CROSSCUTTING RESEARCH

2022

SENSORS, CONTROLS, AND NOVEL CONCEPTS

PROJECT PORTFOLIO

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

DISCLAIMER

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CROSSCUTTING RESEARCH

NETL's Crosscutting Research Program matures novel technologies that can enhance the efficient performance and eliminate or reduce the environmental impacts of fossil energy power plants. On behalf of the U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM), NETL pursues crosscutting research and development (R&D) by collaborating with other government agencies, world-renowned national labs, entrepreneurs, industry, and academic institutions. Efforts are focused on five primary research areas: High Performance Materials; Sensors, Controls, and Novel Concepts; Simulation-Based Engineering; Energy Storage; and University Training and Research (UTR).

The goals are to create transformational technologies under a single research umbrella that improve plant efficiency, flexibility, and security; reduce water consumption; reduce costs; and better enable dependable fossil power systems to maintain the stability and resilience of the electricity grid while maximizing use of variable renewable power sources. The research is leading to enhancements to the fleet such as new ways to address the challenges of load following, better ways to counter cyber intrusions, and advancements in affordable, scalable technical solutions. Because of the broad scope of the Crosscutting Research Portfolio, its technologies often have applicability to other energy-related sectors such as renewable and nuclear power generation, oil and natural gas infrastructure, and aviation (both commercial and military).

Crosscutting Research efforts include sponsorship of two long-running university training programs that prepare 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 Institutions (HBCU-OMI) program. By working with students on the university level, the efforts ensure that key technologies in areas including advanced manufacturing, cybersecurity, smart data analytics, and high-performance computing will be integrated into fossil plants of the future.

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

High Performance Materials: The High Performance Materials program drives to characterize, produce, and certify cost-effective alloys and other high-performance materials suitable for the extreme environments found in fossil-based power-generation systems. NETL supports and catalyzes a robust domestic materials supply chain that prepares materials for advanced ultra-supercritical (AUSC) steam cycles and spinoff applications. The work also enables research in suitable materials for supercritical carbon dioxide (sCO_2) cycles that yield higher thermal efficiencies.

The Crosscutting Materials program works to accelerate the development of improved steels, superalloys, and other advanced alloys to address challenges of both the existing fleet and future power 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: Advanced Manufacturing, Advanced Structural Materials for Harsh Environments, Computational Materials Design, and Functional Materials for Process Performance Improvements.

Sensors, Controls, and Novel Concepts: The Sensors, Controls, and Novel Concepts program is conducting research and development for technologies that will provide pivotal insights into optimizing performance, reliability, and availability of integrated energy and carbon management systems. NETL develops, tests, and matures novel sensor and control technologies that are operable in next-generation energy systems, including hybrid plants incorporating components such as hydrogen-powered turbines and fuel cells, renewables, and energy storage applications. These sensors enable responsiveness to varying conditions in real time, maintaining high efficiencies and reducing emissions.

The Crosscutting Sensors, Controls, and Novel Concepts program explores advances within and the integration of technologies across the following primary research areas: Harsh Environment Sensors, Advanced Controls and Cyber Physical Systems, and Novel Concepts.

Simulation-Based Engineering: Simulation-Based Engineering (SBE) focuses on developing and applying advanced computational tools at multiple scales: atomistic, device, process, grid, and market scales, to accelerate development and deployment of fossil fuel technologies. Research in this area provides the basis for the simulation of engineered devices and systems to better predict and optimize the performance of fossil fuel power generating systems.

Computational design methods and concepts are required to significantly improve performance, reduce the costs of existing fossil energy power systems, and enable the development of new systems and capabilities such as advanced ultrasupercritical combustion and hydrogen turbines.

This effort combines theory, computational modeling, advanced optimization, experiments, and industrial input to simulate complex advanced energy processes, resulting in virtual prototyping. The research conducted in the SBE R&D develops accurate and timely computational models of complex reacting flows and components relevant to advanced power systems. Model development and refinement is achieved through in-house research and partnerships to utilize expertise throughout the country.

Energy Storage: Energy Storage aims to develop a comprehensive strategy to expand FECM's current portfolio of technologies and programs in order to better enable fossil power plants to maintain the electricity grid's stability and resilience while increasingly utilizing variable renewable power. Energy storage at the generation site will be essential to a resilient and flexible electricity network and NETL's Energy Storage program aims to address the needs and challenges of site storage. The goal of this program is to leverage over a century of investment in fossil energy infrastructure, extend the useful lifetime of existing fossil energy assets, enhance the role of fossil assets as contributors to grid stability and reliability, and provide the nation with a reliable fossil-based option by leveraging and extending ongoing energy storage technology development.

University Training and Research: University Training and Research supports two of the longest-running university training programs, the Historically Black Colleges and Universities and Other Minority Institutions (HBCU-OMI) and the University Coal Research (UCR) programs, to support the education of students in the area of coal science. Both programs are promoted through research grants to U.S. colleges and universities that emphasize FECM strategic goals. These training programs were designed to increase the competitiveness of universities in fossil energy research and discoveries. The student-led research programs advance energy technologies and allow for expansion of energy production while simultaneously facilitating energy sector job growth.

SENSORS, CONTROLS, AND NOVEL CONCEPTS

The Sensors, Controls, and Novel Concepts program enables and enhances carbon management technologies ranging from hydrogen fuel production and power generation to post-combustion carbon capture. Crosscutting research optimizes sensor arrays, enabling the optimization of parameters such as temperature, pressure, fluid composition, and the state of materials. Researchers investigate a range of advanced manufacturing techniques (e.g., 3D printing) to determine the feasibility of embedding sensors coupled with condition-based monitoring algorithms to operate in extreme environments, helping anticipate maintenance needs and reducing plant downtime. The information apprises operators of component health and performance in real time. Robots, ranging from drones to crawlers, have transformed the inspection and repair of equipment for a wide variety of systems. These advances in remote inspection are improving performance, reliability, and economics for future energy infrastructure.

Controls research at NETL enables optimized performance under increased energy system complexity. Optimized controls will reduce emissions including carbon dioxide and methane while ensuring safe and efficient performance. Smart control systems enable an optimal balance between operational performance and reliability. Advanced controls will also manage complex interactions of hybrid power systems (featuring renewable generation, energy storage, carbon management, etc.) and other subsystems. These control technologies within integrated systems will help facilitate carbon emissions reductions.

Novel technologies are being developed to support energy applications that will prove essential to an equitable, clean energy future. These activities start with emergent technologies such as quantum sensors, visible light communications, and direct power extraction, move through technology maturation, and transition to the marketplace. These efforts are complemented with cybersecurity projects including blockchain and distributed ledger technology.

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

- Harsh Environment Sensors
- Advanced Controls and Cyber Physical Systems
- Novel Concepts

This research will aid in the achievement of DOE's goal to achieve net-zero carbon emissions in the energy sector by 2035 and a decarbonized wider economy by 2050.

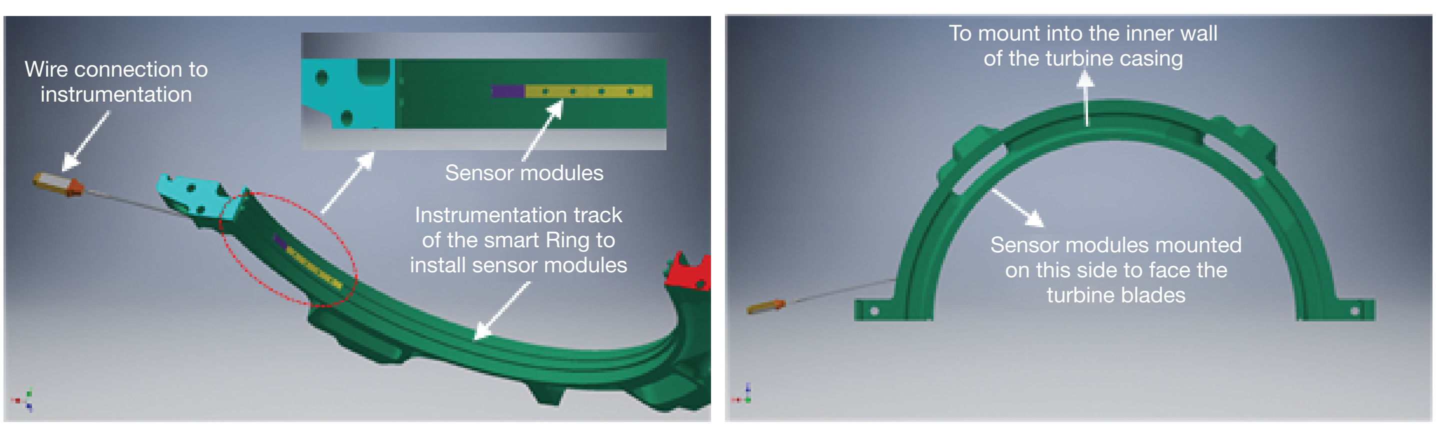
HARSH ENVIRONMENT SENSORS

Additive Manufacturing of Circumferentially Embedded Optical Sensor Modules for In Situ Monitoring of Coal-Fueled Steam Turbines

Performer	**Clemson University**
Award Number	FE0031826
Project Duration	01/01/2020 – 12/31/2022
Total Project Value	$ 1,250,000
Collaborator	General Electric
Technology Area	Plant Optimization Technologies

The main objective of this project is to design, develop, additively manufacture, test, and validate three types (temperature, pressure, and blade tip timing/clearance) of optical sensor modules for in situ monitoring of the critical operational parameters in coal-fueled steam turbines. These sensor modules will be embedded into the Smart Ring (recently invented and patented by GE) and installed circumferentially and flush into the inner wall of the turbine casing for condition-based monitoring and control and maintenance scheduling. The optical sensor modules will be optimally designed based on simulations, and additively manufactured using the novel Integrated Additive and Subtractive Manufacturing (IASM) method developed at Clemson University. The sensor-embedded Smart Ring will be tested and validated under laboratory-simulated conditions as well as demonstrated in industrial-scale turbine testing rigs at GE's turbine testing facilities.

As power plant designs extend the limits of materials into higher temperature and pressure regimes in order to gain efficiency, turbine blade creep becomes a key issue. The sensors developed in this project will help to monitor blade creep and correlate it to operating conditions, thereby enabling condition-based control and maintenance scheduling and contributing to extended turbine lifetime.

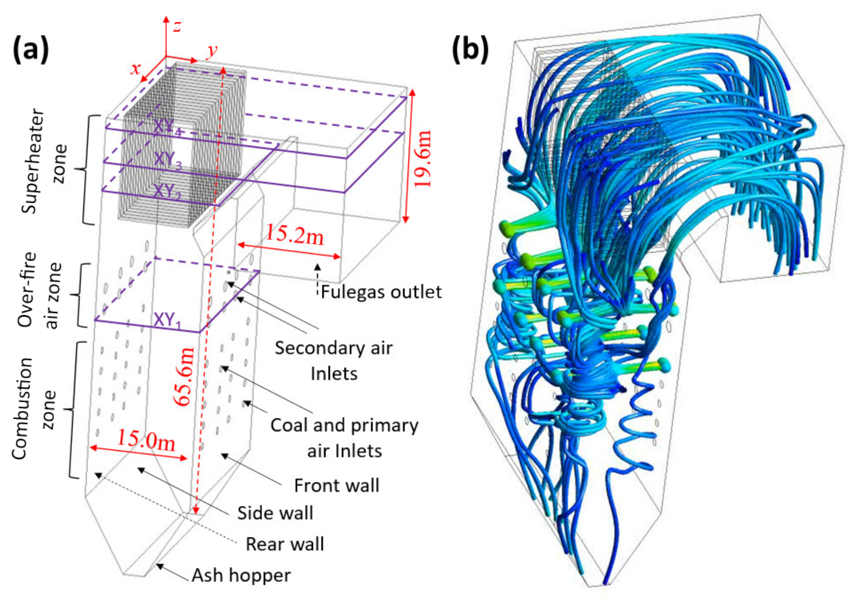


Prototype of field measurement optical system design.

Test and Validate Distributed Coaxial Cable Sensors for In Situ Condition Monitoring of Coal-Fired Boiler Tubes

Performer	**Clemson University**
Award Number	FE0031765
Project Duration	10/01/2019 – 03/31/2023
Total Project Value	$ 3,750,000
Technology Area	Plant Optimization Technologies

The objective of this project is to test, validate, and advance the technology readiness level (from TRL 5 to TRL 7) of a novel low-cost distributed stainless-steel/ceramic coaxial cable sensing (SSC-CCS) technology for in situ monitoring of the boiler tube temperature in existing coal-fired power plants. The novel SSC-CCS sensing technology and associated condition-based monitoring (CBM) software to be demonstrated in this project could lead to improved understanding of the boiler tube failure mechanisms and a prognostic system to improve the overall performance, reliability, and flexibility of the nation's coal-fired powerplant fleet. The new SSC-CCS sensing technology and the associated CBM package could provide the essential capability to enhance boiler reliability by predicting and preventing failures, maximizing the availability, improving generating capacity/flexibility, and saving on maintenance cost. The novel SSC-CCS sensors and instrumentation have the combined advantages of low-cost implementation, proven robustness, easy installation, and distributed monitoring capability to reduce overall deployment and operating cost. The project could have profound impacts on the general field of harsh environment sensing as it fosters a number of technological breakthroughs that may offer solutions to other sensing and control needs in existing and next-generation power and fuel systems. This technology could become an important enabling factor for the U.S. energy industry to achieve the challenging goals of enhanced efficiency, reduced emissions, and improved reliability.



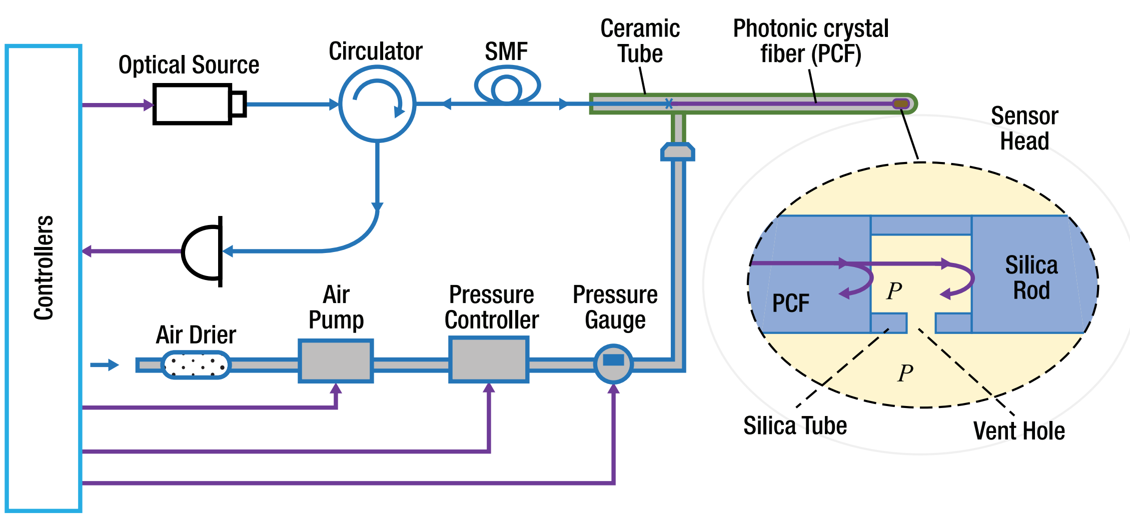
(a) CFD model of a coal fired boiler.
(b) CFD simulation result of the air flow inside the boiler.

High-Accuracy and High-Stability Fiber-Optic Temperature Sensors for Coal Fired Advanced Energy Systems

Performer	**Michigan State University**
Award Number	FE0031899
Project Duration	09/01/2020 – 08/31/2023
Total Project Value	$ 496,475
Technology Area	University Training and Research

The objective of this project is to develop a revolutionary gas-based fiber-optic temperature sensor technology with the required accuracy and long-term stability for temperature control and condition monitoring of the next generation of coal-fired power systems. The temperature sensor technology is based on a Fabry-Perot (FP) cavity filled with a gas (e.g., air) the pressure of which can be changed. An FP cavity is formed by a silica tube that is filled with air and sandwiched between a side-hole fiber and a capping fiber. The holey fiber has air channels in its cladding running along the length of the fiber through which the air pressure in the FP cavity can be tuned. The light coming from the holey fiber is partially reflected at the two fiber/tube interfaces and coupled back into the holey fiber. The system then measures the reflection spectrum which contains the interference fringes of the FP cavity by a white-light source, a fiber-optic coupler, and a spectrometer.

Accurately controlling the temperature is critical for the reliable and efficient operation of future highly efficient coal-fired energy systems. An accurate temperature sensor with long-term operating reliability is key for temperature control. Temperature is also a critical parameter for condition monitoring and lifetime prediction of energy systems. However, the extreme conditions present in advanced energy systems often lead to accelerated degradation in the performance and lifetime of current sensors. Most sensors used today show unacceptable drift and require frequent calibration or replacement, often leading to costly power plant shut down. The movement toward advanced energy systems requires that new temperature sensors be developed which can maintain accuracy and long-term stability comparable to or even better than low-temperature sensors over extended periods of operation under extreme conditions.



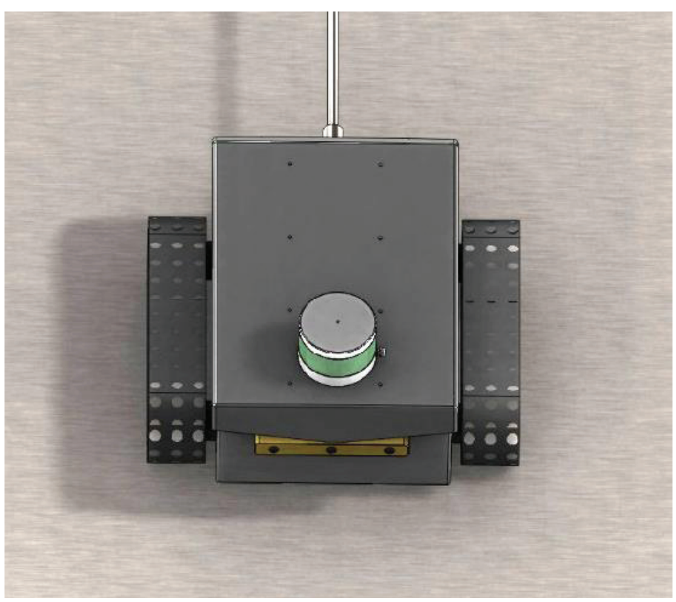
Developed a temperature sensor system that can operate at a temperature level above 1000 °C with accuracy and long-term stability comparable to the sensors of low-temperature version.

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

Performer	**Colorado School of Mines**
Award Number	FE0031650
Project Duration	09/01/2018 – 08/31/2022
Total Project Value	$ 473,972
Collaborator	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	09/01/2018 – 05/31/2022
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.

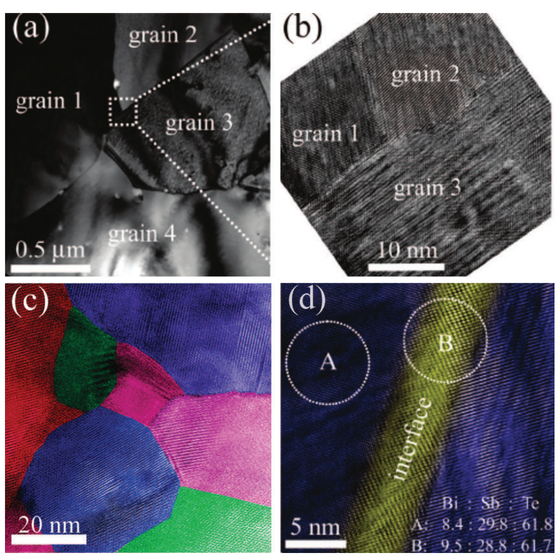
3- and 4-inch pneumatic pipe crawler developed at Florida International University.

Ceramic-Based Ultra-High Temperature Thermocouples in Harsh Environments

Performer	**Morgan State University**
Award Number	FE0031906
Project Duration	08/01/2020 – 07/31/2023
Total Project Value	$ 500,000
Technology Area	Plant Optimization Technologies

Researchers will develop novel, durable, low-cost ceramic-based super-high-temperature thermocouples (up to 2000 °C) for use in high-temperature (750–1800 °C) and 1000 psi and above coal-based energy systems under high corrosion and erosion conditions. The materials, zirconium diboride (ZrB_2) and samarium hexaboride (SmB_6) thermoelectric refractory materials, will be employed as n- and p-type thermocouple legs. The materials will be compacted into isotropic thermoelectric nanocomposites as thermocouple legs with excellent Seebeck coefficient. The legs will be fabricated into ceramic-based thermocouples with p-n junctions. The thermocouples will also have good oxidization and sulfidization resistance, require no protective outer layer, and cost less than acoustic and optical devices. Thermocouple performance will be evaluated in oxygen, carbon oxides, and sulfide atmospheres at high pressure and temperature. In addition, the effects of heat flow, flow rate, and mass flux found in coal power generation on the performance of the thermocouples will be investigated. Physical behaviors and long-term stability will be evaluated.

Accurate and reliable temperature measurements and controls are essential to operating coal-based energy systems at high efficiency and optimal performance. However, present thermosensors, utilizing expensive acoustic and optical techniques, usually do not work well under such harsh conditions. Development and application of new kinds of thermocouples are essential elements for low-cost maintenance and long-term stable thermo-sensing devices. The proposed ceramic-based super-high-temperature thermocouples will lead to the development of low-cost thermosensors and significant reduction in maintenance costs.



TEM images of ball-milled/hot-pressed p-type (Bi, Sb)$_2$Te$_3$ nanocomposites.
(a) BF-TEM at low magnification. (b-c) HRTEM of nanograins. (d) HRTEM of a grain boundary.

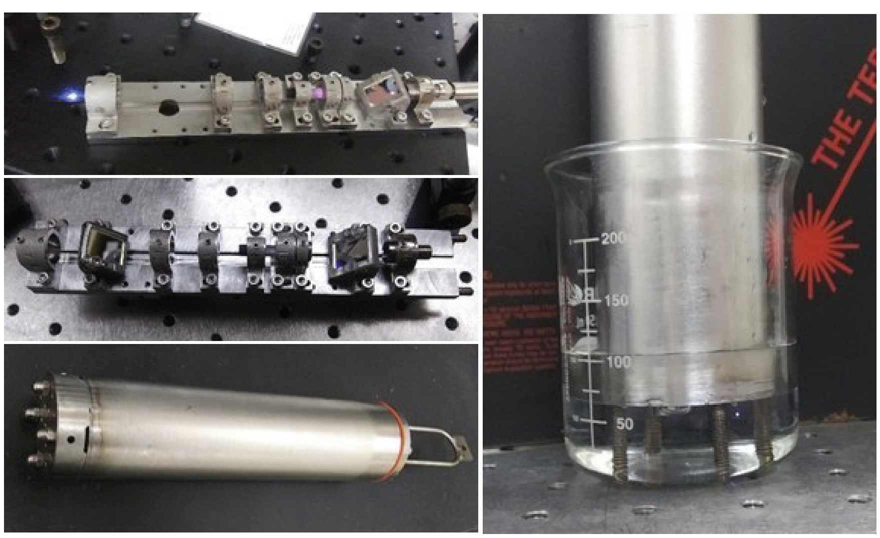
Development of LIBS for Specialized Fossil Energy Applications

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 Advanced Sensors and Controls – Task 71
Project Duration	04/01/2021 – 03/31/2022
Total Project Value	$ 230,000
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 prototype field systems for use in the subterranean environment as well as power plant process environments. The technology development challenges are centered around the optimal application of LIBS 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 be suitable to the application environment and provide enough signal in relation to noise for accurate measurement.

Experimentation with brines relevant to subterranean conditions has indicated that presence of sodium chloride enhances the spectral emission of other atomic constituents within pressurized brine, and the concentration of carbon dioxide affects the concentrations of minerals dissolved in the brine. A pressure vessel with optical accessibility capable of operations up to 6000 pounds per square inch and 150 degrees Celsius provides conditions relevant to subterranean carbon dioxide storage to study the spectroscopic behavior.

A miniaturized prototype downhole LIBS probe, fiber-coupled to the pump laser and spectrometer, was constructed and field tested. The probe is lowered into the well to below the water level to allow in situ measurements of various elements in the groundwater. Through the optical fiber cable connection, the expensive and bulky parts of the system are kept safely at the surface near the well. In the initial field testing, 3 weeks of data collection were performed for five analytes present downhole. This effort provides a step forward in technical readiness of the technology, and the operating experience will be used to improve the system prior to off-site field testing.



Prototype LIBS subsurface probe. The LIBS spark is visible in operational test in air (top left) and the smaller spark in water (right). Prototype of field measurement optical system design.

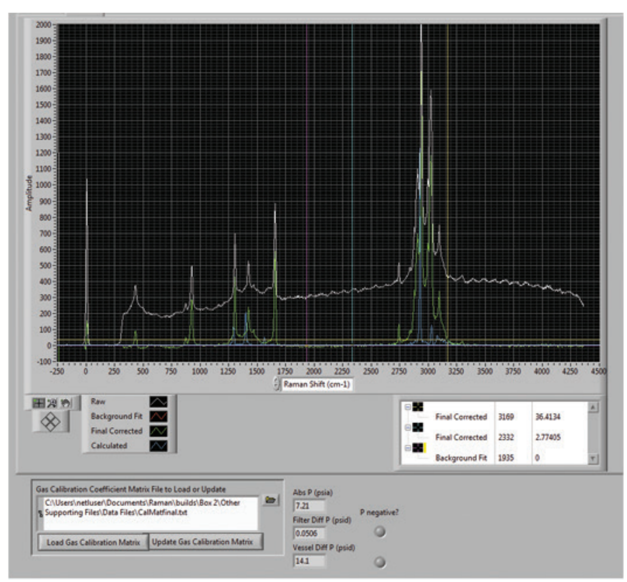
Field Testing of Raman Gas Analyzer

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 Advanced Sensors and Controls - Task 41
Project Duration	04/01/2020 – 03/31/2022
Total Project Value	$ 133,000
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 and improvement of the NETL-developed Raman gas analyzer (RGA), a next-generation technology for real-time composition analysis of fuel gases and other process gases. The RGA measures concentration of hydrogen, methane, ethane, and propane, as well as other common industrial gases (CO, CO_2, N_2, O_2, H_2O). It provides a new enabling technology for faster, smarter process control based on the chemical composition of the gases in the process, including improved fuel flexibility and efficiency for power generation systems.

The RGA applies Raman spectroscopy, a laboratory technique for non-destructive material analysis which has had great success previously with liquids and solids, 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; that 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. Test experience will also be used to improve the RGA to better meet the needs of end-use applications.

Raman gas analyzer field prototype.



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

Optical Fiber Sensors for Harsh Fossil Energy Environments

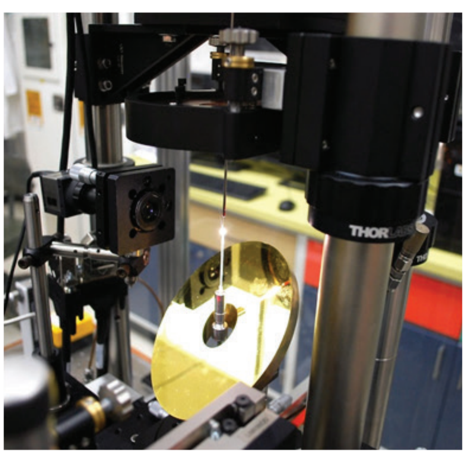
Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 - Advanced Sensors and Controls - Task 21-33
Project Duration	04/01/2020 – 03/31/2022
Total Project Value	$ 655,000
Technology Area	Plant Optimization Technologies

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 along a single optical fiber 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.

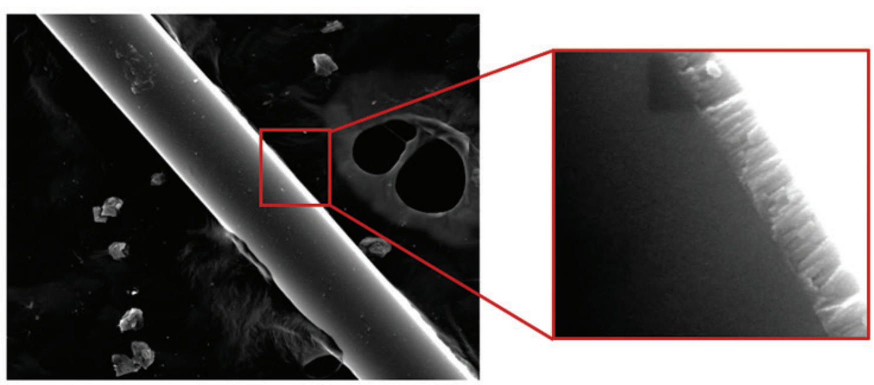
This project is pursuing technology solutions to several barriers to the widespread use of multipoint optical fiber sensors, for temperature, strain, and chemical measurements. NETL's laser-heated pedestal growth system is being utilized to refine the techniques needed to make high-temperature crystalline optical fibers (materials such as sapphire or garnet), and to develop a durable optical cladding. The optical cladding is needed to confine light within the optical fiber in many application environments.

Development of low-cost and durable optical cladding and distributed interrogation for sapphire optical fibers will allow such fibers to be used for sensing in very-high-temperature locations beyond the capability of silica fiber, such as boiler or turbine exhaust.

Development of high-temperature functional materials for sensing of oxygen will support applications in sensing and controlling excess air levels in combustion, and support development of SOFC through measurement of oxygen levels in the 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 help mature new technology toward commercial use.



Laser heated pedestal growth system.



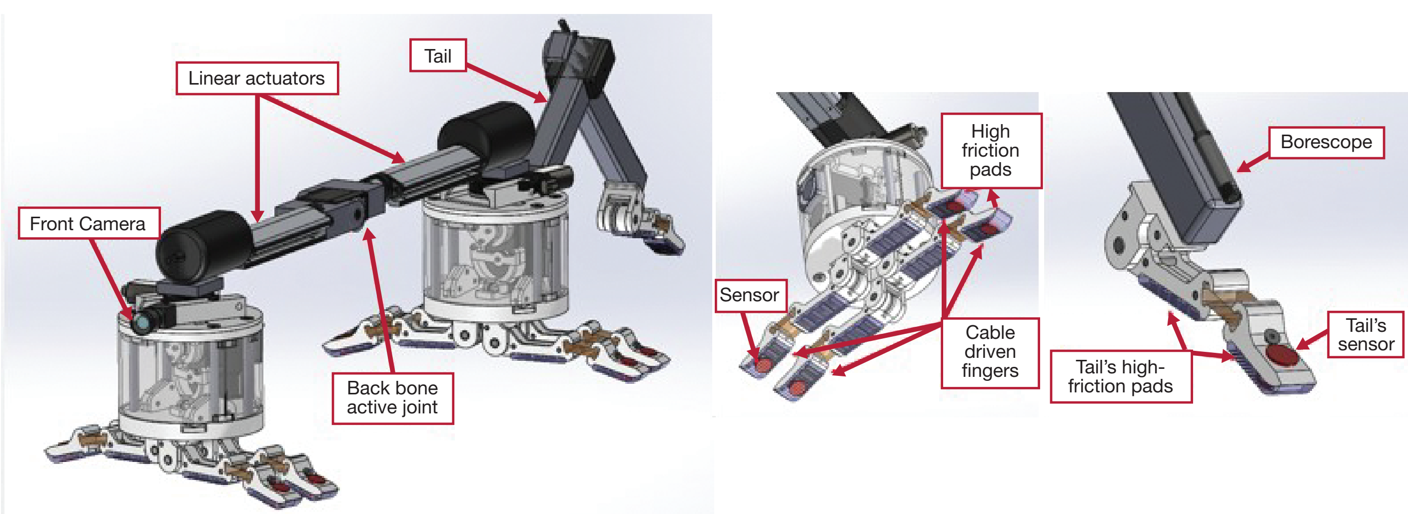
Functional thin films applied to optical fiber for gas sensing.

A Lizard-Inspired Tube Inspector (LTI) Robot

Performer	New Mexico State University
Award Number	FE0031649
Project Duration	09/01/2018 – 08/31/2022
Total Project Value	$ 400,000
Collaborator	Arizona State University
Technology Area	Plant Optimization Technologies

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.

The results of the current project may revolutionize 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 overhaul.



Conceptual design of the LTI robot.

Enabling the Next Generation of Smart Sensors in Coal Fired Power Plants Using Cellular 5G Technology

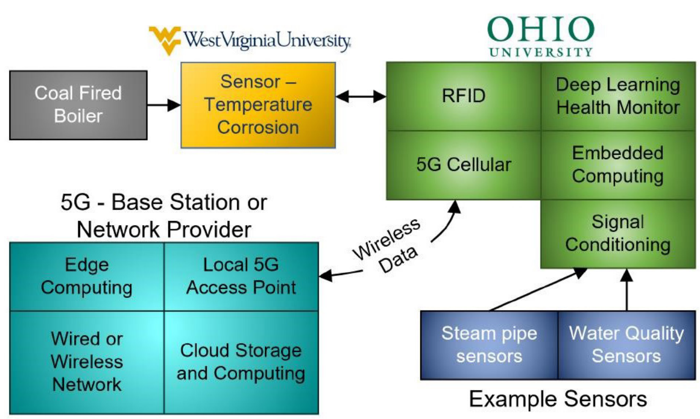
Performer	**Ohio University**
Award Number	FE0032078
Project Duration	08/16/2021 – 08/15/2024
Collaborator	West Virginia University (WVU)
Total Project Value	$ 414,481
Technology Area	University Training and Research

This project will build upon existing experience with cellular based systems, power plant water quality sensing, and high-temperature sensors developed during past projects. The main objective of this project is to demonstrate the effectiveness of 5G cellular embedded, cloud, and edge computing-based sensors specific to coal-fired power plant needs where harsh, noisy RF conditions are encountered. Sensors that utilize 5G for data communications are the first logical step in revolutionizing wireless connectivity that will enable robust operations in coal-fired power plants. Working together, Ohio University and WVU will focus on a high-priority in-situ boiler temperature measurement system that relies on chipless RFID technology and much-needed temperature, pressure, environmental, and water quality industrial sensors.

The specific project objectives are (1) investigate specific needs of interfacing and data collection of identified sensing areas of significance within coal-fired power plants that would immediately benefit from 5G wireless data communications, (2) enable 5G data communication for ‘peel-and-stick’ chipless RFID-based boiler temperature and corrosion sensors, (3) demonstrate effectiveness and performance of 5G enabled Internet-of-Things (IoT) sensors used in coal-fired power plants, (4) investigate sensor-driven deep learning/artificial intelligence using laboratory conditions that simulate power plants for system health monitoring, and (5) determine the limits of 5G systems in harsh environments–hot, humid, and cold.

The duty cycle style of power plant operation combined with a need to lower operating costs has left several components of coal-fired power plants vulnerable to unscheduled maintenance. More advanced, intelligent, inexpensive, and simple-to-install monitoring equipment based on wireless data transfers will support the current and future coal power plant needs. Right now, coal power plant operators could greatly benefit from retrofitting of existing sensors and additional sensor and control systems throughout. In addition, the intelligent health monitoring capabilities that occur at the sensor (embedded computing) or base station (edge computing) will give operators more prediction tools about scheduling maintenance.

Graduate students at both universities will be employed and trained on respective technologies and will cross-collaborate to exchange information and gather laboratory results.



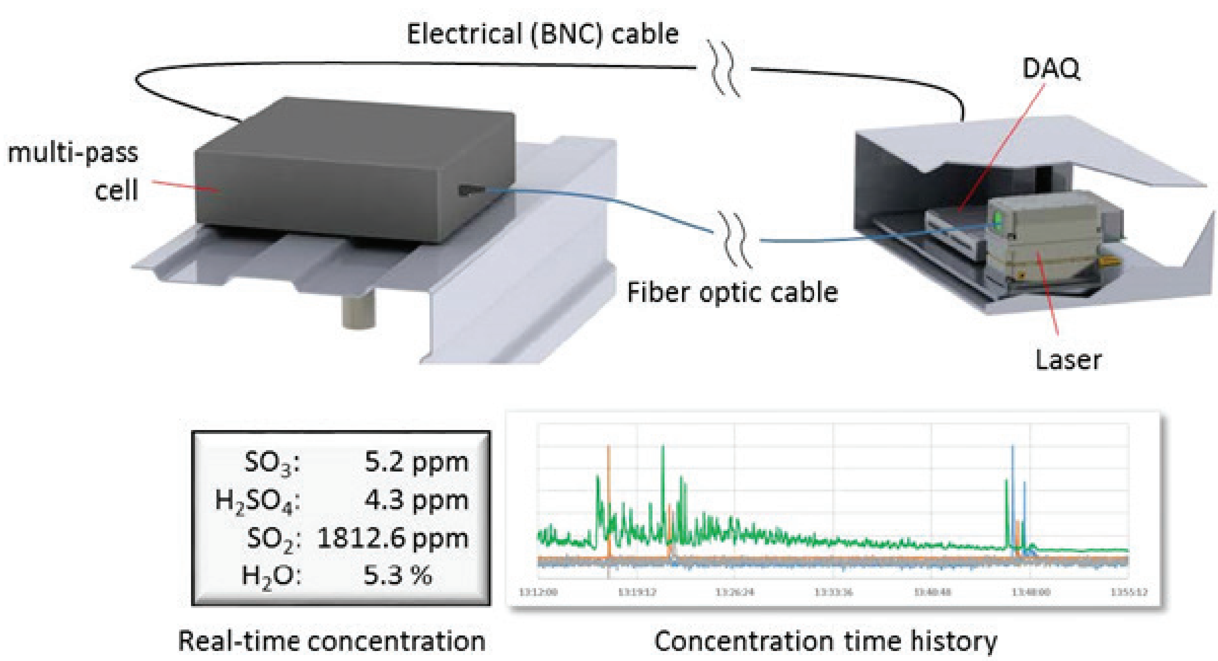
Proposed system integration – identifying contributions.

Mid Infra-Red Laser Sensor for Continuous Sulfur Trioxide Monitoring to improve Coal-Fired Power Plant Performance During Flexible Operations

Performer	**Opto-Knowledge Systems, Inc.**
Award Number	FE0031560
Project Duration	03/30/2018 – 01/31/2022
Total Project Value	$ 625,000
Technology Area	Plant Optimization Technologies

The primary objective of this project is to develop and demonstrate a continuous sulfur trioxide (SO_3) monitoring system for coal-fired power plants—validated in an operational environment—which will provide real-time, actionable information to enable control of additive injection and minimize catalyst deactivation. Currently, without a reliable SO_3 measurement, utilities over-inject alkali to ensure mitigation of a blue plume. The system will utilize the sensitivity, specificity, and real-time capabilities of mid-infrared laser-based sensor technology, along with a close-coupled cell mounted directly to the pollution control duct of a coal-fired power plant. The effort will consist of two rounds of prototype development and field testing at an operating coal-fired power plant. The project is a collaboration among team members for synergistic development and testing of sensor technologies.

A sensor that can make continuous, accurate measurements of SO_3 in coal-fired power plants will provide the information needed to better control the alkali injection systems used to mitigate SO_3, leading to cost savings. In addition, low-load operation would benefit from an online SO_3 measurement, thereby minimizing catalyst deactivation and improving plant capability for flexible operation.



Simple diagram illustrating concept.

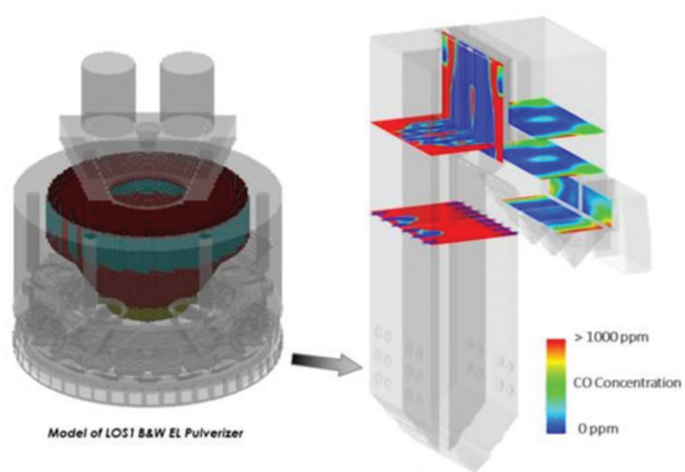
Combustion Performance and Emissions Optimization Through Integration of a Miniaturized High-Temperature Multi Process Monitoring System

Performer	**Reaction Engineering International**
Award Number	FE0031680
Project Duration	10/01/2018 – 09/30/2022
Total Project Value	$ 777,347
Technology Area	Plant Optimization Technologies

The technical goal and objectives of this project will be achieved by designing and fabricating a miniaturized monitoring system, performing validation tests of the sensor system in a pilot-scale coal combustor, and then conducting a field test of the monitoring system in the high-temperature regions of a lignite-fired utility boiler for a sufficient duration to demonstrate the reliability and accuracy of the monitoring system. The design of the miniaturized monitoring system will build on technologies developed by the Recipient for larger, intrusive, probe-based systems. However, the probe-based systems were too large and expensive to be commercially viable for permanent, high-spatial-resolution installation inside a commercial-scale boiler.

The focus of this project will be (a) to miniaturize the sensor design so that it can be installed in a commercial scale lignite-fired boiler without the need for long shut-downs, and without the need to bend boiler tubes already installed in the boiler; (b) to re-design the signal conditioning unit to increased resolution, allowing for determination of localized electrochemical phenomena; (c) to implement the signal acquisition, signal processing, and communication modules onto a single electronic board to reduce cost, power consumption, and required cooling of the sensor package; (d) to use data from previous work to develop quantitative correlations for heat flux and deposition rate on the sensor surface for a lignite-fired unit and validate in pilot-scale tests; (e) to validate the heat flux and ash deposition rate models in a pilot-scale coal combustor and demonstrate the effectiveness of the sensor system in a full-scale lignite-fired utility plant; and (f) to develop logic algorithms that can be implemented into a plant distributed control system (DCS) to improve boiler energy efficiency and reduce NO_X emissions while mitigating waterwall corrosion by automating control of boiler operations including soot-blowing and air flow control.

The miniaturized multi-process monitoring system developed by this work can be used by electric utilities, boiler OEMs, equipment suppliers, design firms, software vendors, consultants, and government agencies to assess boiler operation status and provide boiler data that the advanced control system can utilize for plant performance optimization.



LOS1 Radiant Furnace and Convective Section Model.

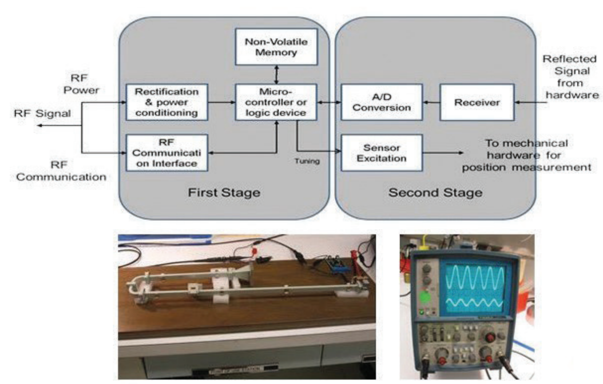
Embedded Sensors Integrated into Critical Components for In Situ Health Monitoring of Steam Turbines

Performer	Siemens Corporation
Award Number	FE0031832
Project Duration	10/15/2019 – 09/30/2022
Total Project Value	$ 1,249,898
Collaborator	United Technologies Research Center
Technology Area	Plant Optimization Technologies

Siemens, in partnership with United Technologies Corporation, proposes a holistic approach to develop embedded sensors to utilize radio frequency for not only coupling to sensors, but as the sensing modality. The goal of this project is to embed the novel sensing approach by using either additively manufactured or extruded waveguides that integrate the communications/sensing network on rotating blades for recording, evaluation, and monitoring of blade vibrations in low-pressure turbines, with applications extending to aeronautical engines.

This project (1) takes a holistic approach of integrating sensing, communication, and power into an otherwise electrically passive structural component without degrading either its functionality or lifetime and (2) renders a path for monitoring conditions inside a steam turbine with limited space, and attachment and routing constraints. The demonstration of sensor performance and acceptable materials interaction with sensor embedding (e.g., interfacing, adequate sensor lifetimes, thermal cycling durability, etc.) can show a tenfold or greater improvement in data bandwidth, communication, and power transfer and a path to engine demonstration within two years. With the current intrusive blade monitoring approach involving the need to magnetize the blade and calculate the vibration amplitude and tip timing, the proposed system will transmit real-time, blade-specific data from the turbine blade, enabling a transition to lower-cost, condition-based maintenance to detect failures and precursors to failure that require maintenance.

A successful sensor could lead to cost reduction, reduced outage time, and increased availability of steam turbine equipment in existing coal-based plants. The primary cost savings come from the potential to extend periods of operation between required maintenance downtime. In a combined cycle configuration, this extension of operations could be from 50,000 to 66,000 equivalent operating hours. In the longer term, this product may allow even longer operating times, but this ability will be determined after much stronger correlations from condition monitoring and inspection findings are established. This wireless transmission technology could potentially save power plants up to $1 million per turbine annually simply by eliminating unplanned downtime associated with the lead time on replacement parts. Another significant cost savings realized by this technology is the reduced validation costs of new engine designs. In order to validate new blade and engine designs, blade data are needed. With this new wireless multifunctional radio frequency sensing technology embedded on the blade, drilling of casings eventually can be avoided altogether. Also, severe consequences and monetary damages (in one example, up to $450 million in claim settlements occurred in an event involving a nuclear steam turbine) can be avoided by early indication of crack size that causes blades to separate.



New class of RF sensors: position, velocity, acceleration, pressure, vibration, temperature, etc.

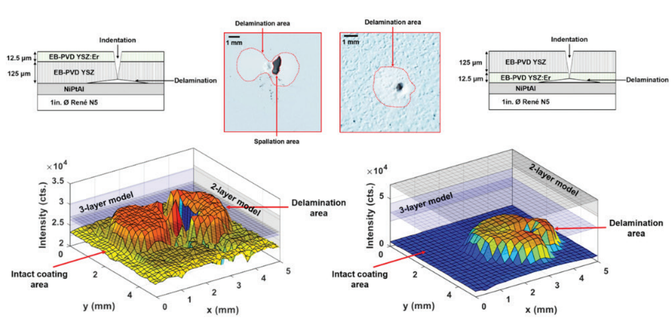
In-Situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments

Performer	University of Central Florida
Award Number	FE0031282
Project Duration	10/01/2017 – 05/31/2022
Total Project Value	$ 1,059,111
Collaborator	Siemens Energy
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 (UCF) has been using 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 properties have been accompanied by research efforts to correlate optical measurements to TBC diagnostic parameters. This capability was demonstrated through the beneficial development of new coating delamination monitoring methods, materials, and models and shown in Figure 1. The methods are being established in this project at the laboratory scale with the goal of future implementation in gas turbine conditions for improved engine efficiency and gas turbine blade lifetime.

UCF has focused on the development of an advanced phosphor thermometry instrumentation (Figure 2) that has shown higher precision and extended temperature range capabilities (the range of temperature that can be accurately measured using rare-earth doped yttria-stabilized zirconia configurations was extended up to gas turbine engine operating temperatures). This was achieved capturing simultaneously the decays and the intensity variations of a TBC system including two phosphors. The results open the way for the applicability of portable phosphor thermometry instrumentation to perform effective temperature monitoring on turbine engine materials and support the advancement of innovative sensing coatings.

This work provides a better understanding of temperature measurement locations in rare-earth doped TBCs. Using the project findings, doped TBC configurations represent a very attractive solution for precise in-situ temperature measurements and damage quantification. Current efforts in the project include the further characterization of thermomechanical properties of sensing coatings with the advanced instrumentation and benchmarked measurements.



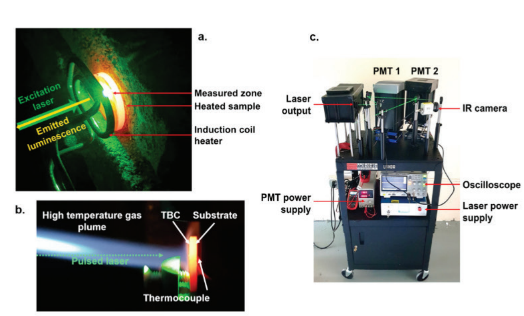


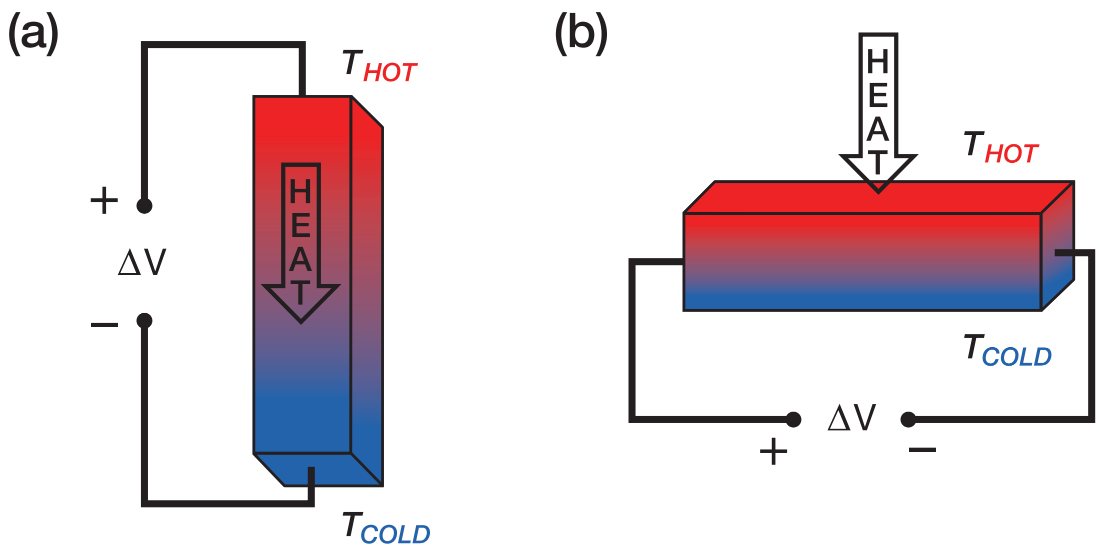
Figure 1 (left): Developed coating delamination monitoring methods, demonstrated using two sensing TBC configurations. [1]. Figure 2 (right): Lab-scale test setup configurations with (a) induction system [3] and (b) burner rig [5]. (c) Laboratory-scale instrumentation developed for the demonstration of in-situ luminescence sensing under typical gas turbine engine temperatures [3].

Robust Heat-Flux Sensors for Coal-Fired Boiler Extreme Environments

Performer	**University of Maryland**
Award Number	FE0031902
Project Duration	01/01/2021 – 12/31/2023
Total Project Value	$ 500,000
Technology Area	Plant Optimization Technologies

Researchers will develop robust heat flux sensor elements, based on the wire-wound Schmidt Boelter gauge architecture and the transverse Seebeck effect, capable of operating in the challenging high-temperature, corrosive environments within the boilers of coal-fired power plants. The heat-flux sensors will utilize thermoelectric effects to directly transduce the heat-flux input to analog electrical voltage signals, will be constructed from dedicated materials that can withstand oxidative atmospheres at temperatures from 700 to 1200 °C, and will maintain adequate performance under these conditions for prolonged periods. Rigorous testing and calibration protocols in furnaces and medium-scale fire research facilities will be employed to understand the significance and reliability of the output signal under a range of dynamic environmental conditions. These conditions will include a range of heat-flux values, temperatures, surface emissivity, cooling rates, flow rates, and concentrations of carbon particulates.

If successful, the project will help extend the power industry's real-time heat-flux sensing capabilities to a challenging regime of extreme environments, offering new opportunities to understand the mechanisms by which operational parameters affect the power generation efficiency. Furthermore, adverse effects of overheating, uneven burner operation and deposition of soot and slag can be detected and remediated before experiencing irreversible damages that could lead to shutdown.

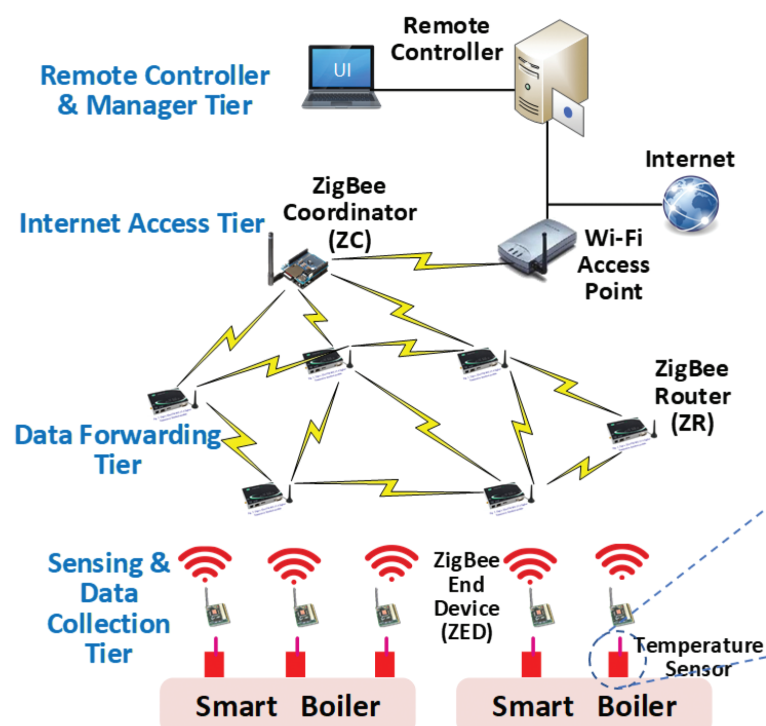


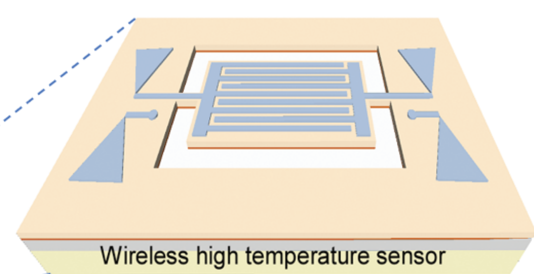
(a) Schematic of the Seebeck effect. (b) Schematic of the transverse Seebeck effect.

Wireless High Temperature Sensor Network for Boiler Systems

Performer	**University of Massachusetts**
Award Number	FE0031895
Project Duration	09/04/2020 – 09/03/2023
Total Project Value	$ 499,958
Technology Area	University Training and Research

This project aims to develop a new wireless high-temperature sensor network for real-time continuous boiler condition monitoring in harsh environments. The wireless high-temperature sensor network consists of wireless radio frequency (RF) high-temperature sensors with integrated attached antennas for wireless internet-based continuous remote monitoring. Each of the new RF high-temperature sensors is based on a high-quality-factor RF filter fabricated on 4H silicon carbide semiconductor material capable of measuring high temperatures over 1,800 °C. The integrated antennas are broadband bow-tie RF antennas that can provide efficient signal transmission and reception. The wireless sensor network enables real-time and continuous monitoring of boiler conditions to achieve smart boiler system management. The high-temperature sensor network enables network-based automatic temperature sensing and data collection, which combined with artificial intelligence algorithms allow the construction of smart boiler systems with boiler condition management and optimization for significant energy savings and reliability improvements. The research will also train graduate students in the critical technology areas of high-temperature materials, advanced manufacturing of integrated RF sensors, wireless sensor network communication, cloud computing with high security, and AI-enabled smart systems.





Schematic architecture of the smart boiler wireless sensor network. Each wireless high-temperature sensor is coupled with a ZigBee end device (ZED) to collect and continuously transmit the boiler temperature data in real time. The temperature data will be routed to the remote controller through the wireless mesh network and the internet as well as Wi-Fi access points. Inset: schematic structure of the wireless high-temperature sensor in boilers. It is based on a Lamb RF filter with integrated broadband bow-tie antennas for wireless temperature transfer.

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

Performer	**University of Missouri**
Award Number	FE0031645
Project Duration	09/01/2018 – 12/31/2021
Total Project Value	$ 410,864
Technology Area	University Training and Research

University of Missouri researchers developed a robotics-enabled eddy current testing (ECT) system for autonomous inspection of heat exchanger tubes. The system is 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 are 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 are controlled for fast and more consistent scanning during testing. A convolutional neural network was developed to enable autonomous inspection via a feedback loop, which is 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 could 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 could enable deep mining of historical data for in-situ analysis and real-time decision making.

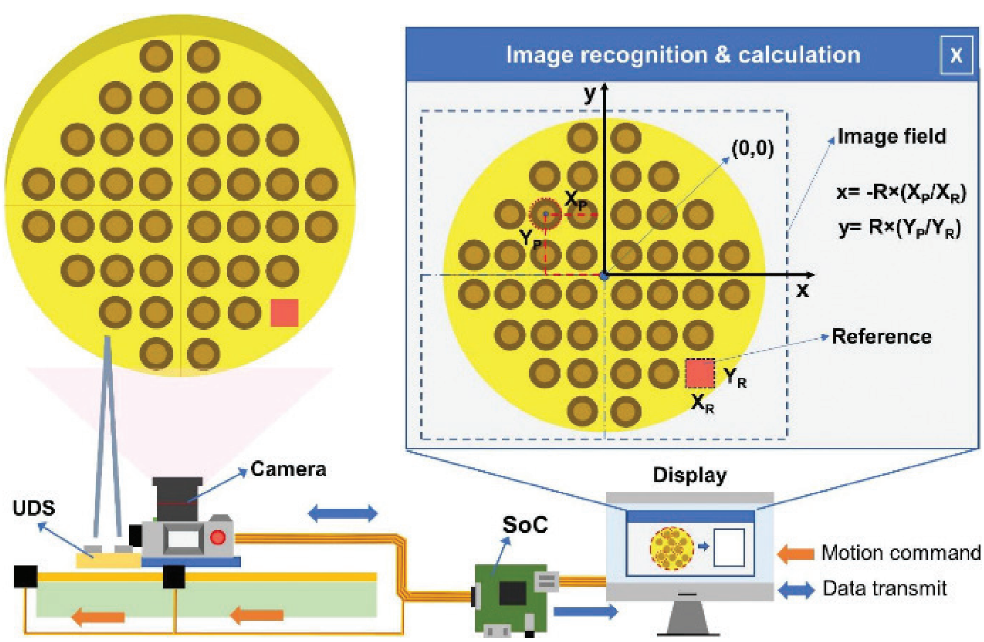


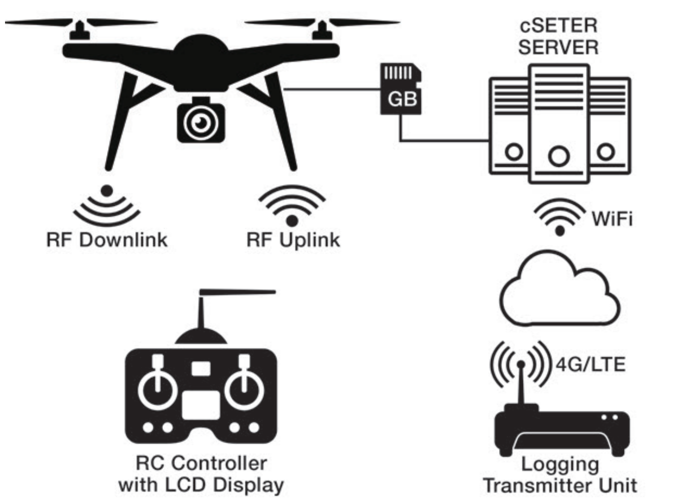
Image processing steps for recognizing geometry and location of tubes' inlets.

Autonomous Aerial Power Plant Inspection in GPS-Denied Environments

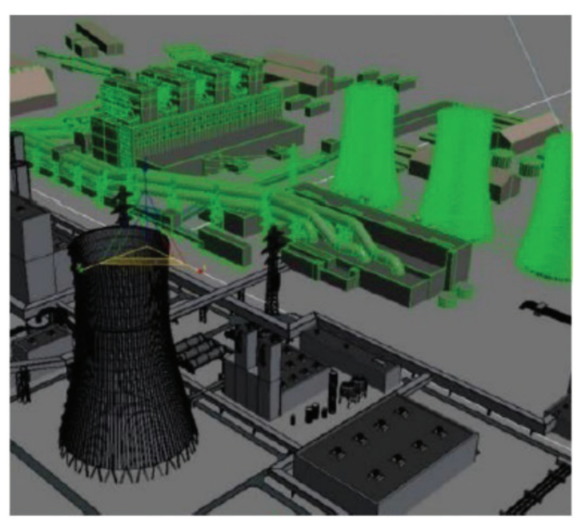
Performer	**University of Texas at El Paso**
Award Number	FE0031655
Project Duration	09/01/2018 – 05/31/2022
Total Project Value	$ 400,000
Collaborator	Southern Research
Technology Area	University Training and Research

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).*

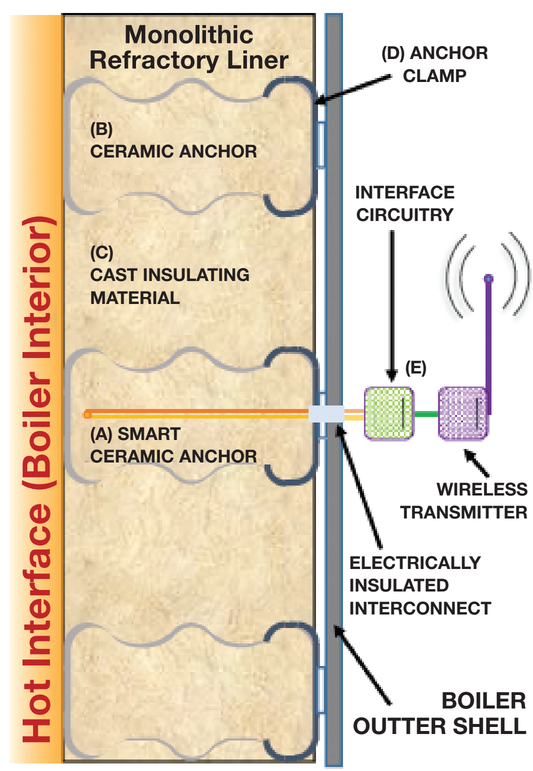
Advanced Manufacturing of Ceramic Anchors with Embedded Sensors for Process and Health Monitoring of Coal Boilers

Performer	**West Virginia University**
Award Number	FE0031825
Project Duration	01/01/2020 – 12/31/2022
Total Project Value	$ 1,254,719
Technology Area	Plant Optimization Technologies

West Virginia University Research Corporation will develop advanced manufacturing methods to fabricate and test ceramic anchors with embedded sensor technology for monitoring the health and processing conditions within pulverized coal and fluidized-bed combustion boiler systems. The goal is to place ceramic anchors within the boiler system (such as within the primary furnace and ash hopper) where information on the temperature, strain, and local crack population can be continuously monitored. The project will include the development of advanced manufacturing technologies and processes for 3D printing electroceramic (conductive ceramic) sensor designs within the ceramic anchor microstructure during the manufacturing process.

Specifically, the project team will (1) define the chemical and microstructural stability, in addition to the electrical properties, of oxide and non-oxide ceramic composites to be embedded within the $Al2O_3$-$Cr2O_3$ ceramic anchor compositions that can operate at temperatures up to 1400 degrees Celsius; (2) develop and implement the 3D printing technology to pattern and control the microstructure of the ceramic anchor and embedded sensor circuits; (3) develop an interconnect technology which will permit easy installation of the ceramic anchors and signal collection at the boiler shell; (4) develop low-power analog electronics and wireless communication hardware to efficiently collect the sensor signal at each processing unit and transmit data to a central hub for data analysis; and (5) demonstrate the smart ceramic anchor system for temperature and liner fracture within a high-temperature processing unit, such as a boiler furnace or glass melting furnace floor/wall liner.

Data collected can be used to monitor the boiler refractory liner temperature and degradation, information that currently is not available to boiler operators because no sensors are currently placed within or near the boiler furnace floor, and inserting access ports within this monolithic (seamless) refractory liner is not feasible.



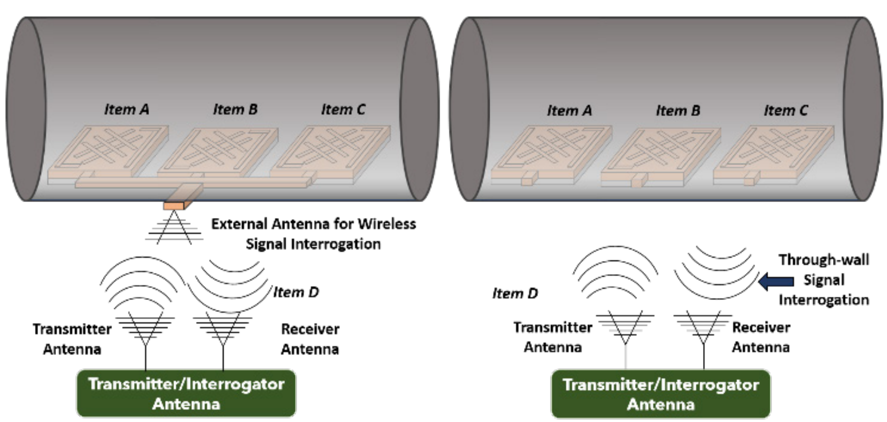
Schematic of boiler liner cross-section with smart anchors, metal interconnect clips/clamps, and low-power electronics.

Passive Wireless Sensors for Realtime Temperature and Corrosion Monitoring of Coal Boiler Components Under Flexible Operation

Performer	**West Virginia University Research Corporation**
Award Number	FE0031912
Project Duration	08/17/2020 – 08/16/2023
Total Project Value	$ 500,000
Technology Area	University Training and Research

This project will develop an inexpensive wireless high-temperature sensor for real-time monitoring of the temperature and corrosion of metal components that are commonly used in coal-fired boilers. This work will focus on the fabrication and testing of harsh-environment, chipless radio-frequency identification (RFID) sensors that will function between 25 °C and 1300 °C in high steam and/or combustion gas environments. Sensor arrays will also be evaluated where each RFID sensor will be designed with a specified frequency band to spatially differentiate the testing site on the metal specimen. Specifically, this project will (1) design passive wireless RFID patch and interrogator antennas for high-temperature sensing of temperature and corrosion/crack propagation at temperatures up to 1300 °C; (2) develop materials and methods to fabricate a microstrip patch antenna sensor composed of a robust conductive electroceramic pattern and interlayer ceramic coating, and then incorporate this sensor into "peel-and-stick" preforms that will efficiently transfer and bond to the metal specimens of interest; (3) investigate the wireless RFID sensor response in accelerated high-temperature and high-steam environments, and correlate corrosion and cracking mechanisms (and kinetics) with the response of the sensors; (4) investigate the wireless signal acquisition and processing of data transferred in various configurations by multiple sensors within the same environment and through-wall transmission of the signal by a single RFID sensor; and (5) investigate the passive wireless sensor system developed (and method of transferring the sensor system) for monitoring the temperature and health of metal components in service within a coal-fired power plant.

Applications for the passive wireless sensors are numerous within a coal boiler power plant, and these sensors will provide operators additional information over the current state-of-the-art temperature and corrosion sensors. An important strategy for managing cycling damage for flexible operation is through real-time monitoring of localized temperature and health of the various pipework, headers, rotors, and steam chests. This technology permits simplified monitoring of these components, which would greatly reduce the cost and provide valuable localized knowledge of thermal condition.



a. Schematic of the multi- sensor array deposited onto the inner wall of a metal pipe to monitor corrosion rates, where each sensor focuses on a specific band range read by an external interrogator antenna.

b. Schematic of the alternative interrogation method, where through-wall transmission will be tested in order to eliminate the need for an access hole.

ADVANCED CONTROLS AND CYBER PHYSICAL SYSTEMS

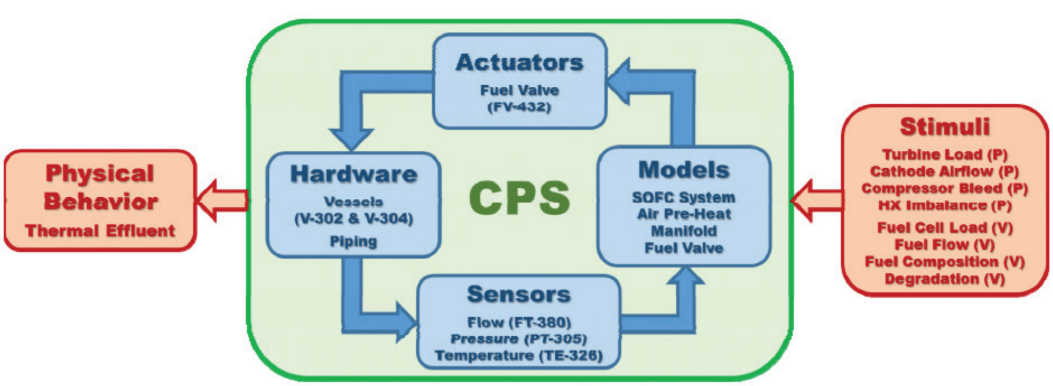
Sensors & Controls (Cyber-Physical Energy System Modeling)

Performer	**Ames National Laboratory**
Award Number	FWP-AL-20-450-023
Project Duration	10/1/2020 – 09/30/2023
Total Project Value	$ 900,000
Technology Area	Plant Optimization Technologies

The goal of this research is to codify the cyber-physical modeling approach developed under the NETL Hybrid Performance (HYPER) project to create an extensible cyber-physical modeling approach to complex energy system development that is industry facing and addresses the needs of industry stakeholders. While cyber-physical systems are becoming increasingly common, today there is no detailed understanding of how to create a model of a component or system using a cyber-physical strategy. Indeed, insofar as is known from the literature, there have been few efforts to integrate computation and hardware in cyber-physical models of energy system components, and none that have generalized the development of cyber-physical models. Rather, the development of cyber-physical models is today limited to ad-hoc efforts.

This research program is focused on filling this gap in our knowledge. Specifically, we are seeking to extend our current knowledge based on the HYPER project to advance Office of Fossil Energy and Carbon Management (FECM) technology development and complement traditional experimental, pilot plant, and device system models. As cyber-physical components are integrated together with other hardware components to create a bench-scale or laboratory-scale cyber-physical systems model, this will create (1) bundled modeling and testing that is moving toward a digital-twinned set of components, (2) a heavily instrumented cyber-physical bench-scale or laboratory-scale model, and (3) a systems model coupled to the cyber-physical system model. With these elements in place, the extensible cyber-physical modeling approach can be developed, refined, and simultaneously studied within the energy system in which it will be deployed and can be readily integrated with other FECM technologies. This will enable increasingly complex systems challenges to be addressed with the goal of co-designing and co-optimizing the concept and energy system—that is, creating a discovery–application feedback loop in which all concerns are addressed simultaneously.

The readily adaptive nature and lower cost of cyber-physical models relative to fully realized physical components enables greater exploration of the design and integration challenges and reduces the need for early lock-in of the concept-to-deployment process. As a result, in a cyber-physical design paradigm, energy system design is a continuum of research, development, and design that reduces uncertainty and risk while reducing the time required for realization of the energy system. This will provide more opportunities for FECM technologies to be explored and implemented within industry.



Deep Analysis Net with Causal Embedding for Coal Fired Power Plant Fault Detection and Diagnosis

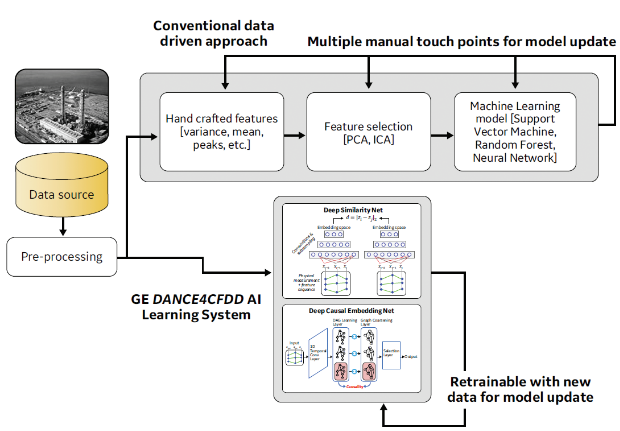
Performer	**General Electric (GE) Company**
Award Number	FE0031763
Project Duration	09/01/2019 – 11/30/2021
Total Project Value	$ 2,499,796
Collaborator	Electric Power Research Institute, Inc.; Southern Company Services, Inc.
Technology Area	Plant Optimization Technologies

GE Research, in collaboration with Electric Power Research Institute (EPRI) and Southern Company Services Inc., is developing a novel end-to-end trainable artificial intelligence (AI)-based multivariate time series learning system for flexible and scalable coal power plant fault detection and root cause analysis (i.e., diagnosis) known as Deep Analysis Net with Causal Embedding for Coal-fired power plant Fault Detection and Diagnosis (DANCE4CFDD).

The objective of the proposed program is to develop the DANCE4CFDD AI learning system and bring the technology maturity from TRL 2 to TRL 5, with final validation performed based on data from a coal-fired power plant. DANCE4CFDD aims to address a range of challenges faced by today's asset health management system for coal-fired power plants: high-dimensional nonlinear interaction among multiple time series measurements; (2) high measurement variance induced by operational conditions/modes; (3) variation among asset types and plant configurations; and (4) a small number of faulty events to learn from. DANCE4CFDD aims to address these real-world challenges with a combination of two novel components: a deep similarity net and a deep causal embedding net.

At the end of this program, the validated DANCE4CFDD AI learning system is expected to produce the following benefits:

- State-of-the-art accuracy.
- Applicability to a broad range of asset types and plant configurations for improving coal-fired power plant reliability.
- Learnability with even a small number of faulty events from plant data, addressing a major real-world challenge.
- High scalability—reduce development time by 50 percent by eliminating the need for manual and time-consuming domain expert feature engineering.
- A foundation for sustainable AI model life cycle updating due to its end-to-end trainability.



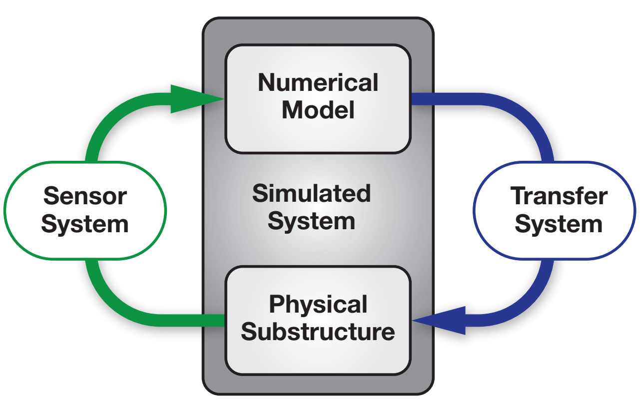
DANCE4CFDD AI learning system approach compared to conventional approach.

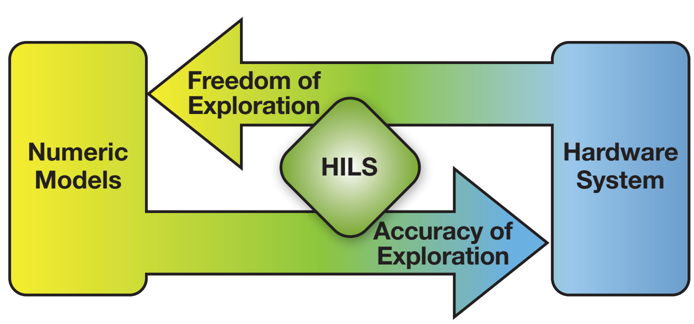
Expedited Real Time Processing for the NETL Hyper Cyber-Physical System

Performer	**Georgia Tech Research Corporation**
Award Number	FE0030600
Project Duration	08/01/2017 – 07/31/2022
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.

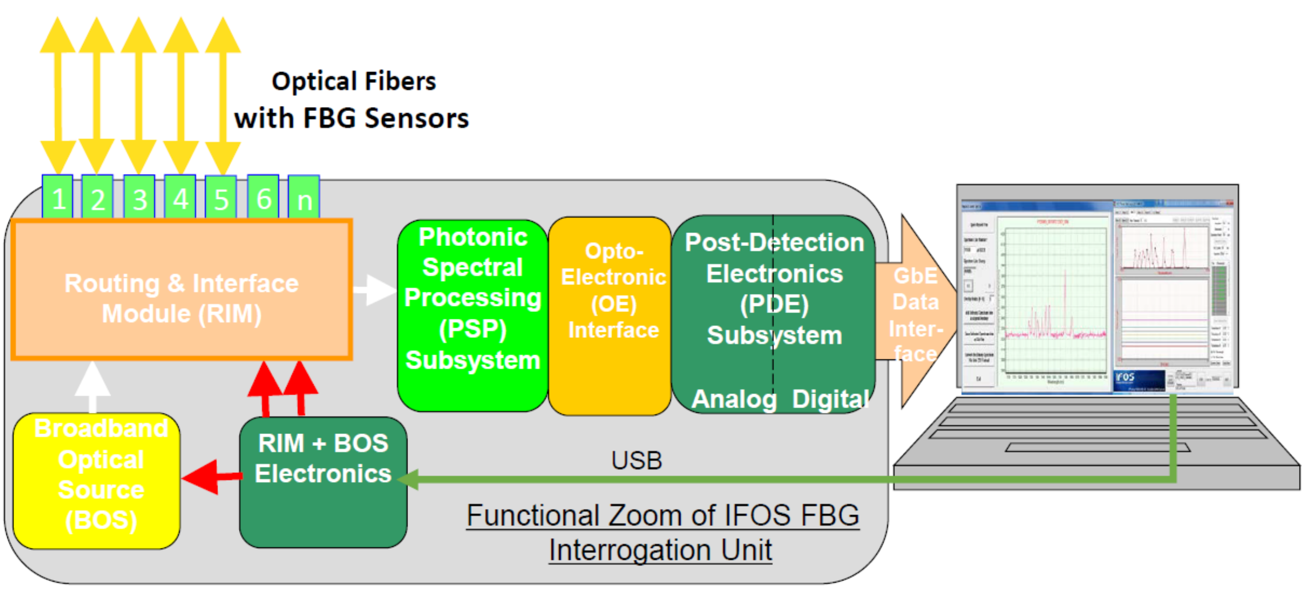
Embedded Multiplexed Fiber-Optic Sensing for Turbine Control and Prognostic and Health Management

Performer	**Intelligent Fiber Optic Systems Corporation**
Award Number	SC0018576
Project Duration	04/09/2018 – 11/25/2021
Total Project Value	$ 1,149,885
Technology Area	Plant Optimization Technologies

Intelligent Fiber Optic Systems Corporation (IFOS) developed an innovative, embedded-sensor-enabled control approach for industrial gas turbines. The IFOS concept leverages advanced existing fiber-optic sensing technology including ultra-thin, sub-50 mm diameter fibers. IFOS's approach could enable measurement of turbine blade temperature and stress parameters that are closer to the harshest of turbine environments and use this information to augment existing control schemes to decrease margins and thereby increase system efficiency. Conventional electronic sensors are relatively bulky and require multiple lead wires.

Few sensors have been able to be deployed on production turbines. In IFOS's approach, however, there are no 'active' components on the turbine blade or shaft—all optical signal processing and post-detection electronics are situated on stationary components in a relatively benign environment, removing the need for ultra-high-temperature electronics.

Fiber optic sensors can provide multipoint measurements of temperature, heat flux, dynamic strain, pressure, and recession, and are immune from electromagnetic interference. Silica fibers allow sensing to approximately 1000 °C, and sapphire fibers to over 1800 °C.



IFOS I*Sense Interrogation System.

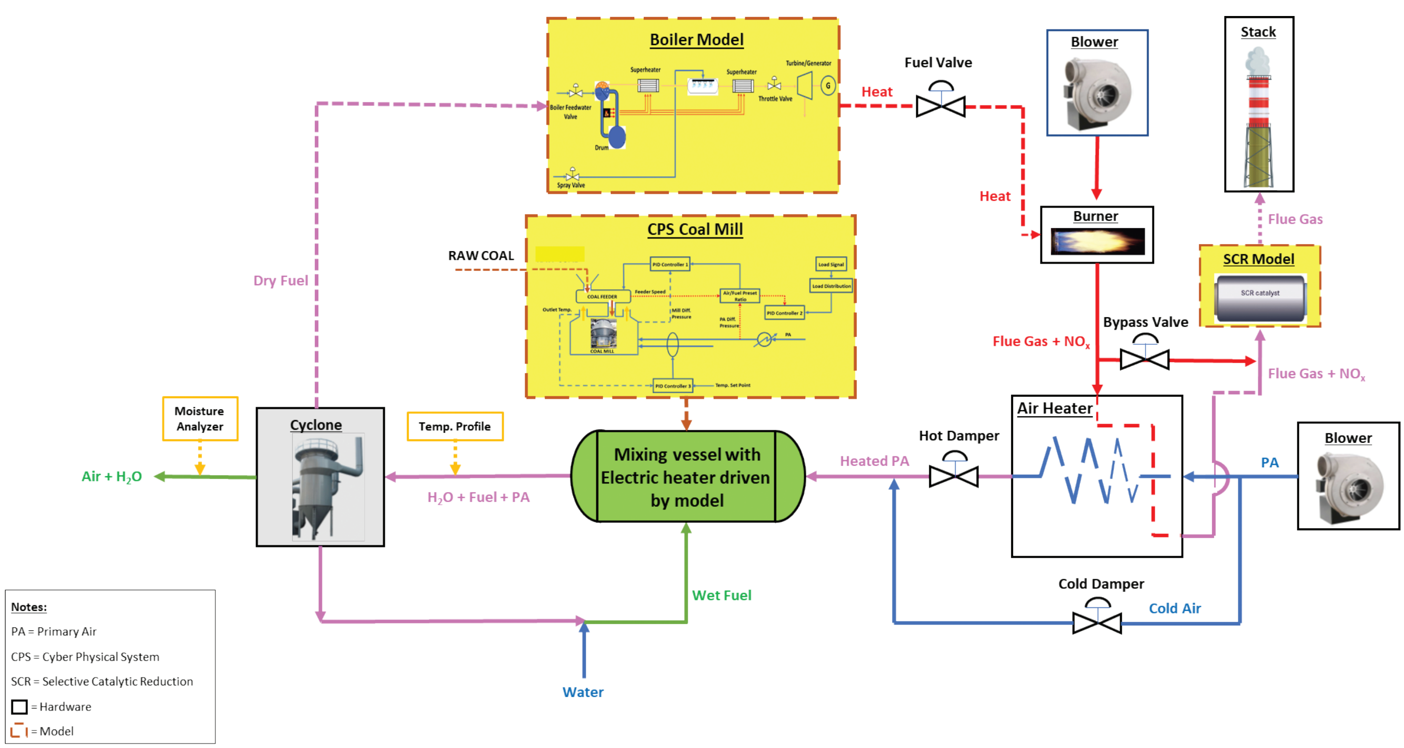
Agent-based Controls for Power Systems

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 - Advanced Sensors and Controls - Task 51
Project Duration	04/01/2020 – 03/31/2022
Total Project Value	$ 175,000
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 continue to be investigated for use in fossil energy power systems. Temperature control of a coal pulverizer, with the power plant responding to load changes, has been identified as an application which is likely to benefit from an agent-based control approach. This project will work with an industry partner to model the control problem and use either a plant simulator or cyber-physical system to develop and test the agent-based control approach. Transition to a field test with the industrial partner is expected following the initial simulation work.

Work on this task also will develop a formalization of the design method and use of cyber-physical systems for research, an area which has been investigated for several years in partnership with Ames Laboratory.



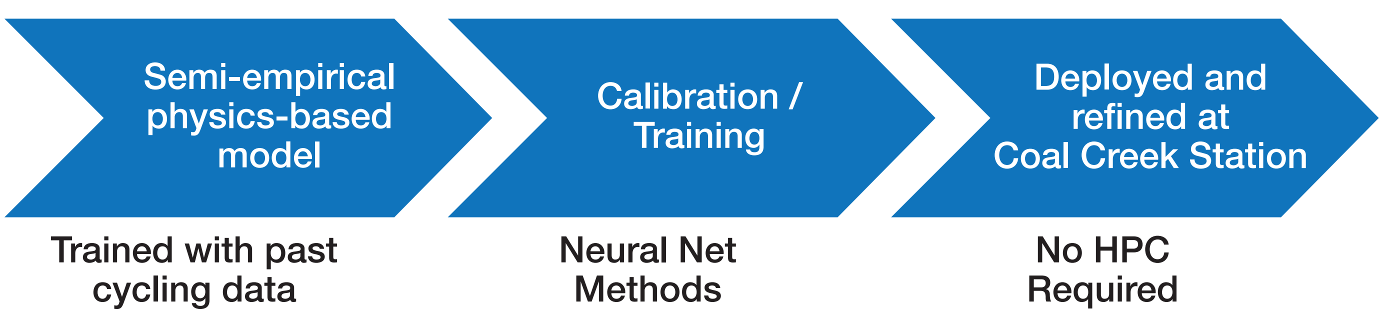
Planned cyber-physical system for coal pulverizer temperature control development and testing.

Generation Plant Cost of Operations and Cycling Optimization Model

Performer	National Rural Electric Cooperative Association (NRECA)
Award Number	FE0031751
Project Duration	10/01/2019 – 03/31/2022
Total Project Value	$ 2,010,400
Collaborator	Great River Energy; Pacific Northwest National Laboratory; Purdue University
Technology Area	Coal Utilization Science

The National Rural Electric Cooperative Association (NRECA) in collaboration with Great River Energy, Purdue University, and Pacific Northwest National Laboratory has undertaken a project to develop resources and tools that will allow utilities to determine the costs of operating their large coal boilers at reduced capacity. The resource will allow large coal boilers to cycle safely to provide enhanced resiliency and reliability while utility systems accommodate increased penetration of renewable resources such as wind, solar photovoltaics, or other small generators.

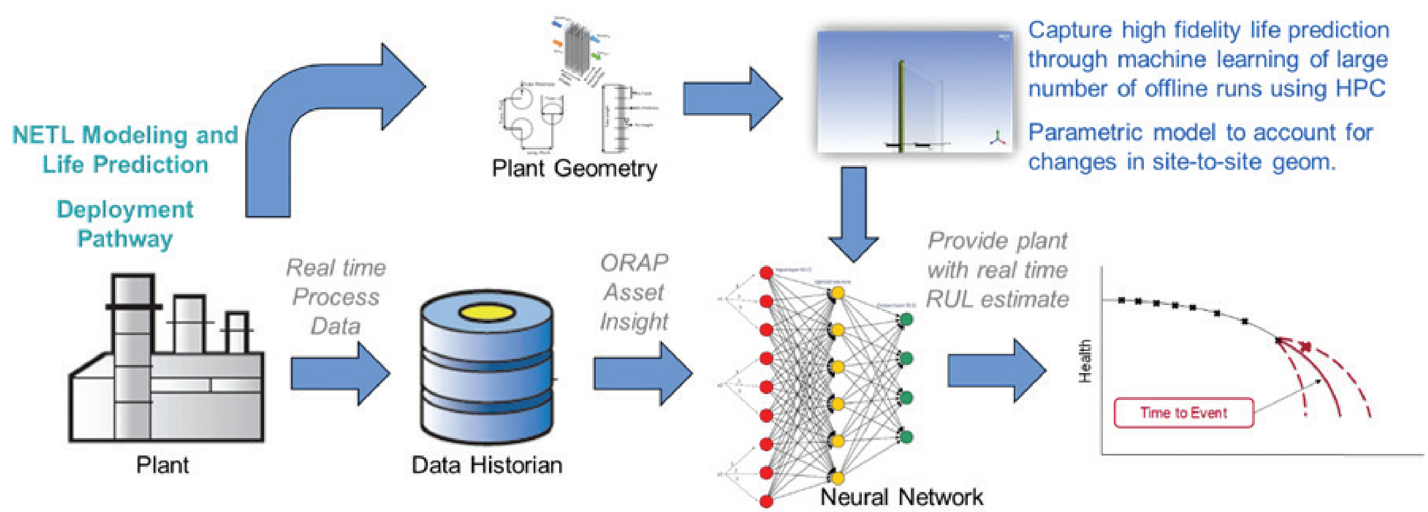
The project team will develop a model to accurately estimate the costs of cycling boilers in large coal plants so that coal generators can be fairly considered and efficiently operated as part of a comprehensive strategy for dispatch and generation planning. The Generation Plant Cost of Operations and Cycle Optimization Model (Coco) will be refined and integrated with one or more dispatch and generation planning models through an application programming interface. NRECA will employ its extensive publishing, education, training, and event management capabilities to publicize and socialize Coco—first to NRECA's 60-plus utilities with coal generating facilities, then to the broader utility community at large.



Continued Development - Real Time and Physics Based Data Analytics for Thermal Power Plants

Performer	**Strategic Power Systems, Inc. (SPS)**
Award Number	FE0032035
Project Duration	06/11/2021 – 06/10/2023
Total Project Value	$ 812,807
Technology Area	Plant Optimization Technologies

The primary objective of this work is to extend the previous research results beyond the proof-of-concept phase. This will include verification and validation testing with direct support and collaboration from operating power plants with advanced power generation technologies and prime mover and downstream systems using the near-real-time data provided through the SPS Operational Reliability Analysis Program (ORAP®) and ORAP Asset Insight data system. The project will result in real measurable value, better informed plant operators, and reduced disruptions, while meeting changing service demands based on enhanced operating flexibility. Extending prior research results to plant systems requires additional time and effort to develop an integration strategy for integrating research results into the SPS ORAP Asset Insight data system. This will enable live, real-time testing and integration with power plant operators.



5G Integrated Edge Computing Platform for Efficient Component Monitoring in Coal-Fired Power Plants

Performer	**University of Texas at El Paso**
Award Number	FE0032089
Project Duration	08/23/2021 – 08/22/2024
Total Project Value	$ 812,807
Technology Area	University Training and Research

The goal of this project is to develop a 5G integrated distributed edge computing (DEC) framework that facilitates real-time monitoring of critical components in coal-fired power plants (CFPPs). The objectives of the proposed effort are as follows:

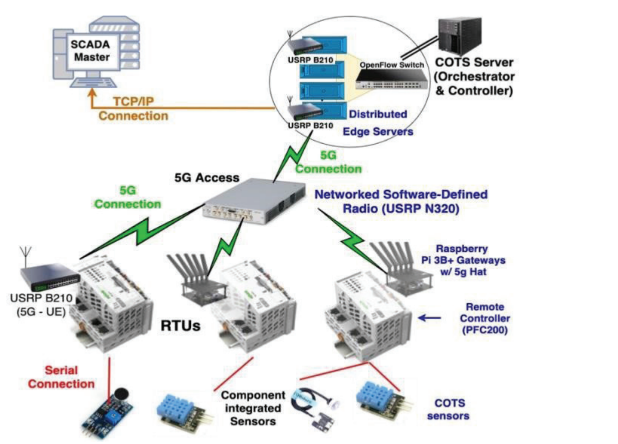
(1) Distributed Edge Computing Service Orchestration for CFPP Component Monitoring—Develop an on-demand DEC platform to gather, process, and efficiently analyze the component health data in the CFPPs. Given that edge computing servers are closer to the field devices in modernized power plants, the efficiency of DEC services with respect to dynamic orchestration, resource data collection, and health information monitoring will be investigated for timely detection of remote faults and to perform diagnosis.

(2) Deploy and Integrate 5G Networking to Enable QoS (Quality of Service)-Aware Network Slicing—Leverage software-defined networking and network function virtualization mechanisms of 5G to instantiate a logically separated component monitoring network slice that will be integrated with DEC services for time-sensitive and efficient transfer of CFPP component health data.

(3) Prototype Development and Empirical Evaluation—Develop a customizable 5G-capable DEC prototype with a separate network slice for efficient plant component monitoring. In addition, extensive performance evaluation of the developed platform will be conducted by measuring several critical metrics.

Since traditional component monitoring in CFPP is done manually using costly portable testing equipment, it is a very time-consuming and labor-intensive maintenance process. Thus, integration of 5G-enabled sensor communication with edge computing infrastructure will be able to monitor the health of components in a CFPP in real time and in an automated manner using machine learning capabilities. The proposed 5G integrated DEC framework will facilitate plant operators in conducting real-time monitoring of critical components in CFPPs. Furthermore, the 5G-based communication infrastructure will allow orchestration of on-demand network slices in order to dynamically meet the component monitoring data throughput and quality of service requirements. This R&D will produce a working prototype using 5G-compliant sensors, remote terminal units, and supervisory control and data acquisition (SCADA) servers.

This technology could be used to monitor the health of components of any power plant in real time, allowing for quicker detection and replacement of worn components with reduced downtime and a reduced need for manual monitoring. This will allow plant operators to dynamically instantiate and manage the QoS needs of the component monitoring traffic in real time. This platform would inherently enhance resiliency of the SCADA network because of the network slicing functionality.



5G Capable Edge Computing Testbed for Component Monitoring.

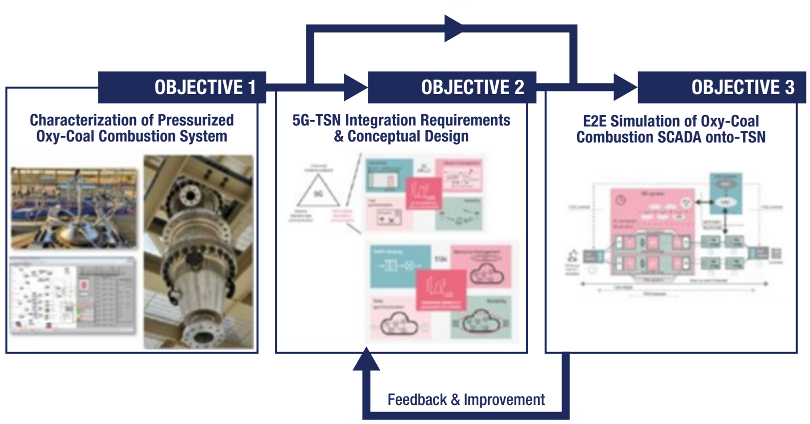
5G-Time Sensitive Networking Architecture Capable of Providing Real-Time Situational Awareness to Fossil-Energy (FE) Generation Systems

Performer	**University of Texas at El Paso (UTEP)**
Award Number	FE0032090
Project Duration	09/23/2021 – 09/22/2024
Total Project Value	$ 400,000
Technology Area	University Training and Research

The overall goal of this effort is the delivery of an integrated fifth-generation time-sensitive networking architecture (5G-TSN) capable of supporting coal-fired power generation systems' operational data while providing the required quality of service. Requirements formulation and design will be based on a thorough network performance and emitted electromagnetic interference (EMI) characterization of the University of Texas at El Paso's Center for Space Exploration and Technology Research pressurized oxy-coal combustion system and the high-pressure oxy-natural-gas combustor. Recorded data and EMI profiles will then be played back into an end-to-end simulation of the 5G-TSN network. The proposed research will demonstrate the ability to design a 5G-TSN network capable of providing the necessary quality of service and security for measurement and control of oxy-coal and oxy-natural gas combustor systems.

The UTEP team will advance this technology by simulating end-to-end live combustor data through a 5G-TSN network. The goal will be fulfilled by the following specific objectives: (i) operational characterization of the pressurized oxy-coal combustion system, (ii) 5G-TSN integration Requirements and conceptual design, and (iii) end-to-end simulation of oxy-coal combustion SCADA onto 5G-TSN ontology.

As power plants evolve, the ability to monitor them in real time is critical to increasing their efficiency and minimizing downtime due to maintenance and repairs. Fifth-generation sensor networks can give operators a way to monitor equipment that would otherwise need to be shut down for inspection and proactive response to maintenance issues. This research aims to characterize and deliver a novel 5G-TSN architecture capable of critical control and real-time measurement. The proposed design will be validated not only through industry-standard simulation but through the characterization of a pilot-scale oxy-coal combustor system during the course of this project. The introduction of a physical system to an otherwise simulated environment paves the way to practical implementation of 5G-TSN networks.



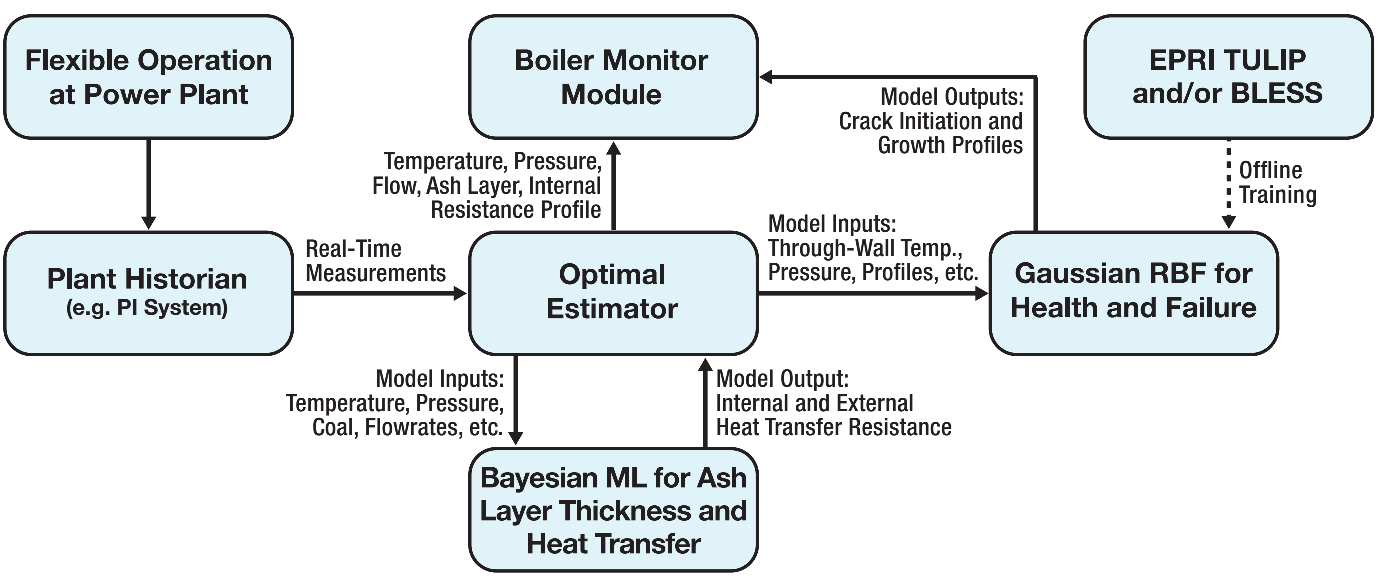
Schematic flow chart showing the over-arching objectives of the project.

Boiler Health Monitoring using a Hybrid First Principles-Artificial Intelligence Model

Performer	**West Virginia University Research Corporation**
Award Number	FE0031768
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 2,509,016
Collaborator	Electric Power Research Institute, Inc.; Southern Company Services, Inc.
Technology Area	Coal Utilization Science

This project seeks to develop methodologies and algorithms to accomplish (i) a hybrid first principles-AI model of the pulverized coal boiler, (ii) a physics-based approach to material damage informed by ex-service component evaluation, (iii) a transformative, online health-monitoring framework that synergistically leverages the hybrid model and plant measurements to provide the spatial and temporal profile of key transport variables and characteristic measures for plant health, and (iv) a field implementation and demonstration at Southern Company's Plant Barry in Bucks, Alabama. The methodologies and algorithms developed in this project will be calibrated and validated using data from Plant Barry. The framework will also be deployed at Plant Barry and evaluated for online monitoring of boiler health.

The Electric Power Research Institute, a sub-awardee, will provide real-world operation and material damage inputs to the hybrid creep and thermo-mechanical fatigue damage models.



Hybrid boiler health monitoring framework.

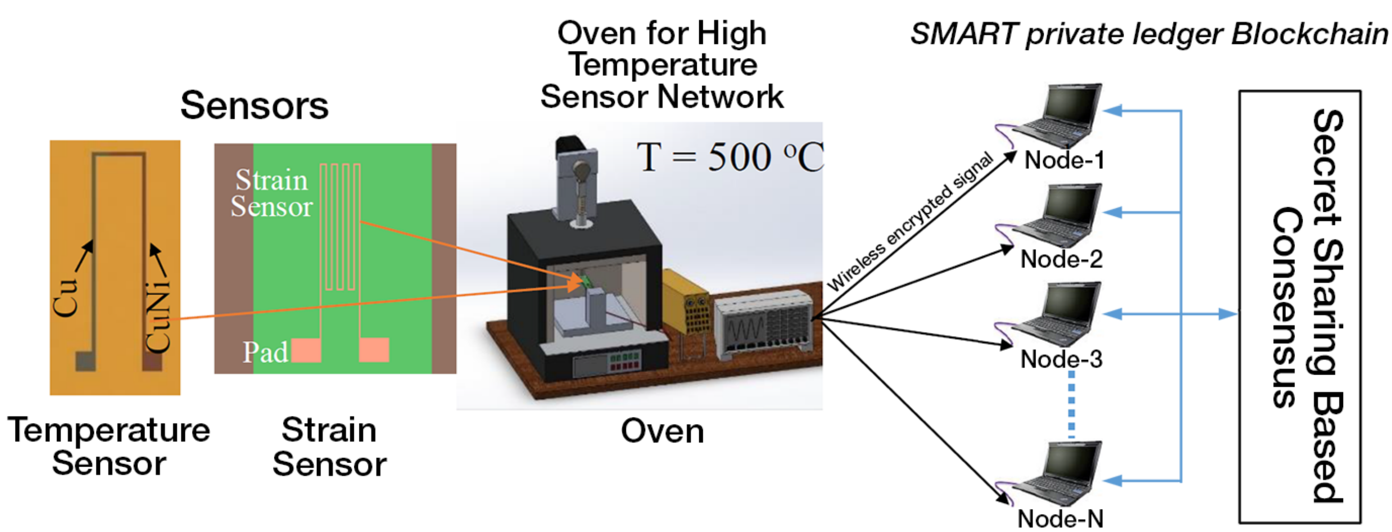
NOVEL CONCEPTS

A Novel Access Control Blockchain Paradigm to Realize a Cybersecure Sensor Infrastructure in Fossil Power Generation Systems

Performer	**Carnegie Mellon University (CMU)**
Award Number	FE0031770
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Technology Area	University Training and Research

The goal of this project is to demonstrate a secure private blockchain protocol designed for fossil power generation systems. The specific objectives include (i) design and implementation of a secure private blockchain architecture that can secure process signal data and other information flows within distributed sensor networks for fossil-based power generation systems, (ii) a simulated power plant environment that uses sensor data with cryptographic digital signatures and integration of the secure blockchain developed by the project team with this system, (iii) demonstration of the effectiveness of the developed blockchain technology by simulating a cyber-attack on the sensor infrastructure.

Benefits include a more secure system for data management for fossil power generation systems and preparation of the next generation of researchers and engineers with highly interdisciplinary and complementary skills in these important areas for their own careers and maintenance of U.S. leadership in fossil energy sciences and technology.



Integration in data acquisition system.

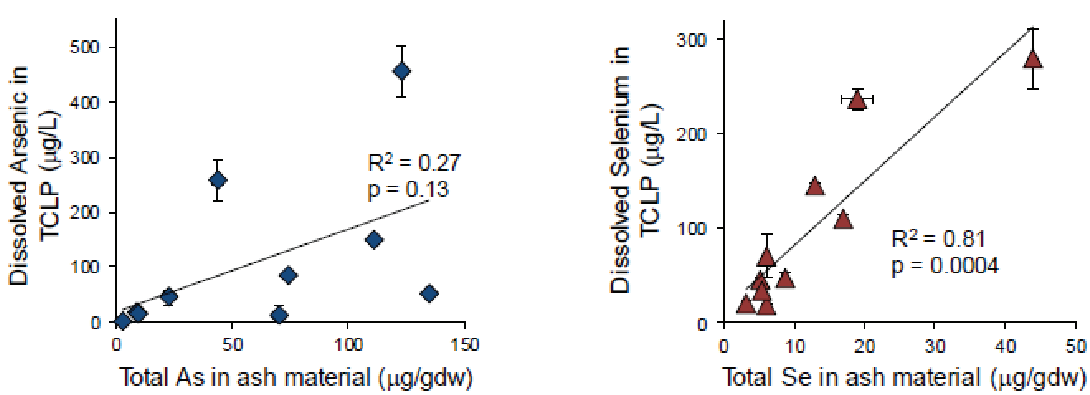
Characterization of Arsenic and Selenium in Coal Fly Ash to Improve Evaluations for Disposal and Reuse Potential

Performer	**Duke University**
Award Number	FE0031748
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Technology Area	University Training and Research

This project aims to establish high-throughput characterization methods for arsenic (As) and selenium (Se) species in coal fly ash and understand how coal combustion parameters might influence leachable As and Se contents from fly ash. Specifically, the project will (1) compare methods for determining As and Se concentration, chemical speciation, and mass distribution in fly ash and establish the efficacy of these methods, taking into account data quality and operator accessibility; (2) evaluate As, Se, and fly ash characteristics and measurement methods that can improve indications of leachability and mobilization potential from fly ash; and (3) perform a survey of As and Se characterization for fly ashes representing a variety of coal feedstocks, combustion conditions, and emissions controls. Duke University will study methods to quantify the chemical forms of As and Se by comparing a series of state-of-the-art quantitative methods (e.g., synchrotron-based X-ray spectroscopy and microscopy) with alternative benchtop spectroscopy methods that are commonly employed in the materials and geological sciences.

The evaluation will consider benefits and trade-offs of each method, including quantitative versus qualitative determination, throughput capacity, and ease of sample processing. These characterization techniques will be compared to As and Se mobilization potential from fly ash as indicated by waste leaching protocols established by waste disposal regulations. These evaluations of As and Se concentration, speciation, mass distribution, and mobilization potential will be applied to a large variety of coal fly ashes that represent a range of coal sources, boiler types, ash collection systems, emissions controls, and combustion conditions.

Results obtained from this work will enable practitioners to understand data generated from qualitative methods that may be more accessible than state-of-the-art synchrotron techniques. A comprehensive database of As and Se speciation in a variety of coal fly ashes and other residuals will be generated. The study will outline advantages and tradeoffs for each method and establish correlations to leaching potential.



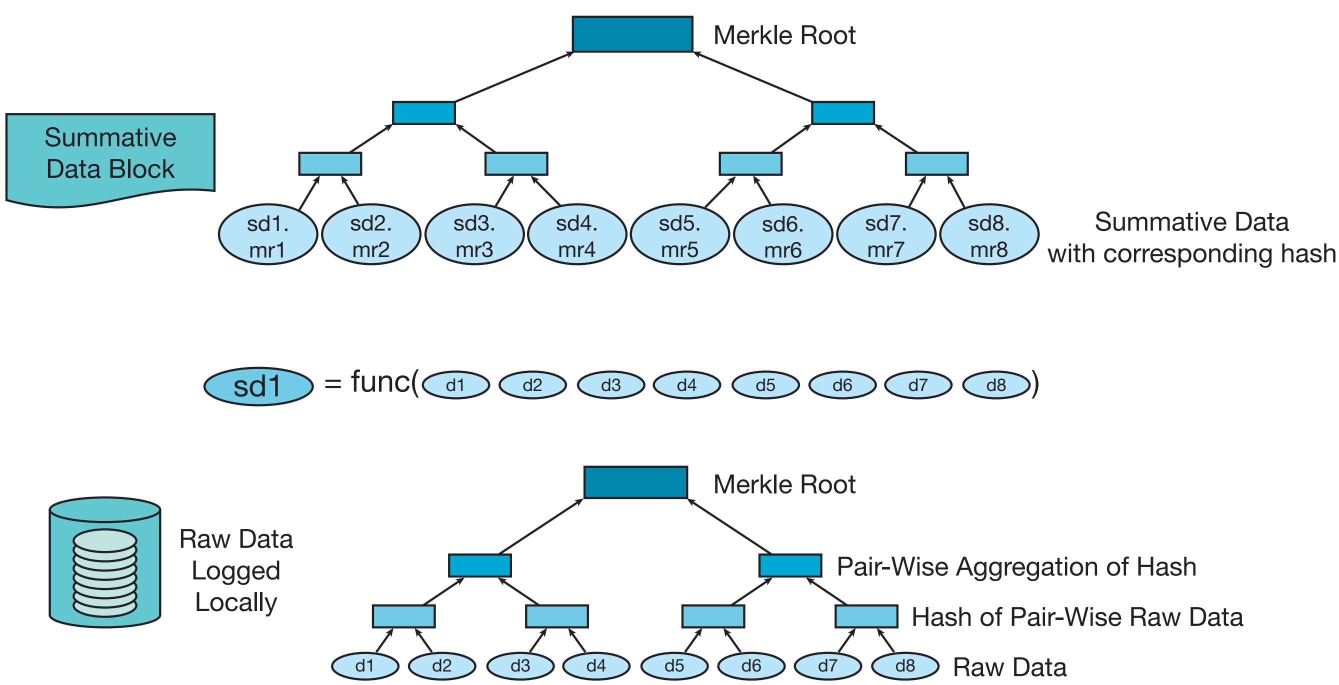
Leachable As and Se from 10 coal ash samples subjected to the toxicity characteristic leaching procedure. Data from Schwartz et al. 2018

Secure Data Logging and Processing with Blockchain and Machine Learning

Performer	**Florida International University**
Award Number	FE0031745
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Collaborator	Cleveland State University
Technology Area	University Training and Research

The scope of work of this project includes (1) secure data logging for smart sensors and wireless communications; (2) authentication and identity verification of sensor nodes, actuators, and other equipment within a network; and (3) decentralized data storage. Florida International University will develop a novel platform that integrates two emerging technologies, namely blockchain and machine learning. This platform will incorporate a mechanism that ensures that only data sent by legitimate sensors are accepted and stored in the data repository, a suite of data aggregation methodologies using machine learning/deep learning algorithms to minimize noise and faulty data, and a two-level secure logging mechanism supported by an energy-aware blockchain solution.

If the project is successful, the fossil energy community will be able to develop a better understanding of how to securely store sensor data from various equipment in the power generating infrastructure. It will reduce data theft while increasing data logging efficiency.



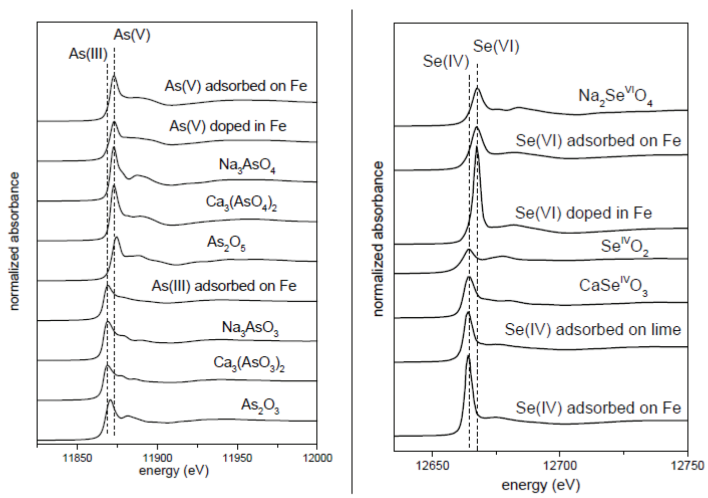
The two-level secure logging mechanism.

Elucidating Arsenic and Selenium Speciation in Coal Fly Ashes

Performer	Georgia Tech Research Corporation
Award Number	FE0031739
Project Duration	07/01/2019 – 06/30/2022
Total Project Value	$ 399,706
Collaborator	Electric Power Research Institute
Technology Area	University Training and Research

This research will systematically characterize arsenic (As) and selenium (Se) speciation within a representative matrix of coal fly ashes using state-of-the-art synchrotron X-ray spectroscopic and microscopic techniques in order to develop a comprehensive correlation and searchable database for coal source/type, generation condition, As/ Se speciation, and As/Se mobility. The project will be implemented in three phases. Phase I will establish a detailed survey documenting the current state of knowledge of fossil power generating units as a function of coal type/ source, operating conditions, environmental control systems, additive use, and fly ash handling methods, as well as common existing techniques for analyzing As and Se concentration. Based on this survey, a matrix of fly ash samples representing a range of conditions will be chosen, collected, and used for Phase II studies. Phase II is composed of three main tasks: (1) traditional characterization techniques will be conducted to provide bulk characteristics of the fly ash samples, such as elemental composition, microstructure, chemical and mineralogical composition, surface area, and particle size distribution, (2) state-of-the-art synchrotron X-ray microscopy and spectroscopy techniques will be applied to reveal the molecular-scale speciation information of As and Se such as oxidation state, association with other elements/minerals, embedded mineral phase, and complexation states, and (3) the mobility of As and Se in the fly ash samples will be evaluated using different leaching methods. Phase III will incorporate the information obtained from phases I and II and establish a searchable database, detailing the correlations among coal type/source, utility operating conditions, As/Se speciation, and As/Se mobility.

When successfully completed, this technology will allow plant operators to quickly assess the amount and valence state of heavy metals in their coal fly ash.



As K-edge XANES spectra of selected reference compounds (left),
Se K-edge XANES spectra of selected reference compounds (right).

Direct Power Extraction

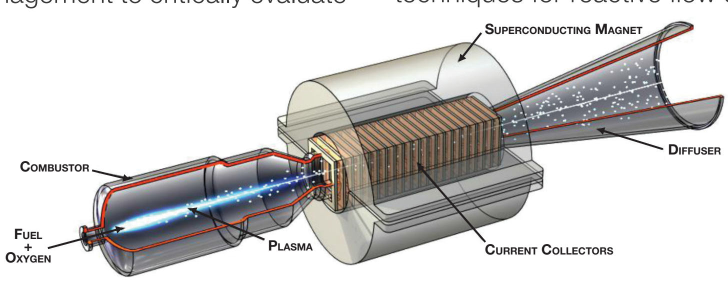
Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022456
Project Duration	04/01/2018 – 03/31/2022
Total Project Value	$ 4,033,095
Technology Area	Plant Optimization Technologies

This early-stage R&D project is investigating and testing magnetohydrodynamic (MHD) power generation concepts for future fossil-derived electrical power generation with and without carbon capture. An MHD power generator directly converts the kinetic energy of a working fluid into electrical power and is shown in the figure. MHD replaces the conventional mechanical conversion steps (e.g., momentum transfer in a turbine) with direct power extraction (DPE). Consequently, the maximum efficiencies are inherently higher than those of conventional turbine-based fossil conversion systems. A combined cycle system with fossil-based MHD power generators could in theory exceed 60 percent higher heating value thermal efficiency, and constructed MHD power generators have yielded expected power performance. It is now apparent that MHD-derived power complements the oxy-fuel approach for carbon capture.

It is generally clear that material durability and overall systems costs were key issues that hampered commercialization following past U.S. Department of Energy research into MHD power generation. Advantageous technology improvements related to magnets and other key technologies have been developed, and oxy-fuel products can yield about twice the MHD power density compared to legacy pre-heated air or enriched-air open cycle systems. A devoted and focused technical effort allows the Office of Fossil Energy and Carbon Management to critically evaluate the promise of this potentially high-efficiency technology. Technology development is focused on the establishment of the theoretical and practical performance of MHD energy conversion systems and experimental validation of the performance and reliability of key components for those systems.

The high-level goal of this work is to improve the viability of MHD power generation for future fossil-derived electrical power generation. To meet this goal, this project is executing techno-economic analysis, developing and verifying the required simulation tools, and experimentally validating device-scale simulations to increase confidence in the performance predictions. Systems which have utilized DPE are being analyzed and ranked according to efficiency, cost, and various other qualitative factors. Standard and novel materials are being developed, simulated, and tested for use as MHD channel materials. This effort focuses on improving fundamentals for technology viability assessments, rather than on demonstrations or detailed optimizations of the technology.

In addition to improving the technical viability of direct power extraction, the project will produce and transfer significant research on fossil energy-relevant topics including mass and thermal flow modeling in aggressive operating environments, functional material development for aggressive applications, and in situ measurement techniques for reactive flow streams, among others.



An oxy fuel fired open cycle MHD power generator.

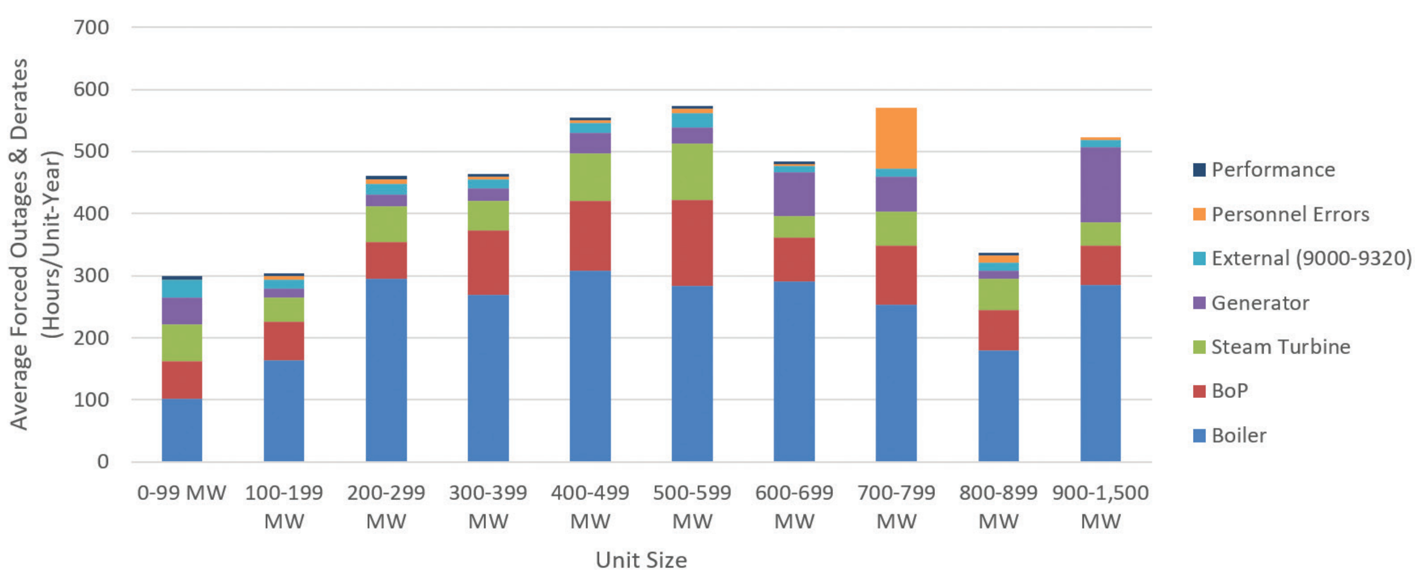
Market and Benefits Analysis

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022427 Advanced Sensors and Controls – Task 64
Project Duration	04/01/2021 – 03/31/2022
Total Project Value	$ 100,000
Technology Area	Plant Optimization Technologies

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, flexible, and intelligent power systems. These projects span harsh environment sensors, advanced controls, inspection technologies including robotics, data analytics and artificial intelligence, and cybersecurity. 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.

This project will map commercial sensor technology and ongoing research and their relation to early detection of boiler failure mechanisms, which will provide insight into technology gaps.



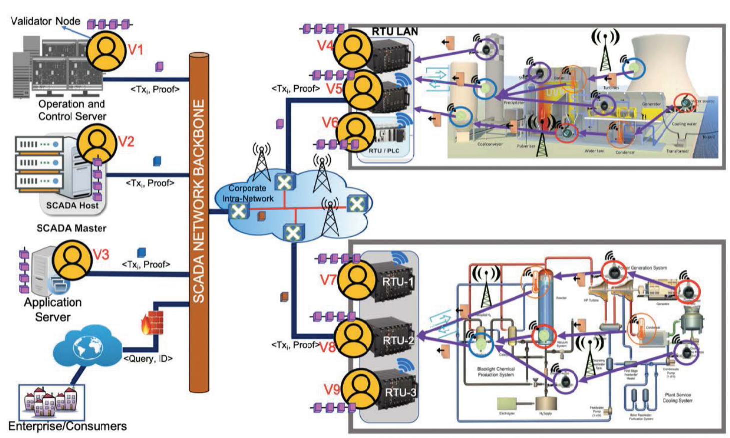
Average annual forced outage hours for coal-fired units (2013–2017), from analysis of NERC GADS data.

Blockchain Empowered Provenance Framework for Sensor Identity Management and Data Flow Security in Fossil-Based Power Plants

Performer	**Old Dominion University**
Award Number	FE0031744
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Collaborator	University of Texas at El Paso
Technology Area	University Training and Research

Old Dominion University will develop a blockchain-based provenance platform that would track data flow traffic from sensors deployed in fossil-based power plants and detect identity violations, unauthorized communication, and process integrity violation. The proposed platform will be scalable across a geographically distributed footprint. The blockchain-based platform would detect the presence of rogue or unauthorized sensors and unauthorized communication among the authorized sensors based on identity profiles derived from the analysis of network traffic. The proof-of-stake consensus protocol in the blockchain platform will be customized to ensure that validation of transactions would take place on the order of milliseconds and achieve a balance between scalability and resilience based on the optimal number of validating nodes. Finally, the team will provide empirical evaluation of the proposed identity management, process integrity, and scalability by testing the system on both uncongested and congested networks.

The proposed framework will ensure high availability of a distributed ledger, which will be used to verify validity of process/signal data. A trusted framework with integrity assurance that is resilient against cyber-attacks will be developed. Analytics software can query the blockchain ledger and be assured that the process data integrity, which cannot be altered by a single malicious entity, is maintained. The provenance capability within the blockchain platform would provide the ability to audit equipment operations to ensure that they are operating according to terms and conditions of a service agreement. This capability would provide real-time validation of sensor data and detect incidental/accidental/malicious incidents that could cause the equipment to operate in violation of the service level agreement.



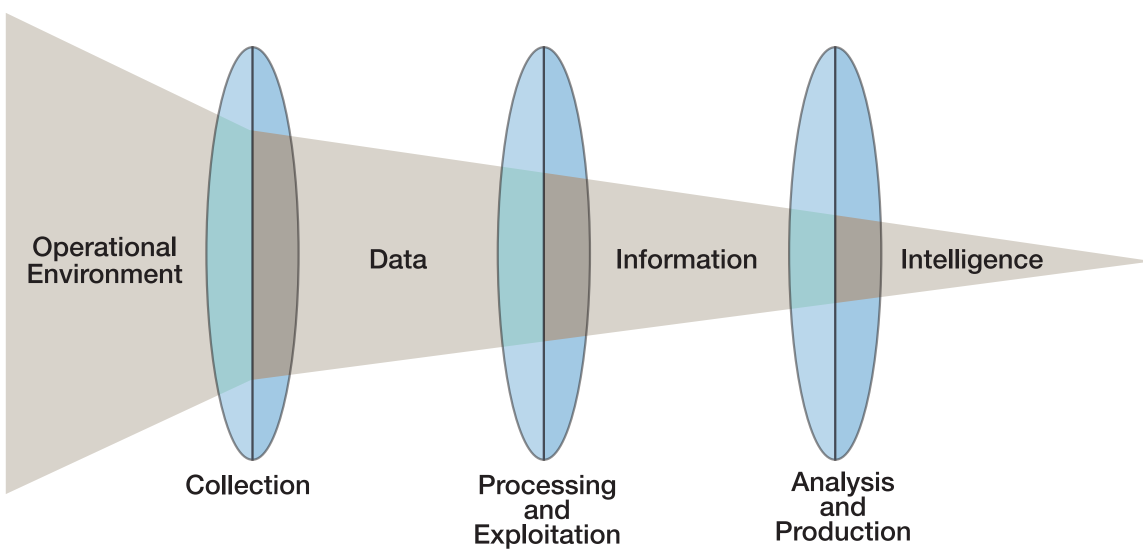
Blockchain architecture for fossil power plants.

Operational Technology Behavioral Analytics

Performer	**Southern Company Services, Inc.**
Award Number	FE0031640
Project Duration	10/01/2018 – 03/31/2022
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.

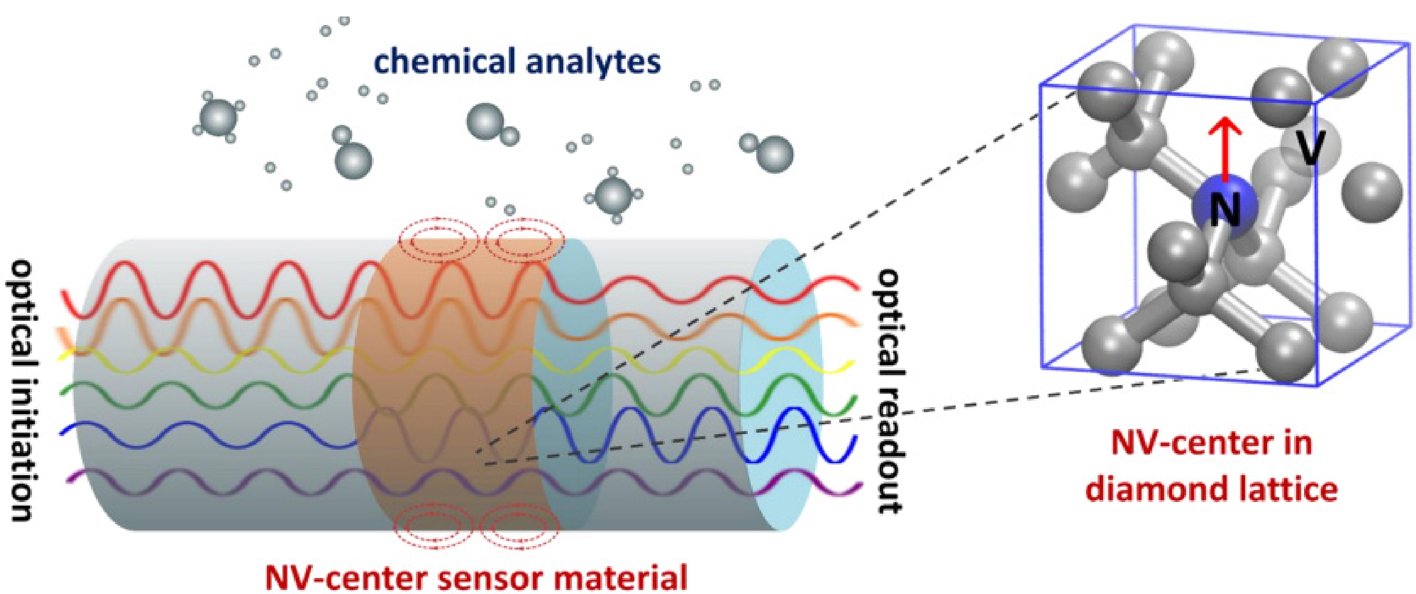


Data analytics approach which leverages process information from operational environments at power plants for enhanced cybersecurity.

Harnessing Quantum Information Science for Enhancing Sensors in Harsh Fossil Energy Environments

Performer	University of California - Riverside
Award Number	FE0031896
Project Duration	09/20/2020 – 09/19/2023
Total Project Value	$ 500,000
Technology Area	University Training and Research

The project plans to utilize real-time quantum dynamics simulations and quantum optimal control algorithms to (1) harness near-surface nitrogen vacancy (NV) centers to detect chemical analytes in harsh fossil energy environments and (2) design optimally constructed electromagnetic fields for initializing these near-surface NV center spins for efficient sensor performance and detection. Together, these objectives will leverage quantum information science to enable new sensing modalities for the extremely sensitive monitoring (i.e., below classical measurement limits) of critical operating parameters of fossil energy infrastructures in harsh environments.



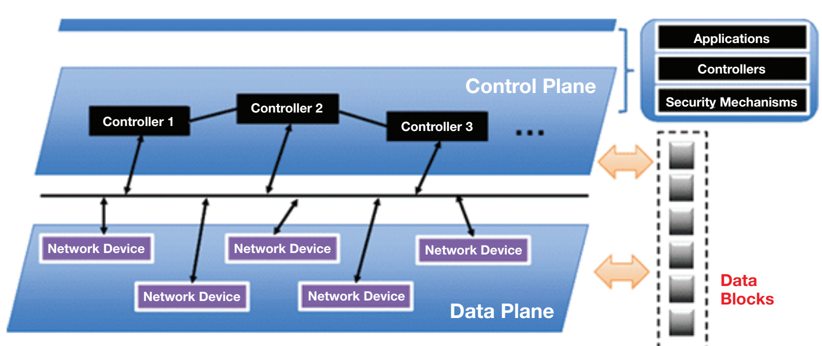
Improving sensing modalities in fossil energy infrastructures.

Incorporating Blockchain/P2P Technology into an SDN-Enabled Cybersecurity System to Safeguard Fossil Fuel Power Generation Systems

Performer	**University of North Dakota Energy and Environmental Research Center (UNDEERC)**
Award Number	FE0031742
Project Duration	09/01/2019 – 08/31/2022
Total Project Value	$ 400,000
Technology Area	University Training and Research

This project will investigate the functionality and performance of a blockchain/peer-to-peer (P2P)-enhanced, software-defined networking (SDN)-enabled cybersecurity protection system. This cybersecurity system will operate on a group of controllers which form the control plane of an SDN system. The group of SDN controllers determine how traffic flows are handled passing through switches in the SDN forwarding plane. The forwarding switches relay the communications traffic flows among the cyber-capable devices (e.g., monitors and actuators) deployed in the industrial control system (ICS) for managing and controlling the power plant, transformer yard and power bus functions, transmission system, and distribution substations. The actions of handling traffic flows reflect the purpose of an ICS in allowing legitimate flows and blocking suspicious traffic flows pertaining to possible network intrusions or denial-of-service attacks. The actions are expressed in the form of rules which can be programmed into the forwarding switches by the SDN controllers. Cybersecurity protection based on the present SDN technology is susceptible to attacks targeting the control plane or targeting the communications between the forwarding and the control planes. However, the PIs believe that blockchain/P2P technology can be incorporated into an SDN-based cybersecurity protection system to mitigate the security risks. The prototype of a blockchain/P2P-enhanced cybersecurity protection system can be used to demonstrate a cost-effective reinforcement of the security protection safeguarding the operations of fossil fuel power generation systems. A testbed needs to be developed to examine the technical feasibility of incorporating blockchain/P2P technology into an SDN-enabled cybersecurity protection system, from both interoperability and performance perspectives.

This project will also create a synergy between the University of North Dakota and its project partner, Minnkota Power Cooperative, for addressing the practical need of cybersecurity protection over fossil fuel power generation systems. In the long term, the project is expected to facilitate sustained efforts in advancing ongoing research in emerging technologies to enhance cybersecurity protection in a broader range of applications.



The generic framework of blockchain-based SDN.

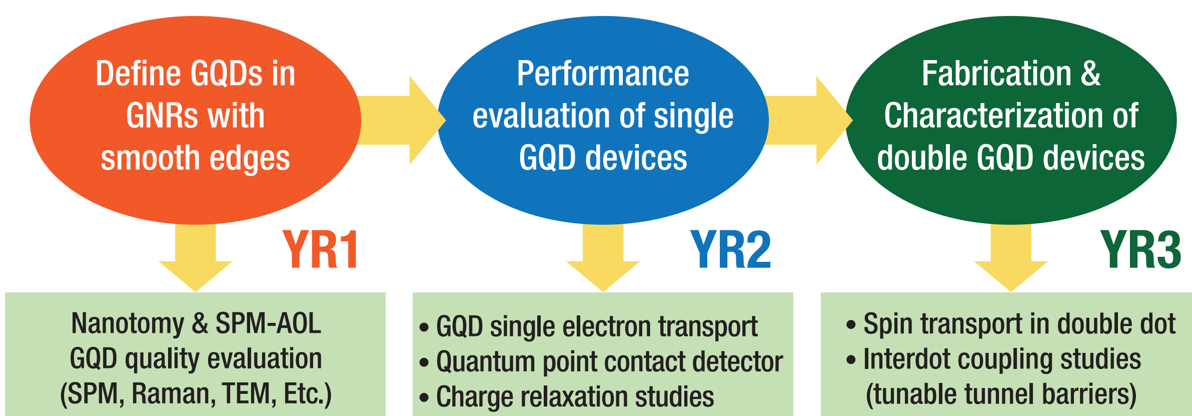
Ultra-Low Disorder Graphene Quantum Dot-Based Spin Qubits for Cyber Secure Fossil Energy Infrastructure

Performer	**University of Texas at El Paso**
Award Number	FE0031908
Project Duration	09/01/2020 – 08/31/2023
Total Project Value	$ 499,546
Technology Area	University Training and Research

The specific research objectives of the project will be to define graphene quantum dots (GQDs) on graphene nanoribbon (GNR) with ultralow local defects and characterize the edge roughness and local disorder by diverse microscopic and spectroscopic techniques; conduct low-temperature characterization of quantum transport and spin relaxation times in GQDs to evaluate the effect of lower local disorder; and develop a multi-GQD-based qubit platform and analyze coupling effects and performance improvements achieved through the new synthetic protocols for quantum communication applications. To achieve the objectives, the team will first leverage the nanotomy technique to prepare GNRs of various widths and characterize its superiority by comparing their structural and disorder status with lithographically prepared GNRs (which will function as the baseline in the project). Subsequently, scanning probe microscopy-based oxidation lithography (SPM-OL) will be used to fabricate geometrically confined GQDs with tunnel barriers on the GNRs. Then the team will fabricate electrode patterns that connect the quantum dots to source and drain electrodes.

An in-depth study will be conducted characterizing the local density of states and conductance of the GQDs with variable widths. Cumulatively, these studies will help in developing an optimized GQD qubit system fabricated using nanotomy and SPM-OL. Quantum transport and spin relaxation measurements conducted at mK temperatures will reveal the superiority of the present GQDs with ultralow defects. Further, the optimized GQD fabrication process will be extended to develop an array of GQDs integrated with local gate electrodes and quantum point contact to study the inter-dot coupling effects in the GQD arrays.

The primary benefit of the project is that it will result in an alternative and significantly improved strategy to formulate GQD qubits (individual and multi-GQDs) with ultralow local defects and higher spin relaxation times (>μ-seconds). The development of such GQD platforms is expected to advance state-of-the- art graphene quantum structure fabrication technologies and semiconductor spin qubits. This project will also be beneficial for ongoing research efforts to develop highly secured communication systems and thus enable the implementation of GQD spin qubits in quantum processors for cyber-resilient grid infrastructure.



Outline of the overall effort of the proposed project.

ABBREVIATIONS

°C ... degrees Celsius
3D ... three-dimensional
5G-TSN ... fifth-generation time-sensitive networking architecture
AI ... artificial intelligence
Al_2O_3 ... aluminum oxide; alumina
As ... arsenic
AUSC ... advanced ultra-supercritical
CAD ... computer assisted design
CFPPs ... coal-fired power plants
Cr_2O_3 ... chromium (III) oxide
DANCE4CFDD ... Deep Analysis Net with Causal Embedding for Coal-fired power plant Fault Detection and Diagnosis
DCS ... distributed control system
DECS ... Distributed Edge Computing Service
DOE ... Department of Energy
ECT ... eddy current testing
ECVT ... electrical capacitance volume tomography
EMI ... electromagnetic interference
EPRI ... Electric Power Research Institute
FECM ... Office of Fossil Energy and Carbon Management (DOE)
FWP ... Field Work Proposal
GE ... General Electric Company
GPS ... Global Positioning System
HBCU ... Historically Black Colleges and Universities
HYPER ... Hybrid Performance Facility
IFOS ... Intelligent Fiber Optic Systems Corporation
IoT ... internet of things
IT ... information technology
LIBS ... laser-induced breakdown spectroscopy
LiDAR ... light detection and ranging
LTI ... lizard-inspired tube inspector
MEMS ... micro electrical-mechanical system(s)
mm ... millimeter(s)
NDE ... non-destructive evaluation
NETL ... National Energy Technology Laboratory
NRECA ... National Rural Electric Cooperative Association
OMI ... Other Minority-Serving Institutions
ORAP ... Operational Reliability Analysis Program
OT ... operational technology
OTBA ... operational technology behavioral analytics
P2P ... peer-to-peer
PID ... proportional-integrative-derivative
QoS ... quality of service
R&D ... research and development
RF ... radio frequency
RFID ... radio frequency identification
RGA ... Raman gas analyzer
SBIR ... Small Business Innovation Research
SCADA ... supervisory control and data acquisition

ABBREVIATIONS

sCO_2 .... supercritical carbon dioxide

SDN .... software-defined networking

Se ....selenium

SiC .... silicon carbide

SO_3 ....sulfur trioxide

SOFC .... solid oxide fuel cell

TBC...thermal barrier coating

TEM.............................transmission electron microscopy

TRL ....technology readiness level

U.S. ....United States

UCR ....University Coal Research

UCF............................... The University of Central Florida

UTEP................................ University of Texas at El Paso

WBG .... wide band gap

NOTES

NOTES

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ACKNOWLEDGEMENTS

The Sensors, Controls, and Novel Concepts Portfolio was developed with the support of many individuals. Key roles were played by principal investigators, federal project managers, the technology manager, the supervisor, and National Energy Technology Laboratory site-support contractors.

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May 2022