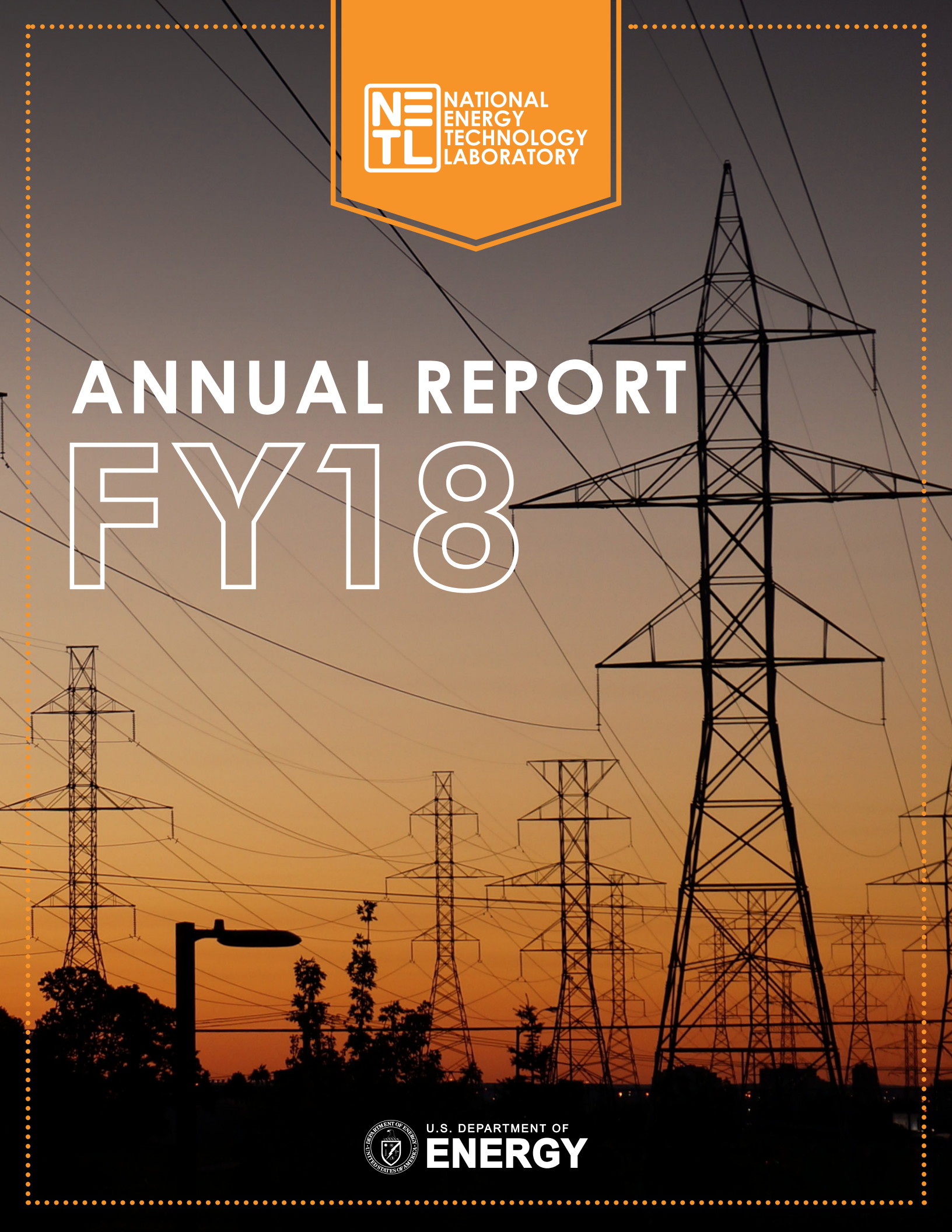
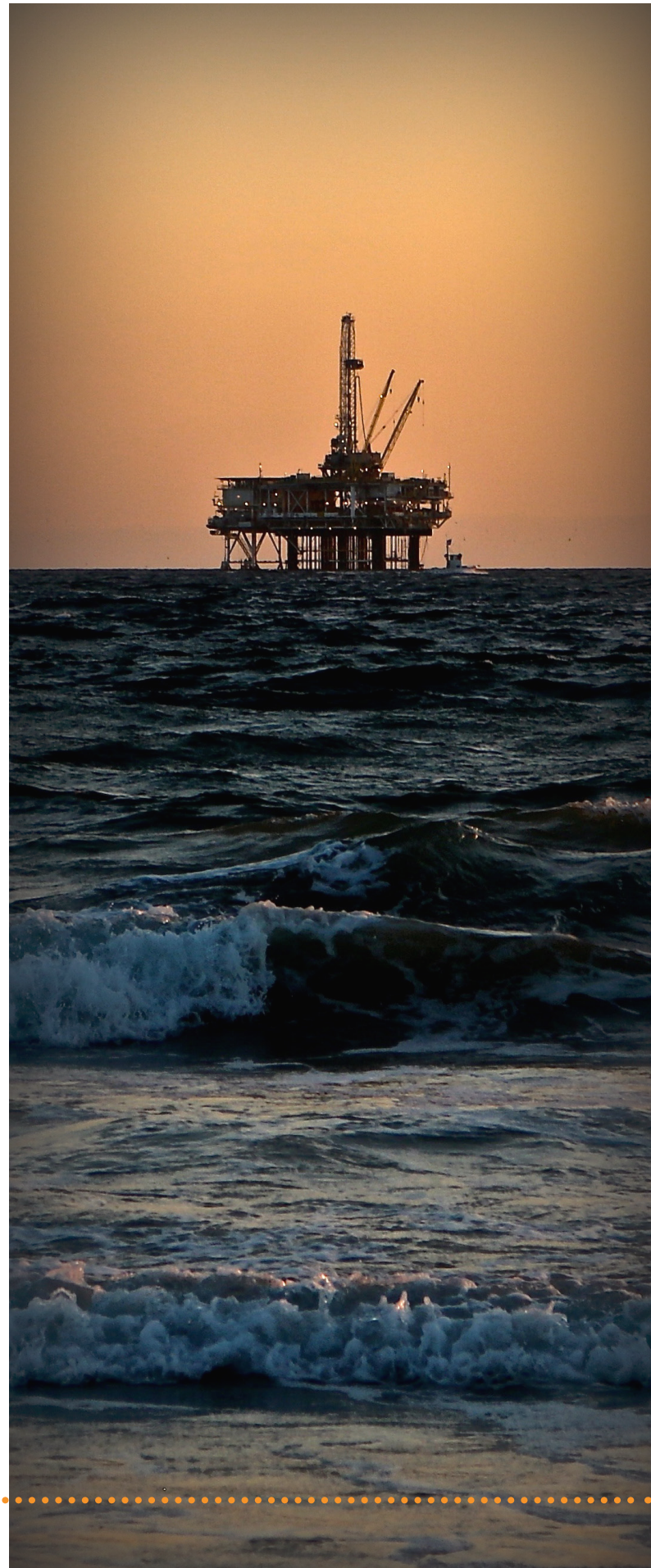

NATIONAL
ENERGY
TECHNOLOGY
LABORATORY
ANNUAL REPORT
FY18
U.S. DEPARTMENT OF
ENERGY

CONTENTS



DIRECTOR'S MESSAGE

Every year, NETL compiles its most notable accomplishments in an annual report to the people of our nation so that they can learn more about the work we do to enhance the nation's energy foundation and protect the environment for future generations.

Dedicated NETL researchers in Albany, Oregon; Pittsburgh, Pennsylvania; and Morgantown, West Virginia remain engaged in work that produces energy-related innovations that will or already touch the lives of millions of Americans.

For example, NETL developed:

- New alloys for cleaner, more efficient coal-fired power facilities that can lower power bills.
- Better ways to capture carbon from industry to create more value-added products.
- Technologies to help create new jobs, products and markets for coal.
- New ways to recover valuable rare earth elements from coal byproducts and acid mine drainage to expand U.S. industries.
- Big data and machine learning to unlock even more of our nation's unconventional oil and natural gas resources and much more.

NETL-led projects have spearheaded innovations at sea in searches for methane hydrate fields; in the Pennsylvania countryside to monitor and ensure the safe operation of oil and gas rigs with new sophisticated sensors; in a world-class supercomputer facility where researchers use simulations to innovate cleaner and safer ways to harvest energy; in the Gulf of Mexico to safely reach difficult oil and gas resources; in the Texas hills to recover greater volumes of oil from fields once thought depleted; and in other locations across America.

I firmly believe that NETL's work has become, through decades of accomplishment and progress, a reliable and trusted element in American life — a source of pride and a symbol of hope and ingenuity for keeping the nation strong and economically vital.

I hope you enjoy reading about the NETL accomplishments that appear in this report and gain a clearer understanding of the work we do for America's energy future.

Brian J. Anderson, Ph. D.
Director, NETL

MISSION

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

NETL's enduring mission elements are effective resource development, efficient energy conversion, and environmental sustainability.

VISION

NETL's vision is to be the nation's renowned fossil energy science and engineering resource, delivering world-class technology solutions today and tomorrow.

CORE COMPETENCIES


COMPUTATIONAL SCIENCE & ENGINEERING


MATERIALS ENGINEERING & MANUFACTURING


GEOLOGICAL & ENVIRONMENTAL SYSTEMS


ENERGY CONVERSION ENGINEERING


SYSTEMS ENGINEERING & ANALYSIS


PROGRAM EXECUTION & INTEGRATION

NETL TECHNOLOGY THRUSTS

OIL & GAS TECHNOLOGY THRUSTS


ENHANCED RESOURCE PRODUCTION


ENVIRONMENTALLY PRUDENT DEVELOPMENT

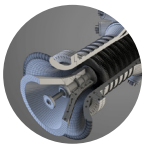

OFFSHORE


METHANE HYDRATES

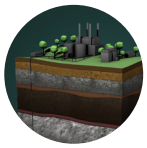

NATURAL GAS INFRASTRUCTURE


UNCONVENTIONAL

COAL TECHNOLOGY THRUSTS

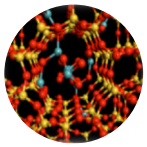

ADVANCED ENERGY SYSTEMS


CARBON CAPTURE


CARBON STORAGE


RARE EARTH ELEMENTS


WATER MANAGEMENT


ADVANCED COMPUTING


SENSORS & CONTROLS


ADVANCED MATERIALS

SUPPORTING OTHER DOE OFFICES

ENERGY EFFICIENCY & RENEWABLE ENERGY (EERE)


VEHICLES


SOLID STATE LIGHTING


GEOTHERMAL

OFFICE OF ELECTRICITY (OE)


MICROGRID


ENERGY STORAGE

CYBERSECURITY, ENERGY SECURITY AND EMERGENCY RESPONSE (CESER)

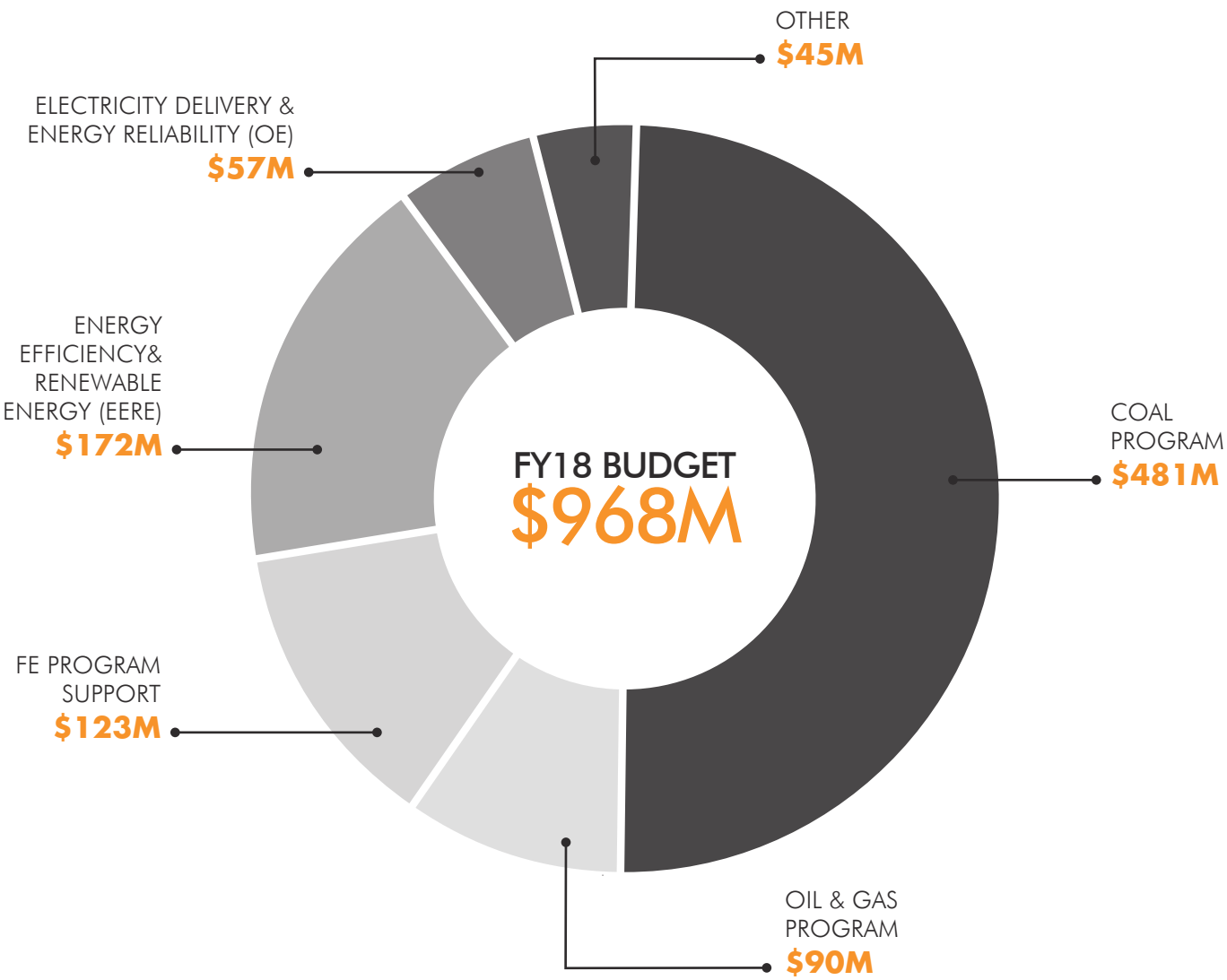

ENERGY SECURITY & RESTORATION


CYBERSECURITY

FY18 BUDGET & FUNDING

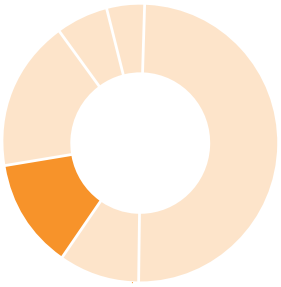
NETL's FY18 federal budget funding was $968 million, with a majority of that funding supporting mission work for the Office of Fossil Energy. The laboratory's research portfolio includes more than 900 projects and activities in nearly all 50 states, with a total value that exceeds $6.5 billion and private cost-sharing of more than $3 billion.

More than 1,100 employees work at NETL—a workforce of 467 highly skilled federal and 714 contract staff.



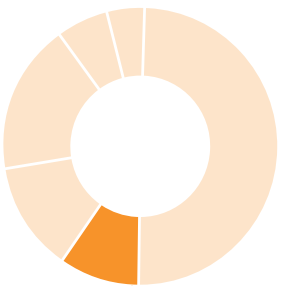
COAL PROGRAM

- CARBON CAPTURE — **$101M**
- CARBON STORAGE — **$98M**
- ADVANCED ENERGY SYSTEMS — **$112M**
- CROSSCUTTING RESEARCH — **$58M**
- NETL COAL R&D — **$38M**
- RARE EARTH ELEMENTS — **$15M**
- STEP — **$24M**
- TRANSFORMATIVE COAL PILOTS — **$35M**



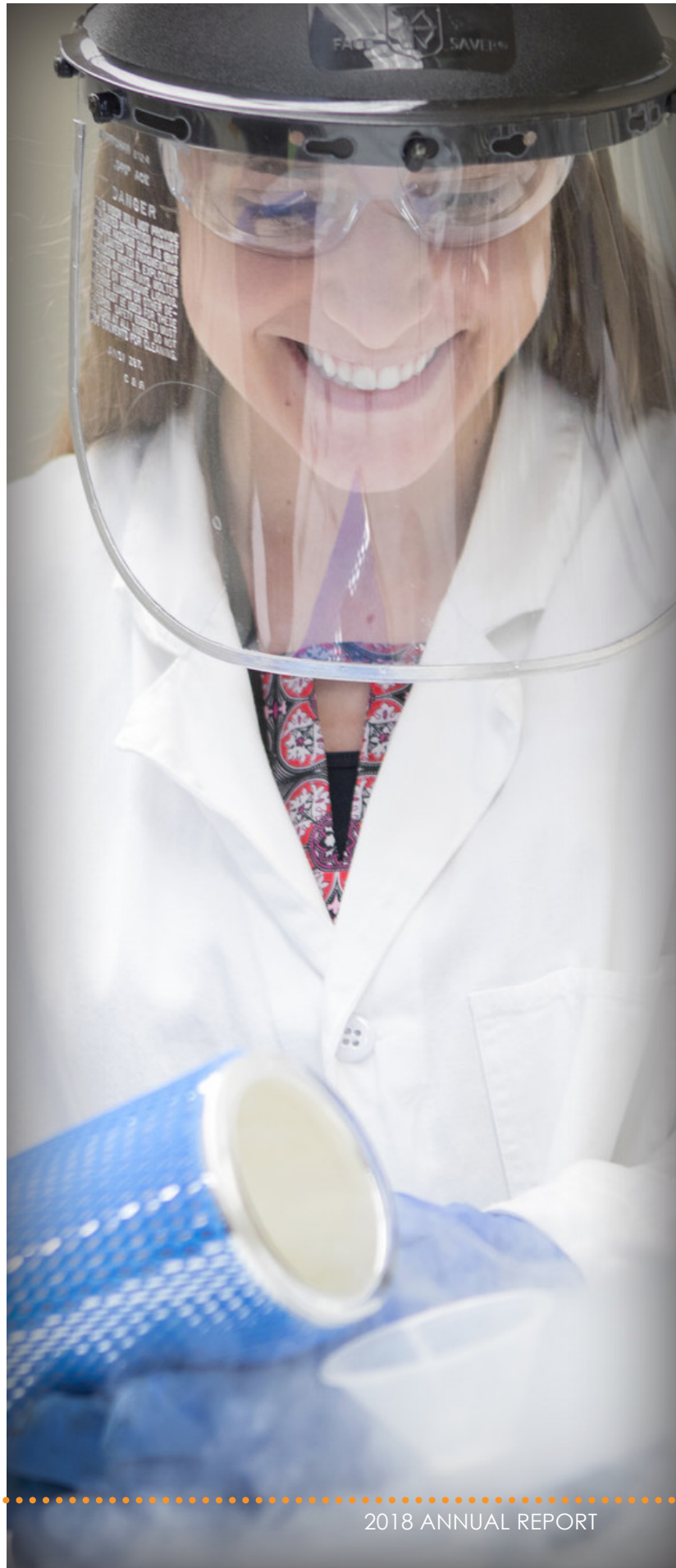
FE PROGRAM SUPPORT

- PROGRAM DIRECTION — **$28M**
- NETL RESEARCH & OPERATIONS — **$50M**
- NETL INFRASTRUCTURE — **$45M**



OIL & GAS PROGRAM

- NATURAL GAS TECHNOLOGIES — **$50M**
- UNCONVENTIONAL FE TECHNOLOGIES — **$40M**



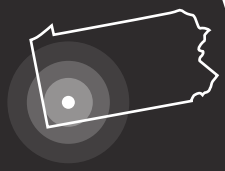
REGIONAL ECONOMIC BENEFITS

An NETL economic analysis revealed that the Laboratory injected a total of $202 million directly into the state economies where the laboratory research sites reside—Oregon, Pennsylvania, and West Virginia. These economic impacts include full-time jobs at NETL research sites, filled by federal and contractor employees, as well as NETL's spending on grants, R&D awards, cooperative agreements, contracts, and purchase orders within the laboratory's host states. NETL's impact on the three state economies is greater than the total of the laboratory's direct spending, because money spent by NETL is spent again by the recipient employees and businesses. NETL had a total estimated impact of $408 million on the three state economies.

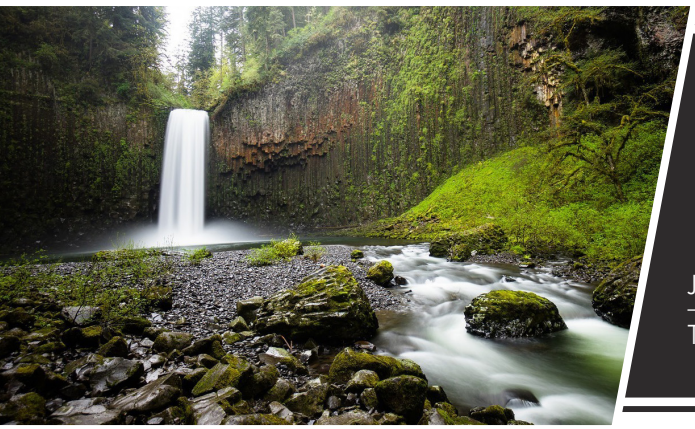
Total Economic Impact of NETL on the **State of West Virginia** [2017]

Jobs (direct, indirect, and induced full-time equivalent jobs)	**1,074**
Total Economic Impact (direct, indirect, and induced)	**$151M**

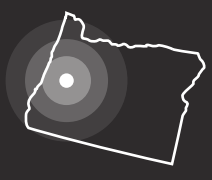
Total Economic Impact of NETL on the **State of Pennsylvania** [2017]



Jobs (direct, indirect, and induced full-time equivalent jobs)	**1,360**
Total Economic Impact (direct, indirect, and induced)	**$222M**



Total Economic Impact of NETL on the **State of Oregon** [2017]



Jobs (direct, indirect, and induced full-time equivalent jobs)	**232**
Total Economic Impact (direct, indirect, and induced)	**$35M**

SELECT ACCOMPLISHMENTS

NETL-Supported Research Cruise Racks Up Methane Hydrate Data Successes

An NETL-supported interagency federal research cruise on the University of Delaware's research vessel Hugh R. Sharp yielded data that confirmed previously detected methane hydrates and discovered new deposits.

A methane hydrate is a cage-like lattice of ice that contains trapped molecules of methane, the chief constituent of natural gas. If a methane hydrate is warmed or depressurized, it reverts to water and natural gas. When brought to the earth's surface, one cubic foot of gas hydrate releases up to 180 cubic feet of natural gas, making it a potentially massive new energy source. Hydrate deposits occur under Arctic permafrost and beneath the ocean floor along continental margins, like the Mid-Atlantic.

This federal research effort to characterize methane hydrate deposits included the U.S. Geological Survey, the U.S. Department of the Interior's Bureau of Ocean Energy Management and the U.S. Department of Energy's Office of Fossil Energy.

Researchers acquired six seismic lines running down the continental slope from the shelf-break to waters as deep as about 12,100 feet (3,700 meters) offshore New Jersey, Delaware, Maryland, Virginia and North Carolina. MATRIX also completed three upper continental slope lines and three deepwater (more than 8,860 feet [2,700 meters] water depth) lines oriented parallel to the coastline in this sector. The work fills a gap in seismic data acquisition along the U.S. Atlantic margin and will be used by academic collaborators and other researchers.

Technology for Recovering Rare Earth Elements from Coal Ash Hits Key Target

An NETL-managed and co-funded project took a significant step toward developing a pilot-scale test facility for creating a more effective way to harvest rare earth elements (REEs) from coal ash, a byproduct of coal combustion created when coal is burned to generate energy.

REEs are used for national security, energy independence and economic growth because they are needed in high-technology products.

Coal-fired power plants are major producers of coal ash. The components of the ash vary depending on the type and origin of the coal. Major ingredients in coal ash include rare earth minerals and elements that remain after the coal is burned in the power plant boiler.

America's vast coal resources can potentially reduce the nation's dependence on other countries for these critical materials.

REEs occur in low concentrations in coals and coal byproducts. Trace amounts are measured in concentrations ranging up to 1,000 parts per million. In a project supported by NETL and using post-combustion coal ash as the feedstock, Physical Sciences Inc. (PSI), in a partnership with the University of Kentucky Center for Applied Energy Research (UK/CAER) and Winner Water Services, produced a mixed rare earth product using a micro-pilot chemical processing system.

Starting with a 500 ppm rare earth concentration in fine ash fed to the micro-pilot system, PSI made a product with greater than 50,000 ppm rare earth concentrations, or greater than 5 percent by weight — a 100-fold increase in rare earth concentration.

NETL Locates Natural Gas Gathering Lines and Quantify Methane Emissions

In 2018, NETL worked to locate and quantify methane leaks in natural gas infrastructure.

A pipeline network spanning more than 3 million miles delivers more than 24 trillion cubic feet of natural gas to 70 million-plus consumers in the United States each year. This infrastructure includes three categories of pipelines: gathering lines, which transport raw natural gas from wells for processing; transmission lines, which move processed natural gas to distribution centers and storage facilities across the country; and distribution lines, which deliver natural gas to customers.

Gathering lines are of interest to NETL researchers because leaks from gathering lines are not as well-characterized.

The first challenge is finding the endpoints of the lines, which are usually wells and processing stations. Processing stations are well-marked on maps, but individual wells are sometimes not well-marked, either on maps or on the ground. A previous NETL study that focused on finding oil and natural gas wells explored the use of aerial surveys by helicopter using powerful magnets or methane detection equipment. Aerial magnetic surveys were determined to be the most accurate, economical and time-effective method to locate steel-cased wells in large areas.

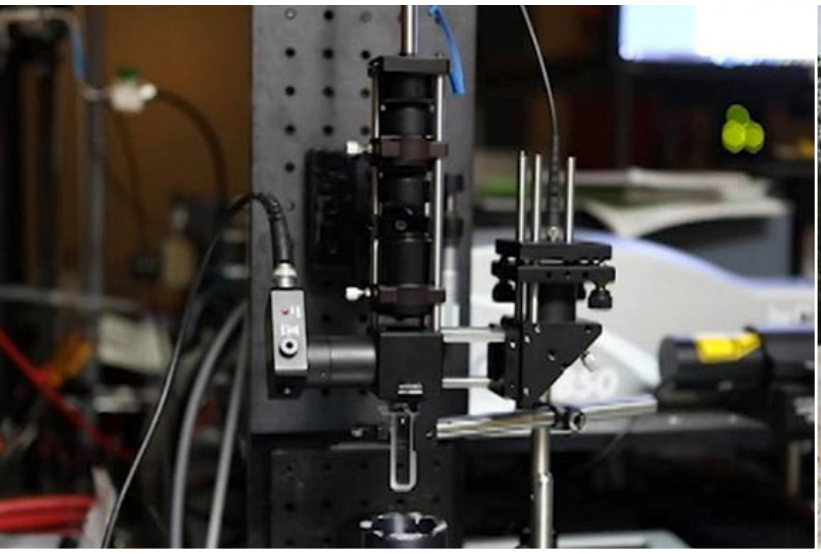
NETL conducted a preliminary two-day ground survey at Moshannon State Forest near Dubois, Pennsylvania. The survey found maximum methane concentrations around 5 parts per million (ppm), a level considered low. Vital information gathered through NETL studies like these contribute to the Lab's efforts to develop robust technological resources that meet energy-related research needs.

Marcellus Shale Research Begins at Second West Virginia Site

Data from three years' worth of research from the Marcellus Shale Engineering and Environmental Laboratory (MSEEL) — a research partnership funded by NETL that involves West Virginia University (WVU) and Northeast Natural Energy (NNE) — will guide more extensive testing at a new well site near Blacksville, West Virginia. MSEEL is a cornerstone of NETL's unconventional oil and gas program. The new work is geared toward improving gas recovery from horizontal drilling and hydraulic fracturing at sites throughout the region.

The work advances hydraulic fracture stimulation techniques that were pioneered by NETL years ago. A key objective of the upcoming field test is to develop advanced completion capabilities that can be applied to other areas of the Marcellus Shale play to improve resource recovery efficiency.

Through core analysis and advanced well logging technologies, WVU and NNE were able to design stimulation zones, or "stages," that optimized perforations around natural fractures in the shale at the Morgantown Industrial Park site. Monitoring using seismic and fiber optic distributed temperature and acoustic sensing during stimulation and subsequent production logging confirm that these engineered stages outperformed conventional geometrically designed stages.



NETL Uses Miniaturized Laser Technology to Characterize Domestic Sources of Rare Earth Elements

NETL researchers developed better ways to characterize a variety of rare earth element (REE) sources using a new miniaturized laser technology to quantify the concentrations of REEs in sources like coal and coal-related byproducts.

The sensor can be used to detect REE concentrations in situ. To determine what elements are present, the device creates a pulse of light that is amplified and focused to make a spark. The spark emits light in all directions, creating characteristic atomic emissions. This light is then back-transmitted through the device, traveling up the optical fiber to a spectrometer that analyzes the light for elemental composition.

The sensor technology is based on laser-induced breakdown spectroscopy (LIBS), but NETL has miniaturized a traditional LIBS system so it can be placed in situ and determine rare earth concentrations without the need to remove a sample and bring it back to the lab. Source characterization is a crucial step for assessing the commercial viability of a potential extraction site. The system has successfully demonstrated rapid measurement of REEs in both solid and liquid samples at ppm-level concentrations.

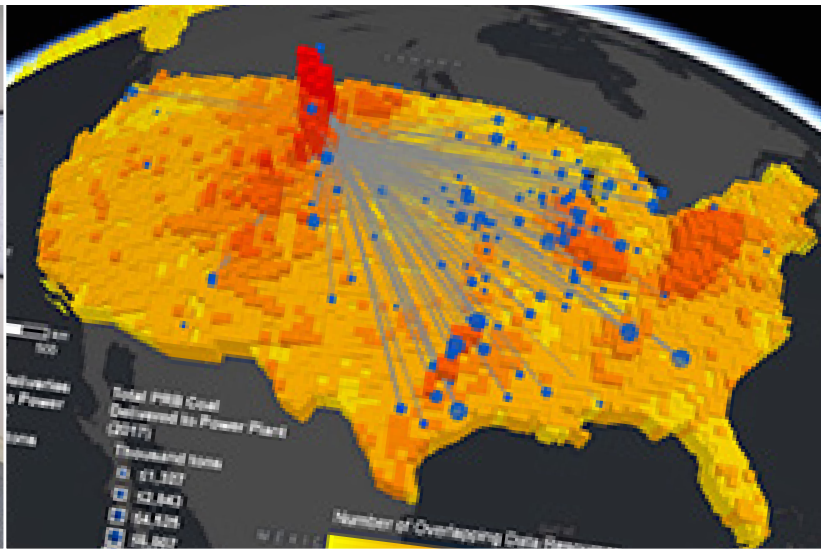
NETL-Developed Methods and Tools to Estimate Prospective Carbon Dioxide Storage in the Subsurface

NETL developed a tool to better predict CO_2 storage potential in geologic formations. The innovation is called CO_2-SCREEN and was designed to estimate underground storage potential for CO_2 captured from fossil fuel-burning power plants.

Large, permeable, porous rock volumes are ideal for securely storing captured CO_2. Storage of CO_2 in these geological reservoirs is crucial for successful reductions in greenhouse gas emissions. CO_2-SCREEN, which stands for CO_2 Storage prospeCtive Resource Estimation Excel aNalysis, was developed to provide a substantive, user-friendly and consistent mechanism to calculate CO_2 storage resources so decision makers have enough information to reach crucial conclusions.

Since 2007, NETL has worked with partners to create an atlas of carbon storage regions in the United States and parts of Mexico and Canada. CO_2-SCREEN is an online tool that applies NETL's method to calculate prospective CO_2 storage resources.

CO_2-SCREEN estimates saline formation storage potential based on pore volume calculations and efficiency factors that gauge the total pore volume accessible for CO_2 storage.



NETL Explores Subsurface Data Using Cutting-Edge 3D Imaging Technology and Analysis

Without ever leaving the lab, NETL researchers explored the microscopic spaces in rocks, called pores, to take measurements as they seek a better understanding of how liquids and gases interact. These measurements expand scientific knowledge of the subsurface environment to ensure safe and effective carbon storage, enhanced resource recovery and basic scientific understanding of subsurface phenomena.

NETL used cutting-edge imaging technology that enables 3D visualization and analysis of volumetric data at the submillimeter scale. The innovative software, called SyGlass, brings data to life through virtual reality, allowing researchers to examine real-world energy challenges in three dimensions.

NETL researchers used SyGlass to measure contact angles, where liquids and gases meet on a solid surface, as they investigate how CO_2 physically interacts with water or brines within rock pores. SyGlass was created by Michael Morehead, a former graduate student studying computer science at West Virginia University, at the request of a neuroscience professor who sought a better way to visualize images of brain tissue in mice. The software is designed to incorporate a series of images into a 3D structure, using a virtual reality headset for enhanced scientific analysis.

When NETL expressed interest, Morehead began developing additional tools to meet the Lab's needs and expand the program's capabilities. Morehead said NETL offered a unique opportunity for SyGlass as the company's first foray into other scientific areas.

NETL Researchers Pinpointed New Domestic Sources of Rare Earth Elements Using Advanced Techniques

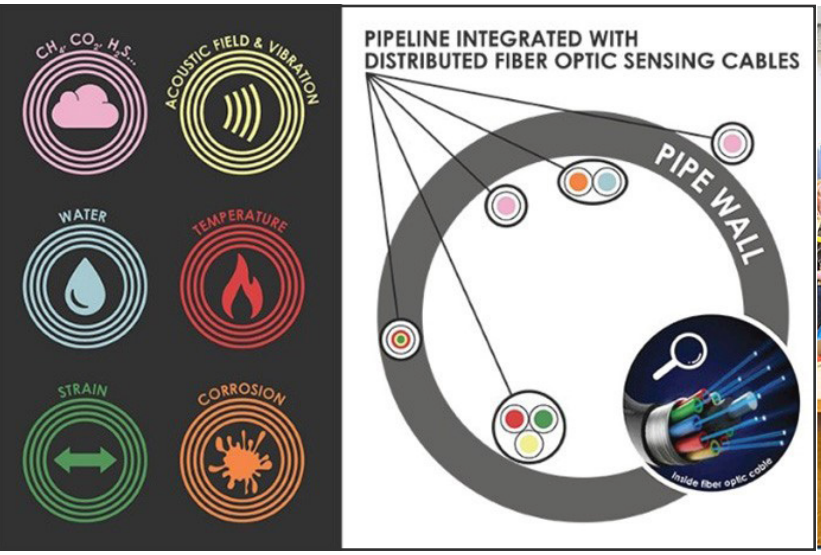
NETL researchers are working to secure a low-cost domestic supply of rare earth elements (REEs) by identifying promising sources using a combination of big data analysis, advanced microscopy and development of innovative exploration and recovery processes.

REEs are essential for the manufacture of virtually all high-tech devices, including many defense and energy technologies. However, nearly all the nation's REE supplies are imported, which can create vulnerabilities when markets shift unpredictably.

In addition to its research projects and strategic partnerships focused on recovering REEs from domestic coal and coal-related byproducts, NETL is investigating the strata around coal, such as underclays, which can contain a significant concentration of REEs. Not all formations were created equally, and some hold far greater potential than others for commercial rare earth extraction.

To narrow down their focus to only the areas likely to contain significant levels of rare earths, researchers are developing a novel approach to systematically predict REE concentrations in coal and coal-related strata. In addition to spatial and statistical analysis of huge datasets from sources like the United States Geological Survey, the effort involves incorporating existing resource characterization methods from the petroleum, coal and mineral mining industries to indicate where conditions are most favorable for REE deposits associated with U.S. coals.

Extraction of REEs from underclay deposits shows great promise as a new way of securing a domestic supply.



Fiber-Optic Sensors Offer New Ways to Protect America's Pipelines

Secure, reliable natural gas delivery is essential to meet America's energy needs. Natural gas accounted for nearly 32 percent of the electricity produced in the United States in 2017, and the U.S. Energy Information Administration expects that figure to rise to nearly 39 percent by 2050.

More than 300,000 miles of large transmission pipelines transport domestic natural gas nationwide. Every inch is susceptible to corrosion, the natural deterioration of metal materials caused by chemical reactions to the environment. Corrosion is one of the leading causes of pipeline leaks and ruptures, which present threats to the safety of employees and the security of the nation's energy supply.

NETL researchers developed advanced fiber-optic sensor systems that protect America's pipelines by preventing leaks and failures before they occur, including optical fibers coated with corrosion proxy materials that deteriorate as the pipeline corrodes. When placed along a pipeline, laser light transmitted through the optical fiber produces backscattered light that shows imperfections in the thin corrosion proxy film. Those imperfections reflect conditions conducive to the onset of corrosion along the pipeline before failures occur, pinpointing the exact location for pipeline operators.

Researchers also developed a novel fiber-optic sensor that can detect and characterize water condensation within the pipeline and will expand the water-detection technology by incorporating additional fiber-optic sensing capabilities – such as dissolution of corrosive gases, fluctuation in temperature and pressure changes – that aid corrosion monitoring.

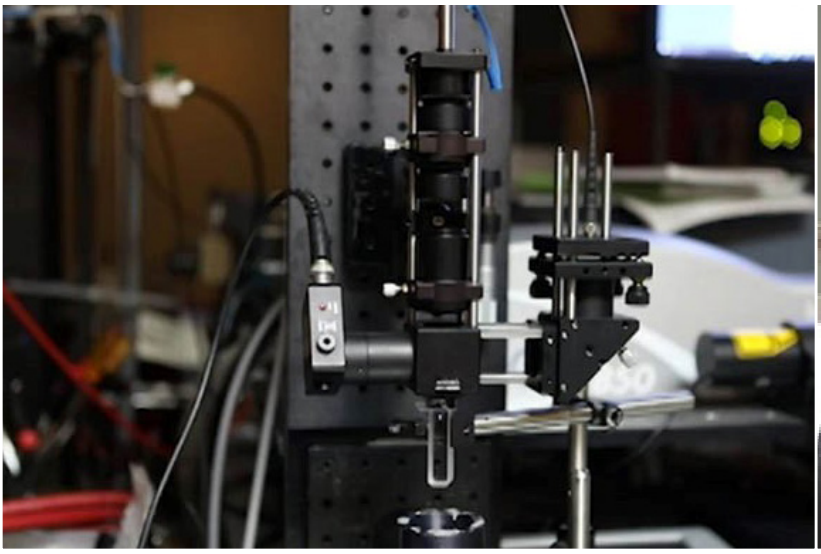
Bench-Scale Facility Launched to Extract Rare Earth Elements

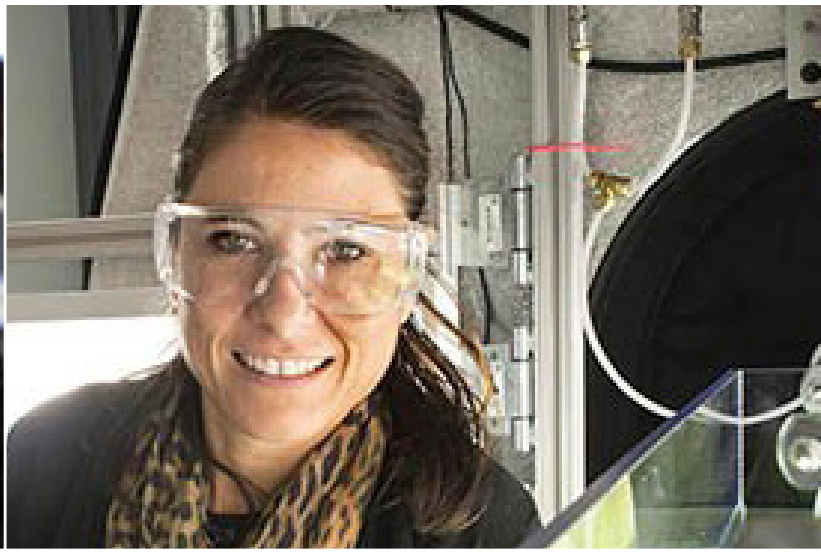
An innovative bench-scale facility established at West Virginia University (WVU) in collaboration with NETL will demonstrate the feasibility of extracting rare earth elements (REEs) from acid coal mine drainage (AMD) to develop a domestic supply of REEs – an effort that will enhance America's economic growth and national security.

The WVU Rare Earth Extraction Facility was created as part of an ongoing DOE project managed by NETL. Lab representatives joined DOE Assistant Secretary for Fossil Energy Steven Winberg, WVU President E. Gordon Gee and other leaders and noted dignitaries for a commissioning event held July 18 to celebrate the launch of the new facility.

REEs are valuable chemical and metallurgical elements that are traditionally found in Earth's crust. They are used in everyday technology devices – such as smartphones and computer hard drives – and by a broad range of industries including transportation, health care and defense.

The WVU Rare Earth Extraction Facility will investigate the technical feasibility of extracting REE concentrates with a purity of at least 2 percent – or 20,000 parts per million – from solid residues or sludge generated during treatment of AMD. The continuously operating facility will employ a two-stage chemical separation process that includes acid leaching and solvent extraction to produce about 3 grams of REE concentrate per hour.





NETL Develops Affordable, Accurate Monitoring Tool for the Subsurface

NETL researchers developed a more affordable, in situ monitoring tool based on laser induced breakdown spectroscopy (LIBS) to provide rapid elemental analysis without extensive sample collection or preparation.

Many of the available LIBS systems are large and complex, employing above-ground, laboratory-scale lasers, but NETL has designed a simple, easy-to-fabricate, handheld LIBS system fully adaptable to field use and capable of measurements even in harsh environments.

Oil and gas exploration companies, land owners, regulatory agencies, municipalities and many others are keenly interested in a simpler and more cost-effective solution — one that can be deployed on-site and survive long-term in downhole conditions.

The NETL device boasts a unique split laser design coupled with solid state optics, allowing for both single and multipoint at-a-distance monitoring. LIBS systems can rapidly analyze solids, liquids and gases and can quickly return results with very little damage to the sample. In a water monitoring scenario, the all-optical sensor can be deployed underground into a source of drinking water.

The technology will benefit Americans by providing accurate analysis of elements from within their environments, ensuring safety and quality. In addition to monitoring water quality in both aquifers and water treatment facilities, this kind of analysis could also be used to check for CO_2 leakage at storage sites and to help identify rare earth elements that are critical to technologies we rely on every day.

NETL Plays Key Role in DOE's New Lab Partnering Service Web Experience

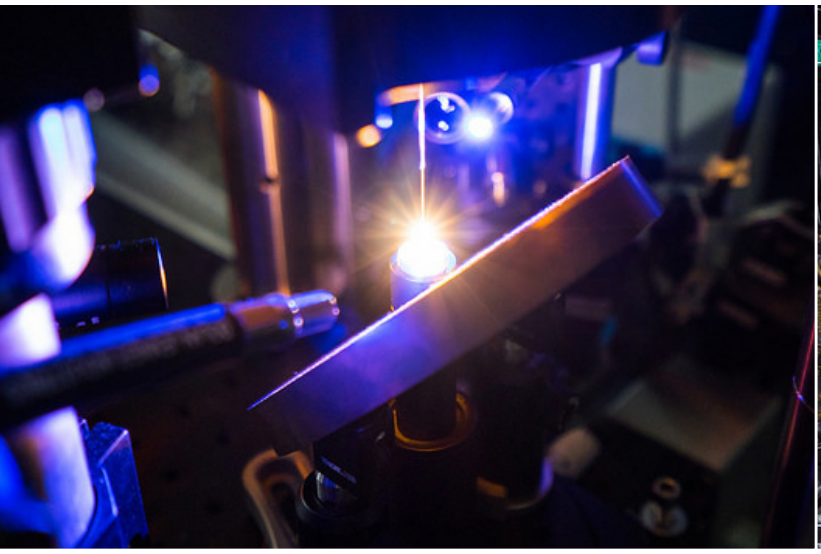
NETL, the only DOE national laboratory focused on development of advanced fossil energy technologies and the only government-owned and government-operated (GOGO) national laboratory, played a prominent part in DOE's new Lab Partnering Service (LPS) Internet presence that offers technology investors and innovators multi-faceted search capabilities across a range of technology areas in the national laboratories.

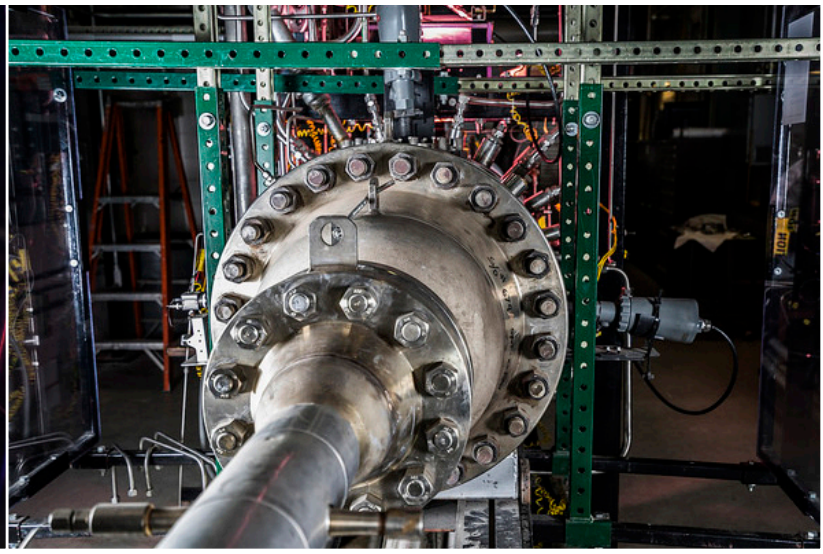
The LPS website is accessible at www.labpartnering.org.

NETL's program management capabilities, onsite analysis and experimental capabilities can be used to pursue high-risk technology developments that enable further industrial development and deployment of commercialized technology solutions. Those capabilities are highlighted on the new LPS website.

The LPS site provides three essential information services: an expert search capability giving users a categorized list of research and a direct conduit to DOE experts; technical summaries of technologies and publications available from national laboratories and participating institutions; and a tool for searching DOE-patent content beyond a simple keyword search.

An additional way NETL's work with the initiative is key is because, as a GOGO, NETL is the only DOE national laboratory authorized to issue funding opportunity announcements on behalf of the Department — a means for NETL to issue hundreds of new financial awards each year.





NETL Researchers Use Lasers to Develop Manufacturing System for Optical Sensors

NETL researchers developed a way to use lasers to make better sensors that work more efficiently inside the harsh environments of power generation systems, from traditional coal-fired power plants to solid oxide fuel cells, gas turbines, boilers and oxy-fuel combustion.

The results of that work are improved controls for power plants, lower costs for power producers, lower bills for customers, reduction in power outages, lower CO_2 emissions and increased power production efficiencies. The challenge for researchers has been to devise sensors that can provide real-time measurements of temperature, pressure, gas species and more amid harsh conditions. That's where lasers come into the picture.

The laser-heated pedestal growth (LHPG) system at NETL allows researchers to fabricate optical fiber sensors that are ideal for the challenging environments associated with fossil fuel-based power generation systems. LHPG is a crystal growth technique that involves using a CO_2 laser, combined with a complex beam delivery system and carefully controlled fiber-pulling mechanisms, to melt and reform high temperature-resistant materials into single-crystal optical fibers.

Optical fibers are flexible, transparent light-guides slightly thicker than a human hair and typically made of glass or plastic. Their resistance to electromagnetic interference and ability to fit into confined spaces make them useful for transmitting light and communications, their most well-known uses. By fabricating optical fibers from single-crystal materials like sapphire and YAG (yttrium aluminum garnet), those same traits can be exploited in harsh environments.

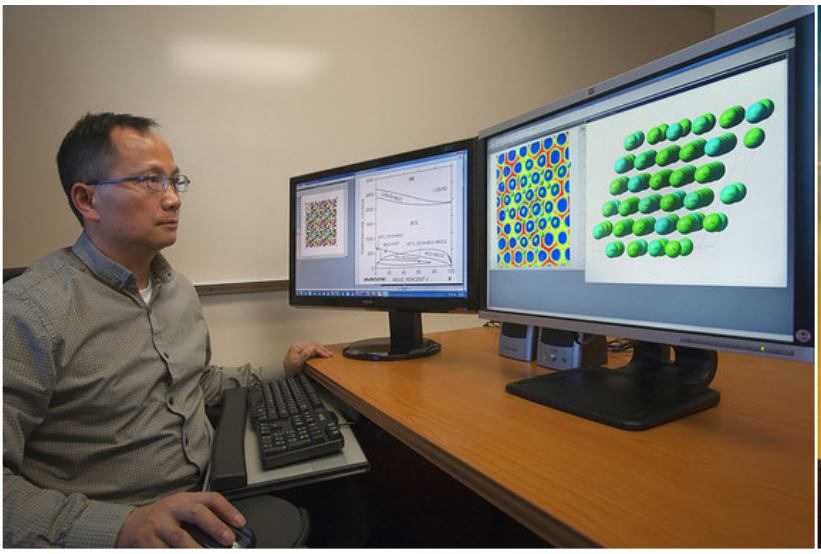
NETL's High-Pressure Combustion Research Attracts Prestigious Research Partners

NETL's groundbreaking research on a process to increase the efficiency of power-producing turbines attracted research partners from some of the nation's leading academic institutions as well as the U.S. Air Force, and the results could someday mean lower consumer electricity bills.

Modern turbines are engineering marvels that provide affordable and reliable energy for the nation. Today's state-of-the-art combined cycle power generation – an assembly of heat engines that work together from the same source of heat to convert it into mechanical energy – are capable of efficiencies of 60 percent or higher. NETL researchers are eyeing efficiencies of 65 percent and beyond, a step-change that could translate to a reduction of electricity costs by more than 15 percent.

Through the University Turbine Systems Research Program, NETL's Advanced Combustion Program provided funding to support studies at the University of Michigan, University of Purdue and Pennsylvania State University. NETL's Advanced Turbine Program and Advanced Combustions Systems Program currently support a six-year study (2014-2019) at Aerojet-Rocketdyne to explore the potential of rotating detonation engines for combustion in a high-efficiency gas turbine engine.

NETL's effectiveness is leading to combined cycle power plants with higher efficiency and reduced emissions for greater energy security, environmental improvements and a stronger economy.



NETL Conducts Computational Materials Modeling for Extreme Environments of Advanced Fossil Energy Technologies

Advanced fossil energy technologies, such as ultra-supercritical steam plants and oxyfuel combustion boilers, have the potential to increase efficiency and bolster clean coal efforts since they operate at higher temperatures and pressures. However, this leads to harsher and more corrosive conditions compared to traditional power plants in use today.

NETL worked to meet the challenges of these and other fossil energy transformational power technologies through the Extreme Environment Materials (eXtremeMAT) initiative — a new research collaboration comprised of NETL, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, Idaho National Laboratory, Ames Laboratory and Oak Ridge National Laboratory. The project develops next-generation advanced modeling tools, material and component simulation models and advanced manufacturing processes that will innovate and accelerate the design, development and manufacture of high-performance materials that are suitably ready for use in these extreme environments of the future.

With success in the eXtremeMAT program, alloys will be fully optimized for future power generation cycles in less time. These high-performance materials will enable a variety of advanced energy systems that will increase efficiency, lower cost and reduce emissions from fossil-fired power cycles, ensuring affordable and reliable energy for the nation well into the future.

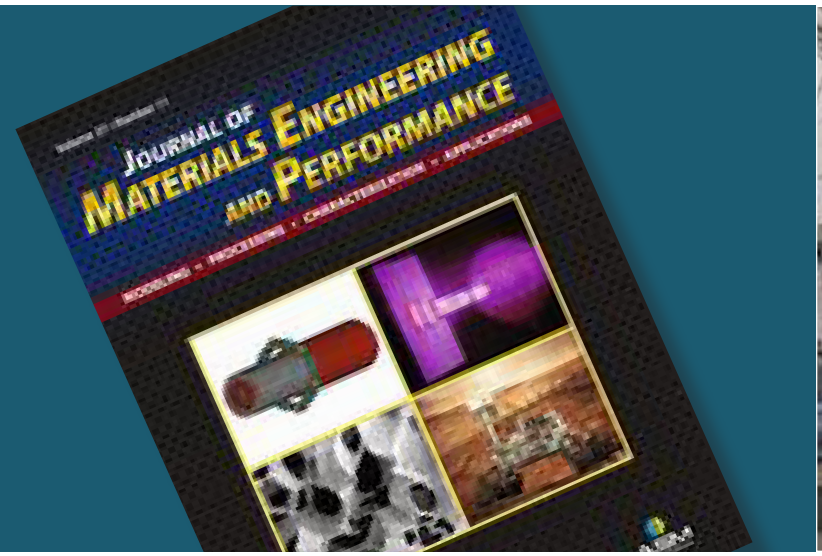
Magnetics Research Uncovers Novel Opportunities for Electric Power Improvements

Advanced power magnetics research conducted by NETL and its partners offers novel opportunities to boost efficiency, spur economic investment and reduce infrastructure as industry looks toward smaller, more efficient power technology capable of meeting the diverse demands of the modern world.

NETL researchers developed a variety of applications, including power electronics, transformers and electrical machinery. Their work is highlighted in the special topic on "Recent Developments in the Processing of Advanced Magnetic Materials," published in the May 2018 issue of the Journal of Minerals, Metals and Materials. In this, they uncover the development of promising new soft magnetic materials and the application of advanced processing technologies for optimizing electromagnetic components.

These components feature metal amorphous nanocomposite alloy cores made with a cobalt-rich alloy system. Researchers use a specialized manufacturing process to anneal the material under tension, adjusting the strain as needed to optimize electromagnetic capability. The technology has unique advantages compared to more traditional inductive components, including improved temperature control and lower overall power losses. The advanced magnetic core technology has already enabled researchers to achieve significant milestones in a project to advance combined solar photovoltaic and battery grid integration.

This research project was funded through the SunShot National Laboratory Multiyear Partnership (SuNLaMP) program, managed by DOE's Solar Energy Technologies Office.



Journal of Materials Engineering and Performance Recognizes NETL Research Paper

A research paper authored by two NETL experts was selected as one of only five editor's choice open access articles for 2017 by the Journal of Materials Engineering and Performance (JMEP). It explains how a new computational algorithm was applied to alloy development to optimize heat treatments and increase consistency of mechanical properties in nickel superalloys and steel castings. Selection by the editors as a highlighted article reflects the comprehensive nature of the paper and its overall excellence.

The NETL paper, "Homogenizing Advanced Alloys: Thermodynamic and Kinetic Simulations Followed by Experimental Result," documented and explained how the researchers used modelling software to design a way to optimize heat treatments.

A process called segregation of solute elements occurs in nearly all metal alloys during solidification. As a result, material properties can be severely degraded, which leads to later problems during processing. Heat treatments, known as homogenization, are often used to minimize segregation and improve performance. Traditionally, those heat treatments can be time-consuming because they are based on trial-and-error experiments.

Using the NETL method, engineers can homogenize casting chemistries to levels that are appropriate for specific applications. The NETL method also enables heat treatment schedules to be adjusted to fit limitations of heat-treating equipment, enabling routines to be used during commercial homogenization of ingots and castings. The process thus helps save time and money in manufacturing components for industrial uses.

NETL Develops New High-Entropy Alloys for Use in Energy-Related Hardware to Increase Efficiency

Increasing the efficiency of how energy is produced in an array of facilities that dot America's landscape is at the core of efforts to reduce the amount of fuel required to produce power, decrease harmful emissions and eliminate waste. Increasing efficiency requires better processes and, especially, better materials for withstanding the pressures and temperatures in everything from the boilers that combust fuels to the power-making turbines that keep the nation warm in winter, cool in summer and its lights on year-round.

NETL researchers worked with the design, development, manufacture and testing of advanced heat-resistant alloys, superalloys and novel alloys such as high-entropy alloys (HEA) that can meet escalating efficiency improvement challenges and help create the next generation of energy industry hardware.

HEAs are substances constructed with equal or nearly equal quantities of five or more metals, combining the strength and characteristics of the individual elements into a superior substance. Based on the analysis they conducted on HEA possibilities, NETL researchers fashioned ingots shaped into plates, sheets, rods and other forms. Most work done in the lab involved exposing HEAs to intense heat and pressure with equipment like a 500-ton hydraulic press and a hot rolling mill.

NETL experts characterized the properties of the newly created HEAs and assessed how they can be used in real-world settings. In addition to boilers and turbines, HEAs have great promise for use as hydrogen storage tanks, radiation-resistant materials, diffusion barriers for electronics, precision resistors, electromagnetic shielding materials, soft magnetic materials, functional coatings and even antibacterial materials.

NETL Collaboration and Life Cycle Analysis Expertise Advances Understanding of Methane Emissions

NETL partnered with a natural gas industry consortium to help assess the efficiency of the consortium's natural gas supply chain and additional methane emissions mitigation opportunities that could increase the efficiency of natural gas delivery.

Working with Our Nation's Energy Future (ONE Future), a natural gas industry partnership dedicated to improving the efficiency of the natural gas supply chain, NETL's efforts demonstrate how industry and government can work together to improve the understanding of methane emissions and identify potential reduction strategies that can improve the long-term operational efficiency of the nation's natural gas production and delivery systems.

In their collaboration with ONE Future, NETL researchers used their expertise in life-cycle analysis (LCA) to compare ONE Future member company's methane performance to the U.S. national average for the industry. The results provide the current state of knowledge on methane emissions in an actionable form to improve the performance of U.S. natural gas production and delivery.

LCA examines the environmental, economic and social attributes of energy systems, ranging from the extraction of raw materials from the ground to the use of the energy carrier to perform work — the life cycle of a product. NETL's LCA model is considered one of the most sophisticated energy models that, in combination with other analytical data, enables policymakers and the public to discern the impact of technology-policy choices.

NETL-Led Team Creates First-Ever International Database for Preventing Natural Gas Infrastructure Failures

The first-ever database inventory of oil and natural gas infrastructure information from the top hydrocarbon-producing and -consuming countries in the world is now available online. The database was born from a massive information acquisition, evaluation and resource integration project led by NETL, which released the database on the Laboratory's Energy Data eXchange (EDX) — an online collection of capabilities and resources that advances research and customizes energy-related needs.

The database, known as the global oil and gas infrastructure (GOGI) inventory, identifies more than 4.8 million individual features like wells, pipelines and ports from more than 380 datasets in 194 countries. It includes information about the type, age, status and owner/operator of infrastructure features.

The GOGI inventory offers an economic, environmental and health and safety tool for researchers, industry representatives and government regulators to help prevent infrastructure failures, improve economics of energy production and address fugitive methane emissions.

One of the key objectives of the work is to help identify and monitor methane leaks from natural gas infrastructure to prevent future leaks and mitigate the associated economic and environmental impacts. Methane is the primary component of natural gas and is a greenhouse gas when released into the atmosphere. Methane leaks from natural gas infrastructure are also a lost opportunity for producers to sell the commodity to consumers.

NETL-Supported Coalition Makes Strides in Addressing Fossil Energy Research Challenges

NETL addressed fundamental fossil energy research challenges in partnership with 16 universities across the country. The University Coalition for Fossil Energy Research (UCFER) hosted its first annual technical review meeting in April at NETL's Morgantown, West Virginia site.

NETL Director (Acting) Sean Plasynski, Ph.D., noted that 33 percent of NETL's research investment funding in the current fiscal year went to university partners through a variety of academic programs in addition to UCFER.

More than 80 percent of U.S. energy demand is met using fossil energy sources. UCFER Director Chunshan Song, Ph.D., of Pennsylvania State University, highlighted energy outlook statistics that show fossil fuels will continue to account for the bulk of U.S. energy use in the decades to come. He said UCFER's goal is to advance basic and applied energy research in collaboration with NETL for more efficient and environmentally friendly use of coal, oil and natural gas.

Partnerships like UCFER help NETL leverage its connections, resources and expertise to develop reliable and affordable solutions to the nation's energy challenges. By finding ways to cut costs and boost efficiency, innovations by NETL and its partners support home-grown energy initiatives, stimulate a growing economy and improve the health, safety and security of all Americans.

NETL Co-hosts Student Mentoring Program in Oregon to Encourage STEM Careers

NETL co-hosted a special event in April to help mitigate participation disparities in science, technology, engineering and math (STEM) fields by connecting enthusiastic professionals with interested students and their educators.

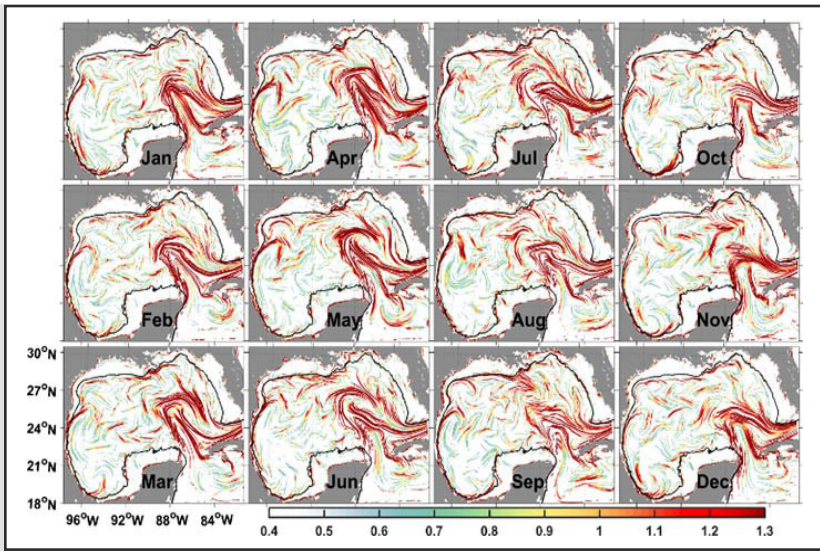
NETL, DOE and the Oregon State University (OSU) College of Science hosted the Mid-Willamette STEM Mentoring Café at OSU's Memorial Union, in Corvallis, Oregon. Middle- and high-school students had the opportunity to chat with STEM role models, see samples of their work and ask questions. Educators received take-home materials to continue STEM engagement with their students. Participating professionals were encouraged to offer ongoing mentoring to students and educators in their community.

The STEM Mentoring Café program is part of DOE's ongoing commitment to fostering the next generation of scientists, engineers and other professionals in high-technology careers. Since 2014, hundreds of students across the country have participated. The Mid-Willamette event was the first STEM Mentoring Café of 2018.

Educational outreach is an important part of NETL's mission to enhance the nation's energy foundation for future generations. Members of the Lab's Education Outreach team organize the West Virginia and Western Pennsylvania Regional Science Bowls, visit classrooms, host workshops and participate in special events year-round to complement learning in NETL's local communities.

NETL also supports DOE's STEM Rising program, launched in 2017. The initiative comprises a wide variety of activities and events held throughout DOE's national laboratory system for students and educators of all ages, designed to grow the pipeline of future energy workers.

CCSI
Carbon Capture Simulation Initiative



NETL Releases Carbon Capture Simulation Toolset as Open-Source Software

The Carbon Capture Simulation Initiative (CCSI), led by NETL, released the CCSI Toolset as open-source software.

The CCSI Toolset is the nation's only suite of computational tools and models designed to help maximize learning and reduce cost and risk during the scale-up process for carbon capture technologies. The toolset is critically important to perform design and calculations, thus reducing the cost of both pilot projects and commercial facilities. The release makes the toolset code available for researchers in industry, government and academia to freely use, modify and customize in support of the development of carbon capture technologies and other related projects.

Since the release of CCSI's first toolset in 2012, the initiative exceeded goals and earned an R&D 100 Award — an "Oscar of Innovation" — as one of the top 100 technology products of 2016. The major capabilities of the newest version of the CCSI Toolset include rapid computational screening, accelerated design and evaluation and risk management support.

Led by NETL, CCSI leverages DOE's national laboratories' core strengths in modeling and simulation — bringing together the best capabilities at NETL, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory. CCSI has more than 50 industrial partners that represent the power generation industry, equipment manufacturers, technology providers, engineering and construction firms and software vendors. The project's academic participants include Carnegie Mellon University, Princeton University, West Virginia University, Boston University and the University of Texas.

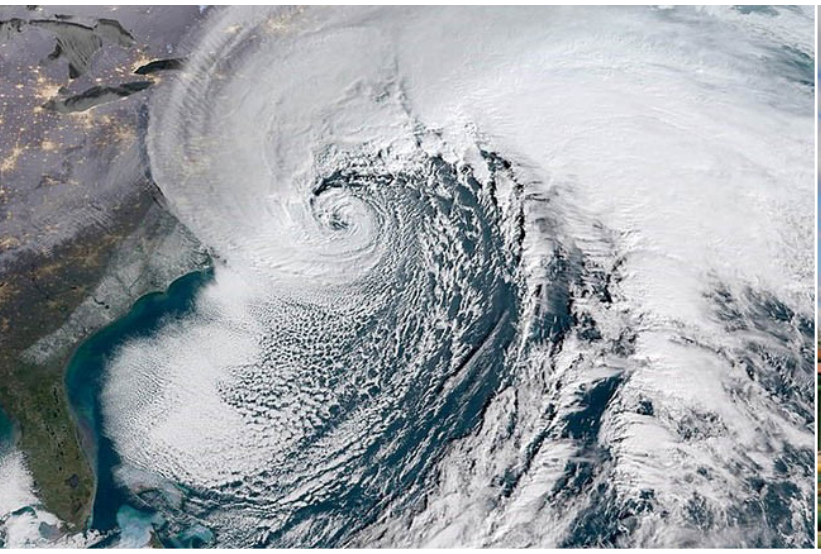
Prestigious Publication Features NETL Offshore Research Innovation and Expertise

NETL has been at the forefront of research to make offshore energy production safer and more efficient ever since the Lab helped assess the Macondo Oil Spill in 2010. In March, a component of that expertise was front and center in the prestigious journal Scientific Reports, released by Nature Publishing Group.

The article, titled "Extracting Quasi-Steady Langrangian Transport Patterns from the Ocean Circulation: An Application to the Gulf of Mexico," described an advanced new metocean modeling tool and approach for extracting likely patterns in ocean circulation.

Metocean refers to a geographic location's combined oceanographic and metereological conditions, such as ocean currents, sea-level changes, storm surges, tides, wind waves, stratification, ice, wind, air temperature, humidity and the occurrence and strength of typhoons and hurricanes. These predictions can help guide offshore infrastructure design, reduce operational costs and provide critical data for assessing offshore oil spill modeling risks.

The work is a culmination of advanced oceanographic data science research that has its roots in NETL's Offshore Risk Modeling (ORM) suite of tools, data and models — a big-data driven system designed to identify knowledge and technology gaps that target offshore spill prevention. The ORM suite can be used to analyze conditions from subsurface to the shore. The system was developed by incorporating lessons learned from previous deleterious events and connects users with tools and datasets driven by advanced computing technologies to address a variety of industry challenges. The ORM suite enables users to characterize and map geologic hazards, optimize planning and maintenance of offshore infrastructure and improve safety and reliability, among other benefits.



NETL Study Highlights the Importance of Coal for Power Generation During 'Bomb Cyclone' Power Demands

An analysis conducted by NETL indicates that continued retirement of fossil fuel power plants could have an adverse impact on the nation's ability to meet power generation needs during future severe weather events.

A winter storm, known as a "bomb cyclone," struck much of the eastern United States between December 27, 2017, and January 8, 2018, plunging the region into a deep freeze and sparking a significant rise in the demand for additional power for heat. Coal provided a majority of the daily power generation required to meet the emergency, according to the study. The report analyzed fossil fleet performance and its contribution to power system reliability and resilience during the bomb cyclone event.

The study showed that coal was the most resilient form of power generation during the event and that removing coal from the energy mix would worsen threats to the electrical grid's dependability during future severe weather events. NETL's Energy Markets Analysis team focused on six organized market areas administered by independent system operators (ISOs) that served regions affected by the bomb cyclone, mostly in Mid-Atlantic and Northeast states.

The NETL study, titled "Reliability, Resilience and the Oncoming Wave of Retiring Baseload Units, Volume I: The Critical Role of Thermal Units During Extreme Weather Events," drew significant conclusions about the importance of fossil fuels in helping the nation answer power demands in times of crisis.

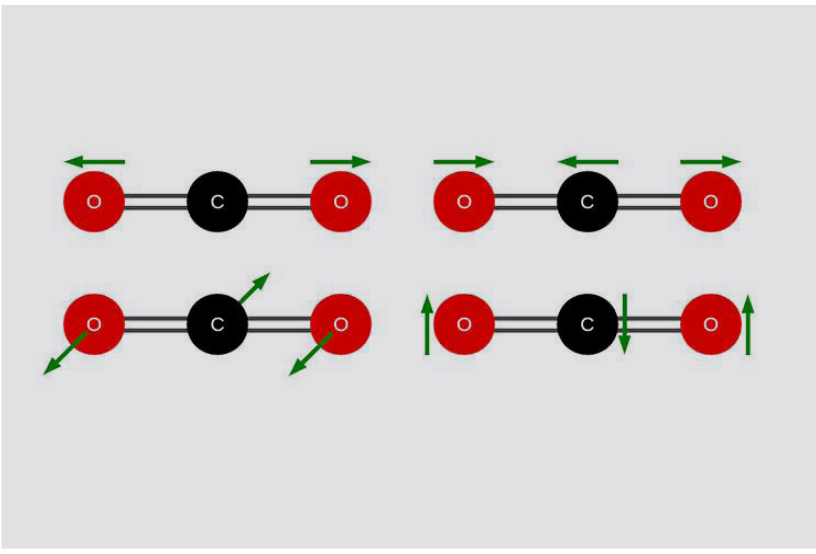
NETL-Managed Project Stores 1 Million Tons of Carbon Dioxide and Boosts Domestic Oil Production

The NETL-managed Midwest Regional Carbon Sequestration Partnership (MRCSP), led by Battelle, achieved an important milestone by safely and permanently storing 1 million metric tons of CO_2 into a series of depleted oil fields in northern Michigan, leading to the production of a significant volume of oil that would have otherwise been left behind.

The project developed novel approaches for monitoring CO_2 in fields that were in different stages of their production life cycles, from initial flooding to late-stage development. MRCSP tested techniques to track the CO_2 and quantify the amount retained in the formation after the oil is removed. This data can be used to further optimize CO_2 storage and energy production in other areas. This work is furthering the understanding of the subsurface by assessing potential storage capacity and validating computer models of the subsurface geology.

The oil was produced through a technique called enhanced oil recovery (EOR), which combines the environmental benefits of storing CO_2 safely and permanently underground with the economic stimulation of increased domestic oil production. The additional oil produced in this project supported hundreds of jobs and generated approximately $70 million in income and associated goods, services and taxes.

The MRCSP region consists of 10 states: Delaware, Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania and West Virginia. A group of leading universities, state geological surveys, nongovernmental organizations and private companies led by Battelle were assembled to carry out this research.



NETL-Managed Projects for Recovering Rare Earth Elements Meet and Exceed Expectations

Four rare earth elements (REEs) recovery projects managed by NETL made significant progress in the development of a domestic supply of REEs from coal and coal byproducts by successfully producing REE concentrates.

The primary goal of these NETL-supported projects is to achieve at least 2 percent — or 20,000 parts per million (ppm) — REE elemental concentration, which represents a significant enrichment from feedstocks that typically contain REEs at 300 ppm (0.03 percent). Each of the projects has met or greatly exceeded this goal. The results are as follows:

- Physical Sciences Inc. (pilot-scale project) achieved 40 percent REE concentration at 15 percent REE recovery using post-combustion fly ash from burning Central Appalachian Basin coal.
- The University of Kentucky (pilot-scale project) achieved greater than 80 percent REE concentration at greater than 75 percent REE recovery using Central Appalachian Basin and Illinois Basin coal preparation plant refuse.
- The University of North Dakota (bench-scale project) achieved 2 percent REE concentration at 35 percent REE recovery using North Dakota lignite coal.
- West Virginia University (bench-scale project) achieved 5 percent REE concentration at greater than 90 percent REE recovery using acid mine drainage solids from the Northern Appalachian and Central Appalachian Basins.

These projects have led to patent applications for new REE recovery procedures.

Patented NETL-Developed Solvent Technology Offers Efficient Process for Carbon Dioxide Capture

A patented technology developed by NETL offers a cost-effective way to enable low-carbon electricity generation and efficient fuel processing, among other benefits.

The technology is a physical solvent that provides a way for chemical plants, power plants, refineries and others to selectively remove weak acid gases, such as CO_2, from high-pressure gas streams composed of CO_2 and hydrogen, such as those found in carbon capture, hydrogen purification and natural gas sweetening applications. What makes NETL's solvent unique is its ability to use waste heat rather than electricity to drive the solvent's regeneration. This translates to cost savings realized by increased efficiency.

The novel solvent can be tailored to a variety of energy applications, including pre-combustion CO_2 capture, hydrogen generation from reformed natural gas and removing CO_2 from syngas for coal and biomass to ammonia and fertilizer. There are also a range of potential markets including natural gas sweetening, ethane cracking, and landfill gas and biogas upgrading. This solvent can make an impact in a wide range of markets, enabling cleaner, more efficient energy production.

NETL-Invented Refractory Brick Increases Service Life, Efficiency

NETL developed a refractory brick that can increase the service life of refractories. The bricks can be used to line gasifiers and reduce wear from molten mineral impurities (slag) in carbon feedstock, resulting in reduced replacement costs and an increased gasifier availability and efficiency.

Gasification chambers, with protected refractory lining, is where a carbon feedstock like coal, petcoke and biomass is converted to carbon and hydrogen during gasification. The carbon-hydrogen mixture is commonly called synthesis gas, or syngas, and can be used to generate power or as a feedstock material to yield other chemical compounds.

Traditional high chrome oxide refractory bricks fail by spalling or corrosion, reducing the refractory lining thickness that protects the gasifier steel shell. Visual inspections and thermal monitoring are needed to determine refractory wear, which require process shutdowns and physical entry into the gasifier. Worn refractory lining is removed and replaced with new bricks to keep the gasification chamber operating efficiently and to reduce the risk of the steel containment vessel having catastrophic failure caused by the severe service gasification environment — something that would cause system shutdown and could result in personnel injuries.

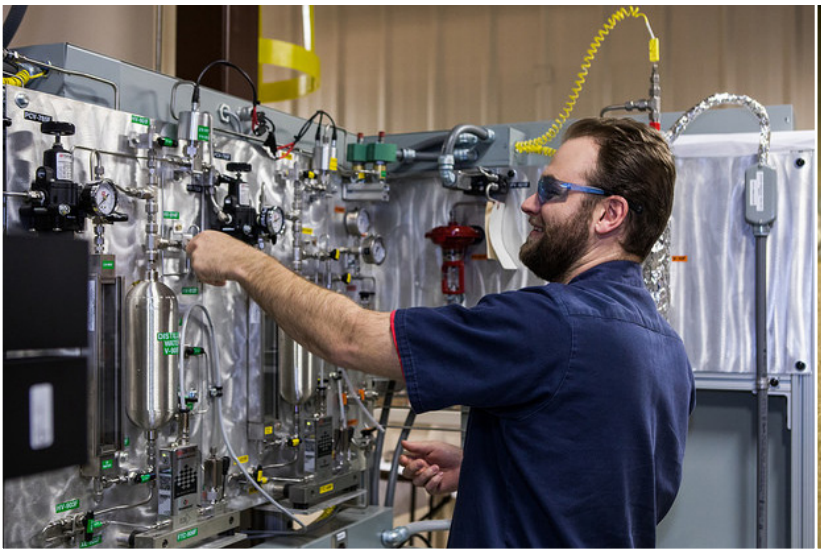
NETL's novel chromia refractory brick was developed using carbon treatment to fill void space. It can be used at gasification temperatures between 1250 degrees Celsius and 1575 degrees Celsius, pressures of between 300 and 1000 psi and under reducing conditions of gasification. It improves refractory service life by reducing slag corrosion and spalling of the gasifier refractory lining.

Recovery of Pressurized Cores Key to Natural Gas Hydrate Research

An NETL-sponsored team led by the University of Texas at Austin (UT-Austin) recovered the first pressurized cores from a gas hydrate reservoir in the deepwater Gulf of Mexico — a key step in opening the door to a vast untouched natural gas resource. Gas hydrates are crystal structures in which frozen water creates a cage that traps methane molecules. Because methane is a clean-burning energy source, understanding the potential of this resource is an important goal for NETL.

Retrieving samples while keeping them pressurized will allow researchers at NETL, UT-Austin and many other laboratories across the country to make breakthroughs in understanding the nature, occurrence and physio-chemical behavior of gas hydrate systems, as well as the Gulf of Mexico hydrate potential.

Gas hydrates occur in great abundance in association with arctic permafrost and in the shallow sediments of the deep-water continental shelves — like those in the Gulf of Mexico. However, many scientific uncertainties and technical challenges must still be overcome before hydrates can be produced commercially in an environmentally benign manner. To solve this challenge, the research team used a revolutionary new coring tool to secure more than 30 meters of pressure core, ultimately resulting in the preservation of 21 one-meter samples of some of the highest quality gas hydrate cores ever collected. Those samples will be further subsectioned and analyzed by the research team. The samples will also be distributed to a number of laboratories for further study.



NETL Works to Transform Stranded Natural Gas into Marketable Products

Pioneering research at NETL on the use of microwaves to create the chemical reactions necessary to transform stranded natural gas resources into usable natural gas liquids and methane led to more intensive work with long-time NETL academic partner West Virginia University (WVU).

NETL researchers have been experimenting with microwave chemistry as part of efforts to increase production and reduce the time and cost of converting hydrocarbon fuels such as coal, oil and natural gas into marketable chemicals and products. The work advances processes to apply microwave radiation to enhance the chemical reactions that cause the conversions. The University of Pittsburgh and Shell also participated in the effort.

Application of successful microwave catalysis can lead to production of chemicals from gas resources once considered physically or economically stranded — like flaring in a shale oil field or shale gas in hard-to-reach locations. Converting those gases to value-added liquid products could reduce the United States' demand for crude oil by up to 20 percent.

Current indirect natural gas conversion to chemicals using traditional product refining is capital-intensive and less energy efficient compared the potential use of microwave catalysis that can increase product yields. A WVU analysis showed that the potential impact of the technology could improve energy efficiency by about 63 percent, reduce capital expenditures by 51 percent and increase energy productivity.

NETL Finds High Concentrations of Rare Earth Elements in American Coal Basins

NETL found high concentrations (greater than 300 parts per million) of rare earth elements (REE) in coal samples taken from the Illinois, Northern Appalachian, Central Appalachian and Rocky Mountain Coal Basins and the Pennsylvania Anthracite region. REEs are vital to the development and manufacture of high-tech devices such as computers, cell phones and national defense systems. Concentrations of rare earths at 300 ppm are integral to the commercial viability of extracting REEs from coal and coal byproducts, making NETL's finding particularly significant in the effort to develop economical domestic supplies of these elements.

The discovery was made in partnership with West Virginia University, the University of Kentucky Tetra Tech and the XLight Corporation.

The findings could encourage technology developers to recover REEs from these basins by helping them find high-quality feedstocks — the raw materials needed for REE recovery processes. Higher REE concentrations in the feedstock will improve the prospect of producing higher-purity REE materials. A separate research initiative is focusing on DOE cost-shared research projects to design, develop and test technology to recover REEs from coal-related materials in a number of American coal basins.

Identifying promising sources of domestic coal and coal byproducts containing high REE concentrations is a key milestone on the pathway toward economic recovery of REEs from U.S. coal and coal byproducts.

SELECT ACCOMPLISHMENTS: OE, EERE & CESER

In addition to its in-house and managed research portfolios, NETL also establishes and manages advanced energy technology research, development, demonstration & deployment (RDD&D) projects in support of the Office of Electricity (OE), Office of Energy Efficiency & Renewable Energy (EERE), and Cybersecurity, Energy Security, and Emergency Response (CESER).

OE - Grid Protection Alliance Released Improved Analytics Platform

As part of an NETL-managed project, the Grid Protection Alliance (GPA) released version 1.1 of its Open and Extensible Control and Analytics (openECA) platform, which offers an improved way to connect phasor data to analytics. The new version was based on feedback from demonstrations and testing of the beta version of the platform. The openECA tool will accelerate the production, use and ongoing development of real-time decision support tools, automated control systems and off-line planning systems.

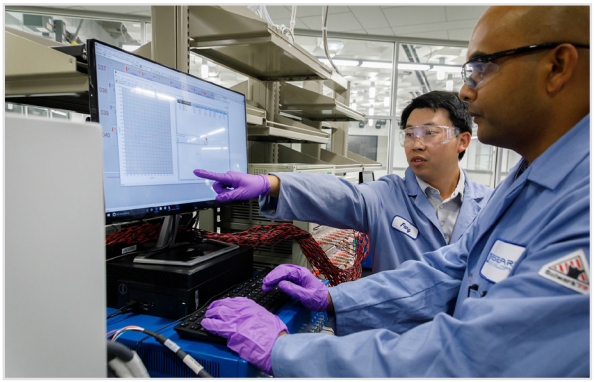
OE - University of California, Irvine Successfully Tested Microgrid Controller

Under an NETL-managed project, the University of California, Irvine (UCI) tested its Generic Microgrid Controller, which proved successful in transitioning to and maintaining islanded mode operation and transitioning back to grid connected mode. Islanding is the condition in which a distributed generator powers a location when electrical grid power is not present. The islanding test demonstrated the UCI Microgrid's ability to disconnect from the grid and operate in islanded mode under conditions of load changes, as well as to resynchronize and reconnect to the larger grid.

OE - Washington State University Built Algorithm for Outage Areas

As part of an NETL-managed project, Washington State University built an algorithm to determine multiple outage areas and multiple fault locations. Testing showed that the technique can accurately identify multiple outage areas, allowing activation of protection devices to ensure that alternative supply can be made to customers in the event of a failure. The technique works with mesh distribution systems, which is an improvement over the previous version of the Outage Management System algorithm that was only suitable for a radial distribution system without Distributed Energy Resources.

EERE - General Motors Developed Pouch-Format Cell for High-Energy Lithium-Sulfur Batteries



An NETL-managed project with General Motors LLC successfully developed and tested a lithium-sulfur (Li-S) pouch-format cell battery with an energy density of 400 watt-hours per kilogram (Wh/Kg). The project marks a solid foundation toward developing a battery pack targeted with a specific energy of at least 500 Wh/kg (compared to the 170-200 watt-hours per kilogram in today's typical EV battery ion) to create a smaller, lighter and less expensive battery that will enable future electric vehicles to drive farther on the same charge.

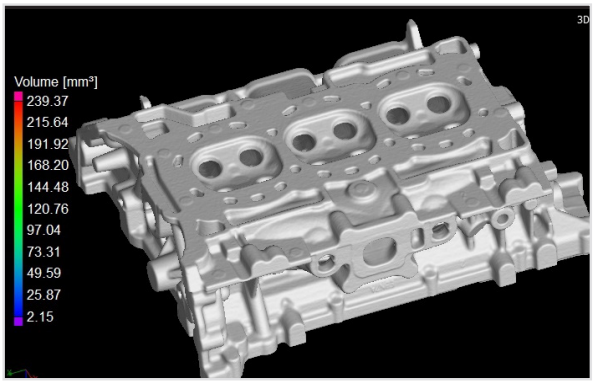
EERE - Cummins Inc. Demonstrated Enabling Technologies for Heavy-Duty Vehicles

An NETL-managed project with Cummins Inc. successfully demonstrated a peak system brake thermal efficiency (BTE) of 54% in parallel with emissions compliance over standard vehicle test cycles while also identifying an achievable path to the 55% BTE target. The project accelerates the development of technologies to enable high-efficiency combustion, shortening commercialization timelines and hastening deployment across industry. Advances in combustion technologies and the associated enabling technologies have the potential to yield a profound reduction in national fuel consumption and associated CO_2 emissions while also successfully providing energy security for the future.

EERE - CALSTART Inc. Demonstrated Bidirectional Wireless Power Flow for Vehicle-to-Grid Technology

An NETL-managed project with CALSTART Inc. successfully demonstrated a highly efficient bidirectional wireless power transfer (BWPT) system suitable for medium-duty plug-in hybrid electric vehicle (PHEV) delivery trucks and power transfer of more than 20 kW to and from the grid. WPT is a paradigm shift in electric-vehicle charging that is autonomous, safe and convenient. The WPT eliminates the need for touching the heavy, bulky, dirty cables and plugs as well as safety concerns with tripping hazards in public parking lots and in highly populated areas such as shopping malls, warehouse loading areas, recreational areas, parking buildings, etc.

EERE - Ford Motor Company Demonstrated Advanced Cast Aluminum Alloys for Automotive Engines



An NETL-managed project with Ford Motor Company successfully demonstrated A319 and A356 alloys in different heat-treatment combinations, that are simpler than those used in industrial productions for both cylinder heads and engine blocks, performed extremely well at elevated temperatures and achieved cost goals. The new class of advanced, cost-competitive aluminum casting alloys provide an approximate 25% improvement in component strength. The work contributes toward improved fuel economy in passenger vehicles, which will be required to achieve at least 58 miles per gallon by 2030 (per fuel economy standards).

EERE - Lumileds Improved Radiative Recombination in AlGaInP Light-Emitting Diodes

An NETL-managed project with Lumileds LLC (formerly Phillips Lumileds Lighting LLC) is improving the efficiency of AlGaInP light-emitting diodes (LEDs) in the amber to red wavelength range. The project successfully achieved in a laboratory prototype an amber LED with external quantum efficiency (EQE) of 18% at current density of 35A/cm2 and junction temperature of 25 degrees Celsius, surpassing the initial target EQE of 15%. Efficient red and amber LEDs are essential building blocks for next-generation lighting products, enabling the ultimate DOE efficiency targets and spectral design freedom in color-mixed white and color-tunable lighting applications.

EERE - American Lung Association Provided Midwest Electric Vehicle Opportunities

Midwest EVOLVE, an NETL-managed project with the American Lung Association in Minnesota, educates consumers and fleet personnel about the performance and environmental advantages of electric vehicles (EVs). The project team, including its Clean Cities partners, holds events that provide hands-on experiences to test-drive a variety of locally available EVs, which help attendees determine the best vehicle and charging options for their needs. So far, the project has reached over 90,000 participants at around 250 events, which includes over 4,500 attendee test-drives. Of attendees who drove a vehicle and completed the project survey, 21% either purchased or leased a PEV. The project has held 17 large ride and drive showcase events, 61 micro ride and drive showcases, 12 dealership trainings, 29 workplace charging challenge showcases, 10 extended test drives programs, 27 forums and more than 90 wraparound/educational outreach events.

CESER - Texas A&M Developed New Tools for Timing Signal Intrusions

Under an NETL-managed project, Texas A&M developed detection methods and tools that manage timing signal intrusions to help assure resiliency of the synchrophasor and legacy energy management systems (EMS). The tools strengthen cybersecurity of phasor measurement units (PMU) and mitigate inaccuracies that may occur should a GPS timing signal be compromised or the synchrophasor measurement transmission be delayed.

CESER - ABB Inc. Announced Inventions for Protecting HVDC Transmission Systems

As part of an NETL-managed project, ABB Inc. is developing three separate inventions for protecting high-voltage, direct current (HVDC) electric power transmission systems. The first invention, "Rule-Based Anomaly Detection for Securing Telecommunicated Operational Data in HVDC Systems," addresses the concern of an attacker injecting false data between the communication of the rectifier (the station operating with power flow from AC to DC) and the inverter (the station operating with power flow from DC to AC) for HVDC stations. This false data could mimic a fault between the two stations and lead to the protective action of shutting down the line. The invention determines the fault type at the rectifier station for verification of the data sent from the inverter station. The second invention, "Secure Emergency Power Control of HVDC Systems," enhances the cybersecurity of the emergency power control within HVDC converter stations. The third, "Detecting Cyber Intrusion and Anomaly for AC Filter Bank in HVDC System," protects the AC filter system at rectifiers by verifying current and voltage harmonics.

CESER - Los Alamos National Lab Achieved Breakthrough in Secure Quantum Communication

Los Alamos National Laboratory (LANL) recently achieved a significant breakthrough in secure quantum communications as part of an NETL-managed project. The LANL team is using quantum communications to transmit secret keys for use in traditional cryptographic algorithms. The principles of quantum physics reveal any attempted interception of the secret key as it is exchanged between trusted parties operating critical energy delivery control systems when the adversarial intrusion is attempted. Generally, the unit cost of a quantum key exchange system is high, but LANL's breakthrough will substantially reduce the unit cost, thereby lowering the barrier to widespread deployment of this technology throughout the energy sector.

CESER - FoxGuard Solutions Released New Platform for Energy Delivery Control Systems

As part of an NETL-managed project, FoxGuard Solutions commercially released its Sentrigard Security Platform™ that includes patch availability reporting, patch gap and vulnerability notification reporting. The platform delivers a defense-in-depth strategy to secure client assets. This is important in cases when patches and updates mitigate security vulnerabilities that may be exploited by the adversary. The platform ultimately streamlines the difficult task of patching and updating devices used in energy delivery control systems.

CESER - New Intel Technology Connected Brownfield Devices to the Cloud

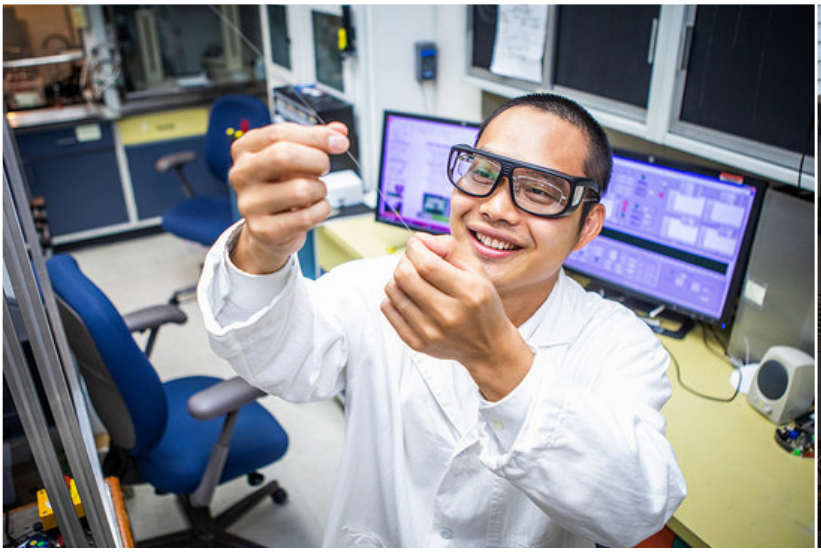
As part of an NETL-managed project, Intel reached a milestone in its Utility Distribution Edge Security architecture that addresses the detection, prevention and mitigation of cyber incidents on the grid edge, where many distributed energy resources are being installed with their accompanying intelligent field devices. In collaboration with Schneider Electric and LiveData Utilities, the project team completed its CPU-based Intelligent Gateway solution, securely connecting Schneider brownfield devices to the cloud. This shrinks the cyber-attack surface, thereby reducing the risk for both existing brownfield and new greenfield deployments.

CESER - GE Developed Attack Detection

An NETL-managed project with General Electric has developed a self-learning and resilient cyber-attack/anomaly automatic detection and accommodation technology (ADA) to provide uninterrupted, controlled and equipment-safe power generation to the grid even in the presence of attacks. This ADA system is integral to the defense-in-depth strategy to support improved resilience in the nation's critical energy infrastructure. ADA technology is designed to effectively detect, localize and mitigate attacks in real time. The project team successfully demonstrated the algorithm for several test scenarios in the threat simulator.

TECHNICAL HIGHLIGHTS

IMPROVING THE PERFORMANCE, RELIABILITY AND EFFICIENCY OF THE EXISTING COAL-FIRED FLEET



Advanced Optical Fiber Sensors for Next-Gen Energy Systems

Developing sophisticated optical fiber sensors to operate and monitor across the energy production chain enhances energy safety, reliability and security. In 2018, NETL's world-class sensor research met with success in two key areas.

- Preventing Natural Gas Infrastructure Failures — NETL research demonstrated that metallic thin film-coated optical fibers can determine corrosion onset and location using an optical backscatter reflectometer, enabling distributive monitoring inside natural gas transmission pipelines. Researchers also demonstrated a multifunctional fiber optic sensor network to monitor water condensation and condensed water chemistry in natural gas transport pipelines. The technology offers the advantages of high selectivity, and sensitive, reversible and fast responses.

- Improved Distributed Sensing in Solid Oxide Fuel Cells — NETL developed new thin-film oxide systems for oxygen sensing in conditions relevant for SOFC cathode and combustion gas streams. These materials will be integrated with an optical fiber platform to explore distributed sensing capability in future tests. NETL research teams also installed and tested 10 optical fiber temperature sensors in an operating fuel cell sample. The sensor grid produced the first experimental 2-D temperature map of cell performance under operation. Multiple fuel cell industrial partners are in discussion with NETL to test the innovative technology in their fuel cell stacks.

(See page 14 for more information)

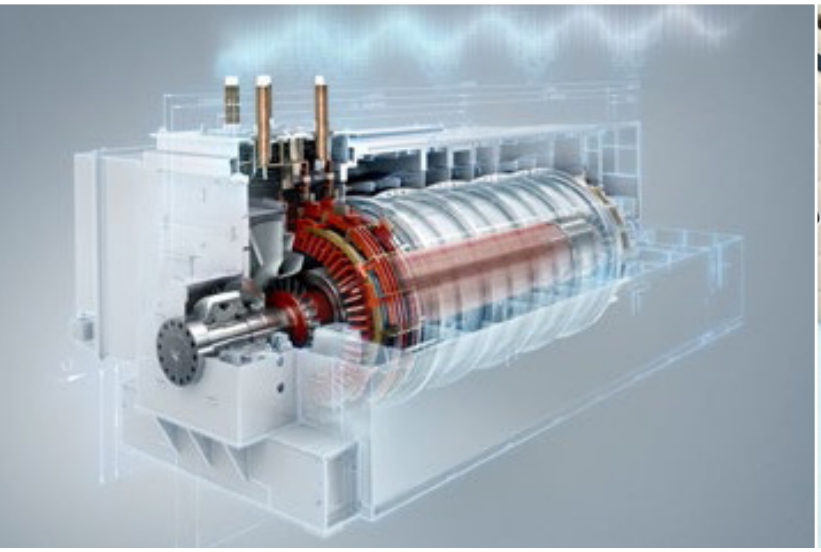
Affordable, Durable Alloys for Fossil Energy Applications

NETL delivers cost-effective alloy solutions for improving the performance of the existing fossil fuel fleet and enabling next-generation technologies. This research increases the performance of heat-resistant alloys while lowering their manufacturing costs.

The NETL cast version of alloy 740 offers another option for advanced ultrasupercritical castings. A modified casting route was developed that leads to more uniform grains throughout the casting and results in comparable strength to the wrought IN740.

NETL is also continuing to improve the performance of Fe-9 percent Cr martensitic-ferritic steels. NETL formulated a new alloy that is an extension of the design strategy for NETL's CPJ7 alloy. This alloy, NETL-JMP, has the potential to increase creep performance close to 650 degrees Celsius. Preliminary results suggest a 2.5-3.0 times improvement in creep capability compared to the CPJ7 steels, representing an increase in temperature capability of roughly 100 degrees Fahrenheit relative to the commercial steam turbine alloy COST-E.

IMPROVING THE PERFORMANCE, RELIABILITY AND EFFICIENCY OF THE EXISTING COAL-FIRED FLEET



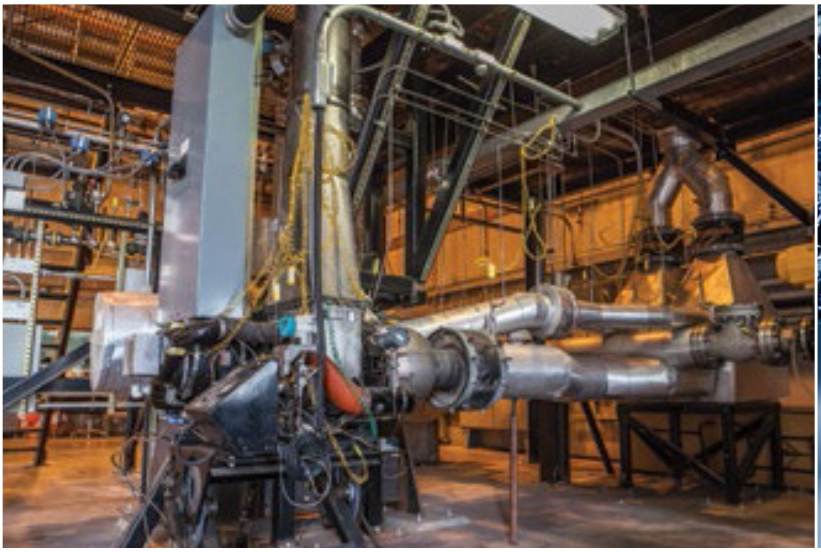
Cybersecurity for Fossil Power Generation

NETL's cybersecurity program is guiding solutions to enable a fully automated, reliable and resilient fossil fleet through intelligent and secure cyber systems. The program seeks to protect the nation's infrastructure from foreign threats and preserve national security through gap analyses, secure data communication, and enhanced situational awareness. By improving cybersecurity for thermoelectric power generation, a baseload source of electricity is protected from weather events or foreign attacks. Cybersecurity enables highly instrumented thermoelectric power plants with advanced controls that may bring about flexibility and reliability benefits through automation, predictive maintenance and fault detection. Utilizing the latest technology and algorithms, NETL's cybersecurity program will continue to investigate the latest technology solutions to improve reliability, control, monitoring and diagnostics.

Rapid Manufacturing Method for High-Temperature Turbine Components

The NETL-funded Rapid Manufacturing Method (RMM,) developed by Mikro Systems, is a breakthrough manufacturing technology that can dramatically reduce the time and cost of designing, prototyping and producing complex high-temperature turbine components. The project will allow turbine manufacturers to rapidly incorporate design enhancement, leading to affordable products and lower plant and electricity costs. Mikro is producing components in higher volumes from industry standard materials, powdered metals and ceramics. The company has also demonstrated advantages in component quality and industrialization over competing layered manufacturing techniques while moving technologies into commercialization. Mikro successfully produced three commercially ready turbine components from Pratt & Whitney that meet specifications and acceptance criteria. Using a tomo-lithographic molding process, Mikro also commercialized anti-scatter grids for multi-slice CT scanners and licensed technology to Siemens to produce advanced ceramic cores for next-generation industrial gas turbine airfoils.

IMPROVING THE PERFORMANCE, RELIABILITY AND EFFICIENCY OF THE EXISTING COAL-FIRED FLEET



New R&D Initiative for Existing Coal-Fired Power Plants

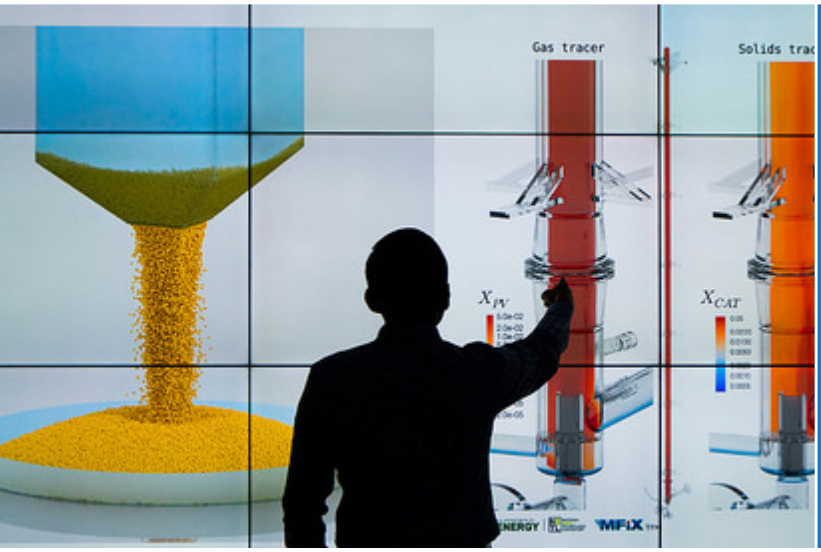
NETL initiated research in 2018 to identify and develop technologies that increase coal-fired power plant efficiency, improve unit reliability and availability, and enhance unit capability for flexible operations (e.g., "cycling"). The new initiative concentrated on dynamic performance and reliability, materials, sensors, controls and diagnostics, and power plant component improvements.

Using real-time analysis of existing data streams, NETL developed a new concept to identify the maintenance condition of power plants. The process was demonstrated on a lab-scale turbine at NETL and is being discussed with coal plant operators for potential use. Project partner GE Power developed a sensor network to monitor and facilitate low-load operation of a pulverizer and combustor for low-load operation at coal plants. The project will undergo field testing at Cross Generating Station in Pineville, South Carolina.

Enabling Responsible Water Use for Power Generation

NETL's 2018 Water Brief raised awareness and guided investment in technical solutions across national, local and regional scales. The Brief's analysis enabled stakeholders to make informed decisions surrounding R&D for thermoelectric power generation to ensure sustainable and reliable generation in geographic locations where water is scarce or population is dense. The Brief identified locations that may benefit from cooling tower blowdown, effluent water reuse, added flexibility, dry and hybrid cooling, and flue gas desulfurization wastewater treatment. Through these recommendations, thermoelectric power generation may secure efficient electricity production for years to come.

IMPROVING THE PERFORMANCE, RELIABILITY AND EFFICIENCY OF THE EXISTING COAL-FIRED FLEET



IDAES
Institute for the Design of Advanced Energy Systems

Computational Tools for Design and Optimization

NETL's multiphase flow science R&D enables design, optimization and troubleshooting of efficient, robust and flexible energy conversion devices and fossil energy reactors. In 2018, NETL researchers achieved the following milestones, demonstrating the benefit of NETL's multiphase flow science R&D in solving industry-relevant problems:

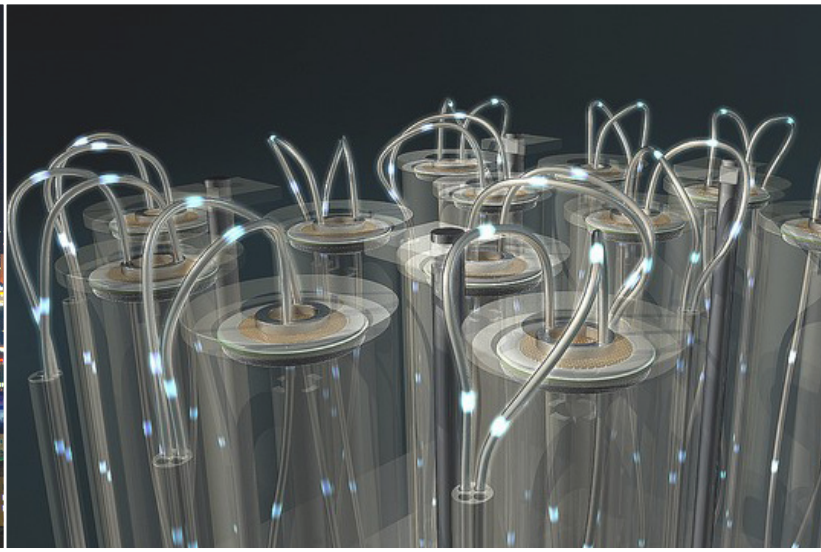
- Billion-Particle Simulation — Collaborators at the University of Colorado, Boulder, using NETL's open-source MFIX code achieved a breakthrough simulation containing 1 billion particles, demonstrating the capability for high-fidelity multiphase modeling at industrial scale.
- Deployment of MFIX in Exascale Computing Platforms — NETL released the newest member of the MFIX software suite, MFIX-PIC, which allows for a more than tenfold speed increase. NETL and Lawrence Berkeley National Laboratory teamed under DOE's Exascale Computing Project to develop the MFIX platform for next-generation exascale supercomputers.
- Industry Collaborations — NETL and Babcock and Wilcox established a collaborative program using MFIX to address circulating fluid bed boiler performance challenges in today's operating environments.

Institute for the Design of Advanced Energy Systems

The NETL-led Institute for the Design of Advanced Energy Systems (IDAES) is accelerating cost-effective technology deployment needed to support critical DOE missions. IDAES and its capabilities will be deployed to improve the design, analysis, and operation of both the existing fleet and innovative, advanced coal energy systems of the future.

During 2018, a general steady-state power plant model was developed consisting of unit models of all major plant equipment. Through a cooperative research and development agreement (CRADA) with Tri-State Generation and Transmission Association Inc., a coal-fired unit served as an initial test case for modeling and optimization activities. Additionally, the first IDAES Stakeholder Advisory Board Meeting was held in Washington, D.C., with representatives from 15 different organizations spanning the energy, chemical and pharmaceutical industries. Several attendees expressed interest in becoming early adopters of IDAES tools. A stable version of the IDAES process modeling framework was developed and documented, forming the basis of the first limited open-source release to existing IDAES stakeholders. These accomplishments will provide initial demonstrations of how the IDAES tools can enable power plants to maximize their profitability during cycling operations by considering optimal tradeoffs between revenue generation and maintenance costs.

ADVANCING THE NEXT GENERATION OF MODULAR, HIGHLY EFFICIENT AND FLEXIBLE COAL-FIRED POWER PLANTS



R&D Initiatives for Coal Plants of the Future

In 2018, a new research focus area was initiated to transform and modernize the coal-fired power fleet. The Coal FIRST initiative concentrates on the development of power plant systems and technologies that will enable the future deployment of efficient, clean, cost-competitive coal power plants that can operate flexibly, maintain high reliability and resiliency and be deployed in small-scale or modular applications to accommodate an evolving electricity market.

NETL activities will identify the most promising plant configurations, analyze their cost and performance and identify R&D needs to develop two large-scale pilot operations using advanced coal conversion and/or capture technologies representing new ways to convert energy. This work is making progress toward the DOE Office of Fossil Energy strategic objective to develop transformational technologies that will enable the coal-based facilities of the future.

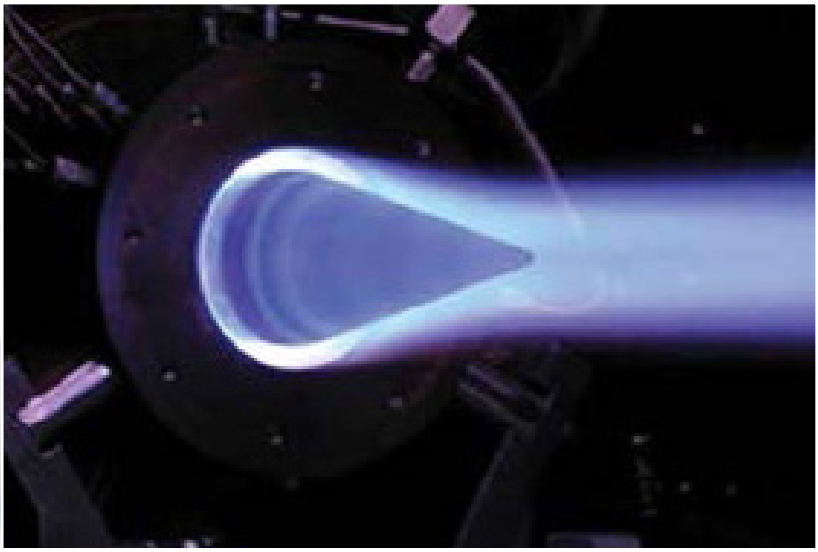
NETL-Industry Collaboration for Solid Oxide Fuel Cell Commercialization

NETL is collaborating with industry to commercialize solid oxide fuel cells (SOFCs) that generate electricity through electrochemical reactions. A collaborative proposal between NETL and WATT Fuel Cell was awarded the Technology Commercialization Fund (TCF) Award through the Office of Technology Transitions to apply NETL-developed SOFC enhancement technologies to WATT's commercial 1-kW SOFC system. The award will focus on NETL's single-step nano-catalyst infiltration work, reforming catalyst work and high-temperature integrated optical fiber sensor work.

A TCF project and CRADA partner, Atrex Energy, has been operating a stack of 48 fuel cells treated with NETL single-step electrode infiltration technology and demonstrated higher cell performance with no degradation for 30 days. NETL has successfully operated Atrex's commercial-scale tubular cells (both baseline cell and NETL-treated cell) at NETL's testing stand, obtained electrochemical performance of the cells, and provided high quality impedance analysis data to Atrex.

An anode infiltration process developed by West Virginia University and NETL was applied to commercial-scale fuel cells of Nexceris, one of the major SOFC manufacturers, and demonstrated 5-10 percent improved performance over untreated cells.

ADVANCING THE NEXT GENERATION OF MODULAR, HIGHLY EFFICIENT AND FLEXIBLE COAL-FIRED POWER PLANTS



Advanced Ultrasupercritical Component Testing (ComTest)

The Advanced Ultra-Supercritical (AUSC) Component Testing project is accelerating the commercial deployment of advanced, coal-based power generation processes that will achieve higher efficiency, lower emissions, and longer life of existing and new power plants. ComTest focuses on building full-scale versions of selected components, which has been identified as the final step necessary to demonstrate the readiness of AUSC technology for a commercial-scale demonstration power plant.

Under an NETL-managed project, Energy Industries of Ohio completed Phase I of the AUSC supply chain project, including the FEED effort for all components. In Phase II the development of AUSC technology will be increased to demonstration-scale readiness level by completing the manufacturing R&D of AUSC components. Fabrication will be performed using commercial scale nickel superalloy components and sub-assemblies. Successful fabrication of these parts will enable U.S. suppliers to participate in the world market for these parts.

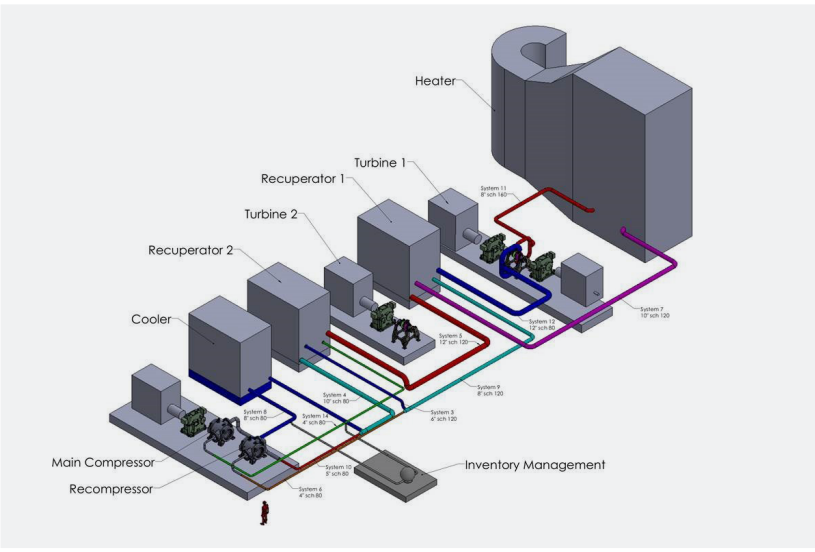
Advances in Pressure Gain Combustion Turbine Systems

NETL partnered with the Air Force Research Laboratory (AFRL) to pursue research on pressure gain combustion (PGC) — a subject of interest to both laboratories because of implications for improved turbine engines. Integrating a rotating detonation engine (RDE) into a PGC system can achieve a combined cycle efficiency equal to or greater than the DOE target of 65 percent. The joint program demonstrated negligible impact on turbine efficiency from rotating detonation combustion when installed in a T63 turboshaft engine and reduced NOx emissions.

Additional fundamental and applied work in the PGC area is also being conducted with U.S. universities and Aerojet Rocketdyne. Hot fired RDE testing was completed at state-of-the-art test facilities at Purdue University, the University of Alabama, and Southwest Research Institute. These tests resulted in hundreds of high energy tests in support of Aerojet Rocketdyne's RDE for Gas Turbines Project.

(See page 16 for more information)

ADVANCING THE NEXT GENERATION OF MODULAR, HIGHLY EFFICIENT AND FLEXIBLE COAL-FIRED POWER PLANTS



Testing Solid Oxide Fuel Cell Prototype Systems

Under an NETL-managed project, LG Fuel Cell Systems (LGFCS) is advancing prototype testing to support reliable and efficient SOFC power generation. The prototype SOFC power system incorporates current technologies and operates under a range of environmental conditions to assess progress of system durability, performance and operating cost toward commercial readiness.

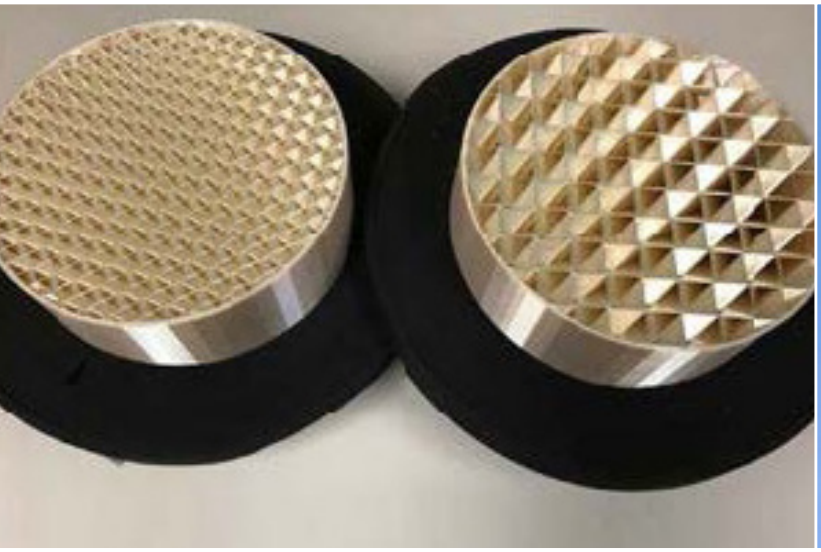
The LGFCS team designed, assembled and ran the fully integrated 250-kWe prototype SOFC system to assess durability, performance and operating cost. The performance was in line with product expectation, with 250 kW-AC power to the grid, greater than 60 percent efficiency and 80 percent fuel utilization. This prototype testing is a key step in the continued development and scale-up of SOFC technology toward commercialization. SOFCs are capable of operating with natural gas or coal-based fuel and produce power to the grid electrochemically, eliminating the need for combustion and its associated thermal and mechanical steps.

Supercritical Carbon Dioxide Power Cycles

NETL is at the forefront of groundbreaking research and development advancing supercritical carbon dioxide (sCO_2) power cycles toward commercialization. Construction of a 10-MWe sCO_2-based pilot plant facility is under way and will be a vital proving ground for larger scale power cycle operation and component performance. This novel power cycle that uses sCO_2 as the working fluid offers the potential for producing power with greater efficiency and at lower costs compared to current steam-based plants. Key research by NETL is closing technology gaps, and systems studies are optimizing plant configurations and showing the magnitude of performance benefits possible.

In 2018, a groundbreaking ceremony was held in San Antonio, Texas, for the largest indirect-fired sCO_2 test facility in the world. The STEP 10-MWe sCO_2 Power Cycle Pilot plant will demonstrate cycle operability at pilot scale to inform future, larger scale-ups; verify performance of components; and produce a lower cost of electricity and thermodynamic efficiency greater than 50 percent.

REDUCING THE COST OF CAPTURED CARBON AND PUTTING IT TO WORK FOR AMERICA



Advanced Manufacturing for Affordable Carbon Capture

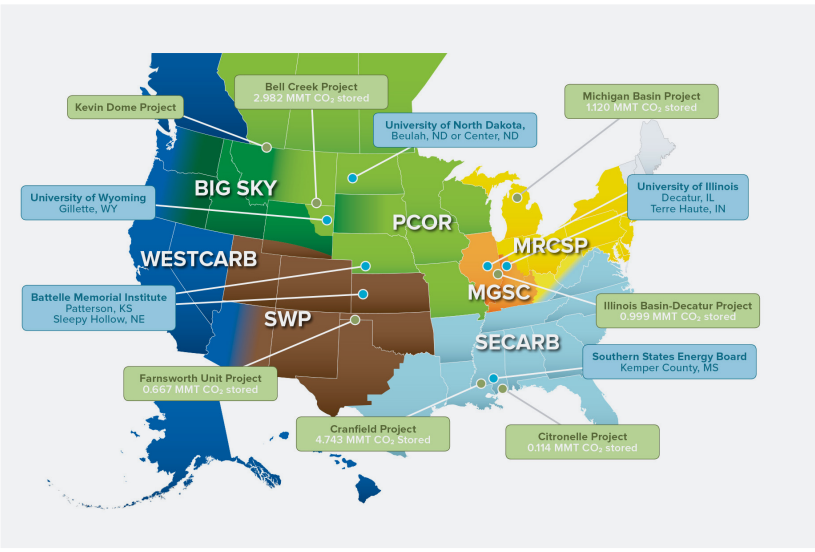
NETL funded a collection of additive manufacturing projects to advance the efficiency and economics of carbon capture systems. In 2018, projects were awarded to Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory (LLNL) and ION Engineering, which are producing rapid prototypes using state-of-the-art 3D-printing processes to enhance the solvent-based capture of CO_2. The technologies offer the potential to improve process performance and reduce the capital and operating costs of capturing CO_2 from coal-based power plants.

Projects are ongoing, and the following successes have been achieved so far: ORNL 3D-printed an aluminum version of a column packing structure with built-in heat exchange. LLNL created silicon-based gyroid structures with one micrometer resolution using stereo-lithography. ION 3D-printed two absorbers on plastic for initial testing.

Capturing CO_2 Using Less Energy at Scale

NETL research is pioneering next-generation non-aqueous solvents (NAS) for CO_2 capture. As part of an NETL-managed project, RTI International completed 1,200 hours of long-term testing of their NAS at the SINTEF Tiller plant in Trondheim, Norway. The NAS captured 90 percent of the CO_2 contained in the flue gas at a specific reboiler duty of around 2.6 MJ/kg-CO_2. The work is validating a water-lean solvent process that can reduce energy use and decrease the cost required for carbon capture compare to current technologies.

REDUCING THE COST OF CAPTURED CARBON AND PUTTING IT TO WORK FOR AMERICA



National Carbon Capture Center and Advanced Flash Stripper

In 2018, Southern Company announced that the National Carbon Capture Center (NCCC) surpassed 100,000 hours of technology testing. Since opening in 2009, the NCCC has worked with multiple third-party technology developers to accelerate the development of advanced technologies to reduce greenhouse gas emissions from natural gas and coal power plants. In 2018 alone, the NCCC operated two major test runs at the Post-Combustion Carbon Capture Center, where multiple technology developers conducted approximately 5,400 hours of testing.

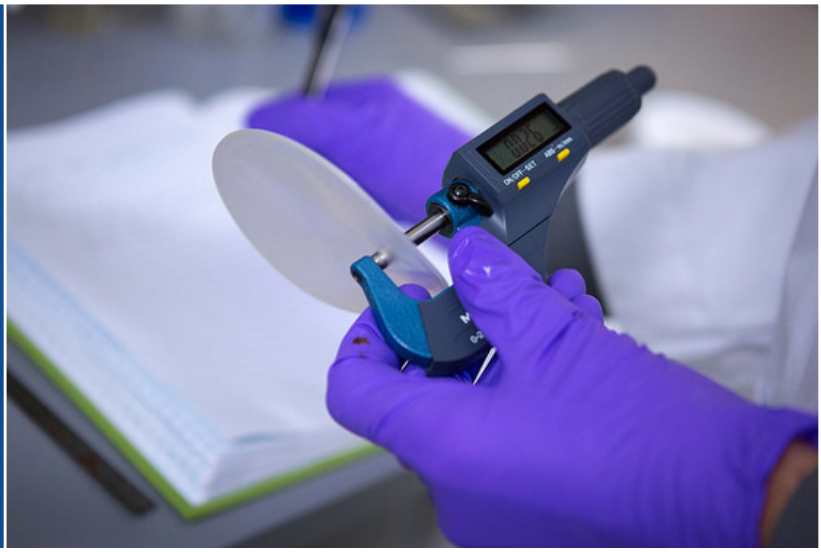
The NCCC operates existing facilities to offer third-party technology evaluation that addresses environmental, health and safety, operational, component and system development issues while collaborating with technology developers. The data generated at the NCCC empowers decision-makers on technology readiness, environmental performance and economic viability of carbon capture from power plants, pioneering solutions for a more sustainable energy future. Recent testing of an advanced flash stripper at NCCC demonstrated its potential to reduce energy requirements and lower the cost of CO_2 capture.

Regional Carbon Sequestration Partnership Initiative

The innovative storage projects performed through the NETL-managed Regional Carbon Sequestration Partnership (RCSP) initiative exceeded Government Performance and Results Act injection targets and demonstrated safe and permanent CO_2 storage to operators, industry, regulators, non-governmental organizations, the financial community, local governments and the public. The effort successfully advanced technologies and methods that improved the understanding of CO_2 behavior in the subsurface, contributing not only to CO_2 storage but also to understanding enhanced oil recovery (EOR) processes essential to American energy independence. Advancements are paving the way toward continued innovative development to ensure that the country has the tools and capabilities needed for reduced risk, uncertainty and cost of industrial-scale CO_2 storage. Efforts undertaken as part of the RCSP initiative have resulted in more than 10.6 MMT of CO_2 permanently stored.

REDUCING THE COST OF CAPTURED CARBON AND PUTTING IT TO WORK FOR AMERICA

NRAP
National Risk Assessment Partnership



National Risk Assessment Partnership for Geologic CO_2 Storage

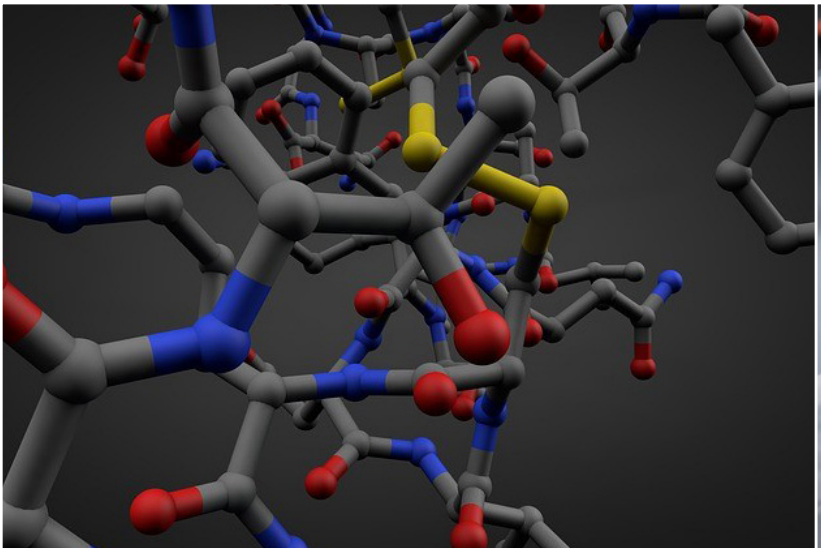
The National Risk Assessment Partnership (NRAP) is developing risk assessment tools, methods, and insights needed for safe, permanent geologic CO_2 storage. The multi-national laboratory collaborative research project is focused on understanding potential environmental risks at geologic CO_2 storage sites. Demonstrating that these risks can be quantified and managed removes barriers to full-scale technology implementation.

In 2018, a key milestone to initiate the application of the NRAP toolsets to field laboratory sites was met. The NRAP tools were tested on at least seven CarbonSAFE pre-feasibility projects, two RCSP large-scale field projects and Taiwan's Industrial Technology Research Institute pre-feasibility sites. The ability to assess the potential risk at a site could lead to the selection of an appropriate site for safe, secure and affordable storage.

Advanced Membranes Lower the Cost of Carbon Capture

NETL successfully developed one of the highest-performing membrane materials for CO_2 capture. Several mixed matrix membranes were developed that have CO_2 permeability greater than 5000 Barrer and CO_2/N_2 selectivity of approximately 30 — well above the Robeson Upper Bound. This is now one of the highest performance membrane materials reported for CO_2 capture from post-combustion flue gas. Preliminary results suggest that the performance is stable when exposed to humidified gas. Ultimately this could lead to a reduction in cost for CO_2 capture. Developing stable, transformational membranes with high CO_2 selectivity and permeability can significantly reduce the cost for post-combustion capture. Membranes with higher permeability lead to a reduced area requirement, smaller capital cost and a smaller equipment footprint.

CREATING NEW JOBS, PRODUCTS AND MARKETS FOR COAL



Catalytic Conversion of CO_2 into Value-Added Products

NETL is developing new technologies that convert CO_2 streams into industrially relevant chemicals. The project identifies, develops and evaluates new technologies for converting CO_2 into chemicals that can be sold to offset CO_2 capture costs, reduce demand for petrochemical-based feedstocks and develop new markets and job opportunities.

New metal oxide catalysts use microwaves to thermally convert CO_2 and methane. Mixed metal oxides absorb microwaves and instantaneously generate heat. This greatly reduces associated heat management issues and makes high-temperature reactions, like methane dry reforming with CO_2, practical. In another effort, a new nano-porous copper-oxide catalyst for electrochemical CO_2 reduction demonstrated 10-60 times better selectivity compared with commercially available copper materials. This is a significant breakthrough that drastically improves selectivity and performance of inexpensive material.

Extracting Rare Earth Elements Affordably and Efficiently

NETL's unique capabilities in advanced characterization, subsurface flow modeling, and process engineering empowers researchers to develop groundbreaking processes that extract high-value and critical elements from our nation's vast coal resources.

NETL researchers have extracted rare earth elements (REEs) from coal and underclays with a minimally invasive technique. These extremely mild solvents have been tailored to only extract easily accessible REEs, leaving most of the source material intact, leading to lower costs and less material to process. In another effort, NETL geoscientists discovered underclays that have considerable levels of ion-exchangeable REEs. Producing REEs from these mining waste materials represents a potential new value stream for coal mining operations. NETL researchers also developed selective extraction solutions that have the potential to extract REEs using mild liquids found in nature, such as lemon juice or vinegar, minimizing potential environmental impacts. This method is selective and is expected to reduce the amount of extraction waste, ultimately reducing cost.

(See page 13 for more information)

CREATING NEW JOBS, PRODUCTS AND MARKETS FOR COAL

Petra Nova and Enhanced Oil Recovery

The Petra Nova project, which received financial and project management support from DOE through NETL, is the largest post-combustion carbon capture system in the world. The project demonstrates the economic and environmental advantages of amine-based carbon capture technology in removing CO_2 from treated flue gas produced by an existing coal-fired electrical generating station. The project captures 90 percent of CO_2 from a 240-MW slipstream of processed flue gas from the W.A. Parish Plant, a coal and gas-fueled power plant located southwest of Houston. The captured CO_2 is transported to the West Ranch oil field, where it is used to boost oil production via EOR from 300 barrels per day (prior to EOR efforts) to more than 5,000 barrels per day.

As of September 2018, nearly 2 million short tons of CO_2 had been captured and used to produce nearly 2 million barrels of oil since beginning operation in January 2017. The project, the first major carbon capture and storage demonstration-scale project in the U.S. with coal-fired flue gas, demonstrates how carbon capture technologies, when coupled with EOR, can support the long-term viability of coal-fueled power plants.

Rare Earth Elements and Critical Minerals

Within its first five years, NETL's Feasibility of Recovering Rare Earth Elements Program successfully met an aggressive schedule for demonstrating production of dual-use, high-purity, market-ready REEs from coal-based materials. Research activities are developing critical technology, conditions, and data necessary to design, construct, and operate facilities to recover domestic REEs from coal, coal refuse, clay/shale over/under burden materials, power generation ash, and acid mine drainage (AMD).

Using continuous solvent extraction in the laboratory, the University of Kentucky produced a mixed rare earth product from coal refuse that contained a rare earth oxide concentrate of up to 98 percent — the highest quality REE product generated to date by external participants.

West Virginia University produced 5 percent REE pre-concentrate at greater than 90 percent REE recovery using AMD solids from the Northern and Central Appalachian basins in laboratory experiments.

If proven economically feasible when tested at commercial scale, these processes to recover REEs from coal refuse and acid mine drainage sludge could provide the nation with a secure, domestic supply of critical materials and an economic boost to communities associated with the coal mining industry.

(See page 23 for more information)

CREATING NEW JOBS, PRODUCTS AND MARKETS FOR COAL

Expanding the U.S. Coal Value Chain

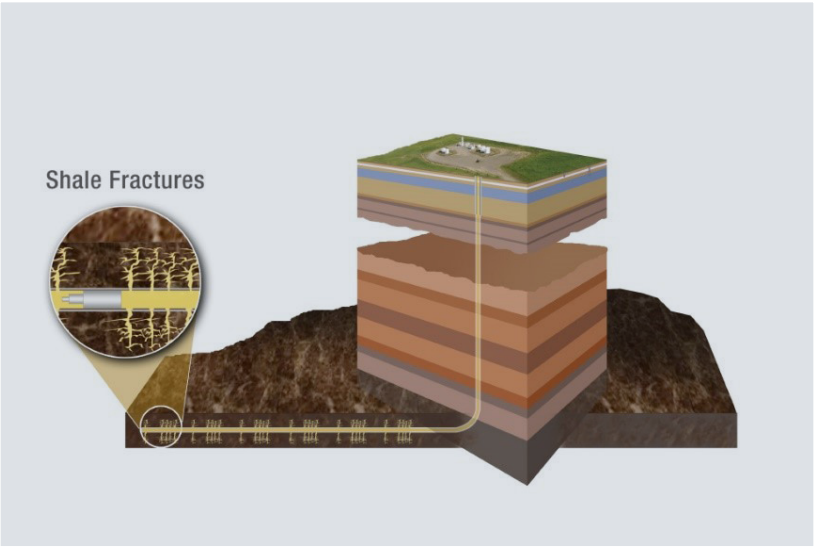
DOE's Coal Beneficiation research is creating new physical and chemical processing technologies to prepare coal for high-value carbon product manufacturing and is expanding markets for existing coal products with new coal cleaning, treatment and processing technologies. In-house research at NETL has indicated that coal-based carbon nanomaterials, such as graphene quantum dots, reduce material costs by at least tenfold and can be used to improve the mechanical strength of cement and polymer composites, filter organic metal impurities from water supplies, and improve the performance of batteries and supercapacitors.

Coal Beneficiation at NETL focuses on enhancing the value of coal as a feedstock for power plants and developing new high-value products derived from coal to extract the full economic value from the nation's coal resources.

Upcycling CO_2 in a Novel Concrete

Flue gas-borne CO_2 and repurposed abundant industrial wastes, such as crystalline slags and fly ash, can be used to create "upcycled concrete." This value-added product provides the coal power industry with a viable path to significantly reduce its carbon emissions. Under an NETL-managed project, the University of California, Los Angeles, created a novel replacement for ordinary Portland cement with equivalent or superior performance using a CO_2-negative upcycled concrete production process that simultaneously uses CO_2 and industrial byproducts, such as flash and slags. The upcycled concrete production process minimizes external energy needs by using low-grade heat sourced from flue gas, which decreases operating costs. Results indicate the upcycled concrete process yields a construction material with a CO_2 uptake of greater than 6 percent by mass and strength development from carbonation. The process offers beneficial use of flue gas-borne CO_2 along with repurposing abundant industrial wastes to create a value-added product.

LEVERAGING BIG DATA AND MACHINE LEARNING TO UNLOCK THE NATION'S VAST UNCONVENTIONAL OIL AND GAS RESOURCES



DOE National Lab Partnership Advances Resource Recovery

Under an NETL-managed project, Lawrence Berkeley National Laboratory (LBNL) is advancing innovative approaches to improve production from unconventional oil and gas resources through a systematic investigation of the fundamental processes involved in hydrocarbon extraction from shale. The technologies and methodologies LBNL researchers are advancing will increase domestic oil and natural gas production and support American energy independence.

LBNL's research is enhancing the fundamental understanding of hydrocarbon storage, release and flow in unconventional reservoirs, enabling the development of transformational technologies and methodologies to improve the economic viability, recovery efficiency, and ultimate recovery of unconventional oil and gas resources. These results are achieved by examining a range of issues that impact reservoir development, sustainability and production, such as water imbibition, fracture conductivity sustainability, EOR, and proppant transport and fate.

Advanced Stimulation to Increase Resource Recovery

Under an NETL-managed project, Oceanit Laboratories Inc. developed a transformational smart proppant technology called FracScan that enables high-resolution mapping of propped fracture networks in unconventional oil and gas reservoirs. FracScan offers several key benefits over current fracture diagnostic technologies, including the ability to measure proppant location, concentration and closure stress, as well as the ability to manipulate acoustic properties for tracer applications.

FracScan proppant delivers a cost-effective and accurate fracture diagnostic approach to enable optimized well completions and improved hydrocarbon recovery. The novel proppant could allow operators to make more informed well completion decisions while optimizing performance and streamlining production.

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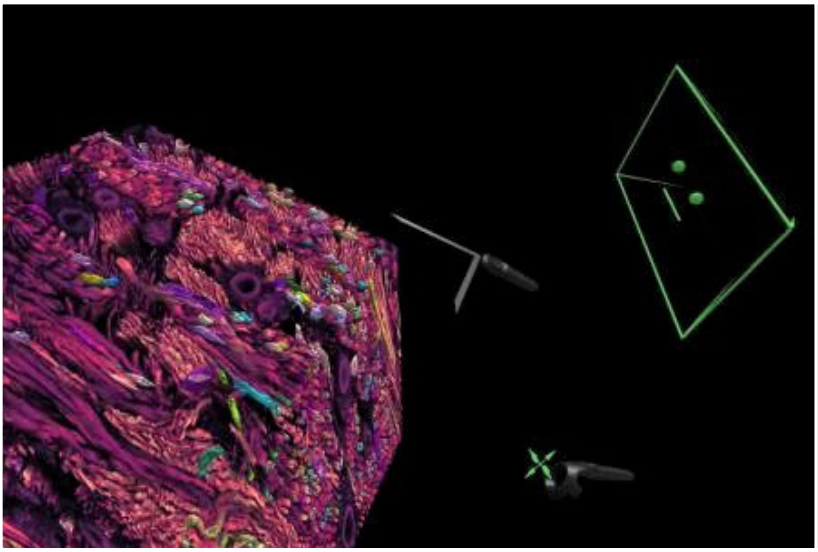

Exploring the Subsurface with 3D Imaging Technology

NETL is leveraging cutting-edge technology from the medical community to improve understanding of subsurface interactions. These resources are used to enhance geologic carbon storage, along with oil and gas recovery parameters. NETL combines computed tomography (CT) scanning technology with immersive virtual reality visualization to enable analysis of core samples at real conditions. Cores are imaged by the CT scanners, under representative subsurface pressures and temperatures, and uploaded into a virtual reality system called syGlass. syGlass allows operators to slice through data and perform measurements in 3D. The combination of these cutting-edge technologies allows energy data to be analyzed with increased accuracy and efficiency. In 2018, more than 2,000 feet of core was scanned, processed and made available to the scientific community on the Energy Data eXchange (EDX) to download, analyze and expand upon.

(See page 13 for more information)

Pioneering Integrated Tools for Optimized Resource Management

The Risk-Based Data Management System (RBDMS) provides a standardized communication tool that shares robust data sets, including well details and strategic planning, which facilitate more efficient decision-making for various state government agencies and industry. The RBDMS is a suite of integrated software products that allows state agencies to oversee and manage oil, gas and underground injection control (UIC) facilities and activities. Increasing drilling results in more bores from a single pad and greater density of wellbore paths in the same geologic area. Tools like RBDMS allow more accurate permitting, construction and management of wells.

The RBDMS Directional Survey Tool, which is installed in California and Utah, provides state agencies with more robust data analysis when reviewing directional drilling activities. The new tool allows users to collect and store survey data from horizontally and directionally drilled wells and view that data in two or three dimensions with third-party applications. This will facilitate faster and more accurate analysis of proposed drilling, injection and hydraulic fracturing activities.

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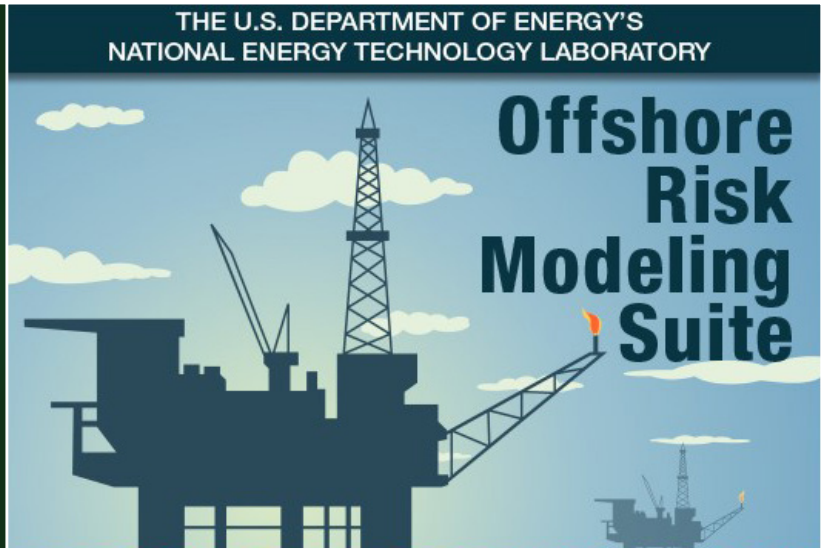

A Knowledge Management Tool for the Shale Community

A new tool developed by NETL is connecting the Office of Fossil Energy and National Lab researchers for more efficient and effective communication, coordination and knowledge curation. Fossil Energy's Knowledge Management (KM) Pilot Tool was launched in August 2018 to support the Shale R&D Community, which consists of nine labs and DOE Headquarters. The Shale Community hosted within the tool includes four technical topic areas: the laboratory, field measurement, modeling and data analytics/machine learning. Registered KM users can join DOE colleagues in a virtual community to share and find information associated with shale and the technical topics. Any DOE user with an EDX account can join the KM and contribute information including: news, publications, and resources; upcoming conferences, workshops, and technical meetings; and solicitations for partners or collaborators.

The KM Tool successfully demonstrated how to connect national labs and HQ, allowing for the fostering of information throughout the scientific community and breaking down the silos between organizations, ultimately leading to more efficient use of information resources.

Offshore Risk Modeling Suite for Safe, Effective Exploration and Production

NETL's Offshore Risk Modeling (ORM) suite is equipping decision-makers with smart, data-driven tools and resources for efficient, effective and safe offshore exploration and production. Since 2011, NETL has been developing the ORM suite — a flexible set of custom data, tools, and models that integrate innovative spatio-temporal analytics, machine learning, big data, and advanced visualization technologies to support DOE's offshore spill prevention, operational efficiency, and safety goals. Five years of development produced terabytes of new data and seven trademarked or copyrighted tools built into the ORM suite that can be used independently or in combination to support data-driven analytics for offshore systems to improve global energy, environmental and economic conditions. NETL has demonstrated how the ORM suite can be used to help improve reserves estimates, increase profitability, guide safety and maintenance decisions, forecast risks, and optimize well/facility designs. These pioneering applications of the ORM suite, and the data science innovations driving them, have garnered national and global attention. This has translated into millions of dollars of funding from DOE-FE and external stakeholders for new projects that apply the ORM suite to address additional energy systems and help inform a range of industry and regulatory decisions. To date, the ORM suite has been adapted to address energy infrastructure, carbon storage, geothermal, REE, induced seismicity, energy materials, and other oil and gas system needs.

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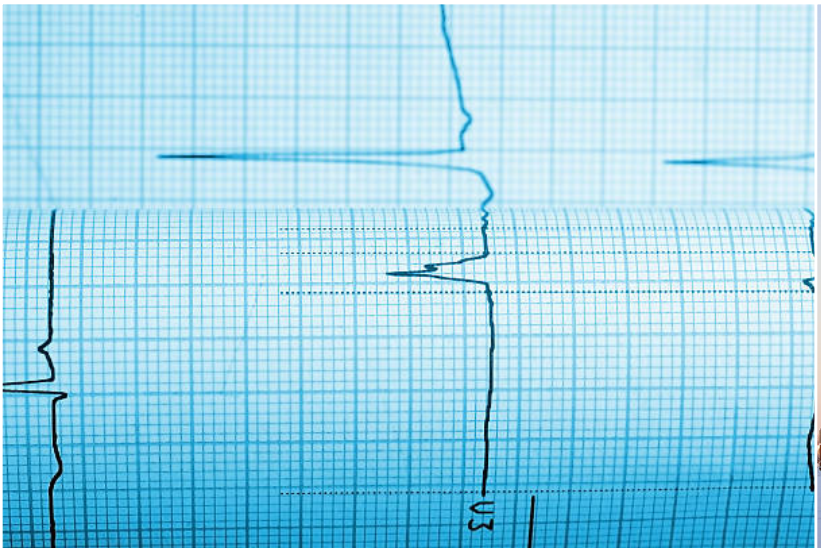


Monitoring Seismicity at Hydraulic Fracturing and CO_2 EOR Sites

NETL significantly expanded the amount of diagnostic information that can be obtained from hydraulically fractured shale reservoirs by analyzing previously ignored low-frequency seismic data that is already being collected by modern geophones, seismometers and distributed acoustic sensing (DAS) cables. Because of poor low-frequency response, DAS was previously thought to be incapable of detecting the low-frequency seismic waveforms generated by the deformation of ductile rocks such as shale, the predominant rock type comprising unconventional reservoirs. Now, NETL researchers using DAS detected low-frequency seismic waveforms of long duration that occur when pumping pressures and rate are at their maximum. The knowledge gained from this research could allow for extended life and increased productivity of many unconventional resources.

Expanding Resource Recovery on Alaska's North Slope

Two research projects on Alaska's North Slope are investigating methods and technologies targeting challenging fossil energy resources.

In December 2018, an international partnership composed of NETL, JOGMEC, Petrotechnical Resources of Alaska and the U.S. Geological Survey drilled an initial test well within the Prudhoe Bay Unit on the Alaska North Slope to confirm reservoir occurrence and to condition and inform planning for a longer-term test. The well was highly successful in the collection of key logging data and retrieval of reservoir samples. This initial success sets the stage for a longer-term gas hydrate production test to validate the stability, producibility and sustainability of gas hydrate resources.

The Alaska North Slope Field Laboratory, operated by the University of Alaska Fairbanks and Hilcorp Alaska is addressing gaps in understanding heavy oil resource behavior through polymer EOR in an arctic environment near the Prudhoe Bay Oil Field. The project will provide a mechanism to improve the underutilized capacity of the Trans-Alaska Pipeline System and improve the energy security of the North Slope's major oil producers, the State of Alaska, U.S. DOE and the nation.

NETL IS AMERICA'S FOSSIL ENERGY RESEARCH LABORATORY

Educating the Next Generation of Energy Innovators

NETL's graduate education programs play an instrumental role in fulfilling NETL's goal to serve as an energy educator and help to ensure that NETL has a robust supply of scientists and engineers to meet the nation's future science and technology needs. Here are two examples of how graduate students are joining NETL to overcome energy challenges:

- Post-doc Robert Fryer contributed to NETL research on thin-film characterization, deposition and testing of harsh-environment surface acoustic wave (SAW) gas sensors during his postgraduate research program appointment as part of the University Coal Research Outreach Initiative. In 2018, the team successfully produced high-quality metal oxide thin films with smooth structures that are suitable for SAW devices. The films enable the SAW sensors to be tuned for sensitivity to varying temperatures and gas conditions.

- Nana Zhou performed research in NETL's Hybrid Performance (HYPER) facility, where her contributions are helping to build a novel cyber physical reformer and internal combustion engine into a hybrid power system. Nana's scientific and technical accomplishments include 16 peer-reviewed papers, multiple presentations and session chair at international conferences. Nana has been a research advisor to 18 undergraduate and graduate students. In addition, she organized the 2018 Consortium for Integrating Energy Systems in Engineering and Science Education Technical Forum, which attracted the attention of 50 researchers and administrators from five consortium universities, two national labs, and DOE headquarters.

Strategic Partnerships: Building Key Relationships

NETL's Strategic Partnerships division engages stakeholders to build the Lab's capabilities, deliver on its mission and develop a world-class reputation. In 2018 the Lab built the following key relationships:

- Oak Ridge National Laboratory — Joint research with ORNL is reducing water consumption in energy production; developing advanced electrical grids, microgrids and cybersecurity technologies for energy infrastructure; and innovating advanced manufacturing technology for energy production, especially fossil energy technologies.

- Xcoal — NETL oversaw sampling of the 62,000-ton cargo shipped by Xcoal at the CNX Marine Terminal in Baltimore, Maryland.

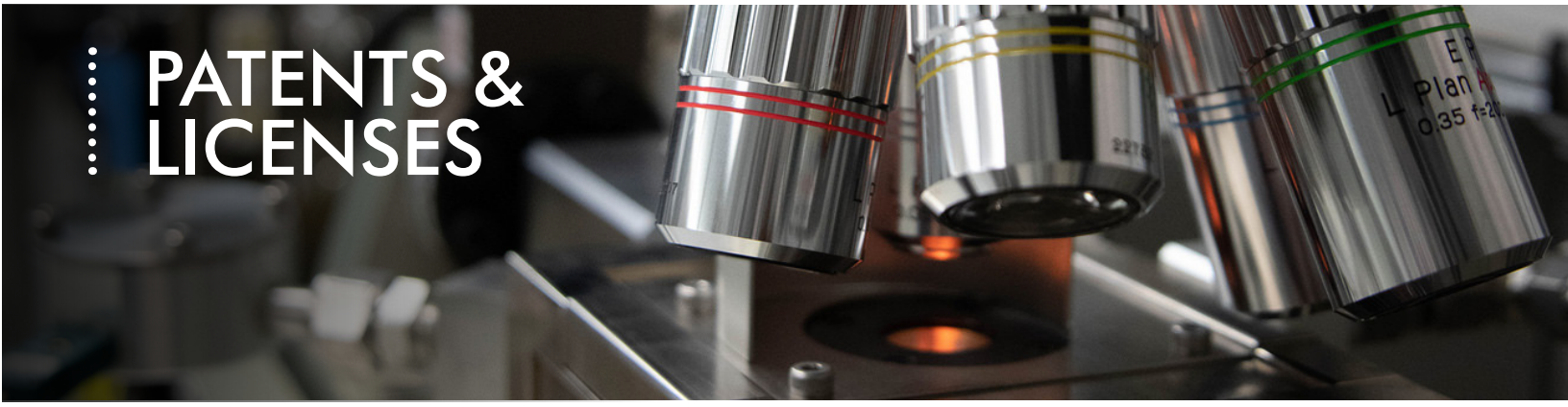
- Ramaco Carbon — NETL and Ramaco Carbon are collaborating on R&D to convert coal into value-added products, develop coal beneficiation processes, and develop technologies for extracting REEs from coal.

- University of Alaska Fairbanks (UAF) — NETL participated in the UAF Lab Day and explored research collaborations between UAF and DOE national laboratories.

- The Carbon Utilization Research Council (CURC) — CURC advocates for research, development, demonstration and widespread deployment of technologies, such as those pursued by NETL, that support the long-term use of coal.

- National Rural Electric Cooperative Association (NRECA) — NETL sponsored many projects with NRECA to develop and enhance the smart grid system.

PATENTS & LICENSES



NETL's technology leadership was reaffirmed this year by the patenting of many novel and new inventions. A list of these inventions follows.

Tri-metallic Ferrite Oxygen Carriers for Chemical Looping Combustion; Ranjani V. Siriwardane (DOE/NETL), Yueying Fan (URS); 9,797,594; issued Oct. 24, 2017.

System and Method for Regeneration and Recirculation of a Reducing Agent Using Highly Exothermic Reactions Induced by Mixed Industrial Slags; James P. Bennett (DOE/NETL), Jinichiro Nakano (URS), Anna Nakano (AECOM); 9,840,756; issued Dec. 12, 2017.

Method for Generating O_2-Rich Gas from Air Using Water; James P. Bennett (DOE/NETL), Jinichiro Nakano (URS), Anna Nakano (ORISE); 9,878,280; Jan. 30, 2018.

A partially exclusive license for Stable Immobilized Amine Sorbents for REE and Heavy Metals from Liquid Sources; issued to PQ Corporation (Malvern, Pennsylvania); March 3, 2018.

Solid Oxide Fuel Cell Cathode with Oxygen-Reducing Layer; David A. Berry, Wayne Surdoval (DOE/NETL), Travis Shultz (DOE/NETL); 9,935,318; April 3, 2018.

Cathodes and Electrolytes for Rechargeable Magnesium Batteries and Methods of Manufacture; Ayyakkannu Manivannan (DOE/NETL); Prashant Kumta (University of Pittsburgh), Partha Saha (University of Pittsburgh), Moni K Datta (University of Pittsburgh); 9,947,962; April 27, 2018.

Method of Forming Catalyst Layer by Single Step Infiltration; Kirk Gerdes (DOE/NETL), Regis Dowd (ORISE), Shiwoo Lee (URS); 9,960,428; May 1, 2018.

Thermally Emissive Materials for Chemical Spectroscopy Analysis; Paul Ohodnicki Jr. (DOE/NETL), Zsolt L. Poole (University of Pittsburgh); 9,964,494; May 8, 2018.

Synthesis and Polymerization of Vinyl Triazolium Liquids; David Luebke (DOE/NETL), Hunaid Nulwala (Carnegie Mellon), Brian Adzima (ORISE), Krzysztof Matyjaszewski (Carnegie Mellon); 9,969,823; May 15, 2018.

Sulfur Tolerant Hydrophobic Ionic Liquid Solvent; David Luebke (DOE/NETL), Hunaid Nulwala (Carnegie Mellon), Fan Shi (URS), Brian W. Kail (URS), Robert L. Thompson (URS), Nicholas Siefert (DOE/NETL); 9,975,080; May 22, 2018.

Sensor Devices Comprising a Metal-Organic Framework Material and Methods of Making and Using the Same; Alan Wang, Chih-Hung Chang, Ki-Joong Kim, Xinyuan Chong, Paul Ohodnicki Jr. (DOE/NETL); 9,983,124; May 29, 2018.

An exclusive license for The Variable Grid Method, Version 1; issued to VariGrid Explorations Inc. (Trinity, Florida); July 6, 2018.
Metal Ferrite Oxygen Carriers for Gasification of Solid Carbonaceous Fuel; Ranjani V. Siriwardane (DOE/NETL), Yueying Fan (URS); 10,030,204; July 24, 2018.

A Pelletized Basic Immobilized Amine Sorbent (BIAS) Utilizing Fly Ash and Polymer Binders; McMahan L. Gray (NETL), Yee Soong, Walter Wilfong (ORISE), Brian Kail (AECOM); 10,065,174; Sept. 4, 2018.

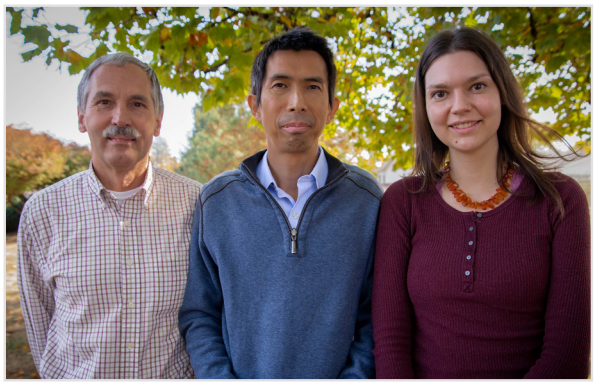
AWARDS & RECOGNITION

NETL received an R&D 100 Award for the National Risk Assessment Partnership (NRAP) Toolset, an innovative computational toolkit developed by NETL in collaboration with a team from Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory and the Pacific Northwest National Laboratory. Known as "the Oscars of Invention," the R&D 100 Awards recognize 100 of the brightest and boldest technologies and services of the year across nine categories. Awarded to **Robert Dilmore**, Elizabeth Keating, **Grant Bromhal** and Phil Stauffer.

Putnam Media Group presented **Stephen Zitney** with a Smart Industry 50 Award for his R&D achievements contributing to the pursuit and embrace of digital transformation by the energy and chemical process industries. Nominations were solicited from the readers of Smart Industry, from past recipients of this recognition, and from more than 20 editors across the Putnam Media family of industry publications.

In recognition of her foamed cement research that is helping to make oil and gas wells safer for operators and the environment, **Barbara Kutchko** was selected to serve as the Society of Petroleum Engineers' Distinguished Lecturer for the 2018-19 program.

The Federal Laboratory Consortium, Mid-Atlantic Region, presented a State and Local Economic Development Award to an NETL team working with the City of Pittsburgh to design and implement infrastructure supporting the use of clean energy in the city: **James Ferguson, Randall Gemmen, Robert James III, Ashley LeDonne, Mark McKoy, Danylo Oryshchyn, Thomas Tarka, Kristen Welsh** and **James Wilson.**



NETL researchers **Jin Nakano, James Bennett** and **Anna Nakano** were honored with a 2017 LMD/EPD Energy Best Paper Award from The Minerals, Metals & Materials Society (TMS) in the Professional category. The award-winning paper, on the topic of fuel production from industrial slag, was nominated by the TMS Light Metals and Extraction & Processing divisions.

The National Organization for the Professional Advancement of Black Chemists and Chemical Engineers honored **Isaac Gamwo** with a Joseph N. Cannon Award for Excellence in Engineering. Gamwo was recognized for his influential research accomplishments in chemical engineering and for his work training engineers at Tuskegee University and the University of Akron.

NETL site-support contractor **USSE$_2$ O&M Services** was the recipient of the U.S. Department of Energy Service-Disabled Veteran-Owned Small Business of the Year Award for exemplifying the entrepreneurial spirit, customer focus, commitment to excellence and an "integrity first" approach to serving their customers.

Douglas Kauffman and **Dominic Alfonso** earned a Best of 2017 Award from the journal Energy Technology for their research on electrochemical carbon dioxide reduction in nanostructured gold, copper and alloy materials.

Michael Nowak and **Seth Lawson** earned recognition from the Maryland Clean Energy Center with a Capital Partner of the Year Award for their work with Maryland-based Redox Power Systems to advance emerging solid oxide fuel cell technology.

In Albany, NETL employees earned recognition from the Oregon Federal Executive Board:

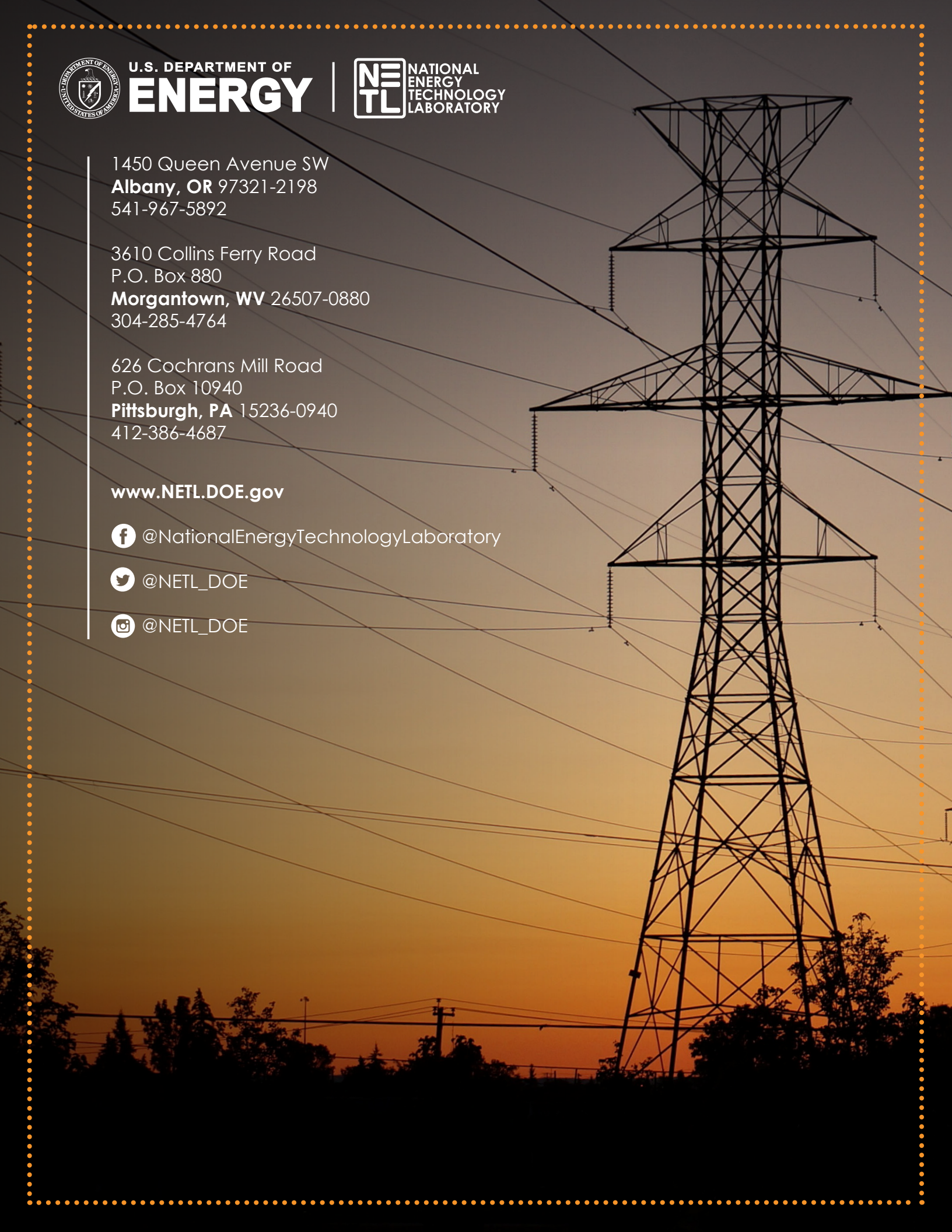
- **Alan Hartman** — Customer Service Award
- **Kelly Rose** — Exceptional Service Award
- **Circe Verba** — Leadership Award

Jessica Lamp was inducted into the West Virginia University Academy of Distinguished Alumni by the Department of Mechanical and Aerospace Engineering.

Michael Buric was presented with a Rising Researcher Award by SPIE, the international society for optics and photonics, at SPIE's 2018 Defense and Commercial Expo. Buric was recognized for outstanding work in research for scientific sensing.

NETL employees earned several honors from the Pittsburgh Federal Executive Board for Excellence in Government:

- **Jonathan Lekse** — Rookie of the Year
- **Jerry Carr** — Rookie of the Year
- **McMahan Gray** — Contribution to Science
- **Garret Veloski** — Contribution to Science
- **James Cox** — Outstanding Administrative Employee
- **Charles Taylor and Anthony Armaly** (Ukraine Coal Team) — Outstanding Team
- **James Briones, Keith Dodrill, Donald Ferguson, Robert Gross, Joseph Hanna, Robert Reed, Clark Robinson, Walter Yamben** (NETL Emergency Support Function) — Outstanding Team



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