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Revolutionizing Energy Systems

NETLImpact

Vol. 04/ Spring 2018

LABORATORY LOCATIONS
Albany, Oregon
Pittsburgh, Pennsylvania
Morgantown, West Virginia

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

For nearly four years, I have had the honor and pleasure of guiding NETL as it executed a diverse $6.6 billion, 1,400-project research portfolio focused on creating commercially viable solutions to energy and environmental challenges. Our Lab's work is dynamic, incorporating strategic partnerships with research universities and the private sector and on-site research in computational and basic sciences, energy system dynamics, geological and environmental systems, and materials science.

Revolutionizing our energy systems for a more efficient and productive future has been one of the key assignments under that broad portfolio. I hope you will find this issue of *Impact* enlightening and informative as we share our very robust research and development efforts focused on that assignment.

The following pages include articles on sensor technologies developed to increase efficiency at coal plants; progress in the development of supercritical CO_2 power cycles; how NETL uses computational systems to analyze data gathered from sensor technologies; the cybersecurity of the electricity grid, and much more.

In this edition, we are also pleased to provide insights from the new DOE Assistant Secretary for Fossil Energy Steven Winberg.

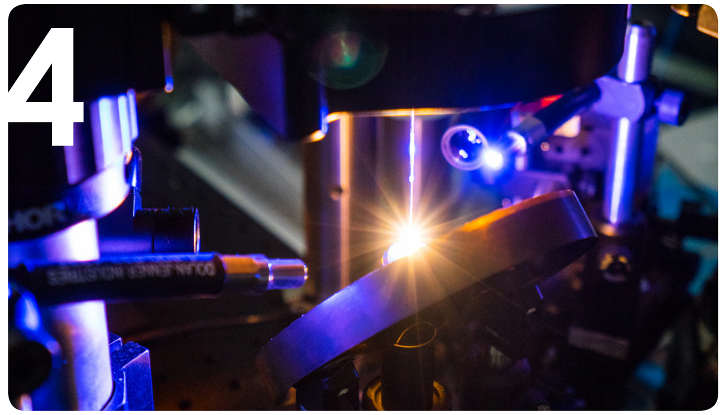
On a personal note, this will be the final edition of *Impact* under my leadership. I will be retiring as director of NETL as this magazine goes to press. I am proud of the advancements that NETL has brought in answer to the energy challenges our nation faces. I'm honored to have worked with so many talented experts, researchers and professionals who shared their expertise and knowledge as we worked to accelerate the nation's energy dominance, prosperity and sustainability. I will fondly remember my time at NETL and now pass the torch to Dr. Sean Plasynski, Executive Director for Technology Development and Integration, who will serve as Acting Laboratory Director effective March 1.

In the meantime, please enjoy the information we have made available to you through this edition of *Impact.*

Grace M. Bochenek, Ph.D.

Director, National Energy Technology Laboratory

IN THIS ISSUE



Improving Efficiencies in Power Systems with Better Sensors

By Gerrill Griffith

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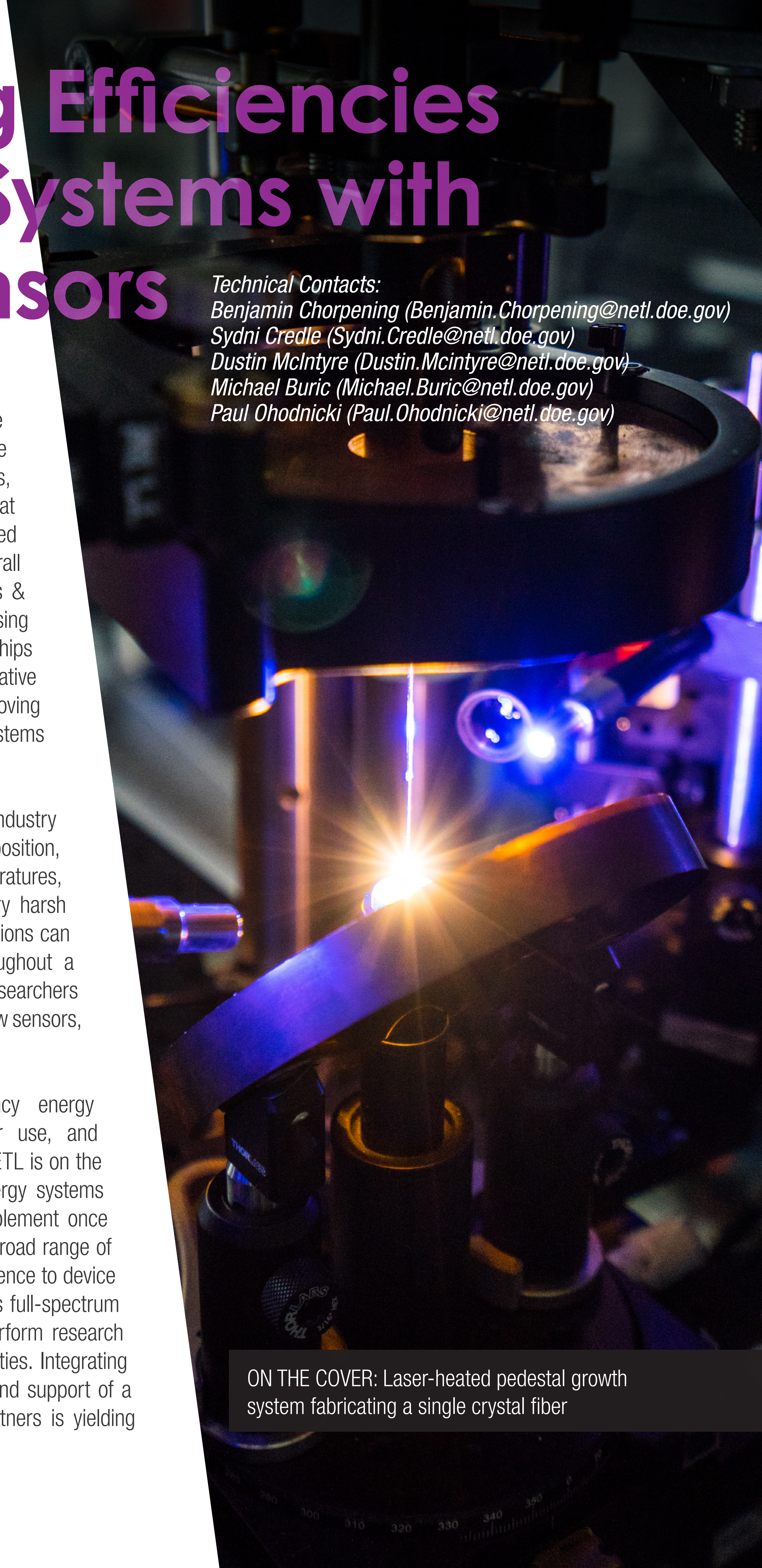
Advanced technologies are needed to create sensors for energy conversion systems, like modular gasifiers, coal-fired boilers, turbines, solid oxide fuel cells, and reciprocating engines that can detect conditions and transmit data needed to make decisions to control and improve overall performance. At NETL, an aggressive sensors & controls (S&C) research program encompassing a robust on-site research effort and partnerships with external researchers is creating innovative approaches and technologies that are improving efficiencies of the nation's power generation systems with improved sensor tools.

Specific sensor needs in the power generation industry include real-time measurement of fuel composition, heat rates, pollutant concentrations, temperatures, pressures, and many other parameters in very harsh environments. In addition, wireless communications can provide benefits for sensor deployment throughout a power plant, including in harsh environments. Researchers are closing in on solutions for development of new sensors, antennae, power sources, and signal detectors.

Sensor research leading to higher-efficiency energy conversion results in lower fuel and water use, and production of fewer pollutants and less CO_2. NETL is on the forefront of sensor development for fossil-energy systems because sensors can be cost effective to implement once they have been developed. NETL supports a broad range of sensing technology development from basic science to device fabrication, testing, and commercialization. This full-spectrum approach leverages government funding to perform research that looks far beyond current industrial capabilities. Integrating NETL on-site research with the engagement and support of a range of external university and industrial partners is yielding solid progress in the field.



ON THE COVER: Laser-heated pedestal growth system fabricating a single crystal fiber

Sensor Research within NETL

A new sensor approach for real-time coalbed methane analysis for combustion: Researchers at NETL are developing a new tool to analyze gaseous fuels by coaxing photons "to do their bidding." Coalbed methane (CBM) can help increase the energy yield and efficiency of regional mining operations, but its unique composition presents challenges. CBM is well suited for local co-generation or pressurization for pipeline sales. But, the composition of CBM can require careful pre-mixing with minimum quantities of other fuels before it can be combusted efficiently in an advanced energy system.

NETL has developed an analyzer system that applies Raman spectroscopy to rapidly determine the concentrations of individual molecular gases in a mixture such as CBM, natural gas or synthesis gas and is shifted in wavelength. Raman is a type of optical phenomena where light, often from a laser, strikes a target and is scattered in all directions. Raman scattering is much like a fingerprint and can indicate molecular structures and discriminate between CO and CO_2 or methane and ethane.

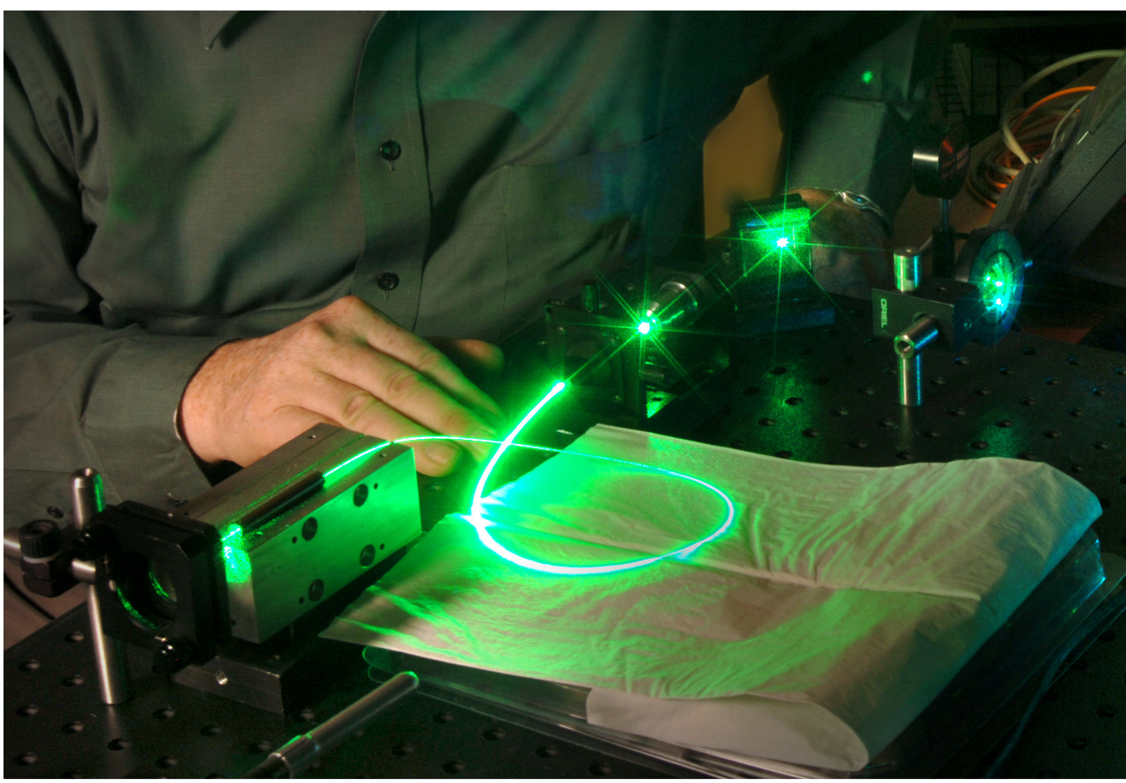
NETL's real-time Raman gas analyzer will help plant operators produce cleaner, more economical energy by providing a fast, low-cost alternative to traditional analyzers like gas chromatographs or mass spectrometers. The Raman gas analyzer is a breakthrough technology for real-time analysis of a process gas and has promise for application in gas turbines and for online analysis of boiler flue gases. This sensor system is currently undergoing extensive field-testing with commercial turbine manufacturers and other end-users of gaseous fuels and is available for immediate licensing.

A split laser system for environmental monitoring: NETL researchers are developing a split laser system for in situ environmental monitoring using laser induced breakdown spectroscopy (LIBS) to provide continuous monitoring of gases, liquids, and solids without prior sample collection or preparation. The innovation features miniaturized, fiber-coupled, optically pumped lasers that are small, portable, low cost, and robust enough for downhole applications in oil and gas production applications.

Environmental monitoring is important in oil and gas exploration for measuring emissions and pollutants. Most technologies, however, are expensive and labor intensive, and require sample collection and preparation that can dramatically alter the sample and its components. The NETL-developed LIBS approach is an atomic emission spectroscopy innovation that provides rapid and simple qualitative and quantitative elemental analysis without the need for sample collection or preparation. In addition, LIBS can be used for measurement of gases, liquids, and solids, making it useful for monitoring air, water, and soil.

Traditionally, most LIBS systems have been large and complex and required stationary, laboratory-scale lasers that were incompatible with monitoring under extreme conditions. NETL researchers designed a hand-sized LIBS system for field use that is capable of measurements in harsh environments. It uses a passively Q-switched laser that provides the same precision timing as conventional lasers but with fewer components. The innovation is useful for a range of work including:

[...Continued on page 6]



An NETL researcher evaluates a photonic crystal optical fiber as a Raman sensor for gaseous materials. The hollow core fiber enables a significant enhancement of the Raman signals from gas phase components, such as the hydrocarbons in natural gas and the hydrogen and carbon monoxide in syngas. Raman sensing also permits measurements of homonuclear diatomics such as hydrogen, nitrogen and oxygen.

- Long-term CO_2 sequestration monitoring.
- Assessment of downhole fluid chemistry before and after hydrofracturing.
- Use in municipal water treatment and filtration systems.
- Monitoring offshore oil and gas discharge/disposal.
- Analyzing pollution/contaminant monitoring and remediation through assessment of ground water and air quality.

Monitoring solid oxide fuel cells (SOFC) with optical fiber sensors: SOFC technology can be used in a range of energy-related activities from clean automobiles to distributed electric power generation systems using an array of gaseous fuels like hydrogen and biogas to achieve high energy conversion with low emissions. However, they are hindered by material and structural degradation that reduces the profitability of large-scale SOFC system deployment. Recognizing the need to observe the temperature distribution inside a fuel cell assembly, NETL researchers partnered with University of Pittsburgh scientists to develop a distributed fiber optic sensing approach to measure the spatial temperature profile of operating SOFC systems that can also have potential for improving measurements in energy applications like combustion systems, boilers, and gas turbines.

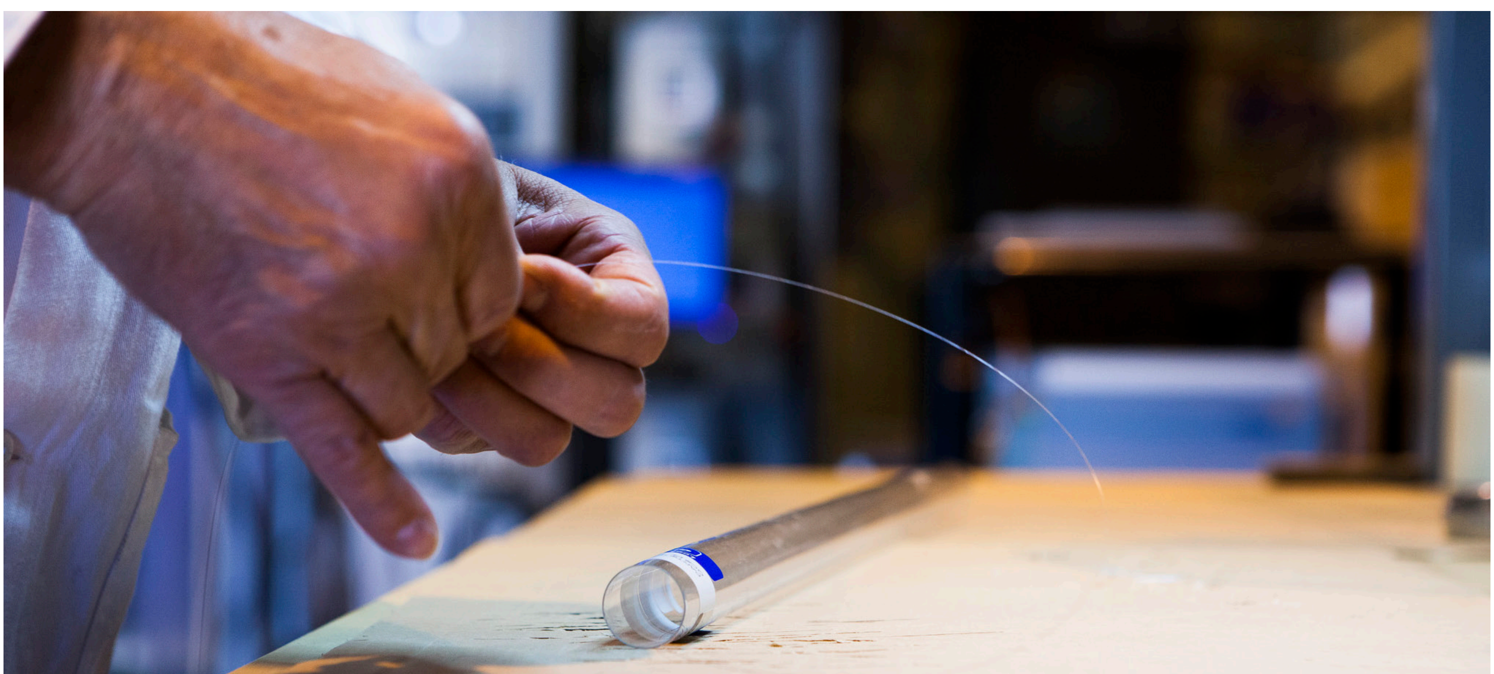
Fiber optic sensing (see related story on *page 24*) is well suited for harsh-environment sensing applications. Sensing schemes like Rayleigh-scattering-based optical frequency domain reflectometry can perform distributed temperature sensing using optical fibers, but it often suffers from weak optical signal intensity. Rayleigh scattering is the scattering of light by particles that are much smaller than the wavelength of the light. The NETL innovation enhances the weak Rayleigh backscattering with laser-processing using an ultrafast laser. The enhanced Rayleigh scattering is stable at elevated temperatures, making it a great technique for harsh-environment sensing. Ultrafast lasers have been used before to fabricate fiber optic point sensors, but the NETL approach identified a simpler technique to produce sensors that can perform continuous temperature sensing with 5-mm spatial resolution in elevated temperature, highly reactive, hydrogen-containing environments. This successful technology development can provide information regarding previously inaccessible temperature gradients in fossil energy systems, which, inturn, can provide better control and improved efficiencies for mitigating emissions, improving safety, and reducing maintenance. When implemented extensively, these new sensor systems will reduce the cost of electricity to the consumer while simultaneously improving environmental emissions.

NETL Support of External Research

In addition to the in-house research efforts, NETL is also supporting a wide range of sensor-related research with industry and other key stakeholders. A new slate of external projects has recently been awarded and is coming online during early 2018. Two specific areas of interest are being pursued through external partnerships.

Condition-Based Monitoring of Coal-Based Power Generation Boilers

NETL-supported **Microbeam Technologies Incorporated** of



An NETL researcher prepares an optical fiber sensor for the Solid Oxide Fuel Cell Test Stand in Morgantown, W.Va.

Grand Forks, N.D., is developing an advanced software tool for coal-fired power plants to actively monitor and manage coal quality and overall boiler conditions that will provide a means to maximize availability and maintain generating capacity while reducing cost. The overall goal of the project is to demonstrate at a full-scale coal-fired power plant the ability to improve boiler performance and reliability through the integrated use of condition-based monitoring that can predict the impact of coal quality on boiler operations.

In another project, NETL is working with **The University of Maine** as its researchers develop, adapt, implement, test, and transition wireless harsh-environment sensor technology for coal-fired power plants. The technology offers several advantages for monitoring coal-based power generation systems including accurate, battery-free, maintenance-free wireless operation. The small footprint of the sensors will potentially allow flexible placement and embedding of multiple sensor-arrays into a variety of components that can be sampled with a nearby interrogating antenna and radio frequency signal processing unit.

In Morgantown, W.Va., NETL is supporting **West Virginia University's** (WVU) work to validate the effectiveness of electrochemical high-temperature corrosion sensors in coal-based power-generation boilers, optimize high-temperature sensors, and develop a pathway toward commercialization of the system. Successful completion of the project will result in an optimized corrosion sensor suitable for industrial-scale applications. The technology will enable operators to more reasonably schedule downtime for maintenance activities and be proactive regarding high-temperature corrosion failure maintenance through condition-based monitoring. The technology also will have applications to other high-temperature environments that would benefit from in-situ corrosion monitoring.

Improvements to Coal Combustion Power Plants (ImPOWER)

NETL is working with **Opto-Knowledge System Inc.** of Torrance, Calif., to produce and demonstrate a continuous sulfur trioxide (SO_3) monitor for coal-fired power plants. The project is intended to show how a sensor can provide continuous, accurate measurements of SO_3; which allows better control of the alkali-injection systems that are used to mitigate SO_3 emission.

In another project, NETL is supporting **SparkCognition** of Austin, Texas, to optimize the sensor inputs needed for fault detection, understand the impacts of control decisions due to flexible operations, and extend the life of critical equipment through data analytics. SparkCognition is analyzing existing sensor and operational data collected at coal-fired power plants with machine-learning algorithms to detect and diagnose premature equipment failure in coal-fired power plants. The project represents a unique area for machine learning because SparkCognition will use artificial intelligence techniques specifically designed for operating on large data sets to identify obscure patterns of degradation in vast amounts of information. Transient states (startups, shutdowns, load-following, and equipment switching) are the most critical operations in coal-fired operations, and providing the ability to capture information and make a diagnosis during these transients is crucial to assessing the health of coal-fired assets.

At the **University of Utah** in Salt Lake City, Utah, NETL is supporting research to advance the technology readiness level of a novel ultrasound method for the real-time measurement of temperature profiles in different combustion zones and components of utility boilers. A prototype multipoint measurement system will be developed and validated in a power plant. The technology will present an economic and scalable option to optimize the efficiency of current and future fossil power systems.

Once successfully developed and commercialized, the technology will be used to measure temperature profiles in different combustion zones and components of utility boilers with higher accuracy measurements (1-10 degrees Celsius) and sampling rates (100 Hz). It will also enable lower uncertainty than IR and acoustic pyrometry measurements, robust continuous availability, scalability to multiple measurement locations, and lower costs by multiplexing instrumentation across measurement locations.

At **WVU**, NETL is supporting researchers as they investigate the feasibility and sensitivity of a new sensor design to detect target gases at high temperatures, and integrate and test the basic components of the proposed sensor in a commercial power plant. The resulting data will allow plant operators to become more knowledgeable about combustion conditions and lead to better process-control.

Conclusion

Technical challenges must be overcome before embedded sensing technology in modular gasifiers, fuel conversion reactors, combustion systems, and other advanced energy conversion systems can be realized. High-temperature operational environments make sensor stability and successful embedding of sensors difficult. In some cases, the technology for sensing desired parameters under operational conditions of interest does not yet exist. NETL's integrated approach to tackling the challenges of developing efficient and cost-effective sensor technology for energy systems is making progress and incorporating the best thinking of a wide range of federal, academic, and private industry researchers. This program will continue to develop new, viable technologies to the fossil-energy sector and provide new fundamental device information and techniques for a wide range of other challenging applications. ☰

NETL Developing Online Simulations to Find Ways to Avoid Degradation Effects of Power Plant Cycling

By Gerrill Griffith // Technical Contacts: David Tucker (David.Tucker@netl.doe.gov) and Paolo Pezzini (Paolo.Pezzini@netl.doe.gov)

The penetration of renewable resources into today's electric grid promises opportunities for sustainable power, but such opportunities come with challenges. Specifically, the intermittent nature of renewable resources puts an ever-increasing strain on existing power plants that are often required to cycle from minimum to full load every day, or shut down and start up daily. This, in turn, accelerates the degradation of existing plants, causing rising operations and maintenance expenditures for plant operators.

NETL researchers are working in a one-of-a-kind facility to build computer transfer function models so that plant disruptions or step changes are no longer required – innovation that can help increase efficiencies and reduce costs at existing power plants as additional renewable resources come online.

The resulting computer models simulate conditions in power plants to monitor fuel and air mixtures that affect degradation. As components degrade, the gains applied to proportional-integral-derivative (PID) controllers in power plants become obsolete, causing instabilities that result in imbalances in the fuel-to-air ratio of the combustors and other system actuators. Ultimately, efficiency decreases and emissions increase.

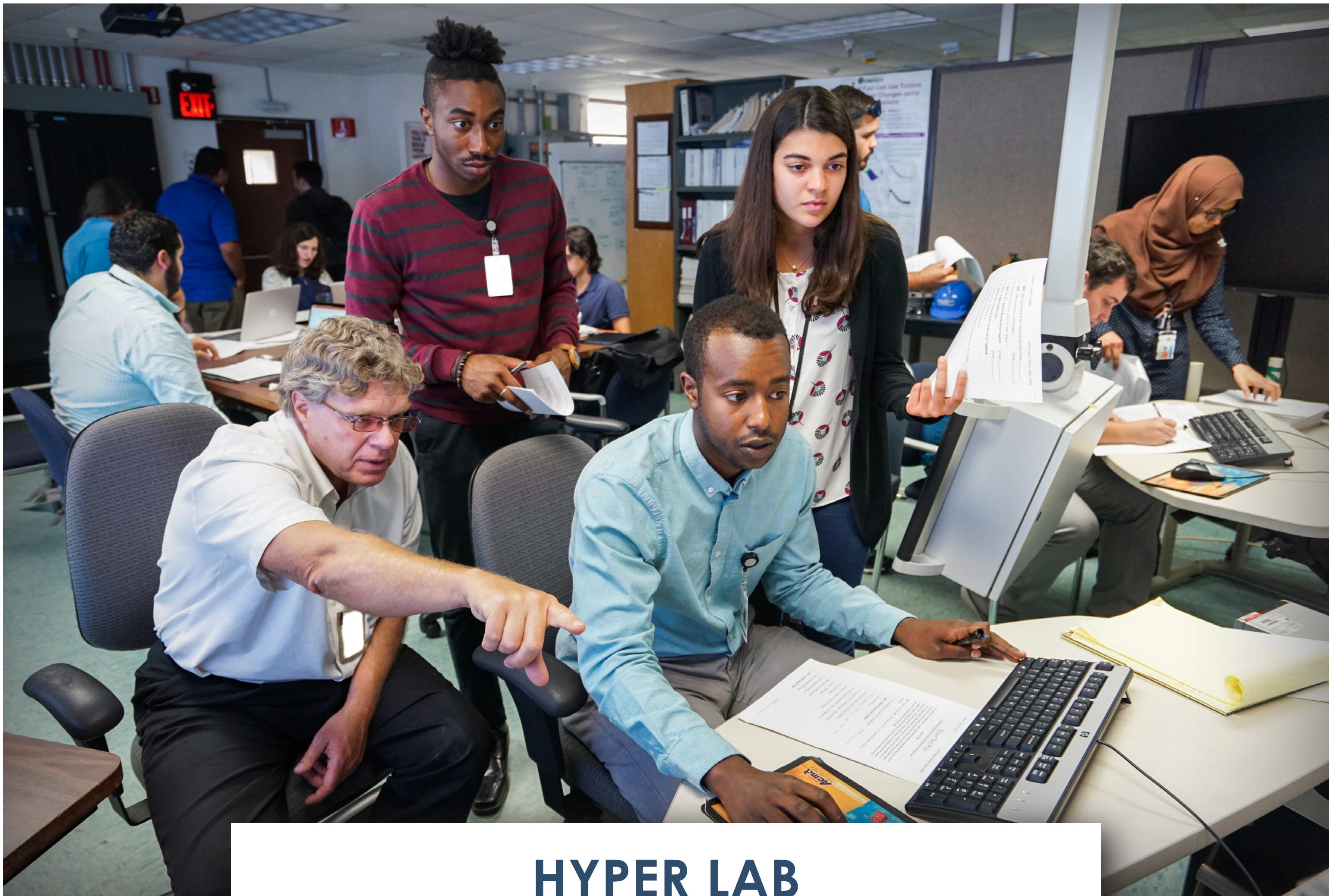
The transfer function models used to design PID controller gains normally require a series of step changes in the power plant that puts equipment at risk and requires some disruption of output. NETL experts are developing a method to build transfer function models online without requiring plant disruptions or step changes. The work requires use of the Laboratory's state-of-the-art Hybrid Performance, or Hyper, testing facility.

If successful, this online system identification method can enable real-time tuning of controller design and provide a mechanism to continuously evaluate the extent of component degradation. The critical parameters (poles and zeros) of the transfer functions resulting from online system identification move on a root locus diagram as the system degrades, and this movement can be used to quantify the degradation. If the poles and zeros move by more than 20 percent or so, robust control can no longer maintain performance, and the gains must be re-tuned.

Online system identification is currently theoretical, but by using the Hyper facility as a power generation system that is not available in academia, it can be developed and tested for application to existing power plants.

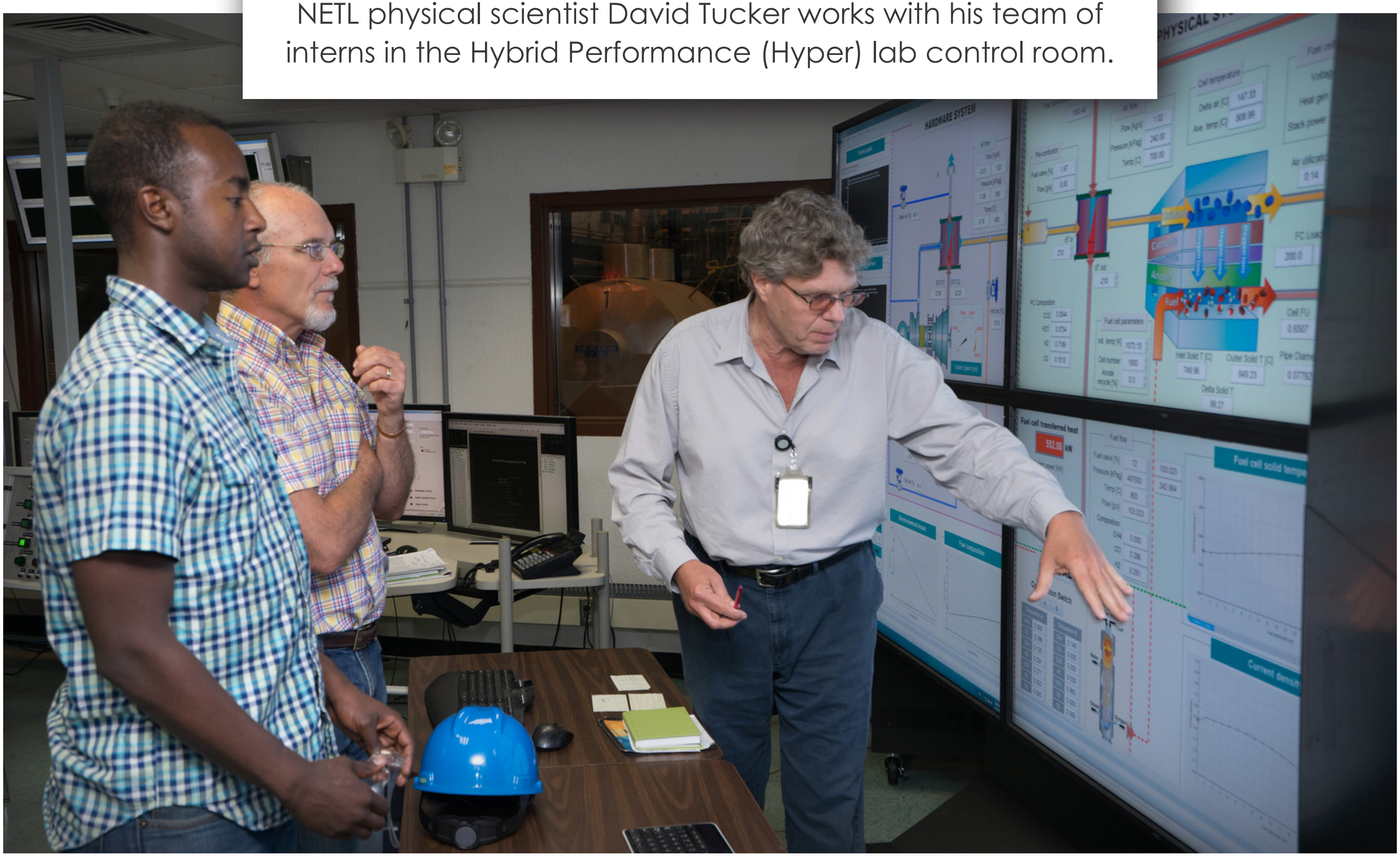
The NETL Hyper facility is designed to explore advanced control concepts safely, mitigating risk to industry power plants. The advanced control logic could be exported to existing power plants, and load following could be enabled without impacting efficiency.

The 250-kilowatt Hyper test unit was constructed to develop control strategies for the reliable operation of advanced power systems of the future and enable the simulation, design, and implementation of commercial equipment. The Hyper facility provides a unique opportunity for researchers to explore issues related to energy conversion technology.



HYPER LAB

NETL physical scientist David Tucker works with his team of interns in the Hybrid Performance (Hyper) lab control room.



MATERIALS BREAKTHROUGHS to Increase Efficiency at Coal Plants

By Jenny Bowman

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Big Bend Power Station, a major coal-fired power plant, located near Tampa, Fla.
Photo: Wknight94, via Wikimedia Commons

Technologies that convert the energy in fossil fuel resources to create heat, power, and chemical products must become more efficient to operate economically and meet increasingly stringent environmental requirements. NETL research is answering the call with innovative energy conversion technologies developed through an aggressive combination of internal research and resource-leveraging activity that takes advantage of the skills and talents in sister National Laboratories and the private sector.

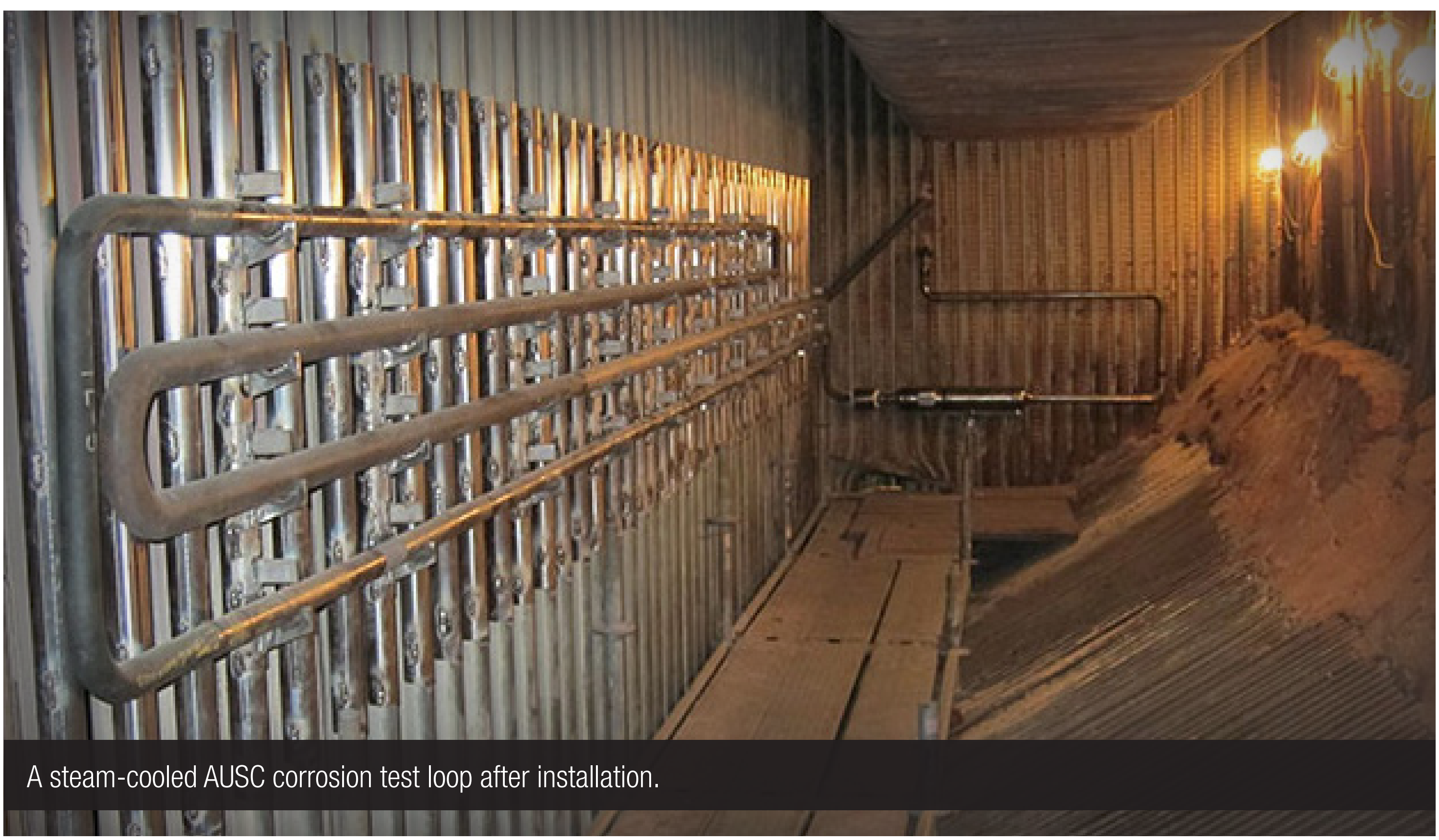
One area of research that is enabling the development of more efficient fossil energy technologies is advanced materials that can withstand the harsh environments that are a part of higher efficiency energy systems.

The heat engine thermodynamic cycles used for fossil energy conversion are most efficient when heat is added at high temperatures and rejected at low temperatures. Therefore, many opportunities for greater efficiency depend on developing structural materials that can operate under extreme temperature, pressure, and chemical environments. Interactions between structural materials and operational fluids as well as material and joint durability must be examined in new applications that feature new alloys, ceramics, and mixed materials. In addition, because extreme materials must operate for years, long-term performance must be reliably predicted using short-term tests combined with detailed models that predict long-term fatigue, creep, oxidation, and corrosion behavior.

EFFECTIVE COLLABORATION PRODUCES IMPROVED MATERIALS FOR HIGHER EFFICIENCES

A significant population of the existing U.S. coal-powered fleet relies on subcritical boilers that operate with steam pressure of 2,400 psi and main steam temperature of up to 538 degrees Celsius – technology that was considered cutting-edge in the 1950s. In the 1960s, “supercritical” plants ushered in a new era of efficiencies capable of operating at 3,500 psi and up to 565 degrees Celsius. In the 1990s the next increase in coal-fired power plant efficiency was achieved by increasing steam temperature to 610 degrees Celsius. Today’s energy and environmental concerns demand even greater efficiencies, and therefore, higher temperatures. Advanced ultrasupercritical (AUSC) plants, with steam temperatures up to 760 degrees Celsius, promise to increase the efficiency of coal-fired boilers from an average of 32 percent (current domestic fleet) to 45 percent (on a higher heating value basis). That means more power with less fuel and fewer emissions at competitive rates. The catch: AUSC power plants will require advanced materials to accommodate higher temperature operation.

NETL laid a foundation of success to tackle this challenge and joined forces in 2000 with the Energy Industries of Ohio, the Electric Power Research Institute (EPRI), and industry partners to form the Advanced Ultrasupercritical Boiler Consortium. The consortium leveraged a wide array of skill sets to identify, evaluate, and qualify the materials needed to create critical components for


A steam-cooled AUSC corrosion test loop after installation.

the coal-fired boilers that could produce the next generation of AUSC power plants.

The team undertook research that addressed eight challenging technical topics associated with material improvements: conceptual design and economic analysis, mechanical properties, steam-side oxidation and resistance, fireside corrosion, weldability, fabricability, coatings, and alterations to existing power plant boiler and piping design codes. For each task, a consortium lead was assigned, and research was generally conducted by multiple organizations, which took advantage of unique expertise and ensured an optimal sharing of work and results among consortium members. The consortium achieved its goals by 2015 by demonstrating that two relatively new nickel superalloys, Inconel 740H (developed by Special Metals, Inc.) and Haynes 282 (developed by Haynes International), were well-suited for used in AUSC power plants.

The nickel superalloy Inconel 740H is an age-hardenable, precipitation-strengthened alloy, and is now approved by the ASME for use in coal-fired boilers, unfired pressure vessels, and pressure piping up to 800 degrees Celsius. Ongoing development continues to increase the maximum allowable use temperatures of Inconel 740H to 825 degrees Celsius.

The nickel superalloy Haynes H282, is also an age-hardenable, precipitation-strengthened alloy that was first tested and selected for use in AUSC steam turbine components and valves. These tests also showed that it could be a very good choice for AUSC steam piping. Later, corrosion tests in an actual coal-fired boiler showed that H282 might also be a good candidate for AUSC boiler superheater tubing in low corrosivity coal combustion environments. As a result, NETL is partnering with Oak Ridge National Laboratory and Haynes International to obtain approval from ASME for H282 to be used in power plant boiler tubing and piping. The project is completing base metal and cross-weld creep and tensile testing needed for an ASME Boiler and Pressure Vessel Code Case, along with microstructural analyses needed to develop accurate creep behavior models of the alloy at boiler-relevant lifetimes. Lab work includes tensile and creep testing of the base metal and cross welds in the temperature range of 593-927 degrees Celsius.

NETL'S MATERIALS EXPERTISE DELIVERS DURABLE NEW ALLOY

In addition to its considerable success in partnering with industry and sister National Laboratories on research and development addressing improved materials for more efficient energy systems, NETL has conducted research in its own labs that resulted in another breakthrough success known as CPJ-7 – an improved heat-resistant ferritic nine-chromium (Fe-9Cr) steel for advanced power plant applications.

NETL research materials engineer Jeffrey Hawk conducts materials characterization experiments at NETL's Creep Laboratory.

Ferritic/martensitic chromium steels form the backbone of current steam delivery systems because they are less expensive to produce and can be recycled. NETL's CPJ-7 is a new Fe-9Cr with superior performance under high-temperature conditions. The innovation has promise for use in applications like advanced boilers, turbines, and other advanced energy systems that require materials with high-temperature creep strength, corrosion resistance, and thermal fatigue resistance.

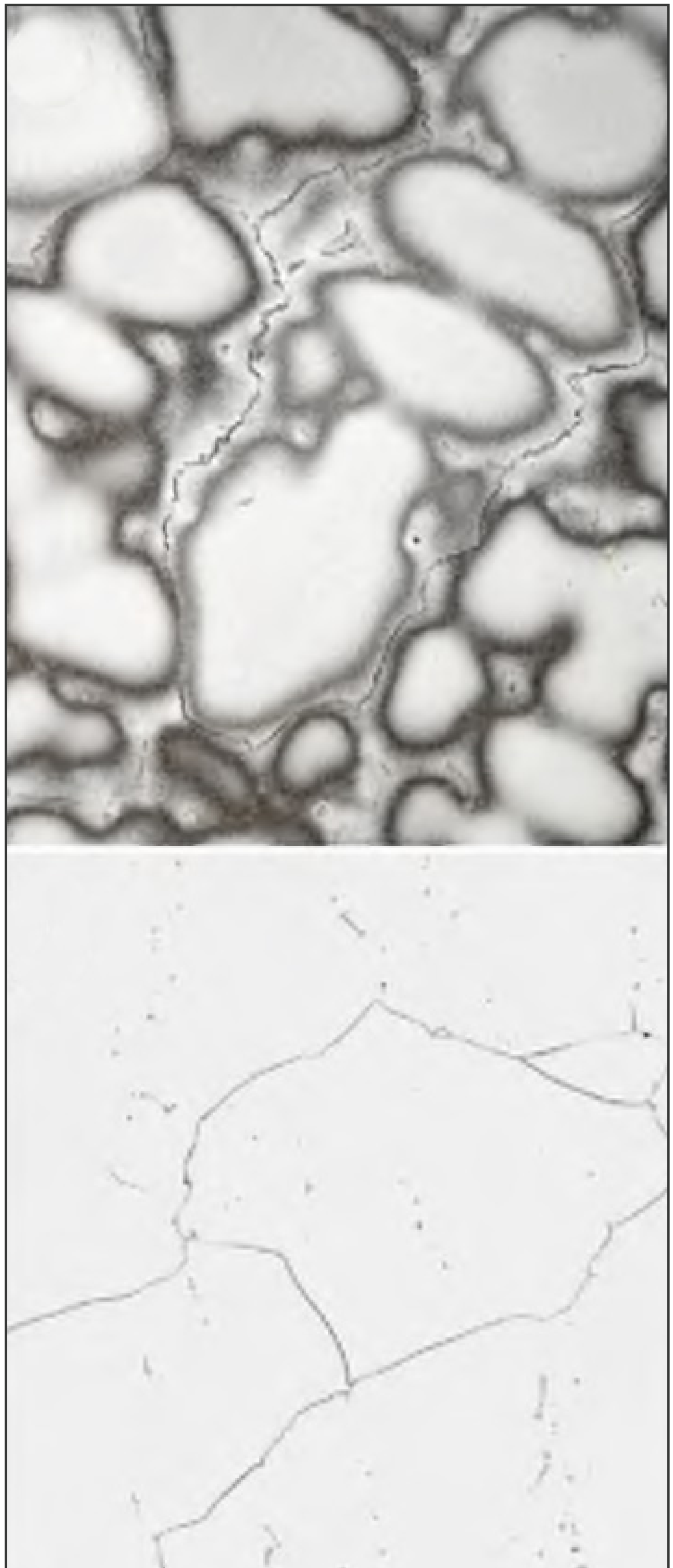
During mechanical testing, CPJ-7 demonstrated creep life that was more than twice that of commercially available martensitic steels. The alloy also displayed more consistent and superior mechanical properties at temperatures up to 650 degrees Celsius.

In developing the alloy, NETL researchers relied on the Lab's world-class facilities to build upon traditional alloy design and to incorporate computational strategies. NETL's Mechanical Testing Laboratory enabled researchers to determine the mechanical behavior and performance of advanced materials under temperatures and pressures common in operational fossil energy systems. The lab's equipment allows technicians to test a material's ability to withstand cyclical mechanical loads for many cycles and evaluate detected crack growth behavior at temperatures up to 1,000 degrees Celsius. The facility also has equipment for testing a material's compressive and tensile strength, as well as instrumentation for impact and hot-hardness evaluation.

In NETL's separate Creep Laboratory, researchers evaluate creep strength at both ambient and operating temperatures. Creep-resistant martensitic steels, like the CPJ-7, are tested at temperatures up to 650 degrees Celsius. Typical tests last several thousand hours, with some alloys undergoing up to 25,000 of testing.

CPJ-7 is expected to significantly extend the functional lifespan of selected components in advanced high-temperature power plants, including coal-fired boilers, steam and gas turbines, and piping. The technology is currently available for licensing and/or further collaboration through NETL's Technology Transfer Program.

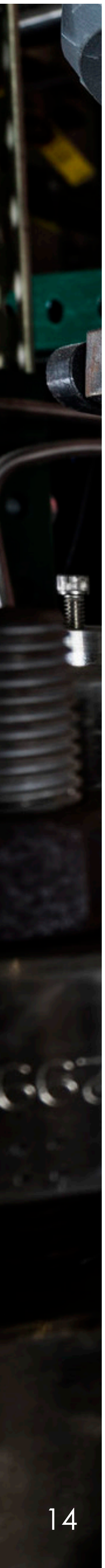
NETL's broad portfolio of internal and extramural research projects are far-reaching, developing cost-effective structural and functional materials that will enable the commercialization of new materials for fossil energy applications in extreme operating environments. Breakthroughs in these materials research endeavors will enable increased efficiency from home-grown energy resources, bolstering America's energy dominance with responsible stewardship of the environment. ≡



Microstructure of Haynes 282 alloy as-cast (top) and homogenized (bottom).

INCREASING TURBINE EFFICIENCY THROUGH PRESSURE GAIN COMBUSTION

By Jenny Bowman // Technical Contact: Don Ferguson (Donald.Ferguson@netl.doe.gov)



NETL research helped create next-generation turbine technologies that ensure the nation's growing demand for energy will always be met by the ability to produce reliable, affordable, diverse, and environmentally friendly energy supplies. As part of that effort, NETL is innovating technologies based on different forms of combustion. Pressure gain combustion is one of those technologies, and it offers a pathway for transformational improvements in fuel efficiency for simple cycle and combined cycle gas turbines.

The conventional approach for efficiency gains in gas turbine engines is to increase the gas temperature at the turbine inlet; however, material limitations ultimately restrict how hot the turbine can operate. Another approach is to increase the pressure at the turbine inlet, but any increase in pressure at the turbine causes additional work by the compressor.

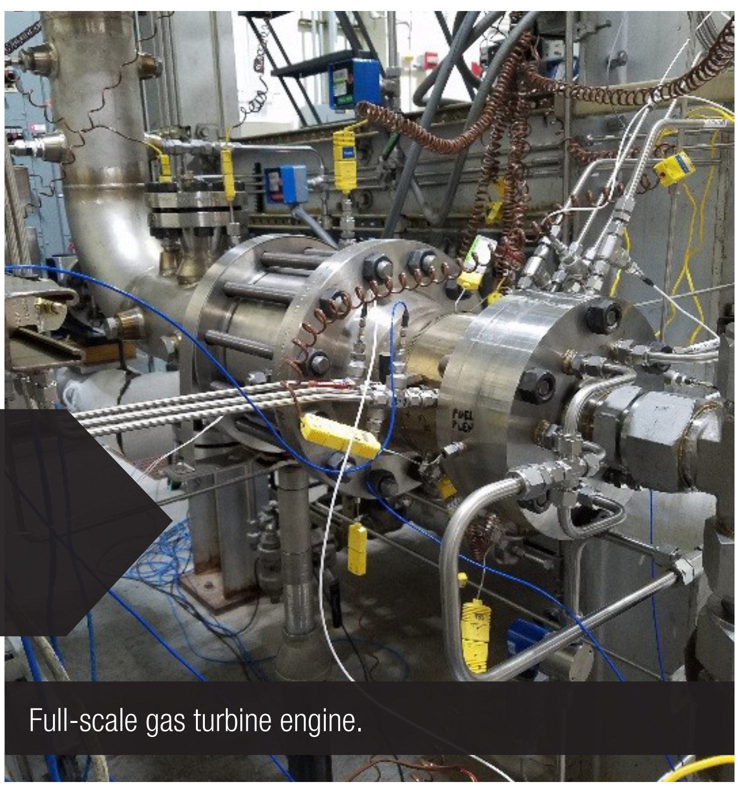
Gas turbines rely on a combustion mode known as constant pressure deflagration, in which fuel (such as natural gas or coal syngas) mixes with air in a can-style combustor burning at subsonic speeds and at a constant pressure. Any increase in pressure at the turbine inlet must come from additional work by the compressor. An alternative form of combustion – constant volume detonation – produces a coupled supersonic combustion and shock wave that compresses the flow, producing a gain in pressure without requiring any additional work from the compressor. The increase in pressure achieved by the detonation wave would be available to the turbine to produce additional work.

NETL's High Pressure Combustion Facility provides the test capabilities needed to evaluate new combustion concepts for high-pressure, high-temperature hydrogen and natural gas turbines. These concepts will be critical for the next generation of ultra-clean, ultra-efficient power systems.

Rotating detonation combustion can be achieved in a rotating detonation engine (RDE) in which a detonation wave continuously revolves around the circumference of an annular combustor. Because of the fast wave speed, detonations occur at high frequencies (thousands of times per second) resulting in a nearly steady flow at the turbine inlet, which helps to maintain efficiency. Conceptualized in the 1950s, RDEs have seen a recent uptake in both experimental and computational studies within the last five to seven years. However, many of these studies have focused on very fundamental aspects of RDE operation.

To advance to a more applied technology, NETL has adapted its unique high-pressure combustion rig to study an RDE combustor. Working with the Air Force Research Laboratory (AFRL), NETL installed and is now testing an RDE at pressures above atmospheric. While testing at elevated pressures is not unique, NETL's enclosed system with ducted exhaust is a more realistic representation of real gas turbine-like operation compared with other facilities currently operating in the United States.

In addition to the full-scale RDE test rig, NETL has smaller rigs that utilize advance manufactured parts to study fundamental aspects of the RDE, including inlet/injector performance and operation on natural gas. The inlet/injector remain a challenge for advancing the technology as the injector needs to address two directly opposed forces. Due to the pressure gain that occurs inside the combustor the inlet/injector must restrict the upstream migration of flow while at the same time limit pressure loss due to inlet restrictions. A combination of computational fluid dynamic (CFD) modeling and abstract, bench-scale experimental rigs are being used to study inlet/injector behavior. Progress in these areas is enhanced by using rapidly produced 3D printed parts allowing researchers to go directly from CFD models to part production and subsequently testing. Complex fluid mechanics and a variety of shockwaves occur in the RDE inlet. Additionally, the rapid motion of the pressure wave (shock) creates an instantaneous, low-pressure region that permits reacted gases to backflow into the inlet ("combustion product backflow"). This translates into inconsistencies of the fuel-air mixture going into the combustion annulus resulting in less stable combustion.



Full-scale gas turbine engine.

Experimental and computational efforts in the bench-scale inlet test rig support the lab-scale RDE combustor that NETL researchers are testing at the Lab's Morgantown, W.Va., facility. The 6-inch lab-scale RDE system was made possible through NETL's collaboration with the AFRL and includes a ducted exhaust that permits variable back-pressure control and operation at elevated pressures akin to a full-scale gas turbine engine. To date, NETL's RDE has operated on hydrogen-air and hydrogen-natural gas-air with a focus on operating on both 100 percent natural gas-air as well as coal-derived syngas. Studies in the NETL rig have focused on understanding detonation wave stability within a realistic RDE annular combustor.

A water-cooled RDE combustor is also being installed in NETL's High Pressure Combustion Facility, which has been limited to short duration tests due to the elevated temperatures associated with detonation.

Beyond the Lab's in-house efforts, NETL researchers have collaborated with AFRL to evaluate performance of a turbine when placed downstream of an RDE, duplicating conditions in an actual gas turbine engine.

"Our research partners at AFRL conducted these tests from 2016 to 2017 using an Allison Model 250 (T63) turbine directly coupled to an RDE and with the compressor flow bypassed around the RDE and turbine," Don Ferguson, Ph.D., of NETL's Thermal Sciences team explained. "The tests demonstrated little to no impact on turbine performance. In 2018, we plan to repeat the tests with the RDE fully integrated into the engine."

In addition to funding NETL's pressure gain combustion research activities and the coal-fired RDE study at the University of Central Florida, NETL's Advanced Combustion Program provides funding through the University Turbine Systems Research Program to support studies at the University of Michigan, University of Purdue and Penn State University. NETL's Advanced Turbine Program currently supports a six-year study (2014-2019) at Aerojet-Rocketdyne to explore the potential of RDEs for combustion in a high-efficient gas turbine engine. ≡

Supercritical CO_2: Tackling Challenges to Boost Turbine Efficiency

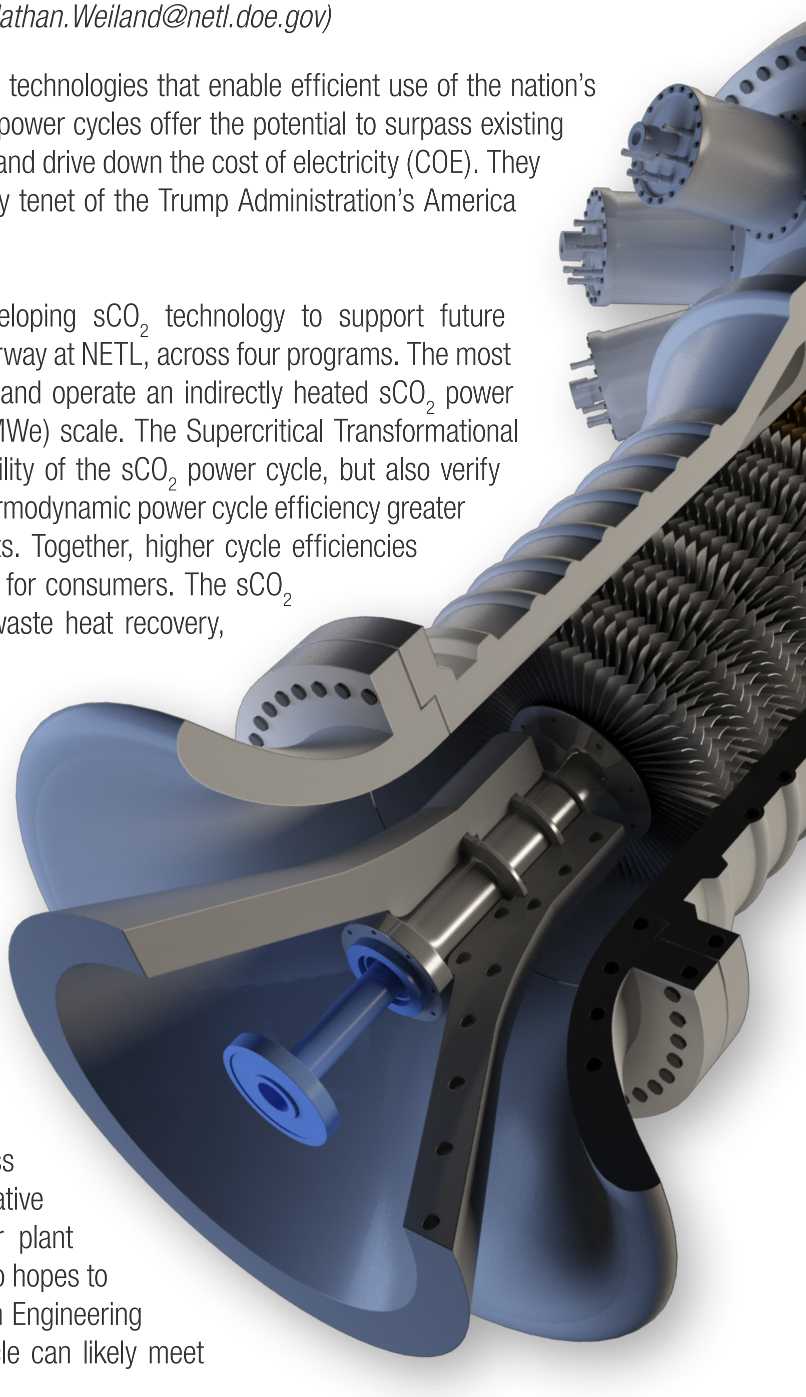
By Cassie Shaner

Technical Contacts: Richard Dennis (Richard.Dennis@netl.doe.gov), Robin Ames (Robin.Ames@netl.doe.gov), Peter Strakey (Peter.Strakey@netl.doe.gov) and Nathan Weiland (Nathan.Weiland@netl.doe.gov)

America's continued energy dominance depends on developing technologies that enable efficient use of the nation's vast fossil fuel resources. Supercritical carbon dioxide (sCO_2) power cycles offer the potential to surpass existing efficiency standards, set new benchmarks for optimal performance and drive down the cost of electricity (COE). They also offer a new opportunity to rejuvenate the coal industry – a key tenet of the Trump Administration's America First Energy Plan – by using coal more efficiently.

NETL researchers are working to achieve these goals by developing sCO_2 technology to support future commercialization. A total of 20 sCO_2 power cycle projects are underway at NETL, across four programs. The most ambitious of NETL's sCO_2 research projects aims to design, build and operate an indirectly heated sCO_2 power cycle pilot plant at a nominal 10 megawatts of electrical output (MWe) scale. The Supercritical Transformational Electric Power (STEP) pilot plant will not only demonstrate operability of the sCO_2 power cycle, but also verify performance of the cycle components and show the potential for thermodynamic power cycle efficiency greater than 50 percent, along with a potential to reduce equipment costs. Together, higher cycle efficiencies and lower capital equipment costs will translate to a reduced COE for consumers. The sCO_2 cycle generates excitement because it also has applications for waste heat recovery, nuclear power generation and concentrated solar power. Having broad applications is a key feature of this technology, supporting commercialization.

"The STEP plant serves as a key opportunity to demonstrate the operability of sCO_2 power cycles," said Robin Ames, federal project manager for NETL. "Our primary intent is to demonstrate that the cycle is operable with the potential to reach the performance and efficiency targets that we've set."



Those targets support DOE efforts to boost efficiency, cut COE and limit CO_2 emissions for power plants nationwide. The U.S. Environmental Protection Agency's carbon pollution standard for new coal-fired power plants is 1,400 pounds of CO_2 per gross megawatt hour, with or without carbon capture technology. Tentative DOE goals call for non-capture systems to boost overall power plant efficiency to 45 percent by 2025 and 52 percent by 2030. DOE also hopes to drive down the COE for coal-based power by 2030. NETL's System Engineering and Analysis team has shown that the indirectly heated sCO_2 cycle can likely meet these goals and emit CO_2 below the 1,400-pound threshold.

INCREASING EFFICIENCY

Supercritical CO_2 is carbon dioxide that exceeds its critical temperature (31.1 degrees Celsius) and pressure (1,071 pounds per square inch), retaining properties of both a gas and a liquid. Its unique physical properties make sCO_2 a useful working fluid in advanced combustion and gasification power systems – using indirect and direct heat, respectively. Thermodynamic power is generated by compressing and heating a working fluid – steam in most coal boiler systems – before it enters a turbine, where it produces energy. After the fluid exits the turbine, it's cooled to be recirculated for continued power production.

An indirectly heated recompression Brayton cycle using sCO_2 employs two compressors and two recuperators for better performance. Because of its unique physical properties, sCO_2 is easily compressed without added heat, making the compression portion of the power cycle more efficient. The recuperators remove excess heat after the sCO_2 leaves the turbine at high temperatures, cooling the fluid and transferring heat to where it's needed on the high-pressure side of the cycle.

Richard Dennis, technology manager for NETL's Supercritical CO_2 Power Cycles Program, said the indirect cycle shows potential for outstanding performance in a coal-fired boiler system without employing carbon capture technology. "Because the cycle is so efficient, you can significantly minimize the emissions of CO_2, which is a good thing," he said.

Nathan Weiland, of NETL's System Engineering and Analysis team, noted that accurately measuring and evaluating efficiency extends beyond sCO_2 power cycles alone. "A lot of emphasis is placed on cycle efficiency, but in our case, we're looking more at plant efficiency, including boiler efficiency and power output versus fuel energy input," he said. "We work on trying to get to a sweet spot in maximizing plant efficiency, which is a large driver in reducing the cost of electricity. That's ultimately what the utility cares about."

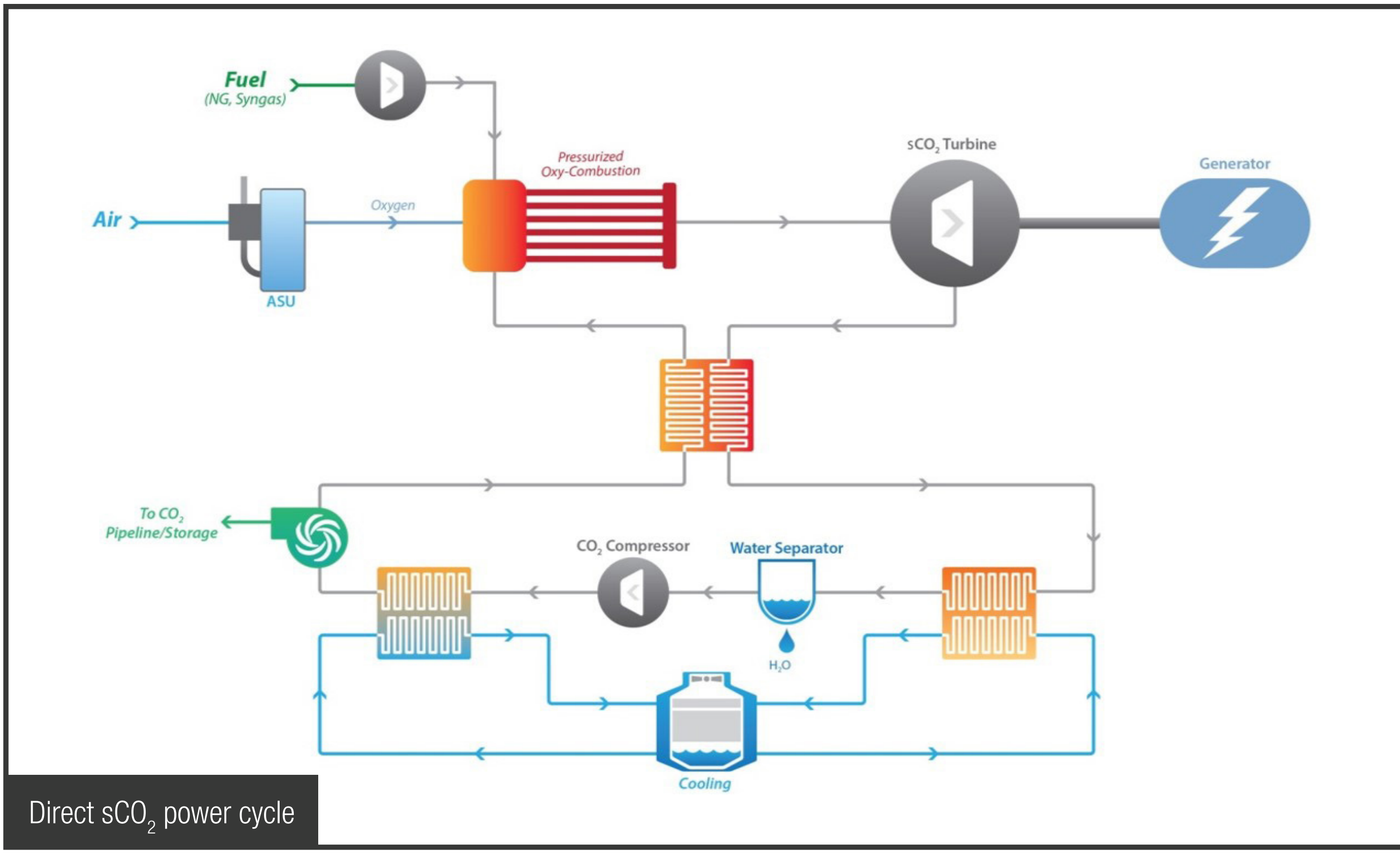
Directly heated sCO_2 power cycles use a special type of combustion, known as oxycombustion, to achieve higher pressures and temperatures that boost efficiency and facilitate CO_2 capture. Oxycombustion uses oxygen instead of ambient air to combust fuel, directly generating sCO_2 to produce thermal energy.

NETL research has shown that using directly fired supercritical CO_2 power cycles in combustion-based systems is one of the most effective methods of power production with carbon capture, outperforming existing integrated gasification combined cycle systems that convert coal into pressurized syngas. Researchers are also studying the use of directly fired sCO_2 power cycles in natural gas systems, which shows great promise.

CONQUERING CHALLENGES

Research shows that sCO_2 power cycles offer the potential for net thermal efficiencies greater than 50 percent, but there are challenges to achieving higher cycle efficiencies. Identifying those obstacles and finding ways to conquer them is critical as NETL and its partners work toward commercialization.

[...Continued on page 18]



Direct sCO_2 power cycle

One of the keys to achieving greater efficiencies is temperature. Research shows that sCO_2 is more efficient in an indirect cycle when it enters the turbine at 760 degrees Celsius versus a turbine inlet temperature of 620 degrees Celsius. But the ability to reach higher temperatures in an indirect cycle is limited by existing equipment, because boiler tubes rapidly degrade when heated beyond their mechanical limit. Manufacturing boiler tubes that can withstand the higher temperatures at high pressure drives up system costs and, ultimately, the COE. "Higher temperatures boost efficiency, but at a cost penalty," Dennis said. As a result, researchers have kept temperatures lower to study sCO_2 performance using more conventional materials. Optimizing performance at a lower temperature helps to inform future scale-ups and efforts to achieve higher temperatures.

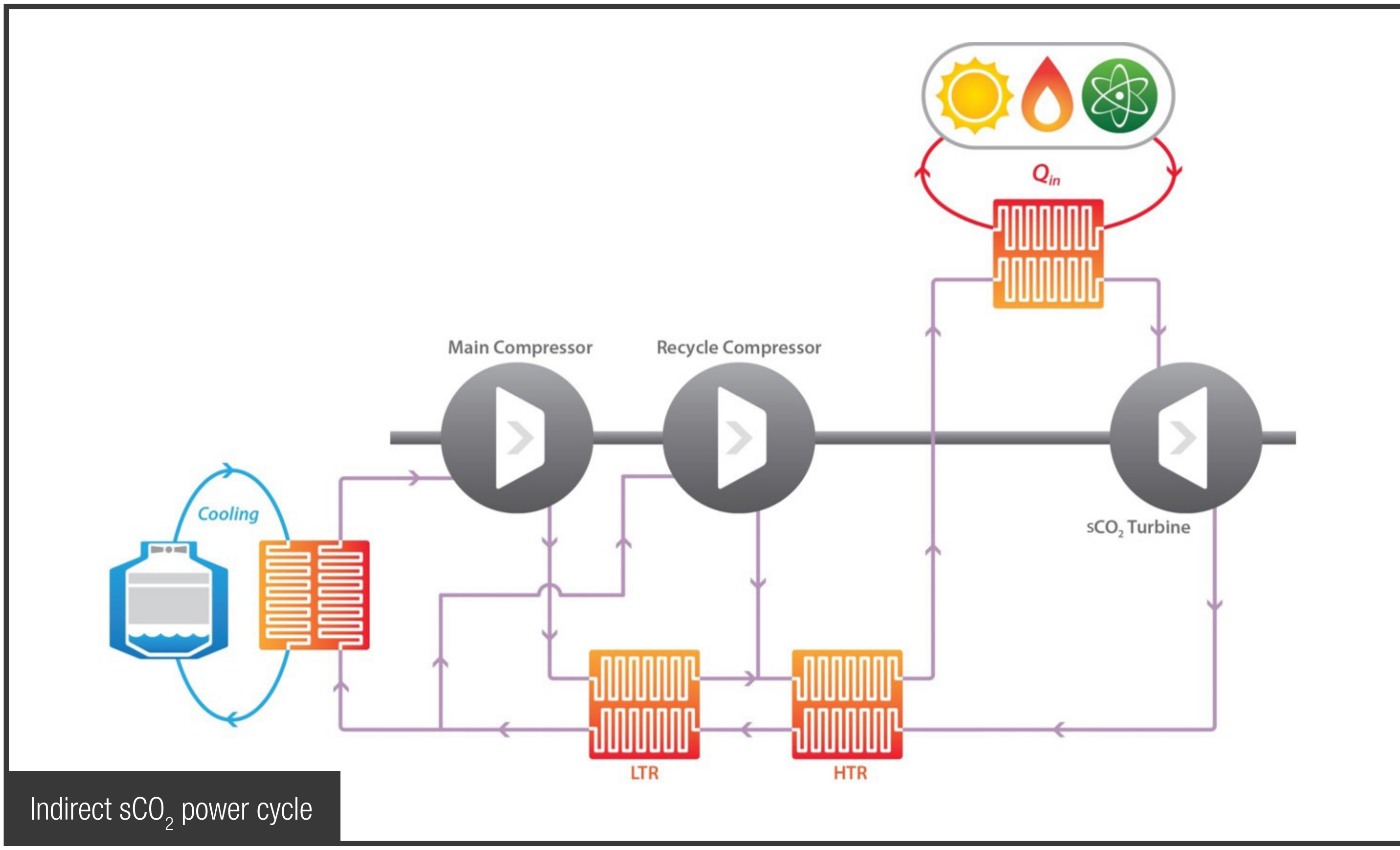
The density of sCO_2 and operating conditions for the cycle also allow for smaller-scale turbomachinery, which will eventually help to reduce capital costs as the technology moves toward commercialization. Weiland said coal-fired boiler plants using indirectly fired sCO_2 cycles can be cost-competitive with existing steam-cycle plants at 2 to 5 percent higher plant efficiency, and that cost is likely to drop as research continues.

Another obstacle is the limited window for adding primary heat when using a highly recuperated indirect heat cycle for sCO_2. Capturing and reusing all the low-grade heat produced by the power cycle is essential to achieve higher temperatures for added efficiency. To conquer that challenge, researchers are exploring alternative cycle configurations for effectively adding heat and comparing performance to achieve the greatest efficiency. Weiland noted that efficient cycle design varies for fossil, solar and nuclear energy systems, which all offer useful applications for sCO_2 power cycles.

With carbon capture, directly heated sCO_2 power cycles offer the possibility of thermal efficiencies near 60 percent, because they can achieve higher temperatures relative to indirect sCO_2 cycles – up to about 1,200 degrees Celsius as sCO_2 enters the turbine. However, existing recuperators can only handle turbine exhaust temperatures of 700-800 degrees Celsius. NETL's Advanced Combustion Systems team is working to develop enhanced recuperators that can accommodate higher temperatures, while balancing cost with efficiency.

Oxycombustion is new territory with limited data available to researchers, which presents another challenge for advancing directly heated sCO_2 power cycle technology. NETL's Advanced Turbines team uses computational fluid dynamics, a type of computer modeling, to simulate the complex physical and chemical processes that occur in the combustor.

"We're kind of flying blind in terms of modeling work," said Peter



Indirect sCO_2 power cycle

Strakey, of NETL's Thermal Sciences team. "There is a lack of confidence in the models at these conditions; however, the modeling must be accurate for the system to work properly and safely."

SUPPORTING PROJECTS

NETL's Supercritical CO_2 Power Cycle Technology Program is a collaboration of four programs – Advanced Turbines, Advanced Combustion Systems, Crosscutting Technology Research and STEP. Collectively, these programs include 20 projects valued at more than $152 million.

The $113 million STEP pilot plant project is part of DOE's sCO_2 Crosscut Initiative, a partnership between the Offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy to address technical issues, reduce risks, and mature the technology. Dennis said the goal is to demonstrate thermal efficiency of 46 percent and predict the likelihood of achieving 50-53 percent at a larger scale, such as a 100 MWe design, using an indirect-fired cycle with a turbine inlet temperature of 700 degrees Celsius. External partners include the Gas Technology Institute, Southwest Research Institute and GE Global Research. A cooperative agreement to design, build and operate the 10 MWe STEP facility was signed in February 2017. Construction is slated for completion in the fourth quarter of FY 2019, and testing of the facility is expected to wrap up in FY 2022.

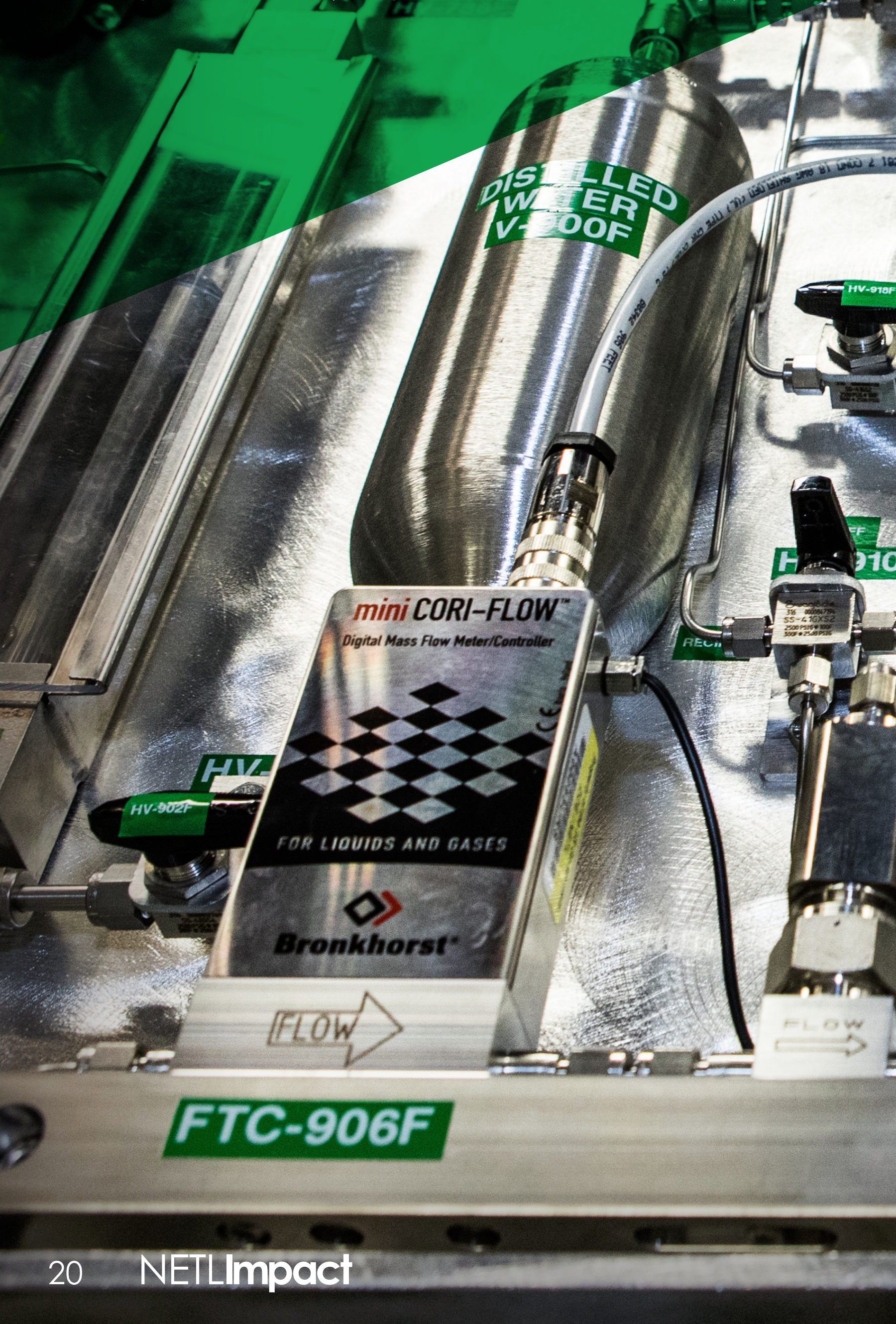
Ames said the facility will help researchers to answer and address critical questions about sCO_2 power cycles. "We have years of experience with steam cycles," he said. "This is going to be a different animal. There are going to be issues we're not familiar with, including material risks and other operational unknowns."

Additional NETL research projects provide support for the STEP effort, while others are pursuing technology for directly fired sCO_2 systems. Researchers in Advanced Turbines are working to study oxycombustion and develop improved turbomachinery for integration in indirectly and directly fired sCO_2 power cycles, while researchers in Advanced Combustion Systems are working to enhance recuperators, cycle integration and indirect heat source integration. Crosscutting Technology Research is focused on materials research and advanced manufacturing.

The innovations developed through many of these projects will help inform and improve the success of NETL's future endeavors to advance sCO_2 technology. All 20 projects included in NETL's sCO_2 Technology Program will ultimately help develop highly efficient sCO_2 power cycles that exceed the performance of existing fossil fuel technologies, cut costs for businesses and consumers, and create new opportunities to promote America's coal industry.

MICROWAVES Offer Unique Advantages for Coal Conversion

By Joe Golden
Technical Contact:
Dushyant Shekhawat (Dushyant Shekhawat@netl.doe.gov)



Around 30 percent of the nation's electricity is generated from coal, but the value of this versatile fossil fuel doesn't end there. This abundant and affordable energy source can also be converted to value-added chemicals that can be used as fuels or as building blocks in the chemical industry. For example, syngas, which is used as both a fuel and an intermediate for making plastics, can be formed by heating coal in large vessels – a process called gasification.

"Traditionally, the heating step in gasification and other coal conversion processes has been very energy intensive," said Dushyant Shekhawat, Ph.D., who leads NETL's Reaction Engineering team. "This is because it requires the entire bulk system to be heated rather than just what is necessary. This is not the case with microwaves."

Thermal heating works from the outside in, but microwaves heat on a molecular level, allowing for selective heating of reacting species and sites. Microwaves heat the microwave-active materials directly while leaving the surrounding areas at relatively low temperatures, resulting in higher product yields and better selectivity.

"Rapid and selective heating is a significant benefit to using microwaves over thermal heat," explained Shekhawat. "But, a non-thermal microwave effect also seems to be part of the observed enhanced conversion and selectivity."

NETL researcher John Johnson operates a state-of-the-art variable frequency microwave reactor (VFMWR) in the newly commissioned Reaction Analysis and Chemical Transformation (ReACT) facility in Morgantown.

These microwave-specific effects are important to understand on a fundamental level because they can affect profound changes in reaction mechanisms, rates and equilibrium positions. They can even yield completely different products than what is created during normal convective heating. NETL research is working to gain a fundamental understanding of the science behind how microwaves interact with materials, so that optimal designs can be obtained of an efficient microwave system for fuel conversion applications.

A recent paper coauthored by Shekhawat investigated microwave-assisted pyrolysis, which is a thermochemical pre-treatment step in any coal conversion process that devolatilizes coal and reduces its sulfur and heavy tar content. The study looked at the pyrolysis of Mississippi coal and compared it to conventional pyrolysis. Results showed that microwaved pyrolysis of the coal produced higher gas yields at low temperatures, with less tars.

Researchers at NETL are also looking toward microwave-activated materials development, along with further microwave research that will advance electromagnetic field characterization by understanding how geometry and surfaces interact with the microwaves and micro-discharges in the spaces between particles.

Capabilities in the lab include an array of state-of-the-art instruments and reactors, including a variable frequency microwave reactor (VFMWR) that can operate from 2 to 8 GHz - a typical lab microwave reactor runs at a single frequency of 2.45GHz.

"Acquiring this capability is a groundbreaking development," said Shekhawat. "It will provide us with the most comprehensive look at the electromagnetic characterization of a wide range of materials for a series of chemical reactions. To the best of our knowledge, the VFMWR capability is a one-of-a-kind system and does not exist in any other research laboratories in the world."

More research is needed to understand the full benefits that are unique to using microwaves to convert coal into useful products, but the work the Lab is doing today is laying the groundwork for better processes and systems in the future.

Shekhawat spoke of the vast potential of the technology. "Microwave-assisted conversion science could be the next frontier," he said. "And by having a world class capability in this area, NETL will secure its place at the forefront of this unique innovation." ≡

DEVELOPING NEXT-GENERATION CYBERSECURITY TECHNOLOGIES TO STRENGTHEN NATIONAL ENERGY INFRASTRUCTURE

By Krista Baker
Technical Contact: Eddie Christy (Eddie.Christy@netl.doe.gov)

Reliable energy supports our prosperity and enables our quality of life. Delivering energy to our homes, hospitals, businesses, and beyond requires a vast network that produces, transfers, and distributes energy where it's needed. Resilient energy infrastructure requires robust energy delivery systems to provide timely and accurate information to system operators and automated control over a large, dispersed network of energy delivery components.

The Office of Electricity Delivery and Energy Reliability (OE) leads the U.S. Department of Energy's efforts to ensure a resilient, reliable, and flexible electricity system. OE works to develop new technologies to improve the infrastructure that brings electricity into our homes, offices, and factories, and the federal and state electricity policies and programs that shape electricity system planning and market operations.

A key aspect of OE's work is cybersecurity – advancing the research and development of innovative technologies, tools, and techniques to reduce risks to the nation's critical energy infrastructure posed by cyber and other emerging threats.*

Supporting OE's important mission in this area are NETL project managers within the Lab's Energy Technology Development directorate, who are applying their program management expertise to OE's Cybersecurity for Energy Delivery Systems (CEDS) Program. In this effort, NETL manages extramural research, development and demonstration of new tools and technologies to enhance situational awareness and cybersecurity of critical energy infrastructure, through research partnerships.

Critical energy infrastructure consists of hardware and software systems that monitor, protect and control processes. It also includes equipment that manages energy generation (electric) or production (oil and gas) all the way to energy delivery to the end user. Advances in communication and computing have enabled promising new benefits to be integrated into this infrastructure, such as improved automation, situational awareness, system performance, efficiency and reliability. However, these advances also brought unfamiliar problems and risks to the security and reliability of these cyber-physical systems. For this reason, OE has aimed its research and development efforts under its CEDS Program portfolio to supporting resilient energy delivery systems that are designed, installed, operated, and maintained to survive a cyber incident while sustaining critical functions.

CEDS research partnerships involve energy sector utilities, suppliers, government, universities and the Energy Department's national laboratories to advance cybersecurity capabilities tailored to the unique performance requirements and operational environments of energy delivery systems. These partnerships transition innovative cybersecurity capabilities from early-stage research to routine use, strengthening the resilience of real-world energy delivery systems. Examples of projects that have successfully transitioned to the energy sector include:

- Quantum Key Distribution (QKD) system that provides cutting-edge security while greatly simplifying the generation, maintenance, and distribution of encryption keys used in energy delivery systems. This uses quantum entangled photons to guarantee tamper detection and provides a secure encryption against even a quantum computing attack.
- Secure advanced metering infrastructure (AMI) and distribution automation (DA) wireless mesh networks with continuous monitoring, anomaly, and intrusion detection and prevention.
- Strong anti-malware and whitelist protection secures field devices that ensures only approved applications, services, and/or executables are ran and executed and all others are blocked.
- A solution to streamline the task of patching and updating devices used in energy delivery control systems. This is particularly important in cases when patches and updates mitigate security vulnerabilities that may be exploited by adversaries.
- Technology that enhances the cyber and physical security that protects both electronic and physical perimeter by monitoring and controlling device assets.
- Software Defined Networking technology for Energy delivery networks that keep working, even during a cyber-attack, by automatically redirecting communications along pre-selected, pre-engineered alternative paths.

"Each research partnership, whether led by industry, academia or national laboratories, is expected to establish a clear path toward industry acceptance and transition the research results to practice, from the earliest stages of the research," said Carol Hawk, Ph.D., the CEDS Team Program Manager.

The dynamic cyber threat landscape, continuous advances in energy delivery system technologies, and the use of legacy devices in ways not previously envisioned underscore the importance of transitioning the innovative CEDS R&D to practice. CEDS R&D helps secure our nation's energy infrastructure from cyber-attack, which is critical to national security, but for which an individual energy sector organization would likely be unable to support a business case.

"More than 40 tools, including guidance documents, and technologies have been made available to the energy sector through CEDS-supported research partnerships," Hawk said. "I, along with the folks at NETL, am excited to be part of these research activities that have national significance to protect our critical energy infrastructure."

For more information on the CEDS program, visit the Office of Electricity Delivery & Energy Reliability's website at www.energy.gov/oe.

** Note: on Feb. 14, 2018, Secretary of Energy Rick Perry announced the establishment of a new Office of Cybersecurity, Energy Security and Emergency Response, which is intended to bolster DOE's efforts in cybersecurity and energy security.* ≡

FIBER OPTIC INNOVATIONS FOR SUBSURFACE SAFETY & EFFICIENCY

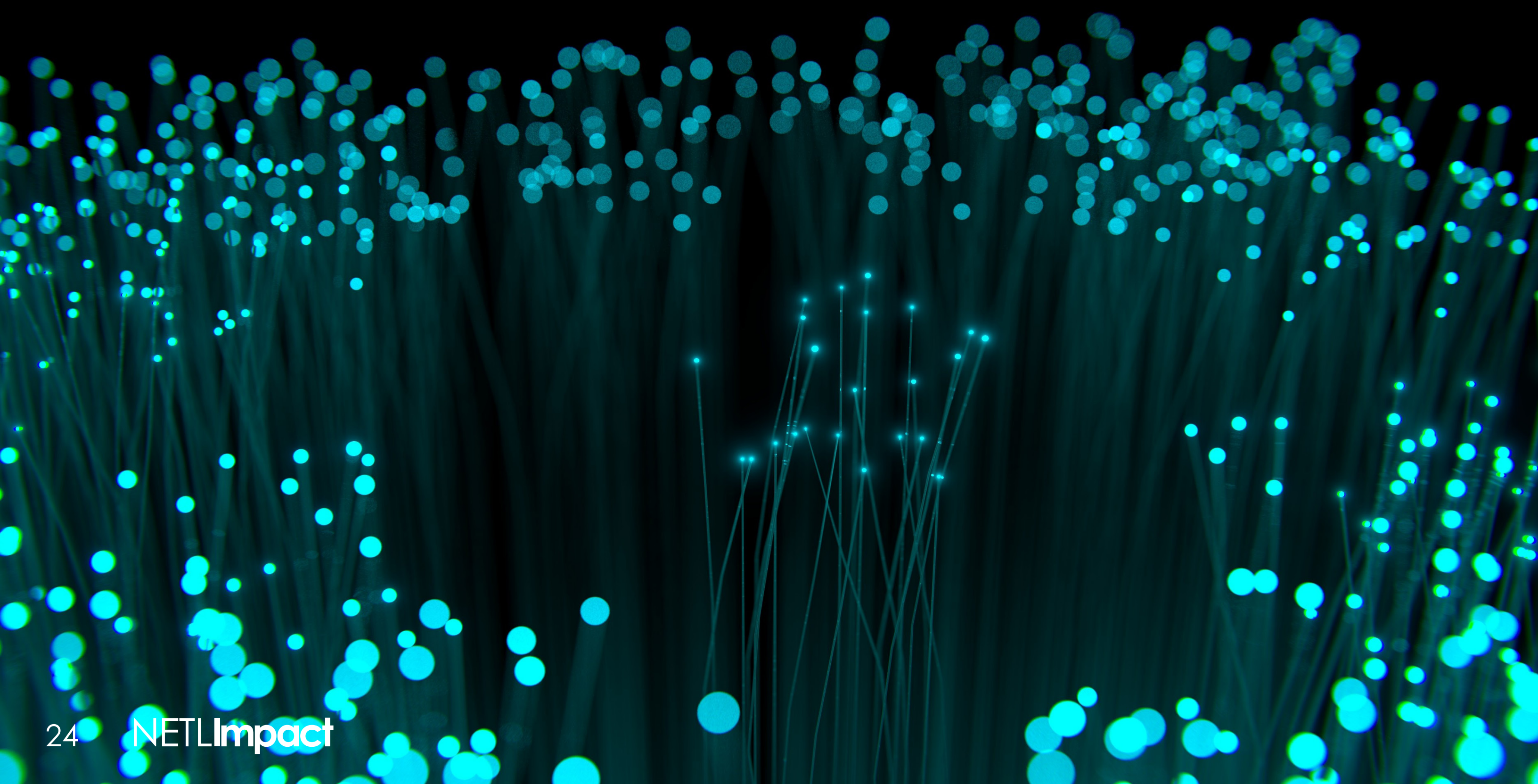
By Gerrill Griffith // Technical Contact: Paul Ohodnicki (Paul.Ohodicki@netl.doe.gov)

Decades worth of energy resources reside deep beneath the surface of the earth where extreme environments created by elevated temperatures and pressure, fluctuating geophysical, geochemical, geomechanical and hydrologic properties, or geohazards present obstacles to safe and efficient resource recovery. Researchers are overcoming those obstacles by creating tools that help better analyze and understand the subsurface domain. NETL experts and their research partners are accelerating development of fiber optic sensors that can quickly provide vastly improved analytical capabilities over distances for safer, more efficient resource recovery.

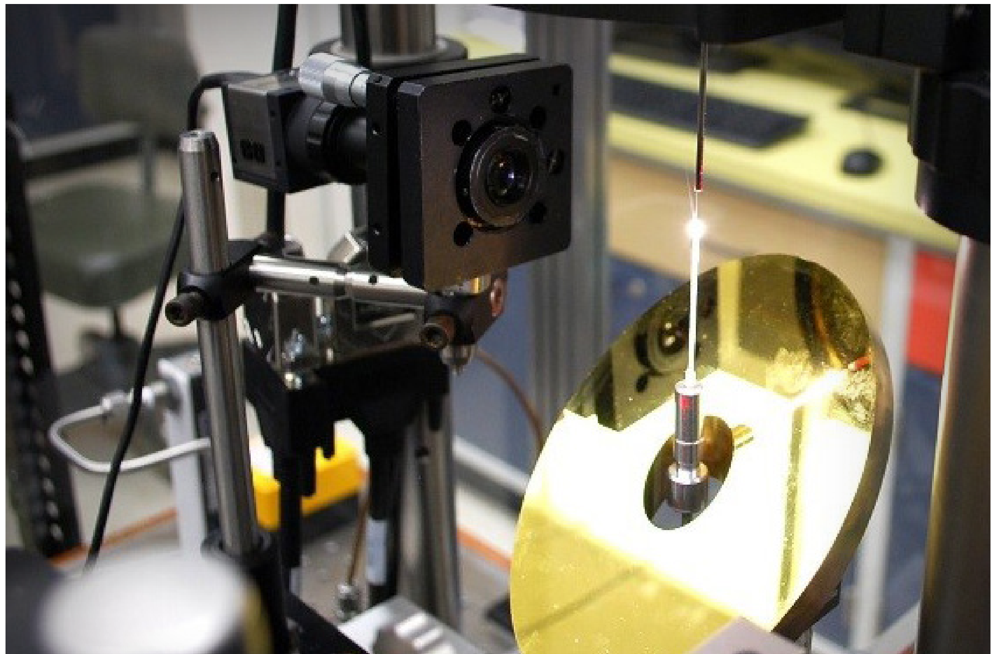
The work is critical in the United States' drive to become energy dominant in an energy-demanding world. More than 80 percent of global energy needs are currently met with energy resources derived from the subsurface in the form of fossil fuels. That demand is expected to steadily rise.

The United States is well-positioned to answer that demand. In addition to vast conventional natural gas, oil, and coal resources, the nation has trillions of cubic feet of untapped methane hydrates on the Alaskan North Slope and in the Gulf of Mexico. A methane hydrate is a cage-like lattice of ice. Inside that ice are trapped molecules of methane, the chief constituent of natural gas. If methane hydrate is warmed or depressurized, it reverts to water and natural gas. When brought to the earth's surface, one cubic meter of gas hydrate releases 164 cubic meters of natural gas.

Increased efficiency, safety, and environmental precautions in the harvesting of subsurface energy resources depend upon the development of new capabilities in imaging, characterization, and modeling of the subsurface – activities that require imaging and sensing technologies that can withstand high temperatures and pressures, the presence of chemically corrosive chemical species, and potentially high salinity. Fiber optic sensing technology is providing those abilities.



Optical fibers are flexible, transparent glass or plastic fibers slightly thicker than a human hair. They are most often used to transmit light between two ends and permit transmission of data over longer distances and at higher bandwidths than wire cables. They are immune to electromagnetic interference, do not require electrical power at remote locations, can be multiplexed, and are ideal for use in confined spaces. Researchers are now finding novel ways to use fiber optics as sensors that can also relay signals to processors that perform the analytic work.


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 brutal subsurface conditions.

New fiber optic sensors are providing transformative improvements to information resolution that helps diminish uncertainty levels when characterizing the subsurface. NETL researchers are modifying fiber optic sensors currently used to just monitor temperature or acoustic signals, into sensors that can measure chemical constituents in formation fluids and under downhole conditions.

Optical fiber-based sensors for subsurface chemical sensing applications have not yet been commercially deployed because of a lack of stable optical sensor elements with useful, reversible, and rapid responses to chemical species of interest. Progress on use of fiber optics to develop responses to chemical species is being made. NETL researchers, for example, have demonstrated fiber optic-based sensing layers composed of metal nanoparticles incorporated into a silica matrix coated on an optical fiber. The new sensing material exhibits strong and reversible optical response to pH variations without the temperature limitations inherent to conventional pH indicators. Eventual deployment of innovations can enable embedded, real-time, remote pH sensing capabilities in extreme subsurface environments.

Fiber optic sensors are also playing an expanding role in monitoring seismic attributes during hydraulic fracturing for oil and gas recovery operations. Traditionally, surface pressure and subsurface pressure gauges, wellhead rates, and radioactive tracers have been the only monitoring tools available for monitoring seismic factors during hydraulic fracturing.

In one innovation, NETL provided funding for a project conducted at the Marcellus Shale Energy and Environmental Laboratory (MSEEL) in Morgantown, W.Va., operated by West Virginia University and several industrial partners. The project developed and tested fiber optic technology to improve recovery efficiency while diminishing environmental implications of unconventional resource development. MSEEL deployed fiber optic technology into active horizontal wells operating at a Morgantown test site that included distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) based optical fiber sensors.

A DAS system allows acoustic frequency strain signals while DTS systems allow local temperature measurements to be detected over large distances and in harsh environments, all along the depth of a wellbore for example. In the experiments performed the DAS and DTS devices provided continuous subsurface vibration and temperature samplings during 28 stages of well stimulation to establish a complex network of permeable fracture pathways. The tests provided positive results, and an expansion of the sensor work is underway.

As research proceeds to develop an enhanced understanding of subsurface systems, development and utilization of new capabilities in subsurface imaging, characterization, and modeling as advanced by fiber optics innovation will continue at NETL. These advances will permit greater resolution in images and models, diminish uncertainty in modeling and engineering, and improve predictions of subsurface responses to engineering – advances needed to improve accuracy and predictive capabilities to improve efficiency in recovering subsurface resources, reducing the risk associated with encountering unknown features, and enhancing the nation’s drive toward dominance in the energy global marketplace. ≡

COMPUTATIONAL TOOLS UNLOCK EFFICIENCY & RELIABILITY

By Joe Golden // Technical Contact: David Miller (David.Miller@netl.doe.gov)

The Energy Department is committed to improving the efficiency, cost, and reliability of the nation's coal-fired power plants while accelerating development of the most promising new advanced energy systems like chemical looping combustion and other transformational carbon capture technologies. NETL's Institute for the Design of Advanced Energy Systems (IDAES) was formed in 2016 to work toward this goal, seeking to be the premier resource for the identification, synthesis, optimization, and analysis of innovative advanced energy systems at scales ranging from process to system to market.

Fossil fuel power plants provide stability and reliability to the U.S. power grid, and NETL researchers are working to increase their efficiencies through improvements to critical components and processes, ensuring that America's energy dominance continues for many more generations. IDAES is developing new advanced process systems engineering (PSE) capabilities to support design and optimization that can transcend the limitations of current approaches.

Engineers rely primarily on state-of-the-art simulation packages to synthesize, model, and optimize process flowsheets; however, commercial simulation tools struggle with large-scale flowsheet optimization and typically limit nonlinear optimization problems to less than 100 degrees of freedom (i.e., the number of parameters that may vary independently). As a result, large-scale process optimization is rarely performed by industry.

On the other hand, many of the capabilities for large-scale optimization are available in general algebraic modeling languages (AMLs), which routinely solve optimization problems with many thousands of variables and degrees of freedom.

"The open-source IDAES PSE framework bridges the gap between state-of-the-art simulation packages and AMLs," IDAES Technical Director David Miller explained. "The result is a modeling tool specifically designed for optimization from the ground up."

This framework is helping IDAES develop flexible design approaches, which enable optimization over a broad range of potential plant operations. Process intensification concepts have also been explored, enabling the identification and scale up of smaller, more modular, and more cost-effective technologies.

"IDAES is not just focused on optimizing existing coal-fired power plants," Miller said. "Its framework is also supporting the development and scale-up of new energy technologies."

This project will develop and demonstrate next-generation computational tools for PSE of advanced energy systems to enable their rapid design and optimization. These tools will be applied to the development of new, innovative energy systems, which are capable of meeting environmental and economic objectives as well as supporting existing plants to maintain grid reliability.

The important work that's been achieved by IDAES is accelerating innovation by identifying and optimizing complete systems in the context of a full energy portfolio. Another benefit of the project will be increased grid reliability from identifying new operational strategies and promising opportunities for retrofitting existing coal-fired power plants.

Vast improvements in design and decision analysis capability have occurred over the past decade due to computational method development and hardware evolution. These improvements could result in tens of billions of dollars in savings through better choices in investments and operations. Optimizations that were previously limited to systems with relatively low complexity can now be done over vastly more complex systems in reasonable amounts of time. The result is the ability to assess more alternatives more quickly while incorporating the entire power system into the evaluation.

A Stakeholder Advisory Board has been assembled to ensure that the work done by IDAES remains aligned with key industry needs. Regular conference calls and biannual face-to-face review meetings are ensuring that stakeholders remain well informed of the program and its progress. This direct interaction also allows stakeholders to provide advice to the program, maximizing value to the industry.

With the success of IDAES, a comprehensive, open-source framework is now in place that is poised to enable large-scale optimization of complex, innovative processes spanning conceptual design and process synthesis to dynamic optimization. Such advancements to the U.S. energy portfolio will ensure that Americans continue to receive affordable and reliable energy, even as demand continues to rise. ≡

IDAES

Institute for the Design of Advanced Energy Systems

Exploring new concepts

Improving efficiency, reliability, and life expectancy of existing plant

Accelerating innovation

The National Energy Technology Laboratory's IDAES seeks to be the premier resource for the identification, synthesis, optimization, and analysis of innovative advanced energy systems at scales ranging from process to system to market. The Institute supports the transformation of the national energy landscape to meet the U.S. Department of Energy's three enduring strategic objectives

Economic Competitiveness

Energy Security

Environmental Responsibility

2020 2025 2030

2020

By 2020, demonstrate next-generation capabilities for synthesizing optimized innovative energy systems.

2025

By 2025, demonstrate a fully integrated framework for advanced process systems engineering.

2030

By 2030, demonstrate a fully integrated advanced multi-scale simulation toolset that supports the complete life cycle from concept to design, start-up, and operation.

IDAES WILL

- **Leverage the computational advances of process systems engineering research and integrate the multiple types of energy analysis typically conducted by disparate groups.**
- **Develop and demonstrate next-generation computational tools to enable the rapid design & optimization of advanced energy systems.**
- **Apply these tools to the development of new, advanced energy systems.**
- **Develop highly innovative processes that go beyond current equipment & process constraints.**

NETL Technology to Assess Subsurface Risks Earns R&D 100 Award

By Cassie Shaner
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Sustainable and efficient use of our nation's abundant fossil energy resources is critical to stimulating the economy, ensuring safety and enhancing America's energy dominance. Carbon capture, utilization and storage technology can enable the continued use of plentiful fossil energy resources by stimulating incremental oil and gas recovery.

Geologic formations found deep underground offer promising repositories for safe and effective storage of large volumes of human-made carbon dioxide (CO_2). Inherent variability and uncertainty in characteristics of these geologic systems make it difficult to know with certainty how a system will respond to large-scale injection and storage of CO_2.

In the context of these uncertainties, investors, regulators and operators must make decisions about the commercialization, permitting and management of geologic carbon storage (GCS) sites. To gain confidence that GCS technology can be successfully implemented, these stakeholders require robust, transparent and science-based tools to quantify the range of potential environmental risk behavior at CO_2 storage sites over time. Quantitative assessment of whole-system performance is required to ensure that GCS activities can be done safely and effectively.

Researchers at NETL are working to assess these risks and develop insights into how they can be managed by developing innovative tools and methods to predict and assess risk behavior at GCS sites. The National Risk Assessment Partnership (NRAP) is an NETL-led collaborative effort that draws on expertise from five DOE national laboratories to develop risk assessment tools for safe, long-term geologic CO_2 storage. In addition to NETL, the NRAP technical team includes researchers from Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory and the Pacific Northwest National Laboratory.

The partnership's most notable achievement to date is the development of the NRAP Toolset, comprising 10 science-based computational tools to predict environmental risks for subsurface CO_2 storage sites – those related to potential fluid leakage and ground motion. The toolset was recognized in November 2017 with an R&D 100 Award. Known as the "Oscars of Innovation," R&D Magazine bestows the annual awards to honor the 100 most technologically significant products introduced into the marketplace in the previous year. The toolset also received formal recognition from the Carbon Sequestration Leadership Forum, which is an international climate change initiative focused on developing carbon capture and storage technologies.

Collectively, the computational tools in the NRAP Toolset represent a resource for stakeholders as they plan and execute GCS projects. The toolkit contains:

- The **NRAP Integrated Assessment Model-Carbon Storage Tool**, which simulates long-term full system behavior from storage reservoir to the surface.
- The **Aquifer Impact Model**, which estimates the impact of a potential leak of injected CO_2 or saline water on groundwater aquifers.
- The **Designs for Risk Evaluation and Management Tool**, which evaluates and selects the optimal monitoring design for a geologic carbon storage site.
- The **Multiple Source Leakage Reduced-order Model**, which predicts the probability that the stored CO_2 will exceed a defined critical concentration and leak.
- The **NRAP Seal Reduced-Order Model**, which estimates migration of brine and supercritical CO_2.
- The **Reservoir Evaluation & Visualization Tool**, which provides key data on reservoir pressure change and CO_2 storage over time.
- The **Reservoir Reduced-Order Model-Generator Tool**, which can be incorporated into the NRAP Integrated Assessment Model-Carbon Storage for site-specific risk assessment.
- The **Well Leakage Analysis Tool**, which evaluates leakage risk from existing wells at CO_2 storage sites.

Accepting a 2017 R&D 100 Award at festivities in Orlando, FL are team members, left to right, Bob Dilmore of NETL, Elizabeth Keating of Los Alamos National Laboratory (LANL), Grant Bromhal of NETL, and Phil Stauffer of LANL. The team's product, the National Risk Assessment Partnership Toolset, was designated as one of the top 100 technologies of the year.

- The **Ground Motion Prediction for Induced Seismicity Tool**, which estimates the surface intensity of potential induced earthquakes at CO_2 storage sites.
- The **Short-Term Seismic Forecasting Tool**, which analyzes seismic history and injection data to forecast potential seismicity in the coming days.

"The NRAP toolset offers a very useful platform to begin addressing questions about critical risk-related behavior of geologic storage sites," said NETL Technical Lead for NRAP Robert Dilmore, Ph.D. "It represents a platform to distill expert science and engineering insight from NRAP and throughout the DOE Carbon Storage Program to inform decisions on site selection and risk acceptability."

For example: How does a geologic reservoir respond to CO_2 injection? How might CO_2 storage affect groundwater aquifers? How can a site be efficiently monitored to detect potential groundwater quality changes? NRAP tackles these questions by dividing the complex engineered geologic system into its critical components, using detailed physics-based simulations to develop reduced-order models (ROMs) describing the important behavior of those components, amid uncertainty, and coupling them together in an integrated simulation framework to quantify whole-system response.

NRAP tools have been accessed by more than 300 people from 50 institutions, including international corporations, regulatory agencies and universities. Experiences from their real-world application are spurring refinement of the tools, and informing the development of next-generation risk management tools and methods.

NRAP is now in its second phase of research, which seeks to validate its Phase I tools and methodologies by collaborating with field laboratory projects supported by the Carbon Storage Program at NETL. Researchers aim to apply and extend their predictive capabilities to actively manage and mitigate subsurface risks related to CO_2 storage. Specific technical objectives include:

- Assessing containment assurance, including verifying and maintaining well integrity.
- Predicting induced seismicity risk.
- Strategic monitoring for uncertainty reduction.
- Validating risk assessment tools and methodologies using synthetic field data.
- Addressing critical questions related to assessment and management of environmental risk at CO_2 storage sites.

NETL Researcher Nicolas Huerta, Ph.D., summed up NRAP's evolution into Phase II: "Based on the foundational, science-based understanding of this complex system developed in NRAP's first phase, we are now really digging in and applying what we've learned to address the risk-related hurdles that remain as impediments to the deployment of geologic CO_2 storage." Huerta expects that "real advancements in our understanding of risk will be made as we apply NRAP's tools and methodologies to the next generation of field sites." It is the expectation that by the end of Phase II the NRAP team's efforts will have tangibly reduced the remaining risk-based challenges of long term storage of CO_2.

MEET STEVEN WINBERG, the New Assistant Secretary for Fossil Energy

By Renie Boyle

On Dec. 14, 2017, Steven Winberg was ceremonially sworn in by Energy Secretary Rick Perry as the new Assistant Secretary for DOE's Office of Fossil Energy (FE). Winberg was officially sworn in as Assistant Secretary on Nov. 22, 2017.

As Assistant Secretary, Winberg oversees FE's research and development program, encompassing coal, oil, and natural gas, as well as the Office of Petroleum Reserves. He serves as a primary policy advisor to Secretary Perry and the Department on issues involving U.S. fossil fuels. He also supervises FE staff, which includes more than 1,000 scientists, engineers, technicians, and administrative staff throughout the nation.

Winberg has 39 years of experience in the energy industry. He began his career at the engineering firm Foster Wheeler as a start-up engineer on coal-fired utility boilers. From there, he spent 14 years with Consolidated Natural Gas working in a variety of positions before becoming vice president for CONSOL Energy Research & Development. Immediately prior to coming to DOE, Winberg served as a Senior Program Manager at Battelle Memorial Institute.

Over the span of his career, Winberg has participated in a number of policy and energy initiatives. He has also gained extensive experience in numerous energy technologies, including advanced fossil energy combustion, coal-to-liquids, fluidized bed combustion, emulsified fuels, fuel cells, alternative fuel vehicles, and carbon utilization.

Winberg received a bachelor's degree in nuclear science from the State University of New York Maritime College in 1978 and an MBA from the University of Pittsburgh in 1991.

IN HIS OWN WORDS

On His Childhood:
"I was raised an Air Force brat and lived in various states, including a short time in Guam when I was very young."

On His Career:
"The best way to summarize my career is that I have wandered around emerging fossil energy technology all my career, usually working to commercialize technology that, in whole or in part, got its start at the Department of Energy."

On DOE and the Office of Fossil Energy:
"DOE, and in particular, the Office of Fossil Energy, has consistently been in the lead on researching, developing and demonstrating technologies to reduce emissions and improve efficiency. . . . Whether we're talking about baghouses, electrostatic precipitators, scrubbers, mercury control, directional drilling, hydraulic fracturing, the Strategic Petroleum Reserve, liquified natural gas, rare earth elements – it all started here!"

On the Future of Fossil Fuels:
"I believe we are at the beginning of the next cycle of fossil technology advancements. . . . We have the wherewithal to keep fossil energy solidly in the U.S. energy mix and, for that matter, the world. We have the opportunity to make great strides in efficiency improvements to the existing coal and natural gas electric generation fleet, commercializing the next generation of coal-fueled technologies, improving fossil fuels production, and doing so in an environmentally friendly and sustainable manner."

On his Vision for the FE Workforce:
"Now is the time to be bold. To push the technology envelope. To come forward with ideas, moon-shot ideas to develop new methods to maximize our energy production capability and our energy assets. . . . Let's do everything in our collective power to make up for lost time, to be bold and to make fossil energy more abundant, more sustainable and cleaner so that 40 years from now whoever is standing up here talking to the next generation of FE personnel will also marvel at just how far fossil has come."

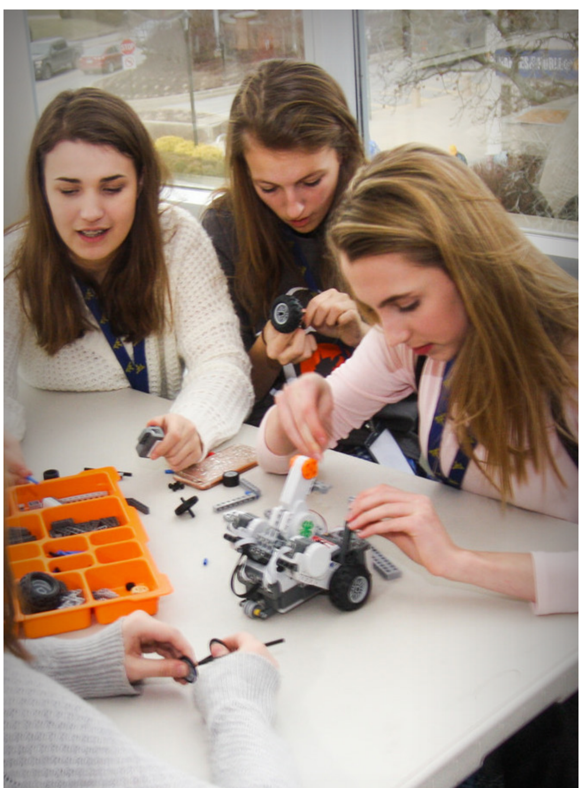
"We have the opportunity to make great strides in efficiency improvements to the existing coal and natural gas electric generation fleet, commercializing the next generation of coal-fueled technologies, improving fossil fuels production, and doing so in an environmentally friendly and sustainable manner."

NETL Congratulates Regional Science Bowl Champions

2018 West Virginia Science Bowl Middle School Regional Champions - Suncrest Middle Team 2

2018 West Virginia Science Bowl High School Regional Champions - Morgantown High Team 2

Two middle school teams prepare to go head-to-head in the third round of Science Bowl competition.



At the West Viriginia Science Bowl, middle school students build a robot for the SUGObot competition where teams vie to push their opponents' robot out of a match circle.

NETL Engineer Wins National Award for Excellence in Chemical Engineering

By Joe Golden

Isaac Gamwo, Ph.D., a research chemical engineer at NETL for more than 16 years, received the 2017 Joseph N. Cannon Award for excellence in Chemical Engineering during the 2017 National Organization for the Professional Advancement of Black Chemists and Chemical Engineers (NOBCChE) conference.

"I'm honored to receive this national distinction as a role model for underrepresented chemical engineers," said Gamwo. "I share this award with all the researchers I have worked with over the past three decades who have made this possible."

NOBCChE established the Joseph N. Cannon Award for Excellence in Chemical Engineering in 2013 to recognize an individual for excellent achievement in chemical engineering and technology development and to highlight role models of color in the STEM disciplines. Gamwo was recognized based on his nearly three decades of influential research accomplishments in the chemical engineering field and for his work training engineers at Tuskegee University and at the University of Akron.

Gamwo leads a mutli-institutional team at NETL that is measuring and predicting the density and viscosity of crude oil over an extremely wide range of temperatures and pressures to foster safer drilling and production operations, enhance domestic energy production, and protect the environment.

Precise understanding of how hydrocarbon fluids behave in these high-temperature and high-pressure (HTHP) environments will provide more accurate predictions of the recoverable reserves and rates of petroleum production from these prolific and critically important reservoirs. The development of a comprehensive knowledge base in this area may also help engineers accurately estimate the magnitude of spills like the Macondo blowout if they do occur.

Gamwo's path to becoming an energy researcher was not always set in stone. "Teaching at the University level was my goal while pursuing my education," Gamwo said. "While in academia, I won a highly competitive university coal research grant from the Energy Department. This award influenced my decision to devote my career to energy research."

Isaac Gamwo, Ph.D.

Since then, Gamwo has become a renowned authority on HTHP viscosity and density modeling. Last year, he was elected to serve as a director of the Separation Division of the American Institute of Chemical Engineers (AIChE).

Currently, findings made by Gamwo and his team are being used by 19 internationally recognized research groups made up of researchers from Australia, Spain, Mexico, the United Kingdom, and the United States. His team was also a finalist in a Worldwide Research Project Competition in 2014.

Gamwo said that he finds the ability to make significant contributions to energy research, and growing recognition from his peers very rewarding. When asked if he had any advice for future energy researchers, Gamwo said, "I think that you should explore various energy-related research areas outside of your expertise. This could be very beneficial for your career."

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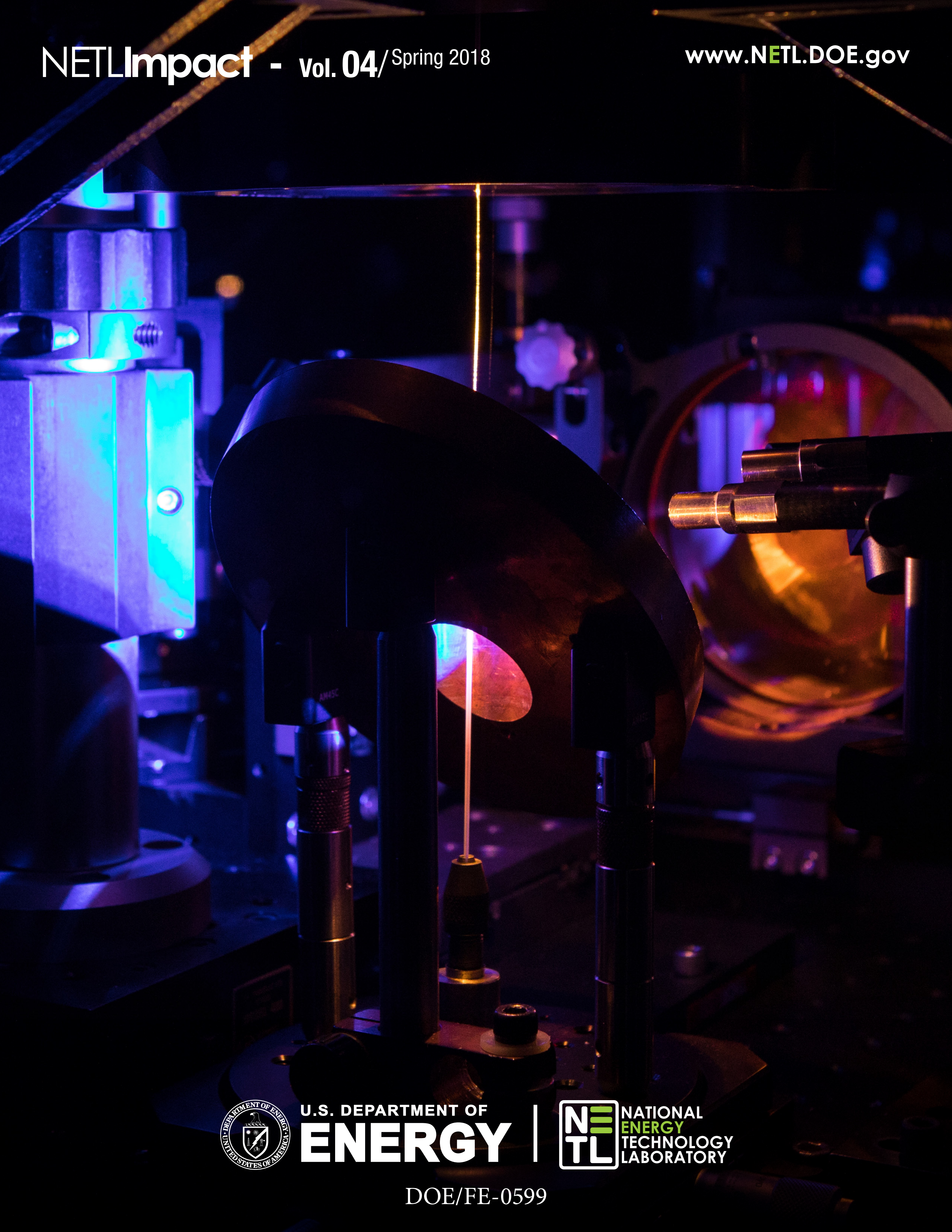

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