Composition Monitor

Performer: National Energy Technology Laboratory, University of Pittsburgh

Date: 8/01/2008 – 9/30/2013

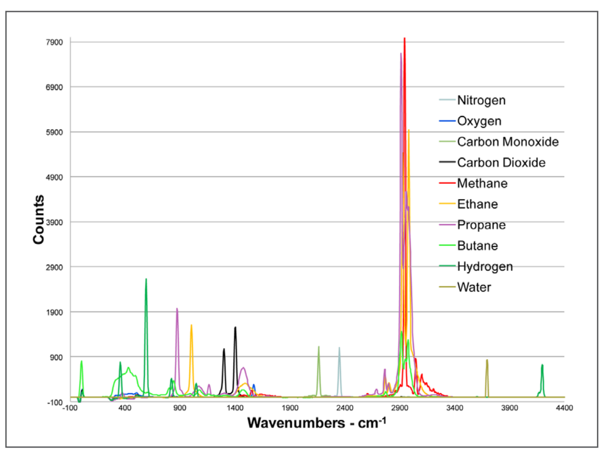
Cost: $950,000

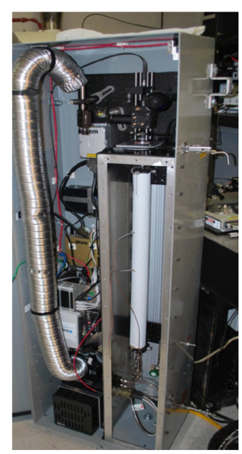
Technology Area: Optical Sensing

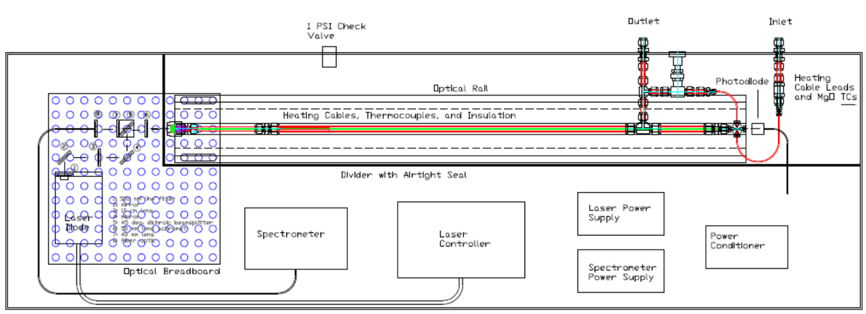
Program Area: Coal Utilization Sciences

Rapid gas composition monitoring of fuel and exhaust streams is critical to control systems for gas turbines, as well as any process with gas feedstock or exhaust. Available gas monitors address one or two components and often respond after many seconds. Raman spectroscopy offers a unique alternative for gas sensing because it measures all gas species (except noble gases) with one technique. In the past, Raman spectroscopy has been handicapped by low signal strength or very high laser power requirements. However, using a new sample cell consisting of a capillary waveguide with a highly reflective coating we have demonstrated that total gas composition can be monitored in less than 1 second with low powered lasers and small CCD array spectrometers. A Rapid Raman Sensor has been developed with this technology and demonstrated to operate at up to 800 psig and 200C in continuous operation. A gas process stream is sampled continuously with low volume tubing, and the sample delivered at process pressure to the sample cell. The total composition including hydrocarbons, the diatomics N_2, O_2, and H_2 and water, is measured and reported in less than one second. A 5 psig pressure drop across the cell permits the gas to be reintroduced downstream in the process, instead of venting. The composition may be reported as individual species concentrations, or as a composite parameter such as the Wobbe number or the heating value.

The sample cell is a 1m long by 0.3 mm ID capillary with sample volume of 0.07 cm^3. The Raman spectra are dispersed over 1024 data points on the CCD diode array and read out to a computer. The computer calculates the concentration of all species using principle component analysis and reports the results to the control system. The high flow, low volume sampling system and detection cell, coupled with the simultaneous data acquisition enables response in as little as .4 seconds. The ability to measure all species without interference and including water with this response time has not been previously possible. The system can also be applied to an exhaust stream to monitor gas recirculation and to alternative fuels such as coal gasification or biodigester gases where non-combustible diluents species must be measured.







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

Performer: The Curators of the University of Missouri (Rolla)

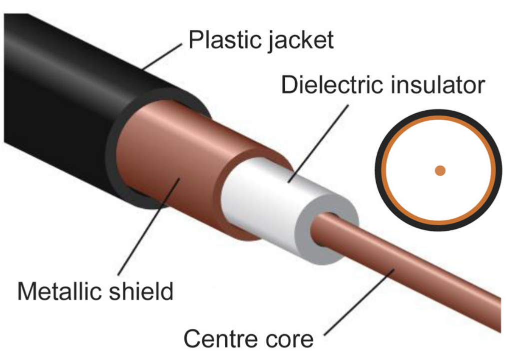
Date: 10/1/2012 – 9/30/2015

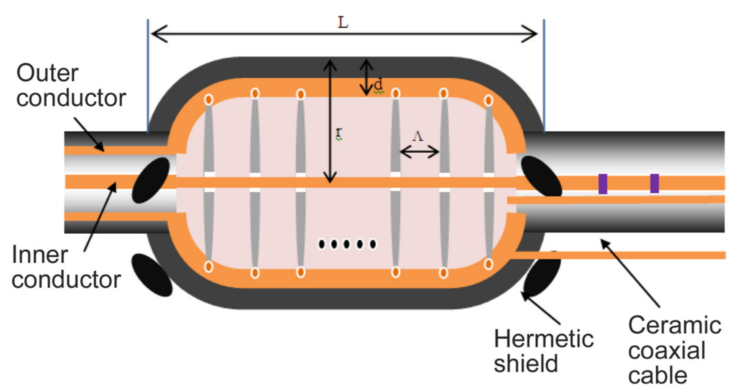
Cost: $1,447,193

Technology Area: Optical Sensing

Program Area: Plant Optimization Technologies

The project will develop a low-cost, distributed, and robust ceramic coaxial cable sensor platform for in situ down-hole monitoring of geologic CO_2 injection and storage with high spatial and temporal resolutions. The novel sensors are based on a recent invention of coaxial cable Bragg gratings (CCBG) and coaxial cable Fabry-Perot interferometers (CCFPI) in conjunction with the latest available high temperature, ultralow loss ceramic coaxial cables. Robust sensors will be created by forming Bragg gratings and CCCFPI 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 interactions between the sensor datum 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 the injection processes.





Multi-Point Strain and Temperature Coaxial Cable Sensor Concept for Monitoring CO_2 Sequestration. (Figures courtesy of Missouri University of Science and Technology)

Laser-Based Detection of Trace Level Contaminants

Performer: Sandia National Laboratory

Date: 5/1/2011-9/30/2013

Cost: $450,000

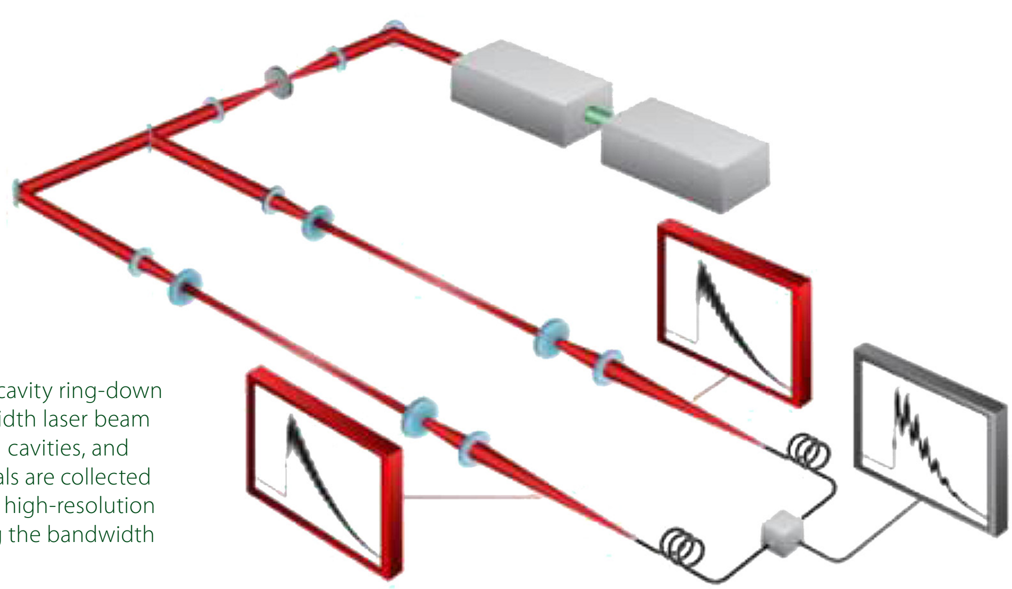
Technology Area: Optical Sensing

Program Area: Plant Optimization Technologies

Utility coal boilers are facing increasing scrutiny for their emissions of hazardous air pollutants (HAPs). Specifically, the EPA's recently promulgated National Emission Standards for Hazardous Air Pollutants from utility sources sets new, lower emission limits for particulate matter, hydrogen chloride (HCl), and mercury. In the case of HCl, the maximum allowed emission levels for existing plants approach the detection limits of currently available instruments, and the limits established for new plants exceed the performance capabilities of current HCl continuous emission monitors. Thus, monitoring and control of HCl emissions to these reduced levels necessitates the development of reliable, quantitative detection methods.

The primary goal of the proposed research program is the development of an instrument for high-sensitivity, real-time detection of HCl. This instrument will employ a novel cavity ring-down spectrometer that enables collection of a broadband width, high-resolution absorption spectrum with a single laser pulse.

The detection approach developed will enable selective detection of trace-level species in the flue gas with greater sensitivity than currently achievable. The project has three main tasks: (1) proof-of-concept demonstration of the spectrometer; (2) development, quantification, and optimization of the spectrometer for the detection of HCl; and (3) construction of a portable system to demonstrate detection of HCl in flue gas samples (extracted from a coal fired, pilot-scale combustor).



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

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

Performer: Stanford University and University of Utah

Date: 10/01/2009 – 9/30/2013

Cost: $1,097,321

Technology Area: Optical Sensing

Program Area: Coal Utilization Science

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

The project's first phase—Sensor Development—focuses on developing the laser sensor and fabricating optical access downstream of the gasifier reactor. The second phase—Sensor Testing—will evaluate sensor performance in the main reaction section of the gasifier. Lessons learned from the first phase have been used to make improvements to the laser and optical access design.

The ability to scale sensor performance from the pilot-sized reactor at the University of Utah to various potential commercial designs requires understanding sensor performance as a function of particulate loading and gasifier pressure. The researcher will develop scaling rules needed to estimate sensor performance in other environments (e.g., different gasifier designs or operating conditions).

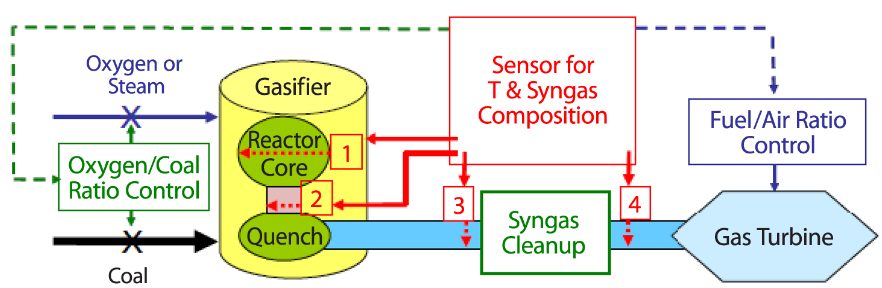


Illustration of the potential locations of gas sensors for control of a combined-cycle power plant. (Figure provided courtesy of Stanford University and University of Utah)

Plasmonics-Based Harsh-Environment-Compatible Chemical Sensors

Performer: State University of New York at Albany, College of Nanoscale Science and Engineering

Date: 01/16/2009 – 01/15/2012

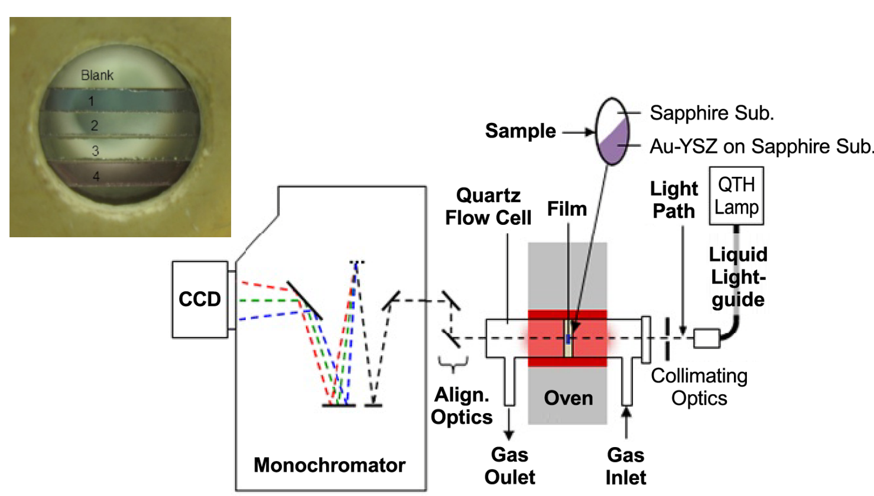
Cost: $432,230

Technology Area: Optical Sensing

Program Area: University Coal Research

Sensors and controls compatible with harsh environmental conditions are critically needed for use in gas turbines, solid oxide fuel cells, gas reformers, or other ancillary equipment in advanced power plants is a critical need. Currently available field-effect sensors based on silicon carbide or gallium nitride are unstable in a typical engine environment where temperatures can exceed 600 °C. Due to the complexity of material-incompatibility challenges, along with the intrinsic complexity of the field-effect device itself, a plasmonics-based all-optical sensing technique has been devised. A novel approach to gas sensing under harsh environmental conditions using the optical properties of tailored nanomaterials as the sensing layer is a much simpler design. This sensing system does not require the development of harsh-environment-compatible ohmic contacts, nor does it require high- temperature electronics, which typically suffer from reliability and stability problems.

The State University of New York at Albany will develop parallel materials-deposition techniques to engineer libraries of metal nanoparticles-based films with a metal-oxide matrix for rapid development of prototype sensing materials. The objective of this project is to further optimize these characteristics while developing a detailed understanding of the sensing mechanism as a function of temperature and humidity. Researchers will make a series of cross-selectivity measurements and exploring two approaches. Initial studies show the sensing response for the target gases to be dependent on the processing of the materials. For instance, the detection of carbon monoxide can be reduced by a factor of 20, while the detection of hydrogen is unaffected for the same film. The first approach will study the intrinsic cause of these sensing modifications, thereby enhancing the selectivity of these films toward nitrogen dioxide, carbon monoxide, and hydrogen. An alternative approach will be the use of a selective catalytic-reactive thin film to enhance the selective characteristics of these nanocomposite films. The development of these novel sensing materials would benefit advanced power systems by providing cost-effective sensors and control technology.



Conceptual example of a gas exposure bench and photo of fabricated plasmonic films. (Figure and photo provided courtesy of State University of New York at Albany)

Heat-Activated Plasmonic Chemical Sensors for Harsh Environments

Performer: University at Albany – SUNY

Date: 10/1/2011 – 9/30/2014

Cost: $528,225

Technology Area: Optical Sensing

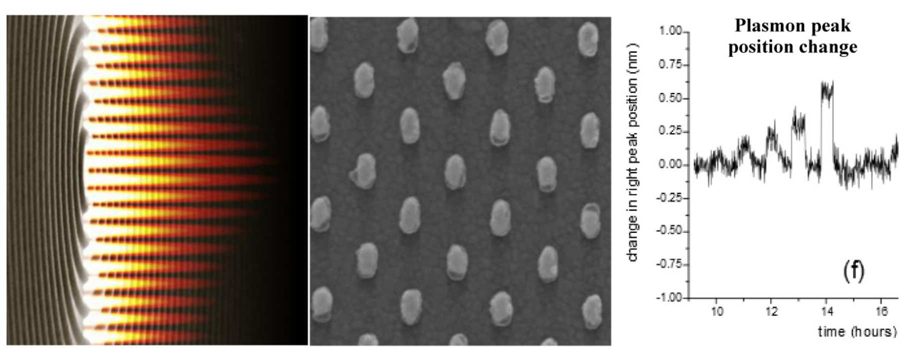
Program Area: University Coal Research

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

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

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

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



Development of Novel Ceramic Nano-Film Integrated Optical Sensors for Rapid Detection of Coal-Derived Synthesis Gas

Performer: University of Cincinnati and Missouri University of Science and Technology

Date: 04/01/2009 – 03/31/2012

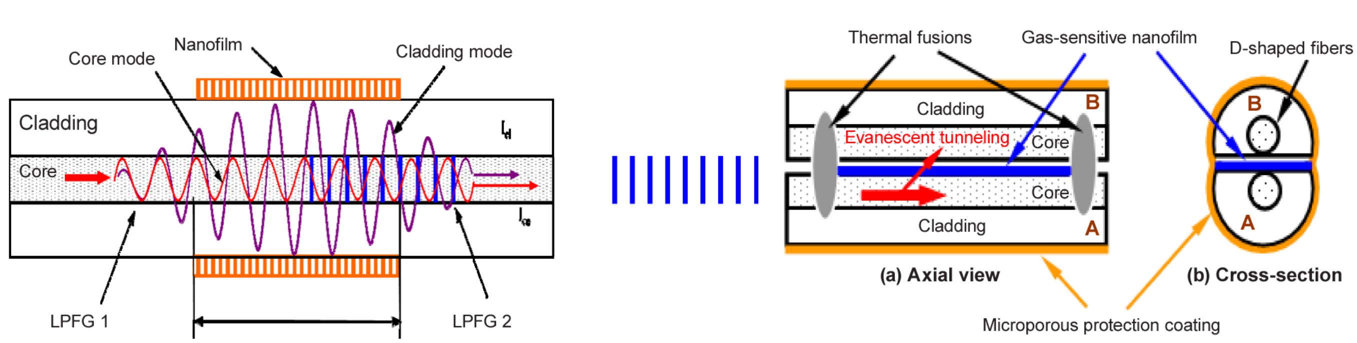
Cost: $326,958

Technology Area: Optical Sensing

Program Area: University Coal Research

The overall objective of this project is to develop new types of high-temperature (>500 °C) devices for the monitoring of coal-derived gases by physically and functionally integrating advanced nano-ceramic materials with fiber optic chemical sensors (FOCS). This project also includes the development of sensors and sensor materials for hydrogen (H2), carbon dioxide (CO_2), and hydrogen sulfide (H2S) detection at temperatures greater than 500 °C and pressures up to 250 psi. The primary technical objective is to investigate and demonstrate two new types of nanocrystalline-doped ceramic-coated FOCS that possess the desired stability, sensitivity and selectivity for in situ, rapid gas detection in coal-derived syngas streams. The first type is a Long Period Fiber Grating (LPFG)-coupled self-compensating interferometer sensor and the second type is an evanescent tunneling sensor. For both types of sensors, high selectivity is targeted through the application of nanocrystalline thin film coatings of doped-ceramics that only interact with specific gas molecules and are inert to others. This project specifically focuses on sensors for H2 and H2S detection at high temperatures and elevated pressures. Fiber sensors have some proven advantages for various applications including their small/lightweight size, immunity to electromagnetic interference (EMI), resistance to chemical corrosion, high-temperature capability, high sensitivity, and their capability for remote operation.

The project will begin the model design of the LPFG-coupled interferometer and evanescent tunneling fiber sensors as well as the development of the nanocrystalline doped-ceramic materials suitable for gas sensing. Then it will be moved to the sensor fabrication (including integration of the nanofilm with fiber devices) and improvement of the ceramic nanofilm properties and fiber structures for enhancing sensor performance. Finally, the sensor performance in multicomponent gas mixtures under high temperatures and pressures will be evaluated. The three-year project involves interdependent research efforts in the areas of material, chemical, and electrical/optical engineering.



Conceptual designs for LPFG-coupled self-compensating interferometer sensor (left) and a nanocoated evanescent tunneling sensor (right). (Figures provided courtesy of University of Cincinnati and Missouri University of Science and Technology)

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

Performer: University of Pittsburgh

Date: 07/30/2010 – 08/31/2013

Cost: $298,395

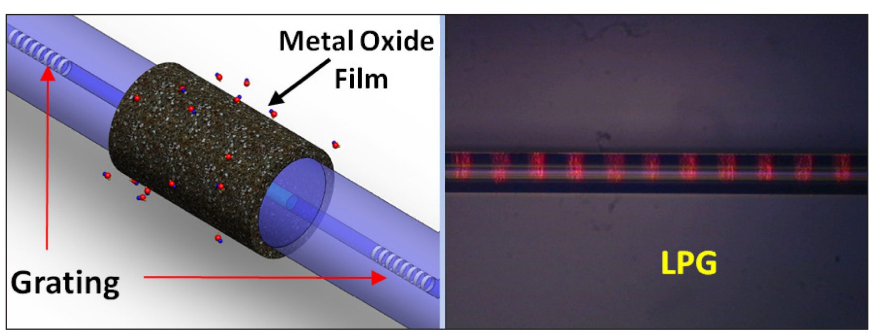
Technology Area: Optical Sensing

Program Area: University Coal Research

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

The objectives of this project are twofold; the first task focuses on the design, fabrication, and three-dimensional (3-D) testing of macro-porous photonic crystals using functional metal oxides. Porous metal-oxide 3-D photonic crystals will be fabricated using a holographic lithography. The surface-chemistry-derived refractive index change or spectroscopic changes will be enhanced by 3-D optical confinement and the large surface area of the porous structure, which can be readily measured remotely through transmission and reflection spectroscopy. To perform multi-species fuel-gas composition analysis, metal-oxide nanostructures can be integrated with high-temperature stable fiber grating devices fabricated by femtosecond ultrafast lasers. The surface chemical-induced refractive index change or structural change can then be measured by the high-temperature stable in-fiber grating sensors. The coating technique can also be developed to synthesize functional metal-oxide films on the inner wall of hollow-core optical fibers. The surface adsorption of fuel gas can then be measured using either Raman spectroscopy or photoluminescent spectroscopy enhanced by the hollow waveguide. The application of hollow-core optical fiber as both the sample gas cell and signal optical collection components can dramatically amplify the sensing signal, leading to orders-of-magnitude enhancements of the signal.

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



Conceptual drawing of coated fiber Bragg grating and photo of Long Period gratings (LPG) on fiber. (Figure and photo provided courtesy of University of Pittsburgh)

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

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

Date: 1/18/2011-1/17/2014

Cost: $1,460,138

Technology Area: Optical Sensing

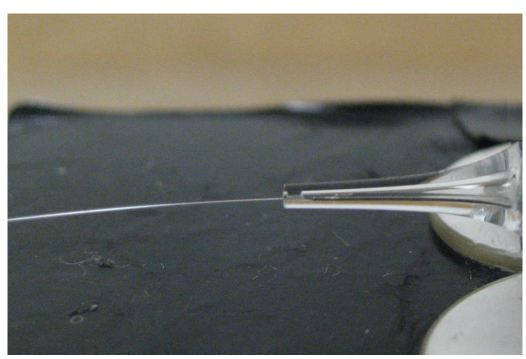
Program Area: Coal Utilization Science

Recent advances in fossil fuel energy production technologies have shown tremendous potential to efficiently create clean, sustainable electricity using a variety of carbon rich fuels. Techniques such as the Integrated Coal Gasification Combined Cycle (IGCC) have been demonstrated as feasible next-generation energy sources, but commercial operation of these facilities poses significant challenges. Foremost among these difficulties is the issue of refractory wear. The high-temperature reducing environment in the gasifier causes rapid corrosion of even the toughest refractory materials, limiting typical useful lifetime. Furthermore, the complexity and uncertainty of the gasification process makes remaining refractory life difficult to predict in working gasifiers.

To address this concern, this project will develop an advanced distributed sensing technology capable of monitoring refractory wear in an operating coal gasifier. The Virginia Tech Center for Photonics Technology (CPT) will develop a prototype sensing system and evaluate it in a laboratory test environment for operation at temperatures over 1000 °C.

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

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



Concept validation setup.

Single-Crystal Sapphire Optical-Fiber Sensor Instrumentation

Performer: Virginia Polytechnic Institute and State University and Eastman Chemical Company

Date: 10/01/1999 – 12/31/2013

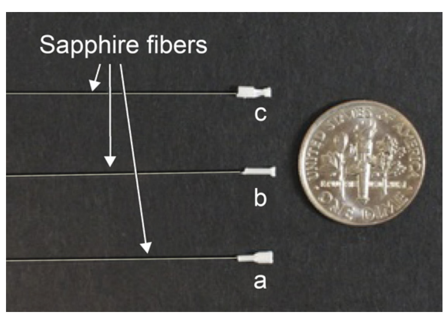
Cost: $3,993,893

Technology Area: Optical Sensing

Program Area: Advanced Systems – Integrated Gasification Combined Cycle & Coal Utilization Science

The Center for Photonics Technology at the Virginia Polytechnic Institute and State University (Virginia Tech) has developed a new, robust, accurate temperature-measurement system that can withstand the harsh conditions found in commercial gasifiers for an extended period of time, thus allowing improved reliability and advanced process control. While coal gasification offers a viable pathway to near-zero emission power generation, the conditions under which coal is gasified are harsh, including high-temperatures (1200–1600 °C), high pressures (up to 500 psi), and high rates of corrosion and erosion. The temperature sensor is based on single-crystal sapphire due to its high-temperature stability and resistance to corrosion. The sensor uses sapphire optical fiber and a sapphire disc joined to the end of the fiber to form the sensor. Light is launched and reflected back within the fiber to sense changes in temperature of the sapphire disc. The single-crystal sapphire allows optically-based measurement to be made and can fulfill the need for the real-time monitoring of high temperatures created in gasification processes.

The project includes fundamental research on high-temperature materials; design of optical temperature-measurement systems; and miniaturization and fabrication method development. The project also examines packaging of the fiber sensors for industrial use and testing of the sensor in full-scale gasifiers. The prototype sensor was subjected to a full-scale field-performance demonstration in 2006 and 2007. The sensor's performance under actual operating conditions was evaluated and optimized at temperatures up to 1400 °C. Initial testing was very successful as the sensor lasted seven months in the gasifier, surpassing an initial goal of around 45 days. In comparison, the thermocouples installed in proximity to the sensor had to be replaced at least twice during the seven month period.



Single-crystal sapphire sensor heads with the sapphire fiber waveguides achieve greater precision through miniaturization. (Photo provided courtesy of Virginia Polytechnic Institute and State University)

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

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

Date: 06/01/2005 – 06/30/2014

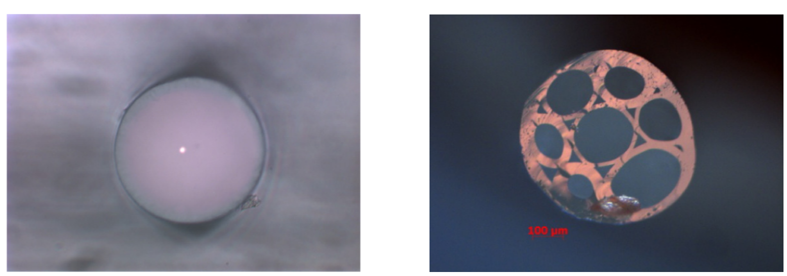
Cost: $1,187,364

Technology Area: Optical Sensing

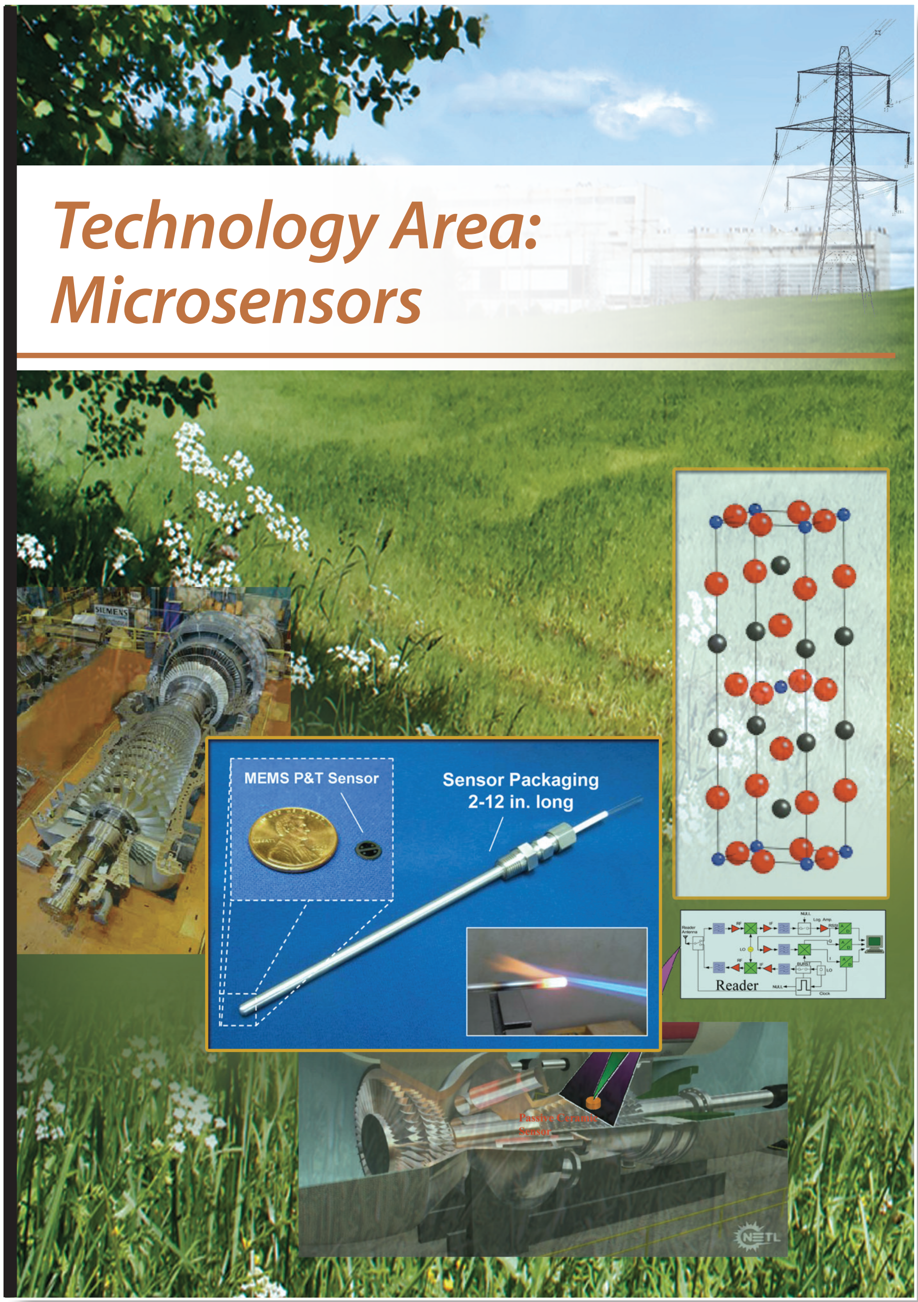
Program Area: Coal Utilization Science

Energy from coal-fired power plants will continue to play a dominant role in the energy landscape well into the future due to the abundant coal reserves available in the United States. Accurate and reliable detection of various gases is necessary for emissions monitoring and advanced process control in coal-fired power plants. Ideal gas sensors in these processes would operate in situ, exposed to high temperatures and harsh environments, where many conventional sensors cannot operate. Very few sensors are commercially available for high-temperature (1000 ºC) and harsh-environment monitoring of gases such as nitrogen oxides, sulfur oxides, carbon monoxide, hydrogen, oxygen, methane, and ammonia, which are present in coal and coal-derived syngas applications. These sensors suffer from a number of major limitations including limited accuracy, extremely short lifetimes, unexpected failure, and intensive maintenance.

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



Examples of Porous Fibers: Solid core with porous cladding (left) and hollow cores with porous interfaces (right). (Photos provided courtesy of Virginia Polytechnic Institute and State University)


Technology Area:
Microsensors
MEMS P&T Sensor
Sensor Packaging
2-12 in. long
Reader

Development of Robust Distributed Ceramic Coaxial Cable Sensor for High-Temperature Harsh Environment Applications

Performer: HABSonic LLC

Date: 07/01/2012 – 03/30/2013

Cost: $149,886

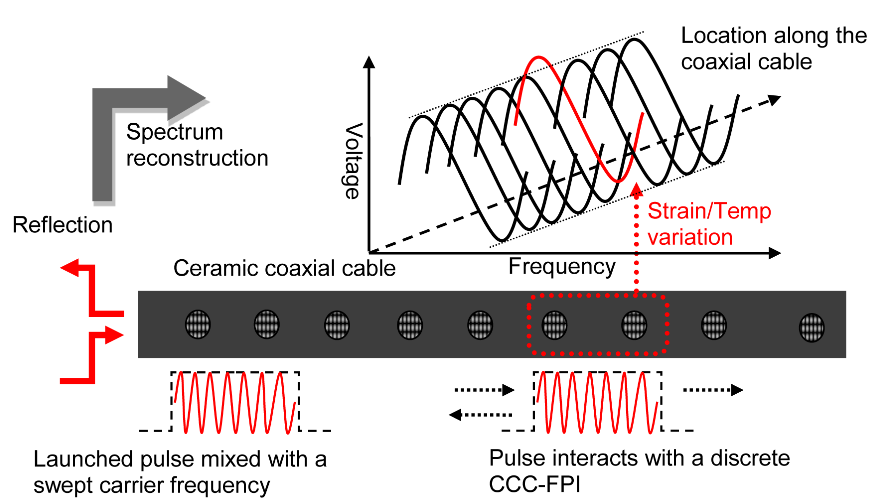
Technology Area: Microsensors

Program Area: Small Business Innovative Research

Improved operational performance of current and future power plants is driving innovation in sensors and controls to enable operation of power systems at higher temperatures for greater efficiency and lower emissions. Few sensors are available that exhibit long term stability/reliability and adequate robustness for harsh environment applications. In addition, the problem of using a large number of sensors with widespread distribution challenges sensor deployment, interrogation and data acquisition/ processing.

In this project, HABSonic, in collaboration with Missouri University of Science and Technology, proposes a novel ceramic coaxial cable Fabry-Perot interferometric (CCC-FPI) sensor and associated signal processing techniques for truly distributed measurement of temperature and strain in high temperature harsh conditions. Inherited from optical fiber sensors, the coaxial cable has the necessary high sensitivity. Operating in radio frequency (RF) domain, the new sensor platform may have the long-desired robustness and stability to be installed and/or embedded into the energy systems for long-term operation. Additionally, HABSonic will develop a novel signal processing scheme to achieve truly distributed sensing with high spatial resolution.

The objective of this project is to prove the concept of the proposed CCC-FPI sensor and signal processing method. Specifically, the sensor models will be developed to derive optimal structural and functional designs; prototype CCC-FPI sensors will be fabricated for proof-of-concept evaluations; a joint-time-frequency demodulation technique will be developed to achieve truly distributed sensing; the key functions of the developed prototype sensors and signal processing unit will be demonstrated under laboratory conditions.



Joint-time-frequency domain interrogation of cascaded CCC-FPI sensors for truly distributed sensing with high spatial resolution.

Integral Packaging of High Temperature Chemical Sensors for In Situ Measurements

Performer: Makel Engineering, Inc.

Date: 08/01/2012 – 07/31/2014

Cost: $996,862

Technology Area: Microsensors

Program Area: Small Business Innovative Research

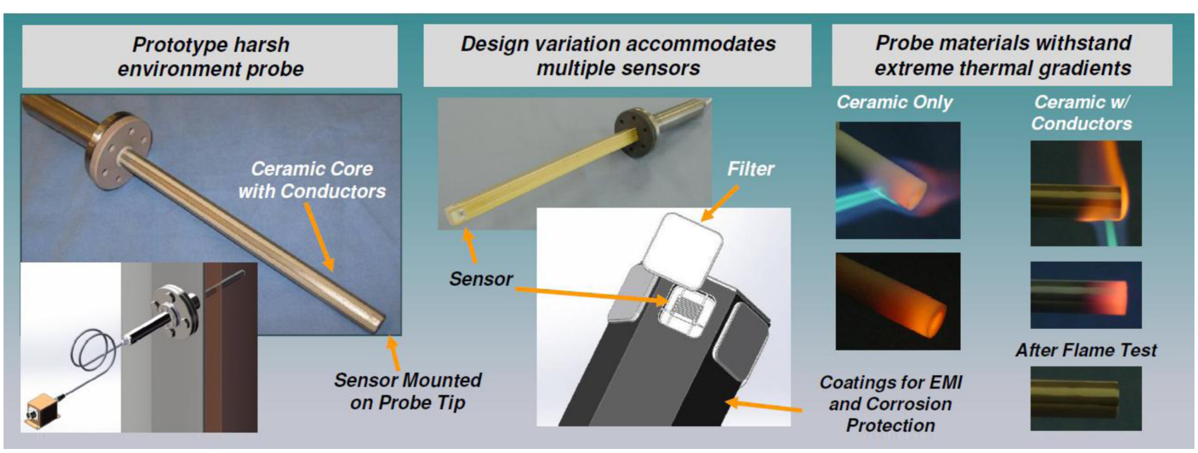
One of the key requirements to efficiently and safely operate advanced power generation systems is to have knowledge of the process conditions. In addition to physical measurements (e.g., pressure, temperature), real-time knowledge of gas compositions at critical locations enables optimizing operational conditions.

The goal of this project is to develop an integrated package to enable operation of MEMS sensors in the harsh environments associated with advanced power systems. This standard package will enable placement of a variety of chemical sensors in the process, and to quickly adjust for process variations (e.g. feedstock energy content, intake air humidity, etc.).

In Phase I, Makel Engineering developed two integral probe designs for harsh environments, meeting the requirements for a wide range of applications within advanced power generation. The T-Style integral packaging was developed for installation in stationary turbines. The R-Style was developed for installation in refractory lined walls. Probes were fabricated and tested in simulated environments.

Phase II will focus on testing chemical sensors in turbine and gasifier systems at a wide range of end user facilities that include DOE coal-fired facilities as well as facilities operated by Sacramento Municipal Utility District (SMUD) and turbine manufactures. This will demonstrate how advanced sensors can play an important role in characterizing the physical and chemical environments within gas turbines and other components present in emerging clean coal technology power systems.

Advanced stationary gas turbines are the primary application for the technology, requiring measurement of species such as NO_X, CO and O_2 at elevated temperatures to optimize operational conditions. On a related application, temperature is the primary limiting factor in the placement of chemical sensor in aircraft engines.



Microsensors probe enable gas composition measurements in harsh environment.

Condition-Based Monitoring of Turbine Blades Demonstrated in H-Class Engine

Performer: Siemens Energy, Inc

Date: 1/30/2011 – 9/30/2013

Cost: $1,685,746

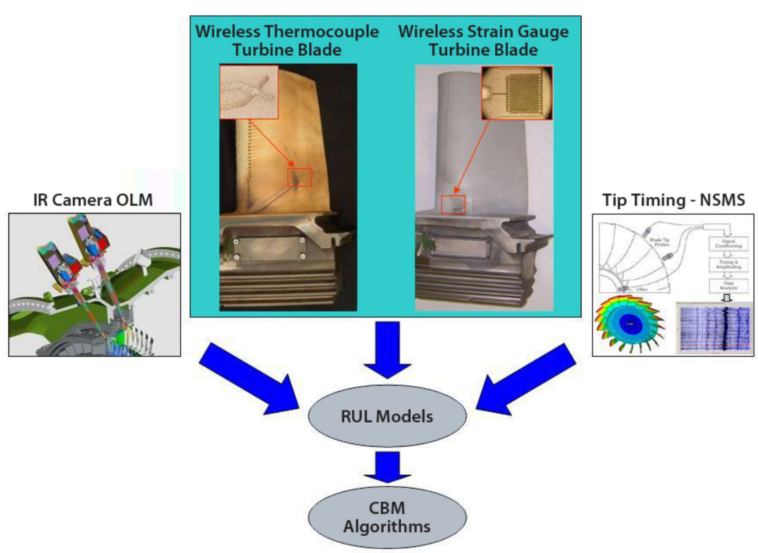
Technology Area: Microsensors

Program Area: Coal Utilization Science

Electrical power generation relies on the use of turbomachinery to provide highly efficient and reliable power. One of the major components of the turbine that is essential are the blades used in the hot high velocity environment inside the turbine. The blade performance and condition are directly related to the efficiency and reliability of the turbomachinery. Real-time monitoring of component condition and accurate information concerning component remaining life is essential for a transition from schedule-based maintenance (current practice) to condition-based maintenance.

To address this concern, Siemens Energy, Inc. will develop Smart Turbine Blades based on technology designed to build self-aware engine components that incorporate embedded harsh-environment-capable sensors and high-temperature-capable wireless telemetry systems for continuously monitoring component condition in both the compressor and turbine sections. The Smart Turbine Blades will have incorporated on their surfaces thermally sprayed thermocouples and dynamic strain sensors capable of operating at up to 1250 °C. An embedded, high-temperature wireless telemetry system capable of operating at 450 °C will be located near the hot section of the turbine. The project team will install wireless Smart Turbine Components and integrate the data with the remaining useful life (RUL) models and Power Diagnostics® engine monitoring program.

Combining fast area sensors with point sensors (such as thermally sprayed thermocouples and dynamic strain gauges connected to wireless transmitters) to enable a real-time, high-accuracy remote monitoring of rotating turbo-machinery will enable true On-line condition-based maintenance procedures to be realized, and will ultimately transform how land-based turbines are designed, optimized, and operated, as well as how they are maintained.



Overview of Real-Time, High-Accuracy Remote Monitoring of Rotating Turbo-Machinery.

Online, In Situ Monitoring of Combustion Turbines Using Wireless, Passive, Ceramic Sensors

Performer: University of Central Florida

Date: 01/01/2010 – 12/31/2012

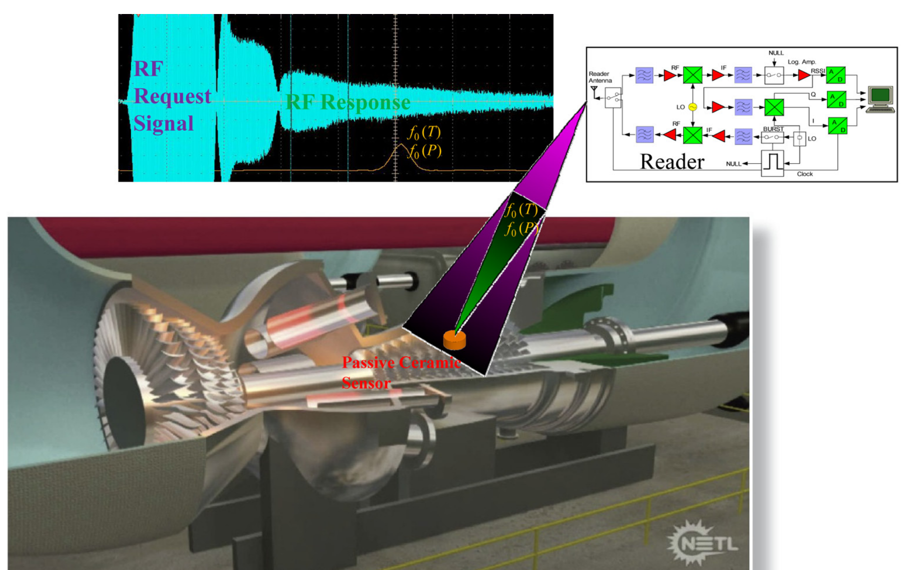
Cost: $1,013,994

Technology Area: Microsensors

Program Area: Coal Utilization Science

Advanced, near zero-emission power systems currently under development require sensing and control technologies that allow real-time, in situ monitoring of system operations involving highly automated process controls. For gasification plants to be more efficient and less costly, sensors used in the process need to be sturdier and more accurate than those currently available. Researchers at the University of Central Florida are developing wireless, passive, ceramic microsensors for in situ temperature and pressure measurement inside combustion turbines. These sensors are being designed to operate in high-temperature (>1300 °C), elevated-pressure (300–700 psi), harsh environments. The primary objective of this project is to develop a set of high-temperature, wireless, passive, ceramic, micro-electro-mechanical systems (MEMS) sensors for on-line, real-time monitoring applications in turbine systems. The project team is providing precise operational parameters in real-time for optimal system control, higher efficiency, increased reliability, and improved emissions.

The development of sensors and controls capable of withstanding high-temperature and high-pressure conditions will help integrate and optimize complex power systems. The sensors being developed under this project possess specific advantages when compared to existing sensors, including these attributes: (1) wireless, (2) passive, (3) accurate, (4) robust, (5) of very small size, and (6) having the ability to network with other sensors. These features permit sensor placement in areas in which it is difficult or impossible to place existing sensors and they enable simultaneous readings by multiple sensors connected to a single display. Their use in combustion turbines will facilitate the use of gasification plants to produce power from various fuels cleanly and efficiently.



Targeted application of sensors: advanced combustion turbine and example of resonant frequency of the ceramic sensor which contains temperature or pressure information. (Figure provided courtesy of NETL and University of Central Florida)

Multifunctional Nanowire/Film Composites Based Bi-Molecular Sensors for High-Temperature Gas Detection

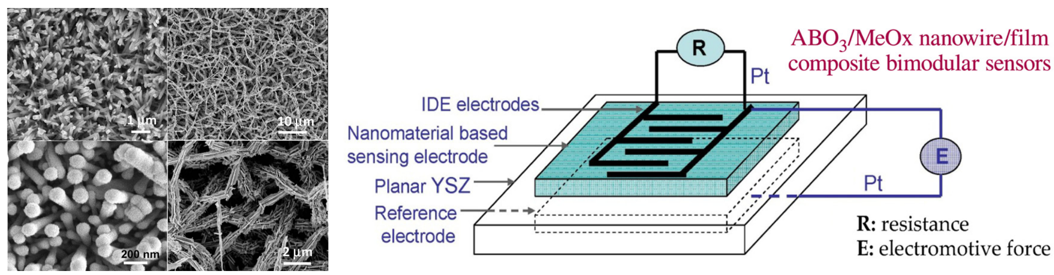
Performer: University of Connecticut

Date: 10/01/2009 – 9/30/2012

Cost: $1,010,772

Technology Area: Microsensors

Program Area: Coal Utilization Science



Metal oxide-based nanowire/film assembly (left), conceptual microsensor design for testing nanowires/films (right). (Photo and figure provided courtesy of the University of Connecticut)

Real-time monitoring of the composition of combustion gases usually requires sensors to be operated at high temperatures in harsh environments. Currently, commercially available sensor technology capable of withstanding such harsh environments is extremely limited; therefore, there is an urgent need to develop novel high-temperature gas sensors. Researchers at the University of Connecticut are developing a unique class of multifunctional metal oxide/perovskite-based composite nanosensors for industrial and combustion gas detection at high temperature (700-1300 °C). A sensing platform is being designed and fabricated with an array of integrated electro-resistive and electrochemical nanosensors to meet the challenge of gas detection in high-temperature, complex gaseous environments in various combustion conditions. The miniaturized platform is bi-modular, and made up of three-dimensional (3-D) nanowire/dendrite arrays and two-dimensional (2-D) composite nanofibrous thin film. The 3-D and 2-D composite architectures are assembled by single-crystal 3-D nanowire/nanodendrites or polycrystalline 2-D nanofibrous films made of multifunctional metal oxides. These nanocomposites combine the functions of wire/dendrite arrays and thin film to increase the nanosensors' sensitivity to catalysts, stability at high temperatures, and ability to detect multiple gases.

The goal of the project is to advance the gas-detection field by developing high-temperature, in situ and real-time gas sensors using a unique class of multifunctional metal oxide/perovskite core-shell composite nanostructures for industrial and combustion gas detection. The specific objectives are to synthesize metal oxide-based nanowire/film composites; to determine and optimize the deposition parameters for growth of nanowire/film composites; to investigate nanowire/film composites; to design and fabricate bi-modular nanosensors using the nanowire/film composite nanostructures; to characterize the resistive detection module and the potentiometric detection module of the nanosensors in different high-temperature, gaseous environments; and to establish their corresponding calibration curves. The bi-modular gas sensor developed through this project will be more robust and provide more information than sensors currently available for harsh conditions at high temperature. Good selectivity, fast response, and enhanced sensitivity in high-temperature gas detection can be achieved by these nanosensors due to the diversity of the nanomaterials, the inherent large specific surface area of nanostructures, and minimized gas diffusion resistance.

Investigation of Tungsten Oxide-Based Hydrogen Sulfide Sensor Materials for Coal Gasification Systems

Performer: University of Texas – El Paso (UTEP)

Date: 01/15/2009 – 01/15/2012

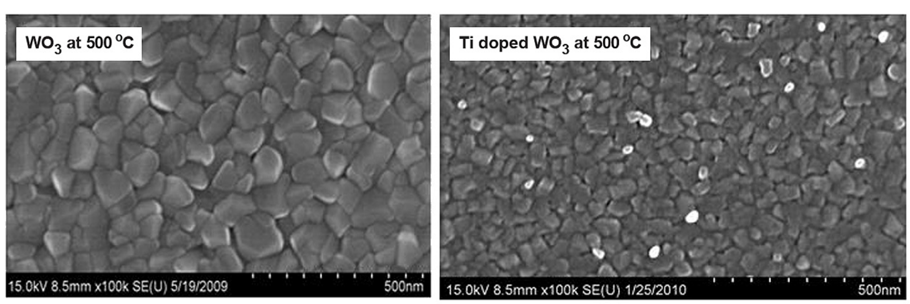
Cost: $199,546

Technology Area: Microsensors

Program Area: Historically Black Colleges and Universities (and Other Minority Institutions)

The University of Texas – El Paso (UTEP) will investigate tungsten oxide (WO_3)-based nanomaterials for use to detect hydrogen sulfide (H_2S) gas in coal gasification systems. The objective of the project is to develop high-quality new sensor materials for achieving improved response time and controlled microstructure for long-term stability, and to narrow particle-size distribution for improved sensor characteristics and performance. Researchers will identify methods to enhance the so-called 3S criteria—sensitivity, selectivity, and stability—by controlling the structure and properties of these materials at nanometer dimensions. Two main areas of investigation are H_2S detection selectivity, sensitivity and stability of undoped and titanium-doped WO_3 and the surface functionalization and stabilization of WO_3 by metals such as gold and aluminum for H_2S sensors. Sensors are being studied at moderate concentrations of H_2S (nominally 5–100 ppm H_2S in nitrogen), using parameters that simulate a real environment with service temperature of approximately 200–600 °C.

Researchers will systematically study the effect of processing conditions on the growth and microstructural evolution of undoped and doped WO_3 thin-films and nanostructures using X-ray diffraction (XRD), scanning electron microscopy, atomic force microscopy, energy dispersive X-ray spectrometry, Fourier transform infrared absorption, Raman, and X-ray photoelectron spectroscopy. Understanding the structure-property relationships and electronic structure changes associated with the oxide surfaces will permit the development of stable microstructures to address long-term stability and H_2S selectivity issues. This comprehensive suite of measurements, together with temperature-dependent electrical characterizations and performance evaluation tests, will be used to assess the feasibility of titanium-, gold-, and aluminum-doped WO_3 materials for detecting and monitoring H_2S in coal gasification systems.



SEM Pictures of Tungsten Oxide (WO_3) and WO_3 doped with Titanium nanomaterials. (Photos provided courtesy of University of Texas at El Paso)

Development of High-Temperature, High-Sensitivity Novel Chemical-Resistive Sensors

Performer: University of Texas at San Antonio

Date: 09/01/2010 – 08/31/2013

Cost: $200,000

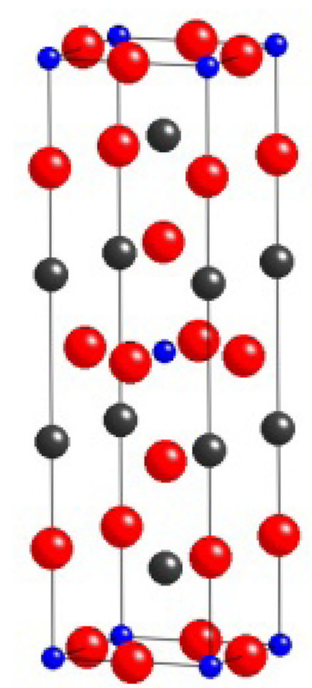
Technology Area: Microsensors

Program Area: Historically Black Colleges and Universities (and Other Minority Institutions) & University Coal Research

The University of Texas at San Antonio's goal is to design, fabricate, and develop novel high-temperature, high-sensitivity, multifunctional chemical sensors for the selective detection of fossil-energy gases in power and fuel systems. Researchers will explore and use the advantages of the thin film referred to as LBCO (LnBaCo2O5+d where Ln=Pr or La) to develop high-temperature chemical-resistive sensors. Highly epitaxial single-crystalline LBCO thin films are chemically stable at high temperature (>800 °C), and extremely sensitive to various oxidizing/reducing environments with very short response time (<0.1 seconds) and ultra fast surface exchange kinetics (extremely low activation energy of 0.26 electronvolts). These characteristics suggest that the LBCO thin film is an excellent candidate for the fabrication of sensors and control systems for power- and fuel-monitoring systems. The final objective of this research is to determine the overall feasibility of the LBCO-based novel electrochemical devices for sensing gases in high-temperature applications.

Details of the research include the following: (1) the systematic study of the physical properties and chemical stability of the highly epitaxial LBCO thin films; (2) characterization of the LBCO thin films at high temperature (>700 °C) for sensing the various gas compositions to allow precision analysis and control of these parameters; (3) design and fabrication of various LBCO thin-film-based chemical-resistive sensors for monitoring the gas composition at high temperature; and (4) theoretical and modeling studies on the absorption, reactivity, and stability of the LBCO thin films to understand thin-film chemical behavior in the target high-temperature range.

Researchers will test the device performance by systematically investigating various gas compositions, poison resistance, and cross sensitivity. These novel sensors will aid in the development of the next-generation highly efficient, near-zero emission power generation technologies.



Conceptual structure of LBCO Material. (Figure provided courtesy of University of Texas at San Antonio)

Advanced Thin Film Sensor Materials for Embedded Fossil Energy Applications

Performer: NETL Office of Research and Development

Date: 2/2011 – 9/2012 (continuing)

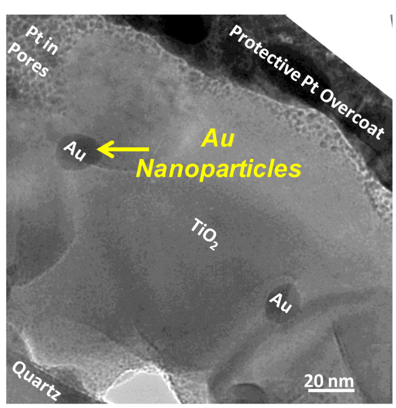
Cost: $451,000

Technology Area: Microsensors

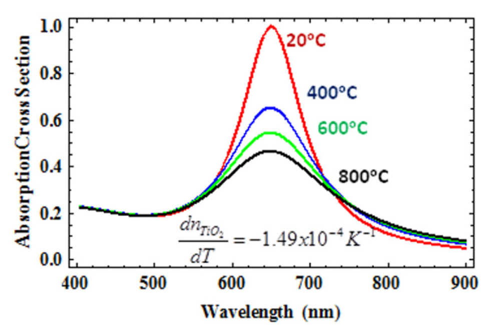
Program Area: Coal Utilization Sciences

Advanced sensors are being developed for embedded sensing in a range of fossil energy power generation technologies including gas turbines, solid oxide fuel cells, advanced boilers, and oxy-fuel combustion systems. Sensors for these applications often require a thin film functional sensor layer with a measurable physical property that responds in a useful, predictable, stable, and repeatable manner to a quantity of interest under harsh process conditions. The lack of an optimized sensing layer can significantly impact the overall performance of a given device and is often the critical technology barrier. Once developed, novel sensing layer designs with improved performance can also be applied across a range of applications and sensor platforms.

This project is investigating and developing nanostructured thin film metal oxide based materials for electrical and optical gas sensing applications in high temperatures and harsh environments. An emphasis is being placed on studying materials that exhibit stability at extreme temperatures (T > 500 ^{o}C) and in highly reducing conditions under which many traditional oxide sensing materials employed for lower temperature chemi-resistive applications are no longer suitable. Candidate material systems to be investigated include base metal oxides with nanometer grain size (e.g. SnO_2 and ZnO), gold nanoparticle based plasmonic nanocomposites (e.g. Au / TiO_2), and other metal oxide based systems. Electrical and optical sensing responses of candidate material systems are being investigated with high temperature laboratory measurements. Material research and development efforts are being carried out in parallel with efforts for integration of superior candidate material systems with optical sensor platforms. The efforts include optical sensor simulations as well as prototype sensor fabrication and testing. Results from this portion of the project will provide feedback to the sensing material research and development efforts. The development of the novel sensing materials in this project will benefit advanced power systems by enabling cost-effective sensors for key harsh environment process parameters to improve control of power systems and achieve higher efficiency with reduced pollutant emissions.



Cross-sectional transmission electron microscopy image of Au nanoparticle incorporated TiO_2.



Simulated temperature dependence of the absorption cross section of a Au nanoparticle embedded in TiO_2 up to 800 ^{o}C showing characteristic broadening and decreased peak height.

Condition-Based Monitoring of Turbine Combustion Components

Performer: Siemens Energy, Inc., K Sciences GP, LLC, Philtec Inc. and JENTEK Sensors, Inc.

Date: 10/01/2008 – 09/30/2012

Cost: $1,673,417

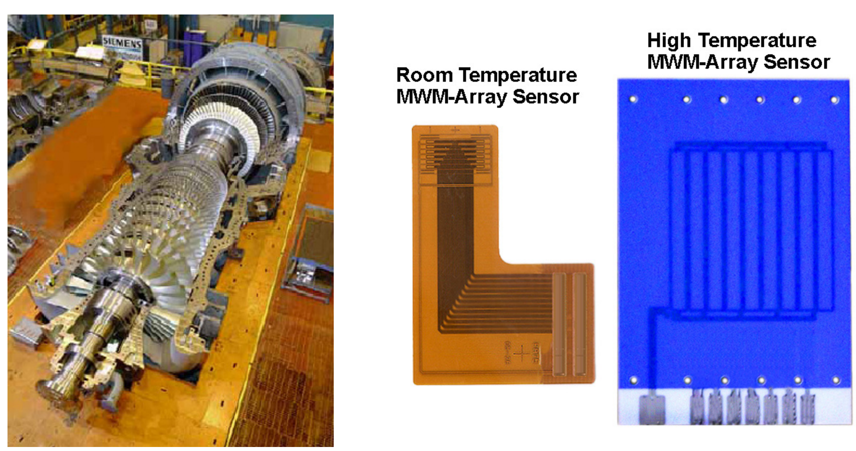
Technology Area: Microsensors

Program Area: Coal Utilization Science

Siemens Energy is leading an effort to develop an integrated condition monitoring system for turbine components. The overall goal of this work is to implement an advanced condition-based maintenance approach that extends the operating time of turbine systems and improves the overall control of the turbine system. The research team is developing sensors to directly assess the condition of critical parts, specifically wear and crack formation at high temperatures (1000–1300 °C); this task cannot be done with current commercially available sensors.

Researchers are using a fiber-optic approach to perform wear measurement, mounting the fiber at the wear surface to continually monitor wear and wear-progression at the contacting faces. The wear sensor has a targeted operating temperature of 1000 °C. Cracking is being monitored by the deployment of a multi-functional high-temperature magnetic sensor developed at JENTEK Sensors, Inc. This sensor uses magnetic fields to continuously monitor crack progression while correcting for temperature variations. The materials and construction of this sensor will be modified to allow operation at temperatures of 1000 °C. The algorithms deployed to monitor cracks and compensate for temperature variations are being developed to allow crack monitoring at high temperatures.

The objective of this work is to design, develop, and demonstrate a condition-monitoring sensor network comprising a high-temperature wear sensor and multi-functional magnetic sensor to monitor cracks in hot section combustion components in real time. The wear- and crack-monitoring sensors are being combined with the basic control system sensors to provide a modular sensor network for condition monitoring and assessment of combustion hardware. The prototype sensors have passed laboratory proof-of-concept tests. The testing demonstrated the wear sensors' capability to provide a stable, repeatable output with 0.12 mm resolution, surviving at high temperatures in short term tests. The crack sensor successfully detected crack growth and surface temperatures of test specimens. Additional validation tests at high temperatures are in progress. After completing sensor life and performance assessments, prototype demonstration tests will be accomplished in an engine environment. The sensors will provide an integrated sensor network for condition monitoring of hot section parts.



Examples of a combustion turbine (left) and crack detection sensors (right). (Photos provided courtesy of Siemens Energy and Jentek Sensors, Inc.)

Advanced Ceramic Materials and Packaging Technologies for Realizing Sensors Operable up to 1,800 °C in Advanced Energy Generation Systems

Performer: Sporian Microsystems Inc.

Date: 6/28/2012 – 3/27/2013

Cost: $149,990

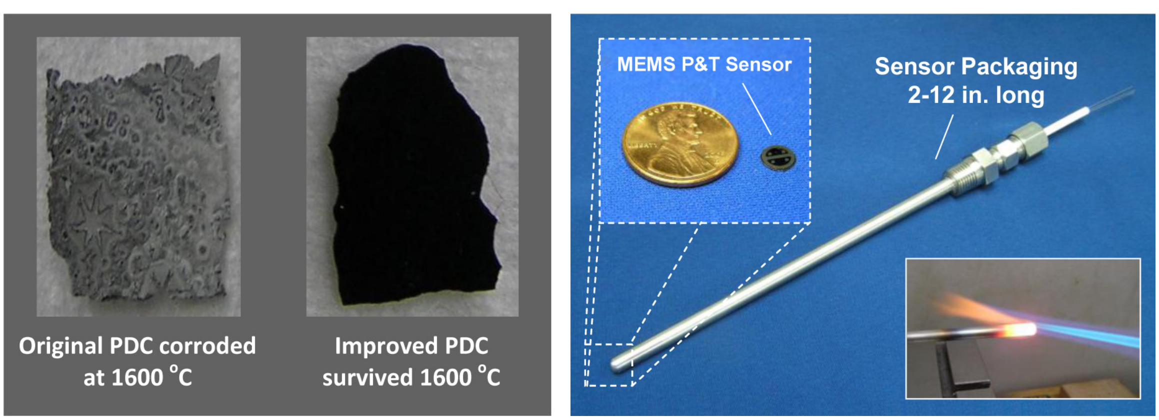
Technology Area: Microsensors

Program Area: Small Business Innovative Research

The implementation of sensors and advanced controls in power systems can provide valuable methods to improve operational efficiency, reduce emissions, and lower operating costs. The harsh environments in power systems include extreme temperatures (800 to 1,800 °C), high pressures (500 to 1000 psi for natural gas, 3,500 psi for coal), and highly corrosive/erosive exposures.

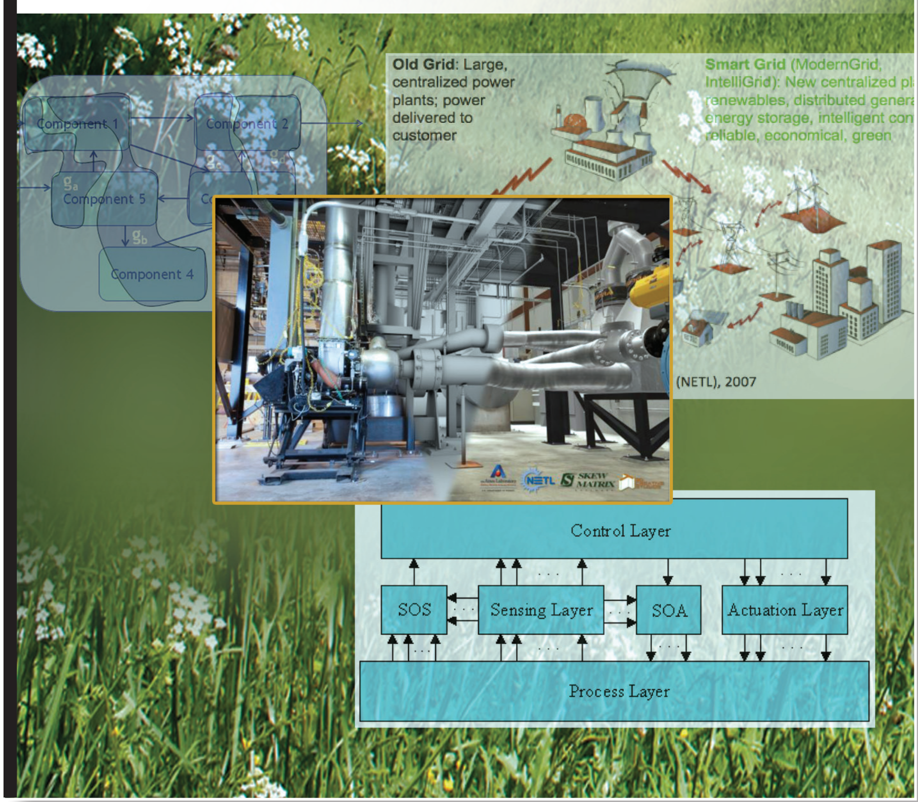
In the past several years, Sporian Microsystems, Inc. has established a solid track record of successful R&D of high-temperature sensors and packaging architectures for turbine engine and other advanced power systems environments. Sporian's sensor technology is based on the combination of high-temperature packaging and polymer-derived ceramic (PDC) sensor materials. The objective of this project is to develop ultra-high temperature PDC-based ceramics, innovative sensor fabrication processes, and advanced packaging approaches to extend Sporian's existing sensors beyond current limitations of 1,350 °C. Phase I efforts primarily include materials/process/design evaluations and the proof of principle demonstration of key aspects, with the long-term goal being packaged temperature, pressure, and/or flow sensors capable of operating up to 1,800 °C (3,270 °F).

There are numerous market opportunities for the advanced sensors and packaging technology. Customers include land-based power generation (natural gas, coal-fired steam, coal gasification, advanced coal combustion systems, nuclear, and concentrating solar power) and transportation (fixed-wing and rotorcraft aircraft turbine engines, turbine-powered watercraft, and rail locomotives).



Samples of original and improved polymer derived ceramics, and a MEMS pressure & temperature sensor element packaged for turbine engine applications up to 1350 °C. (Photos provided courtesy of Sporian Microsystems, Inc.)

Technology Area: Novel Control Architectures and Communication Frameworks



Distributed Sensor Coordination for Advanced Energy Systems

Performer: Oregon State University

Date: 11/01/2009 – 7/31/2013

Cost: $887,606

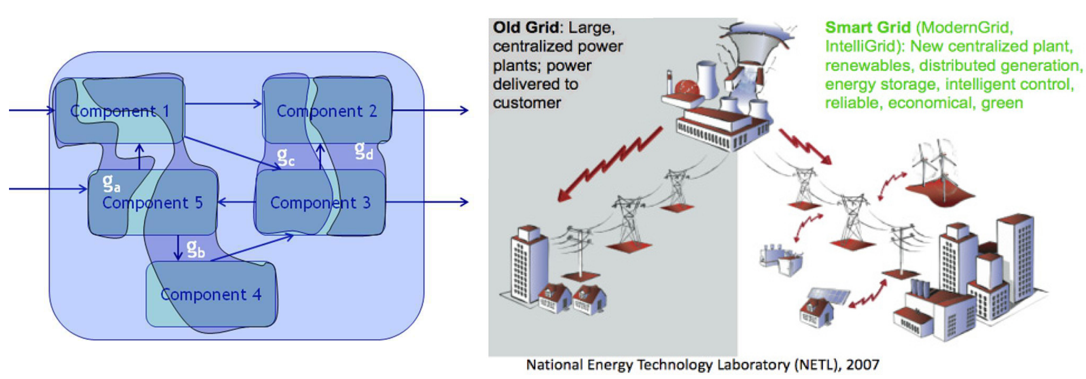
Technology Area: Novel Control Architectures and Communication Frameworks

Program Area: Coal Utilization Science

As advanced energy systems grow in size, they require an increasing number of pressure, temperature, and composition sensors for optimal control and operation. In many cases, communication of individual sensors with a central controller is inefficient. In this project, Oregon State University researchers are developing control algorithms to manage a network of sensors that can collect and process data and provide key control decisions. The project focuses on developing a sensor algorithm that leads to a good network-wide solution, while allowing individual sensors to function independently. The project derives, implements, and tests agent-objective functions that promote coordinated behavior in large sensor networks. The long-term objective is to provide a comprehensive solution to a scalable and reliable sensor coordination problem leading to safe and robust operation of advanced energy systems.

Project work is focused in two areas, including deriving criteria for assessing the impact of sensor locations and objectives, and demonstrating the effectiveness and reconfigurability of sensors in response to a change in performance criteria. Achieving these objectives requires quantifying the effectiveness of various sensor configurations. The project directly evaluates the impact of information quantity on the effectiveness of the sensor configurations and quantifies the amount of global information necessary for different sensor configurations to effectively assess the state of the system.

A successful demonstration of this technology can lead to reliable, robust, scalable, and reconfigurable sensor networks, which can enhance the efficiency of advanced power systems through more precise control. In an advanced energy system, sensor networks allow information to be collected more efficiently, respond more quickly to sudden developments, and allow for autonomous system reconfiguration. In addition, the smart sensor coordination algorithms also provide other benefits to the DOE and the U.S. government through their use in a smart power grid, coordinated search and rescue, and self-organizing nano/micro devices.



Algorithms automatically group sensors into subsystems selected to optimize each group individually for the best overall system performance (left). The same underlying algorithmic approach can also be used with large scale distributed systems such as new smart grid technologies where delivering electricity from suppliers to consumers using two-way digital technology to control appliances at consumers' homes to save energy and reduce cost (right). (Figures provided courtesy of Oregon State University)

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

Performer: Case Western Reserve University

Date: 11/1/2011-10/31/2014

Cost: $1,934,017

Technology Area: Novel Control Architectures and Communication Frameworks

Program Area: Plant Optimization Technologies

Advanced combustion, gasification, turbine, carbon capture, and gas cleaning and separation technologies are used in highly efficient, low emissions power systems. This requires sensor, communication, 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 thermodynamic formalism; (2) enriching the information content of the 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.

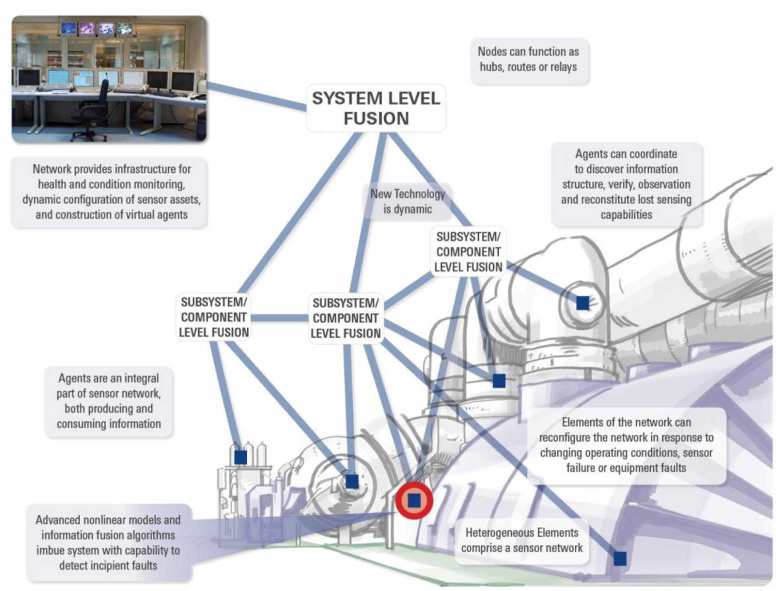


Diagram of System Level Fusion of Sensor Coordination in an Advanced Power System

Merged Environment for Simulation and Analysis (MESA)

Performer: Ames National Laboratory

Date: 5/1/2012 – 9/30/2014

Cost: $350,000

Technology Area: Novel Control Architectures and Communication Frameworks

Program Area: Plant Optimization Technologies

Advanced Power Plants that utilize fossil fuel require higher efficiencies and lower emissions in order to provide for future power consumption needs while meeting higher regulatory standards. Current control strategies involve a hierarchical framework that utilizes large amounts of sensors that 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 will provide 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 is to integrate the graphic and computational representation of the HYPER facility with the physical facility. This will create a dynamic integrated computational environment capable of supporting a broad range of control and operations algorithms based on 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) (that will be constructed separately) in order to test advanced sensors and controls and other complexity-based strategies in the NETL ICE lab. The data gathering 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 will then be 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 will work closely with key technical personnel within NETL to ensure capabilities developed in this project are extensible to other systems and applications.

Rendition of Hyper Facility in both Real and Virtual Space.

Self-Organizing Sensing and Actuation for Advanced Process Control

Performer: CyboSoft, General Cybernation Group Inc.

Date: 06/28/2012 – 3/27/2013

Cost: $148,720

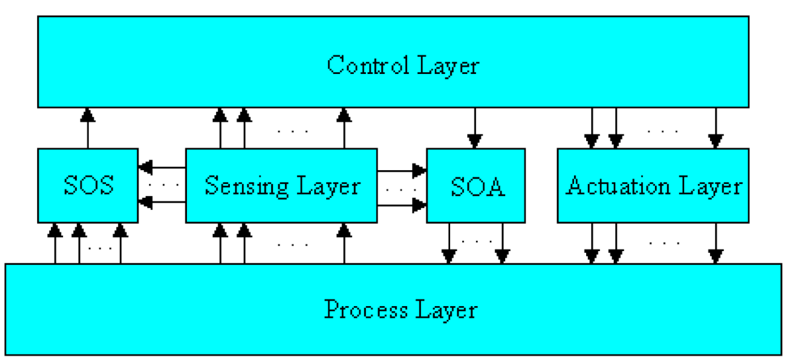
Technology Area: Novel Control Architectures and Communication Frameworks

Program Area: Small Business Innovative Research

As new power generation technologies and systems mature, the plant that encompasses these systems will become inherently complex. In order to manage complexity, the process control architecture that supports these systems will need to evolve to manage the complexity and achieve optimal performance. To meet this demand, a novel process control architecture is to be developed based on distributed intelligence and self-organizing methodologies. This novel Self-Organizing Process Control Architecture can enable distributed intelligence at all levels, and allow the sensing and actuation networks to function in a self-organizing manner to manage complexity and solve real process control problems.

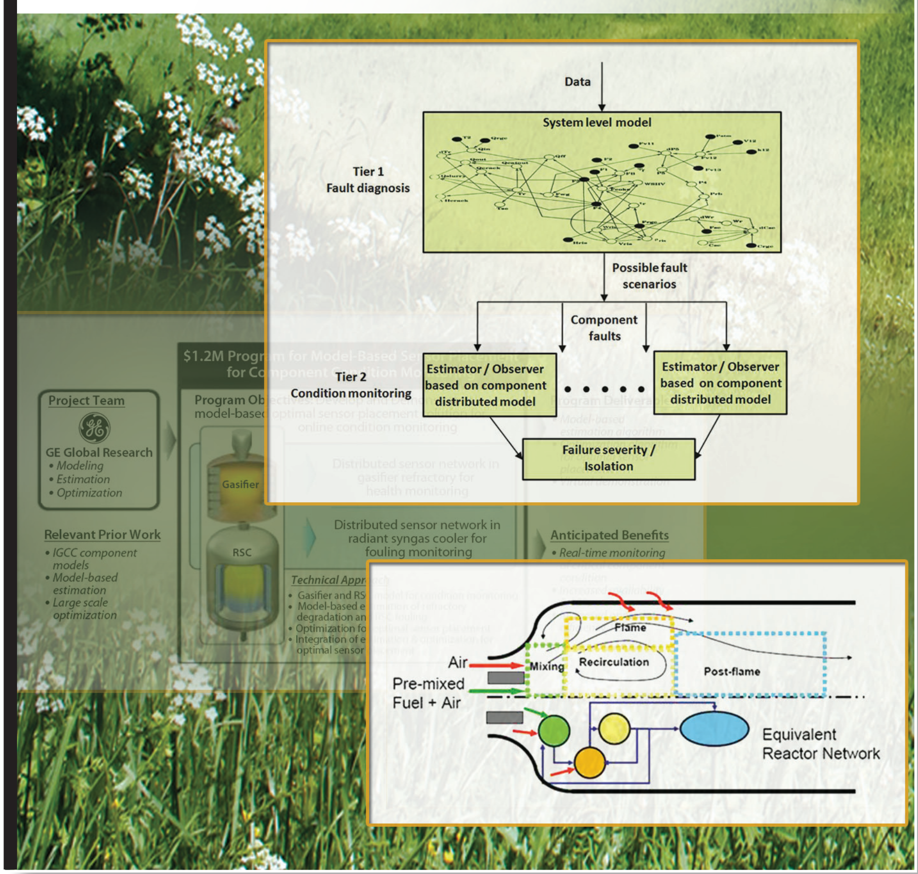
Investigators will research, design, develop, test, evaluate, benchmark, and bring to production a novel advanced process control architecture that includes (1) Self-Organizing Sensing (SOS), and (2) Self-Organizing Actuation (SOA) methods, technologies, and commercial products.

In Phase I, investigators will evaluate, simulate, and determine the feasibility of developing the novel control architecture by investigating 2 realistic sensing and actuation scenarios, where conventional sensors and actuators do not work. The tasks include: (1) Complete the design of the Self-Organizing Process Control Architecture; (2) Develop the concept and features of Self-Organizing Sensing (SOS) technology; (3) Develop an Artificial Neural Network (ANN) based SOS algorithm; (4) Implement the SOS algorithm in LabVIEW software; (5) Test and demonstrate the performance of a novel SOS Bed Thickness Sensor; (6) Develop the concept and features of Self-Organizing Actuation (SOA) technology; (7) Develop an SOA algorithm for controlling disruptive gas flows; (8) Implement the SOA algorithm in LabVIEW software; (9) Develop a real-time simulation model for a gas flow process that has 2 valves in sequence with significant upstream and downstream pressure variations; and (10) Test and demonstrate the performance of the SOA Gas Flow Actuator using the gas flow process model. In Phase II, appropriate software and hardware products will be developed to demonstrate the solution.



A Novel Self-Organizing Process Control Architecture.
(Figure provided courtesy of CyboSoft, General Cybernation Group Inc.)

Technology Area: Computational Modeling for Advanced Sensing



Model Based Optimal Sensor Network for Condition Monitoring in an IGCC Plant

Performer: General Electric Global Research Center

Date: 8/20/2010 – 12/30/2012

Cost: $1,195,894

Technology Area: Computational Modeling for Advanced Sensing

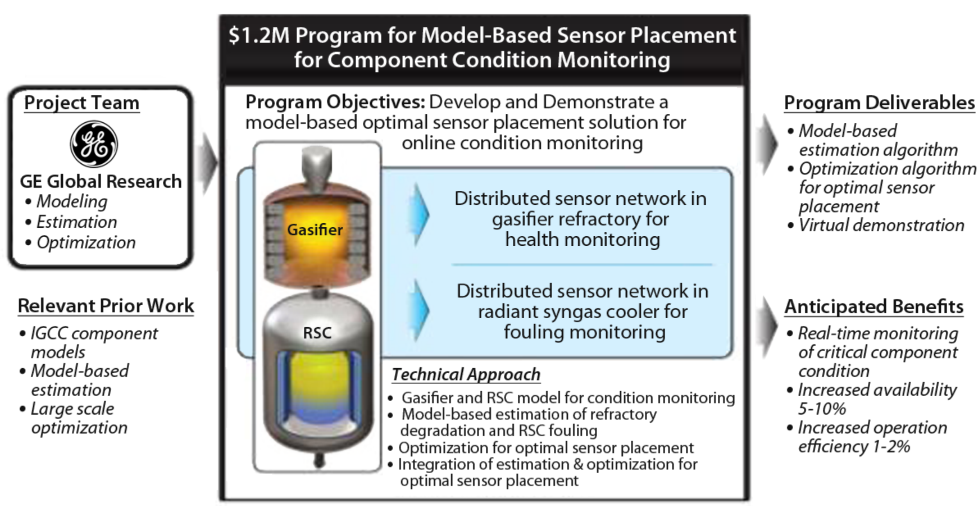
Program Area: Coal Utilization Science

Reliable and robust sensors and controls are essential to the development of high-efficiency, clean energy technologies such as low-emission power systems that use coal or other fossil fuels. Gasification offers a viable pathway for the clean generation of power and fuels and a cost effective option for the sequestration of carbon dioxide. General Electric (GE) Global Research is developing advanced model-based sensing and controls technology for the gasification section in an Integrated Gasification Combined Cycle (IGCC) plant to attain enhanced robustness, efficiency, and operational flexibility through increased computationally based automation.

The gasification section within an IGCC plant is an area where innovative approaches using computational techniques can improve the operation and overall condition monitoring of the components. Modeling techniques based on first principles can be used to identify plausible solutions for improving operation and control of the gasification section where traditional heuristic techniques have proven to be limited.

With an overall strategy of employing first-principles model-based analysis, GE Global Research will extend their models for the gasification section, to implement a nonlinear estimation algorithm to monitor the condition and extent of degradation in gasifier refractory and fouling in the syngas cooler, and to perform optimization for optimal sensor placement (OSP) to achieve monitoring requirements. The performance of the OSP algorithm and resulting monitoring solution will be demonstrated using representative test cases. When completed, the approach will be applicable to other systems for placing sensors to enable the creation of condition monitoring sensor networks.

When implemented, optimal sensor placement will enable more accurate assessment of the components' condition and will lead to operations that support higher reliability, availability and potential increases in plant efficiency.



Program Overview for Model-Based Sensor Placement for Component Condition Monitoring.

Package Equivalent Reactor Networks as Reduced Order Models for Use with CAPE-Open Compliant Simulations

Performer: Reaction Design

Date: 10/1/2009 – 3/31/2013

Cost: $1,045,838

Technology Area: Computational Modeling for Advanced Sensing

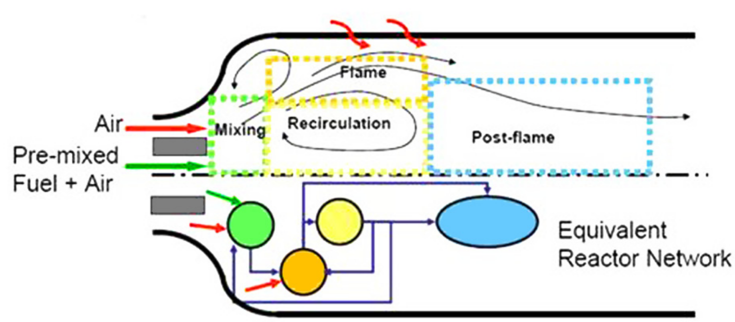
Program Area: Coal Utilization Science

Using high-fidelity fluid-dynamics models as input, Reaction Design will extend existing technology that is designed to automatically extract equivalent reactor networks (ERNs) from the computational fluid dynamics (CFD) simulation. The extraction is based on certain criteria for grouping regions of similar kinetic behavior. The ERNs are composed of idealized reactors (e.g., perfectly stirred and/or plug-flow reactors) that interact through mass-flow and heat-transfer connections to represent the complex flow. In contrast to the CFD simulations, however, the ERNs allow inclusion of detailed kinetics representations of the reacting-flow process, including particle-gas interactions, gas combustion, and emissions production.

A key component of this project is to encapsulate the CHEMKIN™-based ERN models as CAPE-OPEN-compliant objects that can be used in general flow-sheet simulation software. By combining existing detailed-kinetics reactor-network capability from CHEMKIN-PRO (Reaction Design) with CAPE-OPEN interface standards (CAPE-OPEN Laboratories Network), state-of-the-art kinetics modeling will be enabled within flow-sheet type simulations. This will be the basis for developing accurate reduced-order models for gasification/combustor processes.

This effort will involve sequential steps to build and test the new capability in order to achieve validated component models. Industry guidance will provide important design parameters for gasifiers as well as validation data to test resulting models.

The goal of this project is to enable an advanced form of reduced-order modeling for representation of key unit operations in flow-sheet simulations. Using high-fidelity fluid-dynamics models as input, the existing technology for the automatic extraction of ERNs from the CFD solution will be extended. While the technology has already been established for gas-turbine combustors, the aim of this project will be to extend the methodology to gasifiers.



Package Equivalent Reactor Networks as Reduced Order Models.

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

Performer: Texas Tech University and West Virginia University

Date: 01/01/2001 – 12/31/2014

Cost: $981,813

Technology Area: Computational Modeling for Advanced Sensing

Program Area: Coal Utilization Science

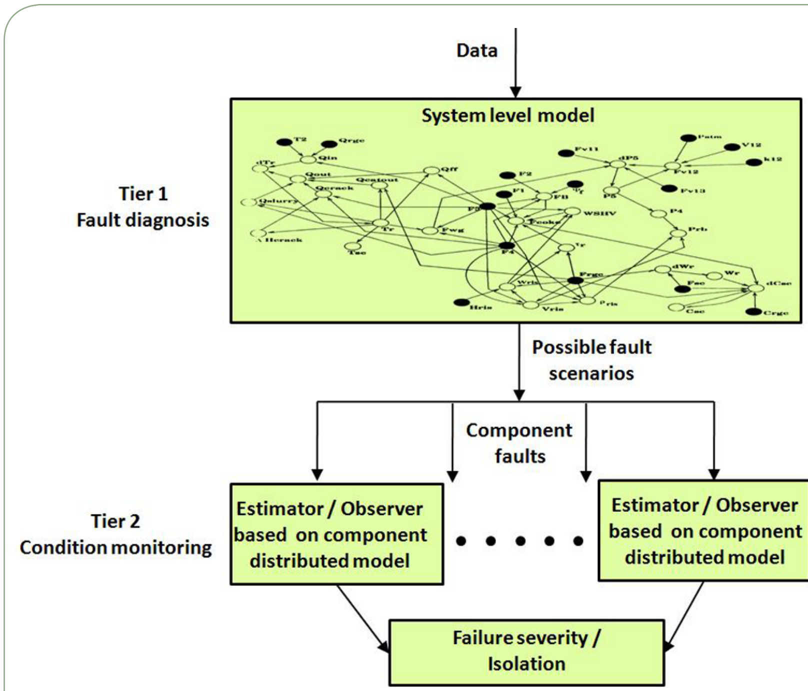
Fossil fuel power plants generate about two-thirds of the world's total electricity and are expected to continue to play an important role in the future. Increasing global energy demands, coupled with the issues of aging, inefficient power plants, and increasingly strict emission requirements, will require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

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

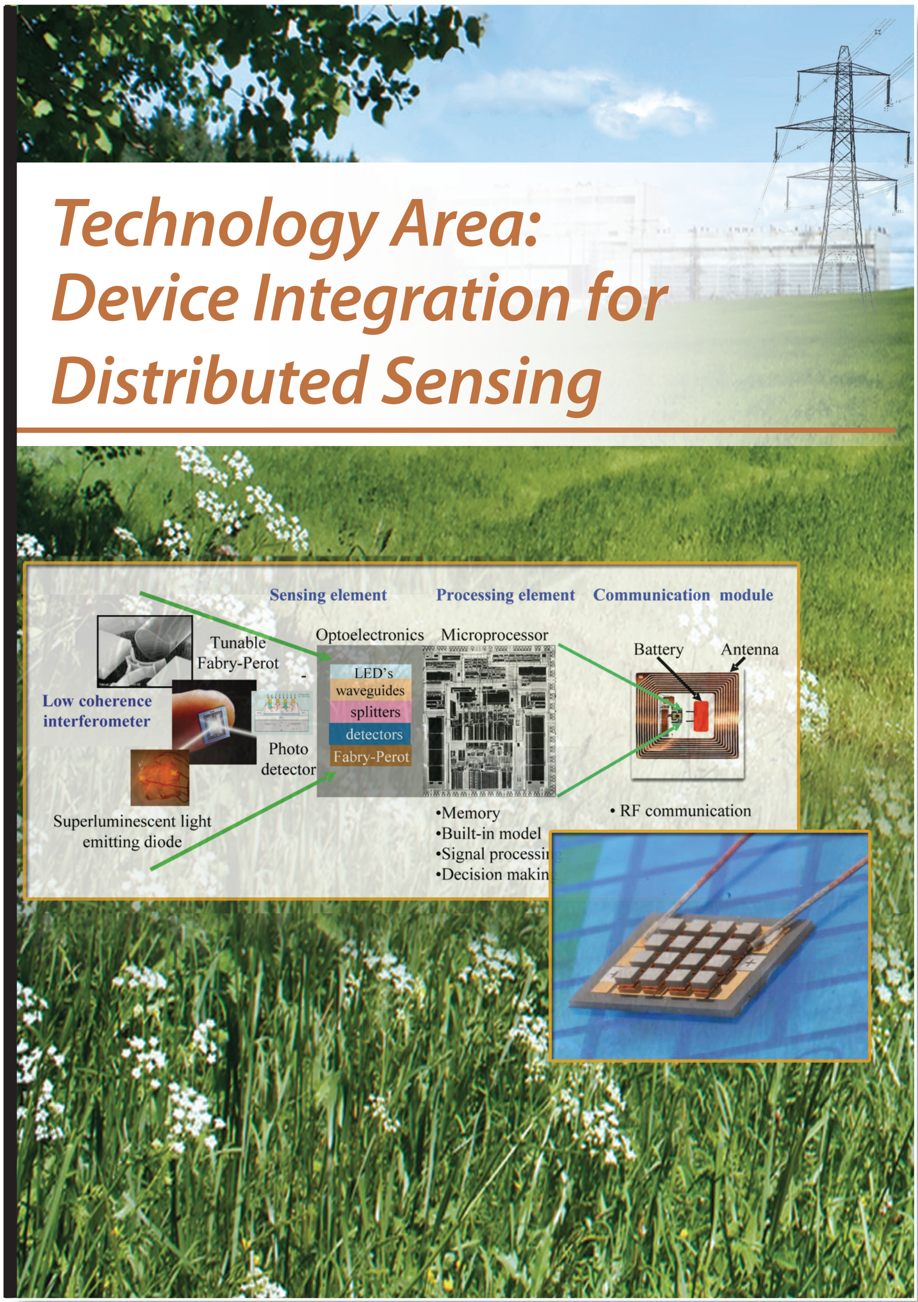
To meet the objective, a comprehensive list of faults in a typical IGCC plant will be identified. Structural changes to the Aspen Dynamics™ (Aspen Technology, Inc.) model will be performed to incorporate simulation models for the identified faults.

Sensor placement algorithms for condition monitoring and fault diagnosis will be developed and tested on the plant-wide dynamic IGCC model

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



Model-Based Sensor Placement Algorithms.


Technology Area:
Device Integration for
Distributed Sensing
Sensing element
Processing element
Communication module
Tunable
Fabry-Perot
Low coherence
interferometer
Optoelectronics
Microprocessor
LED's
waveguides
splitters
detectors
Fabry-Perot
Photo
detector
Battery
Antenna
Superluminescent light
emitting diode
•Memory
•Built-in model
•Signal processi
•Decision makin
• RF communication

High-Density Sensor Network Development

Performer: Ames National Laboratory

Date: 3/1/2006 – 9/30/2014

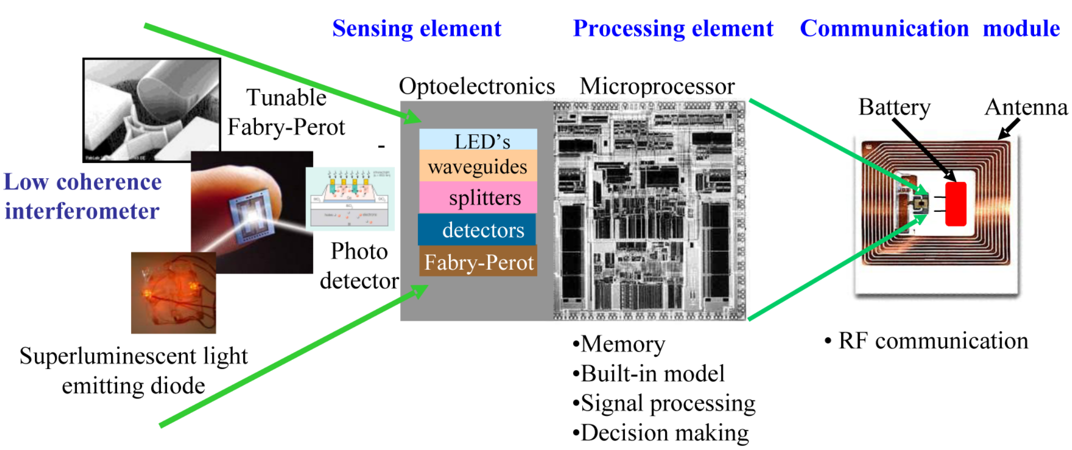
Cost: $2,463,000

Technology Area: Device Integration for Distributed Sensing

Program Area: Plant Optimization Technologies

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

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



Self-Powered Wireless Sensor System for Power Generation Applications

Performer: Wireless Sensor Technologies, LLC

Date: 6/1/2010 – 2/1/2013

Cost: $1,100,000

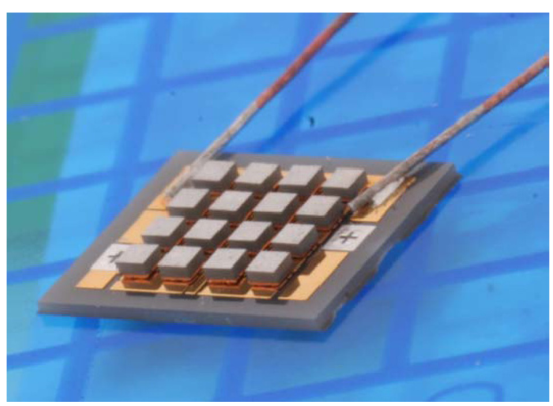
Technology Area: Device Integration for Distributed Sensing

Program Area: Small Business Innovative Research

Researchers at Wireless Sensor Technologies are developing and demonstrating a high-reliability, waste heat-enabled power supply and wireless sensor system for power generation applications. This system enables the addition or expansion of CBM in power generation plants. CBM systems significantly improve the effectiveness of maintenance programs for complex systems by optimizing the timing and focus of the procedure. The approach minimizes the associated maintenance costs, and the wireless sensor system enables CBM sensors to be easily added to existing plants and equipment.

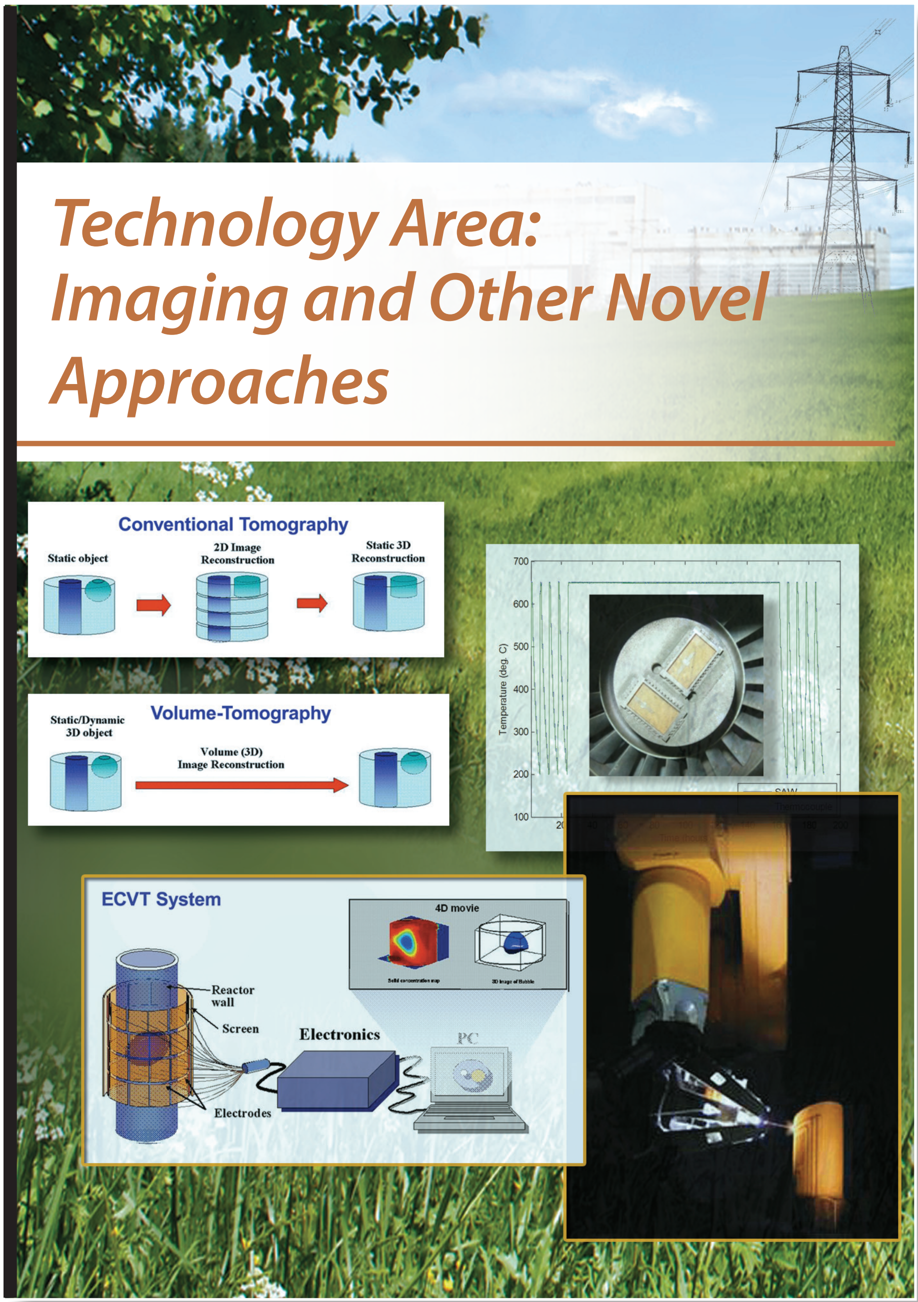
This system includes a unique power supply that utilizes waste heat from the plant equipment. Also provided are pressure and temperature sensors that may be used in the hot sections of turbine engines and mounted on rotating components. The system eliminates most system interconnects through its wireless-networked architecture of individual sensor nodes. The system and its individual temperature and pressure sensors are being effectively utilized in the development phases of power plant equipment such as gas and steam turbines.

The project scope is to develop a self-powered wireless sensor system for power generation applications that is operated using a semiconductor thermo-electric generator (TEG)-based power supply. This supply can provide continuous reliable power to the sensor system. The sensors communicate between sensor nodes via a wireless mesh network that is flexible, self-healing, and uses existing commercial protocols. The wireless network enables the addition of sensors around the plant without the need to add cables for input or output signaling. Capabilities include temperature and pressure sensors to be operated at temperatures up to and exceeding 1,000 °C; passive wireless thin-film temperature sensors to measure the surface temperature of the thermal-barrier-coated (TBC) turbine blades in the hot section of a gas turbine engine-based generator; and passive wireless heat-flux sensor to monitor the integrity the TBC coating of the turbine blade or other areas where temperatures exceed 1,200 °C.



Individual thermoelectric generation module. (Photo provided courtesy of Nextreme Thermal Solutions, Inc.)

Technology Area: Imaging and Other Novel Approaches



Development and Implementation of 3-D, High-Speed Capacitance Tomography for Imaging Large-Scale, Cold-Flow Circulating Fluidized Bed

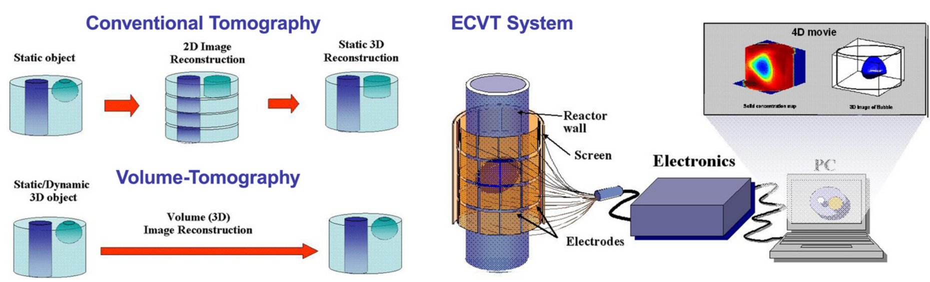
Performer: Tech4Imaging and Ohio State University

Date: 10/01/2008 – 09/30/2012

Cost: $1,167,050

Technology Area: Imaging and Other Novel Approaches

Program Area: Coal Utilization Science



Conventional tomography constructs a 3-D image by stacking 2-D images averaged along the length of the 2-D capacitance sensor (top left), whereas volume tomography produces a 3-D image directly from the 3-D capacitance sensor and avoiding stacking (bottom left). Block diagram of an ECVT system (right). (Figures provided courtesy of Tech4Imaging)

The inherently complex nature of multiphase flows such as those encountered in fluidized beds requires a multi-dimensional measurement technique capable of providing real-time monitoring of the process dynamics and physical properties. Tech4Imaging and Ohio State University will develop and demonstrate a three-dimensional (3-D) high-speed electrical capacitance volume tomography (ECVT) system. The ECVT uses capacitance measuring equipment and high-level computing to render 3-D images directly from the measured capacitance data of multiphase flow systems. Conventional electrical capacitance tomography (ECT) provides 2-D images of flow by averaging a phase concentration over the capacitance sensor length. For proper understanding of flow behavior, 3-D volume images that depict different phases' concentrations are required. Acquiring 3-D images requires distribution of the sensors in three dimensions. In ECVT, changes in the sensor shape and distribution of sensor plates provide 3-D characteristics so that 3-D imaging can be obtained despite the limitation on capacitance sensor size. In the past, this approach led to a highly non-linear image reconstruction problem that was difficult to solve. Tech4Imaging has developed software implementing a reconstruction technique capable of providing a solution.

The goal of the project is to develop a 3-D, high-speed capacitance tomography system to image large-scale, cold-flow circulating fluidized beds (CFB). The overall objective of the project is to develop and adapt an ECVT system to image multiphase flows common to CFB and evaluate its ability to collect data useful for validating multiphase flow models. The specific objectives of the project include developing high-speed capacitance acquisition hardware with up to 50 imaging frames per second; developing 3-D reconstruction software; designing custom 3-D capacitance sensors for the CFB; conducting a thorough analysis of acquired images; and installing the capacitance sensors and delivering a fully operational ECVT system. Multiphase flows are commonly encountered in industrial operations such as fluidized-bed combustors, coal gasifiers, carbon capture processes, and Fischer-Tropsch synthesis. A dedicated 3-D ECVT for imaging fluidized-bed systems can enable a less expensive exploration of options that may improve the processes involved in producing power using cold-flow circulating fluidized beds. This optimization of power production processes can lead to more efficient uses of domestic fuel sources with lower emissions in order to support DOE's energy security mission.

Wireless Microwave Acoustic Sensor System for Condition Monitoring in Power Plant Environments

Performer: University of Maine

Date: 01/01/2012 – 12/31/2014

Cost: $1,198,738

Technology Area: Imaging and Other Novel Approaches

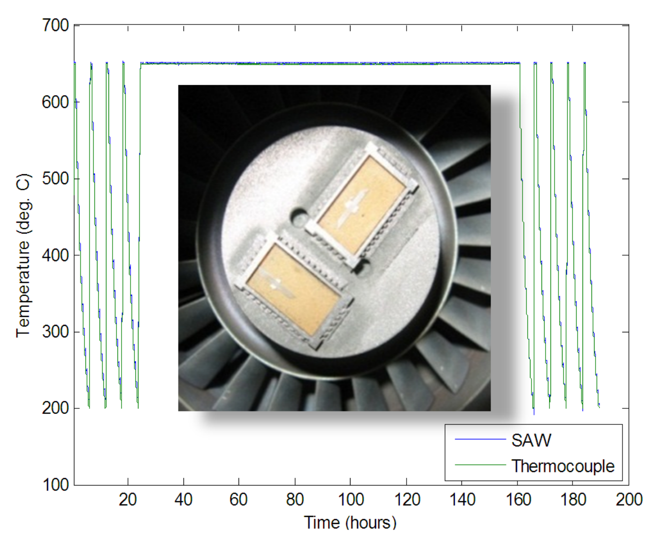
Program Area: Advanced Fossil Energy Research

The development and implementation of embedded wireless temperature, strain, and pressure sensor systems in power plant environments is critical for achieving on-line maintenance assessment and reliable performance of next generation clean, fossil energy power systems. Data from wireless embedded temperature and pressure sensor systems developed in this project will be vital for efficient maintenance planning as well as catastrophic failure prevention, thereby leading to major cost savings.

The major objective of this project is to develop and demonstrate the performance of wireless microwave acoustic sensors and arrays that are embedded in equipment and structures located in fossil fuel power plant environments to monitor the condition of components such as steam headers, reheat lines, water walls, burner tubes, and steam turbines. The project focuses on the R&D of small, battery-free surface acoustic wave (SAW) sensors and integrated antennas, comprised of novel materials that are stable in high temperature harsh environments and engineered to withstand temperatures up to 1200 °C and pressures up to 750 psi. The SAW sensors are being developed to be directly embedded into power generation structures and components, and interrogated wirelessly with a stand-alone radio frequency (RF) electronics unit located outside the high temperature harsh environment.

Researchers from the Laboratory for Surface Science &Technology (LASST) at the University of Maine (UMaine) and personnel from Environetix Technology Corp., a spin-off company out of UMaine, are carrying out R&D activities in the areas of SAW sensor array integration, high temperature thin films, sensor packaging, and RF signal interrogation electronics to realize this wireless sensor system.

The outcomes of this project will include a prototype sensor system to validate the use of a harsh environment SAW wireless sensor technology in advanced fossil energy power plants.



Environetix/UMaine harsh environment wireless SAW sensor response compared to a reference thermocouple showing resolution better than ± 3 °C with < 1 °C drift /135hrs. The inset shows an integrated sensor and antenna packaged onto an integrally bladed rotor (IBR) and continuously tested at 20,000 g's for several hours within a small scale turbine engine environment.

In Situ Acoustic Measurements of Temperature Profile in Extreme Environments

Performer: University of Utah

Date: 10/1/2011 – 9/30/2014

Cost: $300,000

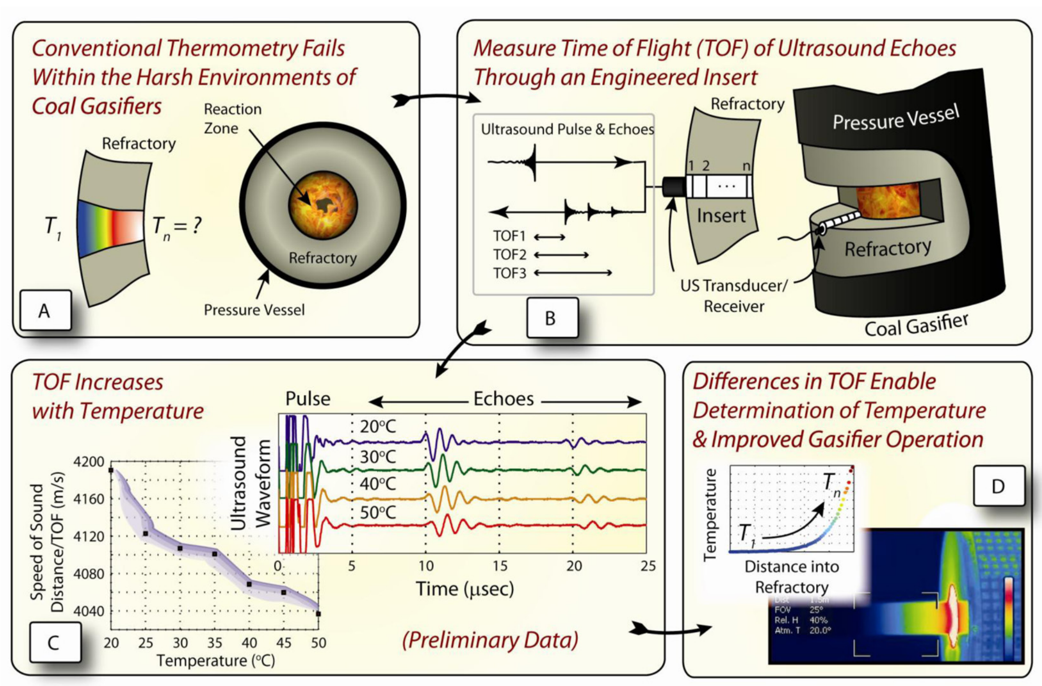
Technology Area: Imaging and Other Novel Approaches

Program Area: University Coal Research

Coal gasification is an example of a process with some of the most extreme temperatures, chemical aggressiveness, mechanical abrasion, and pressure conditions. Currently, several technological challenges impact the reliability and economics of gasification, one of which is the lack of temperature measurement and other sensors that are capable to reliably perform in a harsh environment over an extended period of the operation. The conventional approach of developing hardened insertion sensors has proven to be unsuccessful since the most hardened sensors are unlikely to survive for more than one or two months as the inner surface of the refractory wall degrades and recedes, exposing thermocouples directly to the corrosive slagging environment.

This project pursues an alternative approach to the traditional insertion sensors and aims to obtain the measurements of temperature distribution across the refractory of coal gasifier using noninvasive ultrasound measurements. The overall goal of this project is to develop and validate a novel ultrasound technique capable of measuring temperature distribution in solids and demonstrate its application to monitoring and management of coal gasifier refractories. The graphical summary of the proposed sensing technology shows the integration of noninvasive ultrasound sensors, advanced ultrasound electronics, and signal processing integrated into a system designed to provide real-time data on temperature distribution across the containment of gasification reactors operating at extreme conditions. In addition to measuring temperature distribution, the proposed ultrasound characterization methods will provide real time measurements of refractory thickness.

The refractory measurement and assessment methods developed during this project will function reliably over long-term operation under extreme conditions of pressure (up to 80 atmospheres), temperature (up to 1500 °C), and chemical aggressiveness of slagging gasification reactors. The measurements and methods will be tested experimentally (progressing from laboratory bench-scale to pilot-scale experiments) to quantify accuracy, response time, and robustness.



In the proposed approach, the ultrasound pulse is generated by a transducer located outside the harsh environment of a coal gasifier. 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).

Online, Real Time Coal Measurement and Data Processing to Optimize Boiler Operations

Performer: Energy Research Company and Lehigh University

Date: 06/30/2008 – 08/14/2013

Cost: $850,000

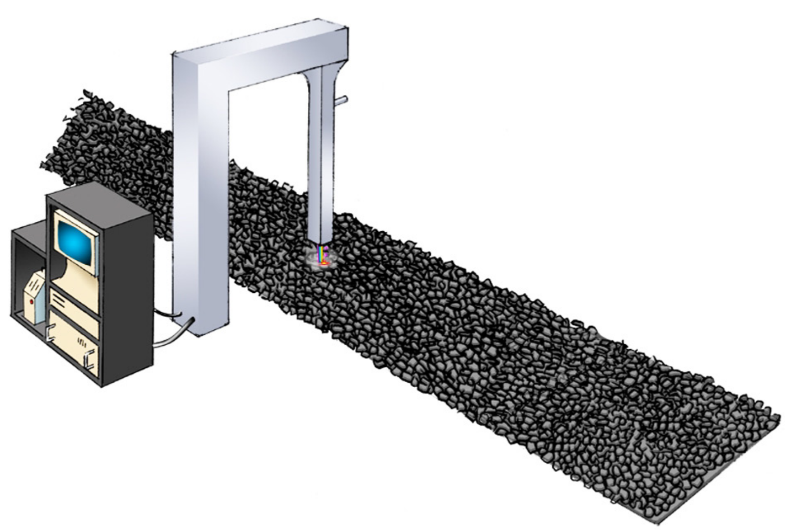
Technology Area: Imaging and Other Novel Approaches

Program Area: Small Business Innovative Research

Slagging and fouling of heat transfer surfaces due to ash deposition is a major concern for coal-fired electric utility boilers. The fouled tube and wall surfaces reduce heat transfer and thermal efficiency, resulting in reduced steam and combustion air temperatures, increased fuel firing rates, and increased fan power (to overcome larger pressure drops in the convective pass). Heavy slag deposits in the waterwall regions of coal-fired boilers reduces local radiation heat transfer, resulting in increased furnace exit flue gas temperatures and higher rates of thermal nitrogen oxides (NO_X) formation. In addition, deposits that grow from partially blocking the spacing between tube banks to form clinkers lead to increased gas velocities and erosion, and major incidents of internal boiler damage due to fused ash material falling to the bottom of the boiler. Corrosion may also occur underneath these deposits. Overall, a reduction in boiler thermal efficiency and an increase in emissions occur, resulting in substantial revenue loss.

The team of Energy Research Company and Lehigh University are designing an On-line, in situ, real-time measurement of coal properties, coupled with artificial intelligence (AI) software, to accurately predict the slagging and fouling tendencies of coal blends as they are fed into a power plant boiler.

Specifically, a system will be used to measure the coal properties in situ and in real time. The information will be synthesized using AI software. The results will be provided to the power plant operators so they can adjust a number of parameters to mitigate slagging.



On-Line, Real Time Coal Measurement and Data Processing to Optimize Boiler Operations.

Development of Standard Packaging and Integration of Sensors for On-Line Use in Harsh Environments

Performer: MesoScribe Technologies, Inc

Date: 07/01/2009 – 08/14/2012

Cost: $940,315

Technology Area: Imaging and Other Novel Approaches

Program Area: Small Business Innovative Research

Sustainable energy initiatives focus on improving the affordability and reliability of power generation systems while eliminating harmful emissions (e.g., CO_2). Advanced process controls, which employ On-line diagnostic feedback, can drive down energy costs through performance optimizations and proactive maintenance scheduling. However, the effects of high temperatures, corrosive/oxidizing gases, and abrasive media have hindered sensor implementation within power systems. Ruggedized sensor packaging is thus needed for sensor deployment within harsh environments to enable On-line diagnostic control.

To address this need, this project will develop new sensor packaging concepts using MesoScribe's Direct Write technology, a process which deposits functional materials in three dimensions (3D) directly and conformally onto power generation components. High temperature moisture/corrosion barrier coatings will be deposited for encapsulating low-profile sensors. Durable lead-wire attachment capabilities will be developed for robust sensor routing and implementation. By leveraging Direct Write approaches for encapsulation and lead wire routing, fiber optic sensors will be integrated onto power generation hardware for advanced condition monitoring.

Direct Write is a highly versatile process well-suited for device encapsulation and robust lead connections, in turn enabling ruggedized sensor implementation. Direct Write technology offers several benefits over conventional lead wires, such as mineral-insulated metal sheathed (MIMS) type cables. Noteworthy advantages include reduced aerodynamic disruption due to the low profile nature of the deposits, improved bonding to the part, and increased repeatability and reduced labor due to the use of high-precision automation.

Direct Write Sensor Fabrication.

Development of harsh environment packaging facilitates will enable the deployment of sensors for advanced power systems to improve operation efficiency, prevent unplanned shutdowns, and reduce costs and emissions. Applications areas specifically addressed include encapsulation of optical sensors for supercritical boilers, diagnostics for industrial gas turbines, and on-cell sensing for solid oxide fuel cell stacks.

High-Temperature Thermoelectric Oxides Engineered at Multiple Length Scales for Energy Harvesting

Performer: University of Washington

Date: 9/21/2011 – 9/20/2014

Cost: $299,956

Technology Area: Imaging and Other Novel Approaches

Program Area: University Coal Research

As part of the University Coal Research (UCR) Program, NETL has partnered with the University of Washington in a project that will engineer high-temperature thermoelectric oxides at multiple length scales that can be used for energy harvesting.

This project will explore a novel class of 'n' type thermoelectric oxides that are stable at high temperature in the coal-fired flue gas environment. It will focus on thermoelectric oxides with high figures of merit, employing the recent observation in the literature that thermoelectric figure of merit increases rapidly in the vicinity of the Curie temperature for ferroelectric materials (thermoelectric-ferroelectric coupling).

The overall goal of this project is to develop 'n' type thermoelectric oxide materials and microstructures with high figures of merit. These, together with the already well established 'p' type thermoelectric oxides with high figures of merit (e.g., Na0.5CoO2), can be used to make highly efficient thermoelectric devices for waste heat recovery in coal-fired power and industrial plants.

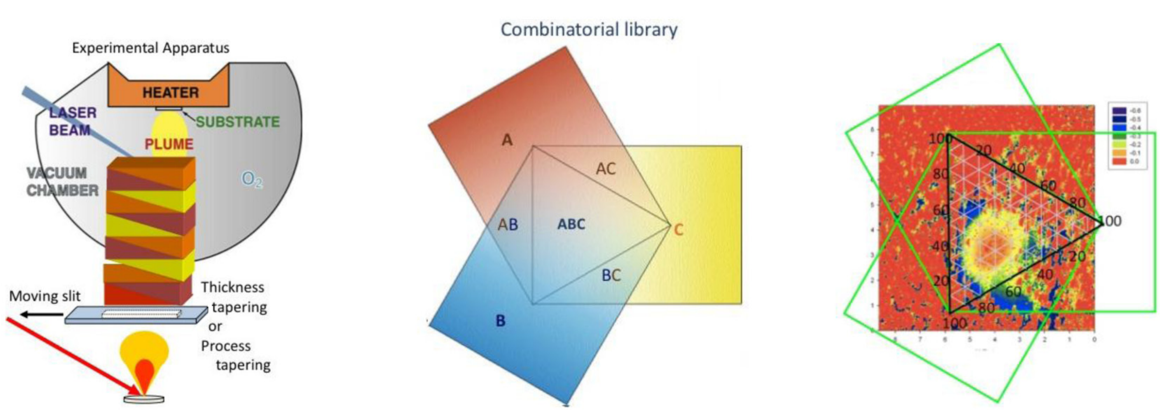


Figure 1. Combinatorial Materials Exploration (CME) is a thin film based technique to rapidly screen materials properties from a broadly distributed compositional range of the specimen (CME library). Experimentally, a pulsed laser deposition is used to fabricate a binary or ternary CME library, from which a compositional range to yield desired functional properties is determined by mapping technique. We will use this technique to screen the compositions of ferroelectric materials for thermoelectric applications.

The specific objectives of the proposed research are to: (1) use combinatorial materials exploration to rapidly screen a broad composition range in order to identify the most promising compositions of ferroelectric materials with high Curie temperatures; (2) investigate the thermoelectric properties of the most promising 'n' type thermoelectric oxides in these families; (3) develop processing approaches to make oriented crystalline oxides (in order to exploit the expected anisotropic nature of the materials); and (4) develop processing approaches to make hierarchical anisotropic porous structures in order to evaluate the effect of micro- and macro-pores on thermoelectric properties.

This project's success will pave the way for the development of efficient high-temperature, stable thermoelectric modules for waste heat recovery from coal-fired power plants and other industrial systems where process heat is an important byproduct (e.g., steel plants), resulting in higher efficiencies and reduced pollution and greenhouse gases (GHGs). Another important outcome of this research is the training and education of a Ph.D. student who will work on the scientific issues outlined in the research and will also be exposed to the broader context of research in this important area of energy efficiency and security.

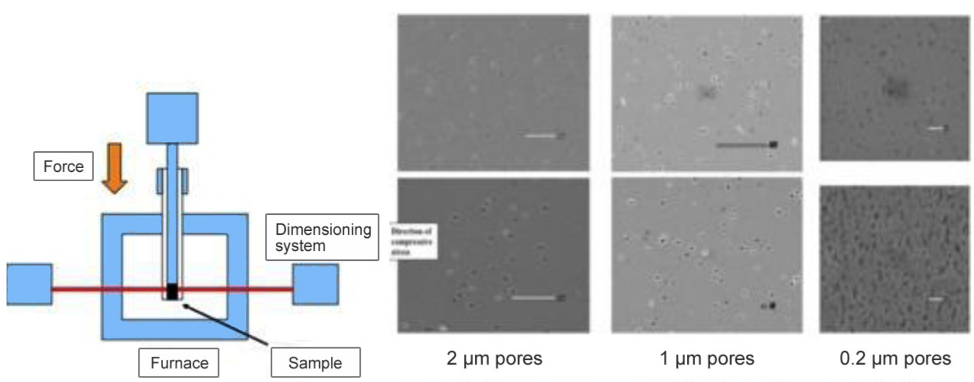


Figure 2. Powders of optimal compositions (determined by the CME process) are sinter-forged to make textured bulk polycrystals.

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

Performer: New Mexico Institute of Mining and Technology

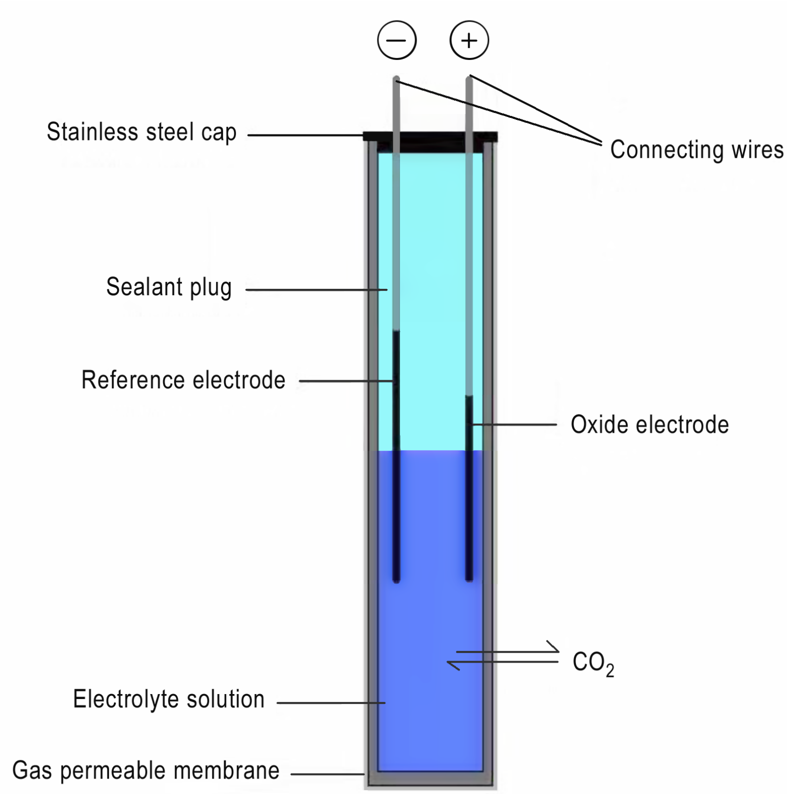
Date: 10/1/2012 – 9/30/2015

Cost: $1,345,414

Technology Area: Imaging and Other Novel Approaches

Program Area: Carbon Storage and Cross Cutting Research (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 infer 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 coreflooding tests, and a data acquisition system will be developed to enable pH and CO_2



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 (WVU), International Lead Zinc Research Organization, Special Metals Corp. (SMC), and Western Research Institute (WRI)

Date: 10/01/2010 – 3/31/2014

Cost: $1,175,827

Technology Area: Imaging and Other Novel Approaches

Program Area: Coal Utilization Science

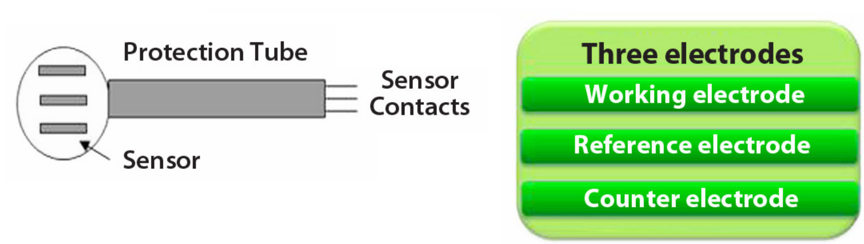
Fossil fuel power plants generate about two-thirds of the world's total electricity and are expected to continue to play an important role in the future. Increasing global energy demands, coupled with the issues of aging, inefficient power plants and increasingly strict emission requirements, will require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

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

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

In situ corrosion monitoring validation will be conducted for several key alloys with conditions closely simulating USC boiler tubes operating conditions.

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



Coupled Multielectrode Sensor (CMS) Probes.

Ultra-High Temperature Distributed Wireless Sensors

Performer: Prime Photonics, LC and Virginia Polytechnic Institute and State University

Date: 10/1/2009 – 3/31/2013

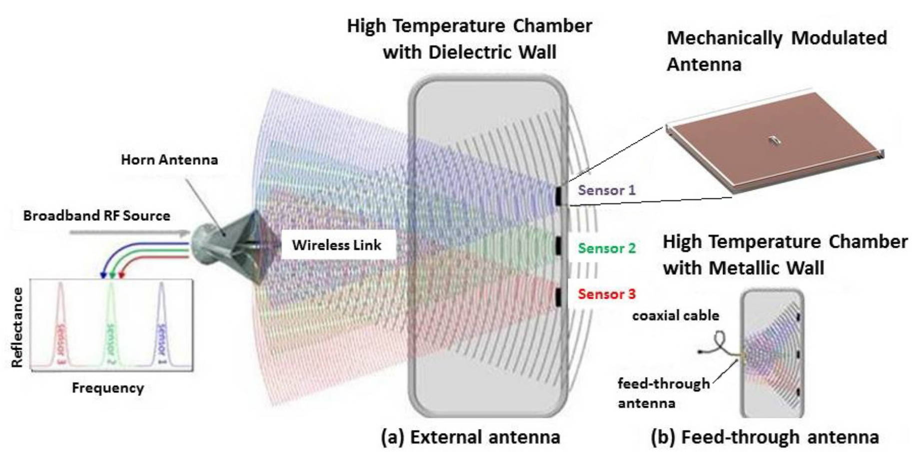
Cost: $810,954

Technology Area: Imaging and Other Novel Approaches

Program Area: Coal Utilization Science

Prime Photonics, LC and the Virginia Tech Antenna Group (VTAG) are developing a wireless sensor technology capable of operating at high temperatures in highly corrosive environments. The technology completely eliminates the need for cables connecting to the sensors. In many cases, it can avoid the need to machine feed-through to gain access into plant interiors. The technology is enabled by recent developments in radio frequency identification (RFID), high-temperature materials, and mechanically modulated antennas.

The goal of this project is to develop and demonstrate a robust and accurate wireless sensing technology for use at extreme temperatures in highly corrosive environments. The project is divided into two phases. The goal of Phase I is to better understand the RF environment where the system will operate, as well as the electromagnetic properties of the materials to be used. Researchers will identify frequency bands where wireless sensing is feasible and perhaps discover additional mechanisms for sensing the environment. The team will create the detailed design of the wireless sensors. The goal of Phase II is to perform the testing of the wireless sensors and their packaging. A number of prototype designs can be tested at low temperature to identify an optimum electromagnetic design. An interrogation system will be designed based on the knowledge gained during the project. The team will complete the sensor design and perform testing in a realistic environment.



Novel wireless sensors using radio frequency identification will allow measurement of temperature and pressure in harsh high-temperature environments. (Figure provided courtesy of Prime Photonics, LC)

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DEVICE INTEGRATION FOR DISTRIBUTED SENSING

IMAGING AND OTHER NOVEL APPROACHES

Glossary/Acronyms

AFM	Atomic Force Microscopy
AI	Artificial Intelligience
CBM	Condition Based Maintenance
CCS	Carbon Capture and Storage
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CL	Chemical Looping
CPT	Virginia Tech Center for Photonics Technology
CUS	Coal Utilization Science
DOE	Department of Energy
ECT	Electrical Capacitance Tomography
ECVT	Electrical Capacitance Volume Tomography
EDS	Energy Dispersive X-Ray Spectrometry
ERN	Equivalent Reactor Network
FDMA	Frequency Division Multiple Access
FOCS	Fiber Optic Chemical Sensors
FT-IR	Fourier Transform Infrared Absorption
GE	General Electric
GUI	Graphical User Interface
GTI	Gas Technology Institute
HBCU	Historically Black Colleges and Universities
HEIFPI	Hybrid Extrinsic/Intrinsic Fabry-Perot Interferometer
HMM	Hidden Markov Model
ICOS	Integrated Cavity Output Spectroscopy
IFPI	Intrinsic Fabry-Perot Interferometer
IGCC	Integrated Gasification Combined-Cycle
LBCO	$LnBaCo_2O_{5+d}$
LGR	Los Gatos Research
LLC	Limited Liability Company
LPFG	Long Period Fiber Grating

MCIC	Multilayer Ceramic Integrated Circuit
MEMS	Micro Electro Mechanical Systems
MFA	Model-Free Adaptive
MIMS	Mineral-Insulated Metal Sheathed
MTBA	Mean Time Between Attentions
NETL	National Energy Technology Laboratory
OSP	Optimal Sensor Placement
PID	Proportional Integrated Derivative
PRLC	Prime Research, LC
R&D	Research and Development
RFID	Radio Frequency Identification
RUL	Remaining Useful Life
SBIR	Small Business Innovative Research
SC	Supercritical
SiC	Silicon Carbide
SEM	Scanning Electron Microscopy
SMS	Single-Mode-Multimode-Single-Mode
TBC	Thermal Barrier Coated
TDL	Tunable Diode Laser
TDMA	Time Division Multiple Access
TEG	Thermo-Electro Generator
TLPFG	Thermal Long Period Fiber Grating
UCR	University Coal Research
UIUC	University of Illinois Urbana-Champaign
USC	Ultra Supercritical
VT	Virginia Polytechnic Institute and State University
VTAG	Virginia Tech Antenna Group
WSN	Wireless Sensor Network
XRD	X-Ray Diffraction
XPS	X-Ray Photoelectron Spectroscopy

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