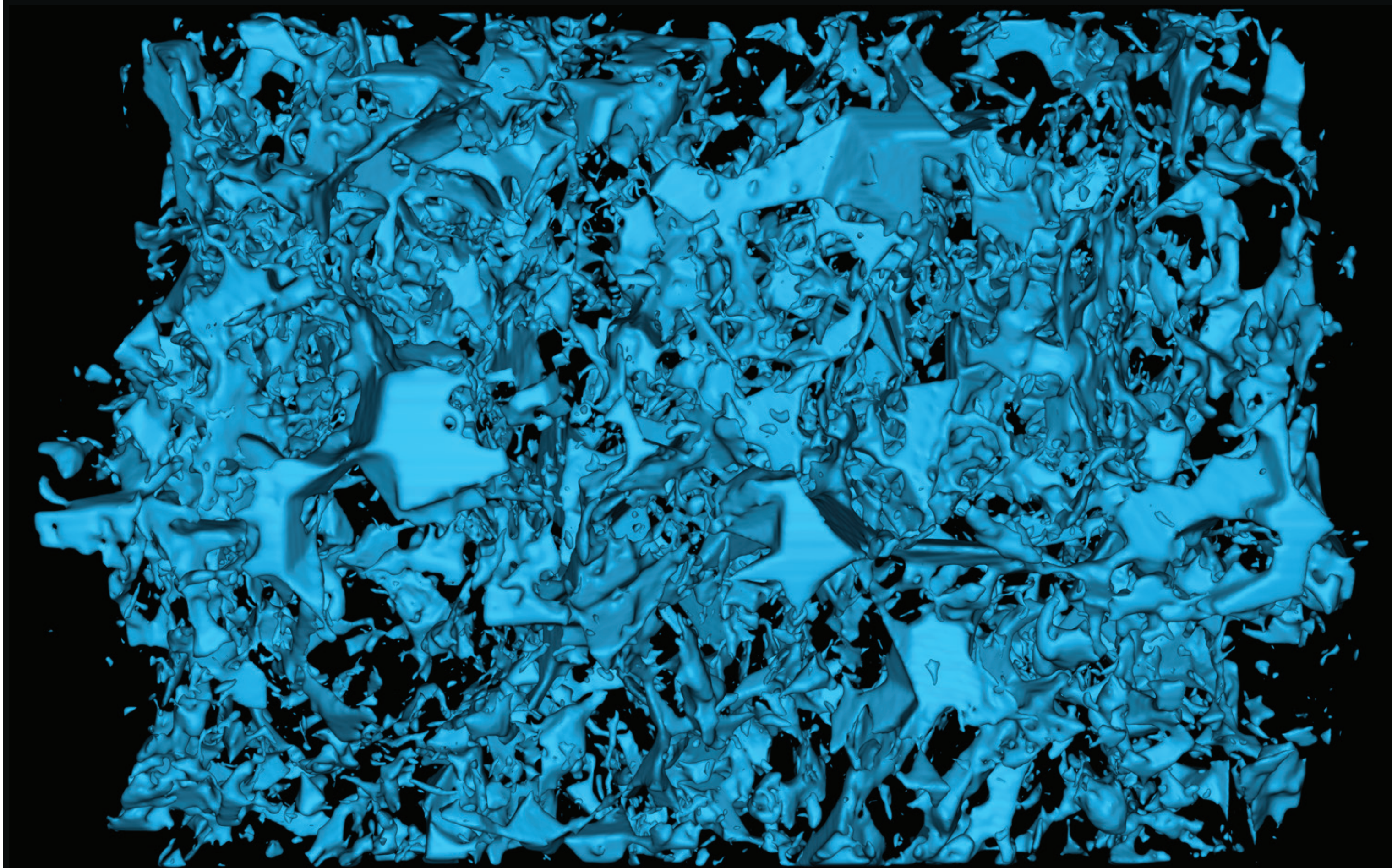
CARBON STORAGE RESEARCH



NATIONAL ENERGY TECHNOLOGY LABORATORY

"Approximately one third of all CO_2 emissions due to human activity derive from fossils fuels used for generating electricity. These emissions could be reduced substantially by capturing and storing CO_2."

— *International Energy Agency Greenhouse Gas R&D Programme,* http://www.ieaghg.org

Geologic carbon storage (GCS)—the injection of carbon dioxide (CO_2) into permanent underground storage sites—is a key component of the U.S. carbon-management portfolio. Several pilot- to intermediate-scale carbon storage projects in the U.S. and across the world have demonstrated the technical feasibility of GCS. Research is ongoing to ensure the safety, reliability, and permanence of GCS technologies.

R&D163, May 2019

DOE–NETL'S CARBON STORAGE PROGRAM

The goal of the U.S. Department of Energy-National Energy Technology Laboratory's (DOE-NETL) Carbon Storage Program is to develop and advance carbon capture and storage (CCS) technologies that will significantly improve the effectiveness of the technology, reduce the cost of implementation, and be ready for widespread commercial deployment in the 2025–2035 time frame. To achieve this goal, technical and economic barriers must be addressed with data, and information must be generated and communicated to inform regulators and industry on the safety and performance of CCS.

NETL capabilities have been created to pursue CCS goals in three technology component areas:

1. Storage Infrastructure
2. Advanced Storage
3. Risk and Integration Tools

http://www.netl.doe.gov/research/coal/carbon-storage

Before year 2035, NETL's Carbon Storage Portfolio aims to develop technologies that ensure safe, secure, efficient, and cost-effective containment of CO_2 in diverse onshore and offshore applications. The portfolio consists of research activities, including laboratory experimentation, geo-laboratory (field work), and numerical modeling, to meet the research goals within DOE–NETL's Carbon Storage Program. Carbon storage research objectives and approaches have been identified through detailed program reviews, systems analyses, emerging technology reviews, R&D activities, and discussions with stakeholders at all levels. The Carbon Storage Program supports multiple research and development projects that include industry cost-shared technology development projects, university research projects, collaborative work with national laboratories and international entities, and research conducted through the NETL Research and Innovation Center (RIC).

NETL'S CARBON STORAGE RESEARCH

The NETL's RIC provides the Carbon Storage Program with an onsite laboratory to conduct fundamental and applied R&D. This effort supports DOE Core R&D goals of developing and advancing the CCS technologies necessary for widespread commercial deployment. The NETL research contribution to the Carbon Storage Program enables the development of technologies to significantly improve safety and storage. This research is designed to meet DOE-NETL's Carbon Storage Program's technical challenges:

- Develop and validate storage reservoir risk assessment, management, and mitigation
- Develop and validate technologies that can be used to ensure safe, secure, efficient, and cost-effective storage reservoir containment of CO_2
- Address technology challenges through "learning while doing" in geo-laboratory field projects

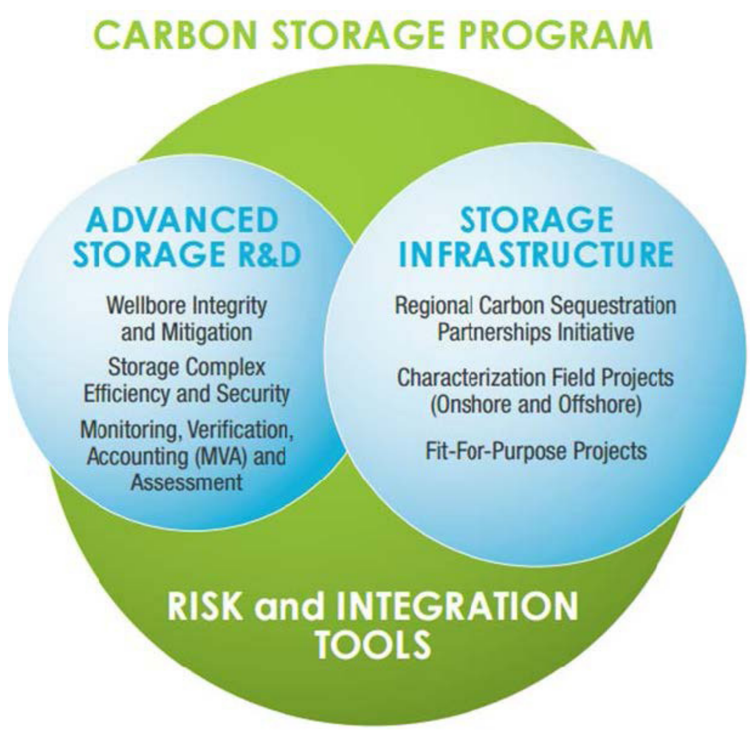


Figure 1. Technology components of the Carbon Storage Program.

GEOLOGIC STORAGE AND SIMULATION

RESERVOIR PERFORMANCE

This work focuses on improving assessments of CO_2 storage for key reservoir classes through experimental measurements of critical properties at in situ conditions. Using unique imaging and core-flow capabilities along with numerical modeling software, researchers are able to characterize property changes as CO_2 interacts with reservoir constituents to improve our understanding of how to best utilize subsurface storage. Work includes measuring relative permeability, residual saturation, and wettability for high priority geologic settings targeted for CO_2 storage.

The following outcomes are anticipated:

1. Improved techniques for characterizing reservoirs and seals related to reservoir performance
2. Improved models for injection into fractured media, including associated storage and natural gas production
3. Public database of key reservoir properties in the presence of CO_2

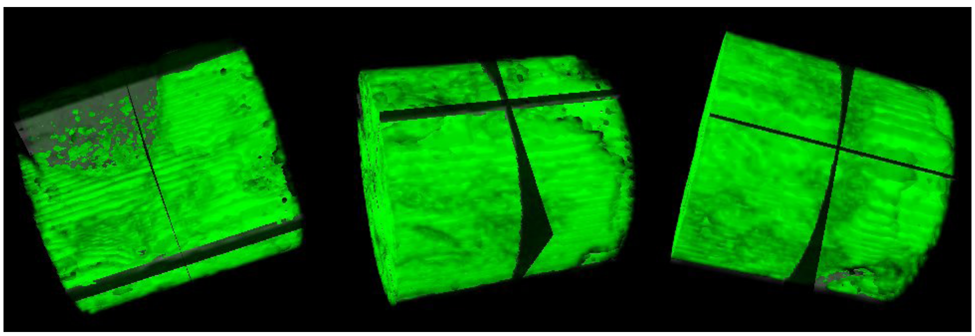


Figure 2. 3D computed tomography rendering of CO_2 (green) displacement through a heterogeneous reservoir rock.

SHALES AS SEALS AND UNCONVENTIONAL RESERVOIRS

Work in this task will improve characterization of shales as seals for CO_2 containment and shales as reservoirs for geologic storage of CO_2 through the characterization of permeability, residual saturation, porosity in shales to reduce uncertainty in long-term CO_2 storage, and efficiency and characterization of physical changes in shale with exposure to CO_2.

The anticipated outcome includes the creation of a public database of observed changes in shale permeability due to CO_2 interactions, with a focus on clay mineralogy and carbon content of the shale.

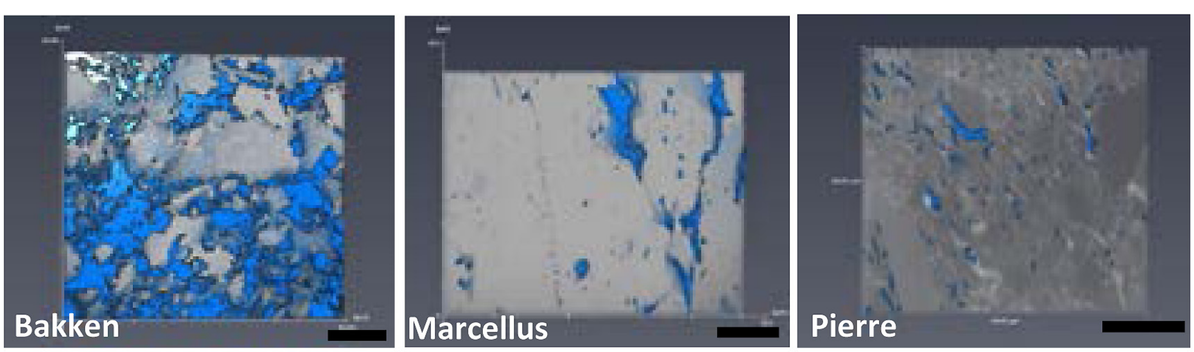


Figure 3. Three reconstructed images of shales that have been analyzed using focused ion beam milled scanning electron microscopy. The isolated blue zones show the pore space and the organic content within these samples.

RESOURCE ASSESSMENTS

This work focuses on developing the DOE prospective CO_2 storage resource estimation methods and tools to quantitatively assess storage resource potential in onshore and offshore reservoirs, including saline formations, oil and gas reservoirs, coal seams, residual oil zones, and shales—all to be reported in future versions of the Carbon Storage Atlas. Updates to CO_2 resource estimation methods will be based on key parameters for high-priority depositional environments targeted for storage. Reviews of methods will be coordinated with the Regional Carbon Sequestration Partnerships (RCSPs) and experts in the carbon storage field.

The following outcomes are anticipated:

1. Defensible DOE prospective CO_2-resource methods for the offshore, residual oil zones, and shales
2. Improvements in storage efficiency ranges
3. Public access to storage tools, such as CO_2-SCREEN (prospective Storage CO_2 Resource Estimation Excel aNalysis)

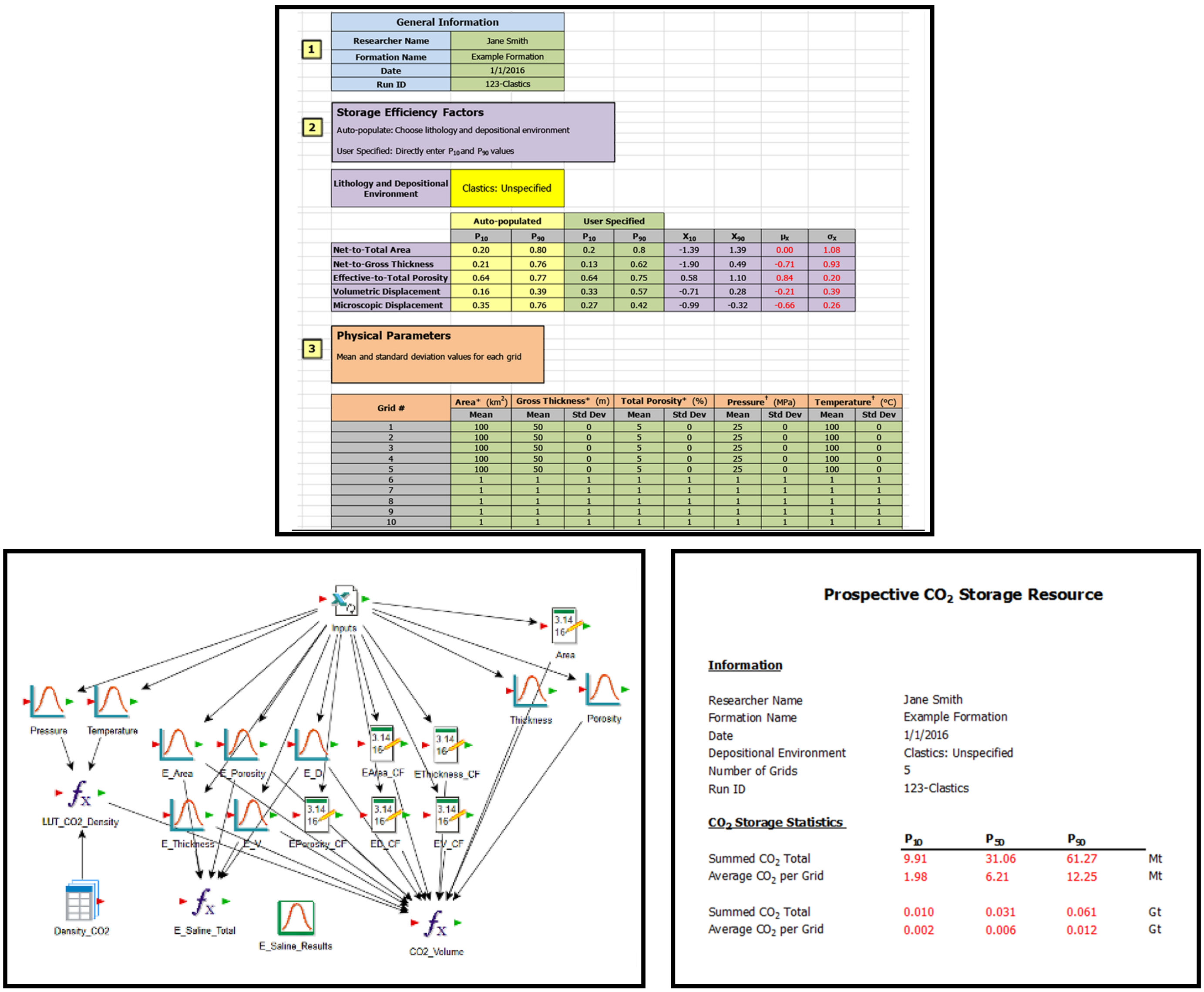


Figure 4. CO_2-SCREEN available on EDX.

ENERGY DATA EXCHANGE (EDX), NATIONAL CARBON SEQUESTRATION DATABASE AND GEOGRAPHIC INFORMATION SYSTEM (NATCARB), AND GEOSPATIAL RESOURCES

This R&D area focuses on developing computing science and geo-data science innovations to improve online data discovery, curation, integration and analytics through development of two DOE data systems: (1) the National Carbon Sequestration Database (NATCARB) and (2) the Energy Data eXchange (EDX). Research is simultaneously a consumer and producer of data. Starting with the first version of NATCARB—a geographic information system (GIS)-based tool for viewing carbon capture, use and storage (CCS) potential across the United States—the carbon storage R&D community has and continues to lead innovations in data curation, integration, and utilization. However, since NATCARB v1, the big data computing, open data, and online systems landscape has emerged and evolved. NETL's EDX is a research tool and system hosted on the worldwide web. Its functionality includes both public, open-access components and content, and secure, collaborative components and content. EDX facilitates access to data, information, and tools relevant to DOE R&D; the system also hosts NATCARB.

Anticipated outcomes include:

1. Larger, more streamlined functionality for the carbon storage R&D community
2. Development of big data computing algorithms to improve data mining, integration, visualization, and analytical innovations

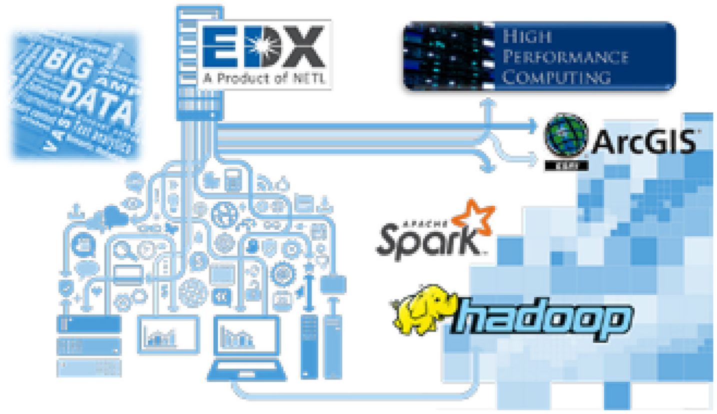


Figure 5. Schematic diagram illustrating how NETL researchers are using big data computing, geo-data science, and carbon storage data to develop data mining, curation, integration, and analytical solutions via the EDX and NATCARB systems.

WELLBORE INTEGRITY AND MITIGATION

This work evaluates the geochemical and geomechanical impact of CO_2 interaction with foamed cement and guides efforts to achieve wellbore security in offshore and onshore storage environments, explore the risk associated with uncertainty and failure of wellbore materials, and validate risk assessment parameters.

The anticipated outcome includes a public database of properties associated with CO_2-exposed foamed cement.

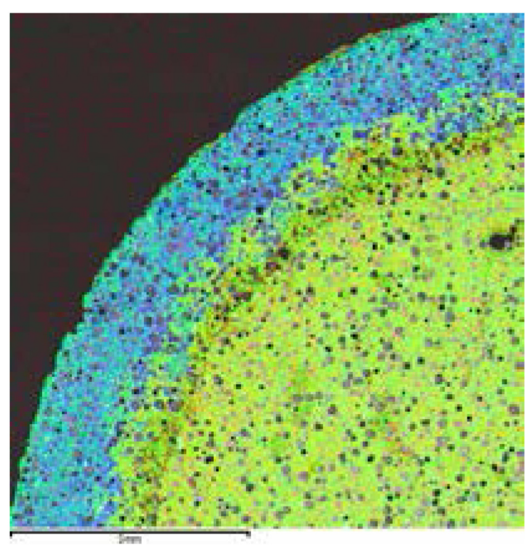


Figure 6. Scanning electron microscope backscatter image of reacted foamed cement overlain with elemental maps (Ca- blue, Si- green).

MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT

GEOCHEMICAL MONITORING OF GROUNDWATER IMPACTS

This work focuses on developing and evaluating new tools and protocols for detecting CO_2 and brine in underground sources of drinking water. This task addresses compliance with the U.S. Environmental Protection Agency goal of zero impact on groundwater systems and verifies the storage goal of 99 percent permanence. To achieve these goals, NETL is collaborating with RCSPs and other demonstration projects to field test and validate NETL tools and techniques for monitoring groundwater. Researchers are statistically characterizing natural groundwater baseline variability in the studied CO_2 storage systems and modeling leakage signals for systems under study. This work leverages NETL's unique perfluorocarbon tracer (PFT) analysis capabilities in conjunction with the Southwest Regional Partnership on Carbon Sequestration's (SWP) Farnsworth Field project to detect PFTs co-injected with CO_2.

The following outcomes are anticipated:

1. Tools and protocols for predicting signal sensitivity in different natural groundwater systems including an isotope geochemistry-based tool, a CO_2 sensing tool for shallow groundwater, a miniaturized laser (LIBS) system, and a functional nanomaterial fiber optic sensing coating designed to sense for changes in pH, CO_2, and methane
2. Field methods and protocols for groundwater monitoring
3. Trace-level analytical PFT CO_2 detection

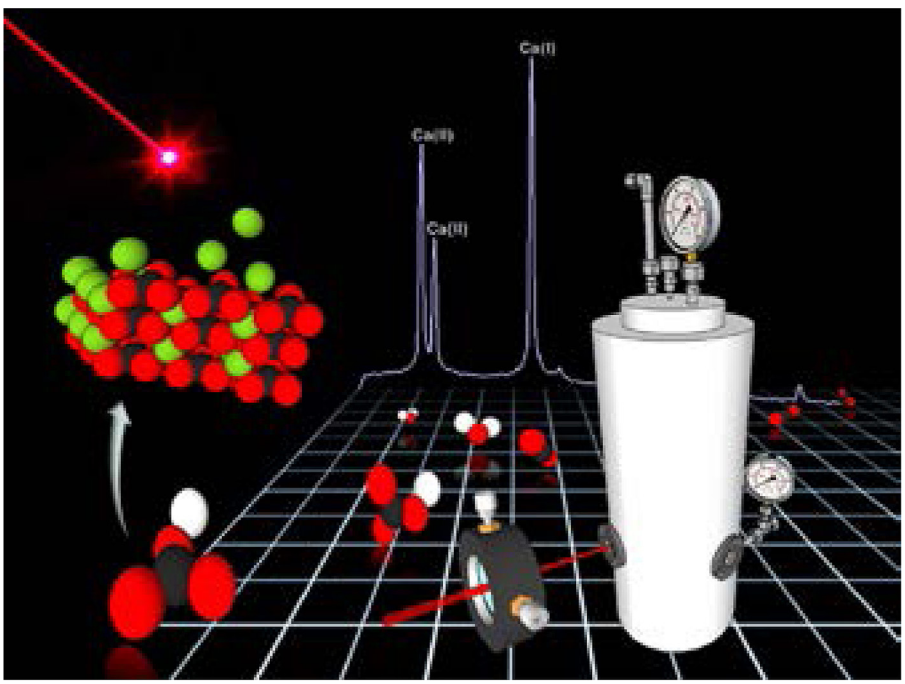


Figure 7. Underwater laser induced breakdown spectroscopy LIBS used to quantify subsurface chemistry.

GEOPHYSICAL MONITORING OF SEALS AND PLUMES

This task focuses on developing and demonstrating non-borehole-based methods for detecting the plume and pressure front in the storage formation. The task will also explore methods that theoretically provide an early warning of deformation within overlying seals. Non-borehole-based methods offer the benefit to facilitate and reduce the cost of locating, permitting, drilling, instrumenting, and abandoning monitoring wells. In addition, these methods enable greater security in detecting and monitoring plume fingering within well networks.

Anticipated outcomes include:

1. Use of passive seismic signals to indicate over-pressurization within the storage formation
2. Use of passive seismic signals to detect deformation of seals above the storage formation
3. Use of passive seismic signals to detect displacement along natural fractures that are sub-optimally aligned in the current stress field

SYSTEMS ENGINEERING & ANALYSIS

This work focuses on evaluating the cost to store captured CO_2 and transport it from a source to a storage site, as well as assessing the cost of utilizing captured CO_2 in enhanced oil recovery (EOR) operations and the potential for use in residual oil zones (ROZ). Researchers are developing cost models for assessing project-level activities, such as individual CO_2 pipelines, saline storage sites, or CO_2 EOR fields. These project-level costs are scaled up through reduced-order models for use in more general economic models that can evaluate deployment of CCS technology over time in regional and national markets. Several models are employed in this analytical effort, all of which can be used in analyses that evaluate technical, financial, and policy aspects of onshore and offshore storage of CO_2 through saline storage or CO_2 EOR:

- The **Fossil Energy (FE)/NETL CO_2 Saline Storage Cost Model** and the **FE/NETL Offshore CO_2 Saline Storage Cost Model** perform cost analysis of saline storage of CO_2 in onshore and offshore geologic formations, respectively
- The **FE/NETL CO_2 EOR Cost Model** performs cost analysis of onshore CO_2 EOR operations. An offshore CO_2 EOR cost model will also be developed
- The **FE/NETL CO_2 Transport Cost Model** estimates the costs of transporting CO_2 via pipeline from a source where CO_2 is captured to a location where the CO_2 is stored, either through saline storage or CO_2 EOR
- The **Power System Financial Model** models the cost of capture and can be used in conjunction with the models above. Together, these models incorporate the necessary aspects of current regulations (e.g., UIC Class VI) for storage and the ability to select and apply relevant technologies to maintain compliance
- The **Capture, Transport, Utilization, and Storage (CTUS) Model** incorporates key aspects of project-level saline storage, CO_2 EOR, and CO_2 transport models to provide analysis of regional or national deployment of CCS technology; this model can also be plugged into the Energy Information Agency's (EIA) National Energy Modeling System (NEMS) to provide necessary data for market modeling. Analytical capabilities are also supported using MARKAL (MARKet and ALlocation)

Figure 8. Output from the NETL CTUS-NEMS modeling of regional CO_2 pipeline options. EIA adopted this modeling capability and has used it in the EIA Annual Energy Outlook Reports since 2013.

NATIONAL ENERGY TECHNOLOGY LABORATORY

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