CROSSCUTTING RESEARCH PROGRAM
ADVANCED MANUFACTURING PROJECT PORTFOLIO

April 2018

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

DISCLAIMER

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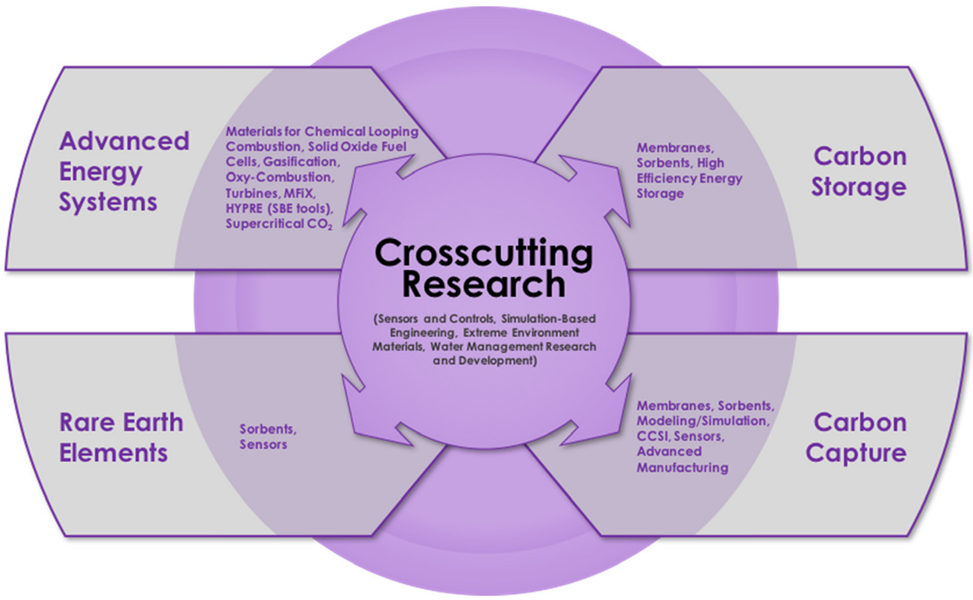
INTRODUCTION

The Crosscutting Research Program develops a range of innovative and enabling technologies that are key to improving existing power systems and essential for accelerating the development of a new generation of highly efficient, environmentally benign fossil fuel-based power systems. The mission space is focused on bridging the gap between fundamental and applied research and development (R&D) efforts. Technologies that successfully bridge this gap are intended to offer viable step-change improvements in power system efficiency, reliability, costs, and environmental impacts.

The research fundamental to the Crosscutting Research Program overlaps and benefits other Office of Fossil Energy (FE) program areas—rare earth elements, carbon capture, carbon storage, and advanced energy systems—as shown in the figure below.



Crosscutting Research Technology Overlaps with Other Fossil Energy Program Areas.

The Crosscutting Research Program executes R&D efforts by partnering and collaborating with research institutions and the power generation industry throughout the United States and in select international locations. The Crosscutting Research Program also sponsors one of the longest running and most important university training and research programs to reinforce the research-based education of students at U.S. universities and colleges with emphasis on fossil energy science. The major objective for this program is to produce tools, techniques, and technologies that map to the Clean Coal Research Program efforts.

The Crosscutting Research Program is comprised of three focus areas: Coal Utilization Sciences, Plant Optimization Technologies, and University Training and Research. A description of each area follows.

Coal Utilization Sciences: The Coal Utilization Sciences technology area research effort is focused on modeling and simulation technologies that lead to a suite of products capable of designing and simulating the operation of next-generation, near-zero-emissions power systems such as gasification and oxy-combustion. Models can also solve current plant operational and lifetime issues. These products are based on validated models and highly detailed representations of equipment and processes.

Plant Optimization Technologies: The Plant Optimization Technologies technology area exists to improve availability, efficiency and environmental performance of coal-based fossil energy power generation plants. Research is focused on sensors and control systems, materials, and water management as the basis for successful implementation of advanced power generation systems in the harsh coal-fired environment. This area also explores novel concepts such as direct power extraction and the application of additive manufacturing towards constructing complex components (e.g., turbine blades with embedded sensing capabilities).

University Training and Research: The University Training and Research (UTR) program awards research-based educational grants to U.S. universities and colleges in areas that benefit the FE and the Crosscutting Research Program. UTR is the umbrella program under which the University Coal Research (UCR) and Historically Black Colleges and Universities (HBCU) and Other Minority Institutions (OMI) initiatives operate. These grant programs address the scientific and technical issues key to achieving Fossil Energy's goals and build our nation's capabilities in energy science and engineering by providing hands-on research experience to future generations of scientists and engineers. The program also coordinates with and seeks opportunities to partner with State and Tribal governments and engage industry, universities, and non-governmental organizations (NGOs) on the responsible use of fossil fuels nationally and internationally.

In addition to the Crosscutting Research Program listed above, the National Energy Technology Laboratory (NETL) uses its participation in the U.S. Department of Energy's (DOE) Office of Science **Small Business Innovation Research (SBIR) Program** to leverage funding, enhance the research portfolio, and, most importantly, facilitate a pathway to commercialization. SBIR is a highly competitive program that encourages small businesses to explore technological potential and provides the incentive to profit from commercialization. By including qualified small businesses in the nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit to meet specific research and development needs. SBIR targets the entrepreneurial sector because that is where most innovation and innovators thrive. By reserving a specific percentage of Federal R&D funds for small business, SBIR protects small businesses and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and encourages the commercialization of the technology, product, or service which, in turn, stimulates the U.S. economy. Since its inception in 1982 as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses compete for Federal research and development awards. These contributions have enhanced the nation's defense, protected the environment, advanced health care, and improved our ability to manage information and manipulate data.

The Crosscutting Research Program fosters the development of innovative power systems by conducting research in these key technology areas:

Sensors and Controls: The basis for this research area is to make available new classes of sensors and measurement tools that manage complexity; permit low cost, robust monitoring; and enable real-time optimization of fully integrated, highly efficient power-generation systems. Sensor development focuses on measurements to be made in high temperature, high pressure, and/or corrosive environments of a power system or underground injection system. Harsh environment sensing concepts and approaches focus on low cost, dense distribution of sensors; exploration of sensor networking using passive and active wireless communication; and thermoelectric and vibration energy harvesting approaches. Advanced manufacturing techniques focus on how to lower cost and improve fabrication of sensors. Controls research centers on self-organizing information networks and distributed intelligence for process control and decision making.

High Performance Materials: Materials development under the Crosscutting Research Program focuses on structural materials that will lower the cost and improve the performance of fossil-based power-generation systems and on functional materials, which are designed to perform specified non-structural tasks (e.g., shape memory materials or barrier coatings). Computational tools in predictive performance, failure mechanisms, and molecular design of materials are also being developed to support highly-focused efforts in materials development and reduce the time and cost to develop new materials. Advanced manufacturing development is represented under High Performance Materials in two capacities: first, the need for advancements in feedstocks such as metal powders for superalloys and second, as a set of methods for producing high-performance materials.

Simulation-Based Engineering: This key technology area comprises the expertise and capability to computationally represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant. Science-based models of the physical phenomena occurring in fossil fuel conversion processes and development of multiscale, multi-physics simulation capabilities are just some of the tools and capabilities in Simulation-Based Engineering. This key technology area enables the development of innovative, advanced energy systems by developing and utilizing advanced process systems, engineering tools and approaches, and the transformation of computationally intensive models into reduced order, fast, user-enabled models for the purposes of study, development, and validation. These tools will be used to optimize data handling and exploit information technology in the design of advanced energy systems with carbon capture.

Water Management Research and Development: Water research encompasses the need to reduce the amount of freshwater used by power plants and to minimize any potential impacts of plant operations on water quality. Research in effluent treatment and water quality sensing, field testing of technologies and processes for treating water produced by injection of carbon dioxide into deep saline aquifers, and exploration of water-limited cooling and innovative multi-stage filtration technologies are being conducted. Data modeling and analysis is being employed to examine existing water availability data on a regional basis. The vision for this program area is to develop a 21st-century America that can count on abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential for continued security and economic health. To accomplish this, Crosscutting Research is needed to lead a critical national effort directed at removing barriers to sustainable, efficient water and energy use, developing technology solutions, and enhancing our understanding of the intimate relationship between energy and water resources.

ADVANCED MANUFACTURING

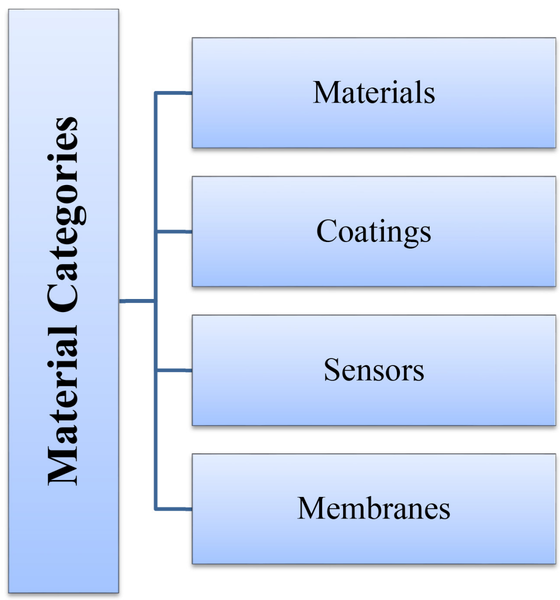
Advanced manufacturing is emerging as an especially potent driver of future economic growth. A distinguishing feature of advanced manufacturing is its continual improvement in processes and rapid introduction of new products. It is this paradigm-shifting aspect of advanced manufacturing that has the most potential to spin off entirely new industries and lead to production methods that are most likely to "stick" in the United States because they are hard to imitate. The Innovative Manufacturing Initiative of the Department of Energy is one element of the Federal portfolio that is seeking to accelerate advanced manufacturing process innovation. It is funding cost-shared R&D of processes that have the potential to significantly reduce energy and carbon intensity over the coming decades. By doing so, the initiative aims to revitalize existing manufacturing industries as well as support the development of emerging industries.

PROJECT PAGES

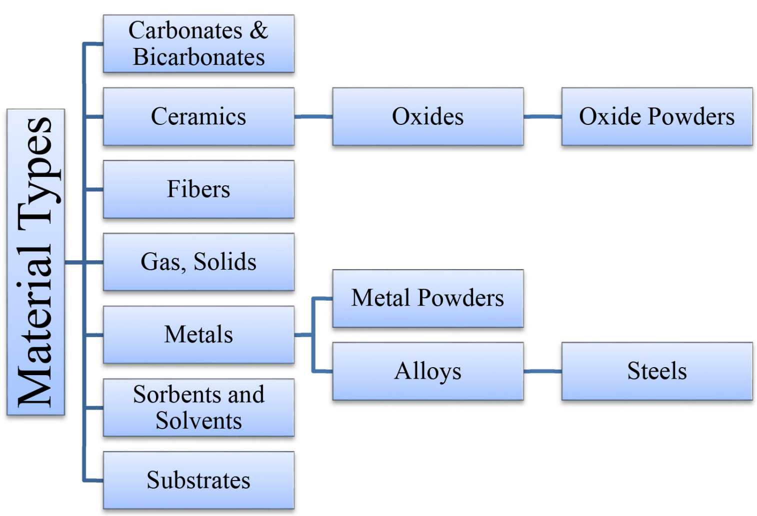
Each project identified as having relevance to advanced manufacturing is described in this report in a one-page summary. Key elements of these pages are as follows:

- **Material Category/Material Type**

  Material Category: higher-level container for Material Type. The four broad categories used are presented graphically below. The Material Category descriptor may be substantial, as in Materials; functional, as in Sensors, or both, as in Coatings, or Membranes.

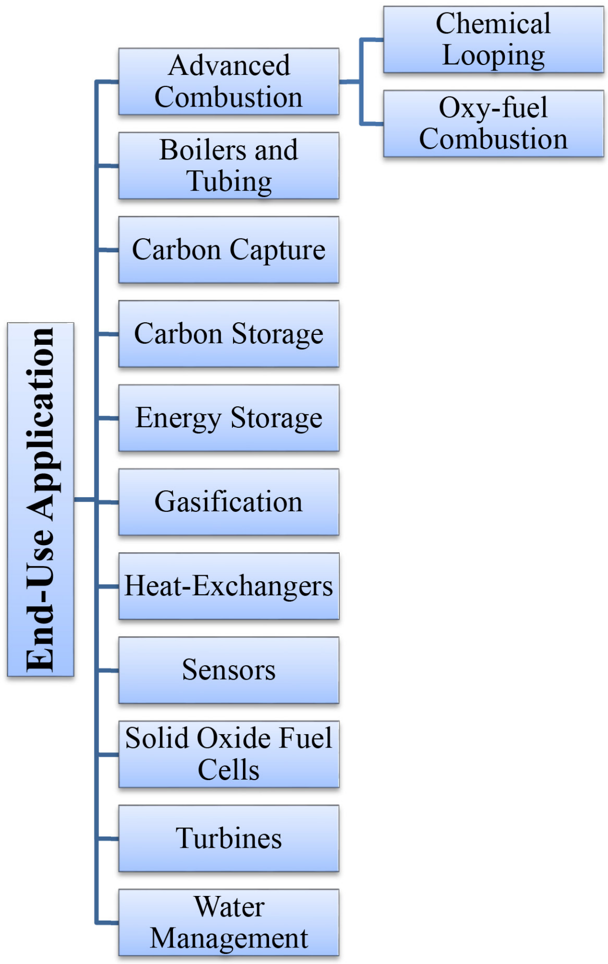


  Material Type (see graphic below): categorizes the nature of the material at issue substantially (e.g., Gas, Solids; Fibers; Metals) or functionally (e.g., Sorbents, Solvents). See graphic below. Where the Material Category is a functional description rather than a substance, Material Type may refer to the application (e.g., sensors used to monitor refractory materials of alloys or ceramics).

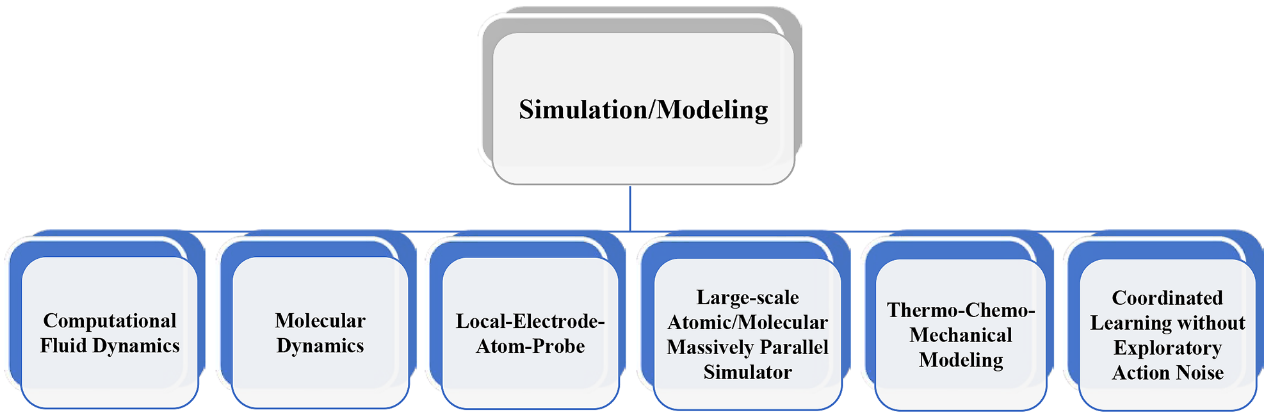


- **Information** specifying exact materials is provided under this heading when appropriate.

- **End-Use Application** – The high-level end-use applications are shown below.



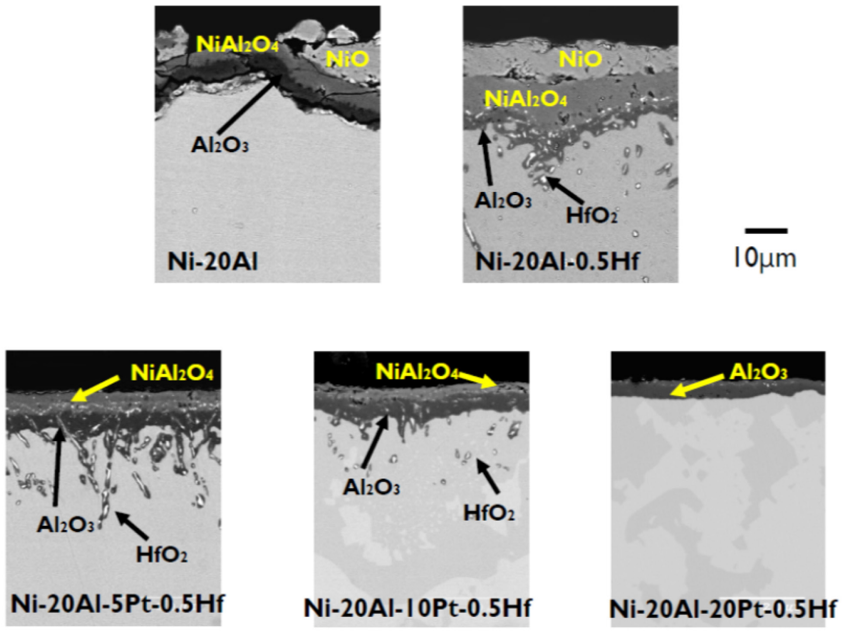
- **Simulation and Modeling** is a subsection of Manufacturing Systems, understood as a set of design support tools.

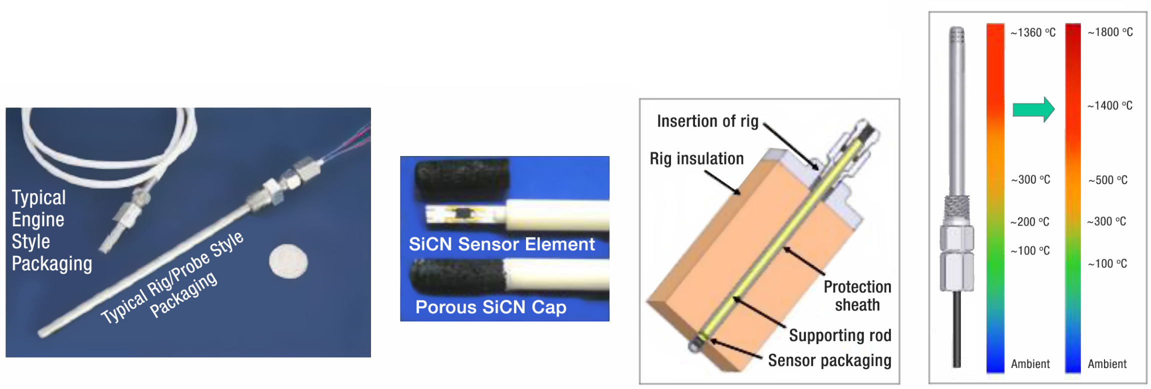


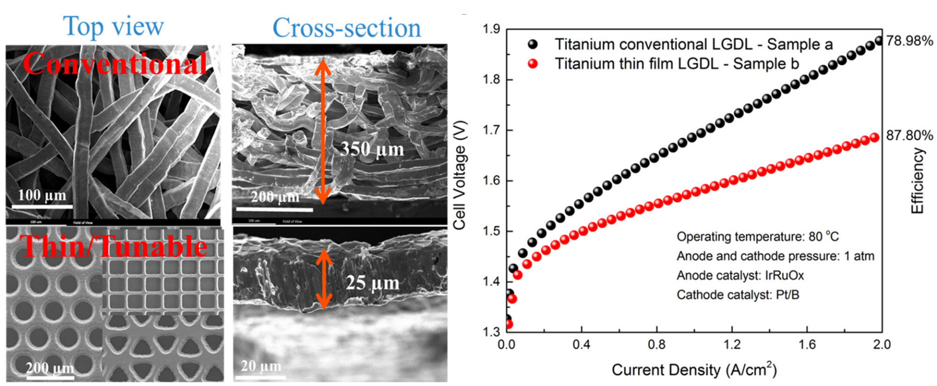
- **Color Legend**

Boxes on the project pages are color coded to differentiate Computational Modeling, Additive Manufacturing/3-D Printing, and Other processes.

PROJECTS BY TECHNOLOGY AREA

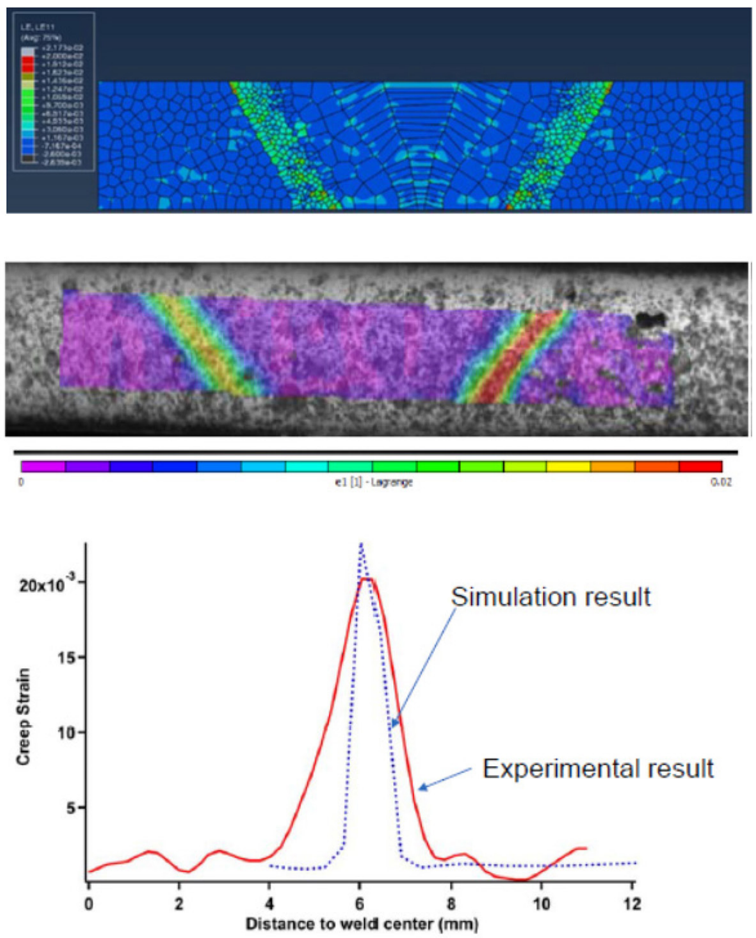






COAL UTILIZATION SCIENCES

PERFORMER	PROJECT TITLE	PAGE
Oak Ridge National Laboratory	Weldability of Creep Resistant Alloys for Advanced Power Plants	14
Oregon State University	New Mechanistic Models of Long Term Evolution of Microstructure and Mechanical Properties of Nickel Based Alloys	15
Pennsylvania State University	Computational Design and Discovery of Ni-Based Alloys and Coatings: Thermodynamic Approaches Validated by Experiments	16



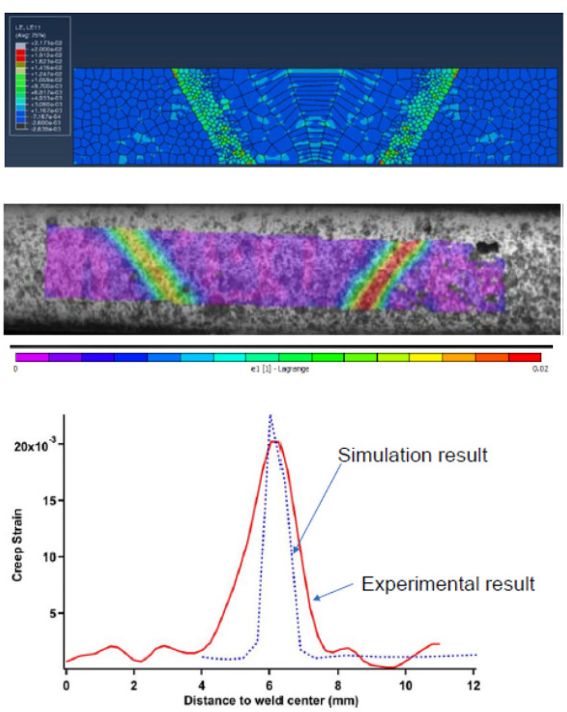
Weldability of Creep Resistant Alloys for Advanced Power Plants

Performer	Oak Ridge National Laboratory (ORNL)
Award Number	FWP-FEAA118
Project Duration	10/01/2013 – 09/30/2018
Total Project Value	$ 1,450,000
Technology Area	Coal Utilization Sciences
Key Technology	High Performance Materials

NETL is partnering with Oak Ridge National Laboratory (ORNL) to develop practical engineering solutions to two key issues regarding the weldability of high-temperature creep-resistant alloys used in advanced fossil energy power plants: (1) the reduced creep strength of the weld region versus the base metal and (2) welding of dissimilar metals.

The work will develop fundamental mechanistic understanding of the weld failure process using advanced in-situ neutron and synchrotron experimental techniques and a state-of-the-art integrated computational welding engineering (ICWE) modeling tool developed at ORNL; apply the ICWE modeling tool to simulate the microstructure and property variations in the weld region; develop an improved weld creep testing technique using digital image correlation to accurately measure the localized non-uniform deformation of a weld under high-temperature creep testing conditions; determine the local creep and creep-fatigue constitutive behavior in different regions of a weld; and develop new welding and post-heat treatment practices to improve the creep resistance of similar and dissimilar metal weldments.

The research will promote the design of advanced power plants capable of operating at higher temperatures and pressures, thus improving their efficiency and operational flexibility and reducing capital and operating costs.



Top: Modeling result.
Middle: Experimental result.
Bottom: Simulation result shows agreement with experiments.

Materials Category/Type:

Materials/alloys, steels

Creep strength enhanced ferritics, austenite stainless steels, Ni-based superalloys, oxide dispersion strengthened alloys

Manufacturing/Fabrication Process/ Method:

Computational welding modeling, rapid cooling, in-situ neutron and synchrotron experimental techniques, pre-weld heat treatments

End Use:

Boilers and tubing, turbines

New Mechanistic Models of Long Term Evolution of Microstructure and Mechanical Properties of Nickel Based Alloys

Performer	Oregon State University
Award Number	FE0024065
Project Duration	01/01/2015 – 12/31/2017
Total Project Value	$ 624,999
Technology Area	Coal Utilization Sciences
Key Technology	High Performance Materials

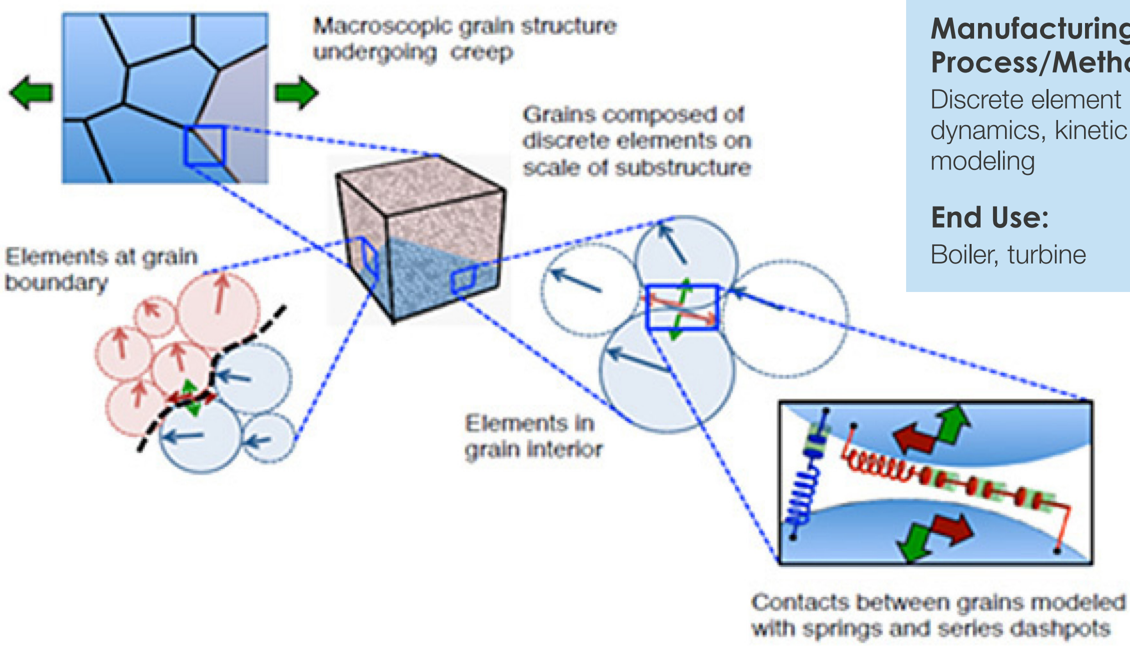
NETL is partnering with Oregon State University to create and validate a robust multiscale, mechanism-based model that quantitatively predicts long-term evolution of microstructure for nickel-based alloys as well as the effect on mechanical properties such as creep and rupture strength, including variable cyclic operating conditions.

Mechanism-based modeling has the potential to simulate long-term behavior (10–30 years) based on shorter time data (diffusion constants, activation energies, etc.) to achieve greater confidence in long-term life, safer and more cost-efficient designs, ability to better predict variable operating conditions, and extended service life beyond initial assumptions.

Materials Category/Type:
Materials/alloys
Nickel-based alloy

Manufacturing/Fabrication Process/Method:
Discrete element method, molecular dynamics, kinetic Monte Carlo modeling

End Use:
Boiler, turbine



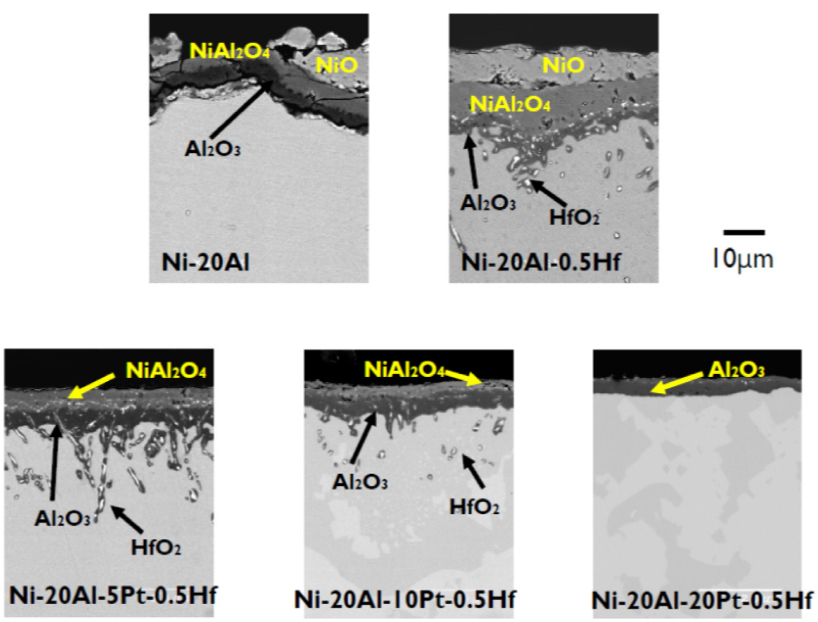
Schematic representation of the proposed DEM model. Crystal grains will be represented using discrete elements that interact and move to allow deformation and microstructure evolution. The element interaction laws will be defined to represent the physical mechanisms involved for nickel based alloys

Computational Design and Discovery of Ni-based Alloys and Coatings: Thermodynamic Approaches Validated by Experiments

Performer	Pennsylvania State University
Award Number	FE0024056
Project Duration	01/01/2015 – 10/31/2017
Total Project Value	$ 632,176
Collaborator	University of Pittsburgh
Technology Area	Coal Utilization Sciences
Key Technology	High Performance Materials

NETL is partnering with Pennsylvania State University to develop a thermodynamic foundation for the accelerated design of nickel-based alloys and coatings. The information derived will be essential for efficiently designing and predicting the performance of alloys, coatings, and coating/alloy combinations. The project will also develop an automated thermodynamic modeling tool that will more efficiently arrive at accurate thermodynamic descriptions and enhance computational alloy and coating design.

The project's resulting database will enable prediction of tunable properties (including phase compositions and fractions), solubility limits, and driving forces—all of which are important in designing high-temperature alloys and coatings that have long-term resistance to harsh service environments.



Cross-sectional images of Ni-20at %Al-Pt-Hf γ/γ' alloys after 500 oxidation cycles at 1150 °C in air.

Materials Category/Type:
(Coatings/alloys) nickel-based alloys, Ni-Al-Cr-Co-Si-Hf-Y system

Manufacturing/Fabrication Process/Method:
Calculation of phase diagram software/database, density functional theory, thermodynamic modeling

End Use:
Boilers and tubing

PLANT OPTIMIZATION TECHNOLOGIES

PERFORMER	PROJECT TITLE	PAGE
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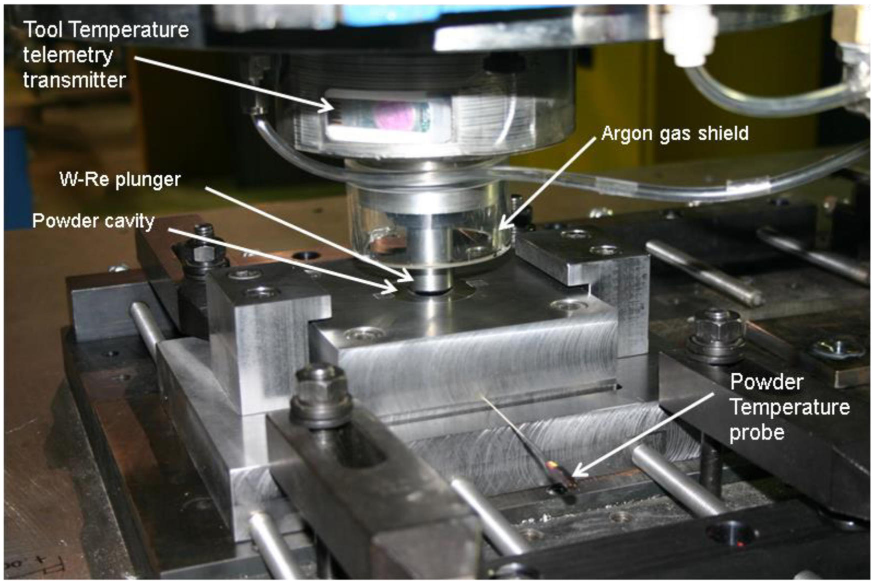
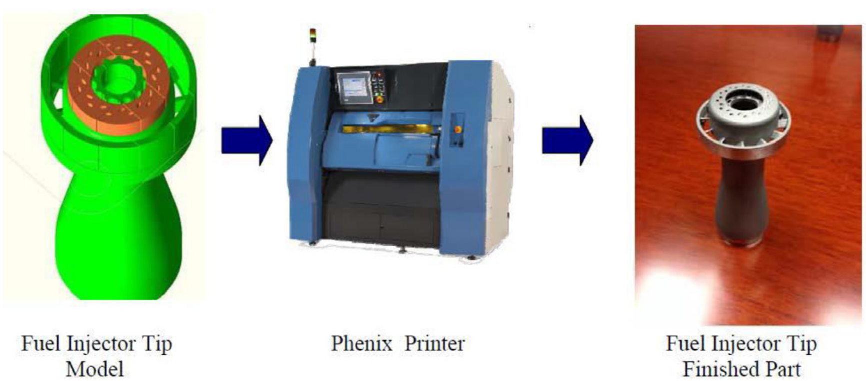


Additive Manufacturing of Fuel Injectors

Performer	Edison Welding Institute, Inc.
Award Number	FE0023974
Project Duration	10/01/2014 – 10/31/2017
Total Project Value	$ 632,447
Collaborator	Solar Turbines Incorporated
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with Edison Welding Institute, Inc. to develop a novel process to qualify the additive manufacturing (AM) technique of laser powder bed fusion for manufacturing complex gas turbine components made of high-temperature nickel-based alloys. Using a fuel injector as a final demonstration piece, project personnel will investigate the effect of input powder stock and AM process variables on resultant microstructure and mechanical properties of the alloy material. Post-processing, including heat treatment and the use of finishing technologies, will also be employed in order to achieve dimensional and surface finish requirements for the component. The benefit will include the development of an AM process that can improve both material and mechanical properties as well as reduce manufacturing cost with little to no impact on durability compared to a traditional investment casting process.

This project will assist in evaluating other turbine components for future AM fabrication. The AM flexibility will allow industrial gas turbine manufacturers to design features into the components that may improve turbine performance and durability. It may also result in lower costs by reducing manufacturing time and eliminating scrap material.



50,000-foot view of AM.

Materials Category/Type:

Alloys/metal powders

Nickel-based alloys, Hastelloy / Alloy X

Manufacturing/Fabrication Process/Method:

Additive manufacturing technique, laser powder bed fusion, abrasive flow machining

End Use:

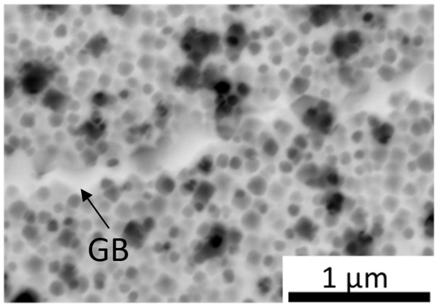
Turbines

Additive Manufacturing of High Gamma Prime Alloys

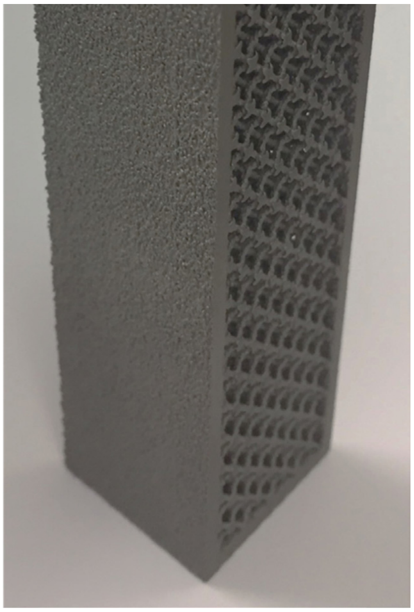
Performer	Oak Ridge National Laboratory (ORNL)
Award Number	FWP-FEAA127
Project Duration	09/01/2017 – 09/30/2018
Total Project Value	$ 424,000
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with ORNL to develop advanced components from high gamma prime alloys (Haynes 282/ Nimonic 105) via innovative manufacturing approaches to enable high temperature/high pressure operation and realize high plant cycle efficiency for advanced ultrasupercritical steam systems (with relevance to gas turbines also). There are several key challenges currently confronting the additive manufacturing (AM) processes for high gamma prime alloys. It is universally recognized that the internal microstructures and performance under load are all dependent on the manufacturing process. Due to the large parameter sets applicable in AM processes and their impact on achievable materials properties and quality, a design of experiments approach will be utilized to achieve the optimal crack-free microstructure with acceptable density.

For AM of high gamma prime alloys, where the understanding of the effects of feedstock properties, deposition rates, thermal history, cooling rates, defect formation and residual stress are still in an early phase, the design of experiments approach will achieve the optimal part properties (density/mechanical properties), surface finish and performance, similar to the rolled plate material. Collaboration between ORNL and Siemens will provide the unique opportunity of developing the process parameters, part microstructure/surface finish, and bulk properties for alloy 282 and Nimonic 105. The final goal is to fabricate Haynes 282 and Nimonic 105 components that are of interest to the AUSC program.



Back scattered scanning electron images of alloy 282 fabricated by electron beam melting showing the grain boundary (GB) carbides and fine gamma prime precipitates in the as-built condition.



Example of a complex Haynes 282 mesh structure fabricated by electron beam melting.

Materials Category/Type:
(Coatings/alloys) High gamma-prime alloys:

Haynes 282, Nimonic 105

Manufacturing/Fabrication Process/Method:
Additive manufacturing

End Use:
AUSC components

PLANT OPTIMIZATION TECHNOLOGIES

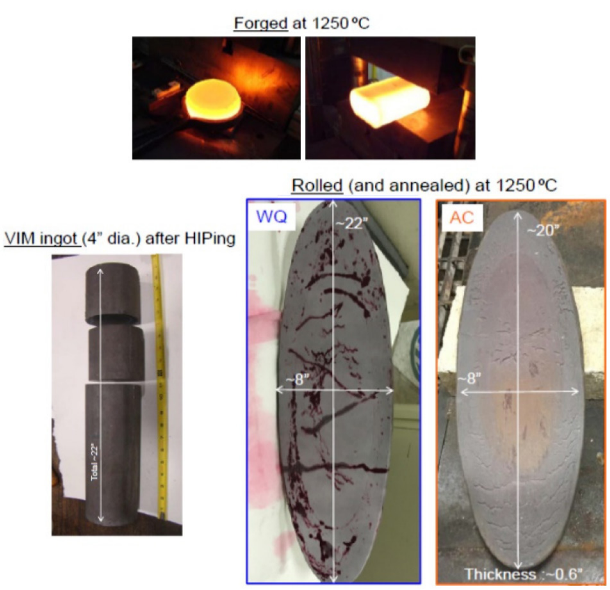
Advanced Alloy Design Concepts for High Temperature Fossil Energy Applications

Performer	Oak Ridge National Laboratory (ORNL)
Award Number	FWP-FEAA114
Project Duration	10/01/2013 – 09/30/2018
Total Project Value	$ 1,934,000
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with ORNL to identify and apply breakthrough alloy design concepts and strategies for incorporating improved creep strength, environmental resistance, and weldability into the classes of alloys intended for use as heat exchanger tubes in fossil-fueled power generation systems at higher temperatures than are possible with currently available alloys.

This work will develop stable microstructures with dispersion of strengthening second-phase precipitates based on guidance from computational thermodynamics and modeling of inter-diffusion, including new directions suggested by ongoing modeling studies in other Crosscutting Research projects; apply mechanistic understanding of the development and evolution of microstructures associated with strengthening phases, and of the influences of and interactions with the concentration and distribution of specific elements necessary to form an inherently-protective outer oxide layer; and use advanced analytical techniques, and especially their evolution as a function of time, temperature, and external environment.

Higher performance from alloys used in fossil-fueled power generation systems at higher temperatures will lead to improvements in efficiency and operational flexibility and result in lower operating costs.



Scale-up efforts (Fe-30Cr-3Al-2Nb-0.2Si-0.12Y).

Materials Category/Type:

Materials/alloys, steels

FeCrAl alloys, Cr-ferritic- martensitic steels, austenitic steels, Ni-based alloys, T91, Inconel 740

Manufacturing/Fabrication Process/ Method:

Inter-diffusion and thermodynamic modeling

End Use:

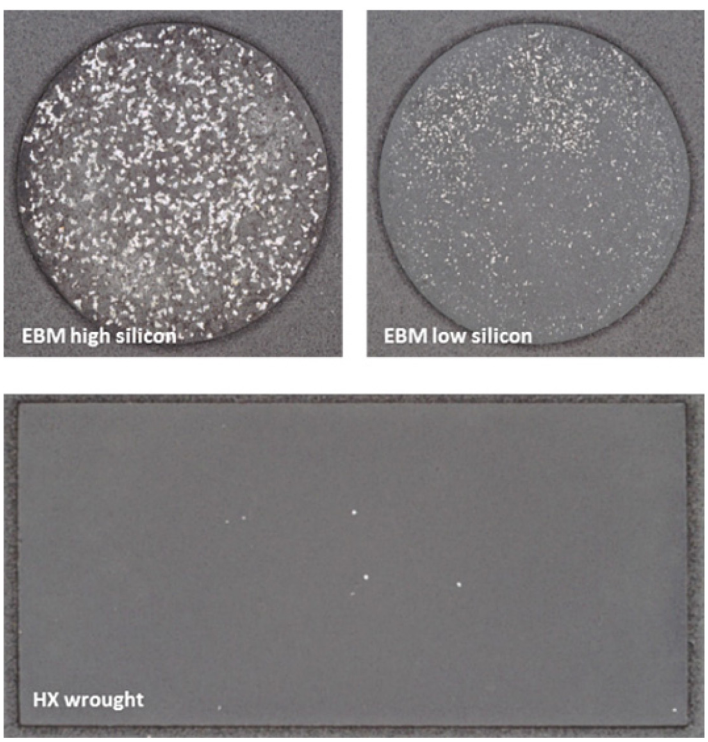
Boilers and tubing, heat exchanger tubes

Microstructure and Properties of Ni-based Components Fabricated by Additive Manufacturing

Performer	Oak Ridge National Laboratory (ORNL)
Award Number	FWP-FEAA119
Project Duration	10/01/2015 – 09/30/2018
Total Project Value	$ 954,000
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with ORNL to optimize the additive manufacturing (AM) fabrication process to produce gas turbine components made of high-temperature nickel (Ni)-based Hastelloy X (HX) alloy. The project team will compare results for HX alloy products made using the three main AM techniques: electron beam melting, laser metal deposition, and selective laser melting. The team will perform extensive microstructure characterization and mechanical testing to determine the relationships among the deposition process, microstructure, and mechanical properties. The mechanical properties of actual gas turbine components fabricated via additive manufacturing will be measured and, as a final step, the three AM processes will undergo cost analyses to determine the potential benefits of using electron beam melting, laser metal deposition, or selective laser melting over conventional fabrication routes.

The technology will be used to produce high-temperature gas turbine components as well as similar-sized components for other advanced fossil energy applications.



No spallation for wrought HX 4x100 hours at 950 °C.

Materials Category/Type:
Metals - high temperature Ni-based Hastelloy X alloy

Manufacturing/Fabrication Process/ Method:
Additive manufacturing (fabrication process - electron beam melting at ORNL, laser metal deposition at Siemens and selective laser melting

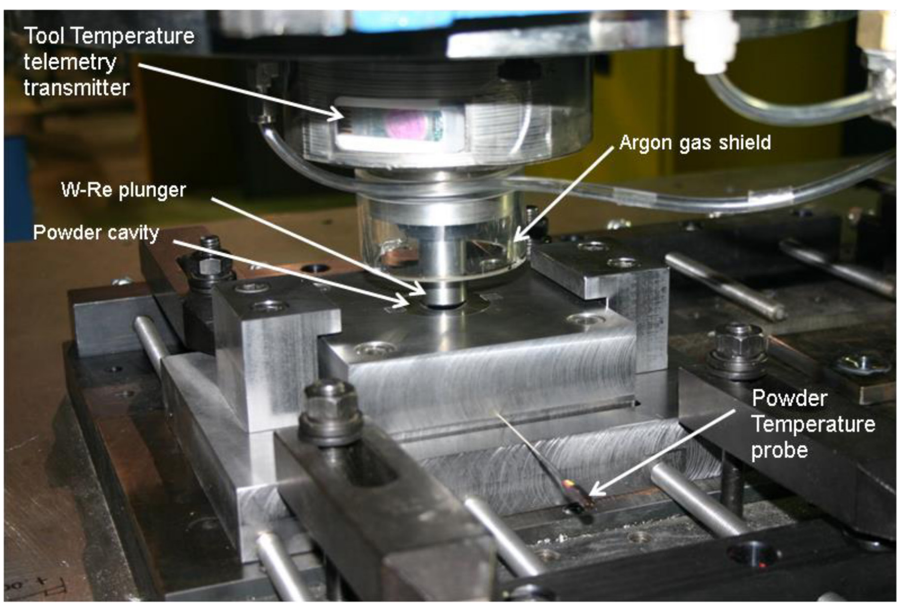
End Use:
Turbines

Low Cost Fabrication of ODS Materials

Performer	Pacific Northwest National Laboratory (PNNL)
Award Number	FWP-60098
Project Duration	10/01/2010 – 09/30/2018
Total Project Value	$ 735,000
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with PNNL to develop a process to fabricate oxide dispersion-strengthened (ODS) materials at lower cost than current manufacturing methods used for these materials, and thus overcome that barrier to their deployment. One approach to enabling the full potential of ferritic ODS materials in an advanced fossil energy power plant cycle is to reduce manufacturing defects and production costs using a new processing methodology. PNNL's recent progress in friction stir welding of ODS alloys suggests that stainless steel powder and oxide powder can be directly mixed and consolidated into full-density rod and tube shapes via a one-step friction stir or shear consolidation process. This project will investigate the new powder metallurgy process, which has the potential to significantly reduce the cost of fabricating ODS products and enable their use in coal and other fossil fuel power plant applications.

The project will contribute to more efficient use of fossil fuels in advanced ultrasupercritical power plants, which will concurrently lead to reduced discharge of carbon dioxide and other emissions.



Friction extrusion die at Pacific Northwest National Laboratory.

Materials Category/Type:
Materials/alloys, steels

Oxide dispersion strengthened alloys

Manufacturing/Fabrication Process/ Method:
Shear consolidation process, high-energy mechanical milling, powder metallurgy processing, hot-isostatic pressing, friction stir welding

End Use:
Boilers and tubing, gasification

Solid State Joining of Creep Enhanced Ferritic Steels

Performer	Pacific Northwest National Laboratory (PNNL)
Award Number	FWP-66059
Project Duration	10/01/2014 – 09/30/2018
Total Project Value	$ 1,075,000
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with PNNL to develop friction stir welding, an alternative solid state joining technology that can enable higher performance from creep strength enhanced ferritic (CSEF) steels anticipated for use in advanced ultrasupercritical (AUSC) coal-fired power plants. A primary problem afflicting welded CSEF steels is that the welds of these steels fail (Type IV cracking) under high temperature at a creep life far below that of the base metal. This problem has led to a reduced performance envelope and either a calculation of reduced strength and lifetime for assemblies made from these alloys, or the use of expensive post-weld heat treatment procedures to recover base metal creep strength in the weldment. Previous work at PNNL on the NETL funded project "Joining of Advanced High-Temperature Materials" (FWP-12461) showed that the friction stir welding process is capable of producing welds in Grade 91M CSEF plate that have significantly improved creep performance over equivalent fusion welds.

It is expected that higher performance CSEF steels used in AUSC coal-fired power plants will improve efficiency and operational flexibility and result in lower operating costs.

Flat plate friction stir welds in HSLA65 plate.

Materials Category/Type:
Materials/alloys, steels

Creep strength enhanced ferritic steels, Gr91, Gr92, Gr122, P91, P92, P122, boron/cobalt enriched 9Cr ferritic steel

Manufacturing/ Fabrication Process/ Method:
Solid state joining, friction stir welding

End Use:
Boilers and tubing, turbines

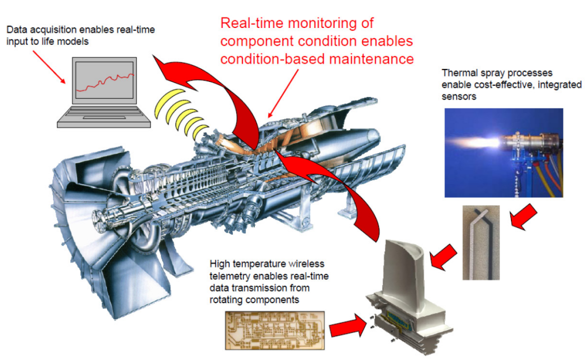
PLANT OPTIMIZATION TECHNOLOGIES

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

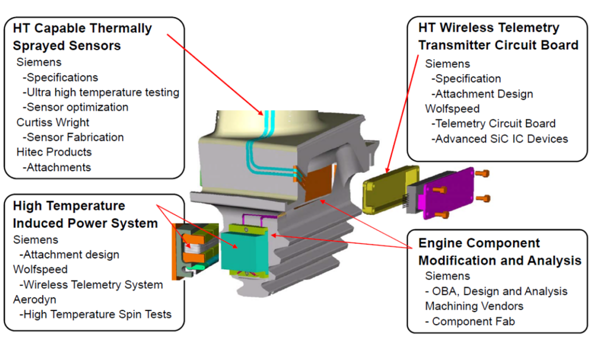
Performer	Siemens Corporation
Award Number	FE0026348
Project Duration	09/16/2015 – 08/31/2020
Total Project Value	$ 4,687,500
Collaborators	Arkansas Power Electronics International, Inc. and Siemens Energy, Inc.
Technology Area	Plant Optimization Technologies
Key Technology	Sensors and Controls

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

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



Anatomy of a smart component.



Novel sensor's wireless telemetry system.

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

Materials Category/Type:
Materials/ceramics

Manufacturing/Fabrication Process/Method:
Thermal spray process

End Use:
Sensors, turbines

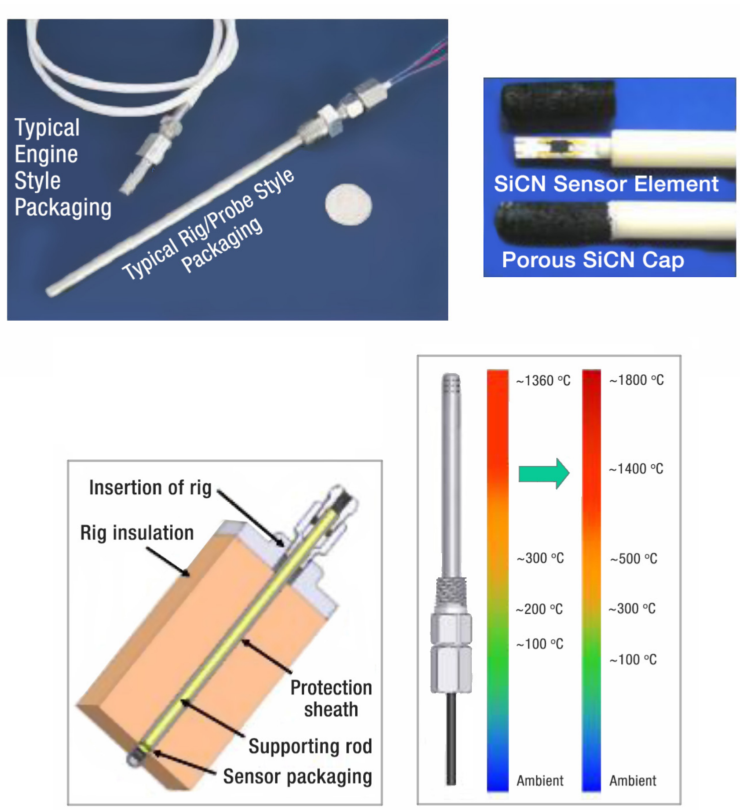
Advanced Ceramic Materials and Packaging Technologies for Realizing Sensors Operable in Advanced Energy Generation Systems

Performer	Sporian Microsystems, Inc.
Award Number	SC0008269
Project Duration	06/28/2012 – 08/13/2018
Total Project Value	$ 2,159,100
Technology Area	Plant Optimization Technologies
Key Technology	Sensors and Controls

Sporian Microsystems, Inc. is developing ultra-high temperature smart sensors from silicon carbon nitride (SiCN) materials for use in energy generating and aerospace systems. The sensors will be developed via innovative fabrication processes and contain internal compensation, health check, and data bus support to the interface.

The project will be accomplished by building a sensor utilizing a class of high-temperature ceramic materials synthesized by thermal decomposition of polymeric precursors, which possess excellent mechanical properties up to 1800 degrees Celsius. In addition, the team will construct and fabricate designs for multiple sensors capable of bench- and pilot-scale operable demonstration-ready sensing.

Use of these sensors to continually monitor high-temperature systems should reduce system failure rates, improve contact, and reduce moisture collection with sensing at the source, resulting in an overall lower cost associated with system lifespan.



High temperature harsh environment packaging.

Materials Category/Type:
Materials/ceramics

Manufacturing/Fabrication Process/ Method:
Thermal decomposition

End Use:
Integrated gasification combined cycle, natural gas combined cycle

High Temperature Sapphire Pressure Sensors for Harsh Environments

Performer	University of Florida
Award Number	FE0012370
Project Duration	01/01/2014 – 08/31/2018
Total Project Value	$ 1,098,191
Collaborator	Florida State University
Technology Area	Plant Optimization Technologies
Key Technology	Sensors and Controls

The University of Florida, in collaboration with Florida State University, began an effort to develop sapphire manufacturing technologies for fabricating and packaging high-temperature sensors by combining ultra-short pulse laser micromachining (LM) and spark plasma sintering (SPS). The primary objective of this project is to develop sensor materials and manufacturing designs for measuring physical parameters in situ and on line under extreme conditions (i.e., high temperatures and pressures and corrosive environments).

The proposed research will employ a multi-faceted approach to develop and quantify manufacturing technologies for fabricating sapphire high-temperature sensors. Laser micromachining processes will be developed using an Oxford Laser J-355PS picosecond laser micromachining workstation. SPS will be used to develop processes for joining sapphire and alumina substrates. These two technologies will help create three-dimensional microscale sapphire structures by bonding planar laser micromachined substrates via SPS. Performance of the machined components will be simulated and experimentally quantified via fracture and dislocation mechanics methods.

These technologies will enable the manufacture of miniature sapphire sensors for a variety of applications of interest (pressure, temperature, stress/strain, etc.); however, for the purpose of this proposal, the primary application will be an optical pressure sensor capable of operating in environments in excess of 1000 degrees Celsius and up to 1000 pounds per square inch. The proposed applied research will help establish critical functions regarding LM and SPS materials synthesis as well as a packaged and experimentally characterized pressure sensor.

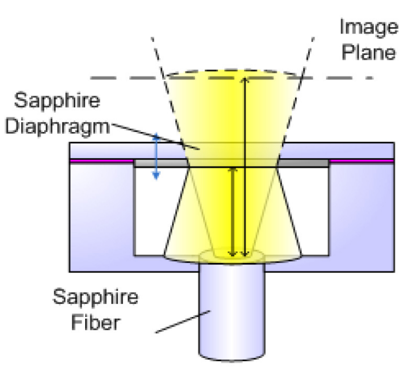
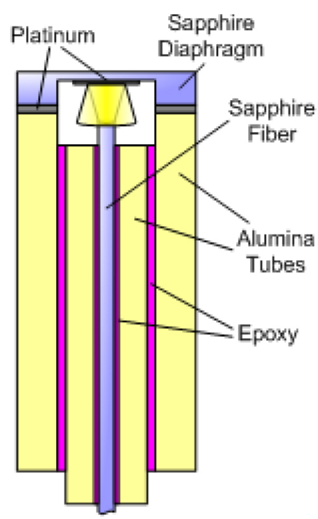


Illustration of the fiber-optic lever transduction scheme implemented in the pressure sensor design.



Schematic of sensor and packaging for the high-temperature pressure sensor.

Materials Category/Type:
Sensors/sapphire, alumina, platinum

Manufacturing/Fabrication Process/Method:
Thermocompression bonding, picosecond laser micromachining, spark plasma sintering

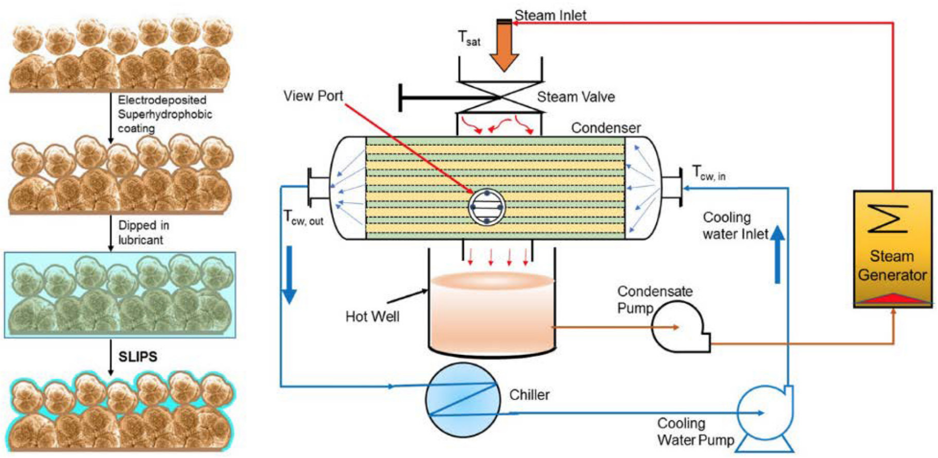
End Use:
Sensors

Novel Patterned Surfaces for Improved Condenser Performance in Power Plants

Performer	Virginia Polytechnic Institute and State University
Award Number	FE0031556
Project Duration	12/15/2017 – 12/14/2020
Total Project Value	$ 938,470
Technology Area	Plant Optimization Technologies
Key Technology	Water Management R&D

NETL is partnering with Virginia Polytechnic Institute and State University to improve thermoelectric power plant performance through engineered superhydrophobic/slippery liquid infused porous surfaces (SLIPS) for condenser tube designs fabricated by a patented two-step electrodeposition technique. The electrodeposition process is a widely-used industrial process that is applicable to a variety of shapes, materials, and sizes. The project will demonstrate and characterize a variety of SLIPS coatings based on copper, nickel, copper/nickel, zinc, tungstite, and other materials on commonly used condenser tube surfaces—namely, copper, copper/nickel, stainless steel, and titanium alloys—through a facile and cost-effective electrodeposition process. The goal is to demonstrate overall condenser heat exchanger effectiveness that is at least 50 percent higher than that of current systems while reducing condenser pressure and improving power plant efficiency.

The research conducted will broaden both fundamental and applied scientific knowledge in the field of transport phenomena using SLIPS surfaces and the robust, scalable fabrication process of the structures. Meeting the project goal could lead to novel, industrially scalable, and low-cost fabrication of durable SLIPS coatings that will lead to improved plant efficiency and performance, and thereby to reduced carbon dioxide emissions.



Proposed SLIPS coating to enhance heat transfer and reduce drag on condenser surfaces.

Materials Category/Type:
(Coatings) Superhydrophobic/slippery liquid infused porous surfaces

Manufacturing/Fabrication Process/Method:
Electrodeposition

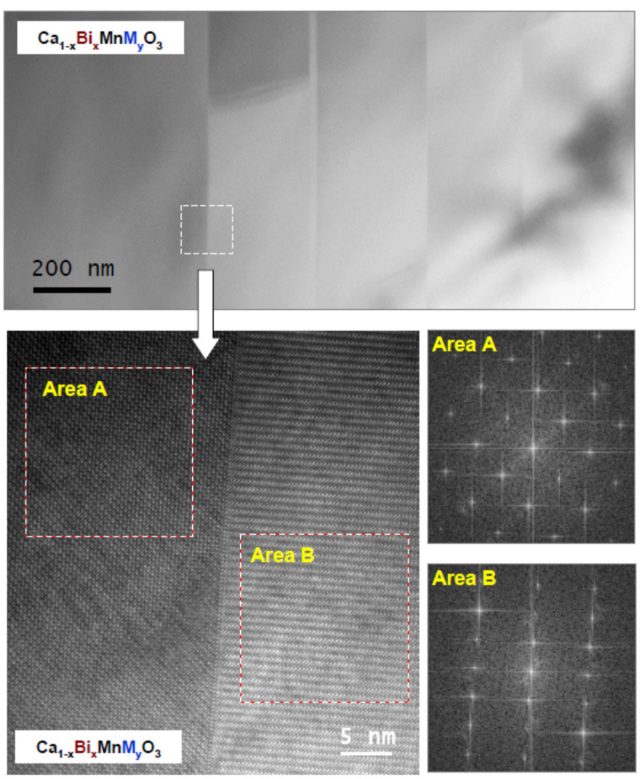
End Use:
Condenser heat exchangers

Ceramic High Temperature Thermoelectric Heat Exchanger and Heat Recuperators in the Power Generation Systems

Performer	West Virginia University Research Corporation
Award Number	FE0024009
Project Duration	10/01/2014 – 03/31/2018
Total Project Value	$ 627,160
Technology Area	Plant Optimization Technologies
Key Technology	High Performance Materials

NETL is partnering with West Virginia University Research Corporation to develop compact and highly efficient all-oxide ceramic thermoelectric (TE) generators to work as compact heat exchangers and simultaneously recover the high-temperature waste heat from high-temperature power systems such as solid oxide fuel cells (SOFCs).

Combining the enhanced performance of oxide materials and the innovative designs of TE generators, the proposed all-oxide TE device will potentially over-perform state-of-the-art TE materials that are made of conventional metallic or semiconductor materials for high-temperature applications. The TE devices proposed in this project will be highly efficient, lightweight, reduced in size, highly stable in air at high temperatures, and non-toxic for powering sensors at temperatures in the 600 to 980 degrees Celsius range. In addition, the new devices will be easy to fabricate and thus will facilitate mass production with a high potential for use in large-scale operations. The incorporation of TE devices into SOFC systems is expected to increase electricity production by more than 15 percent, corresponding to system electrical efficiency increases of five percentage points.



No further crystal defects in calcium bismuth manganese oxide.

Materials Category/Type:
Materials/oxide powders $CaMnO_3$, $Ca_3Co_4O_9$, SiO_2

Manufacturing/Fabrication Process/ Method:
Tape casting, chemical sol-gel process

End Use:
Thermoelectric generators, heat recuperators, waste heat recovery from turbines, SOFCs, ceramic heat exchangers

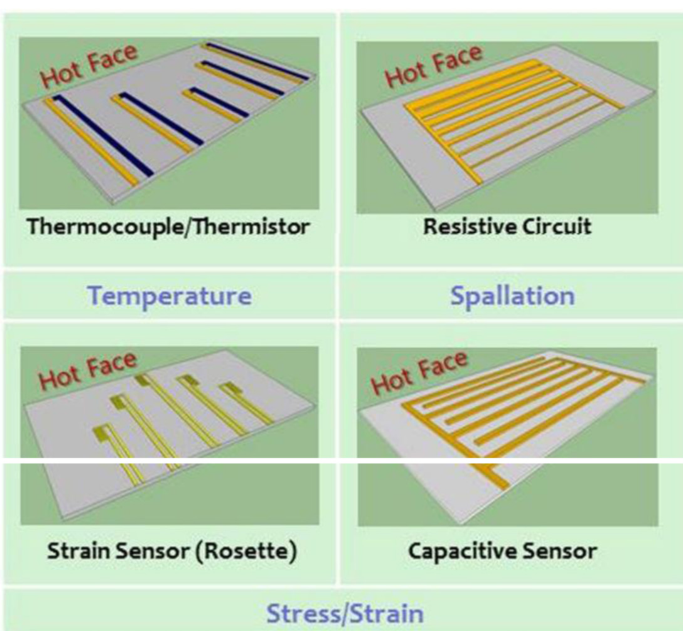
Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health and Degradation of Slagging Gasifiers

Performer	West Virginia University Research Corporation
Award Number	FE0012383
Project Duration	10/01/2013 - 03/31/2018
Total Project Value	$ 1,617,113
Technology Area	Plant Optimization Technologies
Key Technology	Sensors and Controls

The United States Department of Energy National Energy Technology Laboratory has partnered with West Virginia University (WVU) to develop in situ and online sensing capability for advanced energy systems operating at high temperature and pressure in the harsh environments of advanced power generation systems. Researchers at WVU will demonstrate a high-temperature sensor concept for monitoring reaction conditions and health within slagging coal gasifiers. The technology will include the development of smart refractory gasifier brick. The new sensors will monitor the status of equipment, materials degradation, and process conditions that impact the overall health of a refractory lining in the high-temperature, highly corrosive environments of coal gasifiers.

The key aspect of the proposed technology is that these sensors will be incorporated and interconnected throughout the volume of the refractory brick and will not negatively impact the intrinsic properties of the refractory, thereby circumventing the need to insert a sensor into the refractory via an access port. This will ensure the integrity of the sensor within the harsh environment and will not introduce flaws or slag penetration pathways within the refractory, as is typically the issue with inserting sensors through access ports.

The anticipated benefit of this project would be the development of a more reliable and non-intrusive method of monitoring gasifier temperature and refractory health than is possible with current methods. Such improvements are expected to result in lower operating and maintenance costs of slagging gasifiers. The development of the proposed smart refractory and refractory sensor system concept could be applied to other applications, such as conventional coal-fired boiler technology, biomass gasification, and steel and glass manufacturing.



Schematics depicting possible embedded sensor designs.

Materials Category/Type:

Sensors/metals, ceramics

High-chromia smart refractory materials, chromium (III) oxide brick

Manufacturing/Fabrication Process/ Method:

Printed/laminated tape embedding, thermal processing, sintering

End Use:

Sensors, gasification

UNIVERSITY TRAINING AND RESEARCH

PERFORMER	PROJECT TITLE	PAGE
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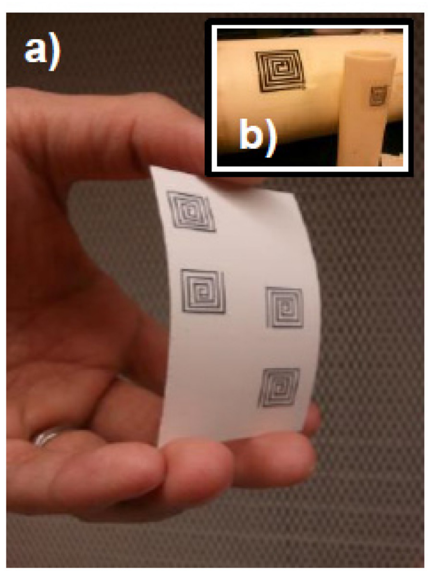
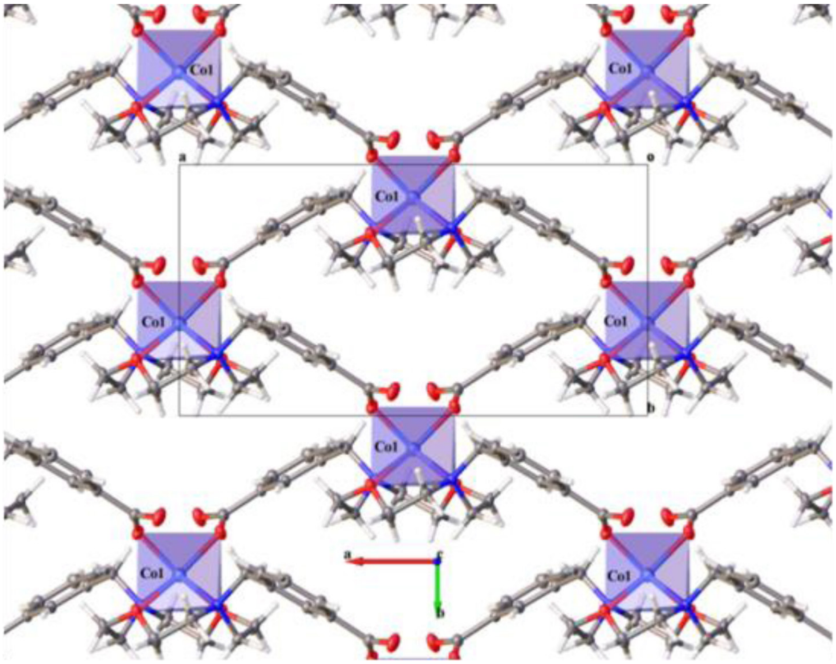


Engineering Accessible Adsorption Sites in Metal Organic Frameworks for CO_2 Capture

Performer	Clark Atlanta University
Award Number	FE0022952
Project Duration	10/01/2014 – 09/30/2018
Total Project Value	$ 249,998
Technology Area	University Training and Research
Key Technology	High Performance Materials

NETL is partnering with Clark Atlanta University (CAU) to synthesize metal organic frameworks (MOFs) with improved site accessibility and thus enhanced carbon dioxide (CO_2) adsorption and selectivity properties. CAU will synthesize and characterize ultra-high-surface-area MOF materials for CO_2 adsorption. This three-year research effort will consist of synthesizing MOFs with organic linkers as well as nitrogen-containing pyrazine linkers and evaluate them based on their CO_2 adsorption properties, framework structure and composition (such as metal content and elemental analysis), surface area, pore size, and thermal stability. The evaluation methods will include X-ray crystallography, powder X-ray diffraction, thermogravimetric analysis, infrared spectroscopy, and other advanced techniques. The downselected CO_2 adsorption material from this research will be used for CO_2 capture and sequestration applications.

The proposed research supports the Department of Energy Office of Fossil Energy and the National Energy Technology Laboratory mission by advancing the science of coal/fossil fuel technologies, specifically carbon capture. The research will guide rational design and synthesis strategies toward producing advanced sorbents for CO_2 capture. Successful CO_2 adsorbent materials can potentially have an industrial and environmental impact. This project will also provide research opportunities for students in the fields of chemistry and materials science related to the use of fossil energy resources.



2D cobalt- diazo crown ether carboxylate metal oxide framework. Ingram et al. 2013, Crystal Growth and Design.

Materials Category/ Type:
Materials/metal powders

Manufacturing/Fabrication Process/Method:
X-ray crystallography, powder X-ray diffraction, thermogravimetric analysis, infrared spectroscopy

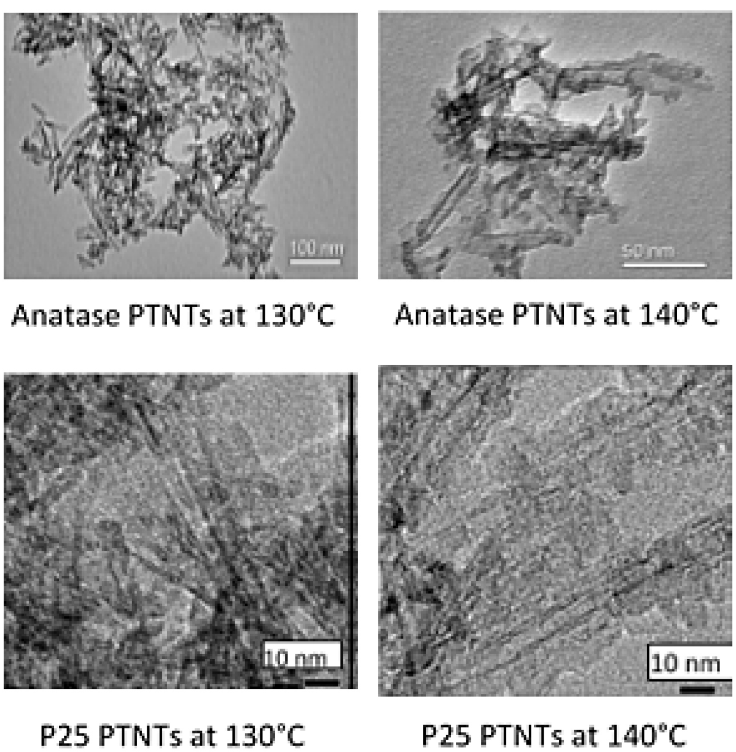
End Use:
Capture from industrial processes, post-combustion capture

Post Combustion Carbon Capture Using Polyethylenimine (PEI) Functionalized Titanate Nanotubes

Performer	Prairie View A&M University
Award Number	FE0023040
Project Duration	10/01/2014 – 09/30/2018
Total Project Value	$ 249,996
Technology Area	University Training and Research
Key Technology	High Performance Materials

NETL is partnering with Prairie View A&M University to develop a novel nanomaterial to efficiently capture CO_2 from the flue gas of fossil energy power generation systems by (1) establishing a knowledge base for the synthesis of titanium dioxide (TiO_2) nanotubes and adsorption characteristics of polyethylenimine (PEI) as well as the various protocols available for the impregnation of PEI; (2) characterizing the impregnated nanotubes and using them for refining synthesis parameters such as temperature, concentration, and time; (3) developing computational fluid dynamic (CFD) simulations in order to optimize the reactor conditions for high carbon capture efficiency; (4) demonstrating the carbon capture efficiency of impregnated TiO_2 tubes under various environmental conditions such as temperature and concentration; and (5) establishing a validated CFD model and a standard operating procedure for carbon capture using PEI impregnated TiO_2 nanotubes. Research will optimize the procedures for synthesizing the nanotubes and the impregnation protocols and develop standard operating procedures for carbon capture at different temperatures and concentrations.

A successful outcome from the study could be development of a high-efficiency, low-cost method to capture CO_2 from effluents of advanced fossil energy systems.



Transmission electron microscopy results.

Materials Category/Type:

Materials/sorbents

Titanate, polyethylenimine

Manufacturing/Fabrication Process/ Method:

Computational fluid dynamics simulation, thermogravimetric analysis

End Use:

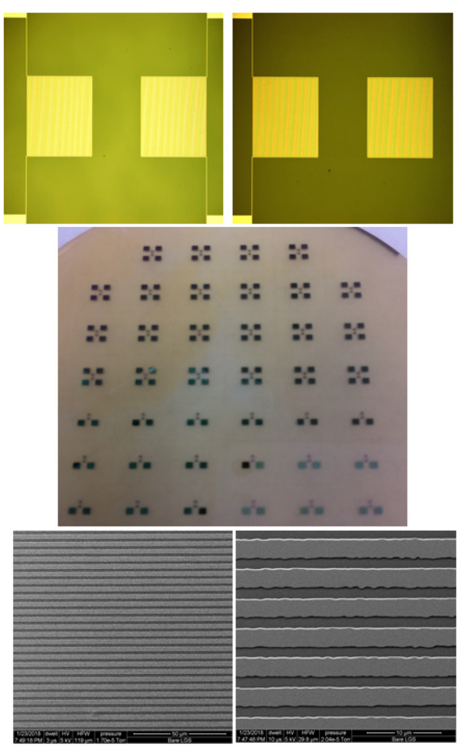
Boilers and tubing, carbon capture

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

Performer	University of Connecticut
Award Number	FE0026219
Project Duration	09/01/2015 – 08/31/2018
Total Project Value	$ 400,000
Technology Area	University Training and Research
Key Technology	Sensors and Controls

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

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



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

Materials Category/Type:

Ceramic - oxides, metals

Sensors

Manufacturing/Fabrication Process/ Method:

Pulsed laser deposition, magnetron sputtering, sol-gel wash coating

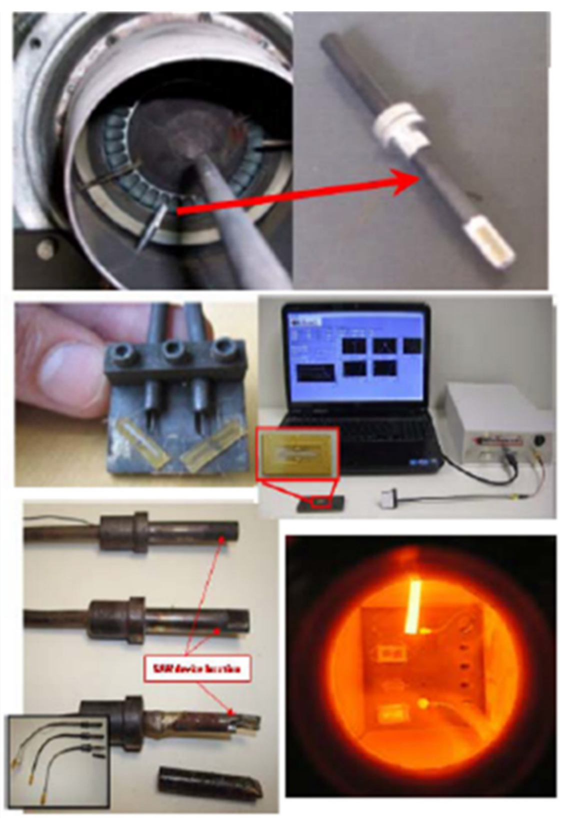
End Use:

Coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems cycles - AUSC

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

Performer	University of Maine System
Award Number	FE0026217
Project Duration	09/01/2015 – 08/31/2018
Total Project Value	$ 399,999
Technology Area	University Training and Research
Key Technology	Sensors and Controls

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



Examples of harsh environment wireless langasite SAW sensors.

The sensor system is based on a surface acoustic wave (SAW) sensor platform that could be used to detect hydrogen (H_2), oxygen (O_2), and nitrogen oxides (NO_x) and monitor gas temperatures in harsh environments. Fully packaged prototype sensors will be designed, fabricated, and tested under H_2 (less than 5 percent), O_2, and NO_x gas flows in laboratory furnaces, and the sensor response will be characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

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

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

Materials Category/Type:
Materials/ceramics, metals/alloys

Manufacturing/Fabrication Process/ Method:
Photolithography, thin film deposition

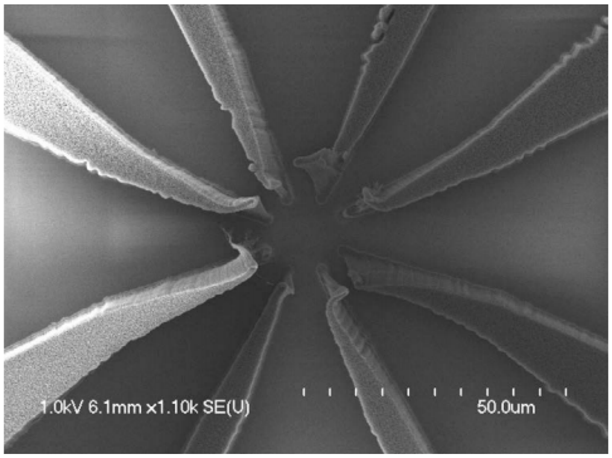
End Use:
Pulverized coal combustion, integrated gasification combined cycle, SOFC

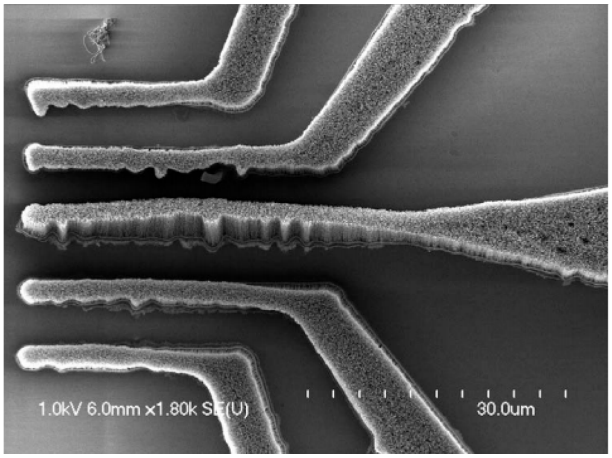
Vertically-Aligned Carbon-Nanotubes Embedded in Ceramic Matrices for Hot Electrode Applications

Performer	University of Nebraska
Award Number	FE0023061
Project Duration	10/01/2014 – 09/30/2018
Total Project Value	$ 400,000
Technology Area	University Training and Research
Key Technology	High Performance Materials

NETL is partnering with the University of Nebraska to develop carbon nanotube (CNT)-ceramic composite structures in which vertically aligned carbon nanotubes are embedded in ceramic matrices for hot electrode applications such as magnetohydrodynamic (MHD) power systems. Four objectives will be accomplished: (1) super growth of vertically aligned CNT carpets, (2) fabrication of CNT-boron nitride (BN) composite structures, (3) stability and resistance studies of the CNT-BN composite structures, and (4) thermionic emissions from the CNT-BN composite structures. The research team will grow vertically aligned (up to 1 cm thick) carbon nanotube carpets on copper.

Successful development of the CNT ceramic composite structures will reduce the capital costs of MHD power systems and establish a new family of vertically aligned CNT-based anisotropic composite structures.





Vertically aligned CNT patterns: two potential models of the carbon dispersion within the SiC bulk.

Materials Category/Type:

Materials/ceramics, metals

Cu substrate, CNT-ceramic composite structures

Manufacturing/Fabrication Process/ Method:

Laser direct writing, modulated photothermal radiometric method, thermionic emission current method, rapid thermal annealing, sputtering, deposition

End Use:

Boilers and tubing, turbines

UNIVERSITY TRAINING AND RESEARCH

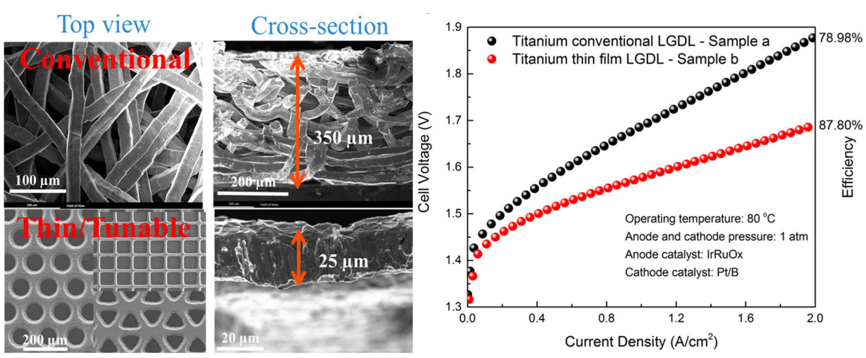
Developing Novel Multifunctional Materials for High-Efficiency Electrical Energy Storage

Performer	University of Tennessee Space Institut
Award Number	FE0011585
Project Duration	09/01/2013– 08/31/2018
Total Project Value	$ 470,084
Technology Area	University Training and Research
Key Technology	High Performance Materials

NETL is partnering with the University of Tennessee to develop a thin and well-tunable multifunctional component via micro/nano fabrication for high-efficiency electrical energy storage, which is critical for the long-term utilization of coal in energy applications to provide reliable, affordable electricity and modernize the electrical grid.

Novel titanium liquid/gas diffusion layers (LGDLs) with well-tunable pore morphologies were developed by employing micro/nano-manufacturing and showed significant performance improvements in proton exchange membrane electrolyzer cells (PEMECs). As shown in the figure below, the operating voltages required at a current density of 2.0 amps per centimeter squared for the LGDLs were as low as 1.69 volts, and efficiency reached a reported high of nearly 88 percent. In addition, the reduction in LGDL thickness from the 350 micrometers (µm) of conventional LGDLs to 25 µm will substantially reduce the weight and volume of PEMEC stacks, which can lead to new avenues for future development of low-cost and higher-performance PEMECs. The well-tunable features of LGDL including pore size, pore shape, pore distribution, and thus porosity and permeability, will be valuable in developing PEMEC models and validating simulations of PEMECs with optimal and repeatable performance.

This project will further optimize novel multifunctional materials to promote the efficiency of energy storage technologies. Improvements to energy storage technologies will promote improved utilization of power plant assets that can provide operational flexibility and result in lower capital and operating costs.



Left: Scanning electron microscopy images of conventional and thin/ well-tunable titanium multifunctional liquid/gas diffusion layers.

Right: Performance enhancement with the developed material.

Materials Category/Type:

Materials/metals

Titanium foils

Manufacturing/Fabrication Process/Method:

Computational modeling of two-phase transport model in electrolyzers, physical and chemical vapor deposition, etching, microfabrication and nanofabrication

End Use:

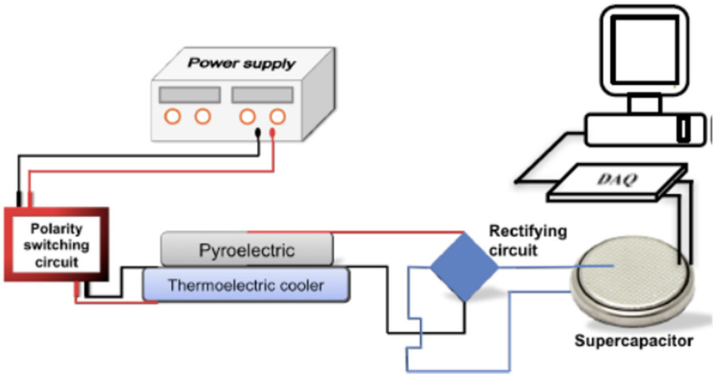
Energy storage

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

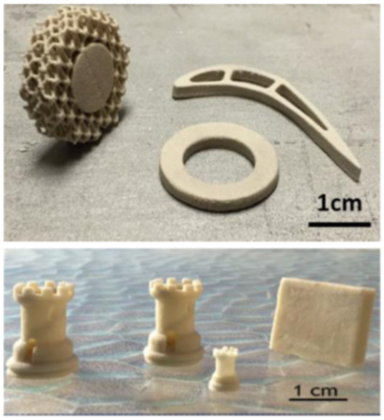
Performer	University of Texas at El Paso
Award Number	FE0027502
Project Duration	09/01/2016 – 08/31/2019
Total Project Value	$ 250,000
Technology Area	University Training and Research
Key Technology	Sensors and Controls

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

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



Thermal energy harvesting setup.



Fabrication of complex shapes.

Materials Category/Type:
Ceramic-graphene composites

Manufacturing/Fabrication Process/ Method:
3D printing fabrication

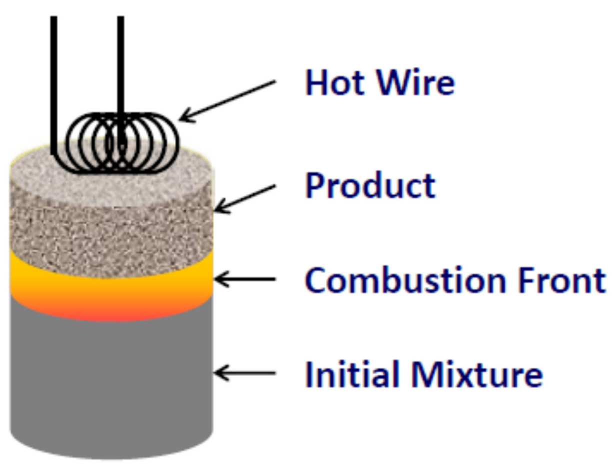
End Use:
Turbines, boilers, power plants

Combustion Synthesis of Boride-Based Electrode Materials for Magneto Hydrodynamic (MHD) Direct Power Extraction

Performer	University of Texas at El Paso
Award Number	FE0026333
Project Duration	10/01/2015 – 08/31/2019
Total Project Value	$ 250,000
Technology Area	University Training and Research
Key Technology	High Performance Materials

NETL is partnering with the University of Texas at El Paso to develop a novel technology for advanced low-cost manufacturing of boride-based ultra-high-temperature ceramics for direct power extraction applications. The project will determine optimal conditions of mechanical activation, self-propagating high-temperature synthesis (SHS), and pressureless sintering for fabricating doped zirconium diboride (ZrB_2) and hafnium diboride (HfB_2) that possess all the required properties needed to function as sustainable magnetohydrodynamic electrodes. The project will also determine thermophysical, electrical, mechanical, and oxidation properties of borides obtained by mechanically activated SHS followed by pressureless sintering. This effort will focus on the use of inexpensive materials such as zirconium dioxide (ZrO_2), hafnium dioxide (HfO_2), boron trioxide (B_2O_3), magnesium (Mg), and sodium chloride (NaCl), which could lead to significantly lower production costs compared to synthesis from elements.

The technology developed in this project will solve certain problems associated with SHS, such as difficult ignition of low-exothermic mixtures and high porosity of products, while exploiting SHS advantages such as low cost, low energy consumption, and high product purity.



Schematic of SHS process.

Materials Category/Type:
Ceramics, zirconium diboride, hafnium diboride, borides, zirconium dioxide, hafnium oxide, boron trioxide, magnesium, and sodium chloride

Manufacturing/Fabrication Process/Method:
Self-propagating high-temperature synthesis

End Use:
Direct power extraction applications

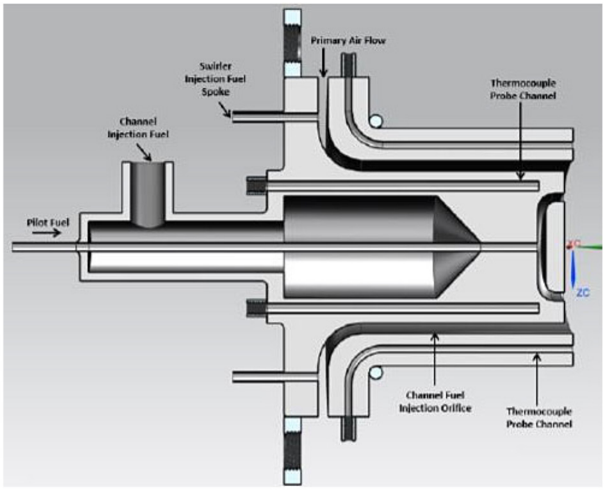
Metal Three Dimensional (3D) Printing of Low-Nitrous Oxide (NO_X) Fuel Injectors with Integrated Temperature Sensors

Performer	University of Texas at El Paso
Award Number	FE0026330
Project Duration	10/01/2015 - 09/30/2018
Total Project Value	$ 250,000
Technology Area	University Training and Research
Key Technology	Sensors and Controls

This project explores design and prototyping of a dry low-nitrogen-oxides (low-NO_X; DLN) fuel injector with integrated temperature sensing capabilities using the electron beam melting (EBM) additive manufacturing (AM) process. Low-NO_X natural gas fuel injectors, commonly used in DLN gas turbine combustors, have complex internal cavities and passages to ensure tailored mixing of air and fuel to achieve ultra-low levels of NO_x emissions. Since the current design methodology of these injectors is based on conventional fabrication techniques (i.e., multi-step machining and welding processes), a new design methodology paradigm must be developed to adapt them to the electron beam melting (EBM) fabrication process.

The proposed effort has three specific objectives: (1) development of design methodologies for low-NO_x fuel injectors with embedded temperature sensing capabilities for EBM-based three-dimensional manufacturing; (2) development of optimum EBM process parameters and powder removal techniques to remove sintered powder from internal cavities and channels of low-NO_x fuel injectors with embedded temperature sensors; and (3) testing of the EBM fabricated low-NO_x fuel injector with integrated temperature measurement capabilities in a high-pressure laboratory turbine combustor.

Metal AM processes enable embedding or integrating sensors into complex energy system components without post-production modification of the component. Conventional manufacturing processes generally require more than five steps of fabrication, assembly, and finishing to develop energy system components such as fuel injectors with complex internal geometries. In contrast, the same part can be fabricated in a single metal AM step with the option of sensor integration and more complex internal geometries.



Test article to be designed and fabricated: DLN fuel injector with integrated ceramic insulated high temperature thermocouples.

Materials Category/Type:
Materials/alloys - Inconel 718, Inconel 625, and/or titanium

Manufacturing/Fabrication Process/ Method:
Additive manufacturing fabrication process - electron beam melting

End Use:
Gas turbines

UNIVERSITY TRAINING AND RESEARCH

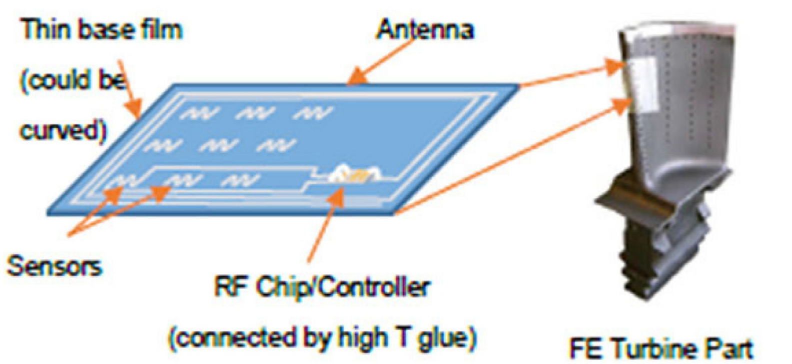
Low-Cost Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems

Performer	Washington State University
Award Number	FE0026170
Project Duration	10/01/2015 – 09/30/2018
Total Project Value	$ 488,738
Collaborator	University of Texas at El Paso
Technology Area	University Training and Research
Key Technology	Sensors and Controls

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

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

It is anticipated that this reseach will improve in-situ monitoring and the performance of FE devices and systems.



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

Materials Category/Type:
Sensors

Manufacturing/Fabrication Process/ Method:
Aerosol jet micro-additive manufacturing

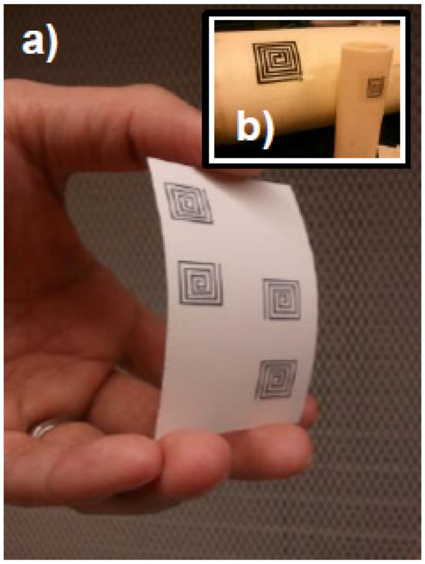
End Use:
Oxy-fuel combustion, chemical looping combustion

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

Performer	West Virginia University
Award Number	FE0026171
Project Duration	10/01/2015 – 09/30/2018
Total Project Value	$ 399,965
Collaborator	NexTech Materials, Ltd.
Technology Area	University Training and Research
Key Technology	Sensors and Controls

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

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



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

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

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

Materials Category/Type:
Sensors

Manufacturing/Fabrication Process/ Method:
2D/3D direct-writing

End Use:
Solid oxide fuel cells, chemical reactors, furnaces, engines, boilers, and gas turbines

ABBREVIATIONS

°C . . . degrees Celsius
3D . . . three-dimensional
AM . . . additive manufacturing
AUSC . . . advanced ultrasupercritical
CAU . . . Clark Atlanta University
CFD . . . computational fluid dynamics
CNT . . . carbon nanotube
CO2 . . . carbon dioxide
CSEF . . . creep strength enhanced ferritic
DLN . . . dry low-nitrogen-oxides
DOE . . . Department of Energy
EBM . . . electron beam melting
FE . . . Office of Fossil Energy (DOE)
HBCU . . . Historically Black Colleges and Universities
HX . . . Hastelloy X
ICWE . . . integrated computational weld engineering
LGDL . . . liquid/gas diffusion layer
LGS . . . langasite
LM . . . laser micromachining
MEMS . . . microelectromechanical systems
MHD . . . magnetohydrodynamic
MOF . . . metal organic framework
mV . . . millivolt
NETL . . . National Energy Technology Laboratory
NGO . . . non-governmental organization
Ni . . . nickel
ODS . . . oxide dispersion strengthened
OMI . . . Other Minority Institutions
ORNL . . . Oak Ridge National Laboratory
PEI . . . polyethylenimine
PEMEC . . . proton exchange membrane electrolyzer cell
PNNL . . . Pacific Northwest National Laboratory
R&D . . . research and development
RUL . . . remaining useful life
SAW . . . surface acoustic wave
SBIR . . . Small Business Innovation Research
SHS . . . self-propagating high-temperature synthesis
SLIPS . . . superhydrophobic/slippery liquid infused porous surfaces
SOFC . . . solid oxide fuel cell
SPS . . . spark plasma sintering
TE . . . thermoelectric
U.S. . . . United States
UCR . . . University Coal Research
UTR . . . University Training and Research
W . . . watt
WVU . . . West Virginia University

CONTACTS

Briggs White

Technology Manager

412-386-7546

Briggs.White@netl.doe.gov

Patricia Rawls

Supervisor

Enabling Technologies and Partnerships Team

412-386-5882

Patricia.Rawls@netl.doe.gov

WEBSITES:

https://energy.gov/fe/science-innovation/clean-coal-research/crosscutting-research

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

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

http://energy.gov/fe/coal-utilization-science

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NATIONAL ENERGY TECHNOLOGY LABORATORY

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

Program staff are also located in **Houston, TX** and **Anchorage, AK**.

Visit us: **www.NETL.DOE.gov**

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