HYDROGEN
with Carbon Management

2024

ADVANCED ENERGY MATERIALS

PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

Hydrogen with Carbon Management 5

Advanced Energy Materials 7

ADVANCED MANUFACTURING 8

Clemson University: Accelerated Discovery of Protection System and Laser Processing of Protective Coatings on CMC for Hydrogen Turbines 9

Microcvd Corporation: New Manufacturing Method for SiC Fiber Reinforced Ceramic Matrix Composites 10

Oak Ridge National Laboratory (ORNL): Development of Functionally Graded Transition Joints to Enable Dissimilar Metal Welds 11

Oak Ridge National Laboratory: Large Area Wire-Arc Additive Manufacturing 12

Pennsylvania State University (PSU): Enhancing Ceramic Matrix Composite (CMC) Temperature Performance in High-Hydrogen Environments using Field Assisted Sintering Technology 13

West Virginia University Research Corporation: Conformal Coatings on Additive Manufactured Robust Alloys for Significant Mitigation of Oxidation, Erosion, and Corrosion 14

HIGH-TEMPERATURE MATERIAL SUPPLY CHAIN 15

General Electric (GE) Company: Advanced Coating Compositions and Microstructures to Improve Uptime and Operational Flexibility in Cyclic, Low-Load Fossil Plants 16

Luna Innovations: Rapid SiC: Room Temperature Roll-to-Roll Production of Polymer-Derived SiC Fibers 17

Oak Ridge National Laboratory: High Temperature Hydrogen Attack in Alloys, and their Weldments, Used for Hydrogen Production and Utilization 18

Ohio State University: High-Speed and High-Quality Field Welding Repair Based on Advanced Non-Destructive Evaluation and Numerical Modeling 19

Raytheon Technologies Corporation: Advanced Energy Materials for Hydrogen Turbines for Stationary Power Generation 20

University of Central Florida: Ceramic Matrix Composites for H_2 Combustion 21

University of Maryland: Development of Hetero-Multilayered Ceramic Thermal Barrier Coatings for Hydrogen Turbines for Stationary Power Generation 22

West Virginia University/Oak Ridge National Laboratory (ORNL): Additively Manufactured Graded Composite Transition Joints for Dissimilar Metal Weldments in Ultra-Supercritical Power Plan 23

General Electric (GE) Company: Robust Dissimilar Metal Friction Welded Spool for Enhanced Capability for Steam Power Components 24

Oak Ridge National Laboratory (ORNL): Low Cost High Performance Austenitic Stainless Steels for A-USC 25

Oak Ridge National Laboratory (ORNL): Effect of Impurities on Supercritical Carbon Dioxide Compatibility 26

Oak Ridge National Laboratory (ORNL): Evaluating Ni-Based Alloys for A-USC Component Manufacturing and Use 27

Oak Ridge National Laboratory (ORNL): Forced Flow Thermal Gradient Chemical Vapor Infiltration (FCVI) of Complex-Shape..... 28

COMPUTATIONAL MATERIALS DESIGN 29

Michigan Technological University: Hybrid Structured Nickel Superalloys to Address Price Volatility and Weld/Weld Repair Based Supply Chain Issues..... 30

National Energy Technology Laboratory (NETL): Advanced Materials Development 31

National Energy Technology Laboratory: eXtremeMAT- Accelerated Design and Manufacture of Next Generation Extreme Environment Materials..... 33

Raytheon Technologies Corporation: TAdditive Predictive Modeling Investigating Steam-Mediated Degradation of Environmental Barrier Coatings in Hydrogen-Fueled Turbines..... 35

Strategic Power Systems, Inc.: Continued Development –Real Time Physics Based Data Analytics for Thermal Power Plants..... 36

HYDROGEN PRODUCTION 37

University of North Dakota: Electromagnetic Energy-Assisted Thermal Conversion of Fossil-Based Hydrocarbons to Low-Cost Hydrogen 38

Abbreviations 39

Contacts 43

HYDROGEN WITH CARBON MANAGEMENT

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

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

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

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

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

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

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

Sensors, Controls, and Other Novel Concepts: The NETL Sensors, Controls, and Novel Concepts program conducts research and development of technologies that will provide pivotal insights into optimizing performance, reliability, and availability of integrated energy and carbon management systems. NETL develops, tests, and matures novel sensor and control technologies that are enable next-generation energy systems, including hybrid plants incorporating components such as hydrogen-powered turbines and fuel cells, renewables, and energy storage applications. These sensors enable responsiveness to varying conditions in real time, maintaining high efficiencies and reducing emissions. This research will aid in the achievement of DOE goals which include net-zero carbon emissions in the energy sector by 2035 and a decarbonized wider economy by 2050.

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

ADVANCED ENERGY MATERIALS

Power generation plants operate under extreme conditions from a materials standpoint. Future advanced generation facilities will be expected to withstand harsher environments due to higher demands for increased efficiency, quicker plant startups and turndowns, cycling, and alternative power source supplementation. To support these expectations, new materials are needed for these conditions and performance expectations.

Advanced ultrasupercritical (AUSC) boilers, pressurized oxy-combustion boilers, pressurized gasifiers, and the advanced turbines for each of these types of plants will operate under higher temperatures and pressures, which promote rapid corrosion and degradation of subcomponent materials. Internal stresses in thick-walled components such as superheater headers, turbine casings, and turbine rotors, along with boiler tube scaling and turbine blade erosion, are critical material issues that must be addressed for reliable plant operation.

Advanced Energy Materials focuses on materials that will lower the cost and improve the performance of existing and advanced fossil-based power-generation systems. There are four research areas within AEM:

- Advanced Manufacturing
- Advanced Structural Materials for Harsh Environments
- Computational Materials Design
- Hydrogen Production (e.g., catalyst development for novel hydrocarbon deconstruction pathways)

Specific Technology Objectives:

- Develop computational materials modeling to enable rapid design and simulation of new and novel alloy materials. Computational design of materials has the potential to produce major breakthroughs.
- Develop superalloys and ferritic materials for use in AUSC conditions of 760 degrees Celsius (°C) and 350 bar pressure (5,000 psi) to reduce costs, improve corrosion and erosion resistance, increase material strength, and reduce wall thickness.
- Develop functional materials for energy storage and high-performance materials with mechanical properties that can perform reliably at temperatures well over 1,000 °C.
- Develop advanced metallic and ceramic coatings, including nanomaterials, to provide thermal barrier protection for turbine blades, combustor components, and tubing.
- Develop validated computational models capable of simulating and predicting performance of materials in various types of transformational power plants.

This project portfolio report showcases 23 Advanced Energy Materials projects within the Hydrogen with Carbon Management Program of the Technology Development Center. Each of the pages reporting on projects describes the technology, the program goals, and overall benefits.

ADVANCED MANUFACTURING

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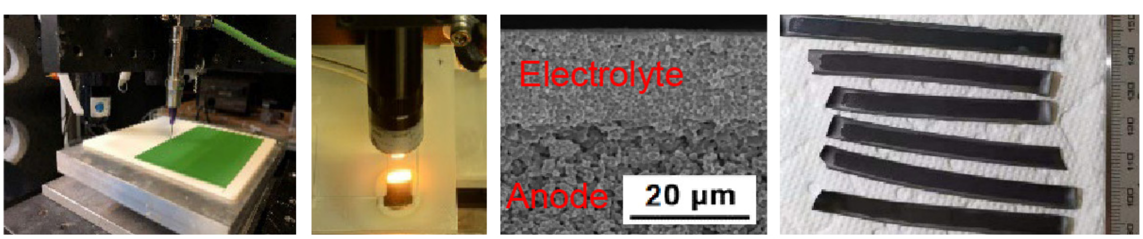
Accelerated Discovery of Protection System and Laser Processing of Protective Coatings on CMC for Hydrogen Turbines

Performer	**Clemson University**
Award Number	DE-FE0032231
Project Duration	02/03/2023 – 02/02/2025
Total Project Value	$ 1,144,045
Collaborators	Advanced Manufacturing, LLC; Siemens Corporation
Technology Area	High Performance Materials

This project aims to design, process, and validate a laser-manufactured integrated and graded bond coat-environmental barrier coat-thermal barrier coat (BC-EBC-TBC) system that can effectively protect and lead to the use of silicon carbide fiber/silicon carbide matrix (SiCf/SiC) ceramic matrix composites (CMCs) in next-generation hydrogen-fueled turbines. Six objectives will be achieved: (1) characterization of the thermal and mechanical properties of the candidate coating materials, including polymer-derived ceramics (PDC), yttrium silicates, and gadolinium zirconate, followed by theoretical design of the integrated and graded BC-EBC-TBC to maximize the thermal protection while minimizing the thermal stress; (2) optimization of the laser processing parameters for various compositions consisting of PDC, yttrium silicate, and/or gadolinium zirconate the achieve the targeted crystalline phase and microstructure, followed by fabrication of micro-sample arrays of the multilayer integrated BC-EBC-TBC on CMC substrates for high-throughput test and characterization; (3) simulation of the thermal and chemical environment during combustion of mixtures of gas and hydrogen with H_2 content between 25% and 100% to provide realistic test settings; (4) testing the sample array and characterizing the microstructure change and any defects, such as cracks and debonding; (5) establishing machine-learning-based in-process monitoring to evaluate the on-the-spot microstructure and defects, ensuring manufacturing reliability and repeatability; and (6) fabricate graded coatings with similar compositions using the air plasma ray (APS) method, then testing them in simulated hydrogen-fueled combustion environments to benchmark the laser method's performance.



Direct ink writing of ceramic paste, and laser sintering of ceramic half-cell with dense electrolyte layer and porous anode simultaneously.

New Manufacturing Method for SiC Fiber Reinforced Ceramic Matrix Composites

Performer	**Microcvd Corporation**
Award Number	SC0023948
Project Duration	07/10/2023 – 07/09/2024
Total Project Value	$ 250,000
Technology Area	Advanced Materials Development

Additive manufacturing (AM) is a process in which a product is fabricated layer by layer, providing flexibility for manufacture of complex designs with relatively little effort and reduced time and cost. Manufacture of ceramic matrix composite (CMC) materials, on the other hand, can be time consuming and expensive, with potential technical hurdles still to be overcome. In response to the challenges of manufacturing CMCs, a hybrid manufacturing technique is proposed that integrates the localized laser chemical vapor deposition (CVD) technique with additive manufacturing (AM) to fabricate low-cost, high-yield, high-performance and reliable CMCs. The silicon carbide (SiC) fibers and nano/micro particles are produced in situ during the CMC additive manufacturing process.

In Phase I of the project, the team will (1) build a hybrid laser CVD/AM manufacturing prototype CMC production system based on their existing laser CVD system; (2) operate the prototype apparatus to deposit silicon carbide (SiC) fiber on SiC substrate through a sintering/melting process using the laser CVD subsystem and X-Y positioning stage; and (3)) consolidate the laser CVD/AM subsystems into a user-friendly CMC manufacturing instrument.

The proposed hybrid laser CVD/AM technique will not only reduce the time requirements and complexity of making SiC fiber, but also it can produce other ceramic or refractory composite materials with fiber- or nanoparticle-reinforced elements that are critical components in CMC manufacturing, thus reducing the cost of CMC manufacturing while improving the product yield.

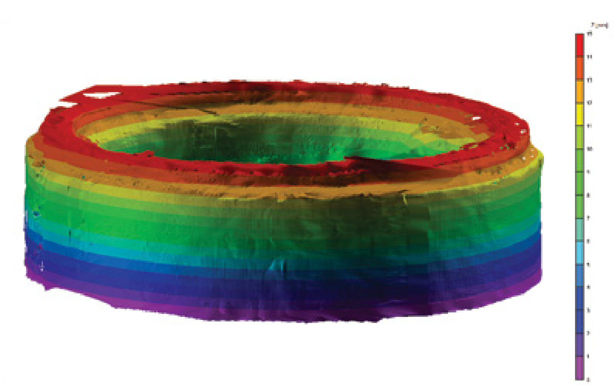
Development of Functionally Graded Transition Joints to Enable Dissimilar Metal Welds

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA151
Project Duration	07/01/2019 – 03/31/2024
Total Project Value	$ 1,025,000
Technology Area	Plant Optimization Technologies

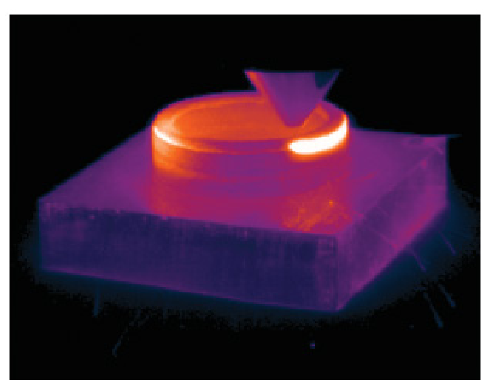
Oak Ridge National Laboratory will weld dissimilar metals using functionally graded transition joints that exhibit high resistance to creep and fatigue and high microstructural stability. The primary focus of the project will be on joining ferritic steels to austenitic steels, in particular alloys that are relevant in coal-fired power plants. A key aspect of the R&D activities will be determining optimum compositional profiles of the transition joint, which will be achieved using computational materials science and engineering. Another key aspect will be avoiding sharp changes in the carbon chemical potential of the joint region. The project entails the integration of several interrelated tasks to achieve project objectives.

- Design optimization of chemistry/microstructure transitions in graded transition joints to minimize carbon diffusion and the formation of stresses induced by thermal expansion mismatch.
- Optimization of processing methods to fabricate the graded transition joint and in situ process monitoring for development. The effect of using powders or wires as feedstock on manufacturability and costs will be addressed, as well as practical aspects of deploying the technology to the field.
- Evaluation of mechanical performance of the transition joints using ex situ and in situ testing as a function of processing parameters, and comparison with historic creep rupture properties of dissimilar metal welds.

The successful completion of this project will set the stage for subsequently developing an ASME code case for wide industrial acceptance and utilization of this technology.



In-situ Imaging of joint during fabrication. Color corresponds to vertical height.



IR image showing temperature distribution with build height.

Large Area Wire-Arc Additive Manufacturing

Performer	**Oak Ridge National Laboratory**
Award Number	FWP-FEAA436
Project Duration	10/01/2023 – 9/30/2026
Total Project Value	$ 1,800,000
Collaborator	Lincoln Electric
Technology Area	Advanced Materials Design

This project has two main objectives: to develop a new alloy design strategy for production of hydrogen-compatible heat-resistant alloys using additive manufacturing methods, specifically focusing on face-centered-cubic (FCC) iron (Fe)/nickel (Ni)-base precipitation-strengthened alloys for high-temperature use, and to investigate the effect of grain structure on property deteriorations under hydrogen exposure, especially at elevated temperatures.

The project will incorporate a wire-direct energy deposition (DED) additive manufacturing process with gas-metal arc welding (GMAW) as a component production process. Initial tasks include studying (1) the mechanical response of the printed materials with various grain structure under hydrogen and (2) the effect of alloy composition in Fe-Ni-Cr-Al-base alloys with variation of Fe/Ni balance and controlled secondary phases on steam oxidation resistance as well as mechanical properties under hydrogen. The knowledge obtained will then be used to produce (3) three candidate alloy compositions and grain structures optimized for the hydrogen-containing environments, and after further downselection (4) a solid-core wire with the target alloy composition.

This technology promotes a significant reduction of the lead time needed to produce near-net-shape structural components, allowing high component design flexibility and accepts in-situ quality inspection during production by applying a properly designed monitoring system. With this approach the alloy design needs to be focused on the compositional refinements as a major control variable, together with solidification control and post-process heat treatment for microstructure optimization, since no thermomechanical treatment is applicable to the entire process.

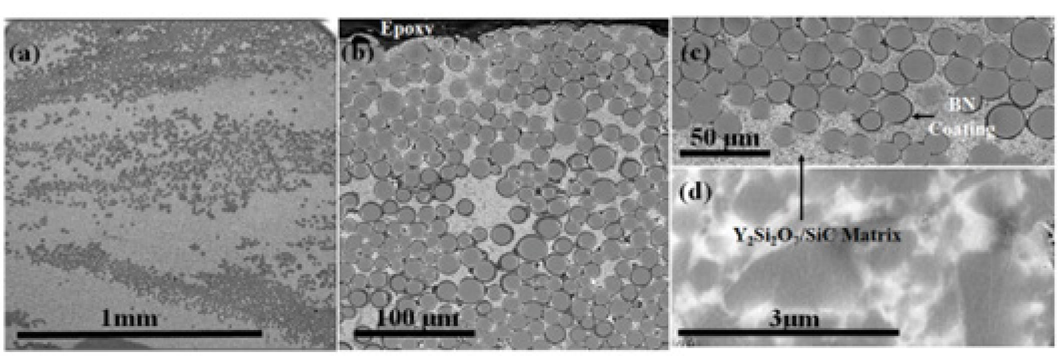
Enhancing Ceramic Matrix Composite (CMC) Temperature Performance in High-Hydrogen Environments using Field Assisted Sintering Technology

Performer	**Pennsylvania State University (PSU)**
Award Number	FE0032226
Project Duration	01/01/2023 – 12/31/2024
Total Project Value	$ 843,750
Technology Area	Plant Optimization Technologies

The overall objective of this project is to significantly improve the temperature performance by at least 150 ° C of ceramic matrix composite (CMC) materials in high-hydrogen environments using field assisted sintering technology (FAST). FAST is a relatively new material synthesis technology that allows for novel materials to be processed at significantly shorter fabrication times by using high-density electrical currents to drive rapid, high-intensity heating.

The project objective will be achieved using the following methodology: FAST-derived CMCs in conjunction with advanced ceramic coatings will be developed to adapt to higher-temperature combustion with higher-humidity contents as a result of the high-hydrogen fuel. The fabricated samples will be tested at a range of combustor operating conditions with up to 100% hydrogen fuel to understand the impact of different CMC formulations and combustion gas environments on the material performance.

The anticipated outcome of this project is a lab-scale demonstration that the FAST-based manufacturing technology can enable high-density silicon carbide (SiC)-based CMC parts with superior water vapor recession resistance, such that their upper use temperature can significantly exceed that of state-of-the-art nickel superalloys and conventional SiC/SiC CMCs, and thus enable an increase in combined-cycle combustion turbine efficiency by up to two percentage points. This will result in reduced fuel consumption and emissions.



CMC microstructure.

Conformal Coatings on Additive Manufactured Robust Alloys for Significant Mitigation of Oxidation, Erosion, and Corrosion

Performer	**West Virginia University Research Corporation**
Award Number	FE0032068
Project Duration	09/15/2021 – 09/14/2024
Total Project Value	$ 400,000
Technology Area	University Training and Research

The project will develop novel high-temperature alloys from nickel (Ni)-based alloys that further integrate additive manufacturing (AM) fabrication, creating novel nanoscale oxide precipitation for strengthened mechanical integrity and enhanced oxidation resistance, and subsequent application of conformal protective coatings on the additive manufactured alloys. To increase the strength and oxidation resistance of nickel alloys, erbium and titanium oxide (Er_2O_3 and TiO) precipitants will be added to the AM powders for the Inconel 625 alloy and result in dense nano-oxide precipitation of Er_2O_3 and $Er_2Ti_2O_7$, which will result in a solution-strengthened novel Ni-based alloy. Furthermore, a conformal protective oxide coating layer will be simultaneously applied on both the internal and external surface of the additive manufactured heat exchangers with complex geometry using atomic layer deposition (ALD). The ALD layer will be conformal, uniform, pin-hole free, dense, and ultra-thin with negligible weight gain to increase both the oxidation and corrosion resistance at elevated temperatures.

The project is organized into 5 Tasks. Task 1 is project management. Task 2 is devoted to introducing the dense precipitates into the Ni-based alloys through AM. Task 3 is devoted to ALD coating of the newly additive manufactured 3D printed Ni-based alloys and ALD repairing and recoating the alloys after oxidation exposure. Task 4 is the oxidation resistance testing of the additive manufactured and ALD coated Ni-based alloys. Task 5 is the comprehensive physical properties testing, and nanostructure analysis of the additive manufactured alloys (including the ones with precipitates), ALD coated alloys, and the alloys after exposure to the oxidation and corrosion environments.

The developed high-temperature materials are expected to possess superior strength, high resistance to external surface oxidation, internal surface carburation, and corrosion, and can be applied to heat exchangers for operation in supercritical carbon dioxide at high temperatures (over 750 °C) and pressure (30 MPa). For after-service heat exchangers that have damaged surfaces, the ALD coating can also be utilized to repair/refurbish the heat exchanger parts that may have been impacted by surface oxidation and dramatically increase their lifetime and reduce costs.

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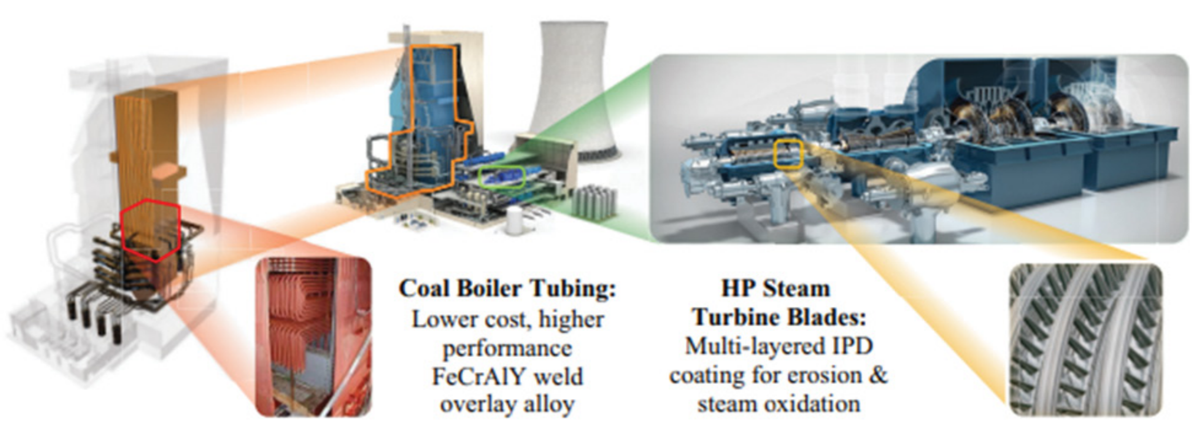
Advanced Coating Compositions and Microstructures to Improve Uptime and Operational Flexibility in Cyclic, Low-Load Fossil Plants

Performer	**General Electric (GE) Company**
Award Number	FE0031911
Project Duration	09/01/2020 – 12/31/2023
Total Project Value	$ 5,549,995
Collaborators	GE Steam Power, Inc. University of Tennessee
Technology Area	Plant Optimization Technologies

This project addresses two principal factors that drive outages in the fossil power plant fleet: corrosion at the outer diameter of boiler tubing and solid particle erosion in high-pressure (HP) steam turbine blades. The overarching objective is to produce coatings that mitigate these damage mechanisms and provide a comprehensive solution to improve fleet reliability and operational flexibility. GE Research will lead a team of researchers to leverage a century of fleet experience and exciting new results obtained from DOE-funded nuclear materials research to develop cost-effective weld overlay compositions for boiler tubing and multi-layered ion plasma deposition coatings that deliver improvements in both erosion and oxidation resistance in high temperature steam for HP turbine blades. Deep technical expertise and world class characterization capability will be provided by Oak Ridge National Laboratory and the University of Tennessee. The team will work collaboratively through a robust, logical project map to achieve the objectives listed below, identified based on the funding announcement and direct input from GE:

- Enable a 25%-50% increase in time between outages for both boilers and HP turbines.
- Eliminate or significantly reduce the nickel content in weld overlay to mitigate cost.
- Provide adequate oxidation resistance for HP turbine inlet steam at >620 °C and >220 bar.
- Apply coatings to actual components, using today's production-scale methods.

Decreased component cost, increased performance, and extended time between outages are direct value propositions for the fossil energy fleet. For the U.S consumer, project success could lead to increased grid reliability (fewer unexpected outages), decreased levelized cost of electricity, and reduced environmental impact due to low loading/load following to accelerate penetration of renewables.



Rapid SiC: Room Temperature Roll-to-Roll Production of Polymer-Derived SiC Fibers

Performer	**Luna Innovations**
Award Number	SC0022875
Project Duration	06/27/2022 – 08/27/2025
Total Project Value	$ 1,874,765
Technology Area	Plant Optimization Technologies

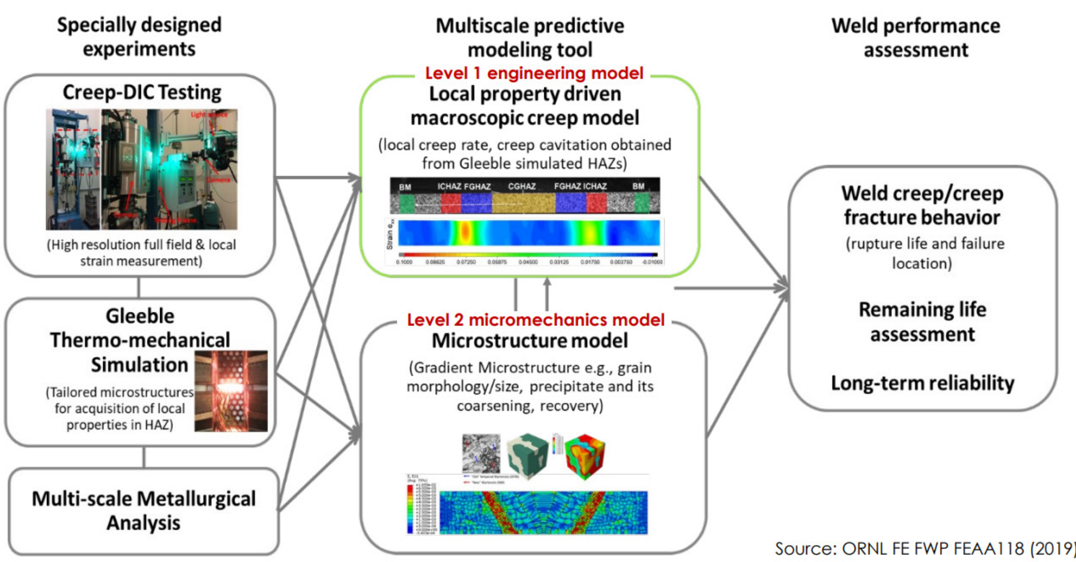
Combustion turbines, which have enabled numerous advances as diverse as hypersonic flight and energy production, have higher fuel-to-power efficiencies when operated at high temperatures. For example, the DOE advanced turbine program demonstrated turbines operating over 1400 °C display 35-40% higher efficiency compared with traditional turbines operating between 800–1000 °C. Ceramic matrix composites (CMCs) have emerged as promising advanced materials to enable turbines to operate at temperatures over 1400 °C. However, the prohibitive cost of silicon carbide (SiC) fibers used to reinforce CMCs has restricted their broader implementation in combustion turbine applications. Given this, there is a critical need to produce high-quality SiC fibers at lower costs. Luna Labs USA, LLC has partnered with Dr. Jeffery Morse at the University of Massachusetts – Amherst (UMA) to prepare high-quality, low-cost SiC fibers.

High-temperature materials, such as CMCs, are enabling new technologies that improve efficiency and performance in power generation, marine applications, aircraft propulsion, space vehicles, and more. For example, increasing the maximum operating temperature of a combustion turbine from 1260 to 1420 °C allows turbines to operate at over 50 – 60% efficiency. This increased energy-to-fuel conversion efficiency results in an increase in the net present value (NPV) of natural gas turbines and, in turn, reduces the overall cost of electricity.

High Temperature Hydrogen Attack in Alloys, and their Weldments, Used for Hydrogen Production and Utilization

Performer	**Oak Ridge National Laboratory**
Award Number	FWP-FEAA431
Project Duration	07/01/2023 – 9/30/2026
Total Project Value	$ 2,000,000
Technology Area	Advanced Materials Development

This FWP is part of a joint R&D project with the National Energy Technology Laboratory (NETL) to assess the propensity of structural steels, alloys, and their weldments, to undergo high-temperature hydrogen attack (HTHA) when used for high-temperature hydrogen production and utilization with hydrocarbon feedstocks. The proposed work at ORNL has been structured in two phases. During phase 1, the propensity of structural steels and alloys, provided by industry partners for use in hydrogen production and utilization, to undergo HTHA will be determined. If the mechanical properties of these materials and their weldments are degraded as a result of HTHA, then during phase 2, ORNL will focus on (1) developing a fundamental understanding of HTHA in these materials, (2) extending ORNL's integrated computational welding engineering (ICWE) modeling and testing framework for more reliable assessment of HTHA that is critically needed by the industry, and (3) supporting the development of next-generation HTHA-resistant alloys, led by NETL. All of these activities will be carried out in close collaboration with industrial stakeholders by (i) investigating relevant field serviced materials, (ii) corroborating laboratory-scale testing results in this work with industry's component-level testing, and (iii) technology dissemination for regulatory body approval and industry acceptance of the developed HTHA evaluation methodology and of alloys with enhanced HTHA resistance. The ultimate goal of this joint NETL/ORNL project is to improve the structural integrity and efficiency of structural components for the hydrogen economy, including high-temperature hydrogen production and utilization.



ORNL's integrated experimental and computational welding engineering modeling approach for creep deformation and failure of CSEF Steels and their welds at structural component level. This same methodology will be used for hydrogen creep testing.

High-Speed and High-Quality Field Welding Repair Based on Advanced Non-Destructive Evaluation and Numerical Modeling

Performer	**Ohio State University**
Award Number	FE0032067
Project Duration	09/24/2021 – 09/23/2024
Total Project Value	$ 400,000
Technology Area	University Training and Research

The goal of the project is to establish the experimental and computational foundations that are crucial to implement high-speed and high-quality field welding repair based on advanced non-destructive evaluation (NDE) and numerical modeling. The scope of work of the project is focused on developing two enabling techniques for repair of CSEF Grade 91 and 92 steel components: (1) microstructure detection using ultrasonic NDE, and (2) hardness prediction using a computational model for multi-pass, multi-layer welding.

Weld coupons will be fabricated using a high-deposition-rate process based on hot wire gas tungsten arc welding (GTAW). These weld coupons will be characterized for microstructure and hardness, which provides the baseline data for Gleeble® physical simulation to produce a bulk weld microstructure. Through the control of peak temperature and time, individual microstructures (especially martensite) with different levels of tempering will be produced. This simulated microstructure is needed since the actual weld comprises a highly inhomogeneous microstructure that is difficult for analysis by raw ultrasonics. Samples containing different microstructures will be scanned using ultrasonic testing and advanced data processing algorithms such as machine learning will be used to find ultrasound parameters that are unique to the susceptible microstructures. The physics-based models will consider the heat transfer and molten pool fluid flow in a multi-pass, multi-layer dissimilar metal welding repair. The Gleeble testing results will also be used to develop a tempering kinetic model to predict the as-welded hardness distribution as well as that after post-weld heat treatment (PWHT).

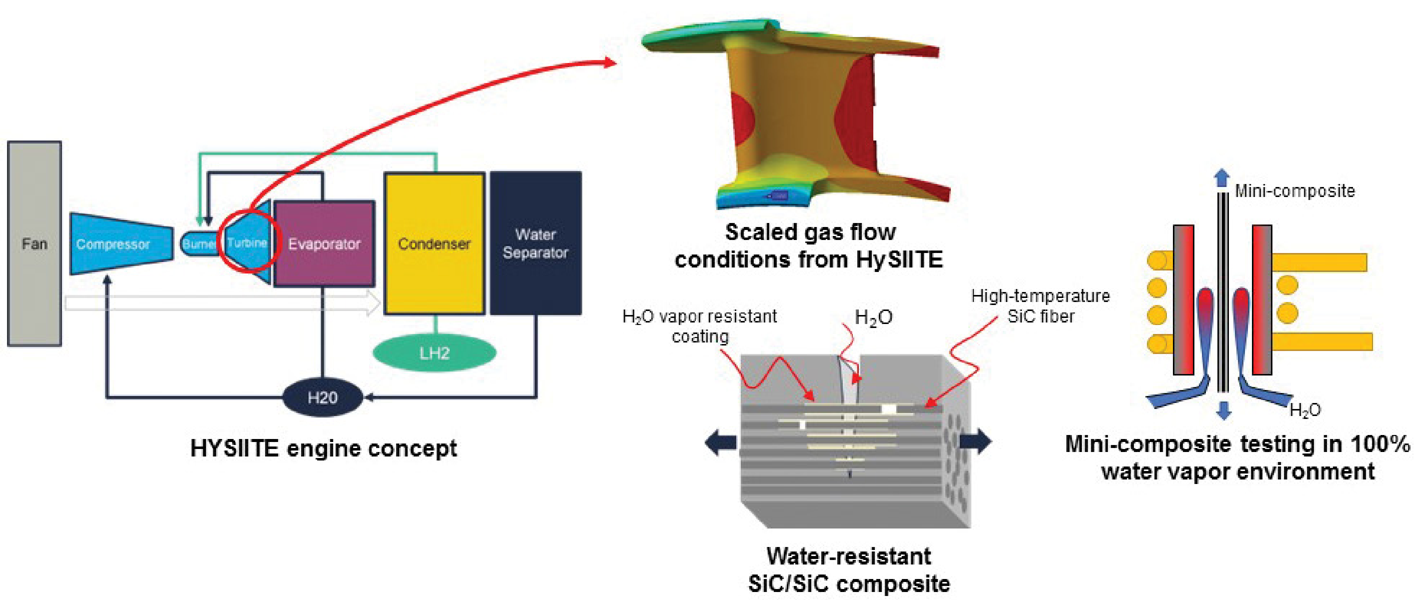
High-quality field welding repairs on CSEF steel components are critical to the reliable and efficient operation of the current fleet of power plants in the United States. Development of a reliable field-usable NDE technique will ensure that the required microstructure is achieved after onsite welding. Additionally, establishing knowledge of weld reparability for newer CSEF steels such as Grade 92 based on advanced numerical models of welding processes will facilitate their adoption. The tools and knowledge to be generated in the project will establish experimental and computational foundations to achieve the overall goal of detecting and controlling microstructure and properties for welding repair onto CSEF steel components.

Advanced Energy Materials for Hydrogen Turbines for Stationary Power Generation

Performer	**Raytheon Technologies Corporation**
Award Number	FE0032225
Project Duration	03/01/2023 – 02/28/2025
Total Project Value	$ 1,002,188
Technology Area	Advanced Materials Development

The overall objective of this project is to develop a silicon carbide (SiC) fiber/SiC ceramic matrix composite (CMC) with enhanced water resistance for future hydrogen turbine engine hot section applications at temperatures of 2700 °F. The project will focus on a pair of materials innovations to raise the CMC temperature capability and mitigate the increased corrosion/oxidation effects of a high-water-vapor combustion environment. These innovations include introducing a new polycrystalline SiC fiber and a dual interface layer to mitigate the effects of H_2O ingress through matrix cracks and the resulting corrosion at the fiber and interfacial region. Data will be obtained to identify the oxidation mechanisms and kinetics of the interface corrosion to expand current oxidation models and calibrate and validate oxidation-coupled damage mechanics models for hydrogen combustion.

The anticipated benefits of this project will be a new baseline for SiC/SiC composites in more aggressive environments and strategies for further improvements. The coupling of the material development with models will identify mechanisms and maps useful for designers. The results of this project will also enable the development of new relevant avenues to improve current and future hydrogen-fueled turbine engines for power generation applications.

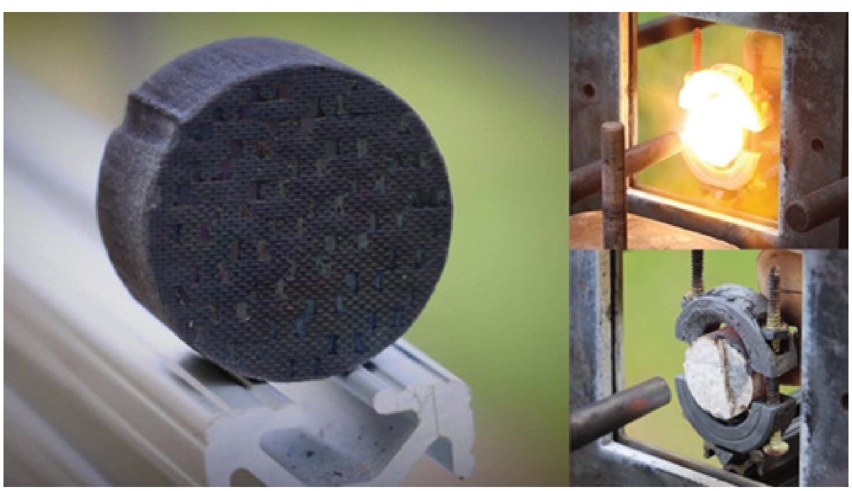


Ceramic Matrix Composites for H_2 Combustion

Performer	**University of Central Florida**
Award Number	FE0032228
Project Duration	01/19/2023 – 01/18/2025
Total Project Value	$ 998,706
Technology Area	Plant Optimization Technologies

Gas turbines for power generation are under transition to hydrogen-based combustion systems to achieve net-zero or net-negative carbon emissions. A transition to hydrogen-based fuel combustion must also coincide with other technological advancements in gas turbines. The project will investigate a new ceramic matrix composite (CMC) material, YSZ/Si(B)CN (YSZ = yttria stabilized zirconia) coated or interlayered with multi-layered nano-ceramic composites assembled at the molecular level, in a hydrogen combustor similar to modern gas turbine combustors. The project scope of work is to develop CMC materials and their manufacturing techniques towards high temperature performance and high resistance to environmental degradation in hydrogen combustion environments, provide an experimental assessment of high-temperature CMC materials in hydrogen-based fuels combustion under gas turbine relevant conditions, and develop a high-fidelity analysis platform that can adequately evaluate the thermo-mechanical performance of CMC materials with direct consideration of environmentally induced material degradation due to chemical reaction and physical material configurational changes..

The work will provide critical knowledge regarding CMC materials design and manufacturing for hydrogen-burning gas turbines components. The project will methodically explore CMC material performance and generate data to identify the best strategies to optimize the performance of CMC materials for hydrogen-based energy production to eliminate carbon emissions. The project will address these specific challenges in design, manufacturing, testing, and modeling of advanced CMC materials in an actual hydrogen combustion facility. The combustor can emulate loading conditions experienced in modern gas turbine combustors. Hence, experimental measurements of materials at elevated pressures (P >10 atm) and load conditions (T >1500 °C) will provide knowledge that is directly applicable to original equipment manufacturers.



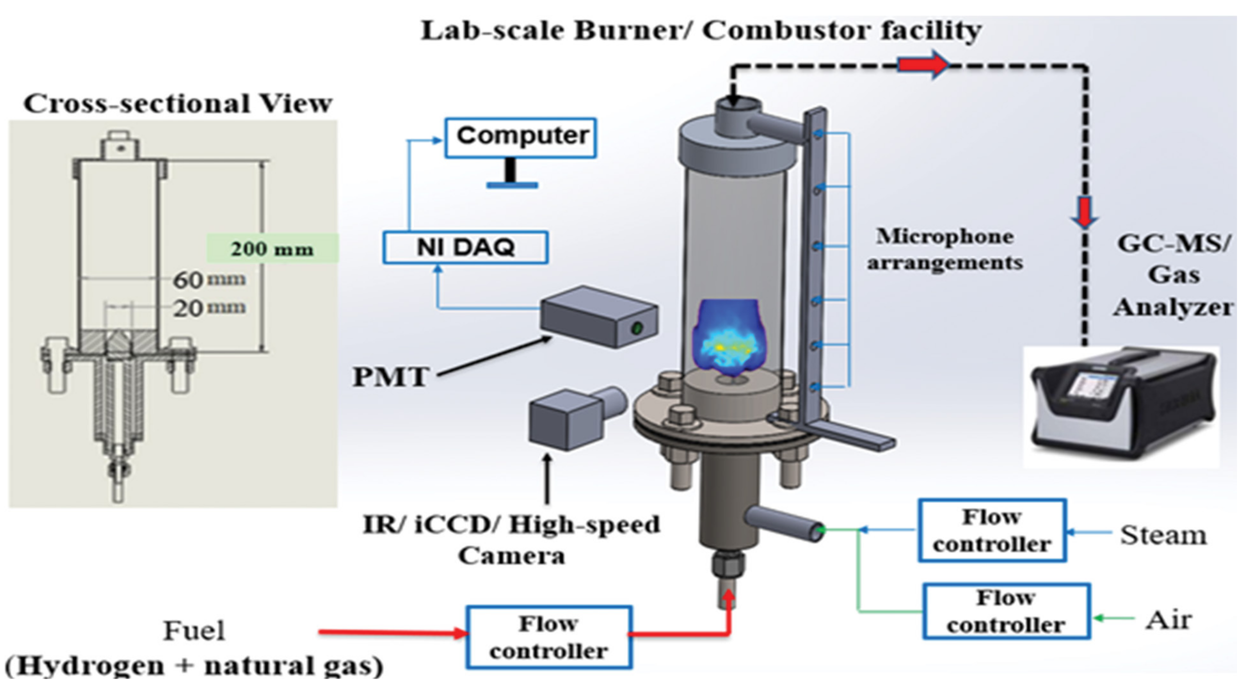
Flame exposure test of Ceramic Matrix Composite under an oxy-acetylene torch

Development of Hetero-Multilayered Ceramic Thermal Barrier Coatings for Hydrogen Turbines for Stationary Power Generation

Performer	University of Maryland
Award Number	FE0032227
Project Duration	05/01/2023 – 04/30/2025
Total Project Value	$ 1,000,000
Technology Area	Advanced Materials Development

The objective of this project is to develop an innovative thermal barrier coating consisting of hetero-multilayers of yttria stabilized zirconia (YSZ) and alpha-phase alumina with the desired thermal, mechanical and ionic conduction properties to enable an additional 150 °C - 200 °C of temperature capability beyond the current ceramic matrix composites (CMC) technology. The proof of concept of the mulltilayered thermal barrier coating technologies will be demonstrated. Specifically, a co-design model for thermal, mechanical and ionic transport properties in the multilayered coating will be developed. The multilayered thermal barrier coating will be manufactured and its structure and properties will be characterized. In addition, the initial tech-to-market analysis will be performed.

The proposed thermal barrier coating offers a unique combination of advantages over the existing CMC top coats, which includes higher use temperature (1500 °C or higher), lower thermal conductivity (<1W/mK), higher moisture resistance, and a functionally gradient coefficient of thermal expansion. The results obtained in this project will be used to optimize the manufacturing process of the coating. By collaborating with leading U.S. rocket engine manufacturers, a strategy for technology to market transfer will be developed.



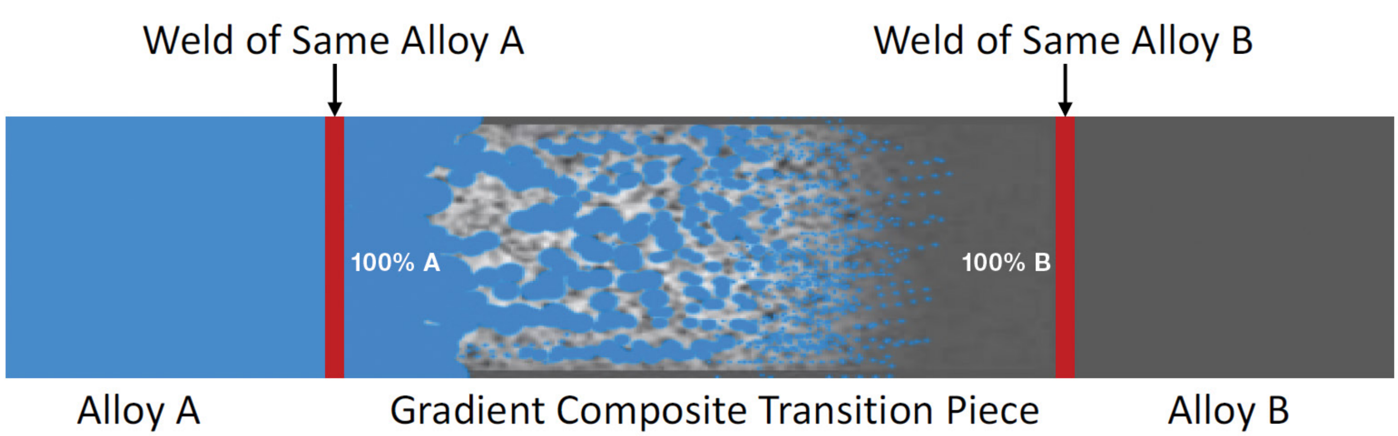
Additively Manufactured Graded Composite Transition Joints for Dissimilar Metal Weldments in Ultra-Supercritical Power Plan

Performer	West Virginia University	Oak Ridge National Laboratory (ORNL)
Award Number	FE0031819	FWP-FEAA372
Project Duration	10/01/2019 – 09/30/2024	10/01/2019 – 09/30/2021
Total Project Value	$ 7,289,004	$ 310,000
Total Project Value (All)	$ 7,599,004	
Collaborators	Carpenter Powder Products; General Electric; Oak Ridge National Laboratory	
Technology Area	Plant Optimization Technologies	

The objective of this project is to develop and demonstrate at lab scale the additively manufactured graded composite transition joints (AM-GCTJ) for dissimilar metal weldments (DMW) in next-generation advanced ultra-supercritical (AUSC) coal-fired power plants, that can significantly improve the microstructural stability, creep, and thermal-mechanical fatigue resistance as compared with their conventional counterparts.

Conventional DMW interfaces of P91/Super 304H and Super 304H/282 will be characterized by neutron diffraction measurement at Oak Ridge National Laboratory (ORNL)'s Spallation Neutron Source (SNS) under simulative thermal cyclic conditions to understand the thermal stresses and establish the baseline. In collaboration with the experimental microstructure characterization and creep and thermal creep fatigue testing tasks, the ORNL's integrated computational weld engineering (ICWE) model framework will be used to simulate the microstructure and property variations and their effects on the thermal stresses in the AM-GCTJ.

The successful completion of this project will develop cost-effective and readily scalable AM-GCTJ that practically eliminates the coefficient of thermal expansion mismatch and sharp compositional transition associated with DMW. The AM-GCTJ will significantly improve the high-temperature mechanical properties as compared with their conventional DMW counterparts. This is not only a key technology advancement toward the development of next generation AUSC plants, but also may extend the lifetime of current fleets that have been through frequent cycling.



Robust Dissimilar Metal Friction Welded Spool for Enhanced Capability for Steam Power Components

Performer	**General Electric (GE) Company**
Award Number	FE0031907
Project Duration	09/01/2020 – 05/31/2024
Total Project Value	$ 6,249,846
Technology Area	Plant Optimization Technologies

General Electric Company will undertake a three-year, $6.25 million project to improve the durability of dissimilar metal welds (DMWs) for boiler and heat recovery steam generator (HRSG) applications with reduced maintenance costs and enhanced capability of plant cycling operations. The Recipient will develop a durable friction-welded dissimilar-metal spool utilizing the higher capability transition material of a nanostructured ferritic alloy (NFA) and an oxidation protective coating across weld joints that can be retrofitted to the existing fleet. The spools will be friction-welded in the shop, allowing for controlled friction-welding procedures, post-weld heat treatment, and non-destructive evaluation (NDE). These spools can then be welded with same-metal fusion welds as replacements or upgrades in the field. Improved joint durability will enable at least a fivefold increase in the number of cold starts and reduce unplanned outages from DMW failures.

Improving the durability of the DMW joints reduces the number of unplanned outages and associated maintenance costs. The improved properties of the joint provided by friction welding and an NFA transition piece can enable an increased number of cold starts and more cycling of the boiler and HRSG systems. Preliminary evaluation of a friction-welded spool showed a fivefold increase in the number of cycles before failure of the joint compared to a baseline traditional DMW. This improvement in life and DMW reliability would lead to less unplanned downtime and longer maintenance windows.

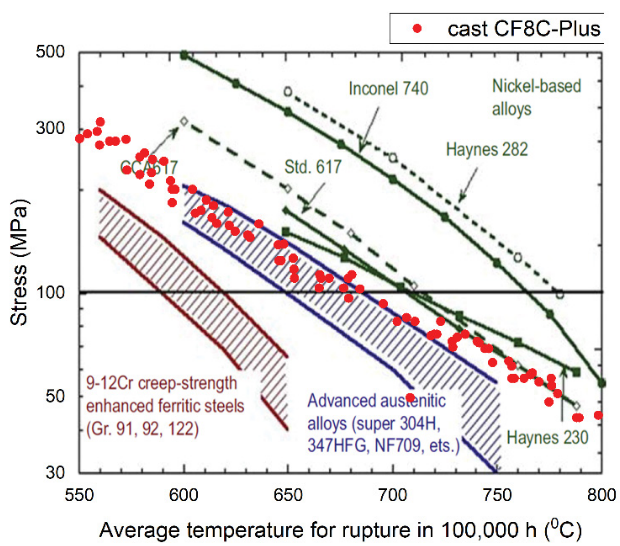
Rotary friction welded T91 to 304H tube.

Low Cost High Performance Austenitic Stainless Steels for A-USC

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA133
Project Duration	10/01/2019 – 09/30/2025
Total Project Value	$ 2,340,000
Collaborator	Electric Power Research Institute (EPRI)
Technology Area	Plant Optimization Technologies

This project evaluated the behavior of high-temperature materials to qualify low-cost alloys for steam turbine designs required for operation under advanced ultra-supercritical (AUSC) steam conditions (760 °C and 345 bar/1400 °F and 5000 psig steam), and in ensuring that any limitations of current materials are overcome. This project focused on obtaining long-term creep properties of full- or near-full-sized components of extruded tubes and pipes or other parts fabricated from the CF8C-Plus alloy for component testing in an actual AUSC power plant environment (ComTest).

The key to enabling higher efficiencies/lower emissions is the availability of materials capable of operation in steam at the higher temperatures and pressures. In particular, the limiting temperature for current steam turbines is set by the strength of the material used for the turbine casings, which are constructed from large castings that have complex shapes to accommodate the turbine vanes and blades; typically, assembly involves welding together several castings. To meet these requirements, the alloy used must develop the required strength in the as-cast state (since the size of the castings and the large changes in section thickness restrict the ability to control post-casting heat treatments) and have good weldability. The alloys used for current steam turbine casings are 2-10%Cr ferritic steels, for which the maximum temperature capability is approximately 620 °C (1,148 °F). For higher temperatures, austenitic steels typically are the next choice, but the thermal fatigue properties of most cast austenitic steels are unsuitable for this application. However, cast CF8C-Plus steel has outstanding fatigue and thermal fatigue resistance, so this steel might be useful for such applications.



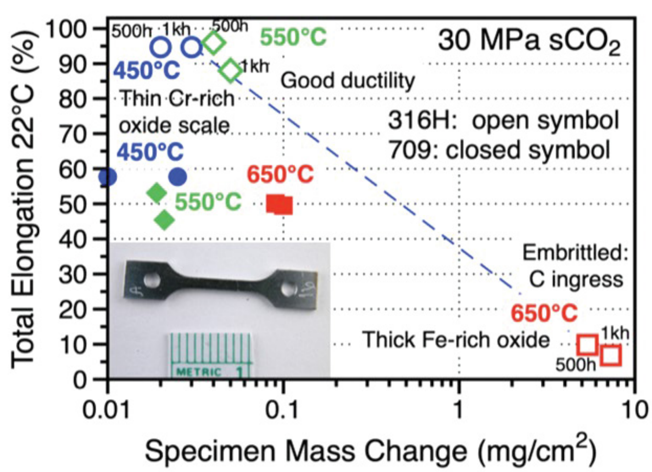
Comparison of 100,000 h creep-rupture strength as a function of temperature between cast CF8C-Plus and other alloy classes.

Effect of Impurities on Supercritical Carbon Dioxide Compatibility

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA144
Project Duration	10/01/2019 – 09/30/2024
Total Project Value	$ 1,650,000
Technology Area	Plant Optimization Technologies

This project will study the effect of impurities (e.g., O_2, H_2O) on compatibility of structural materials in supercritical carbon dioxide (sCO_2) Brayton cycle systems, particularly for direct-fired systems. For economically scaling up to commercial power production, the increased use of Fe-based alloys is needed and impurity studies at (450-650 °C) will determine operating limitations for 9-12% Cr and austenitic steels. In addition to measuring reaction rates and characterizing reaction products, post-exposure room-temperature tensile properties will be used to quantify compatibility as a function of temperature, time, and impurity level. After establishing baseline behavior, coatings and shot peening will be evaluated to increase the maximum temperature capability of Fe-based structural alloys. This information will be used to continue the development of a lifetime model for various classes of structural alloys with and without surface modifications. Previously, high O_2 impurity levels (0.25-1%) have been found to increase reaction rates of both Fe- and Ni-based alloys at 750 °C/300 bar (30 MPa). Further work is needed to isolate O_2 and H_2O effects including the use of isotopic tracers. An additional project goal is to understand creep behavior of thin-walled sections for Fe- and Ni-based alloy heat exchangers.

Supercritical CO_2 (sCO_2) is of increasing interest in a broad range of energy applications, especially for waste heat recovery but also to replace water/steam. If sCO_2 systems could be scaled up from the current <10 MW size this would enable use in power generation in coal, natural gas (bottoming cycle), nuclear (power and propulsion), and concentrated solar power systems. The advantages of sCO_2 are (1) low critical temperature and pressure (31 °C/73.8 bar), (2) single phase over a wide temperature and pressure range, (3) high thermal capacity and density leading to smaller turbomachinery, and (4) low work for recompression (e.g., compared to He). Closed Brayton cycle systems (such as sCO_2) operate at higher pressures to increase efficiency, and these higher pressures require new designs for airfoils, seals, and heat exchangers while typically lowering the working fluid temperature significantly compared to combustion turbines. These new designs may necessitate new materials or processing methodologies. Materials are a key concern for the scale-up to commercial size, particularly the use of lower-cost steels where applicable. Recently, unique experimental equipment was developed at ORNL for simulating controlled impurity levels in sCO_2 conditions. Initial testing was conducted at 750 °C/300 bar and found accelerated corrosion rates compared to research-grade sCO_2, particularly for Fe-based alloys. The next phase of this study is examining steels at lower temperatures where they have sufficient strength. The initial results suggest that all of the candidate steels are showing faster corrosion rates with the addition of impurities and the next phase of coating evaluations is needed.



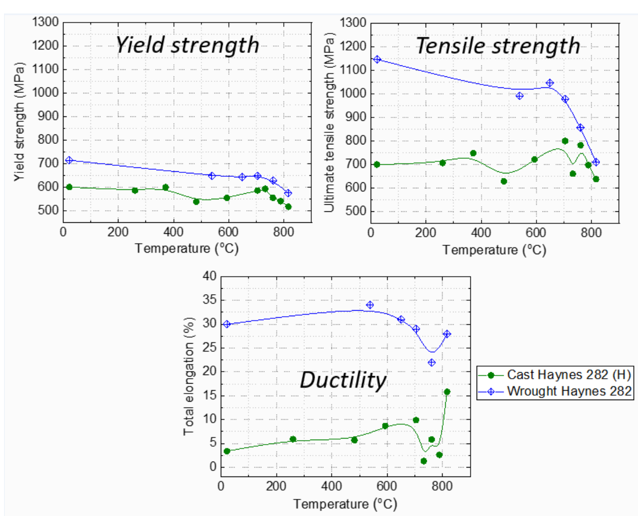
Specimen mass change plotted (mg/cm2) versus the post-exposure room temperature ductility (total elongation in tension with a strain rate of 0.015/min per ASTM E8-13). The open symbols are for type 316H stainless steel and the closed symbols for alloy 709 with 20.

Evaluating Ni-Based Alloys for A-USC Component Manufacturing and Use

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA152
Project Duration	10/01/2019 – 09/30/2025
Total Project Value	$ 2,315,000
Technology Area	Plant Optimization Technologies

The objective of this project is to evaluate advanced nickel (Ni)-based alloys to support the manufacturing and use of components under advanced ultra-supercritical (A-USC) steam conditions, which range up to 760 °C (1400 °F) and 35 MPa (5000 psig). In particular, this project focuses on evaluating materials from near-to-full-scale components, such as Haynes 282 large rotor forging, half-valve body casting, and steam turbine nozzle carrier casting, to provide insights into potential manufacturability issues related to large-scale components made from Ni-based alloys and engineering data and support for actual A-USC plant design. In addition, this project contains substantial efforts in weld characterization and long-term creep testing of Ni-based alloy weldment, which should provide useful data for filler metal selection and future ASME code qualification efforts for cast Haynes 282 weldment.

The bulk of the U.S. fleet of supercritical coal-fired boilers operates with maximum steam conditions of 566 °C (1050 °F) and 238 bar (3450 psig), and net plant efficiencies on the order of 30-32% higher heating value (HHV). In Europe, interest in advanced steam cycles with significantly increased efficiency (and reduced emissions) resulted in the initiation of projects to produce technology capable of operation with 650 °C/340 bar (1202 °F/4930 psig) steam in the COST-522 project, and 700 °C/340 bar (1292 °F/4930 psig) steam in the Thermie project. The efficiencies associated with these advanced steam conditions range up to 45% HHV, representing a reduction in emissions of approximately 28% compared to the U.S. base-case conditions. Various developments in Japan and China are now aimed at 700 °C (1292 °F) capabilities as well. Operation at higher efficiencies/lower emissions is dependent on materials capable of operating at higher temperatures. Therefore, new ferritic and austenitic steels as well as nickel alloys are being explored for use in components and processing for these high temperature and pressure applications.

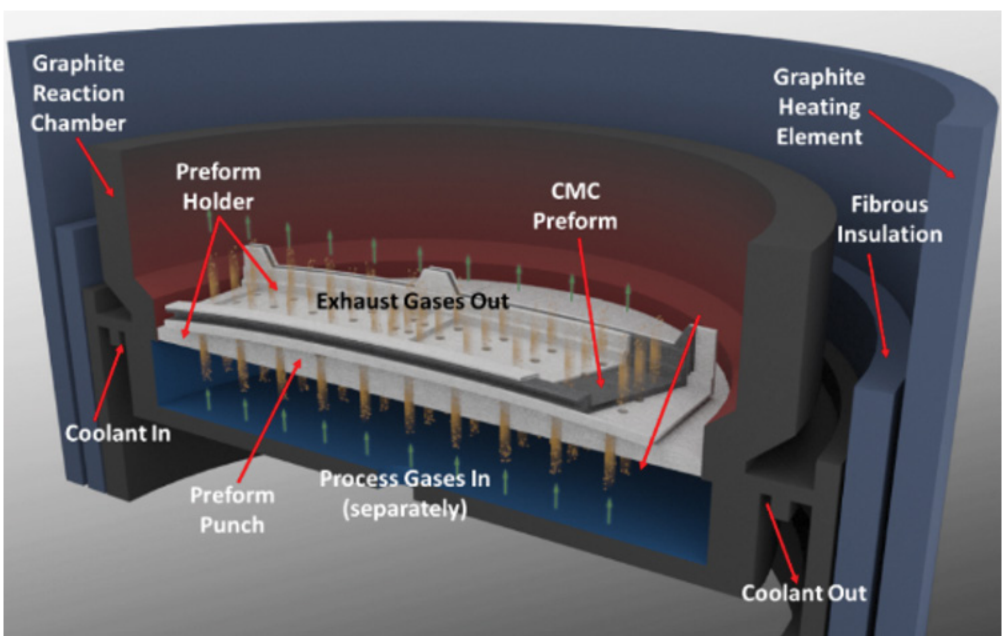


Forced Flow Thermal Gradient Chemical Vapor Infiltration (FCVI) of Complex-Shape

Performer	**Oak Ridge National Laboratory (ORNL)**
Award Number	FWP-FEAA432
Project Duration	07/01/2023 – 06/30/2026
Total Project Value	$ 500,000
Technology Area	Advanced Materials Development

This project aims to contribute to the scalability, yield, rate, and cost of manufacturing the newest class of structural materials for high-temperature applications. Ceramic matrix composites (CMCs) are in ever-increasing demand to elevate performance and efficiency, which will enable next-generation innovations for industrial gas turbines, heat exchangers, aero engines, space reentry vehicles, and nuclear fission and fusion reactors. Chemical vapor infiltration (CVI) deposits a highly stoichiometric silicon carbide (SiC) matrix material for structural CMCs that can operate at temperatures above 1450 °C. However, the current state-of-the-art isothermal/isobaric CVI (ICVI) process used for manufacturing CMC components today is expensive, requiring much time and multiple infiltration runs to achieve the desired thickness.

Previous work at ORNL resulted in the development of a process termed forced-flow, thermal-gradient CVI (FCVI), which demonstrated a reduction in processing time by an order of magnitude and a practical increase in CMC thickness. FCVI is being used to densify carbon/silicon carbide (C/SiC) aircraft brakes, but to date its use has been limited to simple flat puck and disk configurations using machined hot and cold graphite mandrels. This project will design and fabricate a new FCVI reactor and employ complex-shaped mandrels fabricated by additive manufacturing of carbon preforms with subsequent pyrolysis and graphitization. This project will demonstrate FCVI to deposit SiC on a curved component shape.



FCVI process reactor.

COMPUTATIONAL MATERIALS DESIGN

Michigan Technological University:
Hybrid Structured Nickel Superalloys to Address Price Volatility and Weld/Weld Repair Based Supply Chain Issues 30

National Energy Technology Laboratory (NETL):
Advanced Materials Development 31

National Energy Technology Laboratory:
eXtremeMAT- Accelerated Design and Manufacture of Next Generation Extreme Environment Materials 33

Raytheon Technologies Corporation:
Additive Predictive Modeling Investigating Steam-Mediated Degradation of Environmental Barrier
Coatings in Hydrogen-Fueled Turbines 35

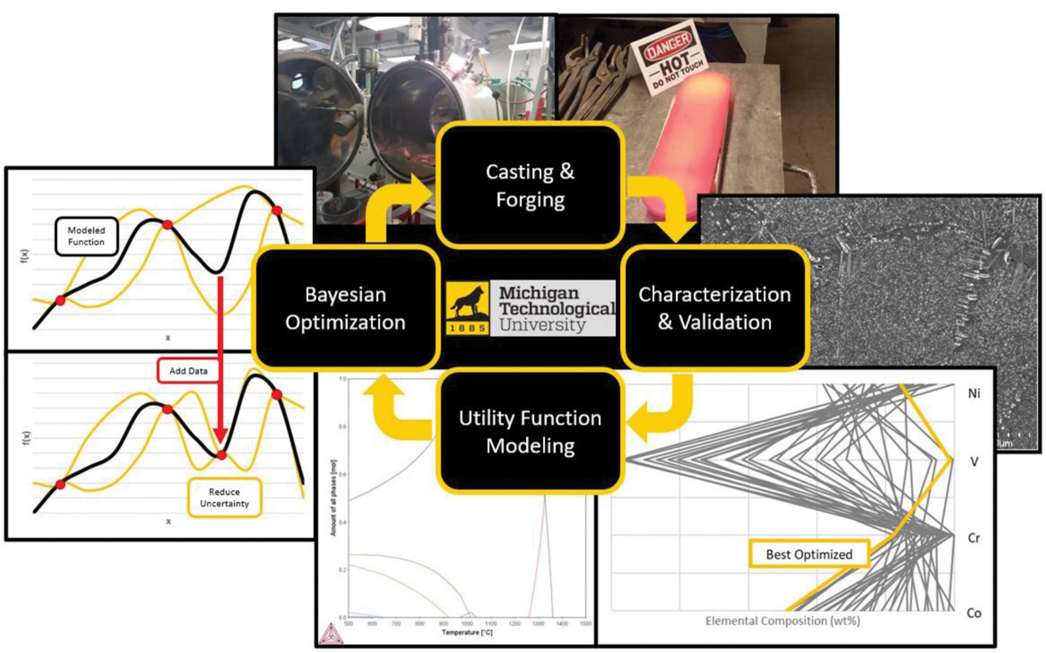
Strategic Power Systems, Inc.:
Continued Development –Real Time Physics Based Data Analytics for Thermal Power Plants 36

Hybrid Structured Nickel Superalloys to Address Price Volatility and Weld/Weld Repair Based Supply Chain Issues

Performer	Michigan Technological University
Award Number	FE0032071
Project Duration	09/03/2021 – 09/02/2024
Total Project Value	$ 400,000
Technology Area	University Training and Research

Two key factors affecting the fossil power high-temperature material supply chain are the volatility of nickel-based alloy prices and the challenges in welding precipitation-strengthened alloys. This project seeks to use integrated computational materials engineering (ICME) design strategies to solve these challenges by designing, casting, forging, welding, and validating the properties of hybrid eta-gamma prime-strengthened nickel superalloys optimized for cost and weldability. Specifically, significant reduction in cobalt to less than 5 wt.% versus 10–20% in candidate alloys for advanced energy systems is sought. Performance in high-temperature strength and creep will be maintained within 10% compared against existing candidate alloys designed for extreme environments. Weldability criteria will be evaluated through use of various susceptibility indices (solidification cracking, liquation, stress relief cracking) with the goal of broadening the welding and post-weld heat treat processing windows to be more forgiving.

Benefits are focused on providing alternatives to existing alloys with significant weldability issues which will enhance fabrication of new components, on-site assembly, and in-service repairs. Additional impacts include training graduate students in "hybrid" real-world/theoretical design methodologies to better prepare for advanced materials development.



Michigan Technological University's experimental process.

Advanced Materials Development

Performer	**National Energy Technology Laboratory (NETL)**
Award Number	FWP-1022406
Project Duration	04/01/2018 – 03/31/2024
Total Project Value	$ 21,738,953
Technology Area	Advanced Energy Materials

NETL's Research and Innovation Center's Advanced Alloy Development Field Work Proposal (FWP) is focused on developing high-performance materials to improve efficiencies in the existing fleet and enable advanced fossil energy systems. NETL uses an integrated materials engineering approach that incorporates computational alloy design with best-practice manufacturing (modified as needed to achieve microstructure and performance objectives) with focused performance evaluation and characterization. Research is conducted to develop and validate computational algorithms for designing advanced alloys and for predicting alloy performance over multiple length scales and multiple time scales relevant to advanced fossil energy power systems.

The Advanced Alloy Development FWP has five distinct research themes:

Systems Engineering & Analysis (SE&A)—Provide techno-economic and market studies on fossil fuel power generation plants operating at the elevated conditions [e.g., advanced ultrasupercritical (AUSC) Rankine cycles] enabled by advanced alloys, identifying applications, and quantifying the cost and performance improvements relative to the commercial state of the art.

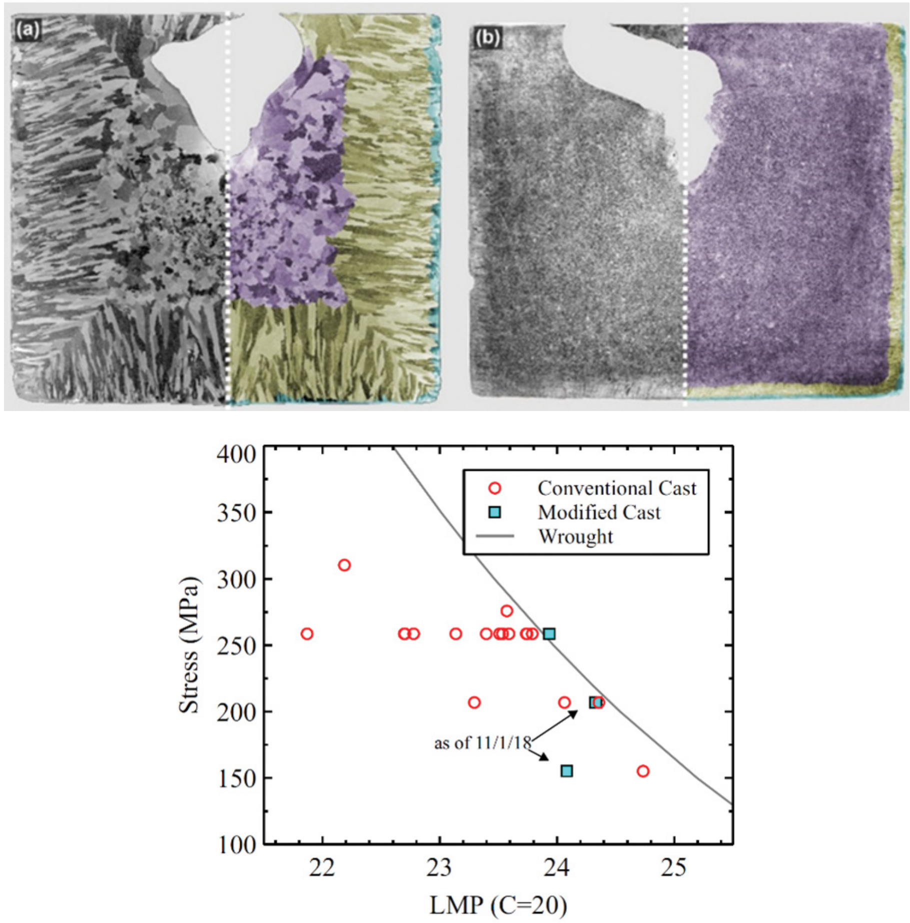
Computational Design and Simulation—Use computational materials modes, multi-scale characterization simulations of microstructural features, and cutting-edge data analytics to guide and accelerate alloy design and manufacturing development.

Processes, Manufacturing, and Properties—Develop and demonstrate at pilot industrial scale improved manufacturing processes to produce advanced alloys with improved service life performance.

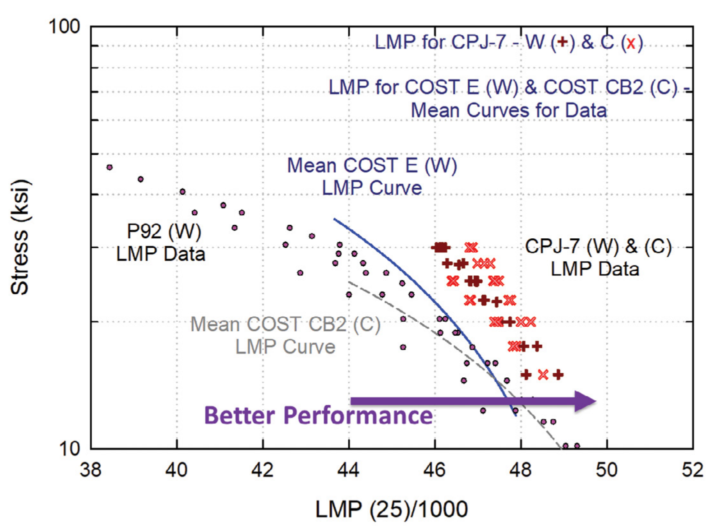
Materials for sCO_2 Power Cycles: Alloy Performance—Determine whether available AUSC power plant materials are suitable for fossil fuel supercritical carbon dioxide (sCO_2) service in terms of temperature and stress, and if they are, assess the potential physical and mechanical consequences of their use.

Materials for sCO_2 Power Cycles: Materials and Manufacturing Issues Associated with Heat Exchangers for sCO_2 Power Cycles—Assess materials selection and joining processes for compact heat exchanger designs to (1) reduce equipment size and (2) enhance heat transfer between the high-temperature and low-temperature working fluids in sCO_2 power cycles.

The structural materials and manufacturing processes researched in this FWP are needed to lower the cost and improve the performance of fossil-based power-generation. Additionally, the development and utilization of computational simulation and broad-based data analytic tools can further reduce the time and cost of developing advanced energy systems.



Cast Version of Alloy 740. A modified casting route was developed that leads to a more homogeneous grain size distribution throughout the casting (b compared to a) and better properties. Creep testing is ongoing, but results indicate that the modified cast materials behave in a manner similar to the wrought material.



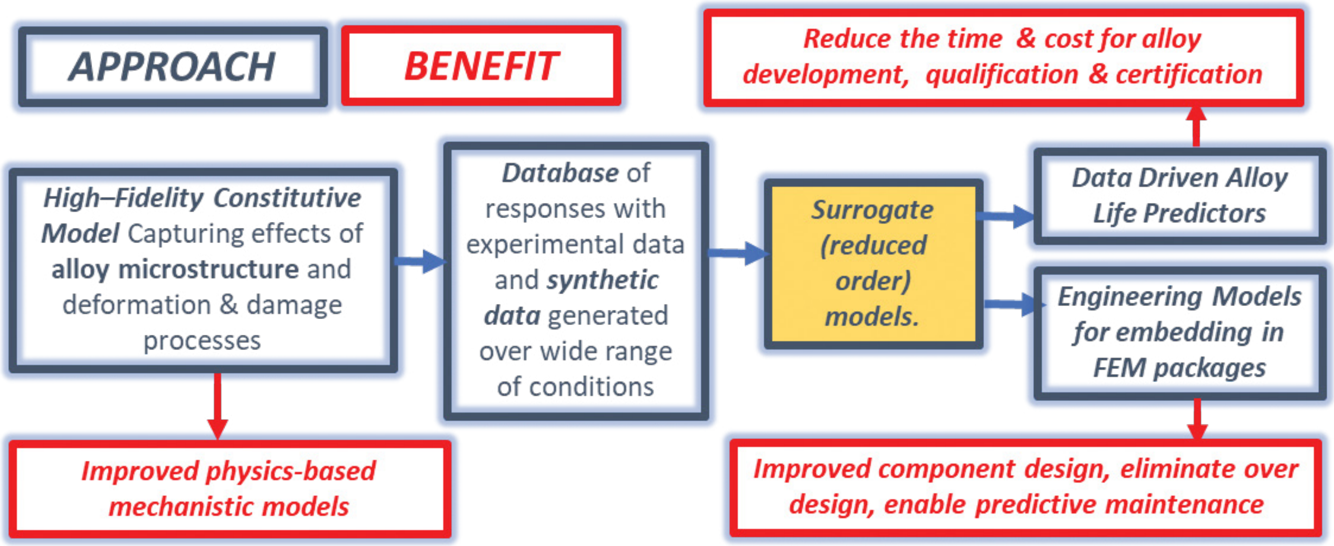
Creep behavior: NETL's CPJ-7 compared to other advanced Fe-9Cr streels, COST E, Cost CB3 and P92. W=Wrought, C=Cast.

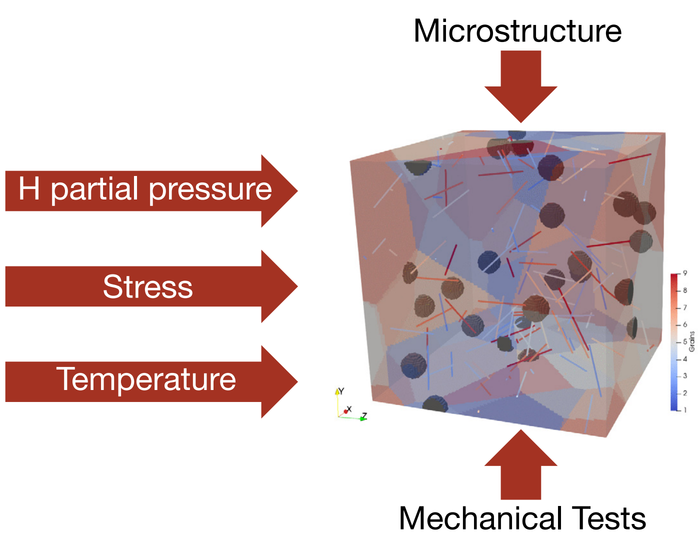
eXtremeMAT- Accelerated Design and Manufacture of Next Generation Extreme Environment Materials

Performer	**National Energy Technology Laboratory**
Award Number	FWP-1022433
Project Duration	10/01/2018 – 09/30/2024
Total Project Value	$ 3,189,921
Technology Area	Advanced Energy Materials

The objective of eXtremeMAT is to demonstrate how state-of-the-art computational materials modeling and cutting-edge experimental tools across the National Laboratory (NL) Enterprise, in conjunction with industry partnership, can accelerate the deployment of conventional and additively manufactured alloys for application in extreme environments and are needed to enable technologies to achieve net-zero carbon emissions by mid-century. Hydrogen has become a focal point of attention, as its production and use pave a way towards eliminating carbon emissions. The production of hydrogen from carbonaceous sources with carbon capture via processes, such as gasification and steam methane reforming, will serve as a transition for the use of hydrogen in the power generation and industrial/manufacturing sectors. These applications (hydrogen production from carbonaceous sources, hydrogen turbines [pre-combustion] for power generation) will impose a harsh constraint on alloys. To improve the reliability and enhance the safety, eXtremeMAT-H_2 aims to study the response of alloys subjected to creep and creep-fatigue under elevated temperatures and in contact with pressurized hydrogen gas. The overall intent is to be able to determine the expected creep-fatigue lifetime of alloys under combined stress, temperature, and hydrogen. This is important, as while the effect of hydrogen on the tensile response of metals has been extensively studied in the literature, little has been investigated on the impact on creep and creep-fatigue scenarios (conditions that are relevant to operating conditions from carbonaceous sources with carbon capture and power generation using hydrogen). In these conditions (elevated temperatures, complex loading states, and long service life), alloy microstructure and moderate changes in composition will have drastic effects on the overall performance of the system. eXtremeMAT developed a framework and a series of toolsets to predict the creep and creep-fatigue behavior of alloys that incorporate the effects of alloy chemistry and microstructural evolution during service. eXtremeMAT-H_2 will expand these tool sets to include materials' lifetime and failure under hydrogen environments. NETL-RIC efforts will focus on four tasks as follows: (i) atomic level calculations to simulate hydrogen-dislocation interactions, (ii) atomic level calculations to simulate hydrogen segregation at interfaces, (iii) quantify the epistemic or model form uncertainty; and (iv) perform as needed creep tests.

XMAT research provides the materials solutions needed to meet the challenges facing fossil energy power generation. Benefits include reducing the cost of alloy development and time-to-deployment; improved fossil energy plant operation performance through condition-based maintenance; eliminating overdesigned components; and enabling new fossil energy-based transformational power generation technologies.





- H effects on creep is poorly studied
- H effects on tensile response is well known (decrease in toughness, embrittlement)
- Creep/ creep fatigue is less studied (increase in creep rate, increase in power law exponent)... Although new studies are poring in

Digital Twin

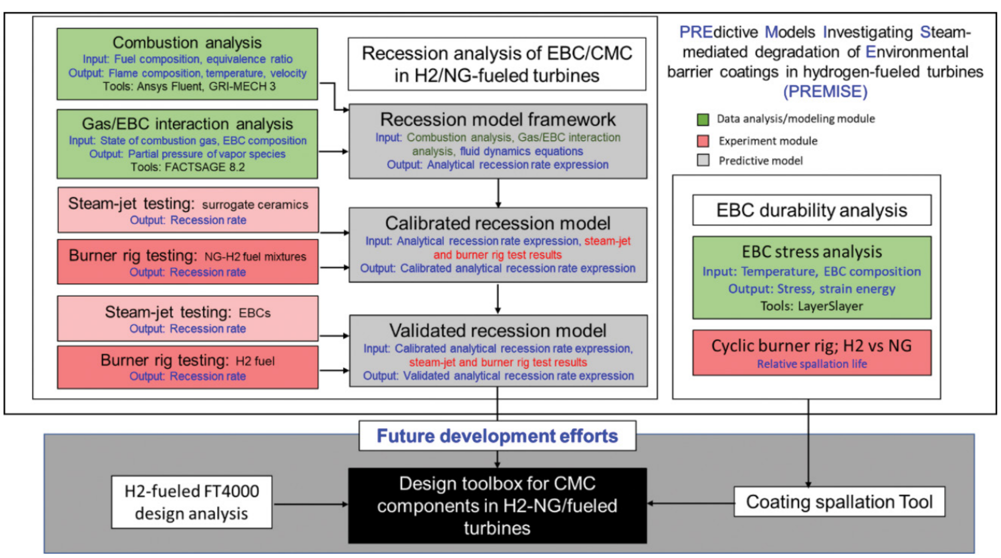
- Local H content at traps as a function of experimental conditions and microstructure?
- Does H increase the likelihood of crack nucleation, does it simply weakens preexisting cracks, does H affect precipitation kinetics?

Additive Predictive Modeling Investigating Steam-Mediated Degradation of Environmental Barrier Coatings in Hydrogen-Fueled Turbines

Performer	**Raytheon Technologies Corporation**
Award Number	FE0032230
Project Duration	04/01/2023 – 03/31/2025
Total Project Value	$ 1,065,987
Technology Area	Advanced Materials Development

This project will develop, calibrate, and validate predictive models describing water-vapor mediated degradation of Pratt and Whitney's SiC/SiC ceramic matrix composite (CMC) system that has been under development, to enable the design of future hydrogen (H_2)-burning turbines. Thermo-chemical and kinetic analysis shall be used to assess the state of H_2 and hydrogen-natural gas (H_2-NG) combustion gases and the interaction between the combustion gas and environmental barrier coating (EBC) materials. This data shall be used to develop models describing the recession rate of EBC materials as a function of combustion gas composition, temperature, pressure, and velocity. The models shall be calibrated using high velocity steam-jet tests and burner rig exposures in NG and H_2-NG mixtures and validated with H_2 burner rig exposures. Additionally, the influence of steam concentration on EBC durability shall be assessed using thermo-mechanical models and cyclic burner rig tests in H_2 and NG combustion gases.

This work will provide a computational model to predict CMC performance in a 100% hydrogen-firing turbine. This computational model will help elucidate CMC performance in a 100% hydrogen-firing environment which will provide insight towards the design and development of a 100% hydrogen-firing turbine. The development of these turbines is critical to FECM 's strategic goals of a fully decarbonized power sector by 2035 and net-zero U.S. greenhouse gas emissions by 2050.



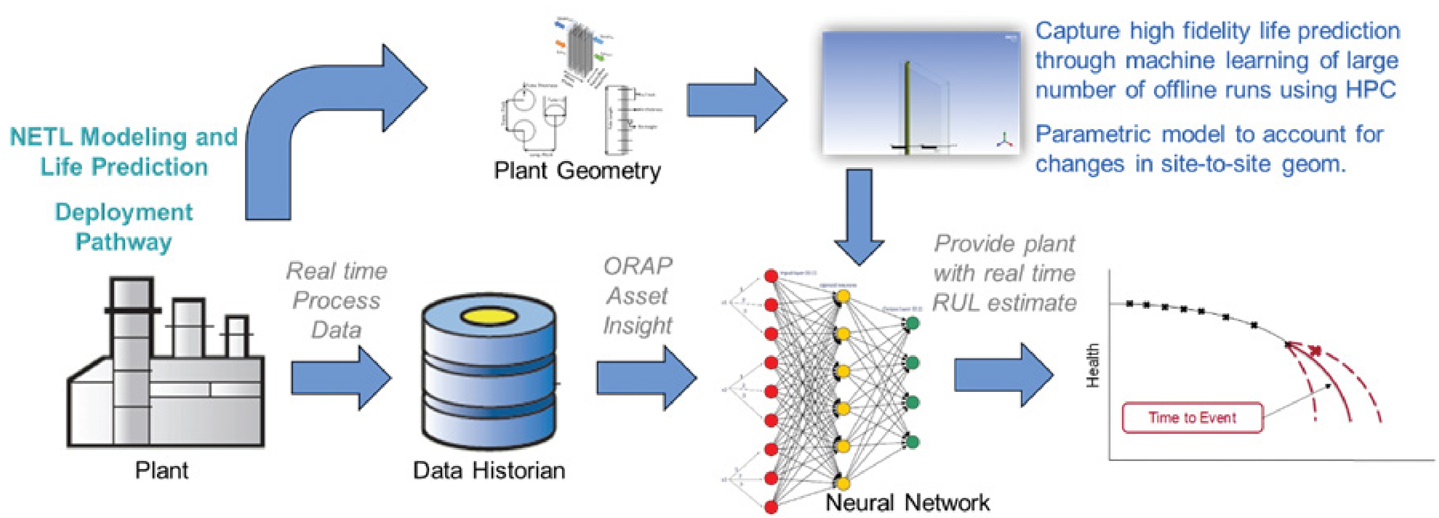
Proposed framework to develop, validate and calibrate predictive models on steam-driven degradation of EBCs for design CMC components in Hydrogen/Natural Gas-fueled turbines.

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

Performer	**Strategic Power Systems, Inc.**
Award Number	FE0032035
Project Duration	06/11/2021 – 06/30/2025
Total Project Value	$ 812,807
Technology Area	Cybersecurity

The primary objective of this work is to extend the previous research results beyond the proof-of-concept phase. This will include verification and validation testing with direct support and collaboration from operating power plants with advanced power generation technologies and prime mover and downstream systems using the near-real-time data provided through the SPS Operational Reliability Analysis Program (ORAP®) and ORAP Asset Insight data system.

The project will result in real measurable value, better informed plant operators, and reduced disruptions, while meeting changing service demands based on enhanced operating flexibility. Extending prior research results to plant systems requires additional time and effort to develop an integration strategy for integrating research results into the SPS ORAP Asset Insight data system. This will enable live, real-time testing and integration with power plant operators.



Real-time data analytics process flow.

HYDROGEN PRODUCTION

University of North Dakota:
Electromagnetic Energy-Assisted Thermal Conversion of Fossil-Based Hydrocarbons to Low-Cost Hydrogen 38

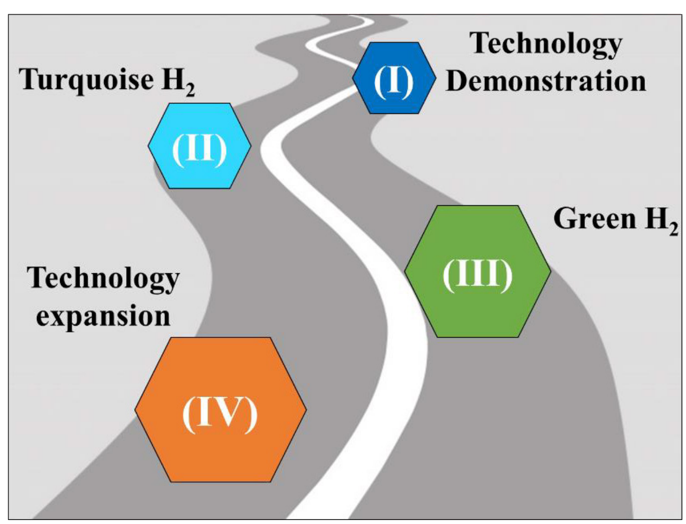
Electromagnetic Energy-Assisted Thermal Conversion of Fossil-Based Hydrocarbons to Low-Cost Hydrogen

Performer	**University of North Dakota**
Award Number	FE0032061
Project Duration	08/01/2021 – 07/31/2024
Total Project Value	$ 578,969
Collaborator	Envergex, LLC
Technology Area	University Training and Research

Hydrogen can be produced from the decomposition of hydrocarbons such as methane, without the production of carbon oxides. This represents a highly favorable route for hydrogen production compared to industrial production methods based predominantly on steam-methane reforming (SMR). Breaking hydrogen-oxygen bonds in water requires about seven times the energy compared to breaking carbon-hydrogen bonds in methane. SMR and methane decomposition processes both require indirect heating to provide the overall endothermic heat of reaction for hydrogen formation, but the heat of reaction for the SMR is more than double that for methane decomposition. In contrast to the SMR process, the methane decomposition process offers a promising path for economical and environmentally sound production of hydrogen without production of carbon dioxide.

The goal of this project is to make targeted improvements to the conventional thermo-catalytic hydrocarbon conversion process using an electromagnetic energy assisted mechanism; resulting in the reduction of downtime associated with catalyst reactivation or replacement due to poisoning. State-of-the-art solid catalysts exhibit short process lifetimes that are not suitable for commercial application. This project uses both experimental and computational tools to understand the fundamental interactions between fossil fuels and their interactions with an electromagnetic energy source. This technology can utilize natural gas or volatiles obtained from coal decomposition to provide carbon dioxide-free hydrogen. The first objective of this project is to identify catalyst supports that enhance the electromagnetic energy-assisted mechanism to ensure in-situ catalyst reactivation to near-initial fresh conditions. The performance of these prepared catalysts will be tested in laboratory units and the results will be used to validate computational fluid dynamics (CFD) and chemical kinetics models. Finally, CFD will be used to investigate the electromagnetic energy-assisted conversion mechanism as a function of catalyst structure and operating conditions for hydrogen production.

This study will provide future researchers with a cost-effective tool to explore a multitude of yet-to-be-conceived electromagnetic systems to ensure long-term catalytic activity. The technology has the potential to extend the longevity of catalyst materials, thereby reducing overall catalyst replenishment costs. With these improvements to the conventional thermo-catalytic hydrocarbon conversion process, it is hoped to enable a wider adoption of hydrogen-related technologies from fossil resources. This project will also support two graduate students focused on fossil energy research.



Technology roadmap for electromagnetic energy-assisted thermal conversion of hydrocarbon feedstocks to low-cost H_2.

ABBREVIATIONS

°C........degrees Celsius

°F........degrees Fahrenheit

AEM........Advanced Energy Materials

ALD........atomic layer deposition

AM........additive manufacturing

AM-GCTJ........additively manufactured graded composite transition joint

APS........air plasma ray

ASME........American Society of Mechanical Engineers

AUSC........advanced ultrasupercritical

BC-EBC-TBC........bond coat/environmental barrier coating/thermal barrier coating

C........carbon

CFD........computational fluid dynamics

CMC........ceramic matrix composites

CO_2........carbon dioxide

Cr........chromium

CSEF........creep strength enhanced ferritic

CVD........chemical vapor deposition

CVI........chemical vapor infiltration

DMW........dissimilar metal weldments

DOE........U.S. Department of Energy

EBC........environmental barrier coating

Er_2O_3........erbium oxide

$Er_2Ti_2O_7$........erbium titanate

FAST........field assisted sintering technology

FCVI........forced-flow thermal gradient CVI

Fe........iron

FECM........Fossil Energy and Carbon Management (DOE)

FWP........Field Work Proposal

GE........General Electric

GTAW........gas tungsten arc welding

H_2........hydrogen (molecular)

H_2O........water

HCM........Hydrogen with Carbon Management (DOE)

HP........high-pressure

HRSG........heat recovery steam generator

HTHA........high-temperature hydrogen attack

ICVI........isothermal/isobaric CVI

ICME........integrated computational materials engineering

ICWE........integrated computational welding engineering

IN........Inconel

mK........millikelvin

MPa........megapascals

ML........machine learning

MPa........megapascals

MR&D........Materials Research and Design

NDE........non-destructive evaluation

NETL........National Energy Technology Laboratory

NFA........nanostructured ferritic alloy

NG .... natural gas

Ni ....nickel

NPV.. net present value

O_2..oxygen (molecular)

ORAP .... Operational Reliability Analysis Program (Strategic Power Systems, Inc.)

ORNL ....Oak Ridge National Laboratory

PDC ....polymer-derived ceramics

PGC .... pressure gain combustion

psi ....pounds per square inch

psig .... pounds per square inch gauge

PSU...................................Pennsylvania State University

PWHT.....................................post-weld heat treatment

R&D..................................... research and development

R-SOFCs .... Reversible Solid Oxide Fuel Cells

SBE................................ Simulation-Based Engineering

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

SE&A..............................systemsengineering & analysis

SiC .... silicon carbide

SiCf ....silicon carbide fiber

SMR ....steam-methane reforming

SNS..spallation neutron source

SOFC .... solid oxide fuel cell

SPS .... Strategic Power Systems, Inc.

TiO .... titanium oxide

UMA .... University of Massachusetts at Amherst

U.S. ....United States

W ....watt

YSZ ....yttria stabilized zirconia

NOTES

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WEBSITES:

https://netl.doe.gov/carbon-management/high-performance-materials

https://netl.doe.gov/onsite-research/materials

https://netl.doe.gov/sites/default/files/2022-11/Program-124.pdf

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

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U.S. DEPARTMENT OF ENERGY

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