NETL Impact
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# *Materials for Advanced Energy Technologies:* THE BUILDING BLOCKS OF **TOMORROW'S ENERGY FOUNDATION**

NETLImpact

Vol. 02/ Summer 2017



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MISSION

Discover, integrate, and mature technology solutions to enhance the nation's energy foundation and protect the environment for future generations.

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*IMPACT* is a quarterly publication from the Department of Energy's National Energy Technology Laboratory. The magazine focuses on the exciting, cutting-edge research performed at NETL by our scientists and through our project portfolio to support the DOE Fossil Energy mission.


# From the Director

Welcome to the Summer 2017 edition of *NETL Impact*, a quarterly publication we compile and circulate to keep colleagues, peers, and stakeholders informed about the many productive accomplishments and robust areas of research that our Laboratory pursues in support of the nation's energy and national security priorities.

Our Lab is the only U.S. national laboratory dedicated to the efficient and environmentally sound use of our abundant fossil fuel resources, but NETL's expertise goes beyond fossil energy. Our researchers are at the forefront of developing improvements in a diverse array of technology areas that have a profound and positive effect on the nation and its economy.

Materials research is one example of NETL innovation that has far-reaching impacts for energy production and environmental protection. New materials developed in NETL labs have the potential to improve performance and efficiency, reducing the cost of existing fossil fuel technologies while ensuring new power systems are both economical and reliable. For example, advanced materials enable sophisticated new sensors and components to operate in the harsh conditions of energy-producing environments where they work to optimize performance and improve efficiency, while materials like cements provide critical barriers during oil and gas extraction to protect the surrounding environment.

In this issue, we explore these and other key material innovations NETL has created and continues to refine for advanced energy technologies. I hope you find this collection of stories interesting and useful in conveying the NETL story.

**Grace M. Bochenek, Ph.D.**

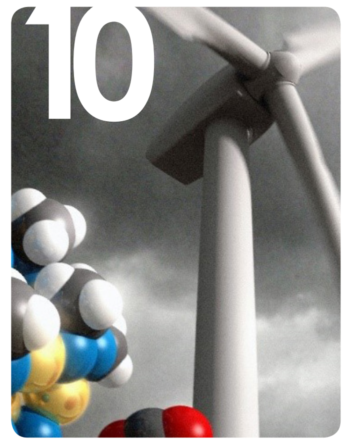
Director, National Energy Technology Laboratory

NETL Impact

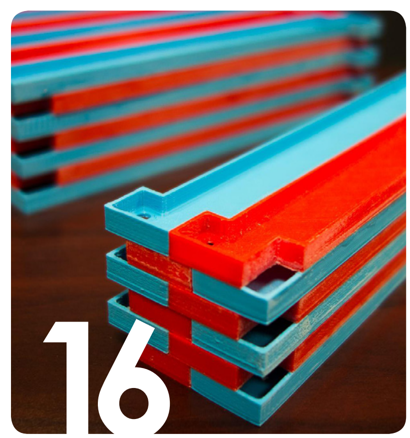
# IN THIS ISSUE

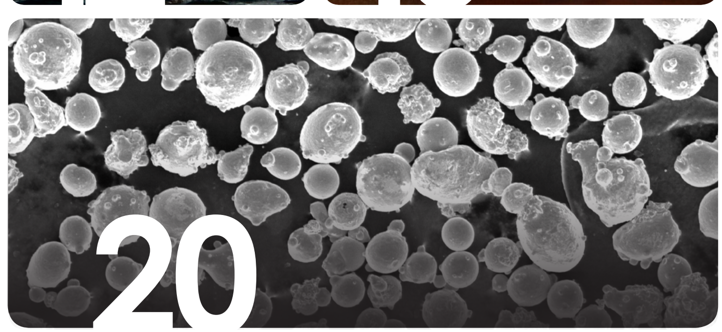










# TAKING THE HEAT

## New Alloy Is a Star Performer for High-Temperature Applications

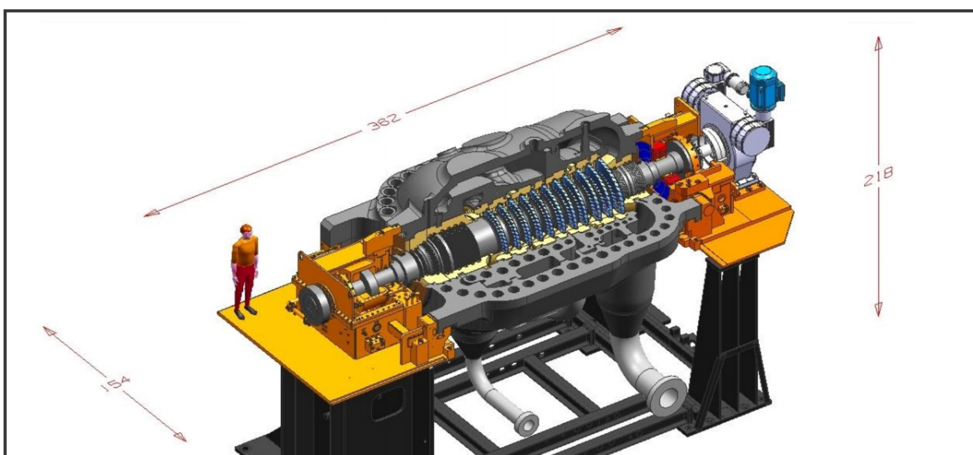
*By Paul Battista, Ph.D. // Technical Contact: Jeffrey Hawk, Ph.D. and Paul Jablonski,Ph.D.*

Incorporating ultrasupercritical and advanced ultrasupercritical (AUSC) steam conditions into new, or existing, power plants increases efficiency and provides a crucial step toward developing a sustainable, efficient, and economically feasible energy infrastructure in the United States. However, the high-temperature, high-pressure operating conditions of AUSC plants exposes system components to extreme environments that dramatically reduce their lifespan. Developing and incorporating materials that can withstand such aggressive operating conditions is a major challenge facing AUSC technology advancement—a challenge that NETL materials scientists are meeting through innovation.

Ferritic-martensitic chromium (Cr) steels form the backbone of current steam delivery systems and are a popular choice because they are less expensive to produce and can be recycled. Traditionally these alloys are composed of less than 5 percent Cr, but in hotter sections—and as operating temperatures increase—advanced 9–12 percent Cr steels must be used.

NETL materials scientists are developing superior heat resistant 9-12 percent Cr ferric martensitic steels with performance characteristics that surpass existing commercial alloys. Their work has yielded impressive results, such as CPJ-7, a ferritic-martensitic steel that has demonstrated several impressive attributes: superior mechanical performance under high temperatures (compared to conventional materials), increased functionality under high-temperature and -pressure conditions, improved high-temperature creep strength (i.e., the ability to resist deformation due to applied stress), oxidation resistance, and thermal fatigue resistance. Notably, CPJ-7 was evaluated at a manufacturing process scale, which translates directly to industrial practice and commercialization.

According to Dr. Jeffrey Hawk, a materials research engineer with NETL, "During performance testing, CPJ-7 demonstrated creep life that was at least twice that of commercially available martensitic steels that were evaluated."




Proposed ComTest 1400 Turbine

# Computational Homogenization Process Enhances Discovery and Optimization

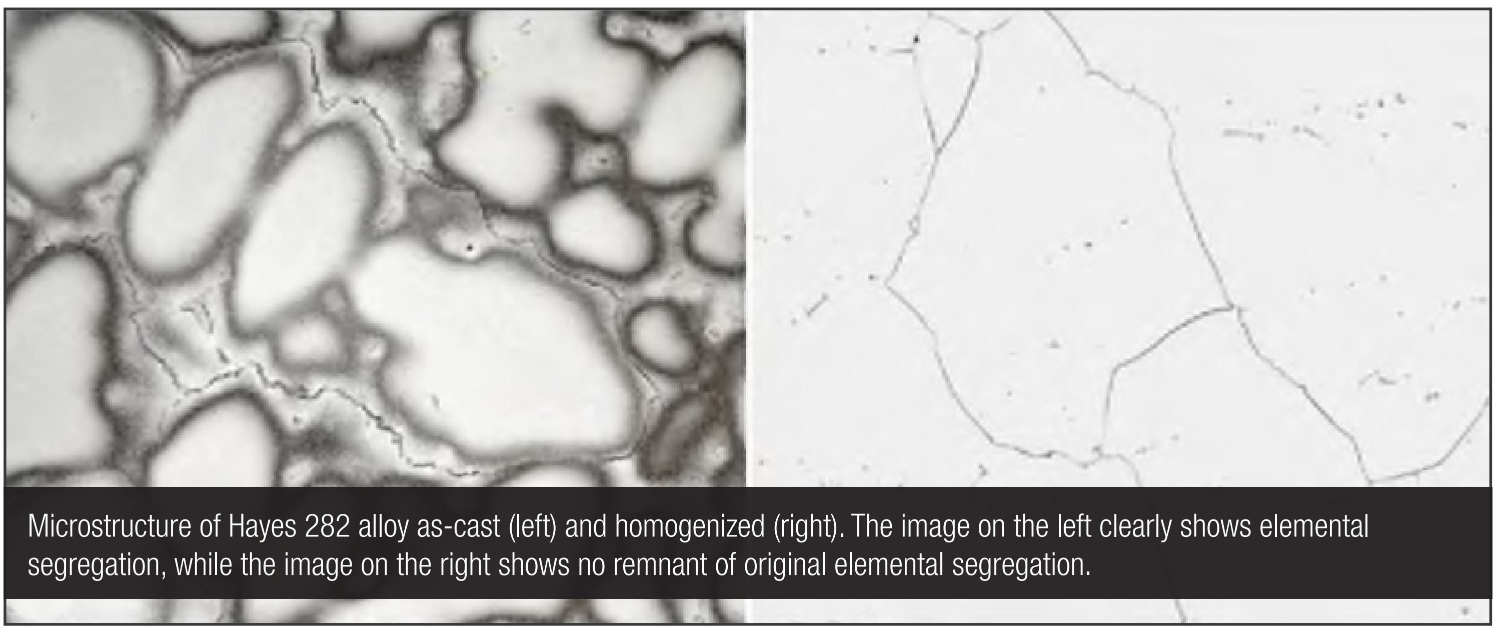
The success of CPJ-7 would not have possible without the use of NETL's novel computational homogenization process. This award-winning innovation significantly reduces or eliminates segregation in the cast ingot.

Heat resistant alloys are composed of a variety of elements that strengthen the matrix at temperature and provide highly stable precipitates to maintain the crystal structure during operation. NETL's computational algorithm allows a stepped heat-treating process to be devised that achieves an optimal level of homogenization for the alloy by diffusing the most segregation-prone elements within the cast microstructure. The end result is improved, more consistent physical and mechanical properties. NETL's homogenization process adds no additional cost to the manufacturing process and can be used for any heat-resistant alloy.

Incorporating novel alloys into the componentry of AUSC power plants will extend the functional lifespan of many fossil fuel-based power generating components, including coal-fired boilers, steam and gas turbines, piping, seals, and valve castings. In addition, NETL-developed alloys can be applied to other high-temperature applications such as aerospace, nuclear, chemical manufacturing, metallurgical processing, and waste management.

Using NETL's process, the homogenization cycle can be mathematically optimized to reduce furnace time and can be made compatible with existing commercial equipment. Most importantly, the cycle can produce the desired degree of homogenization for the given alloy and application. According to Dr. Paul Jablonski, a metallurgist with NETL, "The impact this process will have is far reaching not only for improving manufacturing efficiencies but also for extending the life cycle of alloys exposed to extreme environments, reducing down time and lowering costs."

NETL innovations in alloy development and materials science is paving the way for ultra-efficient power generating systems that provide affordable energy with reduced emissions and rigorous environmental stewardship. ≡



Microstructure of Hayes 282 alloy as-cast (left) and homogenized (right). The image on the left clearly shows elemental segregation, while the image on the right shows no remnant of original elemental segregation.

**Jeffrey A. Hawk, Ph.D. // Jeffrey.Hawk@netl.doe.gov**

Jeffrey Hawk is as materials research engineer and technical project leader of the Advanced Alloy Development Project. The project focuses on improving existing and developing new heat resistant alloys for combustion technologies. Since 2001, he has been a Fellow of ASM International.

# NETL Researchers Work to Create **Next-Generation Sensor Material** & **Device Technology Approaches** for Emerging Energy Challenges

*By Gerrill Griffith // Technical Contact: Paul Ohodnicki, Ph.D.*

When Warren Seymour Johnson developed an effective bi-metal thermostat in 1883, he helped begin the evolution of sensors in heat and power operations. Seymour's device—he called it the "electric tele-thermoscope"—was used to ring a bell to alert heating system operators of the need to open or close heating dampers.

One hundred and thirty-four years later, NETL researchers incorporate lasers, waveguides, fiber-optics, and a host of new high-technology materials to create sensor devices that perform consistently and effectively inside some of the harshest, most difficult environments on earth—but these sensors do much more than ring bells.

Advanced sensors and controls have the potential to help significantly reduce greenhouse gas emissions by enabling the next generation of advanced fossil energy technologies and improving energy efficiency in the existing fleet of coal-fired power plants and domestic manufacturing industries.

Sensors allow operators to measure temperature, pressure, and gases inside harsh energy environments like turbines, boilers, or fuel cells and take appropriate actions for maximum efficiency. Other severe environments that rely on sensors include the downhole environment in oil and gas wells and pressurized natural gas pipelines. New sensors and controls, matched with analytical inputs, are essential to enabling power system technologies to operate under conditions where optimal performance is balanced with reliability.

Not only are sensors critical for future fossil energy applications, they have wide application in other areas like nuclear power generation, industrial process monitoring and control, aviation and aerospace, and monitoring of the electricity and natural gas and oil infrastructure.

A primary goal of NETL sensor research is to develop materials and sensor technologies that can help manage complexity, permit low-cost robust monitoring, enable real-time optimization of fully integrated, highly efficient power-generation systems, and greatly enhance the performance of existing and new power plants. Emerging NETL sensor research is also targeting low-cost sensing technologies for energy infrastructure monitoring including the natural gas pipeline network and critical grid assets such as power transformers.

The research requires a team with many different areas of expertise, including mechanical engineers, electrical engineers, materials scientists, and optic experts. The result of the collaborations are sensors that provide measurement and monitoring strategies that are pioneering in nature and effective in making the nation's energy production technologies more efficient so more power can be generated with fewer resources and less emissions. Estimates are that if the United States could refurbish its entire coal fired power plant fleet with advanced sensors and controls, $CO_2$ emissions could be reduced by more than 14 million metric tons per year for every 1 percent heat rate improvement. This would save approximately $358 million per year.

New sensor technology research at NETL incorporates a wide range of new materials and techniques for a wide variety of applications related to energy fields. Here are a few examples of the array of work underway at NETL in the effort to create better sensors:

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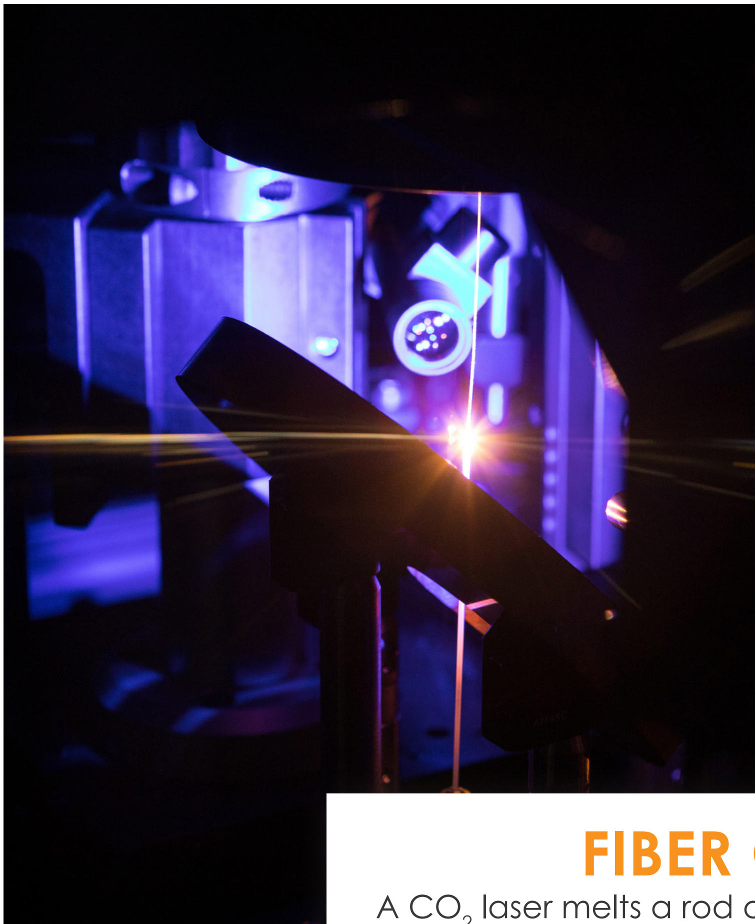
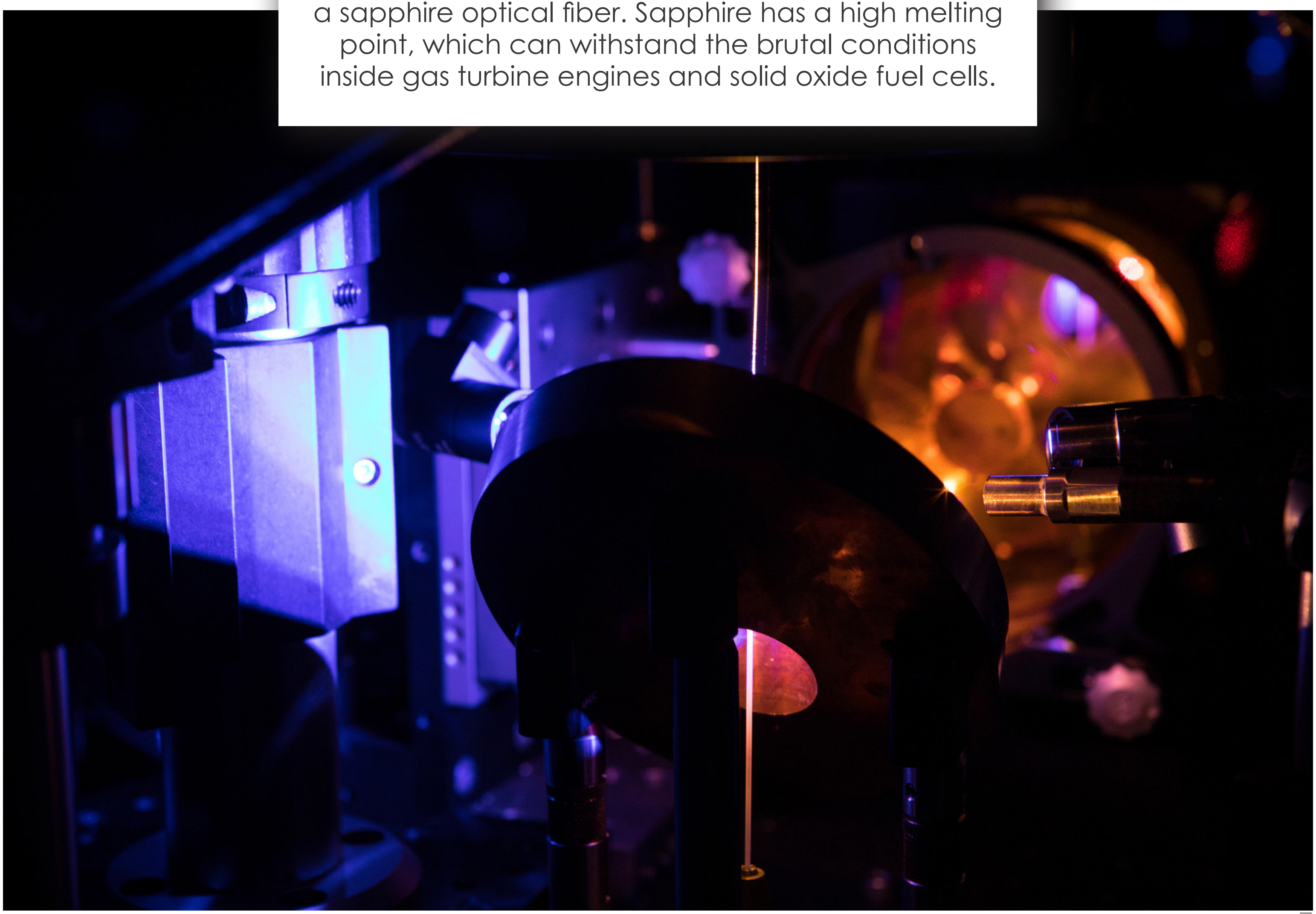


# FIBER OPTICS

A $CO_2$ laser melts a rod of solid sapphire and draws a sapphire optical fiber. Sapphire has a high melting point, which can withstand the brutal conditions inside gas turbine engines and solid oxide fuel cells.

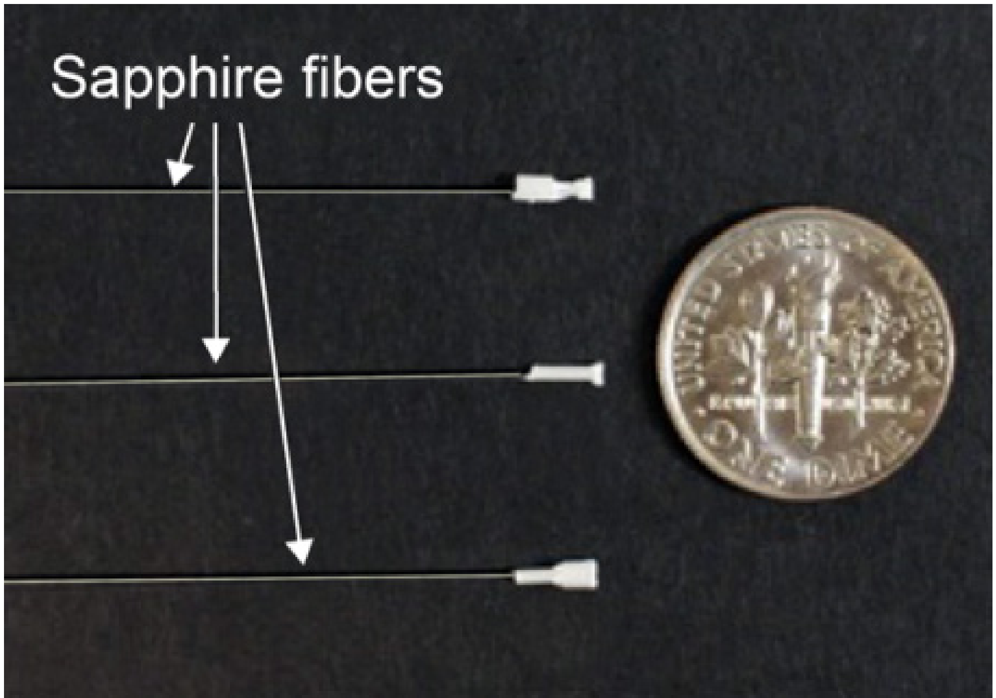


# Advanced Manufacturing of Optical Fiber Based Sensors

NETL researchers fabricate prototype optical sensors with the superior properties needed to function in harsh environments by using a new laser-heated pedestal growth (LHPG) system. LHPG is a crystal growth technique that reforms bulk high temperature-resistant materials such as sapphire or yttrium stabilized zirconium into single-crystal optical fibers. The technique produces optical fiber with very high melting temperatures for use as sensor substrates.

The LHPG system enables researchers to control crystal growth and incorporate novel sensor materials with fiber-substrates during the growth process. The ability to control fabrication parameters generates optical fiber sensors with improved measurement sensitivity and durability.

The optical fibers can be incorporated into fiber sensor assemblies and evaluated for functionality under high-temperature and -pressure conditions. The optical fiber-based sensors offer distinct advantages including broadband wavelength and compatibility, and resistance to electromagnetic interference. They also eliminate electrical wires and contacts, which are commonly associated with sensor failure. In addition, fiber optic sensors are compatible with embedded, remote, and distributed sensing technologies.




Single-crystal sapphire sensor heads with sapphire fiber waveguides achieve greater precision through miniaturization.

# Nanocomposite and Oxide Sensing Layer Integrated Optical-Fiber-Based Sensors

Currently available sensor technologies have limitations, such as functional temperature ranges, durability, and cost. As a result, there is a pressing need for imbedded gas and temperature sensors that can operate at temperatures approaching 1,000 degrees Celsius (C), which are typical of power generation systems capable of 90 percent CO2 capture.

NETL work has helped develop new sensor materials that demonstrate stability and durability in those corrosive and high-temperature environments. They are plasmonic nanocomposites and oxides, which are effective because of their high temperature stability combined with unique optical responses that are compatible with low-cost integration with the optical fiber sensing platform. Through advanced interrogation techniques such as multi-wavelength monitoring and associated data analytics, recent work has even demonstrated that multi-parameter monitoring of multiple chemical species in a complex gas stream and/or temperature may also be possible with a single sensor element using low cost optical components.

# Portable Luminescence-Based Fiber Optic Probe for Rare Earth Elements (REE) Detection and Quantification

REEs are a series of 17 chemical elements found in the earth's crust. Because of their unique chemical properties, REEs are essential components of electronics, computer and communications systems, transportation, health care, and national defense. The demand for REEs has led to an interest in economically feasible ways to detect, quantify, and recover them from domestic coal and coal waste and by-products.

NETL has worked to develop a novel luminescence-based sensor approach for the rapid, in situ detection and qualification of REEs for potential applications in waste recovery. The portable device can detect concentrations of several REEs in aqueous solution within minutes in the field as compared to the high-cost and long-lead time of conventional laboratory based characterization approaches that can take days to weeks for feedback.

## Advanced Sensors for Subsurface Monitoring

NETL researchers are developing new materials that will lead to sensor capabilities to monitor drilling processes, well-bore integrity, and $CO_2$ migration during geological storage. Real-time pH monitoring has been a key focus area of sensor research for subsurface monitoring with recent efforts also targeting $CO_2$ monitoring in geological formations for $CO_2$ sequestration purposes.

Even though there are a variety of options for pH measurement in biological or ambient settings, there is no reliable pH sensing technics available for wellbore and $CO_2$ storage applications. Monitoring the pH of wellbores and $CO_2$ storage sites provides important information on the geochemical conditions in reservoirs because acidic reservoir environments can lead to wellbore corrosion that could cause operational failures. Well operators need to monitor wellbore chemistry conditions to improve oil and gas recovery while ensuring functional integrity of wells and protecting groundwater.

Using a combination of material chemistry and fiber optics, NETL researchers are developing new fiber optic-based pH sensing approaches that will allow for embedded, real-time, remote pH sensing capabilities in extreme subsurface environments.

## Distributed Fiber-Optic Sensing in a High-Temperature Solid-Oxide Fuel Cell

High temperature solid-oxide fuel cells (SOFCs) present a challenging environment for sensor systems because they operate at temperatures above 800 degrees C. In addition, there is a strong gradient in both gas concentration and temperature from the fuel inlet to the outlet as fuel is consumed across the SOFC. NETL research has led to materials and techniques for measuring the spatial distribution of temperature along a SOFC interconnect channel that uses a distributed interrogation system combined with a single-mode fiber optic thin-film stack that yields measurements with sub-millimeter accuracy.

There is potential for expanding the approach for chemical sensing as well as dual hydrogen/temperature sensor fabrication. The team is currently working to increase the technology readiness level of the in-situ optical fiber based fuel cell sensor approach and is seeking industrial partners.

**Paul Ohodnicki, Jr., Ph.D.**
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Paul R. Ohodnicki Jr. earned an MS and PhD in Materials Science and Engineering from Carnegie Mellon University. He is now a senior staff scientist and technical portfolio lead on the Functional Materials Team within the Materials Engineering & Manufacturing Directorate of the National Energy Technology Laboratory in Pittsburgh, Pennsylvania. He is responsible for overseeing several major projects in the areas of functional sensor materials for power generation and sub-surface applications. His primary research interests are focused on studies of nanostructured and nanocomposite material systems with a particular emphasis on materials for sensors, power electronics, and energy conversion devices.

## Nanocomposite-Based Optical Fiber Sensors for Hydrogen Sensing in Infrastructure Monitoring Application

The ability to sense the presence of hydrogen is important for a range of application in energy, defense, aviation, and aerospace. The detection and quantification of low levels of H2 is important for leak detection in applications where H2 is stored, transported, or utilized as well as monitoring of the state of health of electrical grid assets such as power transformers where insulation oil degradation leads to generation of H2 amongst other hydrocarbons. Optical-based sensors are particularly well-suited for hydrogen sensing in such applications because they do not require electrical wiring or contacts at the sensing location, providing benefits in safety and sensor longevity and improved compatibility with electrical systems.

NETL work has been performed demonstrating that incorporation of noble metals like palladium and palladium-alloy nanoparticles into inert matrices like silicon dioxide and integrated with engineered filter layers to impart a new level of optical sensing functionality that can be useful to enabling inexpensive and simple optical hydrogen sensors.

NETL research will continue to focus on identifying materials for use in new sensors that will answer the challenges of new advanced energy generating technologies. The team's work has resulted in a portfolio of patented and patent-pending technologies available for licensing or further cooperative development. ≡

# RESEARCHERS STRIKE GOLD
## with Carbon Dioxide Conversion Process

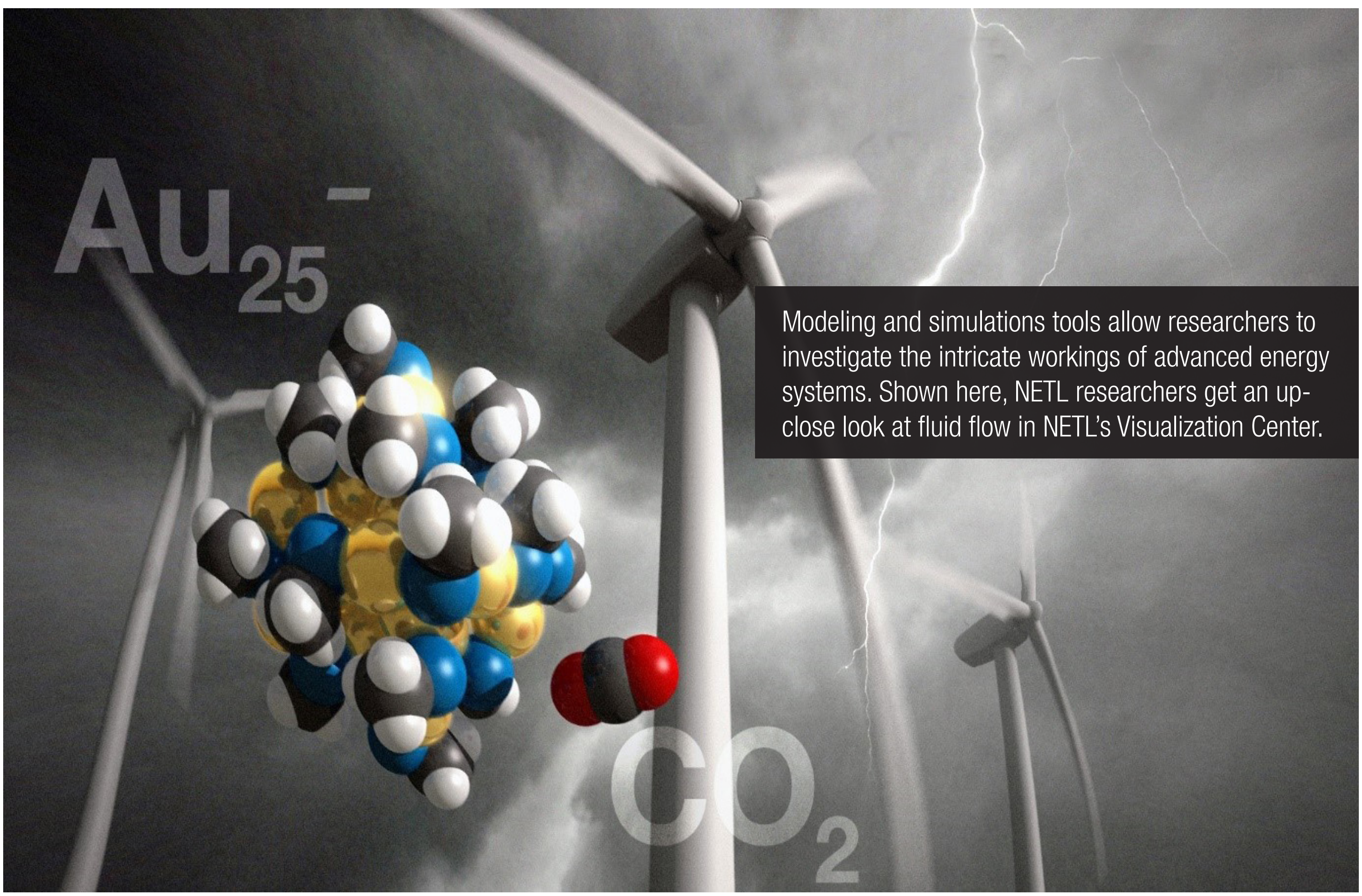
*By Joe Golden // Technical Contact: Douglas Kauffman, Ph.D*

NETL researchers have developed an alternative carbon mitigation strategy that converts unwanted carbon dioxide ($CO_2$) into valuable chemicals, fuels, and materials. This approach can supplement traditional geologic carbon sequestration, and revenue generated from the sale of valuable $CO_2$ conversion products can help offset costs associated with large-scale $CO_2$ capture processes.

"$CO_2$ is extremely stable because it is the end product of fossil fuel combustion," said NETL researcher Dr. Douglas Kauffman. "So, converting $CO_2$ back into something useful requires a large input of energy."

To reduce this energy requirement, Dr. Kauffman and his team are designing and testing new nanomaterials that promote the $CO_2$ conversion reaction. Reducing energy requirements will translate into cheaper reactors and processes, which will ultimately quicken the deployment of large-scale systems.

The NETL team uses a combination of advanced experimental and computational techniques to develop catalysts that use electricity to convert $CO_2$ into other useful and valuable materials, chemicals, and




Modeling and simulations tools allow researchers to investigate the intricate workings of advanced energy systems. Shown here, NETL researchers get an up-close look at fluid flow in NETL's Visualization Center.

## “This approach is also very important because it finds a wonderful use for excess renewable electricity that couldn’t otherwise be handled by the electrical grid.”

fuels. This form of electrochemistry uses principles like those used in batteries, which have become ubiquitous in modern times, powering everything from lap-tops to cell phones.

Dr. Kauffman and his team have developed a special form of gold nanoparticle composed of exactly 25 gold atoms to activate the $CO_2$ transformation. These nanoparticles are very small, measuring around 1–2 nanometers. Their research has shown that both the nanoparticle size and structure is very important for the $CO_2$ reaction and system efficiency.

Using the newly developed nanocatalysts and a small amount of water, $CO_2$ can be converted into carbon monoxide and hydrogen in a controllable ratio. The ability to control how much of each gas is produced is important because it provides the ability to make synthesis gas for downstream processing into other value-added chemicals.

One outstanding challenge was the catalyst’s requirement of electricity. If a reactor used fossil fuel-derived electricity, then the process could become carbon-positive, because power generation would produce more $CO_2$ than the reactor could convert. The team surmounted this obstacle by integrating renewable energy sources into the process—powering their bench-scale reactors with inexpensive solar cells, thus achieving a “carbon neutral” status.

“Incorporating renewable energy is essential for the development of practical $CO_2$ conversion systems,” said Dr. Kauffman. “This approach is also very important because it finds a wonderful use for excess renewable electricity that couldn’t otherwise be handled by the electrical grid.”

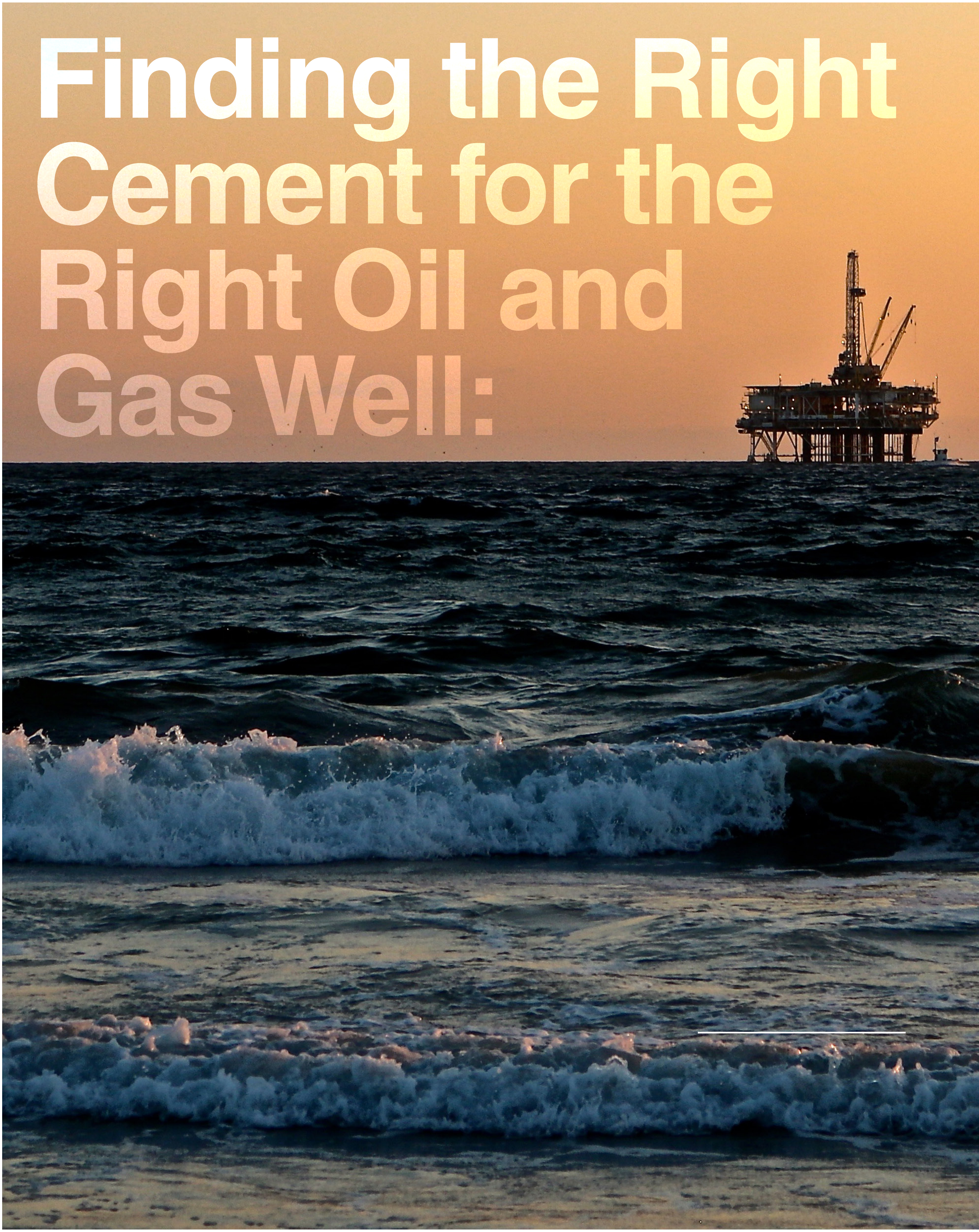
This demonstration is doing more than simply proving large-scale carbon neutral systems are possible. The team’s work is also providing the kind of critical performance estimates that will ultimately push the process into industry where it can begin to make a significant impact on the reduction of $CO_2$ levels.

Based on their results, the research team estimates that state-of-the-art renewable energy sources like solar-cells and wind turbines are sufficient to convert many metric tonnes of $CO_2$ per day, changing this undesirable gas into a valued resource. This ongoing research is currently developing and testing new catalysts to lower costs and improve $CO_2$ conversion efficiencies. ≡

**Dr. Douglas Kauffman // Douglas.Kauffman@netl.doe.gov**

NETL Research Chemist Dr. Douglas Kauffman creates and evaluates new nanocatalyst materials for clean energy applications. By coupling catalyst performance with optical, electrochemical, and computational studies, Kauffman is developing important relationships between the physical and electronic structure of materials and their catalytic activity. Kauffman was one of the first researchers to demonstrate the extraordinary catalytic activity of small gold nanoparticles for electrochemical CO2 conversion, and his approach has been widely adopted within the scientific community. Dr. Kauffman obtained his Ph.D. in chemistry from the University of Pittsburgh in 2010.

# Finding the Right Cement for the Right Oil and Gas Well:



# NETL Innovation Used to Study Foamed Cement Variations

*By Gerrill Griffith // Technical Contact: Barbara Kutchko, Ph.D.*

Wellbore cement plays a critical role in the safe and productive operation of oil and gas wells around the world because it is used to create seals to protect underground sources of drinking water and encase tubes to prevent leaks and spills. NETL research is providing a deeper understanding of this important material to make sure the right cement is up to the right task. This has been particularly important in NETL's innovative research in foamed cements.

Foamed cement is a gas-liquid dispersion that is produced when an inert gas, typically nitrogen, is injected into a conventional cement slurry to form microscopic bubbles. Foamed cements are ultralow-density systems typically employed in formations that are unable to support annular hydrostatic pressure exerted by conventional cement slurries.

In addition to its light-weight application, foamed cement has a unique resistance to temperature and pressure-induced stresses and it exhibits superior fluid displacement, gas-migration control, and long-term sealing through resistance to cement-sheath stress cracking. Because of these properties, it is often the system of choice for shallow flow conditions and prevention of compaction damage in deepwater production in offshore environments. The use of foamed cement has expanded into regions with high-stress environments, like the Gulf of Mexico, where it is an important material used to isolate problem formations.

Meanwhile, on shore, using cement in oil and gas well bores present a different challenge. Depleted and abandoned coal mines fill up with corrosive fluids that can eventually break down the cement that surrounds wells that run through the old mines. Oil and gas companies are designing cements with specifications that consider the chemistry of the groundwater surrounding the wells and how coal mine water interacts with cement.

Despite its wide-ranging use, significant knowledge gaps exist regarding foamed cement. For example, testing methods have been limited to atmospheric conditions and, as a result, many questions remain unanswered regarding the stability and properties of foamed cement as it is placed in the well and during post-placement. Foamed cement stability depends

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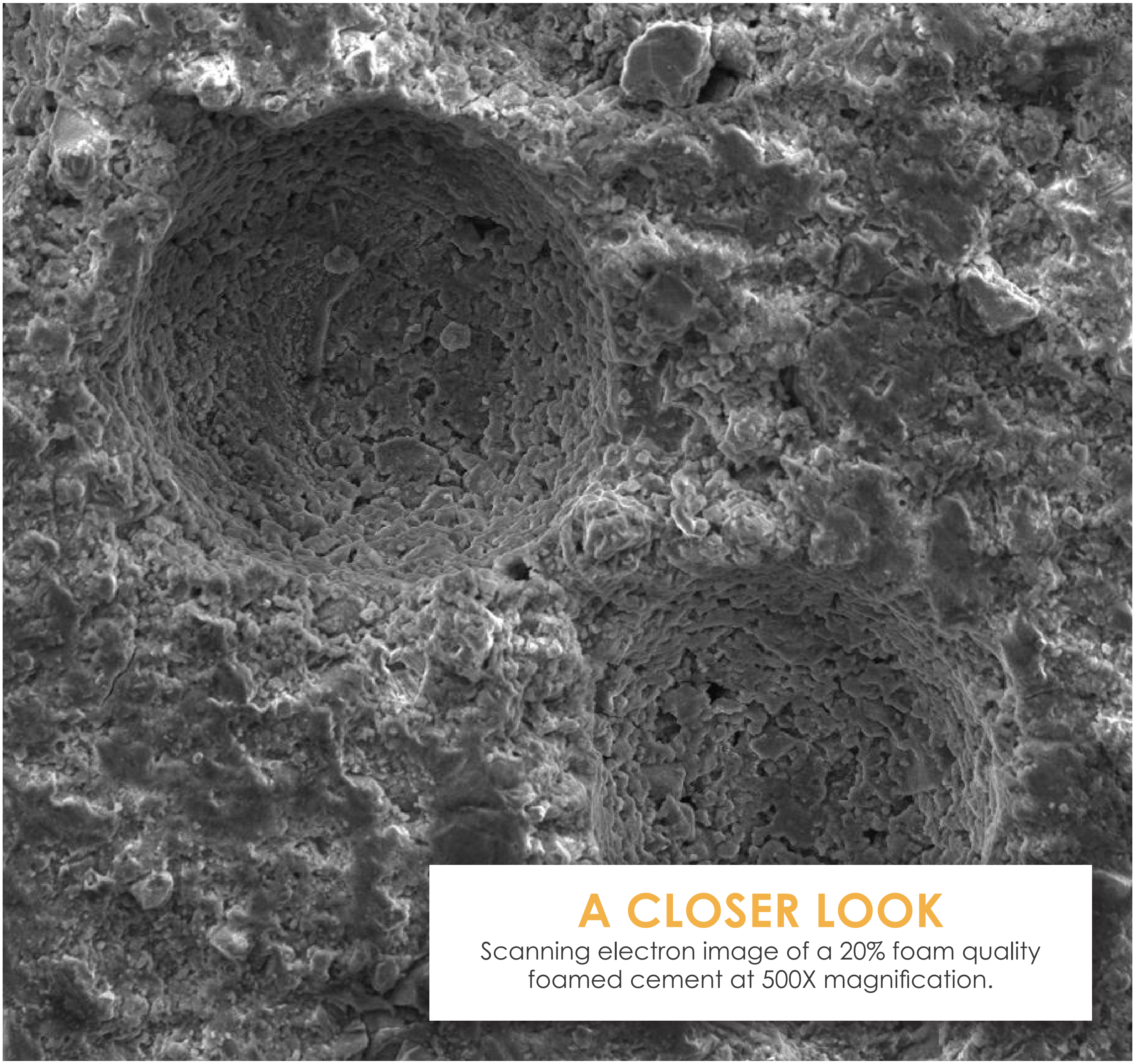


## A CLOSER LOOK

Scanning electron image of a 20% foam quality foamed cement at 500X magnification.

on time evolution of the gas bubble-size distribution (BSD) and varies as it is pumped and placed in the well. If the foam cement is unstable, gas can coalesce and bubbles will increase in size, causing gas pockets to form and rise in the cement column. Unstable foams can result in uncemented sections or channels and failure to achieve zonal isolation. A stable foam provides the desired zonal isolation and casing support when installed properly in the wellbore.

The increased use of foamed cement systems, especially in high-stress environments, makes understanding their stability in the wellbore vital. NETL researchers are making key contributions to understanding the many foamed cement variations that could occur.

According to NETL's Barbara Kutchko, the Laboratory partnered with private industry to investigate the properties of foamed cements at various pressures, shear rates, and foam qualities using NETL's industrial computer tomography (CT) scanner and in situ geomechanics laboratory. The work provided 3-D image data sets of bubble size distribution of atmospheric foam generated with the current American Petroleum Institute (API) RP 104-B test method across a range of foam qualities, and laboratory-generated foamed cement under a range of pressures across a similar range of foam qualities.

To examine the potential impact of the different foam cements' performance in the well, NETL put together a comprehensive plan with a diverse team of experts to analyze field-generated samples, conduct laboratory testing, and execute simulations to address questions that Kutchko said experiments alone cannot answer. These field samples were generated using the identical full scale equipment used to generate foamed cement on an offshore rig.

NETL's geomechanics team performed testing to both the atmospheric laboratory-generated and field-generated samples to determine how BSD impacts performance properties. Physical and mechanical properties such as porosity, permeability, and other properties were comprehensively measured. To test the variation in permeability and strength of various foam cements, stepwise pressure loading and unloading experiments were conducted to simulate well pressure cycling.

Mechanical properties were obtained under cyclic confining pressures ranging from 12–52 Mpa. Kutchko said foamed cement samples that were generated with field equipment displayed better stability and lower permeability compared to cements generated at the same gas volume fraction as the laboratory samples used to test slurry designs.

The resulting mechanical properties of both field-generated and atmospherically generated foamed cements suggests that a maximum 30–35 percent nitrogen volume fraction is suitable for applications to isolate subsurface formations in oil and gas well cementing operations.

Another aspect of testing and understanding foamed cement performance centers on discovering the differences between tests conducted on samples in the laboratory versus testing conducted in the field.

Kutchko explained that an NETL team has been working with the API's Cement Subcommittee 10 for several years to examine the differences between foamed slurries generated with laboratory equipment and field foamed cementing equipment.

"When using foamed cement, laboratory testing is employed to estimate the performance characteristics of foamed cement slurries as they are designed for well applications," she explained. "However, it is well known that significant differences exist between the methods used to generate foamed cement in the laboratory and those used to generate foamed cement for field applications. The implications of these differences on foamed cement characteristics like bubble size distribution, performance properties, stability, permeability, and mechanical properties, have not been well analyzed or understood until this NETL study."

She said that three independent sampling programs performed by three different major service companies enabled the capture of consistent sets of field-generated foamed cement samples under pressure. Upon analyzing the BSD from NETL's CT data, it turned out that foamed cements generated using the atmospheric blender method for slurry stability testing in the laboratory, and the current methods used in industrial-scale foamed cementing equipment, do not provide similar BSDs in foamed cements that have similar entrained air/nitrogen volume fractions. Kutchko said that bubbles in the field generated samples were smaller with a different range of sizes when compared to the samples used for testing stability.

"Cement has been around, obviously, since Roman times," Kutchko told the Pittsburgh Post-Gazette in early 2017 in a discussion of her work. "On the one hand, it's such a staple. On the other hand, the research and development that goes into cement is phenomenal."

Kutchko's research to make sure the material is as safe and effective in wellbore applications will continue to be an important function at NETL whether it takes the form of recreating coal mine fluids in the lab and washing them over chunks of well bore cement to measure damage or subjecting samples to intricate examination using a CT scanner. ≡

**Barbara Kutchko, Ph.D. //** Barbara.Kutchko@netl.doe.gov

Dr. Barbara Kutchko is a senior research scientist with NETL specializing in wellbore isolation, oil well cementing, and subsurface materials characterization. She has a Ph.D. from Carnegie Mellon University's Civil and Environmental Engineering and an M.S. in Geology from the University of Pittsburgh. She works with oil and gas companies, government agencies, and universities to evaluate current cementing practices and research needs to ensure the safe placement of cement related to offshore drilling, shale gas production, and carbon storage. This includes leading and collaborating with teams of diverse researchers, professors, students and industry experts to plan, manage, and execute research related to energy production. Dr. Kutchko currently represents NETL on API's Cement Subcommittee 10C which develops and maintains standards on various oil and gas wellbore cementing procedures for the U.S. petroleum industry.

# NOVEL HEAT EXCHANGER BREATHES HIGHER EFFICIENCY INTO FUEL CELL SYSTEMS

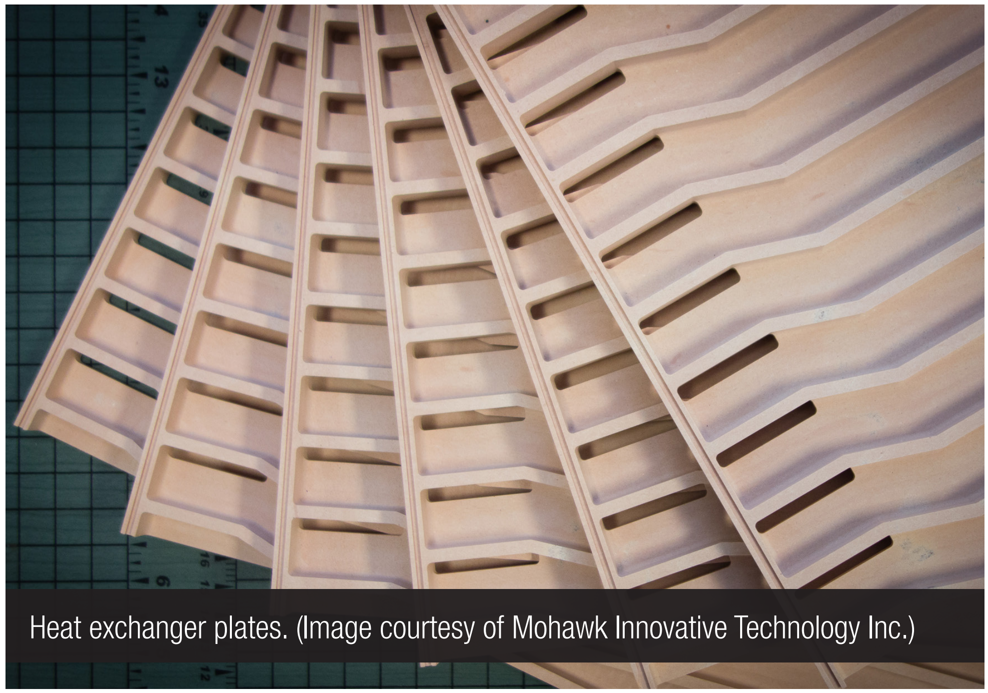
*By Jenny Bowman // Technical Contact: Sydni Credle, Ph.D.*

An innovative heat exchanger developed by Mohawk Innovative Technology Inc. (MiTi) as part of an NETL-managed project is changing the game for solid oxide fuel cell (SOFC) systems.

High-temperature heat exchangers provide an important efficiency element for SOFC systems, which typically operate in the range of 700–900 degrees Celsius, by preheating the incoming fresh air supplied to the SOFC cathode. However, significant design challenges exist. For example, pressure drop (pumping power) must be low to reduce plant auxiliary power requirements and materials must be robust enough to withstand the high-temperatures and corrosive environments of SOFC systems. In addition, manufacturing methods must be cost-effective and appropriate for large-scale production.

Traditionally, heat exchangers for high-temperature operations are fabricated out of superalloys, which are both costly and ill-suited to SOFC systems. Under typical operating conditions, humidity in the SOFC cathode air supply causes metal alloys to release volatilized chromium, which poisons SOFC cathodes and accelerates performance degradation. Ceramics are another option, but the brittleness of the material and the difficulty in manufacturing complex surfaces have posed engineering roadblocks. Ceramics are also prone to pressure drops that can negatively affect performance.

MiTi's new heat exchanger resolves these challenges. The team successfully developed a ceramic heat exchanger with high heat effectiveness and low pressure drop to work as an air preheater for SOFC cathodes. In prototype performance testing at realistic operating temperatures, MiTi's innovation exceeded the heat transfer effectiveness requirements of the target SOFC design specification and easily met the low pressure drop design constraint. Moreover, the ceramic elements held up successfully to the thermal cycling during the tests, operating leak-free and demonstrating the robustness of the design.

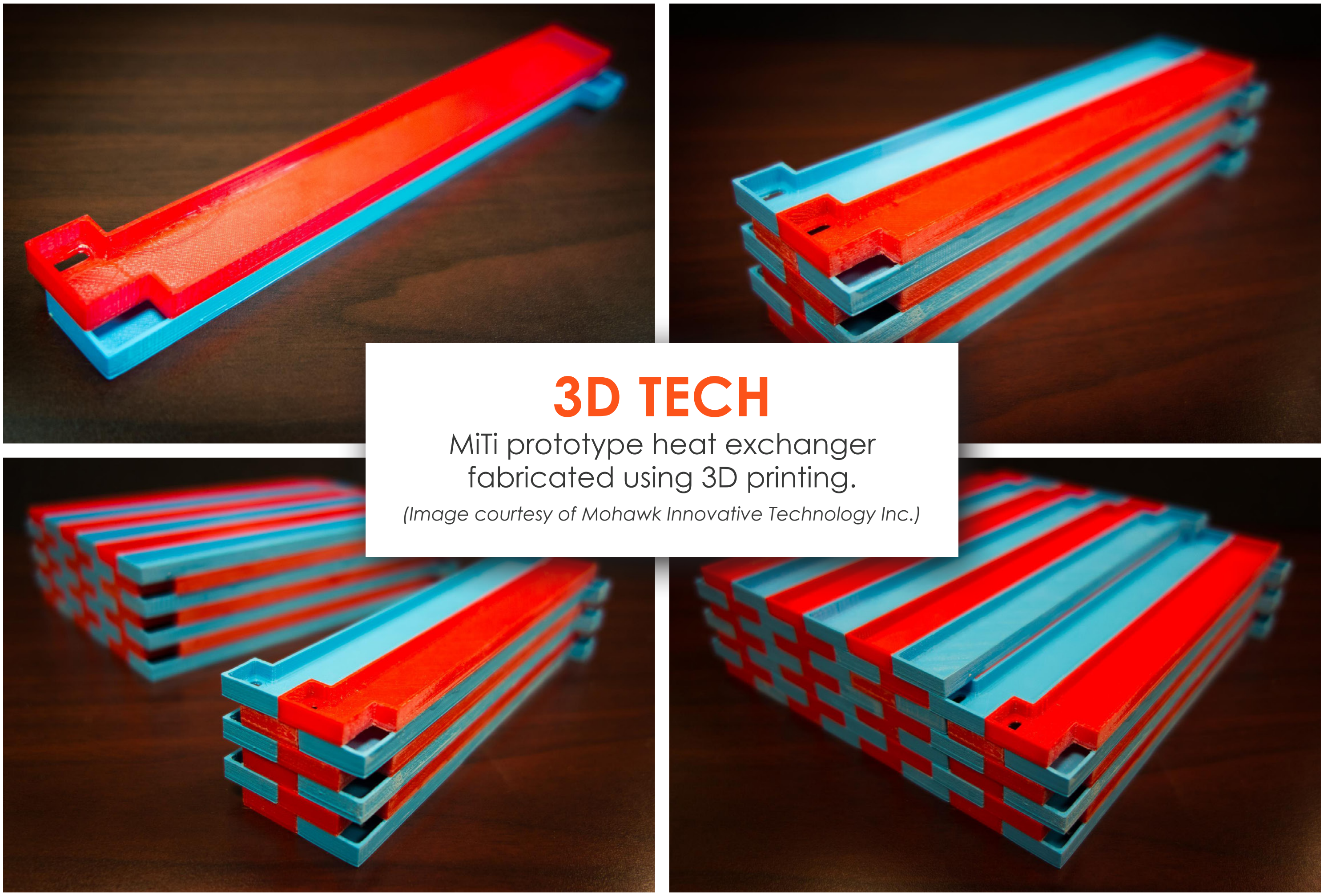


Heat exchanger plates. (Image courtesy of Mohawk Innovative Technology Inc.)

The breakthrough moment occurred when the MiTi project team decided to investigate the role of thermal conductivity in greater detail.

NETL Project Manager Dr. Sydni Credle explained, "The team started with the assumption that the materials used for the heat exchanger must have as high thermal conductivity as possible, and other characteristics like mechanical properties and manufacturing techniques would be secondary to the materials' thermal conductivity. What they discovered was that, due to their unique approach for minimizing pressure drop, the heat transfer process is convection-controlled, and thermal conductivity has less of an effect on overall heat transfer than previously thought. In other words, for this this type of heat exchanger, the rate of heat transfer is not limited by the material conductivity but rather by the working flows. So there is greater freedom for material selection."

Guided by this new discovery, MiTi selected an alumina-silicate that is very soft in the green state—soft enough to be



# 3D TECH

MiTi prototype heat exchanger fabricated using 3D printing.

*(Image courtesy of Mohawk Innovative Technology Inc.)*

scratched by a fingernail—and therefore easily machined to the required shape. Using computer software, MiTi designed a small, modular, and scalable element to serve as a subunit that can be aggregated into larger units. When assembled, the heat exchanger consists of an array of overlapping quasi-helical flow passages. The quasi-helical paths are overlapped, forming a chessboard pattern, and the passages carrying the working flows (i.e., cool fresh air and hot fuel cell exhaust) are staggered through this pattern. The heat exchange established is a combination of counterflow and parallel heat exchange, with minimal losses to the environment.

In their capstone test under the DOE project, MiTi integrated the heat exchanger into a modified fuel cell test stand and tested at steady state conditions. The combined operation of the heat exchanger with the SOFC provided confidence that practical application of this technology is feasible in the near term. Overall, the project has provided invaluable input by highlighting the successes and also identifying shortcomings that will guide improvements to achieve broad commercial implementation.

"We're encouraged by MiTi's results," Credle said. "They earned a strong reputation with a prior heat recuperator innovation for gas turbines, and it's exciting to see that heat exchange technology expanding to SOFC applications."

SOFCs offer one of the cleanest, most efficient options for producing energy from fossil fuels. There is still more R&D to be conducted for high-temperature heat exchangers, but technologies such as this will help enhance our nation's ability to use abundant domestic energy supplies while protecting the environment. ≡


## Dr. Sydni Credle

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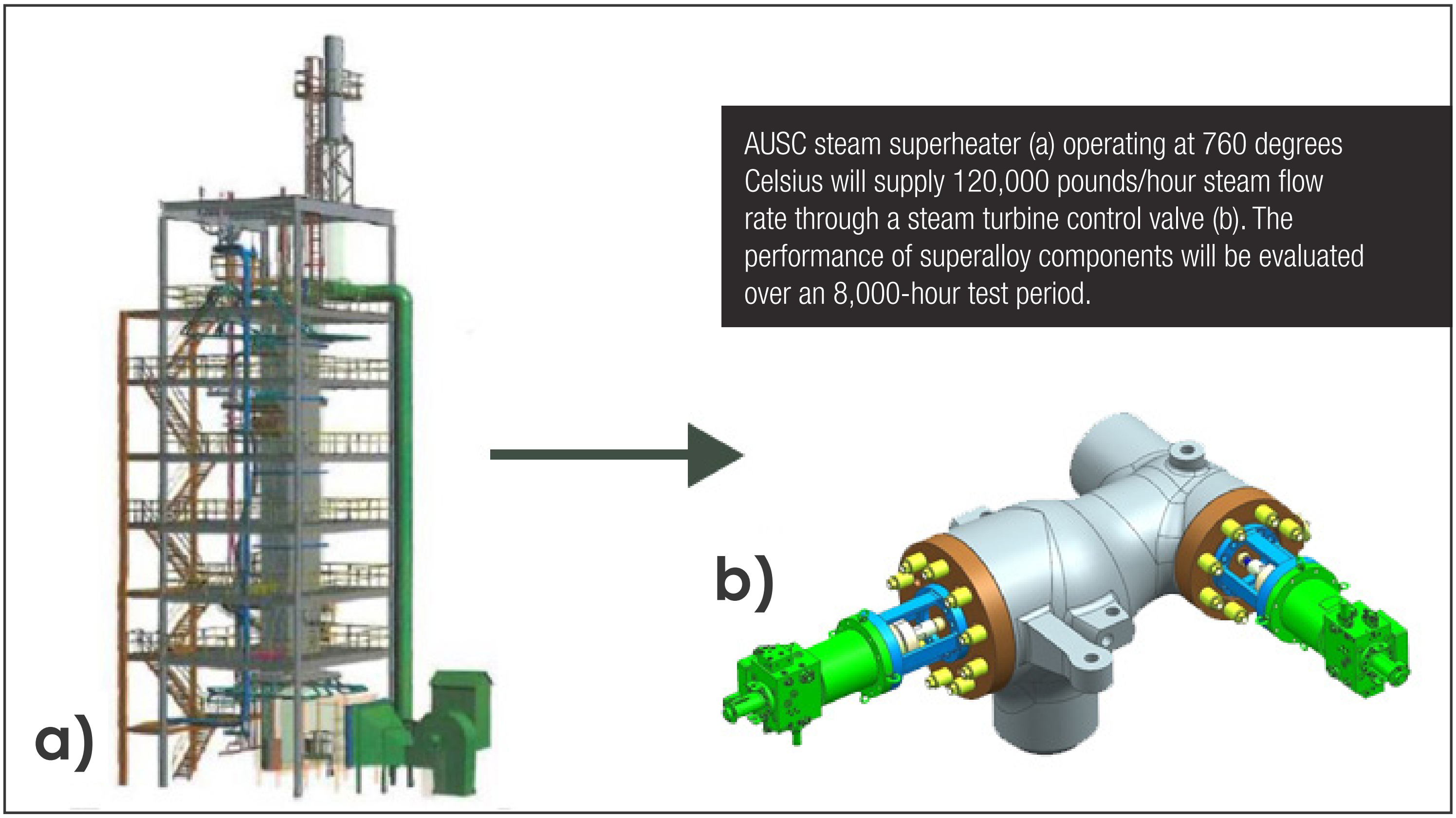
Dr. Sydni Credle is currently a Federal Project Manager for the Enabling Technologies and Partnerships Team at the Department of Energy's National Energy Technology Laboratory within the Office of Fossil Energy. Sydni manages projects relevant to fossil energy in the crosscutting areas of sensors & controls, advanced materials, and computational modeling. Dr. Credle obtained a B.S. and M.S. degree from Florida A&M University in mechanical engineering as well as a Ph.D. from University of Florida in the same field.

# New Pilot Facility will put Advanced Ultra-Supercritical Components to the Test




AUSC steam superheater (a) operating at 760 degrees Celsius will supply 120,000 pounds/hour steam flow rate through a steam turbine control valve (b). The performance of superalloy components will be evaluated over an 8,000-hour test period.

*By Dr. Paul Battista // Technical Contact: Mr. Vito Cedro*

Increasing the temperature and pressure of steam can dramatically improve the operating efficiency of boilers and turbines that rely on steam as the working fluid. Higher plant cycle efficiency means less coal is burned, which reduces emissions—including a decrease in carbon dioxide ($CO_2$). To achieve this, power plant turbines must operate at advanced ultra-supercritical (AUSC) conditions. The major driver for successful AUSC operations is the development and incorporation of advanced materials capable of operating under such extreme conditions. Conventional materials do not possess optimal characteristics and performance criteria under AUSC conditions.

### What is advanced ultra-supercritical?

| Nomenclature | Steam Conditions* | Net Plant Efficiency |
|---|---|---|
| Subcritical | 2,400 psig<br>540°C | 35% |
| Supercritical | >3,600 psig<br>550°C | 38% |
| Ultra-Supercritical | 3,600 psig<br>600°C | >42% |
| Advanced Ultra-Supercritical | 3,000–5,000 psig<br>700–760°C | >45% |

*Pounds/square inch gauge

The AUSC Consortium was formed to achieve a step increase in the operating efficiency of coal-fired power plants using advanced structural materials. The consortium is composed of public and private partners and included input from U.S.-based boiler manufacturers—ALSTOM Power Inc., the Babcock & Wilcox Company, Foster Wheeler Development Corporation, and Riley Power, Inc.—and the Electric Power Research Institute. In addition, critical analysis and recommendations were provided by U.S.-based utility providers to help guide materials development and evaluation. After 15 years of intensive materials research, design, fabrication, and testing, AUSC Consortium members successfully tested two domestically produced nickel-based superalloys. These alloys are Inconel 740H and Haynes H282. Inconel 740H has received approval from the American Society of Mechanical Engineers for use in fired boilers, unfired pressure vessels, and pressure piping up to 800 degrees Celsius. Work is in progress to obtain the same ASME approval for Haynes 282.

While this milestone successfully concluded the consortium's efforts to evaluate and find suitable materials for boiler operation at AUSC conditions, the consortium members were committed to taking the AUSC technology to the next level. In November of 2015, DOE and NETL approved a project aimed at advancing the technology readiness of the new superalloys. In partnership with the State of Ohio's Coal Development Office and a consortium initially composed of Babcock & Wilcox, General Electric and Alstom Power, a 6-year $74 million cost share effort began under a prime contract to the Energy Industries of Ohio, who, along with the Electric Power Research Institute will manage the project.

Known as the AUSC Component Test Facility (ComTest), the project aims to evaluate the performance of equipment fabricated from nickel superalloy materials at AUSC steam conditions. The project will demonstrate AUSC technology up to a commercial-scale demonstration level technology readiness by designing, procuring, constructing, and operating a prototype R&D-scale (approximately 120,000 pounds/hour steam flow rate) test facility consisting of an AUSC steam superheater, main steam piping, steam header, and steam turbine control valve. Functional component testing is expected to start in early 2019 and will entail 8,000 hours of performance evaluation over a 2-year period.

The team has made significant progress for advancing ComTest, including identifying a suitable host site, completing front-end engineering design and preliminary capital cost estimates, working with domestic suppliers on supply chain development for nickel superalloy components and developing a 2-year test plan. Future work will focus on finalizing cost estimates and time lines, completion of the engineering design, followed by construction and operation of the ComTest facility.

The expected benefits of ComTest will be the validation that an AUSC steam turbine can be designed, built, and reliably operated under both steady-state and varying load operating conditions. In addition, the project will allow for the generation of sufficient R&D testing and metallurgical analysis data to design a AUSC demonstration plant with a high probability of technical success, leading to utility industry adoption and participation in commercial-scale deployment.

| **Technology Readiness Levels** | | | **Roadmap to AUSC Demo** | |
|---|---|---|---|---|
| **2000 2005** | **2010** | **2015** | **2020** | **2025** |
| Materials Evaluation (Nickel Superalloy Focus) | Component Mockup | Steam Loop at Plant Barry. Large Forgings & Castings | AUSC Component Test Facility (ComTest) | AUSC Demonstration |
| Laboratory TRL 2-3 | Proof of Concept TRL 4 | Component Test TRL 4-5 | System TRL 5-7 | Overall TRL 8-9 |

**Mr. Vito Cedro, III**
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Mr. Vito Cedro III is a project manager in NETL's Enabling Technologies and Partnerships team. He is a Registered Professional Engineer in the state of Pennsylvania, and a Project Management Professional as designated by the Project Management Institute.

# LAYERS OF SUCCESS

## 3D PRINTING OF TURBINE COMPONENTS

*By Shaelyn Patzer // Technical Contact: Mr. Vito Cedro*

Fossil-fueled power generation is a keystone in America's plan for energy independence, and while investments in other methods of energy production are being made, it is vital that work continues to develop and advance technologies that use all our nation's resources. NETL is committed to pursuing a wide portfolio of energy technology, including designing improvements of power plant technology in projects like Microstructure and Properties of Ni-based Turbine Components Fabricated by Additive Manufacturing.

Turbines are the main electricity generating components in most power plants. A turbine is a mechanical device that extracts energy from a fluid flow and turns it into useful work. A combustion turbine is a type of turbine that converts the chemical energy in fossil fuels into mechanical energy by extracting energy from the hot combustion gases. The mechanical energy can then be used to generate electricity or act as a power source for industrial processes NETL conducts and supports research and development projects that seek to improve turbine efficiency, reduce emissions, increase power output, and reduce costs. One of the most effective ways to increase the efficiency of gas turbines is by maximizing the temperature at which the turbine can operate. Higher temperatures allow turbines to use less fuel and, at the same time, allowing carbon capture technologies to more effectively reduce greenhouse gas emissions.

To design gas turbine components that can handle the increased temperatures of next-generation power plants, researchers at NETL are collaborating with other national laboratories to develop advance alloy materials for use under extreme operating conditions. The inter-organizational team have turned to a process known as additive manufacturing (AM), commonly known as 3D printing. In this case, gas turbine components made from a nickel (Ni) based alloy. Many techniques have been developed to accomplish AM goals, but three main ones were employed, and subjected to assessment, in this project: laser metal deposition (LMD), selective laser melting (SLM), and electron beam melting (EBeam).

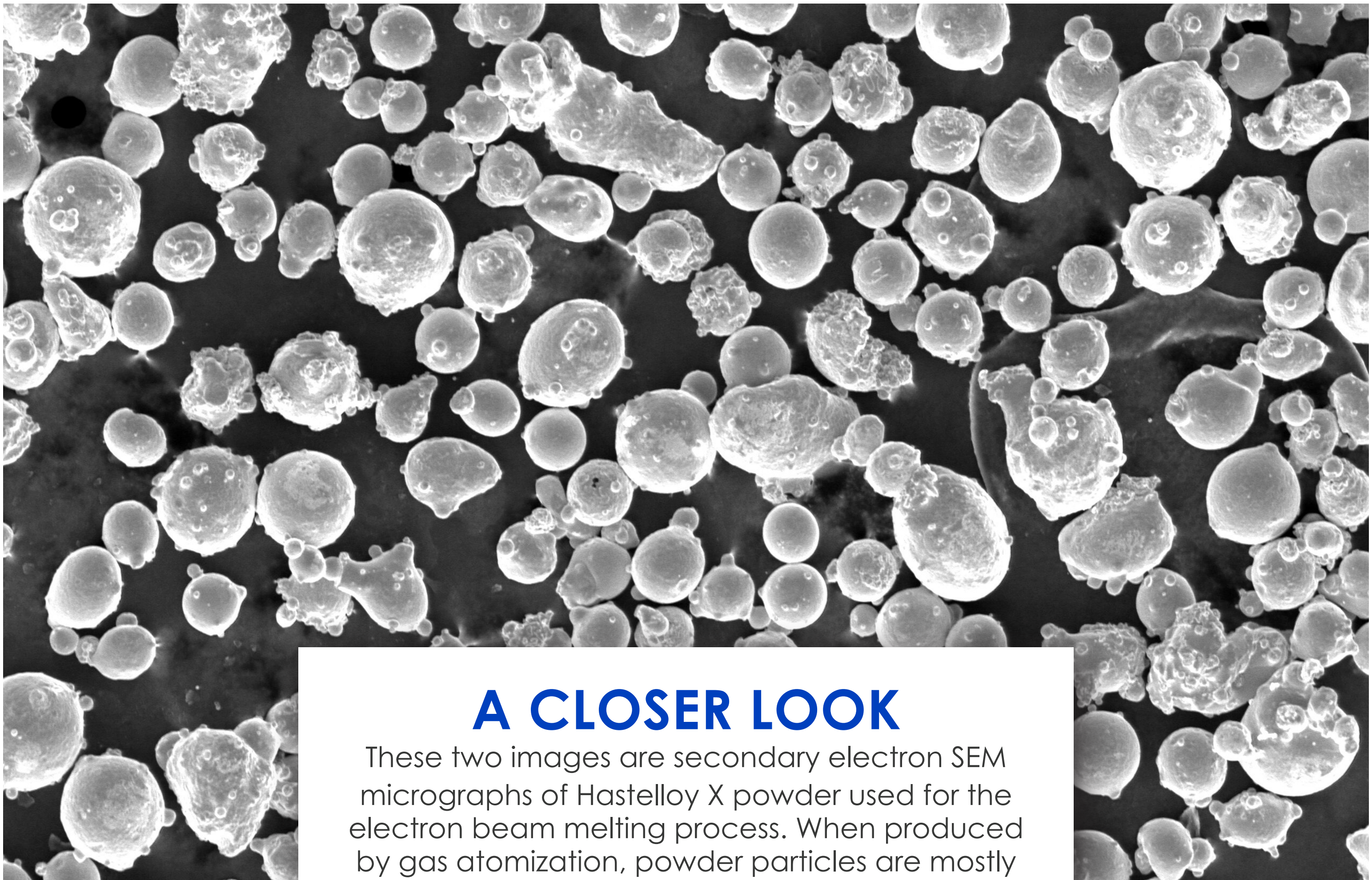
LMD has also been referred to as direct energy deposition or laser cladding. In this process, a laser is used to generate a weld pool on the surface of the component being created. Then, a nozzle is used to add metal powder to the weld pool, producing beads that are welded to each other—allowing researchers to fully create entire components or to augment components that have been conventionally cast.

SLM also employs a laser to fuse and melt metal powders together. A thin layer of metal powder is spread across the surface it will be joined to, and then a laser is slowly moved across the surface to heat the metal, fully melting it. This is an extremely high-energy process conducted inside a tightly controlled atmosphere of inert gas. Ultimately, layer after layer of melted metals are joined together to gradually building up to a completed 3D object.

EBeam is very similar to SLM. The difference between the two processes is that EBeam relies on an electron beam rather than a laser to melt the metal powder. Like SLM, EBeam can only be used on a limited number of metals based on their flow characteristics.

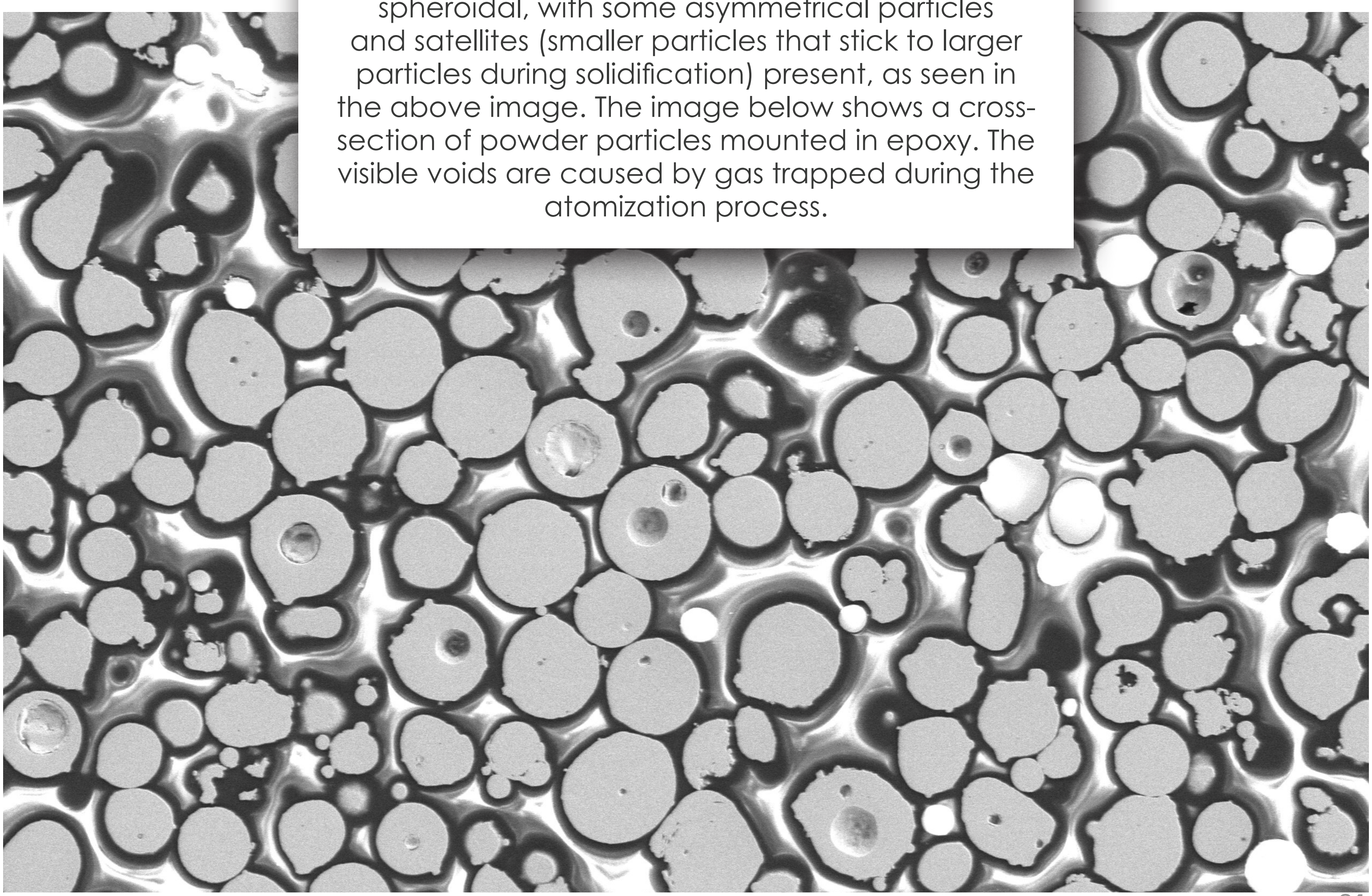
Each of these processes have offered the research team a different approach to creating a gas turbine component that uses a nickel-based alloy. Part of the project involved selecting the optimal alloy to use for the testing, then creating fabricated specimens through each of the AM techniques. Once these specimens were created, researchers began to perform microstructure characterization and mechanical testing to determine how each AM process influenced the properties of the samples. Additionally, the specimens were compared to a conventionally cast nickel-based gas turbine component.

The project is ongoing. Although the specimens have been cast, researchers are in the process of performing extensive testing on the samples to assess each AM method. Once these tests have been concluded, researchers will be able to select the process that is most suited to creating an advanced gas turbine components and eventually use it in the next stage of the project. ≡



# A CLOSER LOOK

These two images are secondary electron SEM micrographs of Hastelloy X powder used for the electron beam melting process. When produced by gas atomization, powder particles are mostly spheroidal, with some asymmetrical particles and satellites (smaller particles that stick to larger particles during solidification) present, as seen in the above image. The image below shows a cross-section of powder particles mounted in epoxy. The visible voids are caused by gas trapped during the atomization process.



# NETL Metallurgist Paul Jablonski's Research Accomplishments Recognized by ASM International

*By Paul Battista, Ph.D.*

NETL Metallurgist, Dr. Paul Jablonski has been elected as a Fellow of ASM International—the world's largest and most distinguished association for materials science professionals. Jablonski is being recognized for his distinguished contributions in the field of materials science and engineering. More specifically, the ASM cited Jablonski for, "Sustained excellence in materials processing and heat treatment, leading to CALPHAD based methodology for efficient homogenization of alloys through utilization of computational thermodynamics and kinetics."

ASM Fellows are recipients of one of the highest honors in the field of materials science; they are technical and professional leaders who have been recognized by their colleagues and now serve as advisors to the society. For more than 90 years, ASM International has recognized the achievements of individuals and organizations that contribute to materials science and engineering.

Jablonski has authored or coauthored more than 80 peer-reviewed publications and over 200 formal presentations. He is the recipient of eight patents and numerous awards, including four R&D 100 awards, five Federal Laboratory Consortium awards for Excellence in Technology Transfer, The Arthur S. Flemming Award, and a Secretary of Energy Achievement award.

Jablonski is active in multiple professional societies, recently completing a 2-year term as the chair of the High Temperature Alloys Committee for the Minerals, Metal, and Materials Society. Jablonski collaborates with other national laboratories (including Oak Ridge, Argonne, Pacific Northwest, and Idaho National Laboratory) to address metallurgical challenges. In partnership with the Army Research Laboratory, he developed a titanium alloy for personal body armor and prototype cast steel vehicle armor—important aids for U.S. troops during the Iraq war. In addition, Jablonski was instrumental in the fabrication of a novel platinum-chromium alloy for use in next-generation coronary stents.

Outside of his professional commitments, Jablonski is actively involved in his community. For the past 10 years, he has served as a parish advisory council member. He has been a member of the Saint Vincent de Paul society since 2003 and currently serves as the society's treasurer. He is also an active member of the Knights of Columbus, helping to raise money for several local charitable groups.

NETL Metallurgist Dr. Paul Jablonski

Jablonski will receive his award at the Convocation of Fellows to be held during the ASM Awards Dinner on Tuesday, October 10th, 2017, in Pittsburgh, PA. The event will be a highlight of the 2017 Materials Science & Technology Conference & Exhibition (MS&T17)—an annual conference organized in a joint partnership among four leading materials science-related societies: the American Ceramic Society, the Association for Iron & Steel Technology, ASM International, and the Minerals, Metals & Materials Society.


# RESEARCH IN ACTION

NETL researcher Dr. Paul Jablonski and his team forge a hot ingot in the Fabrication Laboratory.

# DOE Secretary Perry Praises NETL History of Making a Difference During Site Visits

*By Gerrill Griffith*

NETL Director Dr. Grace Bochenek hosted a 2-day visit by U.S. Energy Secretary Rick Perry July 6 at the NETL Morgantown site and July 7 at the Pittsburgh Laboratory location where some of Laboratory's key energy innovations were demonstrated.

The visitors, who included U.S. Senators Joe Manchin and Shelley Moore Capito, as well as U.S. Rep. David McKinley of West Virginia in Morgantown and U.S. Rep. Tim Murphy of Pennsylvania at the Pittsburgh site, toured key NETL labs for insight into the Laboratory's role in meeting the nation's energy needs.

Perry reflected upon NETL's accomplishments across the country including more than 100 patents, 2,800 publications and lab awards, combating acid rain, and several other accolades. He also highlighted NETL's research into extracting rare earth elements from coal, noting the potential of establishing a domestic supply of these elements.

NETL Director Bochenek said at the end of the Morgantown visit that, "We've had the opportunity to show [Secretary Perry] the breadth and the depth of what we do here at our national lab and how we collectively are important to the Department of Energy's mission…We talked about a lot of things: about innovation, about evolving technology, about advancing energy-conversion technologies, and how we collectively are discovering cleaner, cheaper, more efficient energy conversion technologies."

In Morgantown, Perry, Manchin, McKinley and Capito visited the Chemical Looping and Reactor Facility, the Solid Oxide Fuel Cell Laboratory, the Multiphase Computational Fluid Dynamics Center, and the Institute for the Design of Advanced Energy Systems.

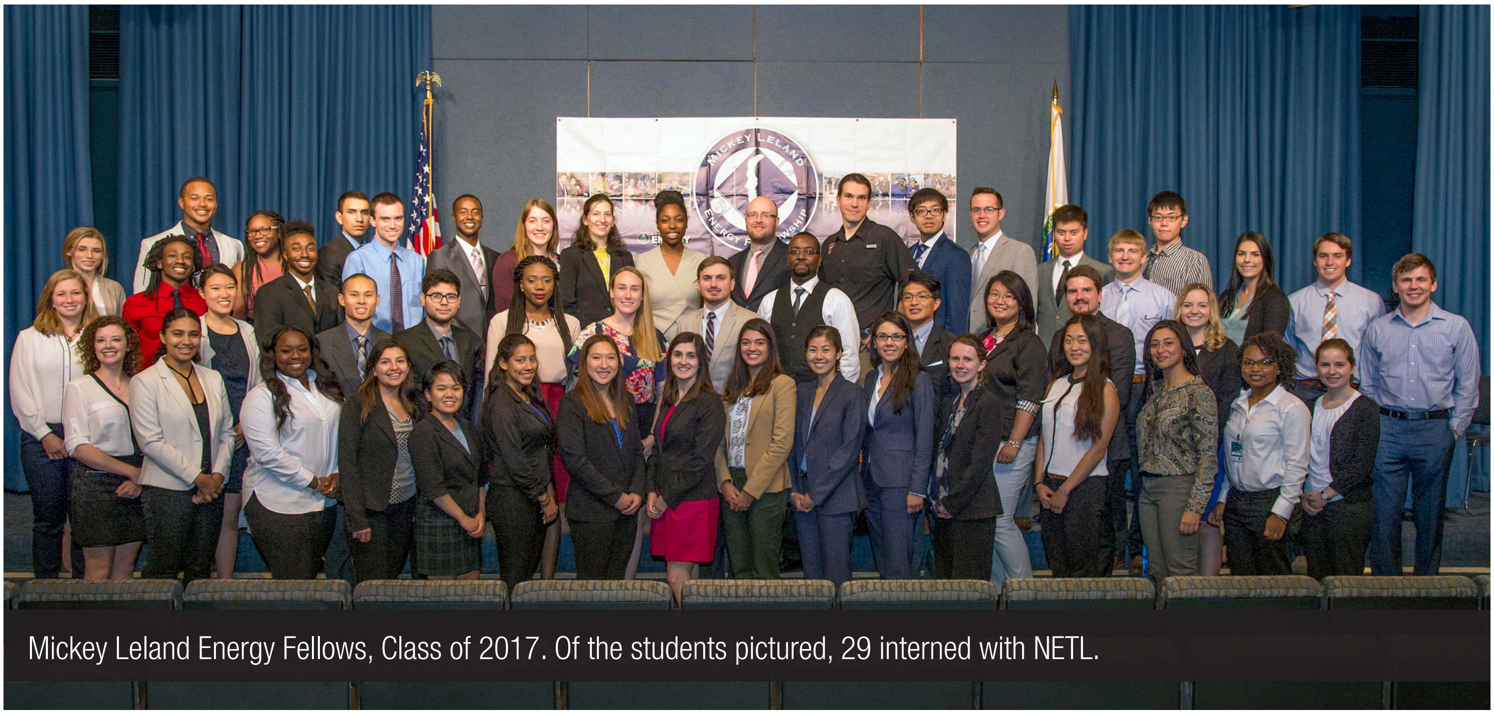
In Pittsburgh, Perry and Murphy visited the Rare Earth Elements and Critical Materials Laboratory, the Sensor Technologies Laboratory, the Polymer Synthesis Laboratory, the Materials Fundamentals Laboratory, the Geological and Environmental Sciences Laboratory, and the Computational Science and Engineering Laboratory. ≡

U.S. Energy Secretary Rick Perry addresses NETL staff at NETL's Pittsburgh site.


*(Left to right)* U.S. Rep. David McKinley, U.S. Senator Joe Manchin, U.S. Energy Secretary Rick Perry, and U.S. Senator Shelley Moore Capito participate in a panel discussion at NETL's Morgantown site.


U.S. Rep. Tim Murphy, left, U.S. Energy Secretary Rick Perry, center, and NETL's Barbara Kutchko review research underway in Kutchko's Pittsburgh lab as part of a Pittsburgh site tour.

# 2017 Mickey Leland Energy Fellowship Interns Mentored by NETL's Talented Energy Researchers



Mickey Leland Energy Fellows, Class of 2017. Of the students pictured, 29 interned with NETL.

*By Joe Golden*

George Thomas "Mickey" Leland was a prominent legislator and advocate for hunger, public health, and cultural diversity issues. Today, his legacy lives on through many government programs, fellowships, and academic organizations, including the Mickey Leland Energy Fellowship (MLEF), which is sponsored by the U.S. Department of Energy's (DOE) Office of Fossil Energy (FE).

The MLEF program began in 1995 as FE's Minority Education Initiative. In 2000, Bill Richardson, Energy Secretary at the time, designated the program as the Mickey Leland Energy Fellowship to honor the late Congressman saying he "could find no better way to honor his memory than to endow his name on a program that will elevate the opportunities for future generations of minority students."

Today, the MLEF program provides valuable research opportunities for women and under-represented minority students of science, technology, engineering, and mathematics (STEM), allowing them to enhance their academic training with applied laboratory experience that prepares the students to excel in a high-tech workforce, including DOE's research team.

NETL, the research arm of FE, hosts MLEF interns each summer for a 10-week program. This year, 29 students filled the cutting-edge energy laboratories across NETL's three sites in Albany, Oregon; Pittsburgh, Pennsylvania; and Morgantown, West Virginia. Their work included such diverse subjects as optical sensors, electrocatalysts, hybrid power systems, and many other energy-related projects.

A STEM-educated workforce is essential for DOE's continued success in serving the nation. The MLEF program has been contributing to this goal for more than 20 years, with hundreds of interns receiving valuable guidance in cutting-edge facilities from the world's most preeminent energy researchers.

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

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

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## Once in a Lifetime Sky

August 21, 2017 was a memorable and historic occasion for employees at NETL's Albany site as the Lab was in the direct path of the solar eclipse. These photos, taken in front of the B-33 research support building, capture the stunning totality. The eclipse marks another moment in Albany's noteworthy history, joining a rich chronicle of pioneering work in metallurgical research dating back to 1943, to the Lab's current work on materials for advanced high-temperature, corrosion-resistant structural ceramic composites, and metal alloys.

*(Photo courtesy of Ken Williamson, NETL)*