HYDROGEN with Carbon Management

2023

# SENSORS, CONTROLS, AND OTHER NOVEL CONCEPTS

## PROJECT PORTFOLIO

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

# DISCLAIMER

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# HYDROGEN WITH CARBON MANAGEMENT

As part of the U.S. Department of Energy (DOE) Office of Fossil Energy's Hydrogen with Carbon Management (HCM) program focuses on production and evaluation of carbon-neutral hydrogen (i.e., coupled to carbon capture and storage (CCS)) as a fuel and development of technologies to use carbon-neutral hydrogen from any source.

The HCM program's efforts are promoted by the Department of Energy (DOE) Hydrogen Shot, with a goal of reducing clean hydrogen costs by 80% to $1 per 1 kilogram (kg) within 1 decade (1-1-1) while expanding employment of the U.S. energy workforce. Seeking a cost-competitive decarbonized alternative to traditional fossil fuels, HCM has a research and development portfolio consisting of a new generation of carbon neutral or net-negative greenhouse gas emissions technologies. HCM comprises six subprogram activities: (1) Gasification Systems, (2) Advanced Turbines, (3) Reversible Solid Oxide Fuel Cells (R-SOFCs), (4) Advanced Energy Materials, (5) Sensors, Controls, and Other Novel Concepts, and (6) Simulation-Based Engineering.

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.

**Gasification Systems:** The DOE Gasification Systems program is developing innovative modular designs for converting diverse types of carbonaceous feedstocks into clean synthesis gas to enable the low-cost production of clean hydrogen, electricity, transportation fuels, chemicals, and other useful products to suit market needs. Advancements in this area will help enable syngas-based technologies to play a role in economy-wide decarbonization in multiple energy sectors while remaining competitive in both domestic and international markets, and spur on the use of abundant domestic carbon feedstock resources, in turn contributing towards increased energy security and promoting justice through reviving depressed markets in traditional coal-producing regions of the United States.

**Advanced Turbines:** The NETL Advanced Turbines Program is focused on the development of advanced turbine technologies that will accelerate turbine performance, efficiency, and cost effectiveness beyond the current state of the art. The program will provide tangible benefits to the public in the form of options for eliminating $CO_2$ emissions, the lowering the cost of electricity, and reducing emissions of criteria pollutants. The efficiency of combustion turbines has steadily increased as advanced technologies have provided manufacturers with the ability to produce highly advanced turbines that operate at very high temperatures. Further increases in efficiency are possible through the continued development of advanced components, combustion technologies, material systems, thermal management, and novel turbine-based cycles. The Advanced Turbines Program supports four key technologies that will advance clean, low-cost power production from fossil energy resources while providing options for $CO_2$ mitigation. These key technologies include: (1) Advanced Combustion Turbines, (2) Pressure Gain Combustion (PGC), (3) Turbomachinery for Supercritical Carbon Dioxide ($sCO_2$) Power Cycles, and (4) Modular Turbine-Based Hybrid Heat Engines. DOE's research and development in advanced turbines technology develops and facilitates low-cost advanced energy options for carbon-negative energy ecosystems.

**Reversible Solid Oxide Fuel Cells (R-SOFCs):** The NETL Reversible Solid Oxide Fuel Cell (R-SOFC) program maintains a portfolio of RD&D projects that address the technical issues facing the commercialization of solid-oxide fuel cell (SOFC) and R-SOFC technologies and pilot-scale test projects intended to validate the solutions to those issues. To successfully complete the maturation of these technologies from their present state to the point of commercial readiness, the program's efforts are channeled through three key technology areas, each of which has its respective research focus: (1) Cell Development, (2) Core Technology, and (3) Systems Development.

**Advanced Energy Materials:** The Advanced Energy Materials program drives to characterize, produce, and certify advanced alloys and high-performance materials that are key to realizing dispatchable, reliable, high-efficiency decarbonized power generation from hydrogen. In addition, the program aims to encourage change and stimulate innovation in the high-performance materials value chain to spur U.S. competitiveness and enable achievement of 2050 zero-emission goals. Materials of interest include those that enable components and equipment to perform in the high-temperature, high-pressure, corrosive environments of advanced energy systems with specific emphasis on durability, availability, and cost. The key focus areas of this program include: (1) development of a robust domestic materials supply chain, (2) lifetime prediction and rapid repair critical to manage a flexible fleet of generators that enable high penetration of renewables into the grid, and (3) low-cost, high-performance alloy development to enable meeting 2050 zero-emission goals.

**Sensors, Controls, and Other Novel Concepts:** The NETL Sensors, Controls, and Other Novel Concepts program conducts 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. This research will aid in the achievement of DOE goals, which include net-zero carbon emissions in the energy sector by 2035 and a decarbonized wider economy by 2050.

**Simulation-Based Engineering:** NETL's Simulation-Based Engineering (SBE) program supports the development and application of innovative physics- and chemistry-based models and computational tools at multiple scales (i.e., atomistic, device, process, grid, and market) in order to accelerate development and deployment of clean, advanced fossil fuel technologies. The SBE program combines a multidisciplinary approach comprising technical knowledge, software development, computational power, data repositories, experimental facilities, and unique partnerships to support research into timely and accurate solutions for fossil and sustainable energy and carbon management systems. Analysis and visualization tools are manipulated to gain scientific insights into complex, uncertain, high-dimensional, and high-volume datasets. The information generated is then collected, processed, and used to inform research that combines theory, computational modeling, advanced optimization, physical experiments, and industrial input.

# SENSORS, CONTROLS, AND OTHER NOVEL CONCEPTS

The Sensors, Controls, and Other 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, Controls, and Other Novel Concepts 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.

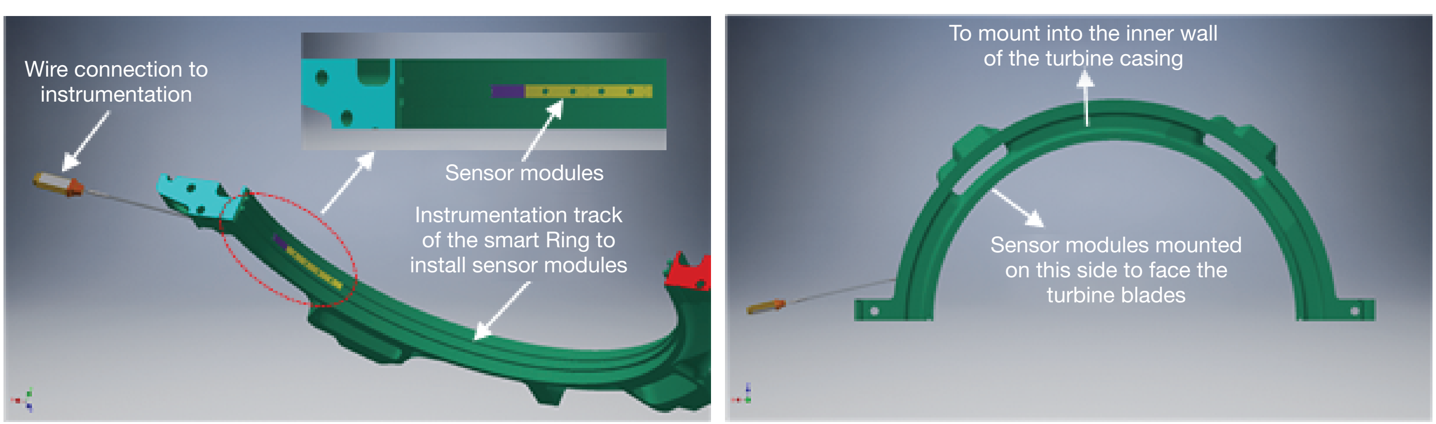
# HARSH ENVIRONMENT SENSORS

# 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 – 9/30/2023 |
| **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 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

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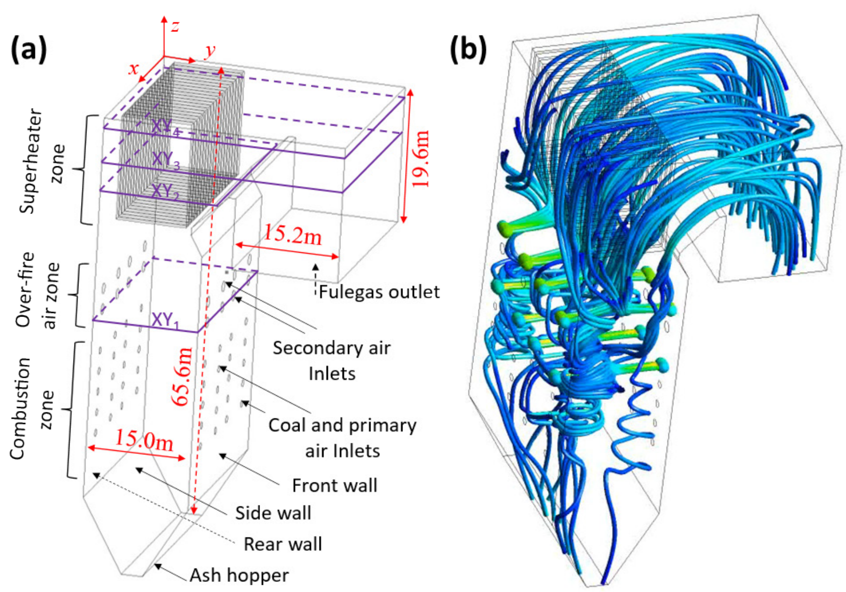
|---|---|
| **Performer** | Clemson University |
| **Award Number** | FE0031765 |
| **Project Duration** | 10/01/2019 – 03/31/2023 |
| **Total Project Value** | $ 3,750,000 |
| **Technology Area** | Plant Optimization Technologies |

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 power plant 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 costs. 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 costs. The project could have profound impacts on the general field of harsh environment sensing as it fosters several 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

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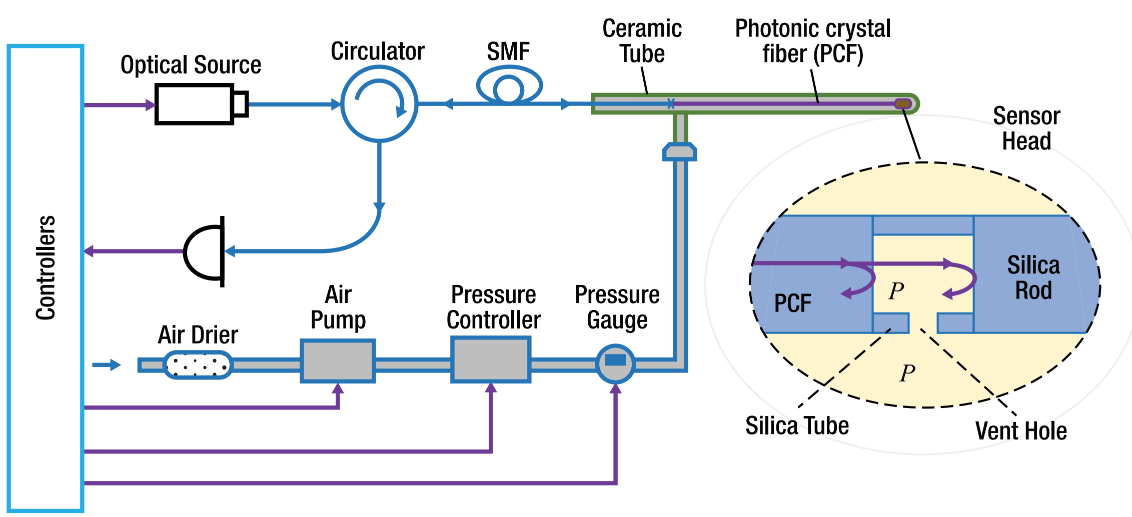
|---|---|
| **Performer** | **Michigan State University** |
| **Award Number** | FE0031899 |
| **Project Duration** | 09/01/2020 – 08/31/2023 |
| **Total Project Value** | $ 496,475 |
| **Technology Area** | University Training and Research |

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 shutdowns. 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, and 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.**

# Integration of LIBs with Machine Learning for Real-Time Monitoring of Feedstock in $H_2$ Gasification Applications

| Performer | Lehigh University |
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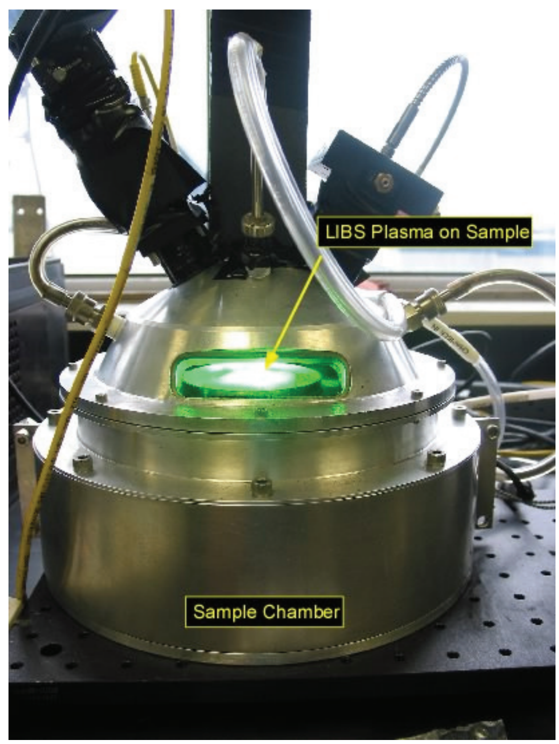
| Award Number | FE0032177 |
| Project Duration | 10/01/2022 – 09/30/2025 |
| Total Project Value | $ 625,000 |
| Technology Area | Plant Optimization Technologies |

This project will focus on assembling a material inventory that includes mixed waste plastics, biomass, and legacy coal wastes, and develop a procedure for sample processing, analysis, chain of custody, and quality assurance. Lehigh University will design and assemble a laser-induced breakdown spectroscopy (LIBS) system for detection and quantification of material samples under both static and dynamic conditions (e.g., material flow on a small-scale research conveyor belt), and optimize this measurement technique to develop an analytical database. Machine learning algorithms for LIBS data processing will be utilized to provide improvement in measurement accuracy of the proposed LIBS technique for parameters of interest and throughput corresponding to on-line measurements, reducing future feedstock sampling, and analysis requirements. A techno-economic analysis of the proposed technology will be performed to assess the benefit of incorporating the proposed system on upgraded operational protocols and control schemes of gasifiers for hydrogen production.

This project will target characterization of waste plastics that would typically go to landfills, in combination with biomass and legacy coal waste, as a feedstock to hydrogen conversion reactors. Landfilling is often the cheapest way to dispose of municipal and industrial wastes; however, landfilling leads to significant environmental problems. This project eliminates these hazards by measuring, in real time and in-situ, the feedstock's chemistry and higher-order parameters so that a gasifier can efficiently and economically use them while producing hydrogen, an environmentally benign fuel. Real-time hydrogen gasifier feedstock analysis would benefit from the features of this combined LIBS and machine learning approach via a smaller footprint, fast analysis frequency, competitive measurement accuracy and precision, relatively easy calibration, and less time and labor intensity. Machine learning would also be able to provide information on higher-order parameters of the feedstock, such as heating value, fusion and slagging temperatures, and thermal conductivity, through classification and clustering methods which will link sample elemental information to those properties of interest in the sample.




LIBS system with labels.

# Ceramic-Based Ultra-High Temperature Thermocouples in Harsh Environments

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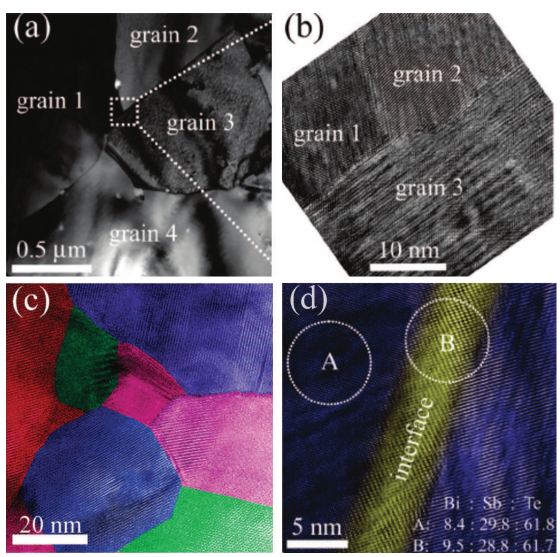
| **Performer** | **Morgan State University** |
| **Award Number** | FE0031906 |
| **Project Duration** | 08/01/2020 – 07/31/2023 |
| **Total Project Value** | $ 500,000 |
| **Technology Area** | Plant Optimization Technologies |

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

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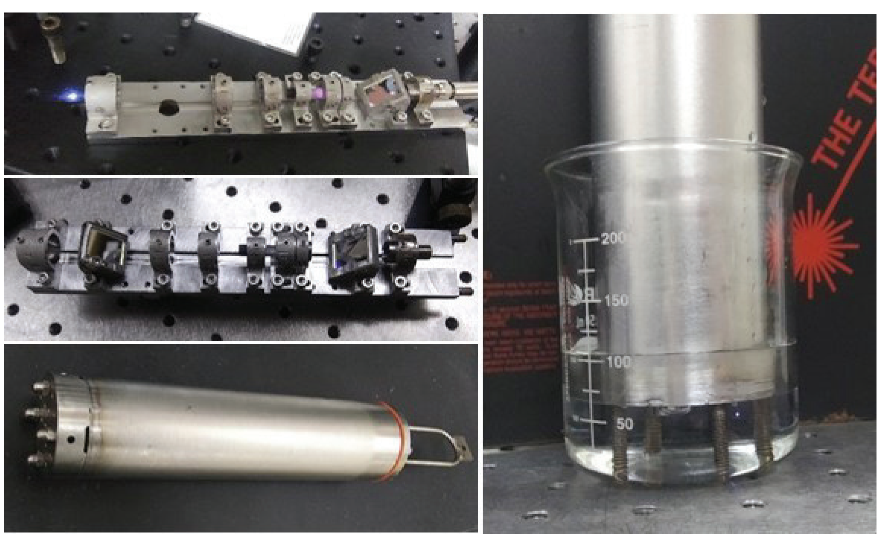
| **Performer** | **National Energy Technology Laboratory (NETL)** |
| **Award Number** | FWP-1022427 Advanced Sensors and Controls – Task 71 |
| **Project Duration** | 04/01/2021 – 03/31/20224 |
| **Total Project Value** | $ 230,000 |
| **Technology Area** | Plant Optimization Technologies |

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 °C 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 was 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 were kept safely at the surface near the well. In the initial field testing, three 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

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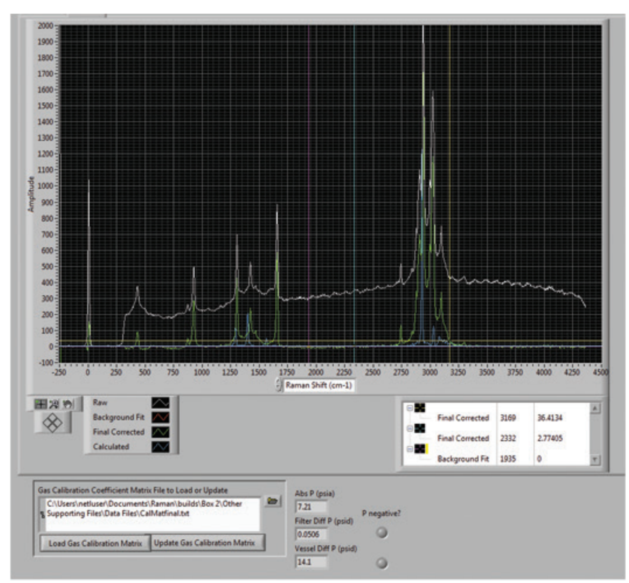
| **Performer** | **National Energy Technology Laboratory (NETL)** |
| **Award Number** | FWP-1022427 Advanced Sensors and Controls - Task 41 |
| **Project Duration** | 04/01/2020 – 03/31/2024 |
| **Total Project Value** | $ 133,000 |
| **Technology Area** | Plant Optimization Technologies |

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

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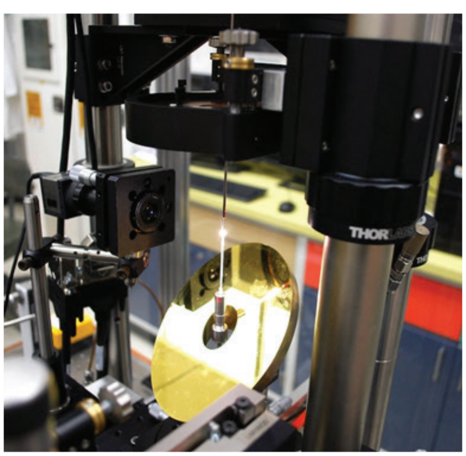
| **Performer** | **National Energy Technology Laboratory (NETL)** |
| **Award Number** | FWP-1022427 - Advanced Sensors and Controls - Task 21-33 |
| **Project Duration** | 04/01/2020 – 03/31/2024 |
| **Total Project Value** | $ 655,000 |
| **Technology Area** | Plant Optimization Technologies |

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.

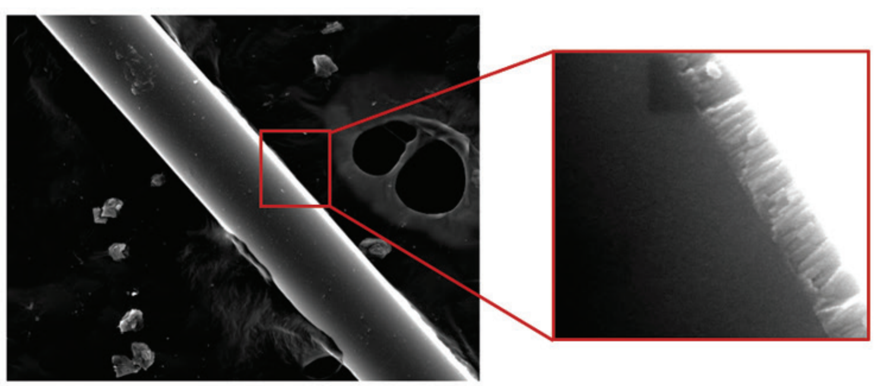
This project is pursuing technology solutions to several barriers to the widespread use of multipoint optical fiber sensors, for temperature, strain, and chemical measurements. NETL's laser-heated pedestal growth system is being utilized to refine the techniques needed to make high-temperature crystalline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

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

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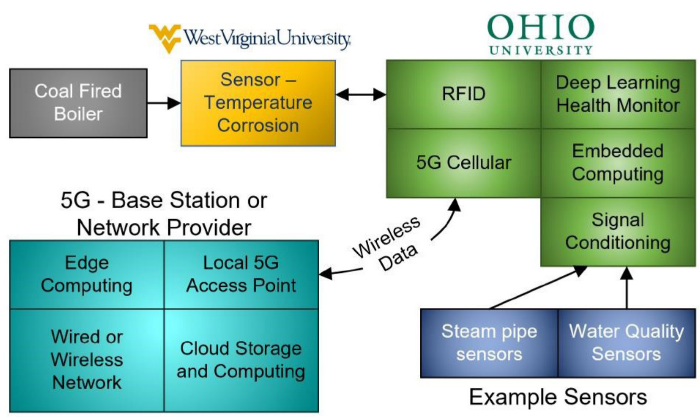
| **Performer** | **Ohio University** |
| **Award Number** | FE0032078 |
| **Project Duration** | 08/16/2021 – 08/15/2024 |
| **Collaborator** | West Virginia University (WVU) |
| **Total Project Value** | $ 414,481 |
| **Technology Area** | University Training and Research |

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 our respective technologies and will cross-collaborate to exchange information and gather laboratory results.




**Proposed system integration – identifying contributions.**

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

| Performer | Reaction Engineering International |
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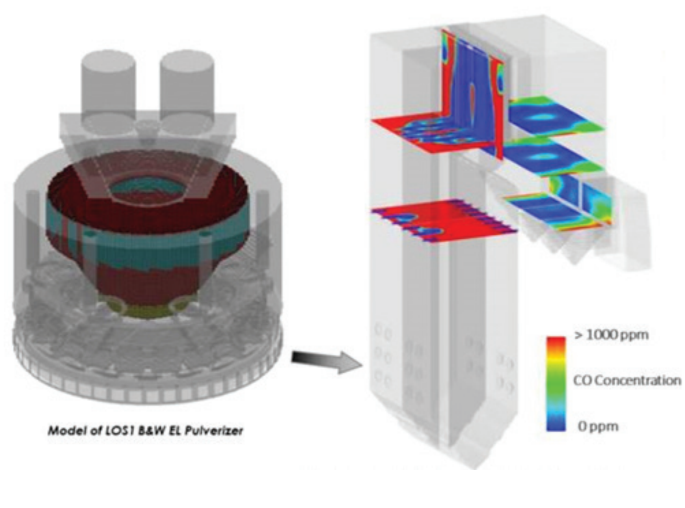
| Award Number | FE0031680 |
| Project Duration | 10/01/2018 – 09/30/2023 |
| Total Project Value | $ 777,347 |
| Technology Area | Plant Optimization Technologies |

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 Reaction Engineering International 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: (1) 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; (2) to re-design the signal conditioning unit to increased resolution, allowing for determination of localized electrochemical phenomena; (3) 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; (4) 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; (5) 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 (6) to develop logic algorithms that can be implemented into a plant distributed control system (DCS) to improve boiler energy efficiency and reduce NOx 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.**

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

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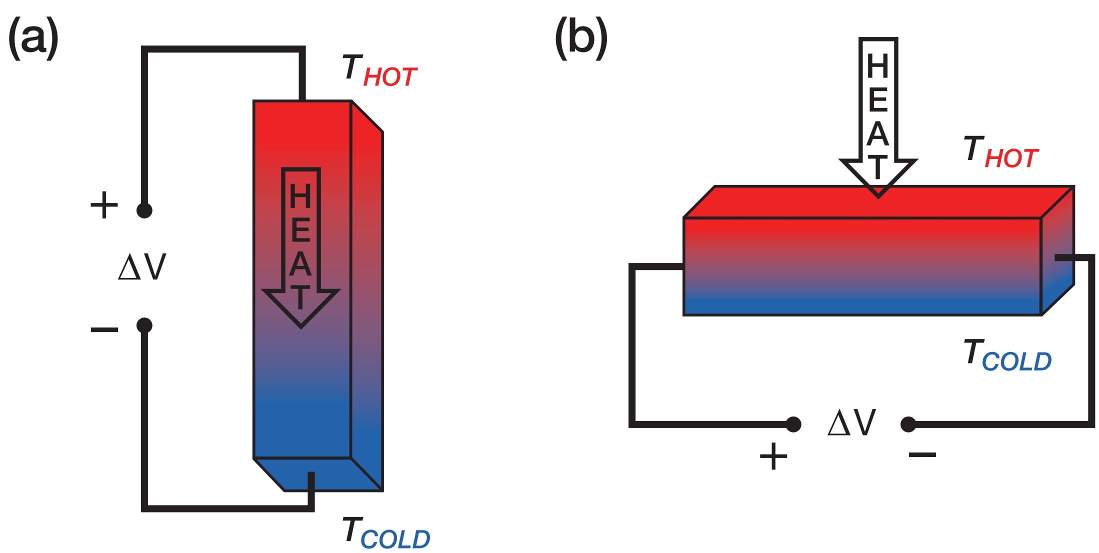
| **Performer** | **University of Maryland** |
| **Award Number** | FE0031902 |
| **Project Duration** | 01/01/2021 – 12/31/2023 |
| **Total Project Value** | $ 500,000 |
| **Technology Area** | Plant Optimization Technologies |

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.

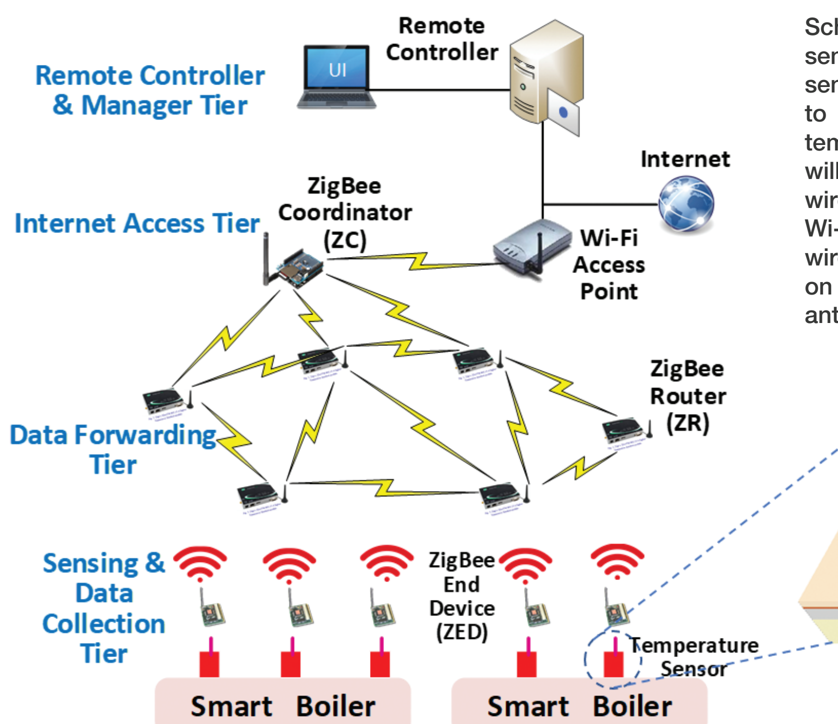



**(a) Schematic of the Seebeck effect. (b) Schematic of the transverse Seebeck effect.**

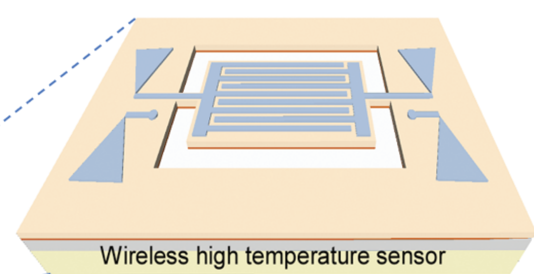
# Wireless High Temperature Sensor Network for Boiler Systems

| | |
|---|---|
| **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.**

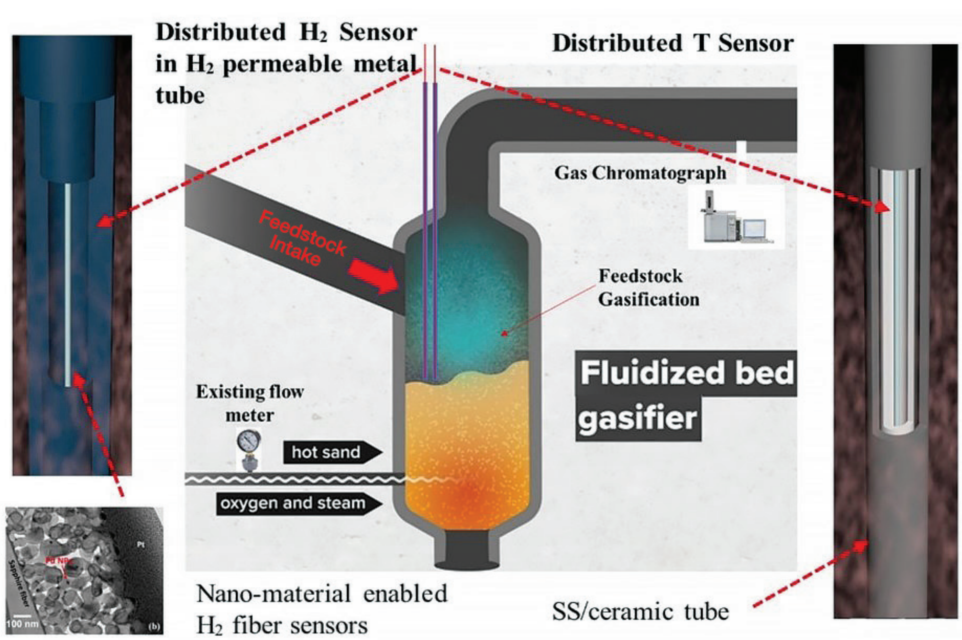


# Distributed Sensors for Waste Plastics Gasification and Clean Hydrogen Production

| | |
|---|---|
| **Performer** | **University of Pittsburgh** |
| **Award Number** | FE0032210 |
| **Project Duration** | 10/01/2022 – 09/30/2024 |
| **Total Project Value** | $ 634,765 |
| **Technology Area** | Plant Optimization Technologies |

This collaborative project seeks to develop distributed fiber sensors to perform real-time temperature and hydrogen concentration measurements to improve hydrogen production and energy efficiency for waste plastics gasification processes. Sensors to be developed by this project can be inserted into gasification reactors to perform in-situ, real-time temperature and hydrogen concentration measurements inside feedstocks to achieve improved spatial resolution. Working with project partners, this project will perform distributed temperature and hydrogen sensors studies using an experimental gasification reactor to understand various gasification feedstocks and reaction conditions. Based on these results, the research team will demonstrate a sensor-enabled gasification optimization process to improve hydrogen production and reduce harmful chemical generation.

The success of this project will significantly improve the scientific understanding of plastic gasification processes for hydrogen production. The new sensing technologies to be developed by this project will provide unprecedented insights into reaction chemistry and thermal dynamics of the gasification processes. It will provide vital data to improve reactor designs, optimize reaction control, reduce emissions, and unleash the scale-up potentials of the plastic gasification technique to support America's clean-energy transition and the hydrogen economy.




System overview.

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

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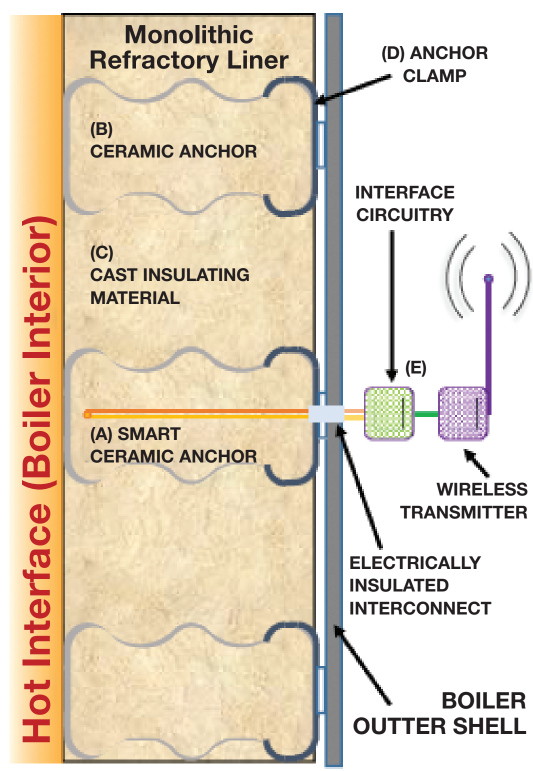
|---|---|
| **Performer** | **West Virginia University** |
| **Award Number** | FE0031825 |
| **Project Duration** | 01/01/2020 – 12/31/2023 |
| **Total Project Value** | $ 1,254,719 |
| **Technology Area** | Plant Optimization Technologies |

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 $Al_2O_3$-$Cr2O_3$ ceramic anchor compositions that can operate at temperatures up to 1400 °C; (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.**

# An Autonomous Robotic Inspection System for Coal Ash and Tailings Storage Facilities

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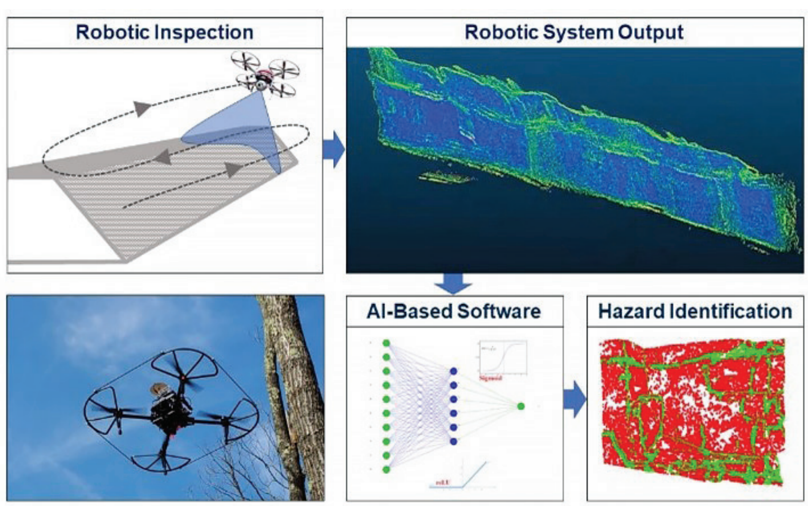
|---|---|
| **Performer** | **West Virginia University** |
| **Award Number** | FE0032206 |
| **Project Duration** | 10/01/2022 – 09/30/2025 |
| **Total Project Value** | $ 499,846 |
| **Technology Area** | Plant Optimization Technologies |

The goal of the project is to prevent negative environmental and socioeconomic impacts of coal waste (coal ash and tailings) by developing an aerial robot-enabled inspection and monitoring system of active and abandoned coal ash and tailings storage facilities. The first objective of this project is the development of a programmable drone, equipped with several complementary sensors, that will autonomously inspect several structures of a storage facility. The second objective of this project is to create artificial intelligence-based hazard detection algorithms that will use multispectral and georeferenced images (i.e., thermal and visual) and 3D Point Clouds data collected by an autonomous drone to detect hazards in the storage facility structure that would indicate uncontrolled leakage to the environment or lead to the potential failure of the structure.

Coal ash is a residue left over after a coal-fired power plant burns coal and tailings are a waste product of the coal cleaning process. Both coal ash and tailings, which contain metals that can adversely affect the environment and human health, are transported to waste storage facilities that are generally embankment dam structures. The waste stored in these structures is also used in the construction of the embankments, failure of which has been shown to be catastrophic, causing massive mudslides that devastate entire communities and create irreversible environmental damage. Wastewater leakages from the storage facilities, although less impactful, may also be very harmful to the environment and the communities they support. The aerial, robot-enabled inspection and monitoring system will be able to detect hazards in the storage facility structures and alert users to these weaknesses, which can be repaired to prevent release of waste materials into the environment and nearby communities.




**Robotic inspection and hazard identification.**

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

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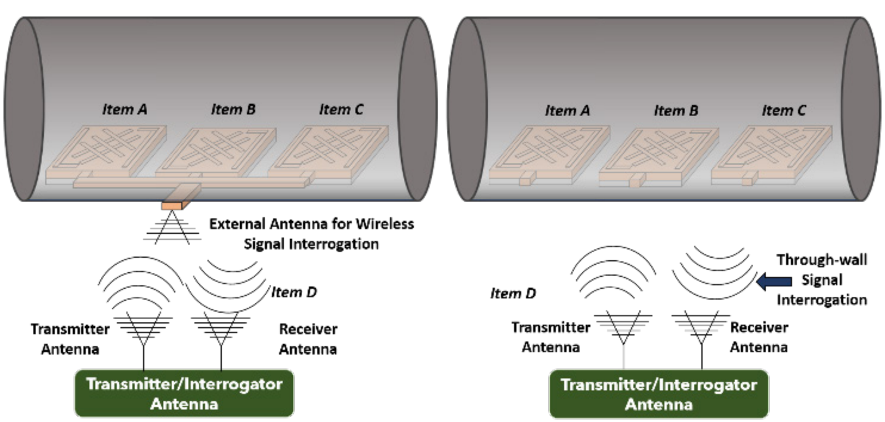
|---|---|
| **Performer** | **West Virginia University Research Corporation** |
| **Award Number** | FE0031912 |
| **Project Duration** | 08/17/2020 – 08/16/2023 |
| **Total Project Value** | $ 500,000 |
| **Technology Area** | University Training and Research |

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 electro ceramic 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

# Agent-based Controls for Power Systems

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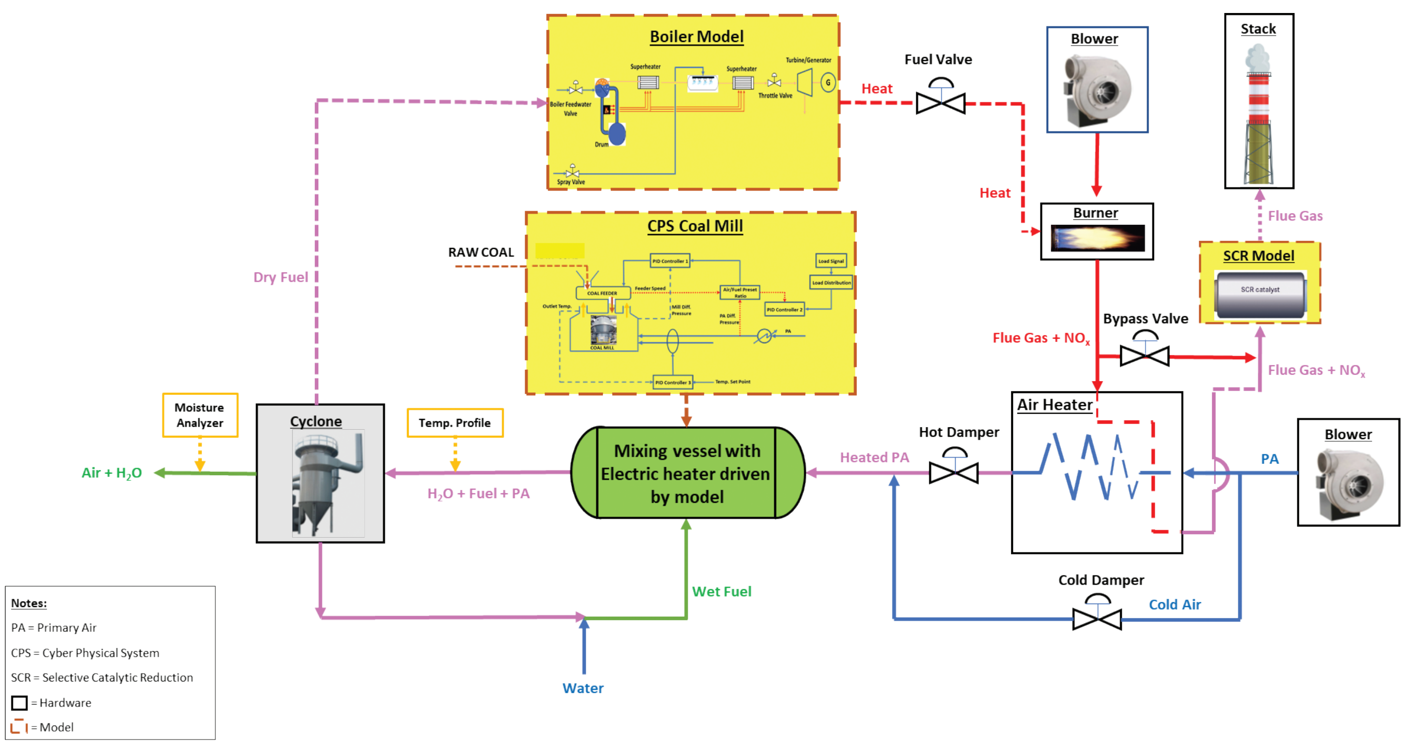
|---|---|
| **Performer** | **National Energy Technology Laboratory (NETL)** |
| **Award Number** | FWP-1022427 - Advanced Sensors and Controls - Task 51 |
| **Project Duration** | 04/01/2020 – 08/31/2024 |
| **Total Project Value** | $ 175,000 |
| **Technology Area** | Plant Optimization Technologies |

Development of next-generation power systems such as fuel cell–turbine hybrids encounter 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.

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

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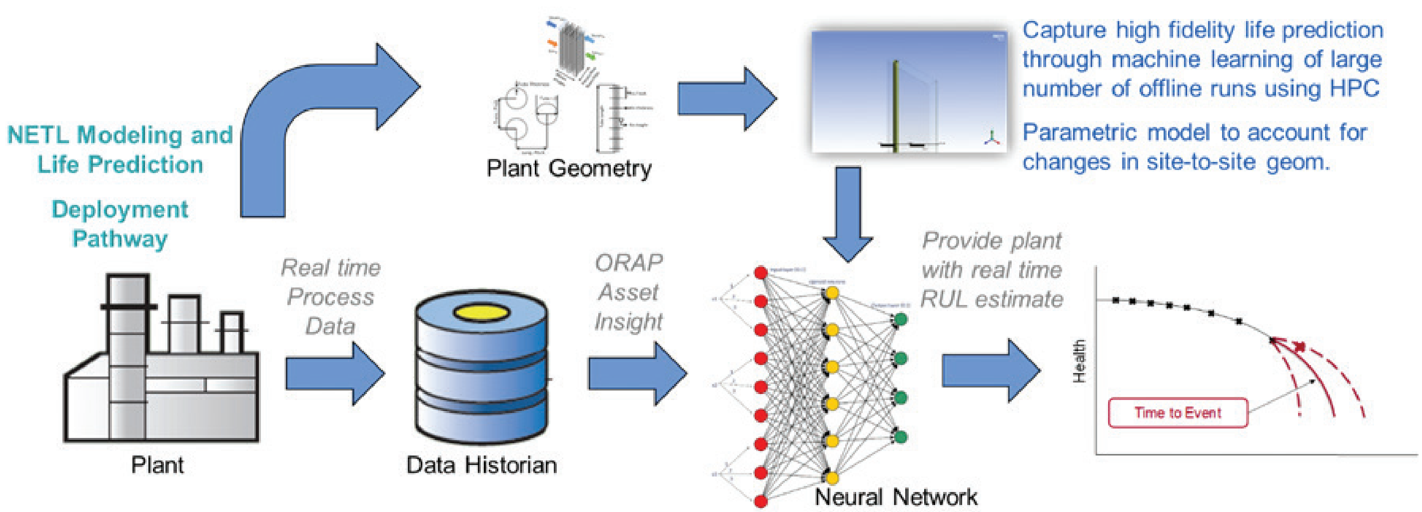
|---|---|
| **Performer** | **Strategic Power Systems, Inc. (SPS)** |
| **Award Number** | FE0032035 |
| **Project Duration** | 06/11/2021 – 06/10/2023 |
| **Total Project Value** | $ 812,807 |
| **Technology Area** | Plant Optimization Technologies |

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

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| **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:

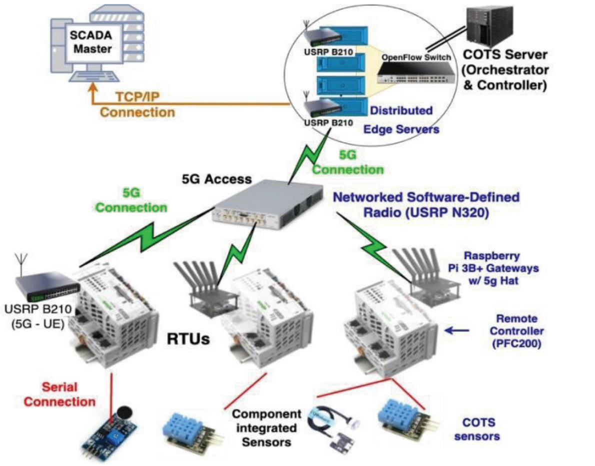
(1) Distributed Edge Computing Service Orchestration for CFPP Component Monitoring: Develop an on-demand DEC platform to gather, process, and efficiently analyze the component health data in the CFPPs. Given that edge computing servers are closer to the field devices in modernized power plants, the efficiency 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 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

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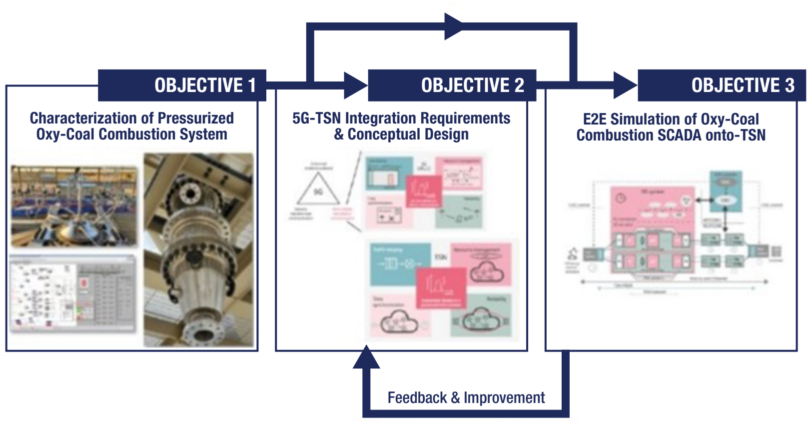
| **Performer** | **University of Texas at El Paso (UTEP)** |
| **Award Number** | FE0032090 |
| **Project Duration** | 09/23/2021 – 09/22/2024 |
| **Total Project Value** | $ 400,000 |
| **Technology Area** | University Training and Research |

The overall goal of the proposed 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: (1) operational characterization of the pressurized oxy-coal combustion system; (2) 5G-TSN integration Requirements and conceptual design; and (3) 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

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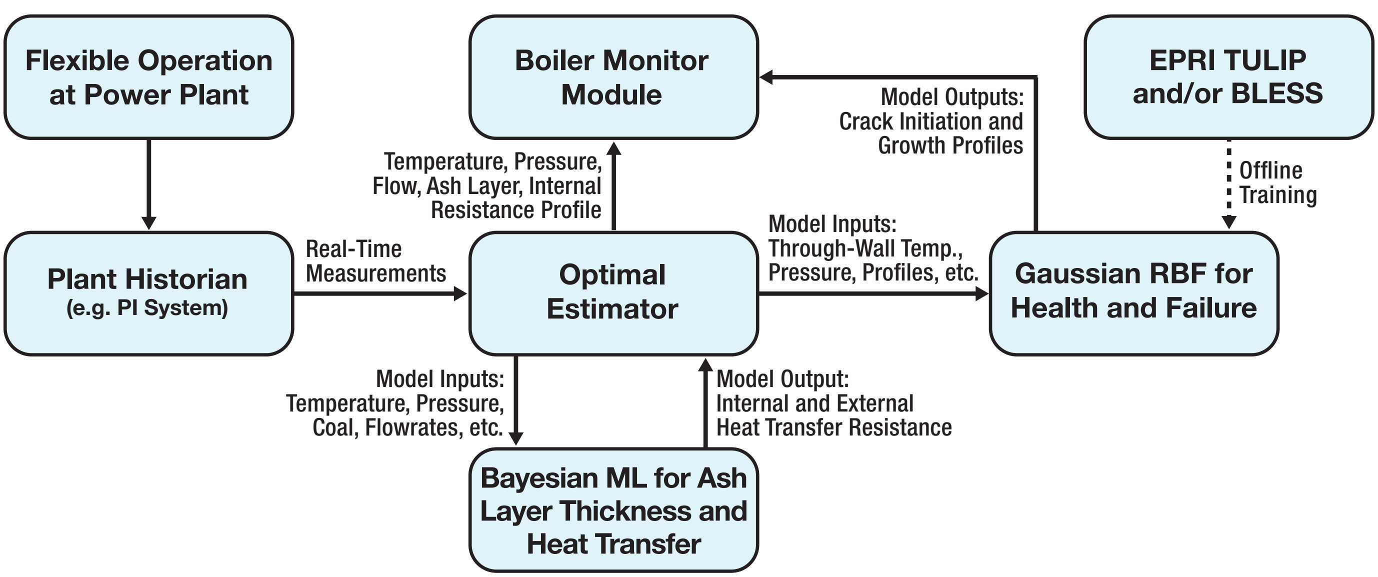
| **Performer** | **West Virginia University Research Corporation** |
| **Award Number** | FE0031768 |
| **Project Duration** | 09/01/2019 – 08/31/2024 |
| **Total Project Value** | $ 2,509,016 |
| **Collaborator** | Electric Power Research Institute, Inc.; Southern Company Services, Inc. |
| **Technology Area** | Coal Utilization Science |

This project seeks to develop methodologies and algorithms to accomplish: (1) a hybrid first principles-AI model of the pulverized coal boiler; (2) a physics-based approach to material damage informed by ex-service component evaluation; (3) 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 (4) 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 hermos-mechanical fatigue damage models.




Hybrid model-based boiler health monitoring framework.

# NOVEL CONCEPTS

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

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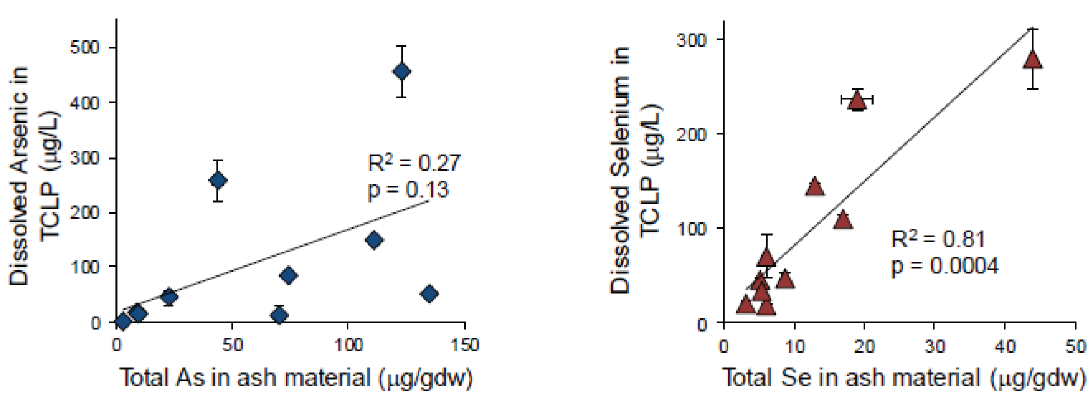
| **Performer** | **Duke University** |
| **Award Number** | FE0031748 |
| **Project Duration** | 09/01/2019 – 05/31/2024 |
| **Total Project Value** | $ 400,000 |
| **Technology Area** | University Training and Research |

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.




**LLeachable 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

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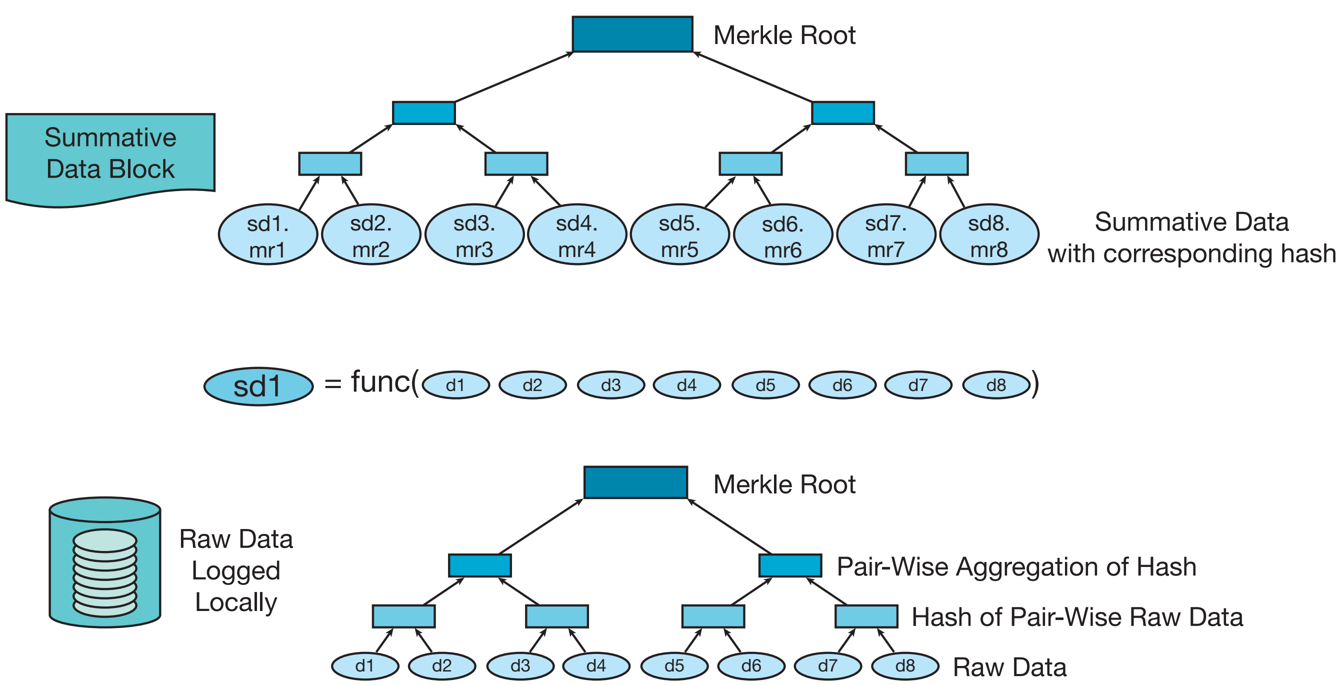
|---|---|
| **Performer** | **Florida International University** |
| **Award Number** | FE0031745 |
| **Project Duration** | 09/01/2019 – 08/31/2023 |
| **Total Project Value** | $ 400,000 |
| **Collaborator** | Cleveland State University |
| **Technology Area** | University Training and Research |

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.**

# Direct Power Extraction

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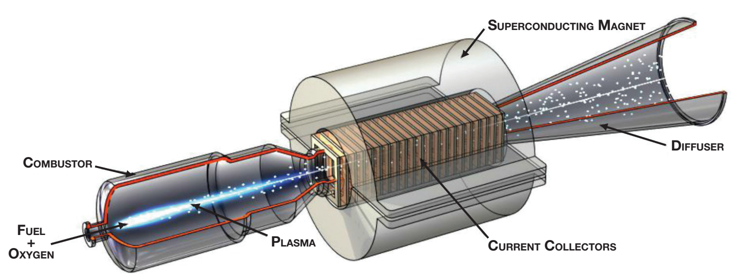
|---|---|
| **Performer** | **National Energy Technology Laboratory (NETL)** |
| **Award Number** | FWP-1022456 |
| **Project Duration** | 04/01/2018 – 03/31/2024 |
| **Total Project Value** | $ 4,033,095 |
| **Technology Area** | Plant Optimization Technologies |

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.**

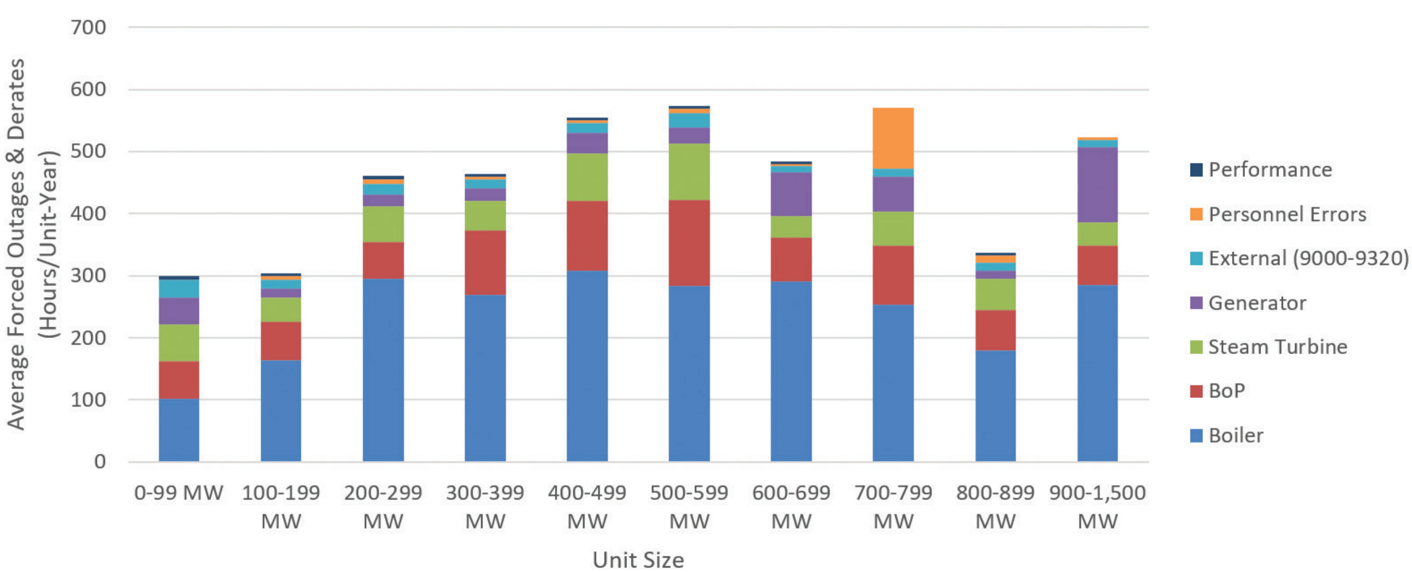
# Market and Benefits Analysis

| Performer | National Energy Technology Laboratory (NETL) |
|---|---|
| Award Number | FWP-1022427 Advanced Sensors and Controls – Task 64 |
| Project Duration | 04/01/2021 – 03/31/2024 |
| 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.



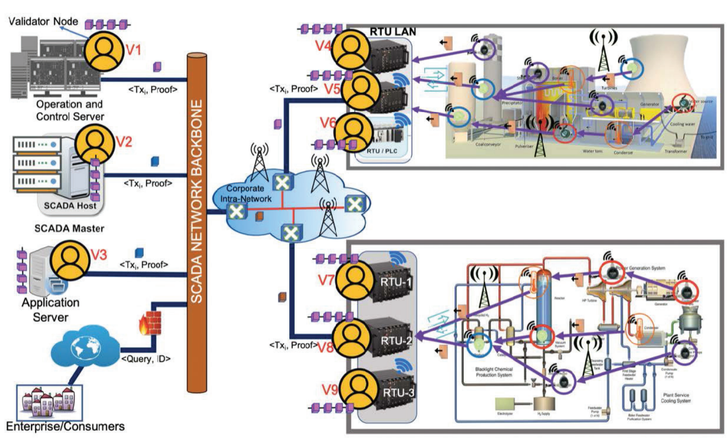

Average annual forced outage hours for coal-fired units (2013–2017), from analysis of NERC GADS data.

# 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 – 08/31/2023 |
| **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.

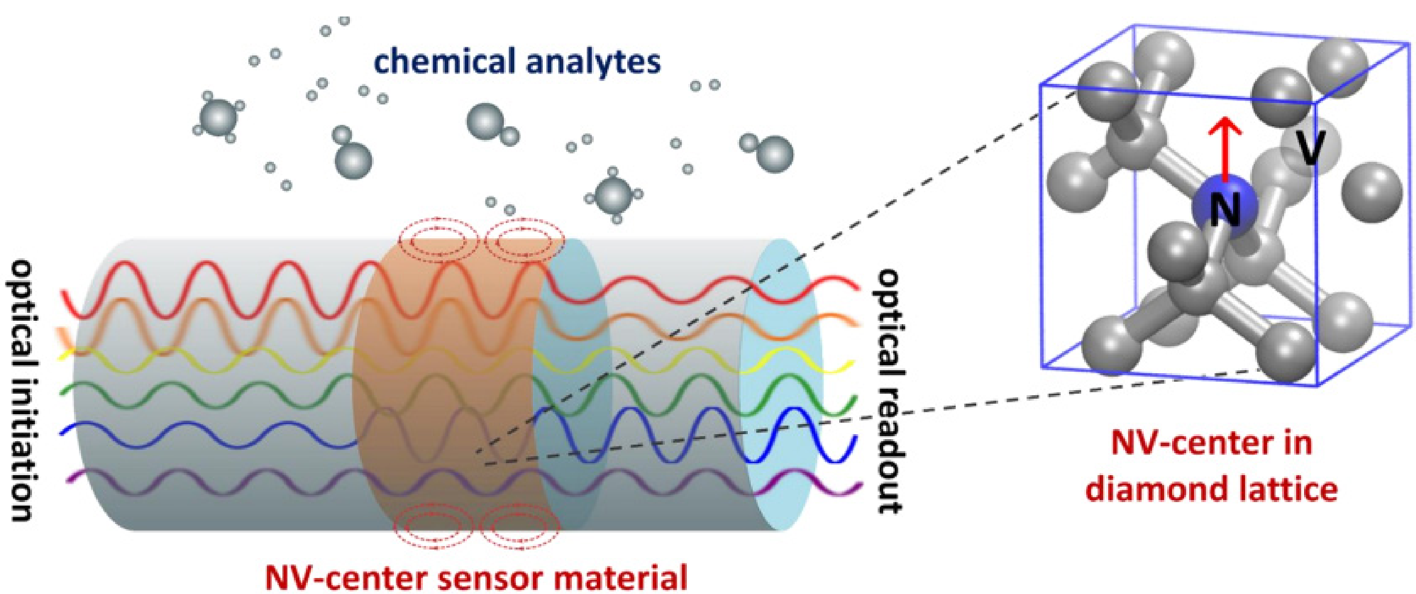



**Blockchain architecture for fossil power plants.**

# 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.



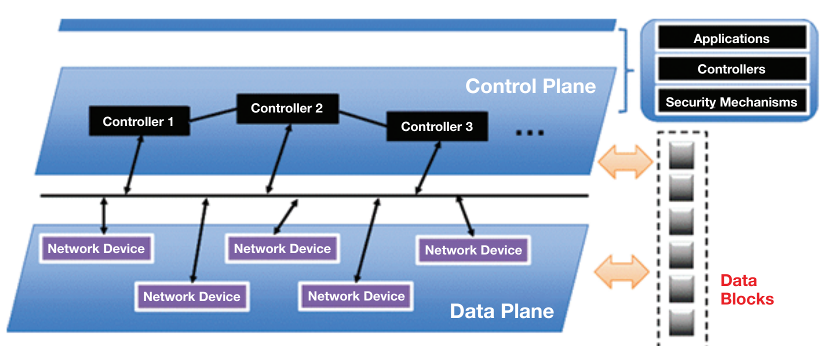

Improving sensing modalities in fossil energy infrastructures.

# 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 – 08/31/2023 |
| 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.

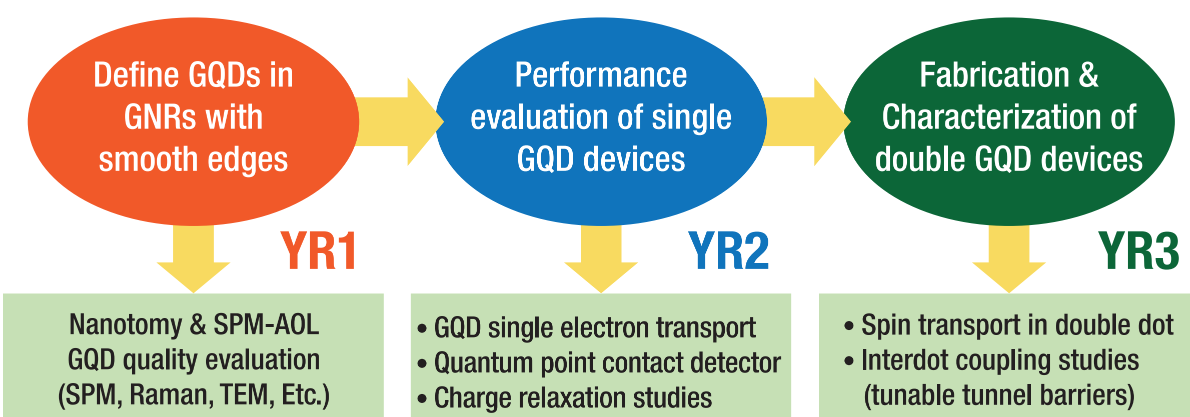
# Ultra-Low Disorder Graphene Quantum Dot-Based Spin Qubits for Cyber Secure Fossil Energy Infrastructure

| 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: (1) 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; (2) conduct low-temperature characterization of quantum transport and spin relaxation times in GQDs to evaluate the effect of lower local disorder; and (3) 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
BF-TEM....bright field transmission electron microscopy
CBM....condition-based monitoring
CCS....carbon capture and storage
CFD....computational fluid dynamics
CFPPs....coal-fired power plants
$CO_2$....carbon dioxide
$Cr_2O_3$....chromium (III) oxide
DCS....distributed control system
DEC....distributed edge computing
DOE....Department of Energy
DPE....direct power extraction
EMI....electromagnetic interference
EPRI....Electric Power Research Institute
FE....Fossil Energy
FECM....Office of Fossil Energy and Carbon Management (DOE)
FP....Fabry-Perot
FWP....Field Work Proposal
GE....General Electric Company
GNR....graphene nanoribbon
GQDs....graphene quantum dots
HCM....Hydrogen with Carbon Management
HRTEM....high resolution transmission electron microscopy
HYPER....Hybrid Performance Facility
IASM....Integrated Additive and Subtractive Manufacturing
ICS....industrial control system
IoT....internet of things
LIBS....laser-induced breakdown spectroscopy
LTI....lizard-inspired tube inspector
MHD....magnetohydrodynamic
mK....millikelvin
NETL....National Energy Technology Laboratory
NOx....nitrogen oxides
NV....nitrogen vacancy
OEM....original equipment manufacturer
ORAP....Operational Reliability Analysis Program
P2P....peer-to-peer
PCF....photonic crystal fiber
PGC....pressure gain combustion
PID....proportional-integrative-derivative
QoS....quality of service
R&D....research and development
R-SOFC....reversible solid oxide fuel cells
RF....radio frequency

# ABBREVIATIONS

RFID .................................. radio frequency identification

RGA .............................................. Raman gas analyzer

SBE.................................. simulation-based engineering

SCADA ............. supervisory control and data acquisition

$sCO_2$.................................... supercritical carbon dioxide

SDN .................................. software-defined networking

Se ...................................................................selenium

SiC ......................................................... silicon carbide

$SmB_6$........................................... samarium hexaboride

SOFC .............................................. solid oxide fuel cell

SPM-OL .................... scanning probe microscopy-based oxidation lithography

SPS ................................ Strategic Power Systems, Inc.

SSC-CCS ...stainless steel/ceramic coaxial cable sensing

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

TRL ...................................... technology readiness level

U.S. ..........................................................United States

UCR .................................. University Carbon Research

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

ZED ..................................................ZigBee end device

$ZrB_2$................................................. zirconium diboride

# NOTES

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https://www.energy.gov/fecm/plant-optimization-technologies

## ACKNOWLEDGEMENTS

The Sensors, Controls, and Other 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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April 2023