Wellbore Integrity Assurance with NETL's Safe-Cementing Research

U.S. DEPARTMENT OF ENERGY | the ENERGY lab
National Energy Technology Laboratory

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NETL's ultra-deepwater research is focused on risk assessment and spill prevention.

Wellbore cement integrity is paramount to safe, successful oil and natural gas drilling. Cement acts as the primary barrier between the wellbore and the environment. An unstable cement can compromise wellbore control, and research indicates that poor cement integrity is a primary factor contributing to loss of zonal isolation in oil and gas reserves. Although cementing designs and placement practices are well established in many operational environments, the extreme subsurface conditions found in deepwater oil and unconventional natural gas reservoirs pose new challenges to achieving reliable cement jobs.

With resource recovery in these types of reservoirs on the rise, the National Energy Technology Laboratory (NETL) is examining the performance and integrity of key wellbore barrier materials for which data in extreme environments are limited. One of those materials is wellbore cement.

NETL researchers are working to understand how various cement mixes perform, with emphasis on potential failure pathways and remediation technologies.

This work builds on long-standing research conducted by NETL research teams to understand and develop technologies for drilling systems associated with onshore oil and natural gas development. It also builds on NETL research in geologic CO_2 storage, which is looking at the effect of stored CO_2, acid gas, and brine solutions on the integrity of cements at high pressure and temperature.

As the breadth and scope of cementing evolves and industry drills toward deeper, more complex targets, the initial and long-term integrity of cement barriers, and the protocols for placing them, are critical to safe, productive hydrocarbon recovery.

A View from the Top

The Current State of Wellbore Cementing Technologies

What is the current state of wellbore cementing, and where can research and development (R&D) efforts best be directed to improve current technologies and develop new approaches? To answer these questions, NETL surveyed industry experts with strategic knowledge, intimate insight, and significant experience in drilling and cementing. These included representatives from major oil and gas service companies, the American Petroleum Institute (API), the International Association of Drilling Contractors (IADC), the Drilling Engineering Association (DEA), and the American Association of Drilling Engineers (AADE).

Collectively these groups identified five primary research challenges related to borehole design placement and long-term integrity, and they suggested R&D pathways that could lead to safer, more efficient operations.

Challenge 1: Developing new monitoring for wellbore integrity

The mechanisms associated with cement failure have been inadequately evaluated, partly because industry lacks appropriate or cost-effective monitoring options. How does cement set across zones? Is it properly emplaced? Does it maintain integrity over time? Immediate and long-term monitoring—particularly tools and techniques that accurately demonstrate and monitor zonal isolation—can answer questions critical to placing wellbore casings that operators can trust.

Challenge 2: Understanding cement stability under field conditions

To more accurately assess risk associated with wellbore placement and operation, the general understanding of cement stability under extreme field conditions must be improved. Placement concerns include fluid loss, contamination, and dynamic settling. Post-placement concerns include cement expansion and shrinkage, free water development, temperature and pressure stability, hydration, gas and fluid migration, and cement-formation interactions. The identification of key elements for cement design can help inform new and updated standards and best practices to improve risk assessment and ensure safe operations.

▲ The deepwater continental shelf is one of the last remaining areas where undiscovered oil and natural gas resources remain. Exploration and production in these remote, high-risk regions pose unique operational challenges and distinct environmental and societal concerns.

Challenge 3: Ensuring quality control

Job-site conditions are difficult to replicate in a laboratory. The condition of bulk cement can also change during transfer, shipment, and mixing. What are the effects of settling during transportation? Does particle shear influence the cement as it is blown and pumped? How do laboratory-prepared cements behave differently from cement that is mixed and pumped in a well? Often, the job modeled in a laboratory is not the job pumped. Finding answers to these and other cement-quality questions will help bridge the frequent disconnect between lab and job site.

▲ Operators and service companies need to better understand the effect of transportation on cement composition, behavior differences between laboratory and field mixers, and other production factors. Industry also seeks a suitable technique for scaling up free-water measurements from lab to job.

Challenge 4: Understanding the impact of temperature- and pressure-induced stress

Reliable cement slurry designs depend on temperature measurements. Wells are large heat exchangers, and unknowns surround emplacement temperature cycles as slurry travels to the bottom of a well, and then moves back up the annulus and cools. Post-placement pressure and temperature cycles can also cause mechanical failures, potential flowpaths, or loss of zonal isolation as the slurry gels. R&D associated with alternative cements and well isolation technologies will help operators better understand and respond to high-risk, high-stress-cycle environments.

Challenge 5: Improving standard calculations

Tests for cement characteristics and properties are available, but many are considered nonstandard because of inconsistencies. These inconsistencies include tests for static gel strength and gas migration, which are important in determining which cement system should be used in a specific well environment. Stress calculations for set cement are also included. While lower-temperature models calculate induced stress values in compression and tensile components, many higher-temperature tests for mechanical properties only include components that address flexural strength. Properly focused research can help develop a set of industry standard tests of cement properties for the writing and updating of standards and recommended practices.

Federal Research

Complementing Industry Efforts

Industry understands the challenges of obtaining reliable cement jobs in deep oil and natural gas production wellbores. Exploration and development companies, with support from major service organizations, continue to expand industry knowledge in this area, while NETL compliments these efforts.

NETL works with drilling and cementing experts to further research and technology development in cement design, placement, and long-term integrity, particularly members of the API Subcommittee 10C on Oil Well Cements. Through experimentation using specialized and standard facilities, NETL recreates downhole conditions with laboratory research maintained as close to field conditions as possible. By doing so, researchers are able to see what happens when cement is transported and pumped into the well, and then determine if current techniques and cement formulations perform as expected.

NETL takes a dual approach to this work: experimental and computational. Traditional lab experiments provide fundamental data, which advance a basic understanding of cement behavior. The laboratory program also produces data that serve as input for customized computer models. By extrapolating scenarios through computer simulations, research that would normally take years can be conducted in months. This helps engineers and scientists balance careful research with speed to distribute reliable results more quickly.

Foamed Cement, Not for Lightweights

Cement integrity is fundamental to fulfilling a well's production potential. In foamed cement, inert gas, foaming agents, and stabilizers are added to slurry to improve the cement's mechanical properties and protect problem geologic formations. Integrity, then, is dependent on even gas distribution and density tailored to depth. Gaining a scientific understanding of foamed cement within the wellbore environment will help ensure the safe construction and maintenance of deep oil and gas wells using this soon-to-be common material.

Because NETL research objectives cut across various industry sectors, discoveries can globally improve wellbore cementing practices. Specifically, researchers seek to reach the following goals.

Improve the process

Find consistent, effective operational approaches to obtaining stable cements designed for specific wellbores. To do so may require new technologies, procedures, protocols, and/or improved standards.

Overcome data-quality limitations

Develop the means to effectively and accurately obtain representative data needed to design, implement, and evaluate a cement job. To accomplish this, new technologies, procedures, protocols, and/or improved standards may be required.

Improve predictive tools

Develop next-generation models that will help researchers understand the physics of cementing and predict the impact of various designs and operational methods on wellbore integrity.

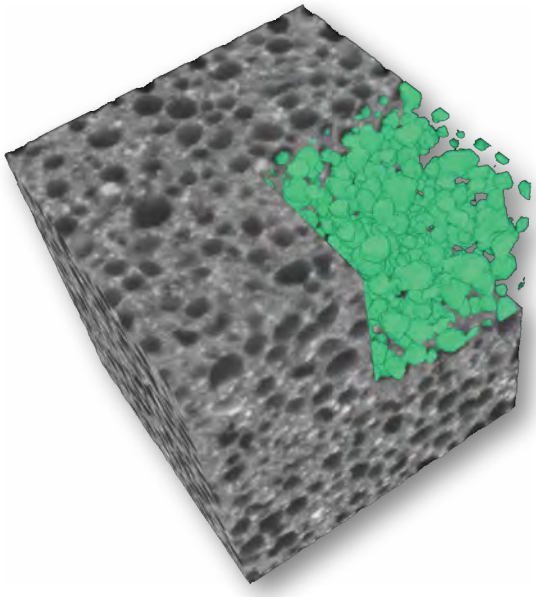
Develop additional basic data

Acquire additional fundamental data from laboratory or field testing that can be useful in supporting the above.

NETL houses a unique combination of facility capabilities for conducting the research needed to achieve these objectives. Our researchers, expert in the cement and use of these facilities, conduct and oversee projects that will help industry agencies better understand the cementing environment, improve cementing practices, and revise standards for this important operational area.

◀ NETL lead researcher Barbara Kutchko works in one of NETL's subsurface experimental facilities.

▶ An image-processed micro-CT cutaway of foamed cement.



Capabilities

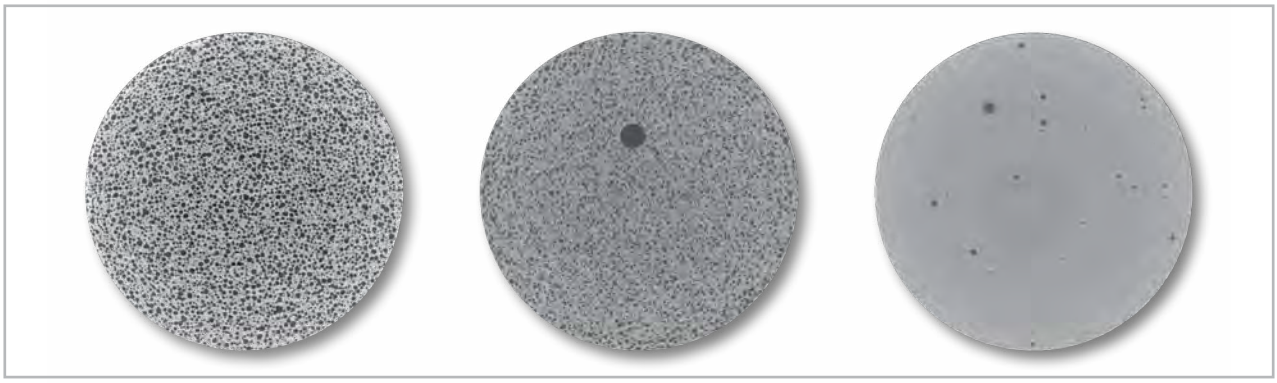
NETL's unique cement research springs largely from its multiscale computerized tomography (CT) imaging facility, which is equipped to produce in situ conditions for experimentation. This facility allows researchers to examine core samples under pressure, at temperature, and with fluid flow. CT scanning and other capabilities housed at the laboratory are helping researchers answer fundamental questions about how cement, casing, and geology interact downhole.

Multiscale CT Scanning

To gain an unprecedented view of how foamed cement forms at elevated pressures typical in the subsurface, NETL uses industrial, medical, and micro CT scanners in conjunction with pressure vessels to study in situ cement conditions over a range of pressures and foam qualities. With these capabilities, NETL researchers are examining this ubiquitous yet under-studied wellbore material to determine gas-bubble stability as it hardens. Researchers also use various software applications to derive statistical relationships related to foamed cement physical structures. The goal is to determine the conditions required for generating stable cement. In addition, injection properties, fluid-gas ratios, and additives are being examined to determine how they, too, affect stability. Because these experiments are non-destructive, difficult-to-obtain core samples are preserved for reuse. Digital images are also archived for future investigations. Researchers use the experimental results to build computer models of subsurface phenomena and processes that can increase the speed and lower the cost of ongoing investigations.

Subsurface Experimental Facilities

NETL's multifunctional subsurface experimental facilities were originally developed for investigations related to the underground injection of CO_2 for carbon management, particularly with respect to reservoir storage, caprock sealing capacity, and wellbore cement integrity. NETL researchers are now using these facilities to conduct offshore and unconventional oil and gas wellbore investigations as well. By exposing lab- and field-generated samples to downhole conditions, researchers are able to collect key data on cement stability and performance in various chemical environments. Researchers also study mechanical properties and behavior of various cement systems, including foamed cement. For example, NETL's tri-axial core flow unit measures sonic velocity and resistivity to determine the dynamic behavior of foamed cement in situ. NETL is also using experimental results to build computer models of subsurface phenomena and processes that can increase the speed and lower the cost of ongoing investigations.



▲ Core scans like these produced using NETL's industrial CT, medical CT, and micro-CT scanner facilities assist researchers in studying foamed cements and other systems. The purpose is to minimize risk of failure, particularly during offshore operations.

Other Capabilities

NETL houses a custom-built tri-axial multisensor core logger to measure key geophysical properties, including resistivity, gamma-density, and p-wave velocity. As a complement to NETL's CT scanning capabilities, the logger can provide high-resolution 2D graphs scanned down the length of a lab- or field-generated sample, providing data on a greater range of properties. NETL also has significant facility capabilities to analyze and characterize a wide variety of wellbore materials. These include petrography, environmental scanning electron microscopy with energy dispersive spectroscopy, x-ray and micro-x-ray diffraction, permeametry, thermogravimetric analysis, differential scanning calorimetry, and infrared and raman spectroscopy. Analyses are used to characterize the fundamental properties of ultra-deepwater and frontier-region reservoirs, unconventional natural gas and oil reservoirs, and reservoirs that offer potential for CO_2 storage. Information gained helps NETL and its partners better understand field test sites, and it feeds computational models and simulations, risk assessments, and experimental investigations.

Energy Data eXchange

NETL administers wide-ranging fossil energy research projects and maintains a highly specialized talent base, thus knowledge management and transfer are strategic priorities. The Energy Data eXchange, or EDX, is designed to make current and historic information generated by NETL, outside agencies, and EDX users available almost instantly through a common portal that features key tools to support analysis and evaluation. EDX also creates a place in which researchers can collaborate quickly and cost efficiently from across the office or across the world. Its secure workspaces, cross-organizational search capabilities, and public features promote information sharing, technology development, and knowledge and technology transfer.

Researchers

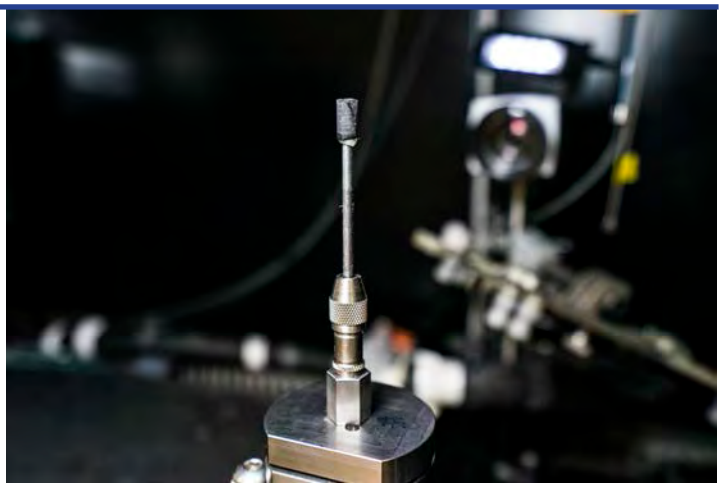
As important as facilities and equipment are to conducting meaningful research, perhaps more so are the skills and knowledge of the people using them. Geologists, computer scientists, engineers, and NETL research teams are contributing to industry's collective understanding of wellbore cementing and well integrity. Top researchers in the field are leading this work.

Name:
Barbara Kutchko

Position:
Geoscientist and environmental engineer

Dr. Kutchko's research focuses on oil and gas wellbore integrity, specifically subsurface drilling and cementing techniques relative to safety and environmental risks. Her areas of expertise include cement chemistry and cement-fluid-rock-gas interactions at subsurface conditions. Dr. Kutchko uses high-temperature and high-pressure experiments and various analytical and imaging techniques to characterize chemical, mineral, microstructural, and mechanical changes within a reservoir, its well cement, and its casing. Dr. Kutchko received her Ph.D. in environmental engineering from Carnegie Mellon University and her M.S. in geology from the University of Pittsburgh.

▲ NETL researcher Dr. Circe Verba evaluates cement alteration using one of the laboratory's petrographic microscopes.



▲ NETL's Xradia micro-CT scanner operates at a single-micron-scale resolution, providing detailed data on porosity, structure, and composition.

Name:
Dustin Crandall

Position:
Research engineer

Dr. Crandall's primary research activities have dealt with using CT scans to understand flow in geologic media, with 17 peer-reviewed publications and multiple conference presentations on the topic. In working with CT scans of wellbore cement, he has focused on understanding the relevant properties of foam distribution. Dr. Crandall graduated from Clarkson University with progressive degrees in mechanical engineering.

Name:
Nik Huerta

Position:
Research scientist

Dr. Huerta's research focuses on laboratory and numerical approaches to understanding how coupling between reactive transport processes, geomechanical stresses, and thermal gradients affects well integrity. Specifically, he studies the long-term fate of leaky wells around geologic carbon storage projects, borehole stability in the presence of drilling fluids, and how thermal fluxes in a well affect zonal isolation in extreme environments (e.g., hydrate- or permafrost-bearing sediments). Dr. Huerta completed his Ph.D. in geological sciences at the University of Texas at Austin, where he also earned an M.S.E. degree in petroleum engineering. He also holds B.S. and M.S. degrees in geology from the University of California at Davis.

▲ NETL's medical CT scanner—used for bulk core characterization and fluid flow experiments—accommodates temperature control, effluent collection, and axial pressure application.

▲ Dr. Dustin Crandall trains NETL intern Charles Alexander in how to use the laboratory's medical CT scanner to evaluate a field-generated cement sample.

Projects

NETL's long-standing wellbore cement investigations span issues related to offshore ultra-deepwater drilling and onshore unconventional gas recovery, as well as CO_2 storage. These projects, three of which are highlighted here, are adding to industry's knowledge related to this important material. Together, industry, government, and academia will find the solutions needed to ensure enduring access to domestic energy supplies through the safe, reliable use of our nation's resources.

Evaluation of Foamed Wellbore Cement Stability Under Deepwater Conditions

Foamed cement is produced when nitrogen or another inert gas is injected into cement slurry to form microscopic bubbles. This produces an ultralow-density material that can be employed in formations unable to support the annular hydrostatic pressure exerted by conventional cement slurries. In addition to its light weight, foamed cement has a unique resistance to the temperature- and pressure-induced stresses found in deep subsurface wellbores. It also exhibits superior fluid displacement, gas-migration control, and long-term sealing through resistance to cement-sheath stress cracking.

The increased use of foamed cement systems in deepwater environments makes understanding their stability in the wellbore vital, particularly to risk assessment and spill prevention. A stable foam installed properly in the wellbore provides desired zonal isolation and casing support. Unstable foams can result in uncemented sections or channels and failed zonal isolation. Industry currently faces a number of challenges to obtaining consistently reliable foamed cement jobs that research can help address. For example, foamed cement testing methods need to reflect downhole rather than atmospheric conditions. Researchers also lack significant knowledge regarding the stability and properties of foamed cement during and after placement.

NETL researchers are working to better understand foamed cement and its interaction with the wellbore environment. To do so, they are evaluating foam stability, bubble size, and channeling (bubble coalescence) as it is affected by pressure, shear, and cement design. Researchers are drawing correlations between atmospheric (in the laboratory) and pressure-generated (in the field) foamed cements and defining materials performance and properties critical to successful cementing. They are also determining foam stability in situ by simulating various depths in the well. These studies utilize NETL's industrial CT scanner to provide related high-resolution, 3D image datasets of bubble-size distribution measured under pressure. Ultimately, this research will provide industry with knowledge needed to ensure safe, reliable operations in which foamed cement systems are used.

Gas Flow from Shallow Gas Formations

Gas flow from shallow formations is not a new problem for the petroleum industry, but a somewhat unique deviation is occurring along the Marcellus Shale gas play in the northeastern United States. Sandstone and coal bed formations in the groundwater zone can compromise the integrity of curing cement by injecting gas at measureable pressures during transition from liquid to gel. The specific mechanisms for risks associated with unwanted gas flows have been magnified along the Marcellus via shallow gas-bearing formations that lie within and directly below groundwater aquifers. The primary concern is that naturally occurring formation gas can enter annular pathways and migrate up the wellbore to other formations, causing safety concerns and potentially compromising water supplies.

To better understand this phenomenon, NETL is characterizing in situ conditions that result in non-production formation gas invading the annulus during hydration and defining temporal material properties of the slurry. Using a high-pressure chamber, researchers are simulating wellbore exposure to gas flows from shallow formations. Results will be used to develop and validate an analytical simulation of cement annulus hydration in regions where gas sands are present. From this research, guidelines for cementing wellbores that contain formation gas in close proximity to groundwater aquifers can be established.

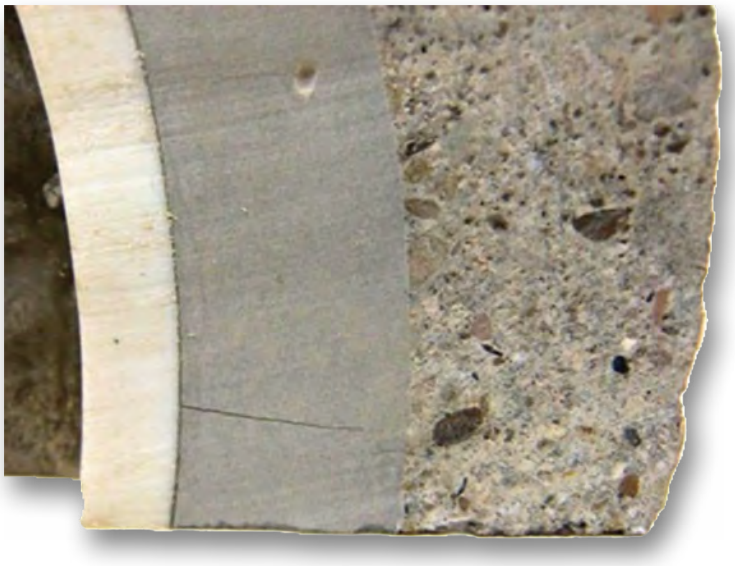
Effect of CO_2 on the Integrity of Well Cement Under Geologic Storage Conditions

Many locations being considered for large-scale CO_2 injection for carbon management have already seen extensive production for oil, natural gas, and/or coalbed methane. Because annular cement is thermodynamically unstable in a CO_2 environment, existing wells could compromise storage in these areas. To bring carbon storage closer to commercial application, it is important to characterize the chemical interactions between injected CO_2 and existing well cements that may cause leakage.

NETL first simulated deep underground injection and wellbore conditions with common wellbore cements, and then examined resulting chemical and microstructural changes using scanning electron microscopy, x-ray diffraction, and other techniques. Results indicated that temperature, pressure, cement type, cement additives, and fluid properties play significant roles in the rate of alteration and reaction. In properly constructed wells with typical cements in good condition, CO_2 reactions were too slow to cause leakage. However, cements in old or abandoned wells in less than pristine condition were shown to pose potential problems.

Further work at the laboratory is being conducted to study situations in which gaps or fractures may be present in the cement column. NETL researchers are also looking at cement interactions under co-sequestration conditions, particularly with acid gas.

▼ The interaction among cement, casing, and geology is fundamental to ensuring wellbore integrity.



CONTACT US

As the United States continues to move oil and natural gas exploration and production into deeper, more complex geologic formations, the ongoing development of safe, environmentally sound drilling practices remains a primary objective. NETL and its affiliated research partners have extensive capabilities to assess and mitigate risks associated with oil and natural gas development, including addressing wellbore cementing issues.

Contact us to learn more about NETL capabilities, discuss partnership opportunities, review technologies ready for license, and hear more about the impact of our research.

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Environmental concerns about shale gas recovery can be partially addressed through advances in cement technologies.

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