CROSSCUTTING RESEARCH

SENSORS AND CONTROLS PROJECT PORTFOLIO 2019

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

INTRODUCTION

The Crosscutting Research Program advances and accelerates promising fossil energy technology by serving as a bridge between basic and applied research. The program intersects the core capabilities of the National Energy Technology Laboratory (NETL) and combines researchers' expertise to address the nation's energy priorities. Its primary agenda is to serve as a space which matures and enables commercialization of novel technologies to enhance new and existing coal-fired power plants and reduce water consumption. As the research matures it benefits other Department of Energy (DOE) Office of Fossil Energy (FE) program areas such as those under Advanced Energy Systems. Due to the broad applicability of the Crosscutting portfolio, technologies tend to generate spillover benefits in other sectors, including gas-based power generation, oil and gas infrastructure, and aviation (both commercial and military).

On behalf of FE, NETL facilitates crosscutting research and development (R&D) through collaboration with other government agencies, world-renowned national labs, start-up and established businesses and academic institutions. Through collaboration, the program advances capabilities that accelerate progress toward enabling the next generation of fossil energy. These efforts address both known existing challenges to the coal fleet as well as developing key technologies to benefit the future of coal power. Enhancements to the fleet include improvements to plant efficiency, advancements addressing the challenges of load following and cyber intrusions, and developments in affordable, scalable technical solutions. The program invests in these enhancements to secure flexible, reliable coal power for future generations.

The Crosscutting Research Program sponsors two of the longest-running university training programs, preparing the next generation of scientists and engineers to meet future energy challenges. These are the University Coal Research (UCR) program and the Historically Black Colleges and Universities and Other Minority-Serving Institutions (HBCU-OMI) program. By training at the university level with students excited about technologies on the horizon, several key technology trends will become embedded in coal plants of the future including: advanced manufacturing, cybersecurity, smart data analytics and high-performance computing.

The activities within the five primary research areas target enhanced fossil energy systems with the goal of creating transformational technology, improving plant efficiency, reducing water consumption and reducing costs. To generate transformational technology, the program connects water, sensors, computational simulation, workforce development and materials under a single umbrella.

In combination these investments in innovation, informed by private sector stakeholders, enable more comprehensive risk assessment and techno-economic analysis, increase the resiliency of our Nation's fossil energy infrastructure and enable the adoption of cutting-edge data technologies for plant owners and operators.

The Crosscutting Research portfolio of programs fosters the development of innovative power systems by conducting research in the following key technology areas:

Sensors and Controls provides pivotal insights into optimizing plant performance, reliability and availability while utilizing and furthering technological megatrends such as advanced manufacturing processes and Industry 4.0 principles.

Sensor research is investigating a range of advanced manufacturing techniques to determine the feasibility of embedding sensors, capable of operation in extreme environments and outfitted with condition-based monitoring algorithms, into turbine blades, boiler walls, piping, and tubing to predict component failure, anticipate maintenance needs and reduce plant downtime.

Controls research is advancing the accuracy of artificial and distributed intelligence systems for process control, automation, and fault detection. The ability to monitor key plant parameters and align results in real-time with self-organizing information networks will enable decision-makers to improve the operational efficiency during challenging transient conditions, increase plant availability and dispatch, tighten cybersecurity and environmental control, and improve plant revenue profiles.

This program is exploring advances within, and the integration of technologies across, three primary platforms: Advanced Sensors, Distributed Intelligent Controls, and Cybersecurity.

High Performance Materials focuses on material discovery and development that will lower the cost and improve the performance of fossil-based power-generation systems.

Materials of interest are those that enable components and equipment to perform in the high-temperature, high-pressure, corrosive environments of an advanced energy system with specific emphasis on durability, availability and cost both within and across each of four primary platforms: Computational Materials Design, Advanced Structural Materials, Functional Materials for Process Performance, and Advanced Manufacturing.

Modeling, Simulation and Analysis applies simulation and modeling capabilities to the full range of maturities and technologies essential to plant operation, from fundamental energy science in reactive and multiphase flows to full-scale virtual and interactive plant performance.

This program supports the development and application of new and innovative physics- and chemistry-based models and computational tools at multiple scales (atomistic, device, process, grid, and market) and investigates the potential positive impact these tools may have in overcoming complexities that confound today's experimental scientists and influencing the discovery of a new generation of advanced fossil-fuel technologies.

Analysis and visualization tools are manipulated to gain scientific insights into complex, noisy, high-dimensional, and high-volume datasets. The information generated is then collected, processed and used to inform research that combines theory, computational modeling, advanced optimization, experiments, and industrial input with a focus in three main platforms: Multiphase Flow Science, Advanced Process Simulation, and Innovative Concept Analysis.

Water Management aims to reduce the amount of freshwater used by fossil-fueled power plants and to minimize the potential impacts of plant operations on water quality.

The vision for this program is to develop a 21st century America that can count on our Nation's abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential to our continued economic health and national security.

Thermoelectric power generation accounts for more than 40 percent of freshwater withdrawals (143 billion gallons of water per day) and more than 3 percent of freshwater consumption (4 billion gallons per day) in the United States. As the cost associated with water consumption increases, so will the cost of water treatment, recovery, and reuse.

The Water Management Program addresses the competing needs for water consumption through research in three dynamic platforms: Increasing Water Efficiency and Reuse, Treatment of Alternative Sources of Water, and Energy Water Analysis.

SENSORS AND CONTROLS

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

The Sensors and Controls project portfolio is categorized into the following research areas:

- Advanced Sensors
- Cybersecurity
- Distributed Intelligent Controls
- Robotics-Based Inspection
- Systems Engineering and Analysis

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

ADVANCED SENSORS

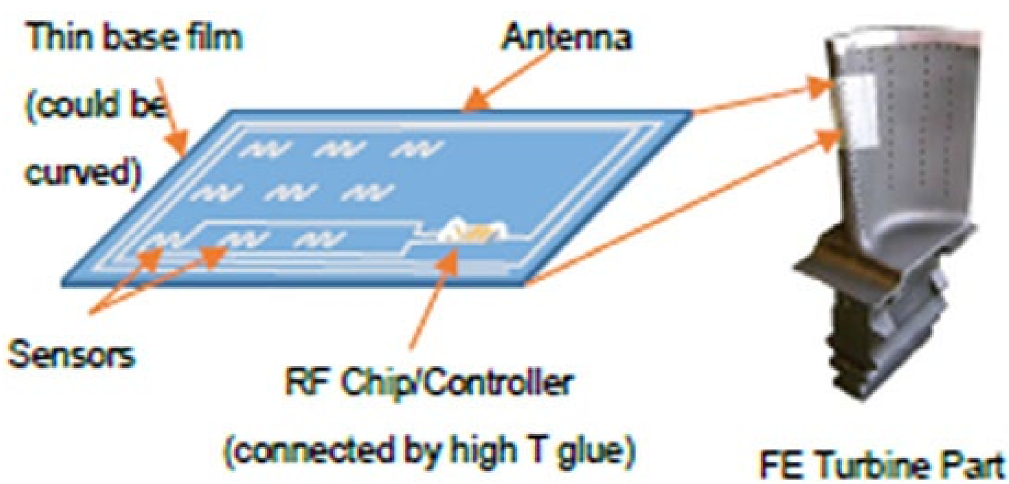
Low-Cost Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems

Performer	**Carnegie Mellon University**
Award Number	FE0026170
Project Duration	10/1/2015 – 9/30/2019
Total Project Value	$ 488,738
Collaborators	University of Texas at El Paso; Washington State University
Technology Area	University Training and Research

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

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

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



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

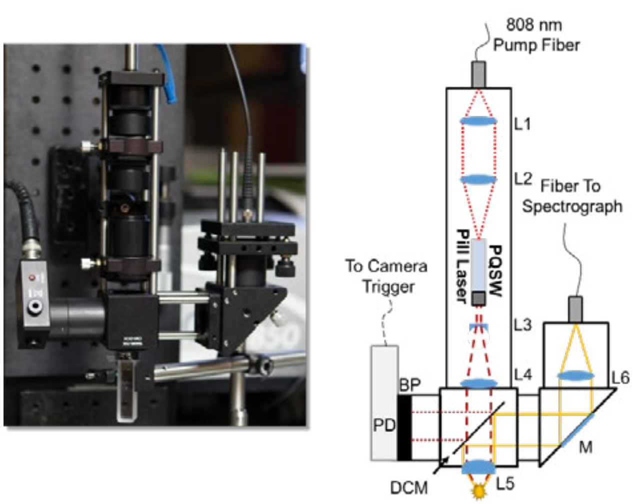
Development of LIBS for Specialized Fossil Energy Applications

Performer	National Energy Technology Laboratory
Award Number	Advanced Sensors & Controls FWP
Project Duration	4/1/2018 – 3/31/2019
Total Project Value	$ 339,018
Technology Area	Plant Optimization Technologies

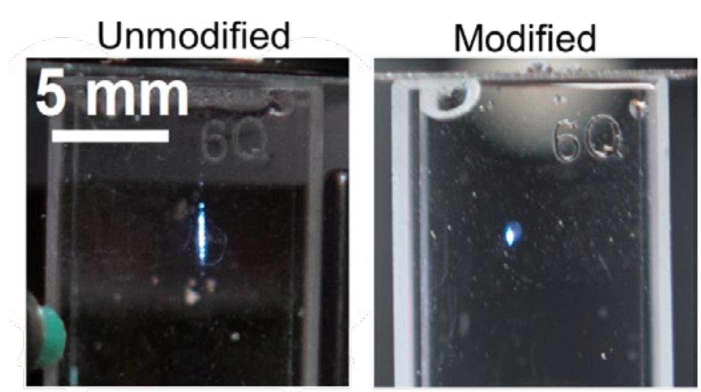
This research by NETL will provide data on the abilities and limitations of laser-induced breakdown spectroscopy (LIBS) at conditions of interest for fossil energy processes and will adapt LIBS technology to optimize measurement capability in field systems. Conditions of interest include the elevated temperatures and pressures of the subterranean environment as well as power plant process environments such as wastewater streams. The unknowns of this research are centered around the application of the optical techniques to the fluids of interest and their optical behavior at these conditions. Technical challenges include the selection and use of suitable optical materials and concomitant optical collection techniques that will provide enough signal-to-noise for accurate measurement.

Experimentation with brines relevant to subterranean conditions has indicated that presence of both carbon dioxide and sodium chloride enhance the spectral emission of other atomic constituents within pressurized brine. A pressure vessel with optical accessibility is currently in place and data is being collected to understand the optical and spectral effects of measuring carbonated brine at reservoir temperatures and pressures. The experimental setup is capable of operations up to 6000 pounds per square inch and 150 degrees Celsius.

Downhole hardware, more appropriate to field use, is being designed and constructed adapting existing NETL technology for LIBS (and possibly Raman spectroscopy) for use at the end of a drill string. Use of fiber optics to connect the pump laser and instrumentation will allow most of the components to be located above ground, with the final laser head below ground. The miniaturized laser systems that will be used will be placed downhole and pumped remotely.



Prototype of field measurement optical system design.



Spark quality improvement from initial design (left) to modified design (right), tested in water.

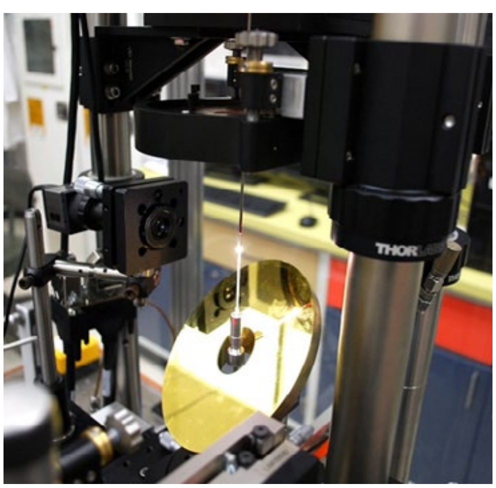
Optical Fiber Sensors for Harsh Fossil Energy Environments

Performer	**National Energy Technology Laboratory**
Award Number	Advanced Sensors & Controls FWP
Project Duration	4/1/2018 – 3/31/2019
Total Project Value	$ 870,000
Technology Area	Plant Optimization Technologies

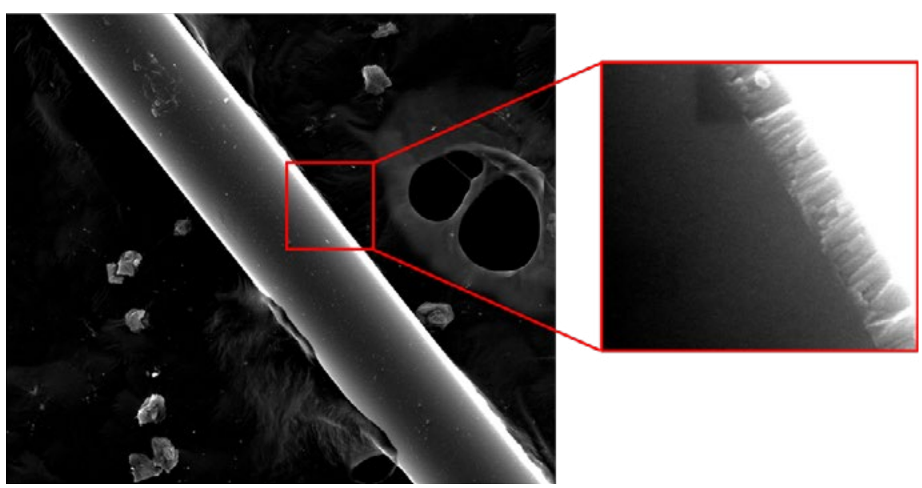
Fiber optic sensors have the potential to be applied at very high temperatures, particularly with the development of low-cost sapphire or other ultra-high temperature optical fibers. Optical fibers may be used in multipoint sensors, allowing multiple measurement points with a single readout instrument. They have been embedded in ambient temperature applications such as structural monitoring of bridges and wind turbine blades, and could be embedded in structures of importance in fossil energy applications such as solid oxide fuel cell (SOFC) interconnects and boiler steam headers. Conventional silica optical fibers, however, have very limited durability in high-temperature process environments, particularly when exposed to hydrogen or water vapor.

NETL's laser-heated pedestal growth system is being utilized to refine the techniques needed to make high-temperature crystalline optical fibers (from materials such as sapphire or garnet) and to develop a durable optical cladding.

Development of a durable optical cladding and cost-effective distributed interrogation for sapphire optical fibers will allow such fibers to be used for sensing in higher-temperature applications beyond the capability of silica fiber, such as boiler exhaust. Development of high-temperature functional materials for sensing of oxygen will support applications in sensing and controlling excess air levels in combustion, and oxygen levels in an SOFC cathode stream. Complementary to those efforts, methods for multipoint measurements along sapphire optical fibers are being investigated. Field testing of multipoint sensing in power plants will be performed to move the new technology toward commercial use.



Laser heated pedestal growth system.



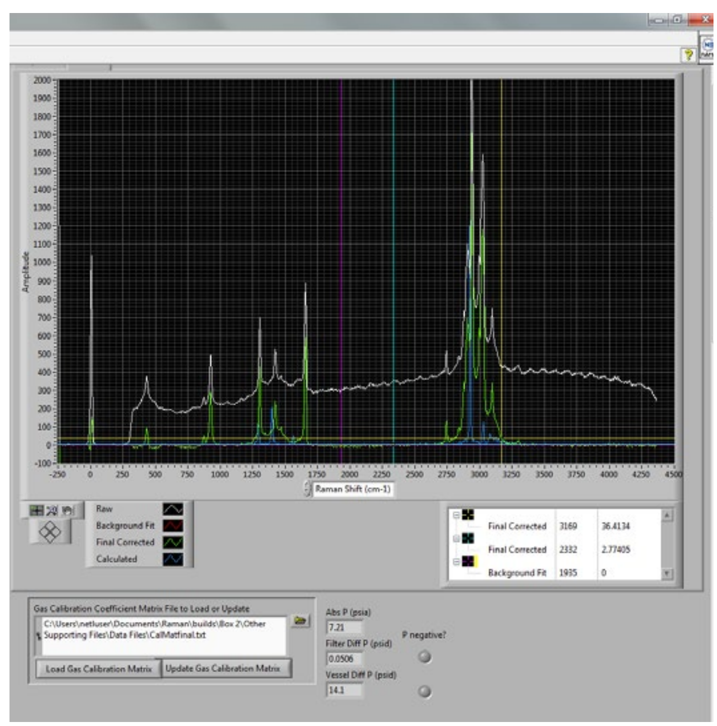
Functional thin films applied to optical fiber for gas sensing.

Field Testing of Raman Gas Analyzer

Performer	**National Energy Technology Laboratory**
Award Number	Advanced Sensors & Controls FWP
Project Duration	4/1/2018 – 3/31/2019
Total Project Value	$ 218,875
Technology Area	Plant Optimization Technologies

Laser-based and other advanced laboratory diagnostics can be adapted to fossil energy research problems to provide non-contact sensing capabilities in harsh process environments, or to provide next-generation measurement capability for process control. Work on this project supports the field testing of the Raman gas analyzer (RGA), a next-generation technology for real-time composition analysis of fuel gases and other process gases. The RGA was developed at NETL, applying Raman spectroscopy, a laboratory technique for non-destructive material analysis which has had great success previously with liquids and solids. The RGA applies Raman spectroscopy to gases with an ingenious optical configuration which increases the signal more than 1000 times above that of the conventional approach. As a result, the composition of a gas mixture (such as natural gas or syngas) can be measured much faster than with conventional commercial technology, which is fast enough to allow the method to be a powerful instrument to support process control. Field testing with commercial partners is the next step for technology readiness level advancement and market acceptance of the new technology.

Raman gas analyzer field prototype.



Example of Raman spectra from gas in real-time analysis.

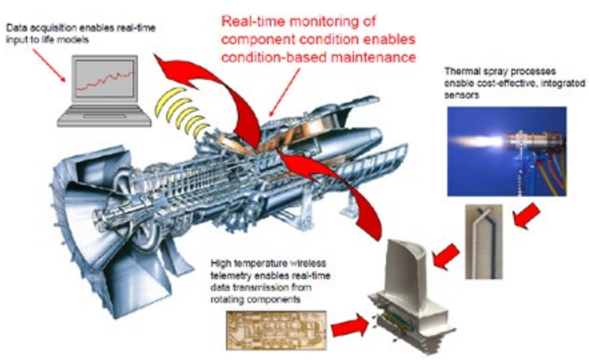
Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines

Performer	**Siemens Corporation**
Award Number	FE0026348
Project Duration	9/16/2015 – 8/31/2020
Total Project Value	$ 4,687,500
Collaborators	Arkansas Power Electronics International, Inc.; Siemens Energy, Inc.
Technology Area	Plant Optimization Technologies

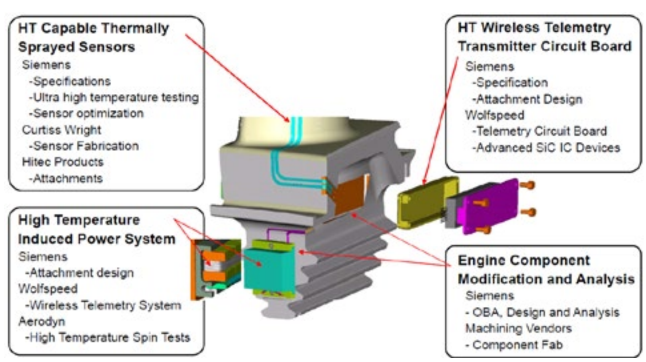
The objective of the program is to develop and engine-test hardware and software technologies that will enable active condition monitoring to be implemented on hot gas path turbine blades in large industrial gas turbines. The specific objectives are (1) to fabricate and install smart turbine blades with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

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

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



Anatomy of a smart component.



Novel sensor's wireless telemetry system.

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

Performer	**Tech4Imaging LLC**
Award Number	SC0011936
Project Duration	6/9/2014 – 7/30/2019
Total Project Value	$ 2,159,964
Collaborator	The Ohio State University
Technology Area	Small Business Innovation Research (SBIR)

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

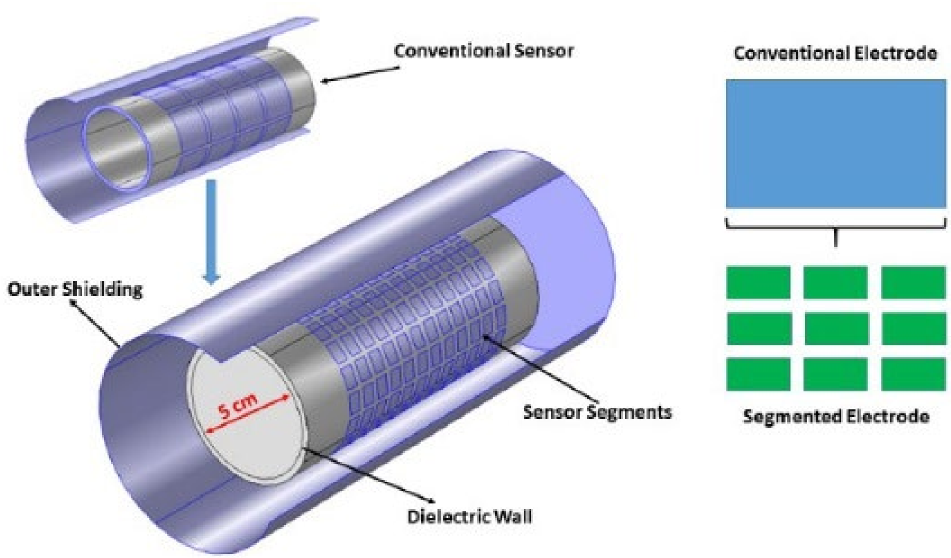


Illustration of AECVT system.

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

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

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

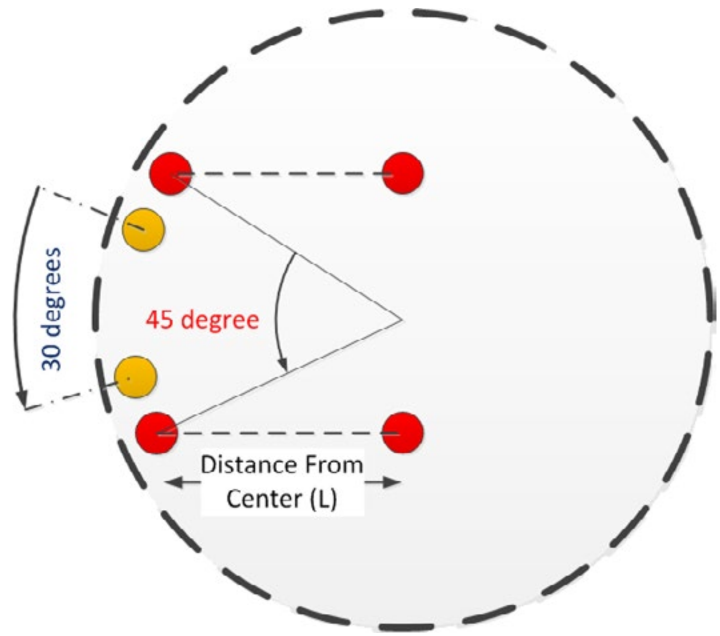


Illustration of simulation setup for AECVT enhanced resolution.

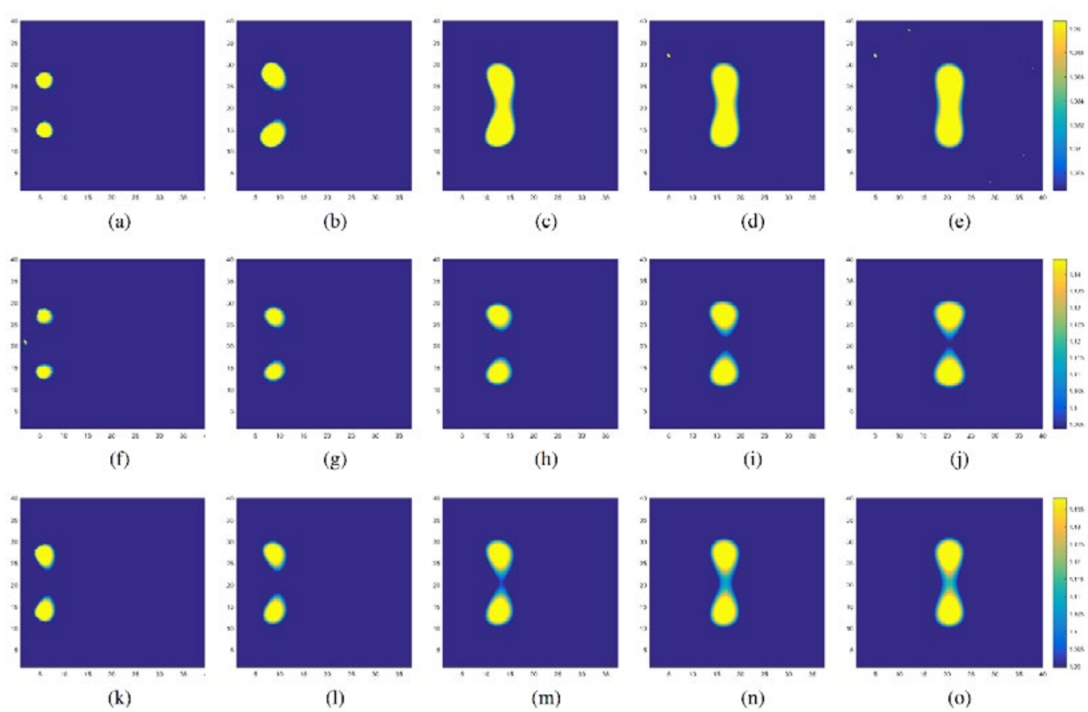


Image reconstruction results for two nearby spherical dielectric objects, placed at different locations inside the imaging domain with initial subtended angle equal to 45 degrees as depicted in figure above. (a-e) Results using conventional ECVT with 12 fixed electrodes (no electronic scanning). (f-j)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

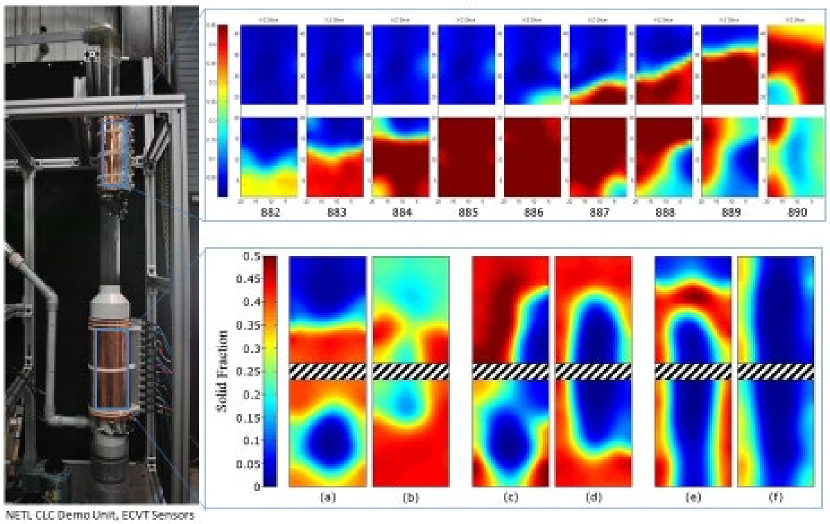
Real-Time 3-D Volume Imaging and Mass-Gauging of High Temperature Flows and Power System Components in a Fossil Fuel Reactor Using Electrical Capacitance Volume Tomography

Performer	**Tech4Imaging LLC**
Award Number	SC0010228
Project Duration	6/10/2013 – 7/30/2019
Total Project Value	$ 2,149,686
Collaborator	The Ohio State University
Technology Area	Small Business Innovation Research (SBIR)

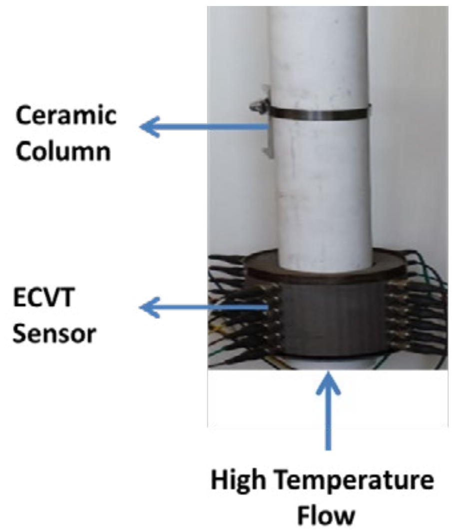
Controlling emissions and increasing efficiencies are essential requirements of future advanced power plants. Next-generation power systems require greater operating flexibility to simultaneously achieve the higher efficiency and lower emissions requirements geared toward meeting consumer demand and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

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

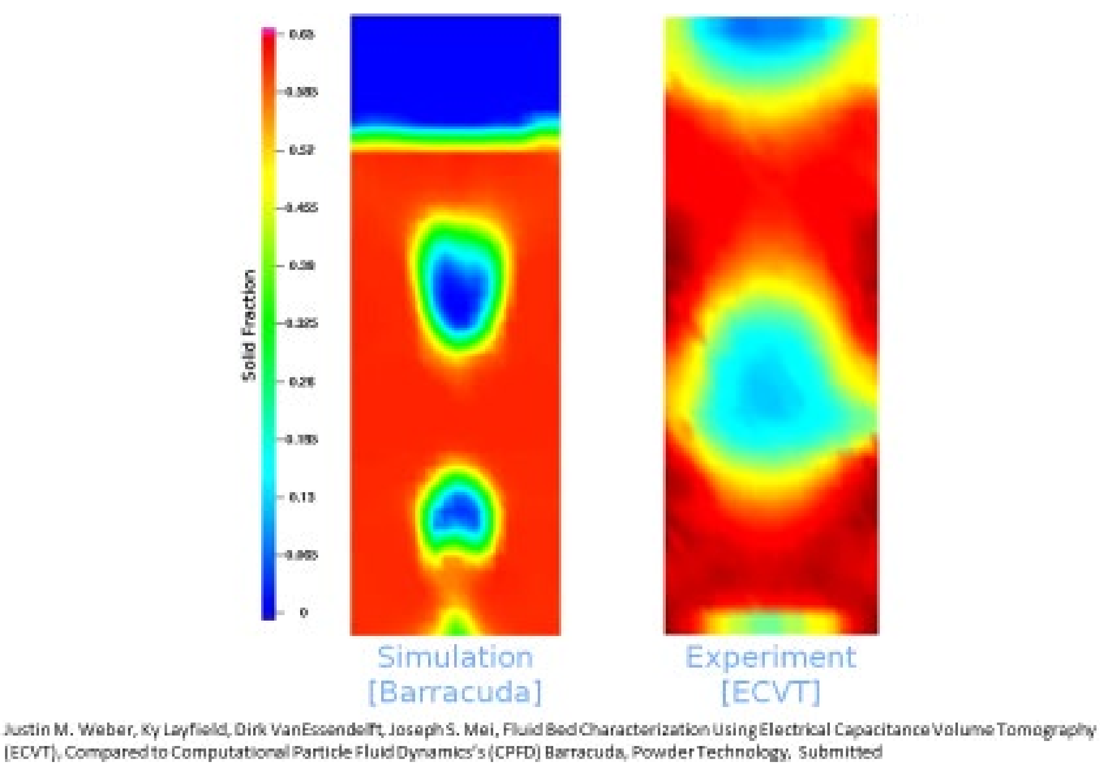
This project could provide significant public benefit due to the potential of this technology for helping the energy industry increase efficiencies and reduce emissions. The proposed system would also advance multi-phase flow research of hot systems by providing access to obscure locations within a flow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



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



ECVT sensor.

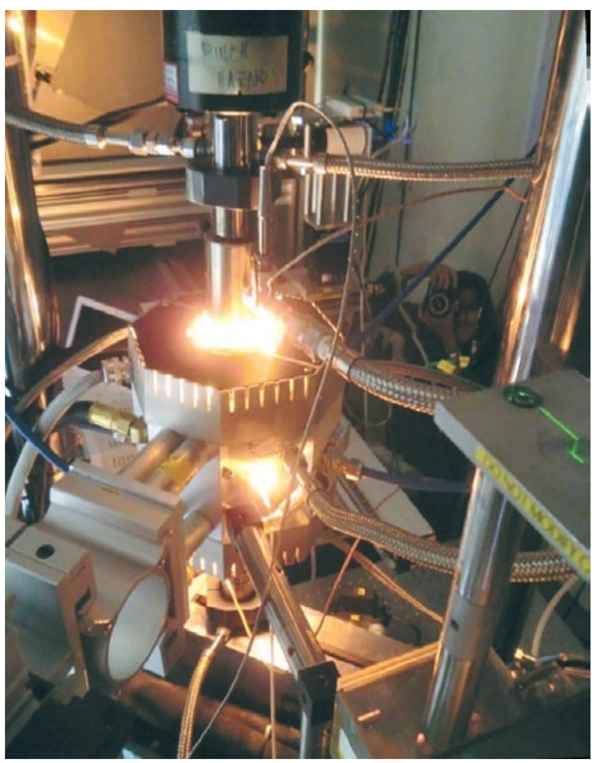


Computational fluid dynamics comparison (10-centimeter diameter fluid bed, 200-micron glass beads, 52 frames per second).

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

Performer	**University of Central Florida**
Award Number	FE0031282
Project Duration	10/1/2017 – 9/30/2020
Total Project Value	$ 879,488
Technology Area	Plant Optimization Technologies

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



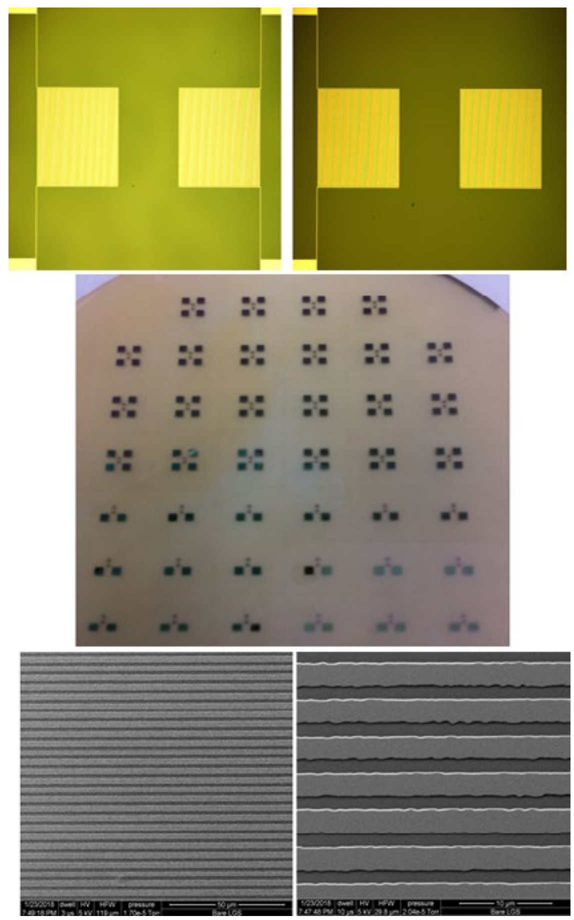
Prototype laboratory-scale test rig for the demonstration of in-situ luminescence sensing under extreme thermal and/or thermo-mechanical conditions.

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

Performer	**University of Connecticut**
Award Number	FE0026219
Project Duration	9/1/2015 – 8/31/2019
Total Project Value	$ 400,000
Technology Area	University Training and Research

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

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



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

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

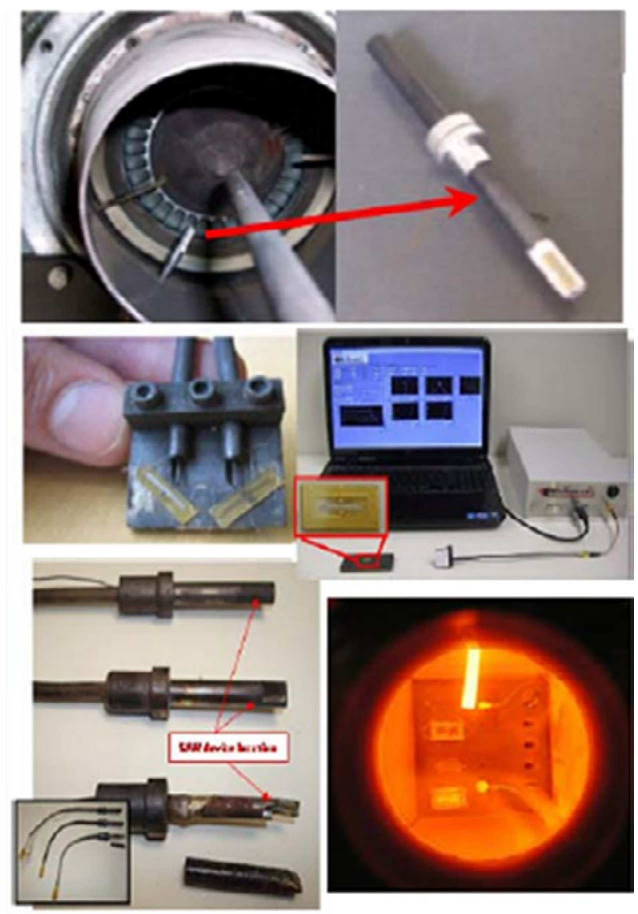
Performer	**University of Maine System**
Award Number	FE0026217
Project Duration	9/1/2015 – 8/31/2019
Total Project Value	$ 399,999
Technology Area	University Training and Research

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

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

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

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



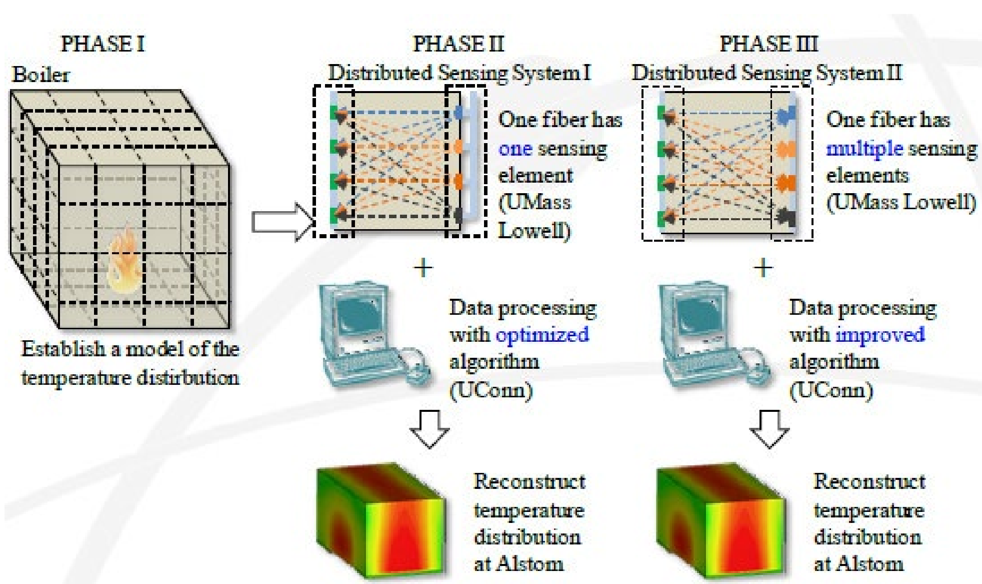
Examples of harsh environment wireless langasite SAW sensors.

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

Performer	University of Massachusetts-Lowell
Award Number	FE0023031
Project Duration	9/1/2014 – 12/31/2018
Total Project Value	$ 400,000
Collaborators	Alstom Power, Inc.; University of Connecticut
Technology Area	University Training and Research

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

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



Phases of project objectives.

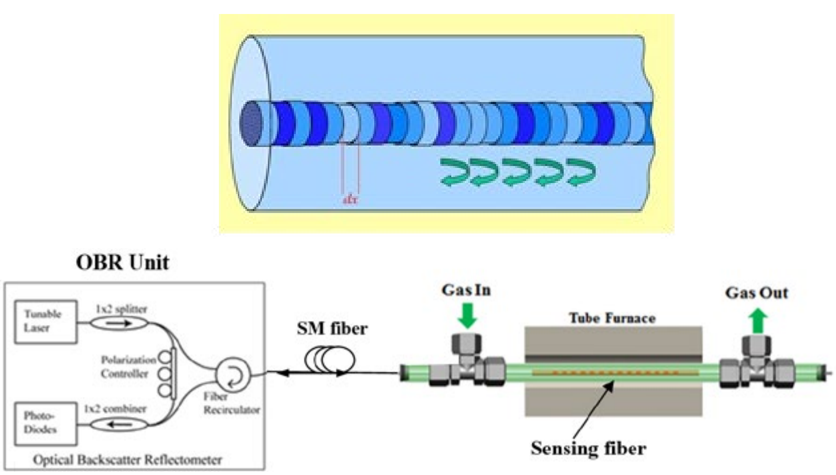
Engineering Metal Oxide Nanomaterials for Fiber Optical Sensor Platforms

Performer	**University of Pittsburgh**
Award Number	FE0028992
Project Duration	10/1/2016 – 9/30/2019
Total Project Value	$ 400,000
Technology Area	University Training and Research

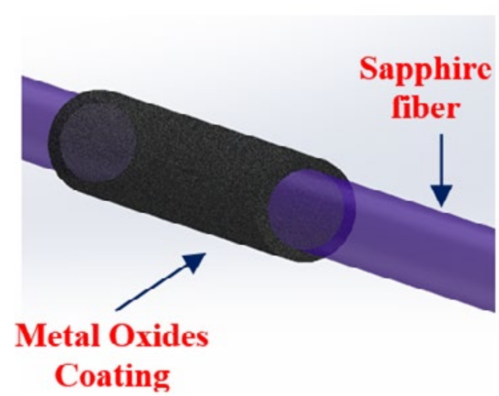
The University of Pittsburgh will explore nano-engineered metal oxides—a class of important sensor materials—for fiber optic chemical sensing for high-temperature energy applications using both silica and sapphire fibers as sensing platforms.

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

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



Distributed Rayleigh scattering.



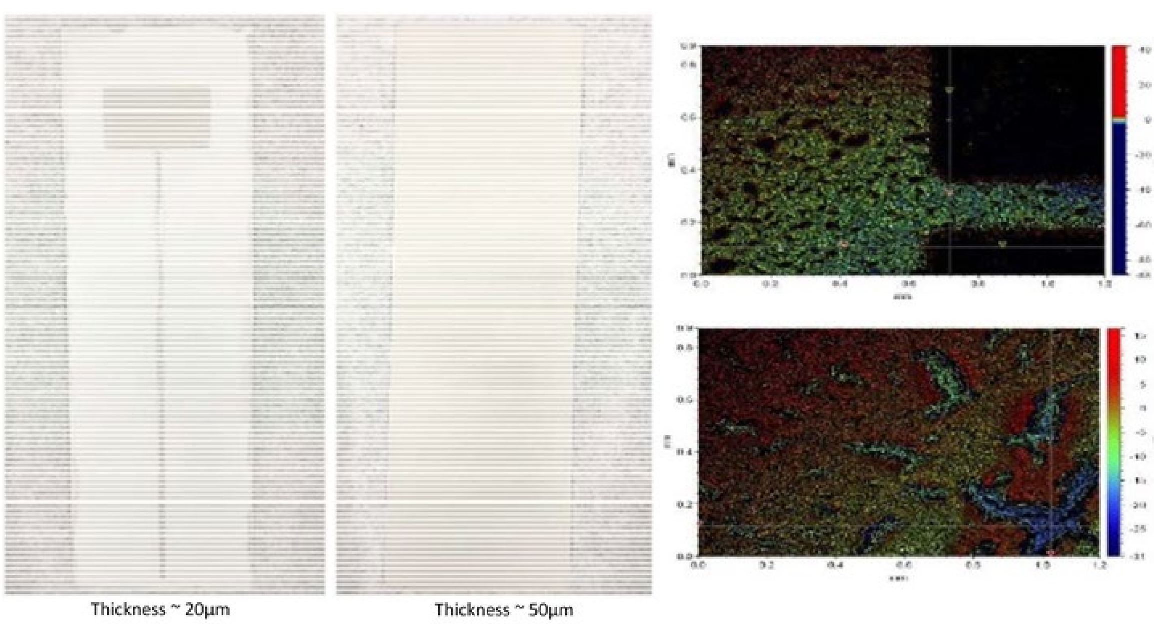
Sapphire fibers.

Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

Performer	**University of Texas at Arlington**
Award Number	FE0023118
Project Duration	1/1/2015 – 12/31/2018
Total Project Value	$ 434,079
Collaborator	University of California San Diego
Technology Area	University Training and Research

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

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



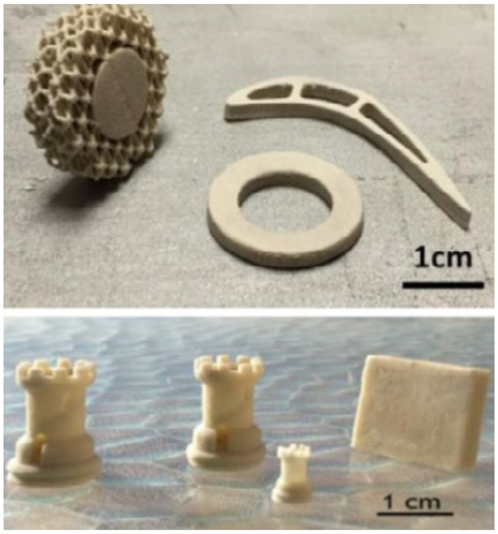
Laser machined antenna sensor.

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

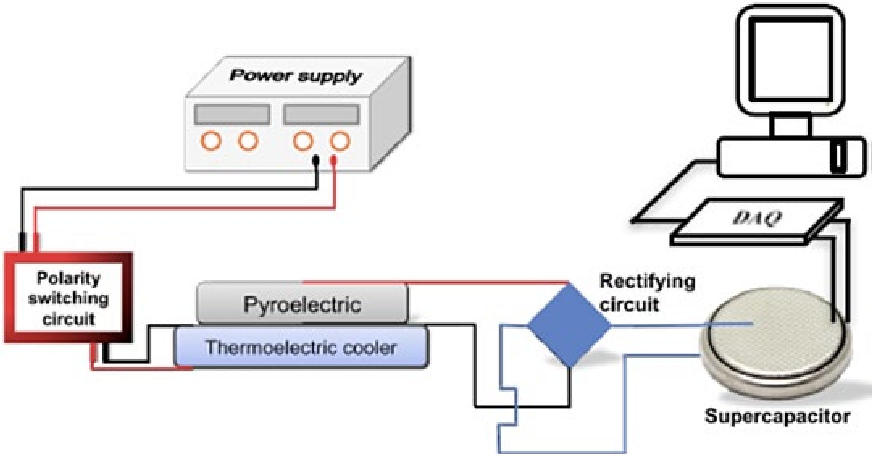
Performer	**University of Texas at El Paso**
Award Number	FE0027502
Project Duration	9/1/2016 – 8/31/2019
Total Project Value	$ 250,000
Technology Area	University Training and Research

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

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



Fabrication of complex shapes.



Thermal energy harvesting setup.

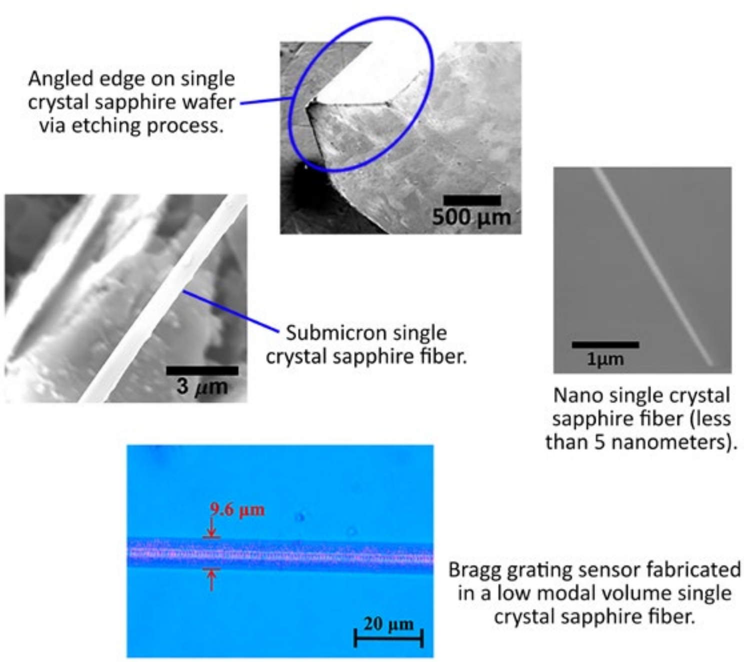
Reduced Mode Sapphire Optical Fiber and Sensing System

Performer	**Virginia Polytechnic Institute and State University**
Award Number	FE0012274
Project Duration	1/1/2014 – 12/31/2018
Total Project Value	$ 2,625,000
Technology Area	Plant Optimization Technologies

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

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

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



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

Performer	**Washington State University**
Award Number	FE0027840
Project Duration	10/1/2016 – 3/31/2019
Total Project Value	$ 400,000
Technology Area	University Training and Research

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

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

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

Raman setup.

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

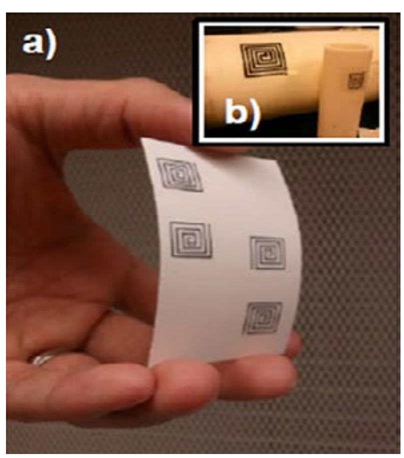
Performer	**West Virginia University**
Award Number	FE0026171
Project Duration	10/1/2015 – 9/30/2019
Total Project Value	$ 399,965
Collaborator	NexTech Materials Ltd.
Technology Area	University Training and Research

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

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

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

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



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

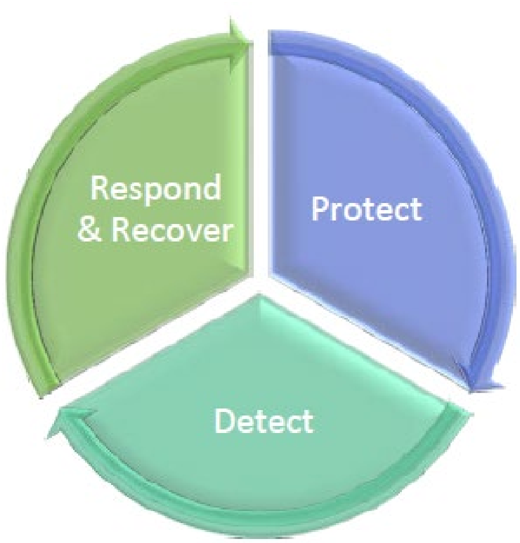
CYBERSECURITY

Cyber Security Risk Reduction Framework for Generation I&C Technology

Performer	**Electric Power Research Institute, Inc.**
Award Number	FE0031643
Project Duration	9/1/2018 – 8/31/2020
Total Project Value	$ 241,193
Technology Area	Plant Optimization Technologies

The objectives of the research are to develop a holistic risk reduction framework that (1) identifies the lifecycle of appropriate use cases of instrumentation and control (I&C) equipment in generating plants, (2) provides methodologies to protect power generation I&C equipment that reduces sensitivity to the changing threat landscape, (3) identifies technologies, programs, processes, integrations, and evolving approaches to detect and achieve threat-resilience against cyber-attacks, and (4) identifies processes for the design of systems to ensure that cyber security principles are incorporated from the outset. In addition, the objective of the framework development is to identify research area gaps and provide recommendations on future research items to advance cyber security for power generation I&C equipment. These objectives will be accomplished by incorporating past power generation-specific and cross-sector cyber security research as well as leveraging an advisory board of utility and vendor subject matter experts to capture operating experience and lessons learned.

The framework developed will enable utilities to: (1) identify the lifecycle use case in which their specific technology is staged, (2) use industry best-practice guidance, cyber security methods, technologies, and design to manage the changing threat landscape and remain compliant through changing regulatory requirements, (3) communicate with vendors and service providers on technology, features, functions, and capability requirements for designing cyber security into products and networks, and (4) identify internal programmatic, process, and integration areas of improvement to enhance overall cyber security.



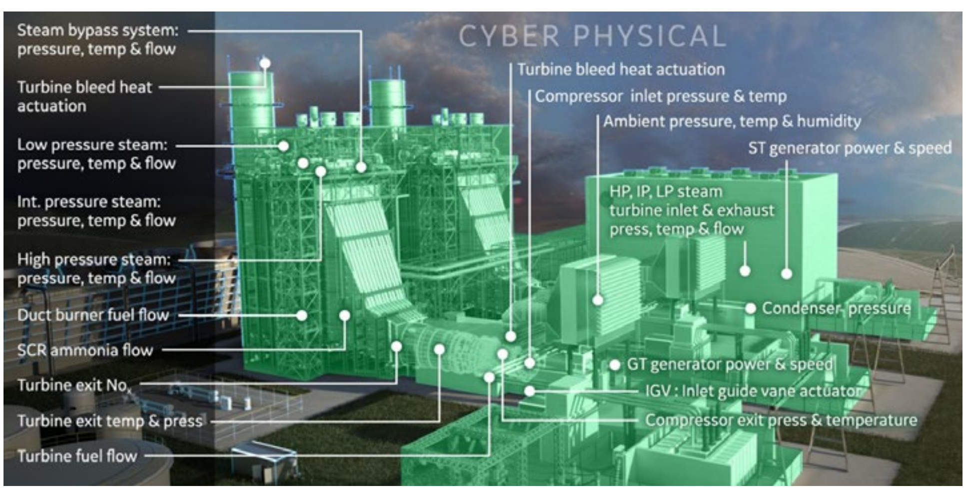
Electric Power Research Institute cyber security applied research focus areas.

Physical Domain Approaches to Reduce Cybersecurity Risks Associated with Control Systems

Performer	**General Electric Company**
Award Number	FE0031641
Project Duration	10/1/2018 – 9/30/2020
Total Project Value	$ 312,076
Technology Area	Plant Optimization Technologies

General Electric Company (GE) will perform a comprehensive analysis of current state-of-the-art approaches that use distributed sensors and controls technology for securing fossil power plants from cyber-risks. The study will analyze physical domain approaches and fault-tolerant controls or similar technology extensible to cybersecurity needs (e.g., detection and neutralization of effects of cyber-attacks or faults). The team will use a generic reference solution example and assess the suitability to fossil power generation assets. The reference solution framework, being a physical defense layer, is unlike the conventional protections offered by information technology and operational technology employed in many industrial control systems. It uses a hybrid technical approach combining theoretical advances from multiple disciplines such as system physics, human physiology, machine learning, and control and estimation, with abilities to simultaneously process copious amounts of data from a heterogeneous sensing environment and learn from it. GE will also investigate further optimization and breakthroughs unique to fossil power plants. The paper study will report on (1) a survey of the cybersecurity landscape affecting control systems of fossil fuel power plants; (2) a list of high-risk threats and faults, identified vulnerabilities, risk factors, and their impacts; (3) capabilities of existing fault-tolerant control systems; (4) the applicability of current DOE-funded efforts; (5) the applicability of secure communications technologies; and (6) identified technical and non-technical gaps.

The key outcome of this study is a comprehensive analysis and methodology—vetted by industry experts to systematically identify gaps—that, when developed, reduces cybersecurity risks in control systems used for fossil powered generation systems such as gas and steam turbines, including those with environmental controls.



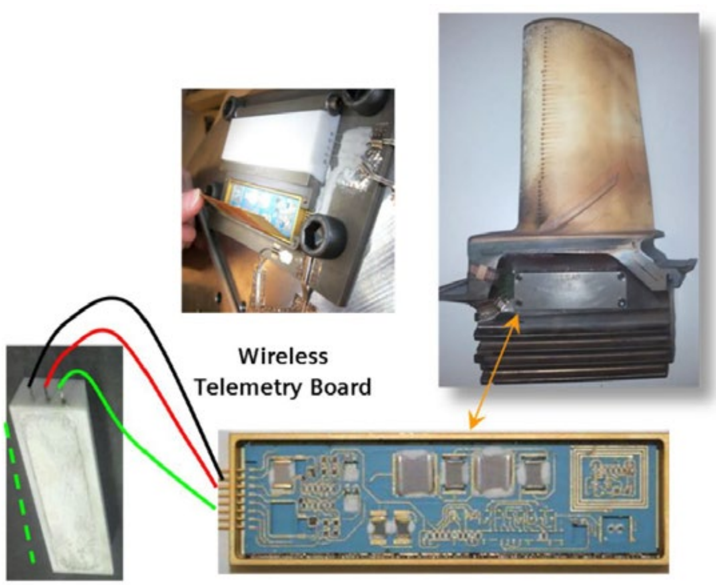
Study current state-of-the-art physical domain approaches applicable to reducing cybersecurity risks associated with the deployment of distributed sensors and advanced controls to fossil power generation assets.

Cyber Secure Sensor Network for Fossil Fuel Power Generation Assets Monitoring

Performer	**Siemens Corporation**
Award Number	FE0031666
Project Duration	8/31/2018 – 8/30/2020
Total Project Value	$ 312,500
Technology Area	Plant Optimization Technologies

The project objective is to develop a technology framework for integrating current cyber-physical security solutions with connected sensors that are deployed within fossil-fueled power generation plants. The proposed solutions will utilize Siemens-developed harsh environment wireless telemetry systems based on state-of-the-art wide band gap (WBG) semiconductor devices, cutting edge embedded passive components, and extreme-temperature packaging systems that can achieve harsh-environment capabilities such as wireless deployment of temperature sensing (greater than 1200 degrees Celsius [°C]) on rotating gas turbine components (high g-loads of approximately 16,000 g) in the hot gas path. Proposed security solutions aim to achieve a protection profile comprising (a) sensor component integrity (including at the integrated circuits level) protection; (b) detection of device firmware/software modification; and (c) detection of sensor parts quality degradation. The proposed cyber intrusion detection technology relies on secure control flow integrity of sensor applications based on side channel information monitoring such as device power consumption and electromagnetic emanations.

The proposed intrusion detection method is passive and "air-gapped", i.e., the setup of signal collection and signal processing platform does not rely on internet connection, so hackers will not be able exploit the detection setup via a remote connection. Because addition of security functionalities requires no hardware modification or software purchase, the intrusion detection method proposed will provide a cost-saving solution.



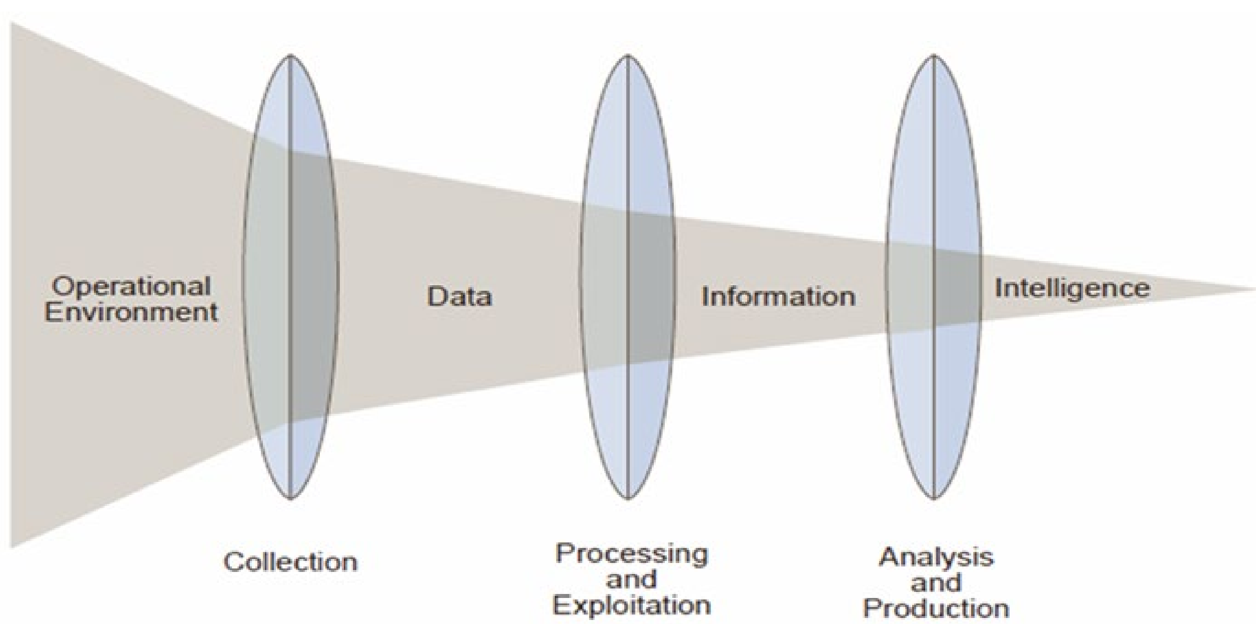
High temperature wireless telemetry system integrate with turbine condition monitoring.

Operational Technology Behavioral Analytics

Performer	**Southern Company Services, Inc.**
Award Number	FE0031640
Project Duration	10/1/2018 – 9/30/2020
Total Project Value	$ 322,894
Technology Area	Plant Optimization Technologies

The objective of this project is to enable, improve, and protect power systems by melding traditional information technology (IT) cyber security, operational technology (OT) sensor and platform information, data analytics, and machine learning. This application of proven cyber security techniques with non-traditional data sources will enable real-time and predictive detection of anomalous power system behavior. The correlation of broad data sources will be used to detect pattern-like trends leading to the theory of operational technology behavioral analytics (OTBA). Models and associated analytics will be deployed for real-time monitoring and protection of operational networks.

The desired outcome is improved operational understanding, protection of power systems, and ability to respond to cyber threats through the creation of a data-centric predictive anomaly detection strategy for OT environments that is repeatable with minimal effort and cost while utilizing existing plant data.



Data analytics approach which leverages process information from operational environments at power plants for enhanced cybersecurity.

E-Blockchain: A Scalable Platform for Secure Energy Transactions and Control

Performer	**Taekion (formerly Grid7, LLC)**
Award Number	SC0017766
Project Duration	6/12/2017 – 8/26/2020
Total Project Value	$ 1,149,210
Technology Area	Small Business Innovation Research (SBIR)

During SBIR Phase I effort, Taekion built an innovative proof-of-concept software platform, E-Blockchain, which is built upon an enhanced blockchain layer to enable secure transaction and control applications within the SmartGrid or "Grid of Things" domain. The focus was on applications that involve the integration of centralized and decentralized powerplant control systems with industrial internet of things (IIoT) networks. The E-Blockchain software platform provides critical capabilities to (1) reduce the risk of cybersecurity threats for power system-based IIoT networks, (2) increase SmartGrid reliability, (3) reduce power plant emissions, and (4) increase plant efficiencies. The E-Blockchain platform is designed to be scalable, resilient, secure, and resistant to quantum computer attacks, which is well suited for power-system-based IIoT networks. In Phase II, E-Blockchain will be beta tested for commercial operation.

Project overview.

DISTRIBUTED INTELLIGENT CONTROLS

Advanced Tool for Cyber Physical Systems and Digital Twins

Performer	**Ames Laboratory**
Award Number	FWP-AL-18-450-015
Project Duration	10/1/2018 – 9/30/2020
Total Project Value	$ 610,000
Technology Area	Plant Optimization Technologies

This project will build the tools needed to integrate the concept of cyber-physical systems and digital twins into the current energy system development process of research and development, design, and deployment to create an energy development paradigm in which the first four steps of the current technology development process can be merged. This will create a "discovery-application feedback loop" in which newly conceived ideas can be rapidly tested and sorted, and various challenges overcome more effectively, reducing the time needed to deploy new energy technologies from decades to years.

Ames Laboratory (Ames) plans to further develop and integrate digital twins and cyber-physical systems as tools that address specific sensor and controls issues for hybrid systems using the Hybrid Performance (Hyper)/merged environment for simulation and analysis (MESA) system. Using system dynamics and controls, the application focus of this research will ensure that Ames research will be readily extensible to solving practical problems in the existing fleet of power plants and to aiding energy system research and development processes.

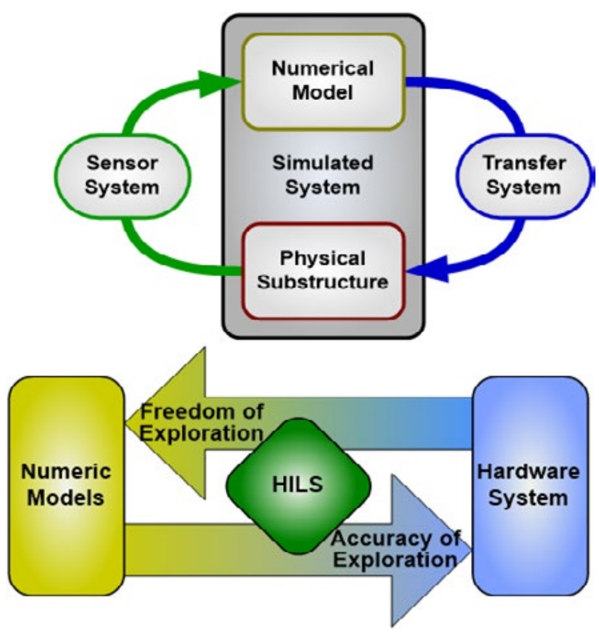
MESA enables seamless transitions from physical to virtual.

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

Performer	**Georgia Tech Research Corporation**
Award Number	FE0030600
Project Duration	8/1/2017 – 7/31/2020
Total Project Value	$ 504,130
Technology Area	Plant Optimization Technologies

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

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

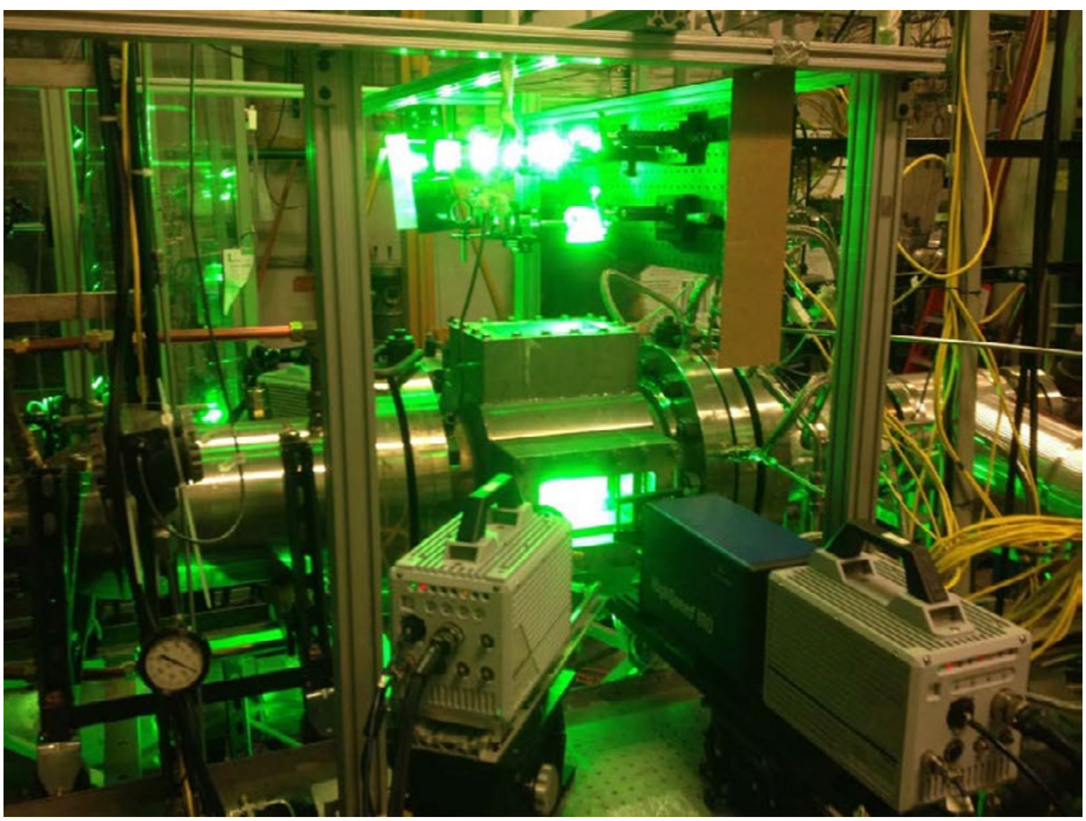


Cyber-physical simulation.

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

Performer	**Georgia Tech Research Corporation**
Award Number	FE0031288
Project Duration	10/1/2017 – 9/30/2020
Total Project Value	$ 750,297
Technology Area	Plant Optimization Technologies

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



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

Agent-based Controls and System Identification

Performer	**National Energy Technology Laboratory**
Award Number	Advanced Sensors & Controls FWP
Project Duration	4/1/2018 – 3/31/2019
Total Project Value	$ 221,965
Technology Area	Plant Optimization Technologies

Development of next-generation power systems such as fuel cell turbine hybrids encounters technical barriers which include the difficulty of dynamic control of coupled nonlinear systems. Start-up, shut-down, and rapid ramping capabilities are needed in these power systems to make them practical for broad implementation. Traditional PID (proportional–integral–derivative) control has struggled to address the dynamic operations problems, so NETL is investigating non-traditional control approaches such as agent-based control as a potential solution.

In this project, a multi-agent controls approach with agent coordination, previously shown feasible on Hyper, will be modified to improve the control response and re-tested. Several near-term fossil energy applications which would benefit from the special properties of agent-based controls will be identified to plan for development and future field testing.

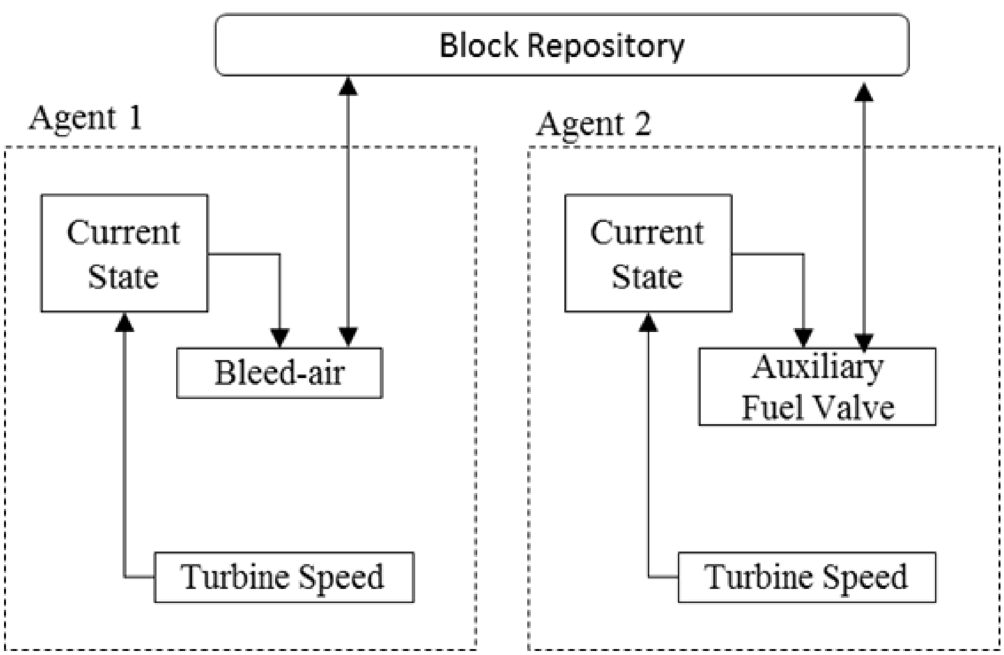


Illustration of the interaction of agent-based controllers for the turbine speed control experiment in the Hyper facility.

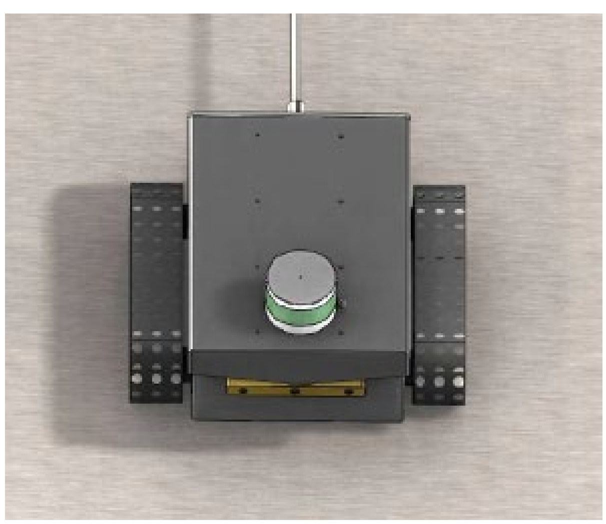
ROBOTICS-BASED INSPECTION

AI Enabled Robots for Automated Nondestructive Evaluation and Repair of Power Plant Boilers

Performer	Colorado School of Mines
Award Number	FE0031650
Project Duration	9/1/2018 – 8/31/2021
Total Project Value	$ 473,972
Collaborators	EnergynTech Inc.; Michigan State University; Xcel Energy
Technology Area	University Training and Research

Colorado School of Mines researchers are collaborating with partners from Michigan State University to develop an integrated autonomous robotic platform that (1) is equipped with advanced sensors to perform live inspection, (2) operates innovative onboard devices to perform live repair, and (3) uses artificial intelligence (AI) for intelligent information fusion and live predictive analysis for smart automated spatiotemporal inspection, analysis, and repair of furnace walls in coal-fired boilers. The autonomous robotic platform will be capable of attaching to and navigating on vertical boiler furnace walls using magnetic drive tracks. Live non-destructive evaluation (NDE) sensors and repair devices will be developed and integrated in the robot. In addition, the robot will be empowered with AI to automate data gathering (e.g., mapping and damage localization), and live predictive analysis will incorporate end-user feedback to continuously improve performance and achieve smart autonomy. Performance will be verified on vertical steel test structures in the principal investigators' laboratories and at facilities provided as in-kind support by Xcel Energy and EnergynTech.

Successful robotic inspection will limit or eliminate the need to send inspectors to assess difficult-to-access or hazardous areas, enable automated live inspection, reduce risk to human operators during maintenance or unplanned outage, and enable smart collection of comprehensive and well-organized data. The impact is increased boiler reliability, usability, and efficiency.



Concept image of the tracked robot platform without the NDE or repair equipment attached traversing a steel plate.

Development of a Pipe Crawler Inspection Tool for Fossil Energy Power Plants

Performer	**Florida International University**
Award Number	FE0031651
Project Duration	9/1/2018 – 8/31/2021
Total Project Value	$ 398,333
Technology Area	University Training and Research

Florida International University researchers are developing a robotic inspection tool to evaluate the structural integrity of key components in fossil fuel power plants. The tool will consist of multiple modular crawlers that can navigate through the 2-inch-diameter superheater tubes typically found within power plant boilers—which are often subject to corrosion and micro cracks—and provide information regarding the health of the pipes. Design modifications to reduce the tether load and maximize the pull force will be made. Multiple systems will then be synchronized to increase the length of pipe that can be inspected. The base system will house a camera for video feedback and contain a module that utilizes thumbnail-size ultrasonic sensors for measuring pipe thickness, and a LiDAR (light detection and ranging) sensor to detect any pipe buildup, damage, and/or misalignment. In addition, the module will provide a means to prepare the surface prior to measuring. The team will develop and conduct bench-scale tests to optimize the design of the crawler and its modules and conduct engineering-scale tests to validate the system.

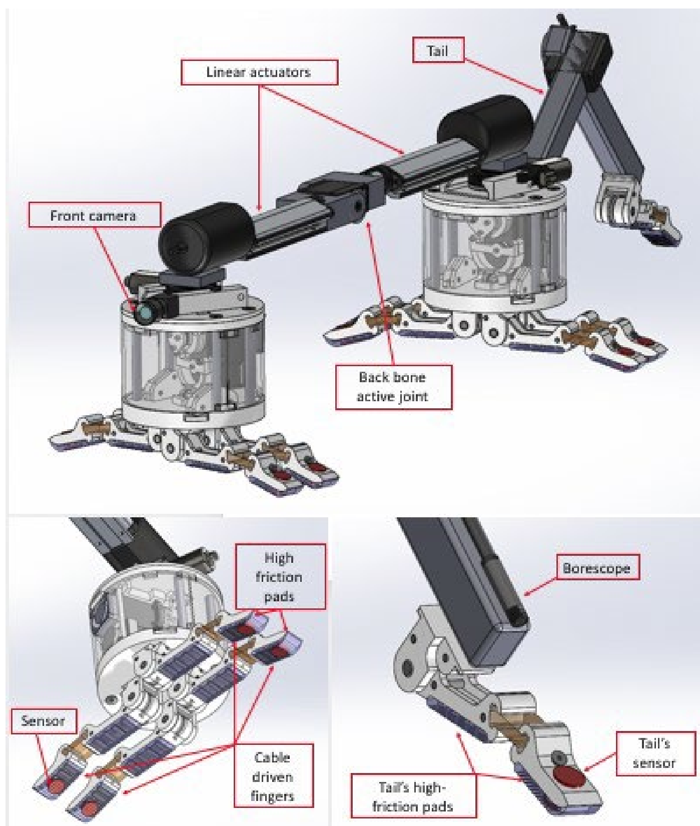
The proposed robotic system will improve the state of the art for inspection tools in pipes that are subject to extreme conditions and for which structural integrity assessments are difficult to obtain. The technology will lead to better understanding of the health of critical components, and plant downtime will be reduced, efficiency increased, and cost savings realized.

3- and 4-inch pneumatic pipe crawler developed at Florida International University.

A Lizard-Inspired Tube Inspector (LTI) Robot

Performer	**New Mexico State University**
Award Number	FE0031649
Project Duration	9/1/2018 – 8/31/2021
Total Project Value	$ 400,000
Technology Area	University Training and Research

New Mexico State University researchers are developing a versatile lizard-inspired tube inspector (LTI) robot with embedded inspection sensing components that will eliminate the need for point-by-point scanning of tube surfaces for detecting and evaluating cracks and erosion. Inspired by lizards which have evolved to live within tight spaces with complex geometries and rough surfaces, the robot will integrate couplant-free ultrasound sensing and transmission, advanced Lamb wave-based ultrasound imaging, and a friction-based mechanical mobility component to eliminate the need for smooth surfaces and simple geometries for mobility and scanning. This project will replace the wheel-based approach to tube inspection with friction and/or adhesion-based mobility to significantly increase the flexibility and maneuverability of the LTI robot, providing easy access to a power plant unit such as a boiler to inspect components of interest (e.g., curved and flat surfaces, non-ferromagnetic or ferromagnetic materials, and tubes with rough surfaces and complex geometries). In addition, advanced imaging will enable the robot to image the entire area between and around the robot's multi-functional mobility system (grippers) using multi helical ultrasound imaging and a Lamb wave-based total focusing method recently developed by the principal investigator.



Conceptual design of the LTI robot.

The results of the current project may revolutionize the robotic inspection technology used to inspect power plant components. The advanced imaging and mobility of the LTI robot makes it a unique tool that can be adopted for inspection of other power plants' hard-to-reach components such as steam turbines, heat recovery steam generators, gas turbines, and electrical generators without a need for overhauling.

A Robotics Enabled Eddy Current Testing System for Autonomous Inspection of Heat Exchanger Tubes

Performer	**University of Missouri**
Award Number	FE0031645
Project Duration	9/1/2018 – 8/31/2021
Total Project Value	$ 410,864
Technology Area	University Training and Research

University of Missouri researchers will develop a robotics-enabled eddy current testing (ECT) system for autonomous inspection of heat exchanger tubes. The proposed system will be capable of precisely controlling the location and speed of the ECT probe into or out of tubes of various sizes and geometries. An imaging system and adaptive control algorithm will be employed to quickly identify the outer geometry of the tubes and their positions relative to the probe, enabling precise movement of the ECT probe to the inlet of each tube. Insertion and extraction speeds will be controlled for fast and more consistent scanning during testing. A convolutional neural network or other machine learning algorithms will enable autonomous inspection via a feedback loop, which will be employed to learn from historical data categorized by the signatures of the various failure modes (e.g., cracking and corrosion, abrasive and erosive wear). If measured data from suspicious regions of the tubes match these signatures, the controller will make a real-time decision on insertion and extraction speeds and probe location for more detailed scanning, thus increasing measurement accuracy while enhancing testing efficiency.

The developed robotic platform will enable automated eddy-current testing, thus reducing labor time and cost. Well-controlled testing speeds will reduce human inconsistencies in data gathering and analysis. The artificial intelligence algorithm will enable deep mining of historical data for in-situ analysis and real-time decision making, which will lead to automated sensing and inspection.

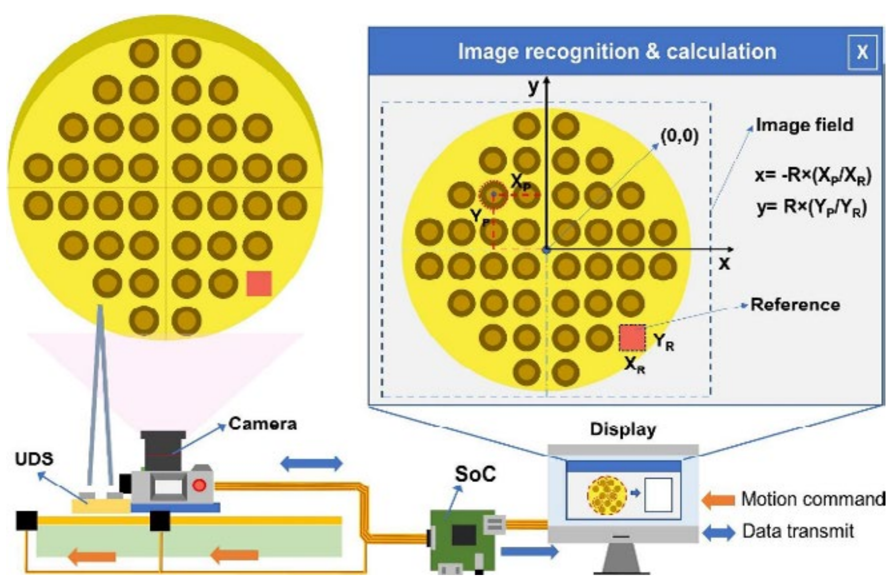


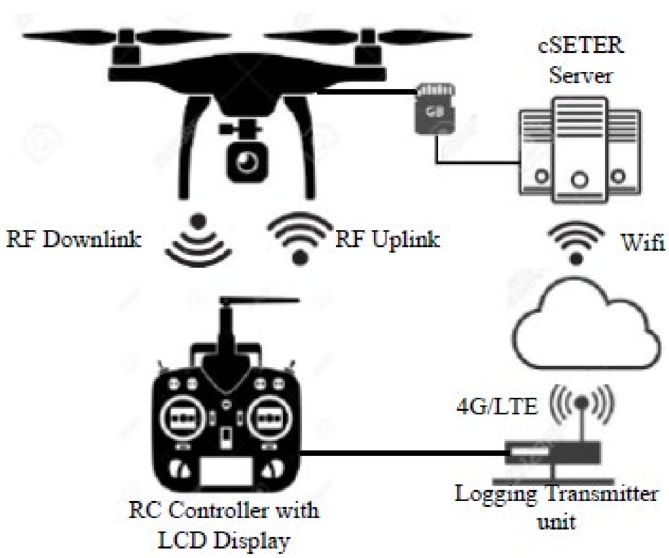
Image processing steps for recognizing geometry and location of tubes' inlets.

Autonomous Aerial Power Plant Inspection in GPS-Denied Environments

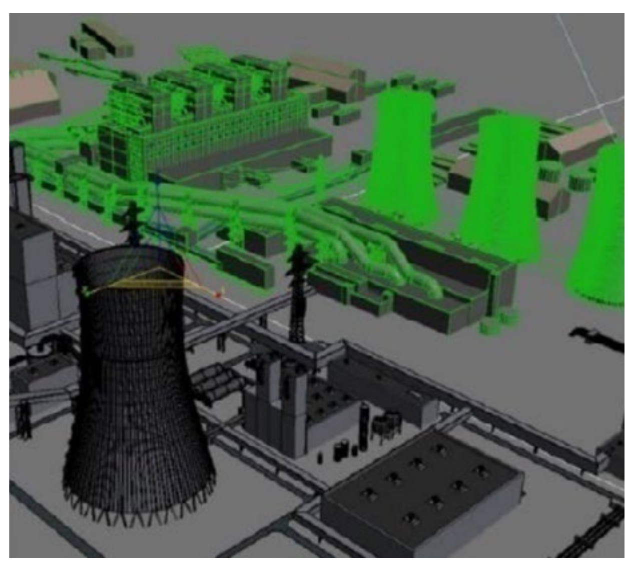
Performer	University of Texas at El Paso
Award Number	FE0031655
Project Duration	9/1/2018 – 8/31/2021
Total Project Value	$ 400,000
Technology Area	University Training and Research

University of Texas at El Paso (UTEP) researchers will test and validate the performance of UTEP's global positioning system (GPS)-denied inspection system, outfitted with electro-optical and infrared inspection sensors, in a representative coal-fired power component that will be determined in conjunction with the El Paso Electric Company. Researchers will use rotary wing flying robots for outdoor inspection and airships for indoor inspection of GPS-denied environments to test the system's guidance and navigation and obstacle avoidance capabilities. The objectives are to develop computer assisted design (CAD)-based inspection profiles for space-constrained and GPS-denied areas of a power plant; test and validate the capability to keep a pre-set distance from complex surfaces (within sub-15 centimeter tolerances in all six directions); and test and validate the capability to perform an automated inspection of uneven vertical and horizontal surfaces in enclosed and GPS-denied areas.

The aerial system will leverage current robotic-based inspection technology in power plants by potentially increasing the area and the types of structural components that can be inspected with unmanned aerial systems; access dangerous and difficult-to-reach structures; inspect areas where GPS is not available; and enable inspection of cluttered and space-reduced areas, internal and external components such as cooling towers and flue gas stacks, and areas with high ash content without disturbing particulate matter.



Data logging and telemetry system.



Model of a power plant *(courtesy of Turbosquid).*

SYSTEMS ENGINEERING AND ANALYSIS

Market and Benefits Analysis

Performer	**National Energy Technology Laboratory**
Award Number	Advanced Sensors & Controls FWP
Project Duration	4/1/2018 – 3/31/2019
Total Project Value	$ 89,231
Technology Area	Plant Optimization Technologies

Sensors that are capable of operating within higher temperature and pressure conditions have the potential to improve operations of existing power plants and will be necessary for even harsher environments that will exist within the next generation of advanced power systems that operate with high efficiency and low emissions. Also, advanced power systems are highly complex, requiring operational control that will exceed the capabilities of current control systems. The research and development projects managed by NETL aim to develop advanced sensors and controls necessary to optimize both operation and performance to achieve seamless, integrated, and intelligent power systems. While most of the R&D is at an early technology readiness level, it is still important to perform system analysis studies to show the benefits and potential market penetration of this research.

Historically, the primary economic benefit of advanced sensors and controls was expected to accrue through improvements to plant efficiency (heat rate). Recent changes to the dispatch and operation of coal-fired power plants, however, have changed the economic management of their operation. Frequent operational cycling is causing increased maintenance costs, and part load performance is of much greater importance. The techno-economic analysis of the benefits of advanced sensors and controls needs thoughtful revision to capture the potential benefits including better information for management of component degradation and greater flexibility of operation.

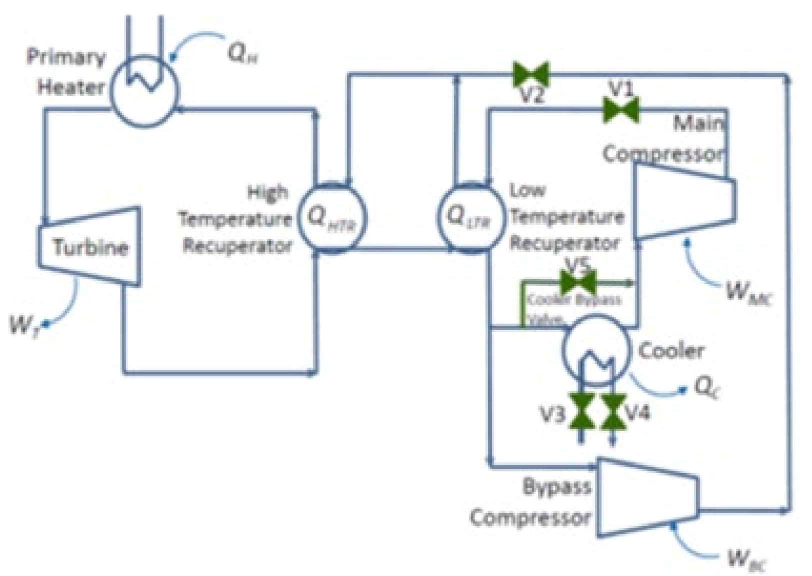


Diagram of an energy power system.

ABBREVIATIONS

°C .... degrees Celsius

3D .... three-dimensional

AECVT .... adaptive electrical capacitance volume tomography

ASV .... anodic stripping voltammetry

CAD .... computer assisted design

ChemFET .... chemical field effect transistor

COTS .... commercial off-the-shelf

CW .... continuous wave

DOE .... Department of Energy

ECT .... eddy current testing

ECVT .... electrical capacitance volume tomography

FE .... Office of Fossil Energy

FGD .... flue gas desulfurization

FWP .... Field Work Proposal

GE .... General Electric Company

GPS .... global positioning system

HBCU .... Historically Black Colleges and Universities

Hyper .... Hybrid Performance Facility

I&C .... instrumentation and control

IIoT .... industrial internet of things

IT .... information technology

LGS .... langasite

LIBS .... laser-induced breakdown spectroscopy

LiDAR .... light detection and ranging

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

LTI .... lizard-inspired tube inspector

MESA .... merged environment for simulation and analysis

mm .... millimeter

mV .... millivolt

NDE .... non-destructive evaluation

NETL .... National Energy Technology Laboratory

OMI .... Other Minority Institutions

OT .... operational technology

OTBA .... operational technology behavioral analytics

pH .... potential of hydrogen

ppt .... parts per trillion

R&D .... research and development

RGA .... Raman gas analyzer

RUL .... remaining useful life

SAW .... surface acoustic wave

SBIR .... Small Business Innovation Research

SOFC .... solid oxide fuel cell

TBC .... thermal barrier coating

UCR .... University Coal Research

UTEP .... University of Texas at El Paso

W .... watts

WBG .... wide band gap

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

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

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