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EFFECTIVE RESOURCE DEVELOPMENT:

Working smarter for a sustainable energy future

NETLImpact

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

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

From the Director

In the 1970s and 1980s, researchers at what would become NETL pioneered horizontal drilling, hydraulic fracturing, and other technologies that would someday enable extraction of the vast shale resources beneath our feet. Now, more than 30 years later, the vision and innovations discovered, developed, and integrated into industry practice by NETL has driven positive growth into the heart of Appalachia.

That kind of effective resource development and environmental sustainability go hand in hand. They are also two of NETL's enduring mission elements. Extracting and using resources efficiently with minimal effect on the environment requires advanced technologies. In this issue of NETL Impact, we highlight the technologies NETL is developing to do just that.

Our researchers are advancing technologies to quickly and safely maximize oil recovery from deepwater offshore fields that are currently at the edge of industry capabilities. We're developing technologies to breathe new life into mature oil and gas reservoirs through enhanced oil recovery, and we're deepening our knowledge of unconventional reservoirs and fractured shale to reduce the cost, increase the efficiency, and minimize the environmental risk of finding and producing natural gas. We're also investigating methane hydrates and their potential as an energy resource.

At the same time, we're exploring the extraction of rare earth elements from coal and coal byproducts, and demonstrating highly effective, economical carbon capture and storage technologies at our nation's coal-fired power plants.

We have prepared the following articles to provide an informative and insightful glimpse into the innovations NETL is pursuing to advance new technologies in support of our nation's energy goals. I hope you find it useful.

Grace M. Bochenek, Ph.D.
Director, National Energy Technology Laboratory

NETL Impact

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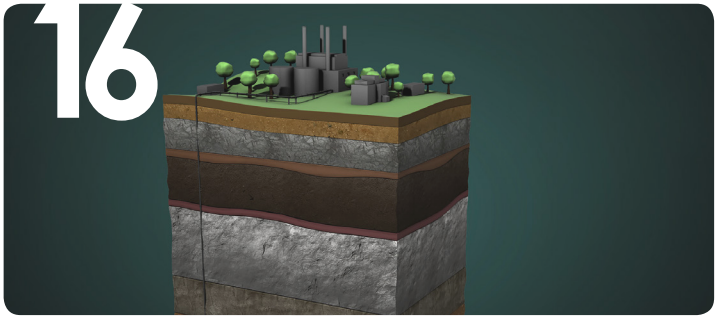

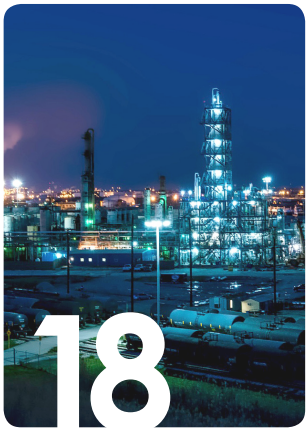

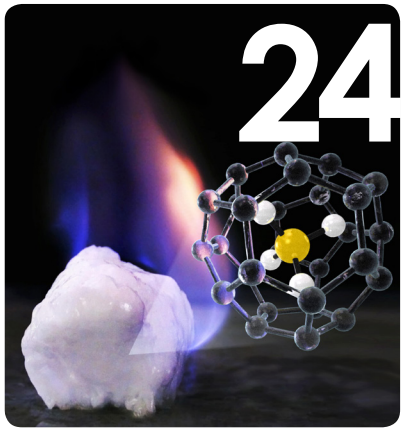

Proving Carbon Capture Can Be a Viable Part of Power Plants

By Joe Golden // Technical Contact: Ted McMahon

POWER magazine named Petra Nova the 2017 Plant of the Year, and described the plant as "both a globally significant environmental breakthrough and a trailblazing revenue-generating facility." (Photo courtesy of *POWER*)

A 15-foot diameter fiberglass duct routes the flue gas from the generating unit to the carbon capture system.

Petra Nova, a joint venture between NRG Energy Inc. (NRG) and JX Nippon Oil and Gas Exploration Corporation (JX Nippon) is wrapping up a hugely successful first year of operations, culminating in being named *POWER* magazine's plant of the year.

Petra Nova began commercial operation at the W. A. Parish Plant in Thompsons, Texas, southwest of Houston January 10, 2017. The project is designed to capture 1.6 million tons of carbon per year using the highly tested Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) Process®.

Secretary of Energy Rick Perry took part in a ribbon-cutting ceremony to mark the official opening of Petra Nova earlier this spring.

"I commend all those who contributed to this major achievement," said Secretary Perry during the ceremony. "While the Petra Nova project will certainly benefit Texas, it also demonstrates that clean coal technologies can have a meaningful and positive impact on the nation's energy security and economic growth."

The Petra Nova project was finished on time and on budget, and despite its unprecedented scale (i.e., the largest post-combustion carbon capture project installed on an existing coal-fired power plant), it was completed in roughly 1.78 million man-hours without a single lost-time incident during construction. NETL played no small part in making all of that happen through the dedicated work of our project management personnel.

The Petra Nova project, which received financial and project management support from DOE and NETL, is showing how carbon-capture technologies can support the flexibility and sustainability of fossil fuels at a commercial scale.

During performance testing, the system met all performance criteria including capturing more than 90 percent of carbon dioxide from a 240 MW equivalent slipstream of flue gas off an existing coal-fueled electrical generating unit at the W.A. Parish power plant.

At this level of operation, Petra Nova can capture more than 5,000 tons of carbon per day, which will be used for enhanced oil recovery (EOR) at the West Ranch Oil Field. The project is expected to boost production at West Ranch from 500 barrels per day to approximately 15,000 barrels per day. It is estimated that the field holds 60 million barrels of oil recoverable from EOR operations.

The successful commencement of Petra Nova operations also represents an important step in advancing technologies that capture carbon. Its success could become the model for future coal-fired power generation facilities and the addition of this capability could support carbon pipeline infrastructure development and drive domestic EOR opportunities.

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EXPLORING THE VAST POTENTIAL OF COAL TO SUPPLY DOMESTIC RARE EARTHS

By Joe Golden // Technical Contact: Mary Anne Alvin

Rare earth elements (REEs) are necessary for the development and manufacture of high-tech devices like personal computers, cell phones, and even national defense systems. Traditionally, rare earths have been mined from mineral ores, then refined and separated. However, NETL is finding a way to answer the growing demand for REEs by devising ways to harvest them from one of the nation's most abundant natural resources – coal.

For more than a century, coal has reliably and affordably fueled the nation, enabling unprecedented gains in the quality of life for generations. Now, NETL is investigating whether this same plentiful domestic resource could economically yield yet another wide-ranging benefit – a domestic supply of REEs. Rare earths are found in coal, coal mining byproducts, and coal preparation residues, making every step in the coal mining process a potential source of REEs.

Producing rare earths at home is important because the Unites States currently imports most or all its supply from other countries, and this foreign reliance creates vulnerabilities when overseas markets shift unpredictably.

NETL REE Technology Manager Mary Anne Alvin explained that, "As a U.S. Department of Energy national laboratory, NETL initiated its Rare Earth Elements Program in 2014 to address the feasibility of extracting and separating REEs from coal and coal byproducts including fly ash, coal refuse, and acid mine drainage."

NETL's overarching goals are to develop extraction and separation technologies that can lead to the economic and efficient domestic production of rare earths from coal-based resources. First up in that process is an effort to validate the technical and economic feasibility of prototype systems to produce high-purity, salable, REEs by 2020.

TECHNO-ECONOMIC ANALYSIS

NETL, along with external stakeholders, are using a comprehensive cost-benefit analysis approach to determine whether REEs can be separated and recovered from coal-based feedstocks economically. The process involves development and implementation of techno-economic analysis models to evaluate the international REE market and then assess the economics of commercially producing REEs from existing conventional, novel, advanced, and potentially transformational separation and recovery processes.

Morgan Summers, an NETL engineer and economic analyst, emphasized the importance of techno-economic analyses.

"Applying techno-economic analysis to the early stages of these design concepts will improve the chances for economic success by making researchers not only ask how we can recover rare earths from coal-based materials but also, how can we do it economically to compete in the global rare earth market," he said.

More economic uncertainty exists for projects in early development because of an emphasis on process performance rather than process economics. Highlighting economics early in the development phase will raise awareness of the economic impacts associated with design decisions. Analysts have determined that driving down operating expenses will have a bigger impact on reducing required revenues than lowering capital costs. Evaluations have indicated that operating costs far exceeded an annualized capital cost, on a per ton of product produced basis. This further emphasizes the need to make sound design decisions early in the development process.

Techno-economic analyses help researchers understand the cost and performance of REE concentration and separation from various feedstocks. Once this is understood, specific research and development for the extraction of REEs from coal feedstocks can be identified and more aggressively pursued. Additionally, techno-economic analysis allows for the evaluation of the economic benefits of conventional, as well as transformational separation processes that are being developed within the REE supply chain.

NETL is incorporating the techno-economic analysis approach into process designs for currently funded REE separation and recovery projects. At its core, techno-economic analysis modeling orients and helps direct research efforts to ensure that researchers are aware of the economics of their processes as early in the design phase as possible. That awareness allows adjustments to be made in designs prior to scale-up. That way, if economic hurdles exist with a design, mitigation strategies or design changes can be implemented early in the development process to help advance commercial readiness without attempting major design changes after the process system is physically built.

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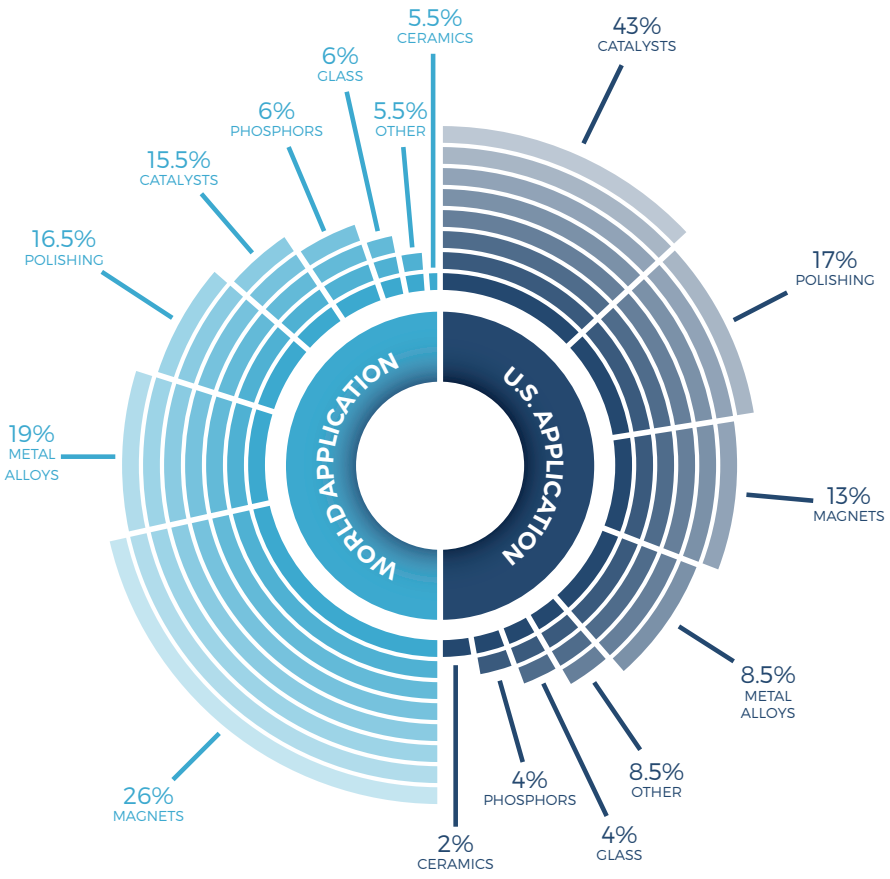
REE APPLICATIONS



WORLD-CLASS RESEARCH CAPABILITIES

NETL's multi-faceted research is helping to establish a reliable domestic supply of rare earths, focusing on many various stages of REE recovery from coal and coal-based products including field sampling, characterization, extraction and separation, and small pilot-scale REE production.

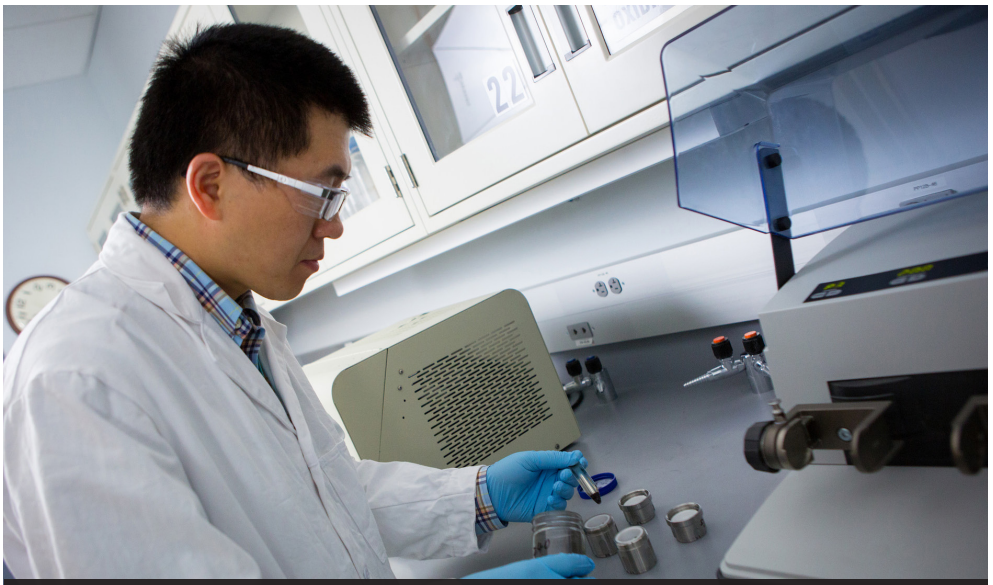
Currently, the U.S. uses over 17 thousand tons of REEs each year. That demand could be completely met by extracting rare earths from domestic coal and coal byproducts. Considering that coal contains 62 parts per million (ppm) of total rare earths on a whole sample basis, and there are more than 275 billion tons of coal reserves in the United States, then 17 million tons of REEs are present within the domestic supply of coal.

Clays and shales located above and below coal seams are also potential sources because they can contain around 200 ppm or more total rare earths. In the United States, burning coal for power generation and industrial uses typically produces around 75 million tons of post-combustion coal fly ash annually, which typically contains more than 400 ppm of total REEs.

NETL Research Engineer Evan Granite said, "By tapping into this vast untouched resource of coal and coal byproducts, the United States could benefit from a 1,000-year supply of REEs at the current rate of consumption."

NETL has developed techniques for characterizing samples in its REE research. In fact, more than 800 field samples have been collected as part of its research since June 30, 2015, by NETL researchers and personnel from the U.S. Department of Energy's Office of Fossil Energy.

NETL has used a variety of techniques to advance its REE characterization work. For example, by improving the methodology for inductively coupled plasma mass spectrometry, researchers have increased the accuracy of determining levels of trace REE concentrations.



NETL's Dr. Ronhong Lin performing particle size reduction of coal samples in a ball mill to release rare earth minerals from coal.

The increased activity surrounding sample characterization work has sparked additional interest in the public and private sector. The United States Geological Survey and the Electric Power Research Institute have both signed memorandums of agreement with NETL calling for additional collaborative research and sampling activity.

After determining which REEs are present and in what quantities, the next step in the process involves selection, development, and progressive improvement of extraction and separation techniques. NETL is developing these capabilities for use with resources such as pre-combustion coal, coal refuse, clay and sandstone over or under burden materials, aqueous effluents, and power generation post-combustion ash.

NETL expertise in computer modeling also plays a key role in critical REE research. The Laboratory has developed advanced computation fluid dynamics (CFD) software to simulate REE separation and optimize the separation process. CFD models serve as virtual test platforms that allow researchers to optimize process separation designs.

STRATEGIC RESEARCH PARTNERSHIPS TO ACCELERATE REE RESEARCH

In FY16 – FY17, Congressional language specified that REE Program objectives should include external agency activities for development and testing of commercially viable, advanced separations technologies at proof-of-concept or pilot-scale stages. The initiative called for near-term deployment of innovations enabling the extraction and recovery of rare earths from U.S. coal and coal byproduct sources with the highest potential for success.

NETL Federal Project Manager Charles Miller explained that, "These strategic partnerships amplify NETL's contribution toward recovering

REEs from domestic coal and coal-based products. The technology developed through this work could help maintain jobs in the coal industry and improve national security by developing a domestic supply of REEs."

In 2017, the DOE-NETL REE Program portfolio consisted of 15 active REE technology development projects that are working toward these goals. In 2018, the DOE-NETL REE portfolio will expand to approximately 30 active projects, including efforts with universities, small businesses, and other national laboratories.

NETL manages five external service contracts that began in October 2016 to identify promising sources of domestic coal and coal byproducts containing high REE concentrations. The University of Kentucky, West Virginia University, and XLight Corporation are undertaking one project each while Tetra Tech Inc. leads two projects.
These projects consist of work to identify, locate, field sample, and analyze REE-bearing materials from various regions of the country including material from the Illinois Coal Basin, Northern Appalachian Coal Basin in Pennsylvania and West Virginia, Central Appalachian Coal Basin in West Virginia, and the Raton Basin in Colorado and New Mexico.

One additional NETL external contract to identify and characterize domestic coal and coal byproducts started in October 2017. The University of North Dakota was awarded a two-year contract to sample and characterize a variety of U.S. coal-based resources containing high concentrations of rare earths. The university will also perform a round-robin interlaboratory study on the analytical methods used to measure the concentration of REEs in U.S. coal-based resources.

Additionally, NETL manages four projects that are developing bench-scale and pilot-scale technologies to economically extract and concentrate mixed REEs from coal and coal byproducts, including aqueous effluents. Each is making noteworthy progress in developing high-performance, economically viable, and environmentally benign technologies to recover REEs from domestic coal and coal byproducts. For instance, during Phase 1 of the four projects, external partners achieved a production of ≥ 2 percent by weight REE pre-concentrate from coal-based materials – a key step toward securing a domestic supply of rare earths. They also developed a project-specific REE recovery system design that will be developed and tested in Phase 2. All four projects will enter Phase 2 by January 2018 and will finish by 2020.

Bench-scale projects include work by the University of North Dakota Institute for Energy Studies, which is using North Dakota lignite and coal-related material as feedstock to test their REE recovery system; and the West Virginia University Research Corporation, which is using acid mine drainage solids from Northern Appalachian and Central Appalachian bituminous coal seams as a feedstock for recovery of REEs and other useful materials.

Pilot-scale projects include work by Physical Sciences Inc., which is using coal fly ash physically processed near Trapp, Kentucky, as a feedstock, and The University of Kentucky Research Foundation, which is using two sources of coal preparation byproducts (tailings) as feedstock for recovery of REEs.

In addition to the four external projects described above, NETL further expanded strategic research partnerships by supporting two new projects that will develop a Phase 1 system design for small pilot-scale production of salable REE products in the form of individual rare earth compounds with a minimum purity of 90 percent.

Inventure Renewables and Marshall Miller & Associates will each lead one of these projects. These Phase 1 salable REE projects began in September 2017 and will compete for a Phase 2 award that will require the development, testing, and operation of the project-specific design that was developed during Phase 1. It's anticipated that one or more Phase 2 salable REE projects will be awarded and begin by mid-2019 with completion expected in 2020.

Aside from the active projects, NETL recently selected under a competitive Funding Opportunity Announcement, nine new external R&D projects for negotiation and award of advanced REE recovery technology at laboratory/bench-scale, to start in late 2017 and finish in 2019.

In describing the future of REE research at NETL, Mary Anne Alvin said, "as the REE program continues, first- and second-generation REE extraction and separation systems will address processing requirements for a broad portfolio of coal-based feedstock materials, as well as enhanced REE and mineral production efficiency, and validation of small pilot-scale systems to technically and economically produce high-purity REE oxides by 2020."

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Improving Efficiency & Safety of Hydraulic Fracturing

By Gerrill Griffith // Technical Contact: Gary Covatch

Laredo Petroleum Field Site in Reagan County, Texas

Fracturing—the process of creating pathways through rock formations to enhance the flow of oil or gas into a wellbore—has come a long way since early innovators used nitroglycerin to stimulate shallow wells in the late 1800s. In the 21st century, advances in hydraulic fracturing in shale plays ushered in a new oil and gas boom. But, there is much more to discover and innovate if producers are to maximize efficiencies and increase environmental safety.

Despite a long history of hydraulic fracturing, fundamental questions about fracture growth, its interaction with natural fractures, and fracture efficiency for production enhancement remain unanswered. According to researchers, fracturing of horizontal wells is often more a hit-and-miss proposition than an engineered, predictable procedure. Usually, only a few of the hydraulic fractures created in an extended reach horizontal well contribute to the bulk of gas flows with low production from the remaining fractures.

In multi-stage fracturing, horizontal drilling, plugging, and fracturing take place deep underground in segmented stages to access oil and gas through fractures in shale plays. Initially, fracturing was limited to four stages more than 1,640 feet in length. Improvements now enable companies to work with additional stages; more than 35 stages were done in each of the 11 horizontal wells at 10,000-foot depth in the work described below. However, the optimal number of fracturing stages possible during multi-stage fracture stimulation in horizontal wells is still being researched.

With a long record of success advancing hydraulic fracturing innovations, NETL teamed with Gas Technology Institute (GTI) of Des Plaines, Ill., to develop and execute a hydraulic fracturing test site to answer questions, advance the understanding of the hydraulic fracturing processes, and attain greater efficiencies and improve environmental impacts. DOE invested $7.6 million in the overall $20 million project with NETL providing management assistance.

Specifically, the effort will gain the knowledge necessary to achieve the following objectives:

- Assess the environmental impact (emissions and water) of hydraulic fracturing
- Determine the optimum well spacing based on fracturing efficiency
- Evaluate inter-well interference
- Understand stimulated rock volume (SRV) and reservoir depletion over time

Core Sample with proppant.

- Evaluate effectiveness of geological fracture barriers
- Test alternative fracturing designs
- Test production performance by stage/perforation cluster post stimulation
- Collect research data to construct detailed models for reservoir simulation and fracture

According to NETL Project Manager Gary Covatch, the initiative, which began in October 2014, has made progress in improving the design and execution of fracturing processes that will reduce the number of infill wells to be drilled, water used, and the energy input required during future oil and gas recovery activity.

"The overarching goal of this effort is to understand and define the relationships of shale geology and fracture dynamics using first-time detailed field data that includes coring of the fracture domain," Covatch explained. "Analyses of the data will then aid in updating fracture design models and improved effectiveness of individual hydraulic fracture stages. Basically, we want to create more effective fractures in every fracture stage, increasing production with no increase in the amount of water, chemicals, proppants, and energy used. That translates to minimized air emissions and other environmental impacts associated with oil and gas production."

In August 2015, Laredo Petroleum provided a field site in Reagan County, Texas, that included 11 existing horizontal wells in the Upper and Middle Wolfcamp formations in the Permian Basin. Nearby vertical wells were used as observation wells. Researchers with GTI conducted cross-well seismic surveys between three wells on test sites prior to and after hydraulic fracturing operations. Water and air samples were also collected. Microseismic monitoring was conducted during all the fracture stages, which totaled more than 400. In addition, chemical and radioactive tracers were used in all fracture stages and colored proppant was used in the fracture stages in the two wells where the slant core well was drilled in between.

A slant core well was drilled at an angle of 81 degrees between two wells starting above one well and ending below the second well. A total of 600 feet of core was retrieved, which included 440 feet from the Upper Wolfcamp and 160 feet from the Middle Wolfcamp. The core was characterized, natural fractures and hydraulic fractures were identified, and trends were noted. Sludge was also removed from the core barrel so it could be examined for tagged proppant used in fracturing to study proppant distribution.

The air quality data and analysis indicated little to no increase in toxic air quality compounds during fracturing and production operations at the test site. In addition, there was no evidence of natural gas or produced water migration to the groundwater aquifer.

As of September 2017, microbial analysis is ongoing for produced water samples collected in July. Sludge from the core barrel to detect colored proppant is also being examined.

Onsite researchers will continue to collect pressure and temperature information and produced fluid samples for oil and water tracer detection from producing and core wells.

"The net effect of the efficiency improvements this research will help us attain will increase production from wells with no increase in the amount of water, chemicals, proppants, and energy required," Covatch said. "In addition, the results and data collected during this wowill be used for many years to come by industry in their future exploration and development of different shale formations."

The work is a good example of how NETL pursues its mission to discover, integrate and mature technology solutions to enhance the nation's energy foundation and protect the environment.

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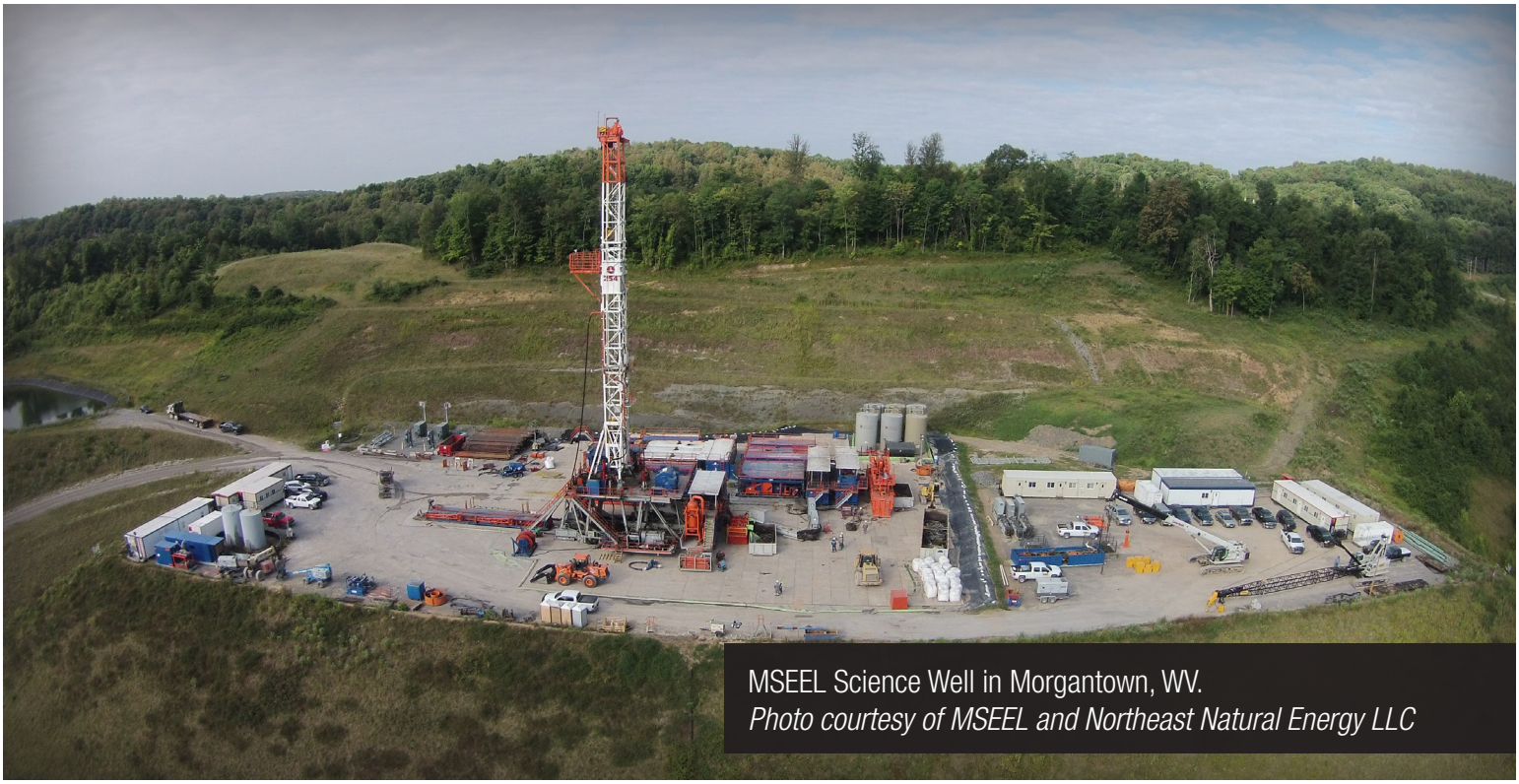
MSEEL

Drilling Down to Discover New Knowledge about Marcellus Shale Natural Gas



MSEEL Science Well in Morgantown, WV.
Photo courtesy of MSEEL and Northeast Natural Energy LLC

By Gerrill Griffith // Technical Contact: Robert Vagnetti

The largest source of natural gas in the United States is the 104,000-square mile Marcellus natural gas trend, but it was once considered to have inconsequential natural gas potential. A productive tradition of R&D partnerships that embraced the best ideas from researchers in industry, academia, and DOE changed all that by contributing innovations that led to the nation's current surge in unconventional oil and gas (UOG) production. Deep horizontal drilling, natural fracture detection, and the application of horizontal drilling and hydraulic fracturing in shales deep underground were just some of the breakthroughs that created the Marcellus Shale boom currently evident throughout the Appalachian region that makes up the Marcellus trend.

That was just the beginning. Despite the growth in the production of UOG resources, the full potential for oil and gas production remains unrealized because there is much more to learn about the complexities involved with pursuing the massive resources still locked away underground.

An effort involving NETL, West Virginia University (WVU), The Ohio State University (OSU), and Northeast Natural Energy (NNE) known as the Marcellus Shale Engineering and Environmental Laboratory (MSEEL) is building upon a cooperative tradition of teaming and collaboration to unravel UOG mysteries for a more secure and safe energy production future.

NETL's Robert Vagnetti, the federal project manager for the MSEEL effort, explained that very little is really known, in detail, about recovery efficiency in the Marcellus Shale reservoirs.

"From the limited information available, the ratio of produced resources to total in-place resources, are thought to remain quite low," he said. "It could be 20 percent in gas-rich shale reservoirs and less than 10 percent in liquid-rich plays. That's why we continue to pursue a robust portfolio of R&D on the topic. MSEEL is contributing to the fundamental science we need to have a practical understanding of UOG reservoirs and their response to stimulation currently used to spur production."

The objective of MSEEL is to provide a long-term collaborative field site to develop and validate new knowledge and technology to improve recovery efficiency and minimize environmental implications of UOG development. MSEEL represents the first ever comprehensive field study of shale gas resources and gives scientists the opportunity to study the entire process of drilling, hydraulic fracturing, and recovery of Marcellus Shale natural gas.

Recognizing the potential for even more efficient oil and gas recovery in the Marcellus Shale, DOE, through NETL, invested $10.5 million in the effort, which began in October 2014 at a site located in the Morgantown, W.Va., Industrial Park and will run through September 2019. NETL is managing the DOE participation.

Why Pursue More R&D for UOG Recovery?

NETL Chief Research Officer and Deputy Director for Science and Technology Randy Gentry, Ph.D., said shale gas and shale oil production will remain a critical part of the nation's energy future.

"One of the driving factors behind the need to increase our knowledge base for more efficient ways to recover oil and gas from shales is the ever-increasing demand for energy," he said. "Clearly, continued robust production from existing and emerging shale gas and shale oil plays will be critical to domestic energy security and continued economic prosperity."

The U.S. Energy Information Administration (EIA) estimates that crude oil and condensate production from unconventional, or tight, reservoirs currently account for 69 percent of U.S. Lower 48 onshore production. But, by 2040, those reservoirs are expected to contribute more than 75 percent of production.

Similarly, natural gas production from UOG reservoirs, like tight gas sands, coal seams, and both gas and oil bearing shales and tight rocks, currently accounts for just under three quarters of U.S. Lower 48 onshore and offshore production, according to EIA's 2017 Annual Energy Outlook. By 2040, that number will be 85 percent.

Vagnetti explained that many of the engineering paradigms that have guided oil and gas reservoir and field management for the past century, "simply do not apply in the new context of nanoporous reservoirs—reservoirs with pores of nanometer size."

He said that the fundamental science needed for a practical understanding of reservoirs and their response to stimulation for increased UOG production is still in its infancy, but new approaches could lead to more efficient recovery of oil and gas resources with fewer environmental effects.

"We need to add to our knowledge so that we can reduce the environmental footprint of oil and gas operations while maximizing the national energy security and economic benefits of UOG development," Vagnetti said. "Our role in this effort through MSEEL helps strengthen America's energy independence, protect environmental quality, and position the nation as a global leader in UOG resource development technologies."

The MSEEL Team

As DOE's national laboratory devoted to fossil energy research, NETL has long supported "cornerstone" field laboratory projects that are longer-term collaborative efforts providing researchers with opportunities to gather data and test new concepts under ideal conditions. Those activities typically include one or more industry partners along with scientists and engineers from academia or other national laboratories.

To be successful, those efforts require a dedicated site or research well of opportunity to enable an open, collaborative, and integrated initiative of scientific data acquisition and technology development and testing. The NETL-WVU-OSU-NNE team put together the MSEEL effort to provide that opportunity.

Timothy Carr, WVU's Marshall Miller professor of geology and the University's principal investigator for MSEEL, said, "to date, there has been no comprehensive long-term field study that addresses baseline measurements, subsurface development, and environmental monitoring with unconventional resource development. No other study can replicate and validate results with subsequent drilling and completion events."

Jeff Daniels, director of the OSU Subsurface Energy Resource Center, said his team is working with WVU to provide subsurface scientific investigations of the geology and microbiology from samples taken in the drill hole, along with guidance and support for the environmental work at the site.

Mike John, chief executive officer of NNE said when the opportunity was announced that his company's participation "is driven by our desire to help improve science, enhance technology and expand understanding of the natural gas industry. The Morgantown Industrial Park site offers a convenient location for researchers and students to conduct their studies and we look forward to working together with them on this project."

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The MSEEL Test Site Details

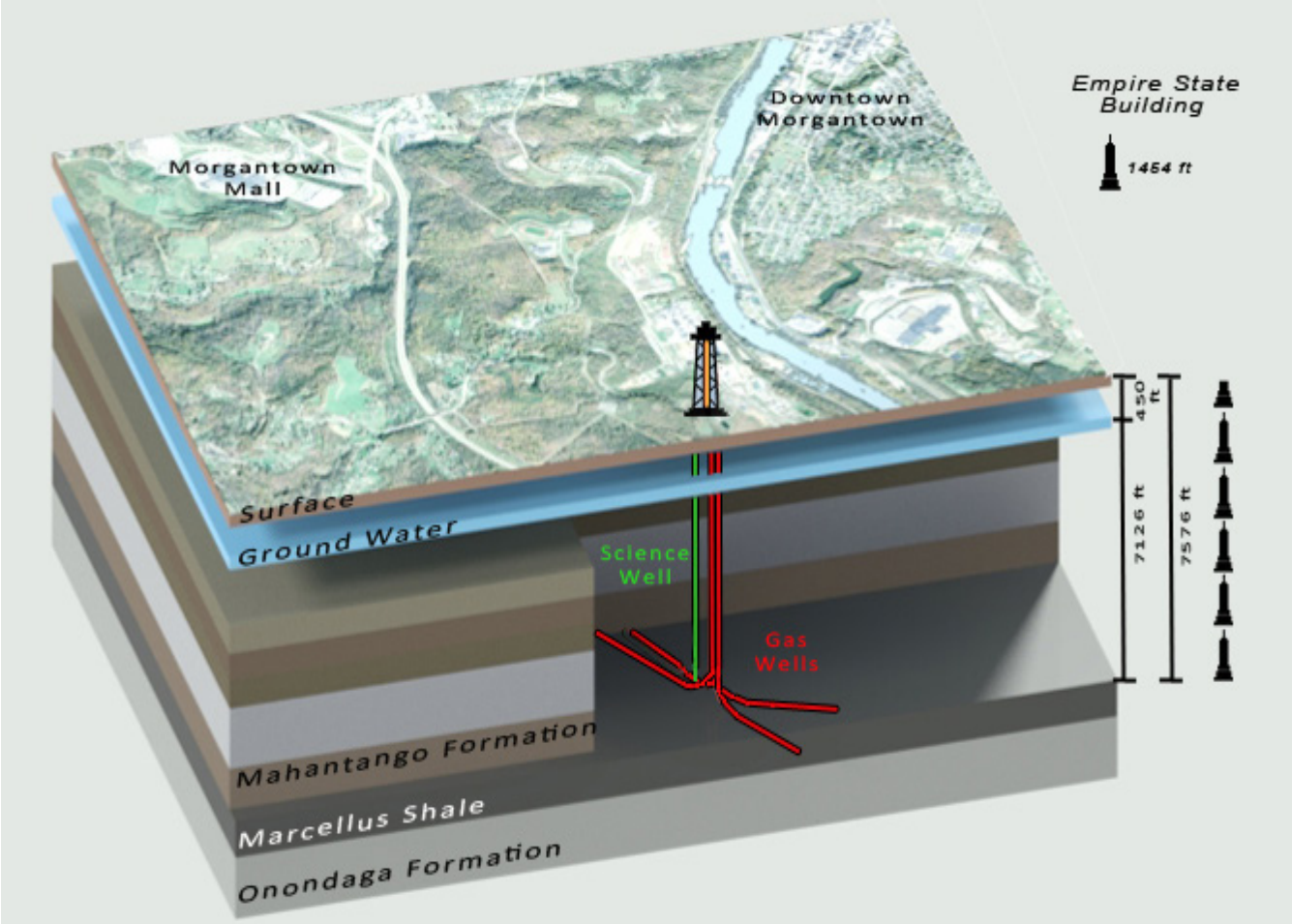
The site, owned and operated by NNE, consists of a 1-acre pad with two pre-existing horizontal wells (4H and 6H) drilled into the Marcellus formation. Prior to drilling operations, baseline air monitoring and surface water sampling occurred at the well pad site. By June 2015, drilling of two additional horizontal wells (3H and 5H) and an approximately 7,000-foot science well between the laterals of the two new wells began.

Cuttings and a total of 111 feet of 4-inch whole-round core was taken from the 3H well— perhaps the only existing core retrieved through the entire vertical span of the Marcellus Shale. In addition to the whole-round core, 197 sidewall cores were extracted from the 3H and science wells. The cores were delivered to NETL where they were logged, sampled for total organic content and scanned using high-precision computerized tomography. The fresh core and cutting samples have been distributed widely to academic and national laboratory scientists throughout the United States enabling studies and analyses not previously possible.

Stimulation of the 3H well combined strategic staging and perforation placement in "like-rock" to optimize perforation cluster efficiency. The stimulation stages were strategically placed in lateral well segments with similar gamma ray, minimum horizontal stress and natural fracture density. Unlike the 3H well, hydraulic fracturing of the 5H well utilized NNE's standard stimulation practices consisting of 30 equally spaced stages with 5 clusters each, allowing for direct comparison of the stimulation efficiency between the two production wells. In February 2017 NNE conducted a production "spinner" test of the 3H well to confirm the efficacy of their variable stimulation approach.

Hydraulic fracturing of the 3H and 5H wells was monitored continuously using borehole seismic in the science well and a surface seismic array. In addition, stimulation of the 3H well was monitored using a fiber-optic distributed acoustic and distributed temperature system installed to the outside casing string.

Since bringing the two wells online, air, gas, and produced water samples have been collected continuously for a variety of scientific investigations.



Science and production wells at the MSEEL site. First ground water contact is at about 450 feet and Marcellus Shale at 7,576 feet. The depth of the Marcellus Shale has been compared to the height of the Empire State Building at 1,454 feet. *Photo courtesy of MSEEL*

A Legacy of Lessons Learned

The MSEEL research-oriented national gas production site is providing a well-documented baseline of production and environmental characterization from its test wells. The project's phased approach allows for additional multiple drilling events and has the flexibility to identify and incorporate new, cost-effective technology and science that is focused on increasing recovery efficiency and reducing environmental and societal impacts.

The MSEEL effort has already yielded a wide range of lessons learned:

- NNE upgraded casings based on MSEEL confirmation of limited entry theory
- Synthetic-based drilling mud is ecofriendly and helps reduce friction resulting in faster drilling and reduced costs while drilling waste from both the vertical and horizontal portions of the wells passed all toxicity standards
- Microseismic events provide valuable clues concerning the extent of hydraulic fractures, but represent less than 1 percent of the total injection energy
- Complex geology in laterals can lead to intercommunication between stages and reduced facture stimulation efficiency, which can be mitigated with limited entry (engineered completions) that significantly improve fracture stimulation efficiency
- CT scans and wireline image logs show numerous vertical mineral-filled fractures in the Marcellus Shale in MIP-3H. Analysis shows that even though most pre-existing fractures are mineral-filled, they strongly influence the fracture stimulation process.
- The significant source of air emissions is from truck traffic, not drilling and fracture operations on the pad. Emissions from both the pad and trucking can be reduced with operational modifications such as reducing dust and truck traffic during fracture stimulation and from biofuel (natural gas-diesel) engine operations.
- Drill cutting radioactivity levels were within West Virginia Department of Environmental Protection standards of 5 pCi/g above background. This was true of both vertical and horizontal (Marcellus) sections.
- Using the green drilling fluid Bio-Base 365, all drill cutting samples, vertical and horizontal, passed the U.S. EPA's method 1311 (Toxicity Characteristics Leaching Procedure or TCLP) for inorganic and organic contaminants. This indicates that under federal and West Virginia solid waste rules, these solid wastes would not be considered hazardous.
- The absence of hazardous TCLP findings suggest that drilling fluids, not the inherent properties of the Marcellus formation, play the dominant role in determining drill cutting toxicity.
- Hydraulic fracturing fluid was nearly identical to makeup (Monongahela River) water. Initial produced water underwent a radical change in ionic composition and a two order of magnitude increase in total dissolved solids. However, there has been negligible change in ionic composition between the initially produced water and that sampled five years' post completion.
- Many of the organisms that persisted throughout the sampling period ferment compounds in the fracking fluids. The fermentation products are likely used by methanogens to produce methane.

A Resource for Guiding Tomorrow's Decisions

In addition to building upon the foundations of scientific knowledge associated with Marcellus Shale natural gas production, the work of MSEEL is informing policymakers as they consider a range of issues surrounding safe access to natural gas by:

- Demonstrating the best approaches to drill, complete, and produce new horizontal wells that minimize environmental/social costs while maximizing economic productivity
- Monitoring and documenting impacts in a controlled environment on greenhouse gas emissions, local air pollution, water supply and quality, noise and activity, and societal impact
- Developing new technologies in microseismic monitoring, production monitoring, and advanced logging
- Developing new scientific and engineering approaches to apply to multi-disciplinary and multi-institutional natural resource studies

The mission of NETL is to discover, integrate, and mature technology solutions to enhance the nation's energy foundation and protect the environment for future generations. The Laboratory's support of MSEEL with its public and private sector partners is one more example of how its pursues that mission.

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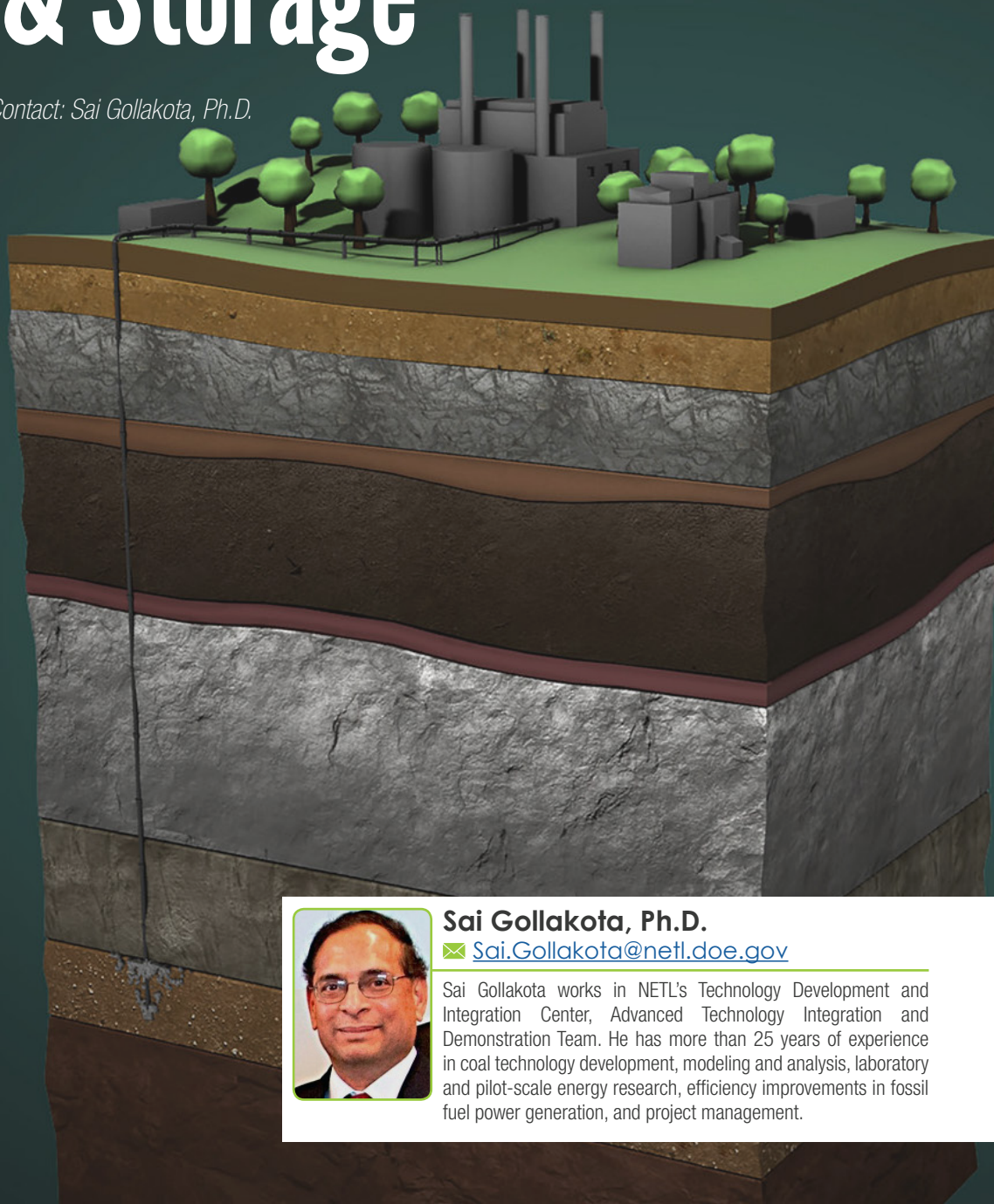
Robert Vagnetti has more than 28 years of experience in energy, providing analytical and technical services to various DOE offices. He has worked for the Energy Information Administration and currently works with NETL's Technology Development and Integration Center, Unconventional Oil and Gas Team.

MAKING MAJOR GAINS in Technology Deployment of Industrial Carbon Capture & Storage

By Paul Battista, Ph.D. // Technical Contact: Sai Gollakota, Ph.D.



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Sai Gollakota works in NETL's Technology Development and Integration Center, Advanced Technology Integration and Demonstration Team. He has more than 25 years of experience in coal technology development, modeling and analysis, laboratory and pilot-scale energy research, efficiency improvements in fossil fuel power generation, and project management.

ADM's agricultural processing and biofuels plant, Decatur, Ill. (Image courtesy of ADM)

DOE has collaborated with industry in cost-sharing arrangements to advance the next generation of technologies that will capture carbon from industrial sources and either store or beneficially reuse them. The technologies have advanced to a scale that can be readily replicated and deployed into industry.

Archer Daniels Midland Company (ADM) has made significant progress in advancing carbon capture and storage technologies and started large-scale geological storage of carbon in April 2017. NETL manages the ADM project. Additional partners include Schlumberger Carbon Services, Illinois State Geological Survey, and Richland Community College.

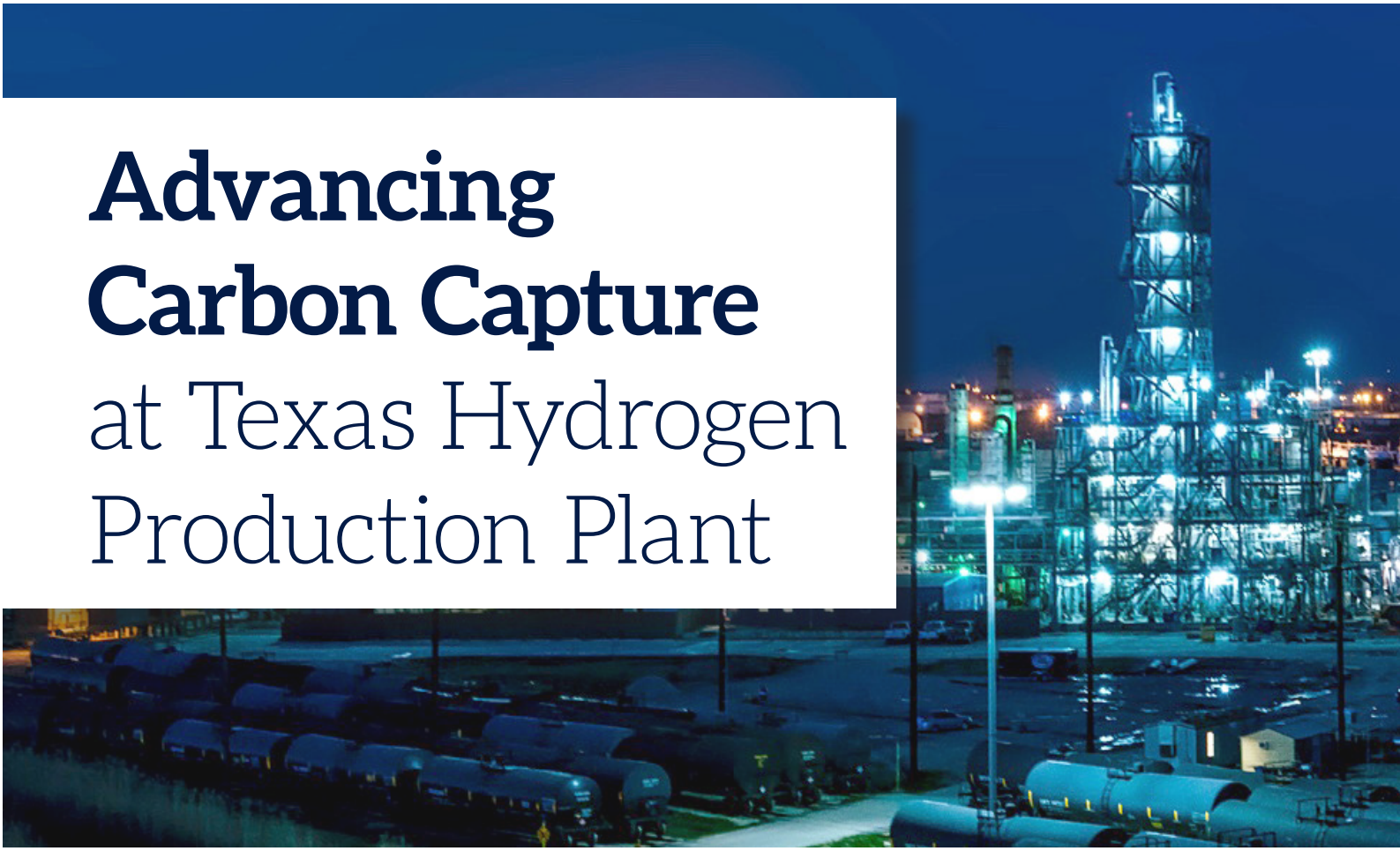
The overall objective of the ADM effort is to develop and deploy an integrated system for collecting carbon dioxide from an ethanol production plant and geologically storing it in a deep underground sandstone reservoir. The carbon dioxide produced is a byproduct from processing corn into fuel-grade ethanol at the ADM ethanol plant in Decatur, Ill.

The captured carbon is stored in the Mt. Simon Sandstone, a prolific saline reservoir in the Illinois Basin. Geological features of this reservoir (porosity and permeability) make it a favorable location for carbon storage. The ADM project can store approximately one million tons of carbon dioxide per year at depths of approximately 7,000 feet. Researchers estimate that the sandstone formation can potentially store more than 250 million tons in the Illinois Basin region. Nearly 50 years of successful natural gas storage in the Mt. Simon Sandstone indicates that this saline reservoir and overlying seals should effectively contain stored carbon dioxide.

To date, the ADM facility has successfully operated cost-effective carbon capture, compression, dehydration, and injection technologies. In addition, this project is testing cutting-edge technologies for intelligent monitoring in the deep verification well. These technologies include Schlumberger's IntelliZone compact modular multi-zonal management system, which is the first such installation in North America; a Sercel SlimWave acquisition unit with WAVELAB surface control (a downhole seismic monitoring system in the geophysical well); and Schlumberger's WellWatcher monitoring system, which integrates advanced downhole measurement technology with surface acquisition and data communication systems.

The ADM effort presents a unique opportunity to gather crucial scientific and engineering data and to add to the understanding of large-scale carbon storage in saline formations. Successful implementation will facilitate exploration of long-term carbon utilization options such as enhanced oil recovery in the Southern Illinois Basin—efforts that will help bolster domestic fossil fuel production and support America's energy dominance.

Advancing Carbon Capture at Texas Hydrogen Production Plant



By Gerrill Griffith // Technical Contact: Anthony Zinn

A large-scale project, made possible through NETL support, is capturing about one million tons of carbon dioxide per year from a state-of-the-art hydrogen production facility in Texas and forging a successful new direction for hydrogen production technology.

For years, use of hydrogen has centered on the petroleum refinery and chemical manufacturing sectors because refineries use hydrogen to lower the sulfur content of diesel fuel. According to the U.S. Energy Information Administration, refinery demand for hydrogen has increased as demand for diesel fuel has risen and as sulfur-content regulations have become more stringent. However, since 2011, interest in hydrogen for use in fuel cell technologies and other energy-related processes has also increased dramatically. Hydrogen consumption for non-traditional applications is estimated to grow from 168 million kilograms in 2013 to nearly 3.5 billion kilograms in 2030.

There are two forms of hydrogen production: on-purpose hydrogen production using steam methane reformers (SMR), and hydrogen production as a byproduct of other chemical processes. SMR is a process that heats methane in natural gas with steam and a catalyst, to produce a mixture of carbon monoxide and hydrogen.

Natural gas is used almost exclusively as feedstock for on-purpose hydrogen production in SMR units in the United States. In the SMR process, methane and water are converted to hydrogen and carbon dioxide, and virtually all the co-produced carbon dioxide is emitted to the atmosphere. However, the process streams in the SMR plants contain carbon dioxide at concentrations that are amenable to effective use of conventional adsorption and emerging carbon capture technologies.

DOE partnered with Air Products and Chemicals Inc. to advance this first-of-a-kind retrofit system to capture carbon from large-scale industrial SMR plants. NETL managed the project.

Working with the support of Denbury Onshore LLC and its affiliate, Denbury Green Pipeline-Texas LLC, Air Products designed, constructed, and continues to operate a state-of-the-art system located at the Valero Port Arthur Refinery in Port Arthur, Texas.

This effort is unique because the site has two large-scale, highly integrated SMRs located in proximity to one another. The carbon dioxide removal units were designed by Air Products and use vacuum swing adsorption (VSA) units that were retrofitted into each of the SMR trains upstream of existing pressure swing adsorption (PSA) units.

A VSA system is a gas separation technology that segregates certain

gases from a gaseous mixture under minimal pressure according to molecular characteristics. The separation technology process then uses a vacuum to regenerate the adsorbent material for reuse. The new process concentrates the carbon from the two SMR waste streams.

The Air Products–NETL project, after separating carbon dioxide from the process gas stream, compresses and dries it until its purity is greater than 97 percent and then delivers it into the Green Pipeline-Texas for transport to and use in the West Hastings Unit enhanced oil recovery (EOR) project. Denbury Onshore operates the oil field for EOR carbon injection. Carbon dioxide is a popular gas for injection because it reduces oil viscosity and is less expensive than liquefied petroleum gas.

September 2017, the Air Products–NETL effort had successfully captured and sent for storage about 4 million tons of carbon dioxide.

“The goal of the project is to advance carbon capture and storage technologies from the demonstration stage to commercial viability,” NETL’s Anthony Zinn, who oversees the effort, explained. “The project objective is to capture carbon from two of these hydrogen production plants and store it in an oil reservoir for enhanced oil recovery. These activities will successfully demonstrate the technology and maximize the economic viability of commercial-scale carbon capture and storage.”

There are numerous benefits resulting from the project. The carbon capture technology can increase the annual domestic oil production by about 1.6 to 3.1 million barrels by using captured carbon dioxide for EOR applicationsIn addition, the process enhances the U.S. hydrogen market for refinery use, which is estimated to be almost 4 million tons annually. The two Port Arthur SMR hydrogen production plants represent 4.3 percent of the hydrogen market.

The project and its partnership with the private sector to advance effective new carbon capture technologies for industrial purposes—hydrogen production—is just one additional way that NETL works to discover, mature, and integrate technology solutions that enhance the nation’s energy foundation and protect the environment for future generations.

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Putting Communities Back Together in Hurricane Ravaged Regions

By Krista Baker

Starting out as a Category 4 storm, Hurricane Harvey ripped through Rockport, Texas, and continued its path of destruction through the southern part of the Lone Star State as a tropical storm. Harvey broke records, dropping 40–52 inches of rainfall and decimated homes, businesses, and infrastructure, including electrical power. A little more than two weeks later, another hurricane, tore through the eastern Caribbean and the state of Florida resulting in similar damage.

A common quote from TV legend Fred Rogers comes to mind when people experience heartache, "always look for the helpers." Some of those helpers are NETL's own. As part of the NETL Emergency Support Function #12 Team—Rob Gross, Walter Yamben, Don Ferguson, and Jay Hanna first traveled to the Texas Emergency Operations Center (EOC) in Austin to help facilitate Harvey recovery.

In their day-to-day jobs, the NETL team of experts work on issues related to improving the nation's power grid, increasing cyber and physical security of the grid, updating technologies for electric transformers, and dozens of other critical power topics. But, when tragedies strike, the team packs up and heads to where their specific skills can best assist the Federal Emergency Management Agency (FEMA) with disaster response.

"The team provides situational awareness with all energy issues," said the Emergency Response Team Lead Bob Reed. "Our team will coordinate between federal government, state government, and industry—state government is the lead in a disaster and we are there to support them."

It's not uncommon for the members of the team to see 13-hour work days. With all their efforts, it still took two weeks to restore power to the heaviest hit areas.

The devastation from Hurricane Harvey wasn't all Mother Nature had in store for the United States. Hurricane Irma hit the U.S. Coast Sunday, September 10 as a Category 4 and brought destruction to Florida. That meant additional travel and recovery efforts for the NETL team. Members were dispatched to assist in key locations: Jay Hanna went straight from his position in Texas to the FEMA Regional Response Coordination Center (RRCC) for Region II in New Jersey (Region II includes New Jersey, New York, Puerto Rico, and the U.S. Virgin Islands) and was later joined by Bob Reed. James Briones went to the Virgin Islands, and Keith Dodrill and Clark Robinson began work in Atlanta.

Staff working out of the St. Croix, Virgin Islands, location were near the heart of the storm on September 6 when Irma ripped through. Staff operating out of the VITEMA St. Thomas facility felt the wrath of the storm when her winds cracked the windows and compromised the roof of the building. FEMA released an update saying the staff was safe after the "high significance event."

While most of the residents who live within the paths of these major storms evacuate or bunker down, members of this critical NETL team head straight into the places most affected. Their efforts don't go unnoticed.

Gross said Secretary of Energy Rick Perry also went to the frontlines of Hurricane Harvey.

NETL's Rob Gross with Secretary Rick Perry at the Texas Emergency Operations Center in Austin.

"I really didn't think I'd get the chance to meet Secretary Perry when he came and thought it best to stay at my work station," Gross said. "[Secretary Perry] was just about to leave when he turned around and said, 'Where's Rob Gross?' I couldn't believe it. I had a chance to tell him what I've been doing to assist Harvey survivors and the response community, that I work at NETL, and that him stopping at the EOC was an awesome thing for us all. The next thing I knew he was pulling out his phone to get a picture."

The Secretary applauded the public and private sector cooperation that is making the recovery achievable.

NETL Director Grace Bochenek, Ph.D., thanked the NETL experts for their "exceptional efforts."

"As a partner with DOE's Office of Electricity Delivery and Energy Reliability since 2005, our emergency response team remains a necessary element for successful response efforts related to electric power restoration," she said. "We provide a critical role during times of need."

> **"We provide a critical role during times of need."**

The Office of Electricity Delivery and Energy Reliability's mission is to ensure the Nation's energy delivery system is secure, resilient, and reliable.

The full team working on the emergencies over the last month include Bob Reed, Rob Gross, Jay Hanna, James Briones, Keith Dodrill, Clark Robinson, Don Ferguson, and Walter Yamben along with local support from Alicia Dalton-Tingler, Joe Dygert and Eddie Christy.

Kickstarting Commercialization at the TransTech Energy Business Development Conference

By Gerrill Griffith

Because integrating innovative technology solutions that enhance the nation's energy foundation into the marketplace is a key part of NETL's mission, the Laboratory sponsored and participated this fall in the Sixth Annual TransTech Energy (TTE) Business Development Conference—a popular annual event that offers innovators from throughout the Mid-Atlantic Region the opportunity to pitch ideas to venture and angel investors for potential strategic partnerships.

NETL's David Lyons networks at the TransTech Energy Business Development Conference

TTE highlights transitional technologies, strategies, products and processes that move the nation along the pathway to a lower carbon, industrially vibrant, and sustainable economy of the future. The conference is organized every year by West Virginia University and supported by Carnegie Mellon University, Case Western Reserve University, and the University of Pittsburgh. Additional support is provided by local sponsors, including NETL.

NETL experts joined an extensive list of innovators who pitched ideas, products, apps, and discoveries to investors, potential strategic partners, project and economic developers, potential customers, and the public. NETL experts were also available to network with potential technology partners during special sessions at TTE.

NETL made four official "pitches" on a range of innovative technologies. The presentations, which were brief overviews of key new innovations developed at NETL and available for commercialization, included the following technologies:

- Optimized magnetic cores by Paul Ohodnicki
- Removal of carbon dioxide from high pressure gas streams by Nick Siefert and John VanOsdol
- Catalytic conversion of carbon dioxide into high-value chemicals and fuels by Dan Haynes and Dominic Alfonso
- Optical sensors for failure prediction, by Aidong Yan, University of Pittsburgh, working with Ohodnicki

A wide range of NETL leaders and researchers attended conference events and extensively

NETL Deputy Director Dr. Randy Gentry, right, moderated a keynote session on "Building a Next-generation Regional Entrepreneurial Ecosystem: Innovate, Invest, Incorporate" with Catherine Mott, left, founder and CEO of Blue Tree Venture Fund.

NETL's Paul Ohodnicki presented information about an innovative technology for optimizing magnetic cores at the TransTech Energy Business Development Conference.

networked with conference participants. Randall Gentry, deputy director of NETL, moderated the conference keynote session on "Building a Next-generation Regional Entrepreneurial Ecosystem: Innovate, Invest, Incorporate."

Each of the technologies featured in the NETL pitches are currently available for licensing opportunities or further research through partnership arrangements. NETL research is focused on creating innovations that more efficiently and effectively use fossil fuels to support the nation's energy security.

Other TTE sessions provided participants with key information on a range of aspects related to commercialization of technology. For example:

- The U.S. Small Business Administration West Virginia and Pittsburgh district offices presented a workshop called "Access to Capital" designed to educate business owners on the commercial lending process from the borrower's perspective
- Speakers from West Virginia University, the University of Pittsburgh, Carnegie Mellon University, The Great Lakes Energy Institute, and Lucius Pitkin, Inc. addressed "From World-Class Research to Real World Jobs—Commercializing Technologies from Regional Universities"
- Representatives of the U.S. department of Energy Advanced Manufacturing Office and the GE Center for Additive Technology Advancement presented on "Opportunities for Innovations in Smart Advanced Manufacturing"

Outreach initiatives like TTE are an important piece of NETL's technology transfer efforts designed to help bridge the gap between research and commercialization and connect corporate and investment partners to the Laboratory's emerging technologies.

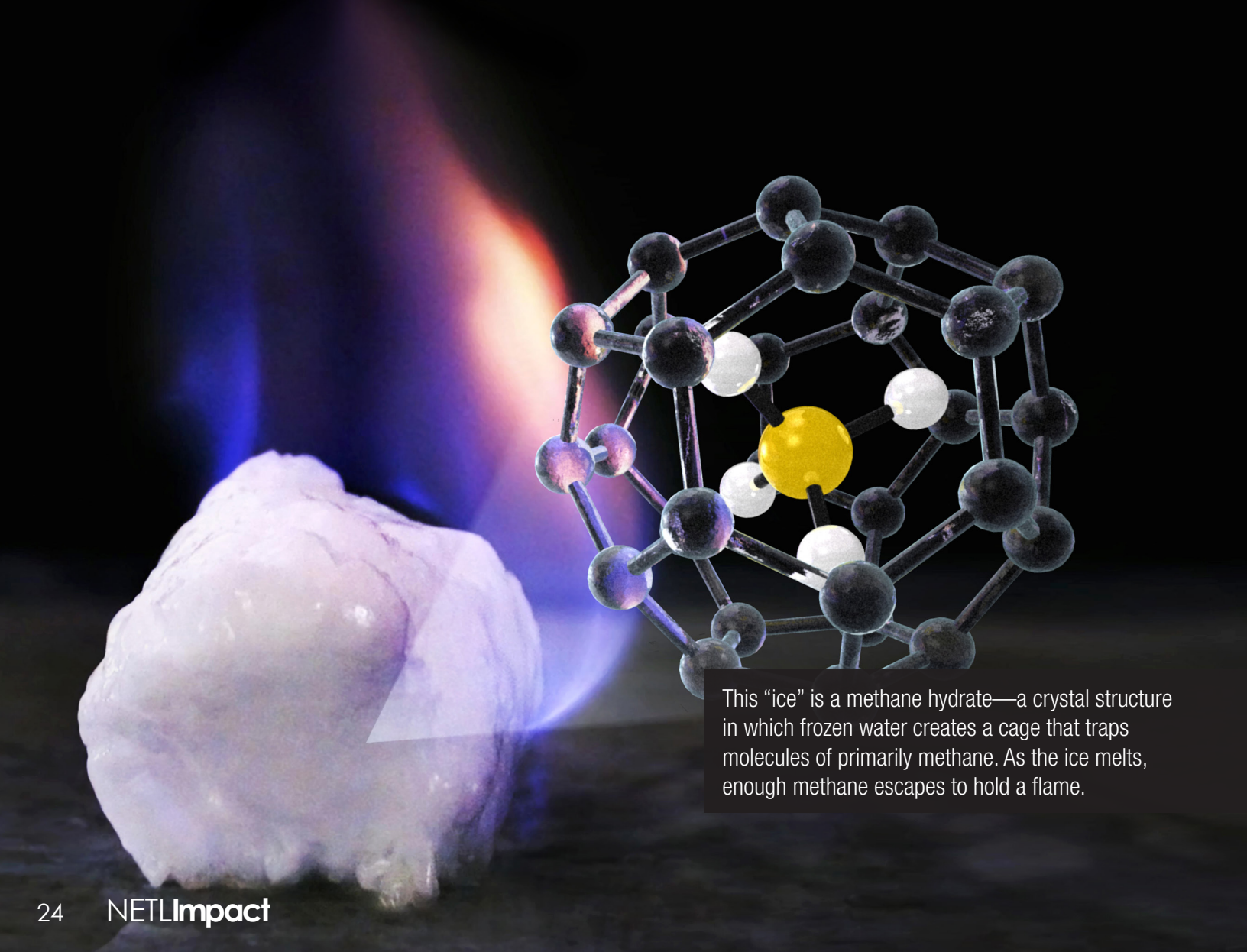
As part of a federal agency, NETL grants licenses that permit private companies to make, further develop, use, or sell a patented technology or process. NETL looks for licensing partners with a plan for technology development and marketing—a high probability for commercial success—and expects those partners to make the benefits of the technology reasonably accessible to the public.

The ways a technology traverses from laboratory to marketplace can be varied, but NETL's technology transfer work is focused on fostering innovation in any way possible, matching the most promising new inventions and technologies to the right people for commercialization. NETL's technology portfolio contains a broad range of innovations that have resulted from research in areas such as carbon capture and storage, mercury capture, fuel cells, sensors and controls, computational modeling, and materials science, among many others.

Participation in the TTE conference is one more way NETL demonstrates its commitment to discover, integrate and mature technology solutions to enhance the nation's energy foundation and protect the environment for future generations.

Recovering First Pressurized Samples from a Gulf of Mexico Gas Hydrate Reservoir

By Joe Golden // Technical Contacts: Richard Baker; Yongkoo Seol, Ph.D.; Ray Boswell, Ph.D.



This "ice" is a methane hydrate—a crystal structure in which frozen water creates a cage that traps molecules of primarily methane. As the ice melts, enough methane escapes to hold a flame.

A team led by the University of Texas at Austin (UT-Austin) has recovered the first pressurized cores from a gas hydrate reservoir in the deepwater Gulf of Mexico (GOM). Retrieving these high-quality samples at in situ temperatures and pressures will allow researchers at NETL, UT-Austin, the U.S. Geological Survey (USGS), Ohio State University, Georgia Tech, and many other laboratories across the country to advance the understanding of the nature, occurrence, and potential behavior of gas hydrate systems as well as the GOM hydrate potential—a key step in opening the door to a vast natural gas resource.

Gas hydrates are crystal structures that form under specific conditions of low temperature and high pressure, 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.

Once thought to be rare in nature, gas hydrates are now known to occur in great abundance in association with arctic permafrost and in the shallow sediments of the deep-water continental shelves—like those in the GOM; however, many scientific uncertainties and technical challenges must still be overcome before hydrates can be produced commercially and sustainably.

"Much of what still needs to be understood about hydrate system occurrence and behavior can only be learned through the study of samples that are as close to natural conditions as possible," said Rick Baker, NETL project manager. "But, capturing and recovering such samples to the surface under those conditions can only be achieved using specialized equipment and techniques."

To help solve this challenge, the expedition set forth on a one-month initiative to recover samples of gas hydrate from a site known as Green Canyon Block 955, about 145 miles off the Louisiana coast. The location was chosen based on a previous expedition to the same area in 2009 as part of the GOM Gas Hydrates Joint Industry Project.

"The 2009 expedition not only confirmed the existence of resource-quality gas hydrates in the GOM, it confirmed the gas hydrate exploration methods that were developed through collaboration between NETL, the USGS, the Bureau of Ocean Energy Management, Fugro, and Schlumberger," said NETL Geologist Dr. Ray Boswell. "NETL scientists now advise research activites around the world on these methods."

The team was based on Helix's Mobile Offshore Drilling Unit Q-4000 in 6,670 feet of water. From there, the UT-Austin-led team employed a pressure coring device called the pressure core tool with ball valve (PCTB). Two assemblies of the PCTB were deployed: (1) the "cutting shoe" type, which was like those types successfully used in previous international deep-water expeditions; and (2) the "face bit" type, which was a prototype of a new tool design intended to minimize sample disturbance by limiting rotation of the core during cutting.

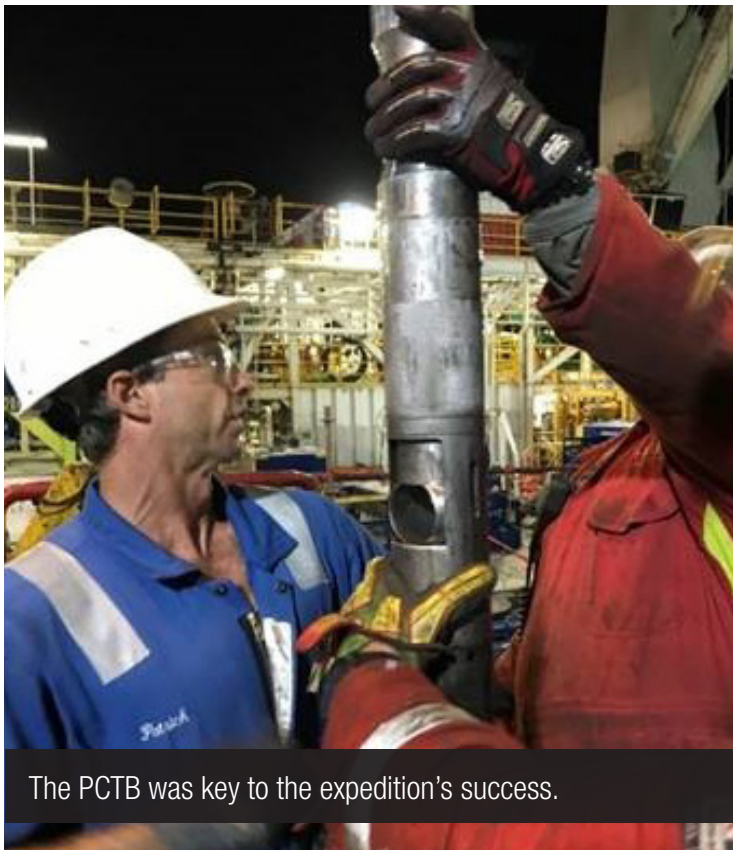
One of the two primary objectives of the expedition was to test these two configurations and assess relative performance with respect to recovery and quality of samples.

"The cutting shoe was used in the first of two holes and ran into early operational issues," said Baker. "But the team was able to effectively take corrective actions resulting in much greater success in the second hole using the modified system with the face bit configuration of the tool."

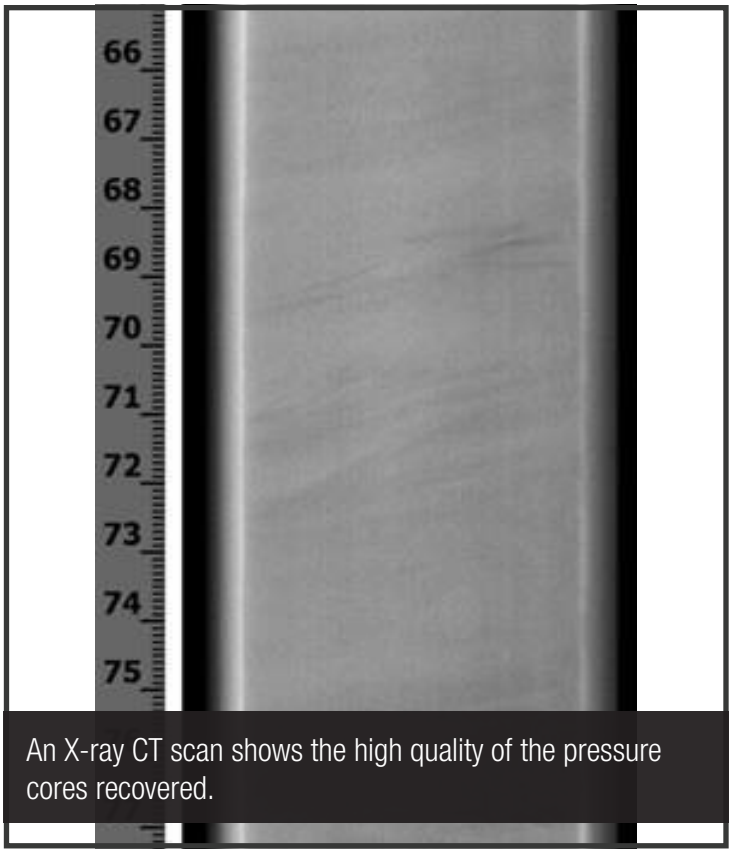
Through the team's persistent efforts, they accomplished the second primary objective

[...Continued on page 26]

The research team aboard the Helix Q4000, the Gulf of Mexico's premier deepwater well intervention vessel.



The PCTB was key to the expedition's success.



An X-ray CT scan shows the high quality of the pressure cores recovered.

of the expedition, which was to gather enough high-quality samples for further scientific investigation.

"Core samples will allow the collaborating science teams to address a range of first-order science issues that could not be pursued from well log data alone," said Boswell. "With these samples, we will obtain information on the chemistry of the gas and of the water, providing insights into how the deposits formed. In addition, analysis of samples onshore will provide information on key reservoir properties such as permeability and sediment strength, providing ground truth data for predictions of gas hydrate's potential as a source of natural gas."

In all, the team secured more than 30 meters of excellent quality pressure core. That core was imaged via CT scanning immediately following the expedition, and key intervals of core were sub-sectioned and are now stored in 21 1-meter pressurized storage chambers. These samples represent some of the highest quality gas hydrate cores collected anywhere in the world to date. The cores will be further subdivided (under pressure) and analyzed by the research team. The cores will also be distributed to a variety of laboratories, including NETL, USGS, and others for comprehensive hydrological and geomechanical characterization of the natural hydrate-bearing sediment.

"NETL has invested in a range of advanced devices that will be used in the study of this core," said NETL scientist Dr. Yongkoo Seol. "I am most anxious to extract subsamples of the core for high resolution imaging using NETL CT-scanners. These will be among the first images that will tell us basic information, such as how the gas hydrate resides within the pores spaces of the sediment."

This coordinated initiative of collaborative science will help advance the study of gas hydrate science and will disseminate results through peer-reviewed publications. This forward-looking hydrate research is shedding new light on this abundant substance and opening a potential avenue to a new clean-burning energy resource.

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