From NETL's Office of Research & Development

Research news

March 2015, Issue 6

FEATURE STORY:

NRAP: Making a Business Case for Geologic Carbon Storage

page 2

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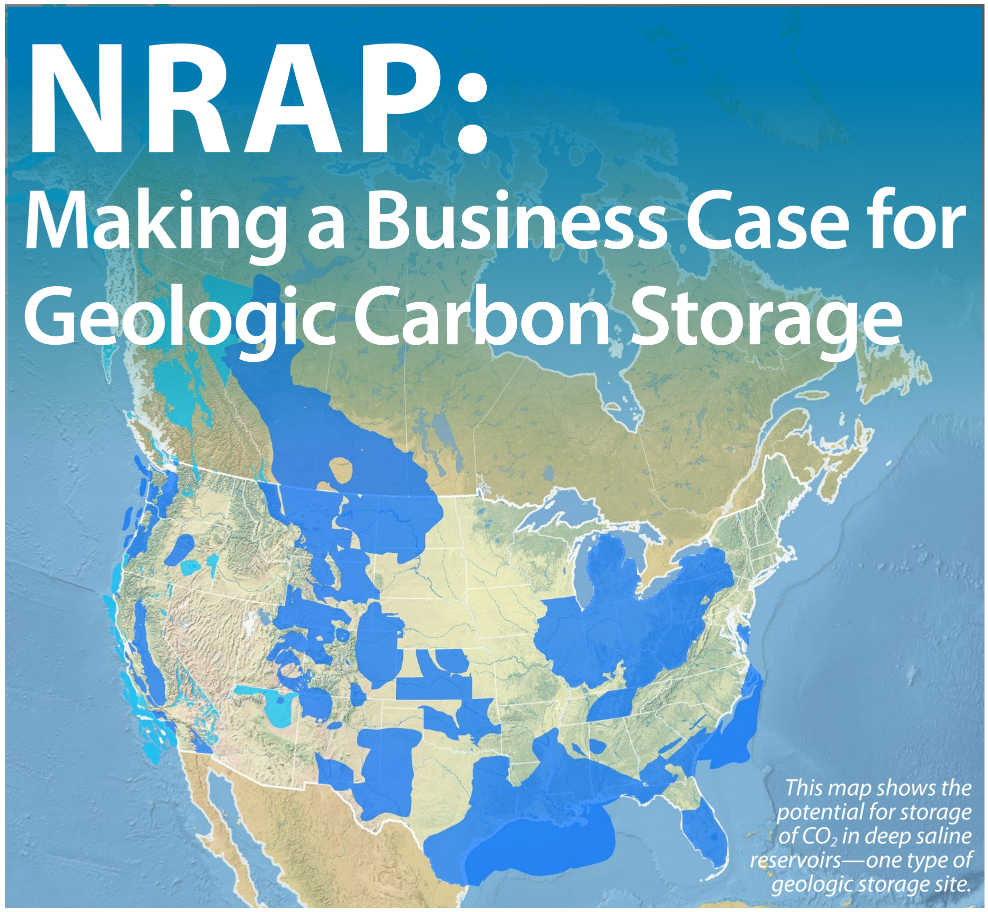
Contents

Research News is a monthly publication from the National Energy Technology Laboratory's Office of Research and Development. We focus on the exciting, cutting-edge research done at NETL by our scientists and collaborators to support the DOE Fossil Energy mission.

Research News welcomes your comments, questions, and suggestions.

NRAP: Making a Business Case for Geologic Carbon Storage



This map shows the potential for storage of CO_2 in deep saline reservoirs—one type of geologic storage site.

NETL is the in-house research arm of the U.S. DOE's Office of Fossil Energy. The lab extensively pursues ways to mitigate the environmental impact of burning fossil fuels, with significant focus on preventing the release of carbon dioxide (CO_2) into the atmosphere. With leadership from NETL, techniques for capturing anthropogenic CO_2 are quickly becoming more feasible; when they become widely integrated throughout the power generation industry, a safe, reliable, and permanent method for storing the captured CO_2 will need to be ready.

Deep underground geologic formations offer promising repositories for storing CO_2, but subsurface complexity can present major difficulties in guaranteeing the safe, permanent storage of the greenhouse gas at every site. Being natural formations, no two geologic storage sites were formed in the same

manner; each varies by type (deep saline formations, unmineable coal seams, and depleted oil and gas reservoirs), mineral makeup, caprock characteristics, potential natural and artificial CO_2 migration pathways, and history of tectonic activity.

All of these variables make it difficult to provide science-based assurances that CO_2 injected into these geologic formations will stay below the surface and remain separated from any sources of drinking water. But in order for industry to move forward to scale up storage sites around the world, such assurances are necessary. Regulators, too, need information about the risks of carbon storage in order to make informed permitting and policy decisions. The National Risk Assessment Partnership (NRAP) is finding answers to these difficult questions. A DOE initiative led by NETL, NRAP also includes researchers at four other national labs (Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory) and interactions with industry and regional partnerships (read more about the collaboration in "NRAP Advances Carbon Storage Through Collaboration and Partnership", page 5, this issue).

NRAP's primary objective is to develop a defensible, science-based methodology and platform for quantifying risk profiles at most types of CO_2 storage sites to guide decision making and risk management. NRAP will also develop monitoring and mitigation protocols to reduce uncertainty in the predicted long-term behavior of a site. To accomplish these goals, researchers listen to industry and regional partnerships to make sure their research is relevant to market needs and working towards solving real-world problems associated with the risk assessment of carbon storage.

NRAP
National Risk Assessment Partnership

NRAP has advanced several computational technologies that are affording industry confidence to move forward with large-scale injection of CO_2. These technologies are examining and accounting for every variable to help minimize any potential risk that the stored gas may leak. Chief among these computational tools are:

- **Reduced Order Models (ROMs)**—Fast, but accurate, prediction models. Running predictions on all of the variables of any given geologic site could take weeks, so ROMs are used to generate results for particular subsurface components (e.g., reservoir, wellbore, groundwater aquifer) in a fraction of the time that a detailed process model requires. One ROM can then be connected to others within an Integrated Assessment Model (IAM), forming a chain of results for an array of variables.
- **Integrated Assessment Models (IAMs)**—A simulation toolset that is an integration of the ROMs and that uses numeric models to incorporate all of the information that researchers have gathered across multiple disciplines to describe fluid migration, leakage pathways, and potential receptors at a site. The IAMs are run many times (e.g., thousands of times) to explore

...Continued on page 4

A well head at a CO_2 injection site.

Continued from page 3

the range of possible system behaviors given uncertainty in key system properties. Results of these analyses provide useful information to help industry stakeholders and regulators understand the impact of those uncertainties on the performance of CO_2 storage systems.

- **Detailed process models**— Simulators developed at each of the national labs that are used to build or train the ROMs. These simulators predict a wide variety of variables including fluid pressures and saturations, ground motion, groundwater and contaminant flow, and wellbore flow among many others.
- **Energy Data Exchange**— An online platform for sharing data where researchers can collaborate in workgroups to efficiently solve problems using large data sets (read more about EDX in the sidebar, this page).

These cutting-edge tools have been developed by some of the most preeminent researchers in the world. **Dr. Grant Bromhal**, NRAP technical director, is a recognized expert among industry and his peers in reservoir storage performance and simulation, as well as risk assessment, and the expertise extends throughout the other national labs. **Dr. Robert Dilmore**, general engineer at NETL, said of collaborative results, "We have a highly skilled team making huge advancements in the knowledge base for risk assessment of geologic carbon storage sites."

It's these "huge advancements," that will support the DOE goal of 99 percent storage permanence over a 100-year timeline, a goal that NRAP is working to assure, allowing industry and government to confidently move forward with large-scale CO_2 storage.

Watch a 3D animation about carbon storage here.

Contacts: Grant Bromhal, Robert Dilmore

The Facilities and Tools of NRAP

NETL is uniquely equipped to work on the challenges of ensuring the permanent storage of carbon dioxide (CO_2) in geologic formations. The facilities and tools available for NRAP research range from experimental labs to simulators to collaborative online workspaces.

The industrial CT scanner can observe how fluid travels through rock core samples—giving researchers a glimpse of how CO_2 will react far underground.

Computer Tomography Imaging Laboratory

The CT Scanners in the imaging laboratory at NETL in Morgantown have been modified to observe how fluids behave when injected through fractured core samples. These injections replicate the conditions underground, and the scanners give researchers a window to view how fluids will behave under realistic conditions.

NFLOW and FRACGEN

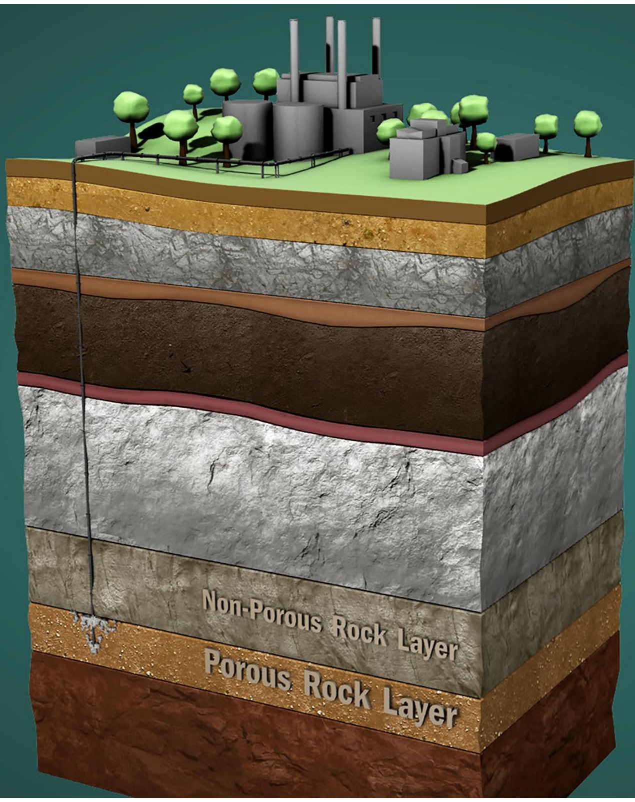
These two codes work together to create predictions that model how reservoirs drain through discrete irregular fractured networks with thousands of individual fractures in the matrix rock. These numeric models help to quantify variables that contribute to risk when storing CO_2.

Energy Data Exchange (EDX)

EDX is a web-based tool to coordinate energy research. Because NRAP is a collaborative partnership across multiple national labs, the ability to share large amounts of data over the web in "real time" is crucial to the success of the project. EDX allows researchers the ability to instantly access and disseminate data for integration into ongoing projects.

Contacts: Grant Bromhal
Robert Dilmore

NRAP Advances Carbon Storage *through* Collaboration *and* Partnership



NRAP is working to understand and reduce the risks associated with long-term geologic storage of CO2. Shown here is an illustration of how CO_2 can be captured at a power plant and stored safely, permanently underground.

The International Energy Agency predicts that [carbon capture and storage (CCS)](#) technologies can play a vital role as the world transitions to a sustainable low-carbon economy.[1] The [National Risk Assessment Partnership (NRAP)](#), led by NETL, is helping to accelerate implementation of CCS technologies by providing the science base needed for regulatory agencies and industry to move forward with confidence. What makes NRAP unique and highly effective is its collaborative approach that brings together the best minds from across five DOE national labs.

NRAP applies DOE's core competency in science-based prediction for engineered–natural systems to the long-term storage of CO_2. NRAP functions by integrating expertise and resources from Los Alamos National Laboratory, Lawrence Berkeley National Lab, Lawrence Livermore National Lab, NETL, and Pacific Northwest National Lab. Each of these labs has developed expertise in subsurface behavior over the past several decades through research on coal, oil and gas, geothermal, and nuclear resources. The NRAP collaboration also leverages its accomplishments with those of the [Regional Carbon Sequestration Partnerships](#) that have been developing and demonstrating carbon storage technologies in the field since 2005. In addition, NRAP incorporates input from industry and regulatory agencies, including the U.S. Environmental Protection Agency, to ensure its investigations are relevant. This collaborative approach means that NRAP researchers are providing the information decision-makers need to make sound regulatory decisions, and that industry needs to confidently invest in CCS technologies and insure CCS projects.

NRAP's research is "use-inspired." **Dr. Robert Dilmore**, who works as an engineer in NETL's Predictive Geosciences Division, explains, "The goal of NRAP is to develop tools that stakeholders can use to understand the behavior of a system and therefore better plan a successful CO_2 storage strategy." The NRAP Stakeholder Group comprises a select group of experts from industry, academia, and other government agencies. The Group's diverse perspective and expertise covers many aspects of CCS, helping to ensure that work is appropriately focused and effectively disseminated. Researchers present progress and get feedback on the quality of that progress, as well as feedback on areas of investigation to expand or modify. The Stakeholder Group also identifies new scenarios for investigation. This input helps NRAP researchers ensure the resulting technologies will make an impact. Dilmore says this approach "helps to focus on important questions that stakeholders view as critical to addressing uncertainty and risk." (For more information on the science of NRAP, please read this month's feature article.)

Long-term, NRAP's collaborative approach and solid science base aim to provide critical benefits toward removing barriers to and accelerating the implementation of CCS technologies. Operators will be better informed regarding designing and applying monitoring and mitigation strategies, helping to ensure CO_2 storage is safe. Also, financiers and regulators will have more confidence investing in and approving CO_2 injection, helping to facilitate rapid deployment of CCS as a workable solution to CO_2 emissions.

Contacts: [Robert Dilmore](#), [Grant Bromhal](#)

[1] International Energy Agency, http://www.iea.org/topics/ccs. 20 Feb. 2015.

U.S.–U.K. Collaborations Produce Results for Future Power Generation Materials

For decades, leaders of the United States and the United Kingdom have stressed the close political and economic relationship the two nations enjoy on the international stage. But there is also a strong energy research bond that has yielded important materials research results. NETL is at the forefront of a collaborative effort to help industries in both countries design more durable, more efficient, and more environmentally acceptable power generating facilities.

The U.S. Department of Energy and the U.K. Department of Energy and Climate Change are supporting a memorandum of understanding to share and develop knowledge and expertise in the key area of high-temperature materials for advanced fossil energy power plant applications. The Advanced Materials Collaboration has yielded key results on steam oxidation, boiler corrosion, gas turbines fired on syngas and other fuel gases, and oxide dispersion strengthened alloys.

Dr. Gordon Holcomb, an NETL materials research engineer, leads work on steam oxidation and boiler corrosion in the collaborative effort. He said a full understanding of advanced materials is important to future energy policies because meeting increasingly stringent environmental and efficiency targets will require more advanced components, systems, and manufacturing methods. "Changes in fuel types, plant operating cycles and the introduction of new carbon capture technologies will place demands on the materials and components used in power plant equipment," Holcomb said.

U.S. and U.K. researchers worked together to generate more than one million hours of new steam oxidation data for 30 alloys; created two new high-pressure steam test facilities; improved service life prediction methodologies for future power plant designs; examined and measured the effects of novel technologies on boiler corrosion problems; tested and ranked a range of alloys and coating systems for gas turbines fired on syngas; successfully demonstrated the strength of new alloys for allowing power plants to operate at maximum operating stress; and made many more technology improvements.

According to Holcomb, "Our joint research on advanced steam power cycles, boiler corrosion and monitoring, and high-temperature corrosion testing will help us move forward with new technologies capable of meeting changing demands for efficient power production."

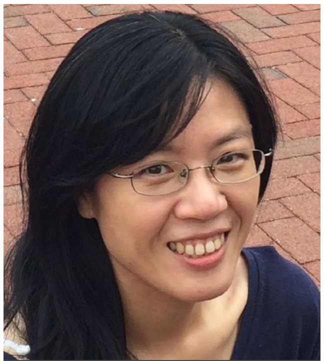
Contact: Gordon Holcomb

Intern Designs CO_2 Monitoring Network

The National Risk Assessment Partnership (NRAP) harnesses the multitude of capabilities available at the five participating Department of Energy (DOE) national labs. Together, the laboratories are undertaking a mission-focused effort to develop a defensible, science-based quantitative methodology for determining risk profiles at carbon storage sites.

The National Energy Technology Laboratory (NETL) is the leader of this partnership, with scientists and researchers of every career level working to further benefit the mission of the alliance. **Ya-Mei Yang** is one such researcher. An intern working with NRAP, her focus has been on CO_2 monitoring technologies and how best to interpret data from multiple monitoring technologies to assess risk.

Ya-Mei is excited about having the opportunity to work with such a multi-organizational effort. "Collaboration with other researchers from different national research labs is a special feature of NRAP. This collaboration not only allows us to expand our knowledge base all together, but also create a synergy… We're able to efficiently incorporate different resources among DOE labs to successfully accomplish a large scale project like NRAP."



Ya-Mei Yang

For Ya-Mei, NRAP and NETL have given her the opportunity to develop skills and have real world experience. From hard skills, like witnessing and participating in inter-laboratory research and development to the softer skill set of functioning as part of a larger team, NRAP has been a career-shaping experience. And in return, NRAP has been able to reap the benefits from the cutting-edge work that promising early career scientists have been doing. Ya-Mei's mentor, Dr. Grant Bromhal, is enthusiastic about her contributions: "Her Ph.D. work was to take two near-surface monitoring technologies and integrate the two data streams to help design an efficient and effective monitoring network. This is one of the key future areas that NRAP is focusing on."

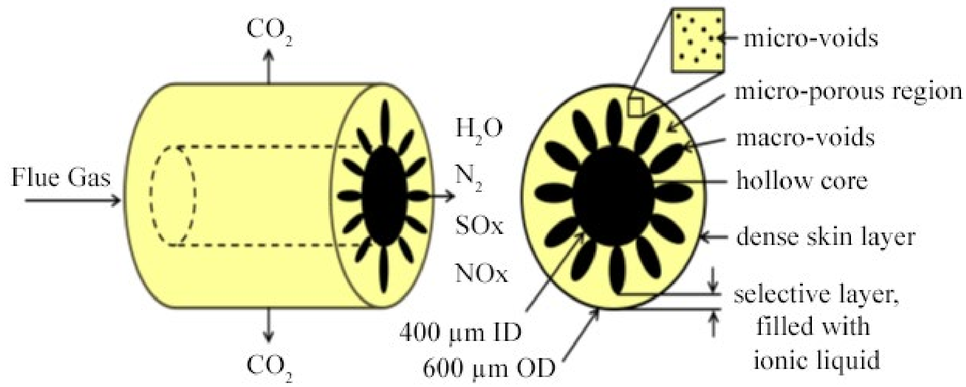
Contact: Ya-Mei Yang

Making Inroads in Carbon Capture Using Novel Membrane Materials

Carbon capture from coal-based power plants is a critical component in the reduction of the greenhouse gas emissions associated with global warming. Currently available technology options for capturing carbon dioxide (CO_2) need refinement to make them more efficient and to minimize their impact on the cost of electricity.

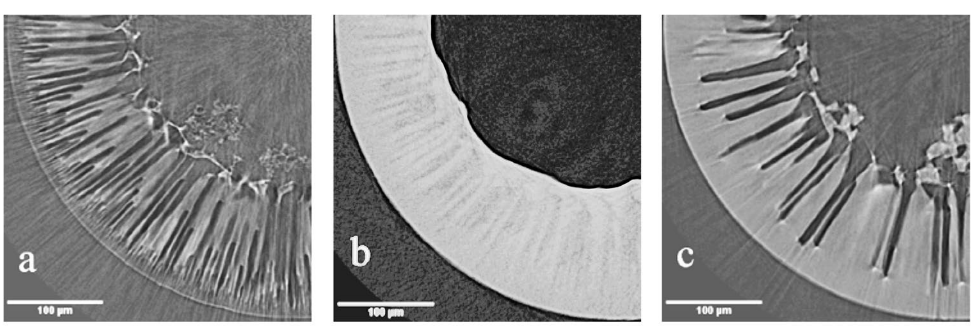
While liquid solvents are the traditional choice for separating CO_2, membranes have also shown promise for carbon capture. Membranes separate gases according to differences in their rate of permeation through the membrane material. The driving force for gas permeation in a membrane is the partial pressure difference of the gas species across the film. Since there is a relatively high concentration of CO_2 in coal plant flue gas and the gas is at high pressure, membranes are well suited for CO_2 separation.

As part of a multi-faceted approach to discovery, development, and demonstration of efficient and economical approaches to carbon capture, one NETL research program is focused on developing supported ionic liquid membranes—or SILMs. Taking advantage of novel ionic liquid (IL) formulations and polymer materials, this technology has the potential to provide a cost effective and scalable process for selectively capturing CO_2 from flue gas streams. SILMs are composite membranes composed of an IL solvent suspended within the pores of a polymer support. ILs are organic salt solutions that display promising characteristics for gas separation due to their high CO_2 capture ability. ILs are particularly interesting membrane materials because of their high permeability and selectivity values. The gas diffusion rates through a liquid membrane are often much higher than traditional polymer films.



Schematic of a typical hollow fiber membrane with an ionic liquid filled selective area. The inside diameter (ID) and outside diameter (OD) of the fibers are measured in microns (µm). On average a human hair is about 100 µm, which would represent fiber diameters the width of 4 to 8 human hairs.

NETL researchers took SILMs to a new level by developing a unique method for supporting ILs in hollow fiber membranes. Due to the high surface area per unit volume, hollow fiber supports represent an industrially relevant technology for CO_2 capture. The fabricated support materials have high mechanical strength and temperature stability while maintaining gas transport properties. Moving forward, researchers are working to optimize materials and ILs for high temperature stability and enhanced CO_2 selectivity with the most promising formulations being evaluated at bench scale using simulated flue gas and realistic pressure and temperature conditions.



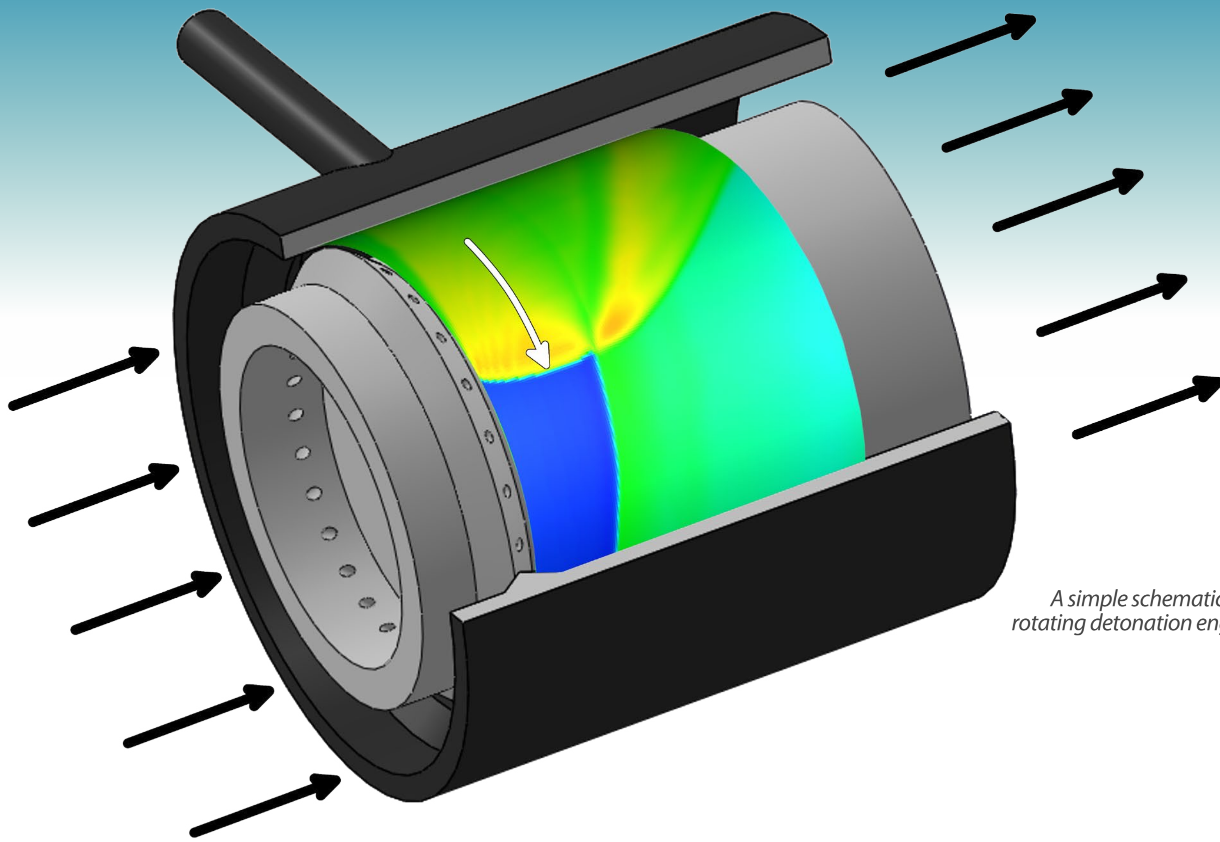
Computerized tomography scan images showing the location of the ionic liquid in the fiber: a) fiber without IL; b) uncleaned fiber saturated with IL; c) fiber that was saturated with IL and subsequently cleaned.

According to **Dr. David Hopkinson**, technical portfolio lead for Carbon Capture, "The successful development of commercially viable materials and technologies will aid energy producers in achieving efficient and cost-effective carbon capture. Additionally, materials produced through this research program are expected to have applications for natural gas purification."

Development of novel CO_2 capture technologies will be key in meeting program goals for the design and operation requirements of advanced, coal-based power systems with 90 percent carbon capture capabilities.

Contact: David Hopkinson

A Novel Combustion Approach Improves Efficiency of Gas Turbines



A simple schematic of a rotating detonation engine.

After decades of improvements and extensive funding by DOE's Turbine Program, large gas turbine engines are currently capable of achieving a combined cycle plant efficiency of about 60 percent. But NETL researchers are working to attain efficiencies in the 65 percent range. Increasing the gas temperature at the turbine inlet was responsible for many recent efficiency improvements. However, increasing gas pressure during combustion also can increase thermal efficiency, impacting overall plant efficiency.

Historically, gas turbine engines have used a relatively slow combustion process known as deflagration. But deflagration actually produces a pressure loss that results in decreased efficiency. NETL researchers are investigating a novel combustion approach that uses detonation as opposed to deflagration in the process—an approach that could result in a 2 to 4 percent improvement in combined cycle efficiency.

According to **Don Ferguson**, a research engineer in NETL's Thermal Science Division, using detonation for pressure gain combustion to increase efficiency is not well understood and too risky from a business perspective for industry to explore on its own. That's why NETL experts are at work optimizing turbine design characteristics and improving turbine capabilities—features which will accelerate application of the detonation approach in the private sector.

Pulse detonation offers one approach to achieving a pressure gain through combustion. However, the approach is challenging in a turbine because intermittent combustion is not ideal. NETL researchers are pursuing rotating detonation combustion (RDC) as an alternative. RDC produces a more continuous flow because the detonation wave travels around an annular region between two cylinders (as opposed to axially along the length of a cylinder), igniting fuel and air as they are fed in, expanding gases and generating energy more conducive for maintaining turbine efficiency because of steadier flow at higher pressure.

NETL research, conducted by individuals with extensive aeroacoustics and combustor design expertise, has several objectives: to optimize RDC injector design, make improvements allowing longer periods of operation, and prevent feedback from the detonation wave to maximize turbine efficiency. The research will lead to combined cycle power plants with higher efficiency and reduced emissions for greater energy security, environmental improvements, and economy.

Contact: Don Ferguson

NETL's In-House Research Program:
National Risk Assessment Program

The complex behavior of carbon dioxide (CO_2) stored in geologic reservoirs—how it migrates through pores, how it attenuates pressure, how it interacts with formation brine and rock—influence the integrity and long-term performance of a carbon storage site. If a reservoir is compromised, brine or CO_2 can escape from containment and be released to the environment—and, in particular, to groundwater aquifers.

To enhance our understanding of the likely performance of CO_2 storage sites, DOE's National Risk Assessment Partnership (NRAP) researchers are developing methodologies and simulation-based tools to quantify risks through time at CO_2 storage sites. NRAP, led by NETL and with members from four other national labs (Lawrence Berkeley, Lawrence Livermore, Los Alamos, and Pacific Northwest National Laboratories), incorporates the fundamental science necessary to understand the risks associated with carbon storage. In this way, NRAP links the applied research conducted by the DOE Office of Fossil Energy, such as the Regional Carbon Sequestration Partnerships, with basic research that occurs in DOE, such as the Office of Science's Energy Frontier Research Centers.

Researchers at these national laboratories collaborate to advance the state of understanding in the following areas:

- Developing a methodology for quantifying site-specific risk profiles by refining risk profiles, integrating models between the storage reservoir and the groundwater resources, and developing CO_2 storage site models that take into account monitoring and mitigation.
- Creating tools to estimate CO_2 plume monitoring areal coverage and time horizons.
- Validating methodologies and models for quantifying site-specific risk performance using synthetic data sets and real field data from CO_2 storage demonstrations.
- Developing monitoring and mitigation strategies to reduce the time to detection of leakage from containment in CO_2 storage sites, the uncertainties surrounding CO_2 storage sites, and the risks associated with storage.

To learn more about NRAP, contact Grant Bromhal.

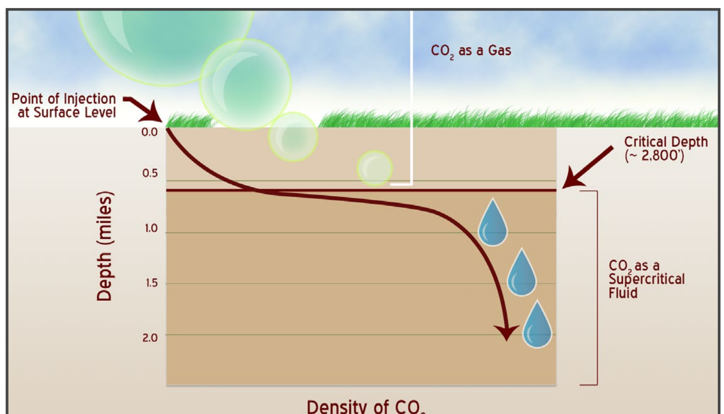
FUNDAMENTAL FUN

Carbon Storage Basics

Carbon dioxide (CO_2) is a natural part of our atmosphere, where it mixes freely with other gases, but it behaves much differently when injected into deep geologic formations. At depth (below 2,800 feet), the pressure and temperature are higher than at the surface and CO_2 becomes a "supercritical" fluid with the density of a liquid and the viscosity of a gas. CO_2 in this supercritical state can be stored in much the same way that oil and natural gas are found—in the tiny holes, or pores, throughout certain types of rock layers deep below the Earth's surface. And as long as there is some confining caprock—a layer of rock with very few pores—above it, the gas will remain in place far below the surface.

Did you know?

- The United States is estimated to have the potential to store between 1,800 and 20,000 billion metric tons[1] of CO_2 in deep saline formations, unmineable coal seams, and depleted oil and gas reservoirs. That is equivalent to 600–6,700 years of emissions—at current levels—from large stationary sources such as power plants.[2]
- As CO_2 is stored far underground, it can react with minerals in the rock surrounding it, creating other solid minerals, a process called mineral carbonation.



At great depths, the density of CO_2 increases until it becomes a supercritical fluid that can be stored underground.

- To assess a geologic formation's suitability for carbon storage, NETL uses a wide array of scientific disciplines, including geology, geophysics, mathematical modeling, computational science, and seismic interpretation—all working together to ensure the safe storage of the greenhouse gas.

See a short 3D animation on carbon storage here.

Contact: Angela Goodman

[1]NACAP (2012) *The North American Carbon Storage Atlas*, The U.S. Department of Energy (DOE), Natural Resources Canada (NRCan), and the Mexican Ministry of Energy (SENER).
[2]GHGRP(2012) EPA Greenhouse Gas Reporting Data–Subpart PP–Suppliers of Carbon Dioxide. Based on 2011 data.

EXTRA! EXTRA!

This presentation from NETL's Strategic Energy Analysis and Planning Division provides an overview of the coal industry, focusing on the United States, but within a global context. Areas covered include coal prices, consumption, production, imports, exports, reserves, productivity measures, and more.

Juxtapositions between the U.S. and other countries' coal industries are provided. In addition to providing a current snapshot of the U.S. coal industry, this work portrays both historical and projected aspects of the coal industry.

BLOSOM

Offshore Technology Focus digital magazine recently featured a story about NETL's BLOSOM (Blowout Spill and Occurrence Model) software. BLOSOM will help prevent future subsea oil spills and improve responses when they do occur. Read about it here.

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