

***High Temperature, Harsh Environment Sensors for Advanced Power Generation Systems***

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***Abstract:***

One mission of the Crosscutting Technology Research program at the National Energy Technology Laboratory is to develop a suite of sensors and controls technologies that will ultimately increase efficiencies of existing fossil-fuel fired power plants and enable a new generation of more efficient and lower emission power generation technologies. The program seeks to accomplish this mission through soliciting, managing, and monitoring a broad range of projects both internal and external to the laboratory which span sensor material and device development, energy harvesting and wireless telemetry methodologies, and advanced controls algorithms and approaches. A particular emphasis is placed upon harsh environment sensing for compatibility with high temperature, erosive, corrosive, and highly reducing or oxidizing environments associated with large-scale centralized power generation. An overview of the full sensors and controls portfolio is presented and a selected set of current and recent research successes and on-going projects are highlighted. A more detailed emphasis will be placed on an overview of the current research thrusts and successes of the in-house sensor material and device research efforts that have been established to support the program.

***Introduction:***

The Crosscutting Technology Research Program (CTRP) – located within the Office of Coal and Power R&D (OCP) of the National Energy Technology Laboratory (NETL), which serves as the lead research and development office for the U.S. Department of Energy’s Office of Fossil Energy (FE) – is committed to developing a suite of sensors and controls technologies for advanced fossil energy power generation and carbon capture utilization and storage (CCUS) toward the realization of high-efficiency, low-cost, reliable power in a manner that minimizes environmental impact.

Sensors & Controls (S&C) is one of five (5) key technology areas within CTRP which also includes High-Performance Materials (HPM), Simulation-Based Engineering (SBE), Innovative Energy Concepts (IEC), and Water Management R&D. The High-Performance Materials program is focused on the development of both functional and structural materials for deployment within advanced energy system components. HPM also includes computational materials modeling to enable the rapid design of new and novel alloy materials as well as performance prediction for relevant power plant conditions. The SBE program is devoted to the development

of multi-scale, multi-physics models to computationally replicate a full-scale, virtual power plant environment. This capability provides engineers with a novel way to visualize (and interact) with data streams in order to solve complex process and design problems. IEC comprises transformational technologies that promote increased efficiency and are projected to be implemented on a 10-25 year horizon. Lastly, a relatively new program area is Water Management R&D which has a program focus minimizing the amount of freshwater utilized in power plant systems and conducting fundamental research to increase understanding of the interrelationship between water resources and energy production.

The S&C technology area within CTRP and is focused on growing new classes of sensors, measurement tools, self-organizing information networks, and distributed intelligence for process controls to conduct real-time performance monitoring and health assessment for FE power plants. This investment in S&C technologies has a direct impact by increasing performance via improved heat rate [1], increasing availability and reliability, minimizing unplanned outages, and aiding in coordination of maintenance. Model simulations show that improving the heat rate by 1% for the entire coal-fired power plant fleet translates to \$358 M/year of coal cost savings and a respective reduction of CO<sub>2</sub> emissions by 14.4 Mt/year [2, 3]. A respective increase in availability by 1% generates more than 2.1 GW of additional power from within the existing coal-fired fleet [2, 3]. These benefits serve as the central motivation for investigating advanced S&C methods and implementing cutting-edge research and development (R&D) programs in this technology area.

CTRP uses a balanced approach to R&D investment in the Sensors & Controls area by conducting both in-house research through the NETL's Office of Research & Development (ORD) and sponsoring extramural projects with other organizations. Extramural sensors projects incorporate a wide variety of research topics including high-temperature fiber optic sensors, advanced 3D imaging concepts, microsensors, passive wireless sensing, and embedded technologies. These efforts are performed in concert with the in-house sensors team that has a research emphasis on functional sensor materials, growth of ultra high-temperature optical fibers, fabrication of specialized capillaries for advanced optical sensors and diagnostics, and also advanced sensors testing using NETL's pilot-scale combustion facilities.

The research conducted within the CTRP portfolio of projects are predominantly in the lower technology readiness level (TRL), which includes applied research ranging from established paper-based concepts with little to no experimental verification (TRL 1) through laboratory-scale demonstration in relevant environments (TRL 4). Novel sensor concepts are incubated within CTRP with the goal of establishing feasibility. Within these lower TRLs, there is high risk and high reward. CTRP accepts that some, if not most S&C technologies under investigation may never achieve full commercial-scale deployment. The CTRP portfolio is structured in a nimble manner such that knowledge gained from advanced concepts (whether

commercially successful or not) can be leveraged to keep moving forward and continually improve the current state-of-the-art.

Once a given technology elevate to the level of proof-of-concept and/or demonstration, the technology is transitioned to other OCP Programs or directly to industry for further process and engineering development. The other OCP Programs within NETL include Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Solid Oxide Fuel Cells, Carbon Capture, and Carbon Storage. As the Crosscutting name implies, some technologies will provide benefit to multiple programs and can be further developed for each program's specific applications simultaneously.

This article will give an overview of the current CTRP sensors project portfolio within S&C Program and is divided into two portions – 1) extramural research and 2) in-house research. In both cases, the predominant focus for CTRP is advanced sensing technologies for high-temperature, harsh environments that are typically observed in FE components. The nature of harsh environment conditions depends on the component within the FE-based power plant energy system. Example components include gas turbines (combustion temperatures in excess of 1300°C) [4], boilers (760°C & 34MPa steam conditions) [5], gasification (1300 – 1800°C) [4], etc. Key issues for these components include such features as reducing/oxidizing environments, high levels of corrosion and erosion, extreme vibrations, and shock. Therefore, advanced materials, designs, and packaging concepts for sensors are needed to ensure survivability, durability, and robustness. A discussion of how CTRP is meeting these challenges for sensor measurement and monitoring is given below.

#### ***Extramural Research Program Overview:***

The Crosscutting Technology Research Program (CTRP) utilizes a bipartite approach to implementing R&D – 1) management of extramural research, and, 2) performing in-house research through NETL's Office of Research and Development (ORD). Extramural projects include financial assistance in the form of grants and cooperative agreements to a wide variety of non- and for-profit organizations. CTRP also funds research with other national laboratories and governmental entities through Field Work Proposals (FWP). The FWP that supports NETL ORD's in-house research activities for Sensors and Controls is the Innovative Process Technologies (IPT) FWP. Detailed overviews of both NETL's extramural research and NETL in-house activities through the IPT Program for advanced sensors development are given in the sections that follow.

All projects within CTRP for Advanced Sensors & Distributed Intelligent Controls portfolio are categorized as follows:

- Advanced Sensors

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

The Advanced Sensors program within CTRP is predominantly focused on expanding the functionality of sensors technologies in order to achieve durable, reliable operation in harsh environments. The three main research focus areas within Advanced Sensors include optical sensors, microsensors, and novel sensor concepts. Optical sensor research is dedicated to a range of techniques from non-contact, laser-based methods to novel fiber optic designs. Microsensor research encompasses development efforts to achieve sensing at elevated temperature (>500°C) with improved selectivity and accuracy with respect to a specific parameter such as gas concentration. Novel Sensor Concepts refers to innovative sensing methods including non-traditional sensing and interrogation techniques, wireless sensors, energy harvesting and management, advanced sensor manufacturing and fabrication methods, embedded sensor technology, and investigating the use of novel materials. These technology groupings cover a wide spectrum with respect to the end-use component applications within a coal-fired power plant. Typical end-use components include boilers, gasification systems, industrial gas turbines, and carbon sequestration. Specific measurement parameters for each component are discussed below.

Virginia Tech (#FE0012274) is currently investigating a new modal waveguide design for sapphire optical fiber. Using wet acid etching techniques, this project team can tailor the microstructure and size of single crystal sapphire fibers with low modal volume (LMV) [6]. This research will also demonstrate a Raman-based distributed sensing system that will allow for real-time monitoring of temperature at distributed locations inside a gasifier or boiler [6]. Optical sensors are also being deployed to perform three-dimensional temperature profile of boilers by the research team at University of Massachusetts (#DE-FE0023031). This research utilizes optically generated acoustic signals to create real-time temporal and spatial distributions for temperature profile in coal-fired boilers. Another project with Tech4Imaging (#DE-SC0010228) is using Electrical Capacitance Volume Tomography (ECVT) to conduct imaging and mass-flow measurement of process variables in real-time for multiphase flow systems.

A second end-use application for fossil energy generation is industrial gas turbines. Key sensing needs for this component includes typical process conditions such as temperature and pressure, but also thermal and mechanical damage of materials due to high fatigue cycling [7, 8]. University of Central Florida (#DE-FE0007004) is developing polymer derived ceramics (PDCs) made of aluminum-doped silicon carbide nitride materials to create radio frequency resonator-

based wireless stress/strain sensors for in-situ measurement inside a gas turbine[9]. Sensor prototypes have been demonstrated at temperatures up to 1300°C [9]. Another project that is focused on doped PDCs for gas turbine application is Sporian Microsystems, Inc. (DE-SC0008269). Materials development of the resistance-based temperature sensor, rated up to 1800°C, includes thermal decomposition analysis of various precursors in order to optimize the mechanical properties at high temperatures [10]. Lastly, University of Florida (#DE-FE0012370) is currently investigating advanced manufacturing techniques for sapphire optical fibers. The research effort is developing standardized manufacturing process profiles which combine ultra-short pulse laser micromachining (LM) and spark plasma sintering (SPS) to realize packaged structures capable of temperatures up to 1000°C and pressures up to 1000 psi [11].

General Electric Global Research (#DE-FE0010116), Intelligent Optical Systems, Inc. (IOS, #DE-FE0010318), New Mexico Institute of Mining and Technology (#DE-FE0009878), and Missouri University of Science and Technology (#DE-FE0009843), have developed sensing methods to conduct remote monitoring for deep underground CO<sub>2</sub> sequestration cavities. GE recently investigated a fiber optic multiplexing technique for Microelectromechanical (MEMS) pressure sensors. Through this research effort, GE has developed a pulsed laser interrogator scheme capable of multiple (100+) simultaneous sensor measurements in environments up to 250°C and 10,000psi [12, 13]. Intelligent Optical Systems, Inc. has developed technology which uses polymer-coated silica fiber enhanced with colorimetric indicator that changes color (and attenuation) with CO<sub>2</sub> exposure. The IOS research team has established that changes in color depends on CO<sub>2</sub> concentration and is reversible [14]. Demonstration of the prototype technology will be conducted via subsurface sensor deployment and operation at depths of approximately 5,900 ft. and static pressures up to 2,000 psi by FY16 [14]. New Mexico Institute of Mining and Technology is investigating an iridium oxide electrode based CO<sub>2</sub> sensor that is able to measure the dissolved CO<sub>2</sub> concentration in produced water [15]. Research for this project has included the preparation of the iridium oxide electrode by oxidation of iridium wire in carbonate melt at high temperature, then conducting observations of sensor response with respect to pH [15]. A smooth, linear response was observed for pH from 1 to 13 [15]. Lastly, MS&T is investigating a novel ceramic coaxial cable sensor platform for in-situ monitoring of CO<sub>2</sub> injection and storage. The basis for measurement includes coaxial cable Bragg gratings (CCBGs) and coaxial cable Fabry-Perot interferometers (CCFPis) [16]. This technology is capable of multiple measurements including temperature, pressure, and strain [16].

CTRP currently has a portfolio of active projects that deal with embedded sensor technology, representing a transformational breakthrough for structural health monitoring. The vision for these novel sensor concepts is to achieve a “smart part” that enables structural components such as refractory lining with embedded intelligence that offers in-situ information about the health of a component. This can give information to avoid unplanned outages (and even catastrophic failures), optimize process controls, and also provide information for

engineers to schedule routine maintenance. University of Texas El Paso (UTEP, #DE-FE0012321) and United Technologies Research Corporation (UTRC, #DE-FE0012299) are optimizing 3D printing techniques to realize embedded sensors for gas turbine applications. UTEP is employing electron beam melting to demonstrate “stop and go” manufacturing techniques. The “stop and go” process includes fabrication of a compartment within Ti-6Al-4V material, pausing the process to insert a PZT/LiNbO<sub>3</sub> piezoelectric sensor, then completing the 3D layering process fabrication steps to encapsulate the sensor [17, 18]. UTRC is using high-velocity metal powder cold spray deposition combined with direct metal laser sintering (DMLS) to demonstrate their Additive Topology Optimized Manufacturing with Embedded Sensing (ATOMeS) process methodology. This novel method seeks to yield near net shape components by incorporating structural and electromagnetic modeling along with real-time diagnostics via health-utilization-monitoring system (HUMS) [18, 19]. Researchers at Missouri University Science & Technology (MS&T, #DE-FE0012272) are investigating using optical carrier-based microwave interferometry (OCMI) embedded sensors for the realization of “smart liner block” and “smart pipes.” MS&T employs a freeze-form extrusion fabrication (FEF) process which enables the creation of functionally graded materials including gradings from ceramics and refractory metals [20]. This AM technique, used in concert with the OCMI sensor will allow for in-situ measurement of temperature up to 1600°C, pressure, and refractory wall cracking and thinning via strain sensing [21]. The overarching research emphasis for each of these embedded sensing projects is the assessment of sensor parameters before and after fabrication along with mechanical testing to demonstrate that the component can still achieve its sought-after structural purpose in a seamless fashion. The lasting impact of projects such as this will be improving the understanding of component health which in turn will lead to more efficient operation and increased availability of energy system components.

CTRP also funds sensors projects that are fundamental in nature. The State University of New York (SUNY; DE-FE0007190) is developing heat-activated plasmonic chemical sensors for H<sub>2</sub>, CO, and NO<sub>2</sub> capable of 500 – 800°C operation [22]. The technology is centered on creating gold (Au) nanoparticles embedded in a metal oxide matrix with stabilized geometry and optical signature at high temperatures [22, 23]. The University of Pittsburgh (#DE-FE0003859) have conducted research in fiber optic sensor platform technology that is stable up to 1100°C and capable of measuring optical flow, temperature (up to 800°C), pressure (15 – 2000psi), and H<sub>2</sub> concentration (0.2 – 10%) [24]. The underlying technology for their research includes regenerative techniques for fiber Bragg grating (FBG) fabrication [24, 25, 26]. A number of breakthrough have come from this project including high-temperature fiber laser sensors and distributed chemical sensing at high operation temperatures up to 700°C [24].

It should be noted that the essential purpose of the data stream that comes from component-level sensors and sensor networks is the production of actionable information that aids in the achievement of optimal performance (high thermal efficiency; low emissions) for

power plant operation with Carbon Capture and Sequestration (CCS) technology. Research conducted by CTRP that focuses on dynamic process modeling, real-time data management, and resulting decision process for sensor information comprises the Distributed Intelligent Controls (DIC) program. There are two research thrusts within DIC – 1) Advanced Process Control, and 2) Sensor Placement & Networks. Advanced Process Control includes computational efforts to produce high-fidelity models that realistically represent inherently complex, non-linear processes observed in FE systems. Reduced order and computationally fast models allow for advanced state estimation and predictive control using real-time data as input. Sensor Placement & Networks refers to the computational and measurement-based approaches to investigate the optimal placement of sensors to accomplish multiple objectives such as performance, fault management, and low cost. Central to both research efforts is the goal of realizing cognitive functionality between sensing and actuation in a manner that achieves distributed intelligence within a given control architecture. Simulation tools and hardware-based test beds through CTRP have been developed to evaluate such novel concepts and also provide a platform to assess advanced control technologies [27 – 35].

#### *Future Research Pathways*

As shown in the discussion above, CTRP actively supports a wide variety of cutting-edge research for advanced sensing technologies representing the current state of the art for high-temperature, harsh environment applications. Looking toward the future, CTRP will continue to play a key role within this field by leveraging current technologies into new, near-term research areas.

A key technology area that CTRP is delving into is sensors for water resource management related to fossil energy generation systems and the Water-Energy Nexus [36]. The ability to conduct real-time water quality measurements of properties such as total dissolved solids (TDS), temperature, pH, clarity (turbidity), and other key indicators for process control, efficiency, and environmental safety is a critical issue of the future. Additionally, integrated sensor packages that are capable of conducting multiple measurements is a key technology target that is essential in order to maximize the investment in utilizing such technologies over traditional methods.

CTRP is also investigating smart sensor technologies that integrate sensing mechanism, power, electronics, and wireless communication into a stand-alone packaged unit for any high-temperature, FE-relevant component. CTRP also seeks to incorporate rapid fabrication techniques into the manufacture of the sensor itself. An example of this would be to use additive manufacturing to print the electrical circuitry directly in a manner that would reduce the overall fabrication process steps and also lower production cost.

High-temperature sensing in harsh environment remains a foundational, fundamental objective for CTRP. One such sensing need is within the hot gas path (HGP) for industrial gas turbines. Process temperatures near the combustion zone for gas turbines are in the range of 1700 – 1800°C and pressures up to 35MPa. CTRP is investigating novel sensor concepts that advanced the current state of the art for HGP sensing which has yet to achieve measurement capability able to withstand such high-temperature operation in a durable, low-cost fashion.

***In-House Research Program Overview:***

In support of the Crosscutting Technology Research Program (CTRP), an in-house sensors research effort has been established within NETL's Office of Research & Development (ORD) through the Innovative Process Technologies (IPT) Field Work Proposal (FWP). The program within IPT has a strong focus on harsh environment sensor material and device technology research and development. By placing an emphasis on the establishment of unique testing facilities for sensor materials and devices representative of various power generation and unconventional resource recovery environments, the team has developed a laboratory which can be deployed in a flexible manner to support current and future CTRP research priorities and thrusts. A near-term emphasis has been placed on research and development of high temperature compatible optical-based sensing materials and optical fiber sensors due to several inherent advantages of the sensing platform for harsh environments including (1) elimination of wires and electrical components at the sensing location, (2) compatibility with distributed interrogation methodologies, and (3) increased safety for deployment in flammable gas mixtures among others. In contrast with chemi-resistive based sensing responses in metal oxides and related functional sensor materials which have been widely studied and reported on, high temperature optical sensing responses of analogous materials systems are not as well understood in terms of both the mechanistic fundamentals and response optimization [37-38]. Over the last few years, the in-house team has therefore performed a combination of fundamental and applied materials investigations coupled with prototype device fabrication, testing, and simulations. In parallel, the team has also developed strong partnerships with extramurally funded projects by the CTRP to further accelerate and promote the development of harsh environment sensing material-enabled devices. An overview of the recent successes and developments that have resulted from these efforts and collaborations is provided below.

It should be pointed out that the discussion presented below is not intended to be an exhaustive review of the field. Instead, it is intended to highlight the unique contributions and successes reported by the in-house team at the NETL. The reader is encouraged to review the references contained in the original published works that are summarized here for a broader perspective regarding recent and current relevant research that is on-going in the field by other groups working in related technical areas.

### *Metal Oxide Functional Sensor Layers*

Because of the need for an improved fundamental understanding of the optical based sensing responses, early efforts were focused on common sensing materials utilized for chemi-resistive sensing platforms including SnO<sub>2</sub> [37], ZnO [39], and TiO<sub>2</sub> [40]. A particular emphasis was also placed upon H<sub>2</sub> sensing at temperatures of 500°C and greater due to the applicability to solid oxide fuel cells as well as gas turbine combustion environments. In the case of SnO<sub>2</sub>-based sensing layers, significant optical responses were observed for H<sub>2</sub> sensing at elevated temperatures. However, they were attributed to partial film reduction to metallic Sn and reoxidation upon exposure to oxidizing conditions. Partial film reduction is non-ideal for high temperature sensing applications in highly reducing conditions as would be relevant for anode streams of solid oxide fuel cells, for example [37]. In the case of both ZnO and TiO<sub>2</sub>, sensing responses could not be resolved using standard transmission spectroscopy based interrogation of films deposited on planar substrates [39-40]. In addition, the ZnO films that were investigated displayed volatility in reducing atmospheres at temperatures above approximately 400°C [39] while the TiO<sub>2</sub> films under investigation showed microstructural instabilities at temperatures of 850°C in reducing atmospheres associated with the anatase to rutile transformation [40-41].

By increasing the free carrier concentration in the conduction band and hence the electrical conductivity of conventional sensing oxides through doping of ZnO by Al and TiO<sub>2</sub> by Nb, respectively, dramatically enhanced optical sensing responses were demonstrated in both the near-infrared region as well as near the ultraviolet band-edge. The responses could be successfully modeled based upon standard optical constant models for transparent conducting oxides in both planar film and optical fiber sensing tests, with the near-infrared response directly linked with the electrical conductivity of the films and the band-edge response attributed to the well-known Burstein-Moss effect [39, 42-43]. A particularly interesting observation for this class of materials was the ability to tailor the magnitude and even the sign of the optical response through roughening of the film surface to impart a significant degree of attenuation due to light scattering rather than absorption [42]. However, potential instabilities of materials systems noted in the previous section would be expected to limit their relevance for the most aggressive high temperature conditions of interest.

Perovskite-based oxides such as SrTiO<sub>3</sub> are well known to be highly stable under elevated temperature conditions relevant for solid oxide fuel cells and other high temperature applications due to their widespread deployment as catalyst, infiltrate, and anode or cathode materials amongst others [44]. Such materials have also been previously demonstrated to show attractive properties as metal oxide-based sensing layers for extremely high temperature and harsh environment resistive based sensing applications [45]. The optical sensing responses of undoped and La-doped SrTiO<sub>3</sub> were therefore explored in the near-IR wavelength range for high

temperature H<sub>2</sub> sensing at temperatures approaching 900°C and an enhanced response was observed for the doped variants which exhibited a higher electrical conductivity in reducing atmospheres, consistent with observations previously reported in the TiO<sub>2</sub> and ZnO-based systems [39, 42, 46]. The La-doped SrTiO<sub>3</sub> films investigated were shown to have a monotonic response up to 100% H<sub>2</sub> in a background of ultra-high purity N<sub>2</sub> at temperatures of 750°C, thereby making them directly relevant for anode stream sensing in solid oxide fuel cell applications.

#### *Au-Nanoparticle Incorporated Metal Oxide Sensing Layers*

Au-nanoparticle incorporated metal oxides including YSZ, TiO<sub>2</sub>, ZnO, CeO<sub>2</sub>, NiO, and Co<sub>3</sub>O<sub>4</sub> have been demonstrated to display enhanced optical chemical sensing responses at elevated temperatures in the visible range relative to the corresponding base oxides by a number of different groups including Carpenter et al. [47-50], Martucci et al. [51-52], and Ando et al. [53-54]. The earliest work by the in-house team pursued the addition of Au nanoparticles to TiO<sub>2</sub>-based thin films and observed (1) enhanced stability of the microstructure as a result of Au-nanoparticle incorporation under highly reducing conditions and (2) large and reversible optical sensing responses in the vicinity of the Au localized surface plasmon resonance (LSPR) peak associated with shifting of the LSPR peak at temperatures as high as 850°C which were not present for the base TiO<sub>2</sub> films prepared in a similar manner [40-41]. The team subsequently investigated a class of so-called Au / “inert” oxide films such as Au / SiO<sub>2</sub> and Au / Al<sub>2</sub>O<sub>3</sub> in an attempt to identify sensing materials with higher ultimate temperature stability for the most harsh environment applications while also reducing the refractive index of the sensing layer for increased compatibility with the optical fiber sensing platform [55-56]. For Au / SiO<sub>2</sub> based optical fiber sensors, useful high temperature H<sub>2</sub>, CO, and O<sub>2</sub> sensing responses were observed at temperatures as high as 850-900°C in the form of a shift in the Au LSPR absorption peak [55].

In addition, a characteristic temperature dependence of the Au localized surface plasmon resonance absorption peak was also observed and explained through theoretical modeling [55,57]. A particularly interesting result of this work was a demonstration that unique wavelength dependences associated with these effects could potentially allow for the simultaneous monitoring of information about the chemical composition as well as the temperature of a high temperature gas stream through broadband or multi-wavelength interrogation approaches [41, 55, 57]. The concept was subsequently extended to other Au-nanoparticle incorporated oxide based systems and was expanded upon by exploiting temperature dependent shifts in the band-edge of the oxide matrix to simultaneously and selectively monitor temperature in the ultra-violet wavelength range [41].

### *Optical Fiber Sensor Device and Interrogation Methodology*

In parallel with sensor material research activities conducted under the Innovative Process Technologies FWP, NETL's in-house team has also pursued the development of ancillary technologies and methodologies that would ultimately be required to successfully enable the realization of fabricated sensor devices capable of robust operation under high temperature environmental conditions. As one example, the team has developed waveguide modeling tools to simulate the transmission through a sensor element comprised of a single layer thin film on the core of a multi-mode optical fiber based upon the Fresnel equations [43]. The developed code has been used to successfully reproduce the sensing response features observed in optical fiber sensors fabricated using several different sensing materials explored in this body of work including Au-nanoparticle incorporated oxides (e.g. Au / SiO<sub>2</sub>) as well as high electronic conductivity transparent conducting oxides (e.g. Al-doped ZnO)[43,58]. The code is capable of simulating the total power output from an evanescent wave absorption spectroscopy sensor region of a desired geometry for a sensing material layer of arbitrary assumed values of optical constants and thickness. The wavelength and angular distribution of light intensity at the input of the waveguide can also be specified allowing for an investigation of the launch and collection conditions on the overall signal to noise ratio of a fabricated sensor element [43, 58].

Early optical fiber sensor prototype tests demonstrated that the presence of H<sub>2</sub> in the gas stream at elevated temperatures as high as 700-800°C can result in transmission modifications to the sensor due to interactions with the silica matrix of the optical fiber sensing device platform [55]. Therefore, an increased emphasis has been placed on understanding and mitigation of optical fiber instabilities under application relevant high temperature operational conditions. First, new investigations were initiated that aimed to better understand the stability of conventional silica based optical fibers with a particular emphasis on the impacts of high temperature H<sub>2</sub> exposures on the measured optical fiber transmission [59]. Second, new facilities have been established for manufacturing of custom optical fibers consisting of higher temperature stable materials such as sapphire using a laser-heated pedestal growth technique. As the technology under development continues to mature, identification of a low-cost and stable optical sensing platform will become increasingly important for the ultimate realization of commercially deployable and harsh environment compatible optical fiber sensor devices.

A primary advantage of the optical fiber based sensing approach under investigation is the ability to perform distributed interrogation for a single sensor element through integration with Fiber Bragg gratings or scattering based interrogation approaches [60-63]. While the former have been employed widely with significant success, the majority of Fiber Bragg gratings are inherently unstable under elevated temperature operational conditions of approximately 500°C and greater [64-65]. In contrast, scattering based approaches employing optical time domain and optical frequency domain reflectometry (OTDR and OFRD) show significant promise for extreme temperature distributed sensing applications as they can take advantage of inherent scattering processes within the silica fiber. Research activity has been initiated that

seeks to apply these techniques to fabricated sensors under high temperature operational conditions. Preliminary successful results for localized monitoring of H<sub>2</sub> concentration along the length of a fabricated optical fiber sensor element has already been reported by the team and will be a subject of continuing investigation into the future [66-67].

#### *Collaborations with NETL Extramurally Funded Projects*

The in-house team has developed strong partnerships with a number of extramurally funded research projects which have been sponsored through CTRP and is always in search of new opportunities for fostering collaborations that leverage on-going funded activity to more effectively advance and promote the program mission. One example of a successful collaboration exploited the unique surface science facilities available at the laboratory in collaboration with the Carpenter group at University of Albany to provide additional potential evidence for an electronic charge transfer mediated mechanism of the observed Au LSPR absorption peak shift in Au incorporated oxides such as yttria-stabilized zirconia (YSZ) [68]. Another successful collaboration with the Chen group at the University of Pittsburgh resulted in the development of a nanostructuring approach for the engineering of refractive index of functional metal oxide based sensing layers for optimized compatibility with the optical fiber sensor platforms [66-67]. Several on-going collaborations are active with these same partners as well as a significant number of additional funded projects with a number of significant new successes and accomplishments resulting from these interactions to be reported in the very near future.

#### ***Conclusions and Summary:***

The Crosscutting Technology Research Program within the U.S. Department of Energy's National Energy Technology is dedicated to the development of advanced sensors and controls technologies to enable high-efficiency, low-cost fossil energy-based power generation. Research in S&C technology area allows for improved heat rate for coal-fired power plants through process monitoring and health assessment as well as increasing availability and reliability. CTRP has a broad charter that utilizes Advanced Sensors in concert with Distributed Intelligent Controls for a wide variety of high-temperature and harsh environment components including gas turbines, boilers, gasification systems, carbon capture, and carbon storage. By conducting applied research in the TRL 1 to TRL 4 range, CTRP is meeting the sensing needs for each component by incubating new ideas in a host of different sensor technologies including optical sensors, microsensors, and novel concepts such as advanced manufacturing and embedding techniques.

CTRP uses a balanced approach to investing in research to support the advancement of sensors technologies – via 1) extramural projects, and, 2) in-house research through the Innovative Process Technologies FWP with NETL's Office of Research & Development.

Extramural projects include financial assistance to a diverse group of non- and for-profit organizations. Project highlights presented in this article featured the breadth of technologies that are currently under investigation including 3D imaging techniques at high temperatures for boiler application, fiber optic-based sensing for downhole CO<sub>2</sub> monitoring at high pressures, and also embedded sensing projects for structural health monitoring.

Extramural projects within the CTRP portfolio are leveraged by the expertise in advanced sensor materials and device technology provided by NETL's in-house Advanced Sensors Development Team. Through IPT, the in-house research team has made large strides in the area of chemi-resistive based sensing response for metal oxide and related functional sensor layers. A brief overview of the fundamental and applied materials investigations including how this expertise has been coupled with device fabrication, modeling, and testing was presented. Also, collaborations with extramurally funded projects were featured.

Looking ahead to the future, CTRP is delving into new FE-relevant application areas including water resource management, passive wireless sensors, and high-temperature sensing for hot gas path within industrial gas turbines. Each of these applications offer challenges that only next-era technologies will be able to solve. Through both extramural and in-house expertise, CTRP is poised to continue its leadership role within the sensors and controls technology area for high-temperature, harsh environments and will strive to continue advancing the current state of the art.

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### ***Acronyms and Nomenclature***

AM	Additive Manufacturing
ATOMeS	Additive Topology Optimized Manufacturing with Embedded Sensing
CCBG	Coaxial Cable Bragg Gratings
CCFPI	Coaxial Cable Fabry Perot Interferometer
CTRP	Crosscutting Technology Research Program
CCUS	Carbon Capture Utilization Storage
DIC	Distributed Intelligent Controls
DMLS	Direct Metal Laser Sintering
FBG	Fiber Bragg Grating
FE	Fossil Energy
FGM	Functionally Graded Materials
FWP	Field Work Proposal
HGP	Hot Gas Path
HPM	High-Performance Materials
HUMS	Health Utilization Monitoring System
IGCC	Integrated Gasification Combined Cycle
IEC	Innovative Energy Concepts
IPT	Innovative Process Technologies
LSPR	Localized Surface Plasmon Resonance
MHD	Magnetohydrodynamics
MS&T	Missouri University Science & Technology
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
OCP	Office of Coal and Power R&D
OMCI	Optical Carrier-Based Microwave Interferometry

ORD	Office of Research and Development
S&C	Sensors & Controls
SBE	Simulation-Based Engineering
SBIR	Small Business Innovative Research
SCC	Strategic Center for Coal
TRL	Technology Readiness Level
TDS	Total Dissolved Solids
UCR	University Coal Research
UTRC	United Technologies Research Center
UTEP	University of Texas El Paso
YSZ	Yttria-Stabilized Zirconia