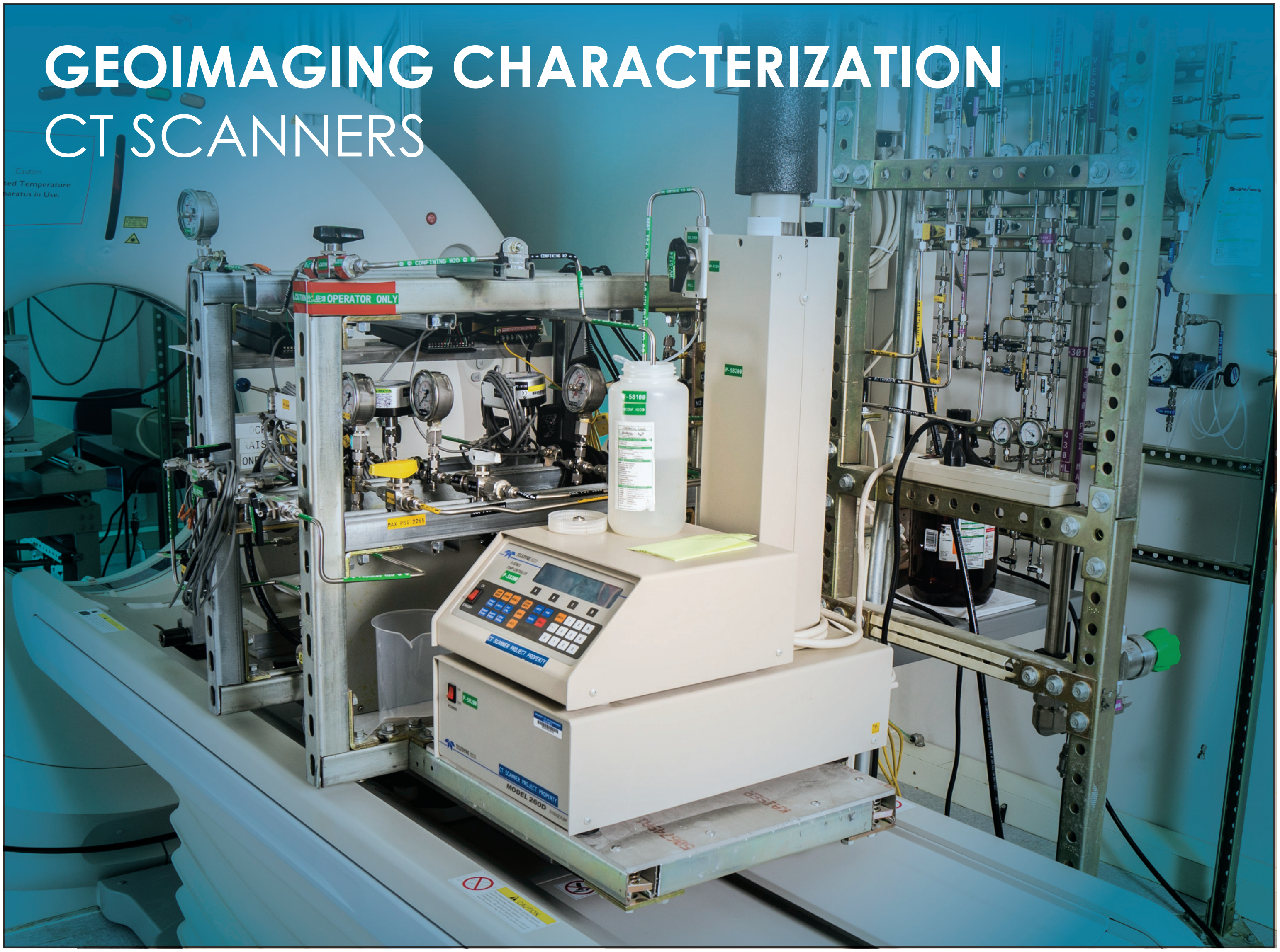
GEOIMAGING CHARACTERIZATION
CT SCANNERS



NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

BACKGROUND

Traditional petrographic and core-evaluation techniques typically aim to determine the mineral make-up and internal structure of rock cores and to analyze the properties influencing fluid flow. Often this type of evaluation is destructive, physically sectioning the core to capture details of the sample's internal composition. The National Energy Technology Laboratory's (NETL) geoimaging facility provides a non-destructive alternative to these traditional methods. The lab hosts three computed tomography (CT) X-ray scanners, an assortment of flow-through instrumentation, and a multi-sensor core logging unit. These technologies work in tandem to provide characteristic geologic and geophysical information at a variety of scales:

- NETL's medical CT scanner and core logger analyze and dynamic flow (sub-cm resolution)
- NETL's industrial CT scanner images pore and fracture networks undergoing alteration (sub-mm resolution)
- NETL's micro-CT scanner allows evaluation of microscopic structure and static fluid distribution (µm resolution)

Porosity, permeability, fracture properties, and composition can all be analyzed, yielding quantifiable and relevant parameters, while leaving core samples obtained from the subsurface—which can be difficult or costly to attain—available for further testing. Additionally, all scanners are equipped with temperature and pressure controls to enable in-situ flow testing during non-destructive visualization.

R&D178, February 2020

FACILITIES

MEDICAL CT SCANNER

CORE-SCALE CHARACTERIZATION AND FLUID FLOW

The state-of-the-art **Toshiba Aquilion™ RXL medical CT scanner** (Figure 1) is used for bulk core characterization and fluid flow experiments. Although the scanner's resolution of 100 to 500μm is the lowest of NETL's three CT scanners, it boasts the fastest scan times. The medical scanner is also adaptable for temperature control, fluid flow, effluent collection, and the application of 3D stresses to the samples. With scan times lasting only seconds, the system can capture, in real time, the migration of fluids and changes in rock material at in situ conditions for petroleum and CO_2 storage reservoirs, thus expanding the knowledge base of fluid mechanics and rock physics at those conditions. The ability to rapidly scan at sub-millimeter resolution makes this the equipment choice for rapid non-destructive characterization of cores from wells in relevant energy applications. Figure 2 provides an example of a time series of viscous fingering (top) when liquid CO_2 displaces brine in a sandstone core and the same experiment showing plug flow behavior (bottom) when a surfactant is added to the CO_2. Please see Past and Present Research section for links to the supercritical CO_2/brine relative permeability database and core characterization performed with the medical CT scanner.

Figure 1. Toshiba Aquilion™ RXL medical CT scanner.

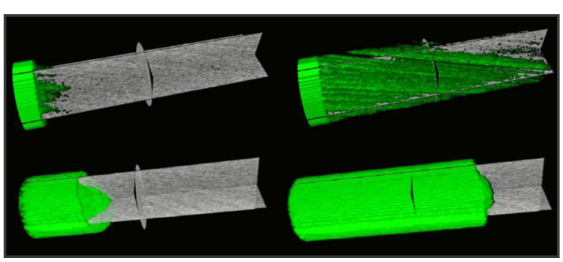


Figure 2. Medical CT scanner images show brine (top) and brine with surfactant (bottom) being displaced by liquid CO_2.

INDUSTRIAL CT SCANNER

PORE-SCALE CHARACTERIZATION AND FLUID FLOW

The **North Star Imaging M-5000 industrial CT scanner** (Figure 3) bridges the gap between NETL's medical and micro-CT scanner machines. The industrial CT scanner allows core-scale characterization of geomaterials, and with NETL's ancillary systems the ability to measure geomechanical and geochemical alterations to these cores. Compared to the medical CT scanner the industrial scanner provides enhanced resolution (5–50μm depending on sample size) but significantly longer scan times (1–2 hours). Conventional samples can be imaged at pore-scale resolution, allowing for the analysis of pore and fracture networks. As with the medical CT scanning system, core holders allow sample imaging at in situ pressure and temperature conditions. When coupled with the industrial scanner's flow-through capabilities and effluent collection, samples can be imaged during flooding experiments to quantify the physical and chemical changes taking place. Unique systems have been developed to alter fractured cores in this system while simultaneously measuring structural and flow properties. Figure 4 highlights a sequence of images showing the changes to a fracture aperture undergoing shear while under confining pressure (see Past and Present Research section for references to work with this shearing apparatus).

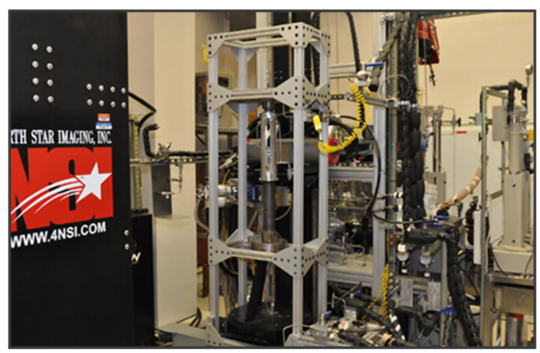


Figure 3. North Star Imaging M-5000 industrial CT scanner.

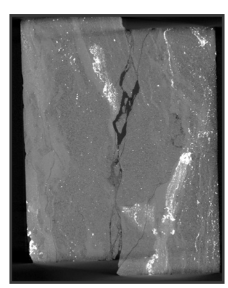


Figure 4. Sheared rock core under confining pressure imaged with NETL's industrial CT scanner.

MICRO-CT SCANNER

SUB-PORE-SCALE CHARACTERIZATION AND FLUID FLOW

The **ZEISS Xradia micro-CT scanner** (Figure 5) operates at the highest resolution, scanning samples ranging from the size of a piece of thread up to 25mm. This type of resolution at and below the single micron scale has been primarily used to provide detailed data on porosity, structure, and mineral composition on small samples of geomaterials. This unit is also equipped with several pressure vessels that allows flow experiments to be conducted under in situ reservoir conditions at elevated temperatures and pressures. The trade-off for this high level of detail is the length of time for each scan, which can take over eight hours, limiting capture of behavior in the controlled cores to quasi-static conditions. Figure 6 is an illustration of a droplet of super-critical CO_2 trapped in the pore space of a sandstone imaged with this system; see Past and Present Research section for references to work on residual fluid trapping behavior captured with this system.

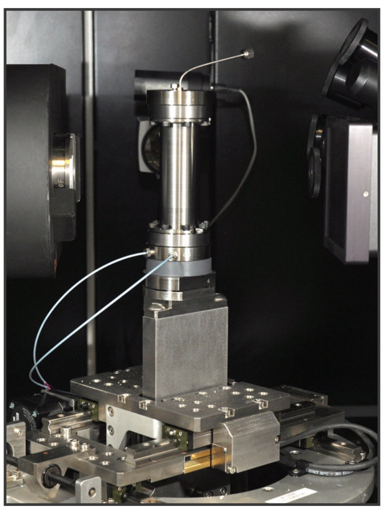


Figure 5. ZEISS micro-CT scanner with core holder.

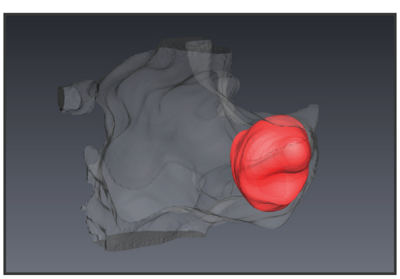


Figure 6. Super-critical CO_2 droplet trapped in sandstone pore space.

FLOW-THROUGH CAPABILITIES

LONG-TERM FLUID FLOW

Experiments conducted to examine long-term chemical and morphological changes can last up to many months, but NETL's CT scanners are typically in constant use and down-time is rare. To accommodate long-term fluid flow studies, NETL's geoimaging laboratory hosts additional flow-through equipment, which enables researchers to carry out longer-term experiments without putting a CT scanner out of commission for the duration (Figure 7). In addition, researchers can still non-destructively image samples before and after the conclusion of the experiment or during planned interruptions in fluid flow.

Figure 7. High pressure, high temperature controlled flow through units at NETL.

MULTI-SENSOR CORE LOGGER

BULK GEOPHYSICAL PROPERTIES

NETL's multiple-sensor core logging unit (Figure 8) measures bulk physical properties of geomaterials in a fashion comparable to downhole methods, producing data akin to borehole well logs. The NETL logger rapidly obtains high-resolution data including p-wave velocity, gamma-density, natural gamma, resistivity, magnetic susceptibility, and chemical composition using X-ray fluorescence spectrophotometry on whole-round and split core samples. These measurements assist researchers in understanding characteristics of rocks and sediment that are meaningful for geologic, fluid flow, and physical analyses. Coupled with the medical CT scanner, thousands of feet of core have been imaged and the data has been made publicly available through technical reports and NETL's Energy Data Exchange.

Figure 9 provides an example of types of data and the level of detail that can be produced by the mobile core logging system.

Figure 8. Multi-sensor core logging unit.

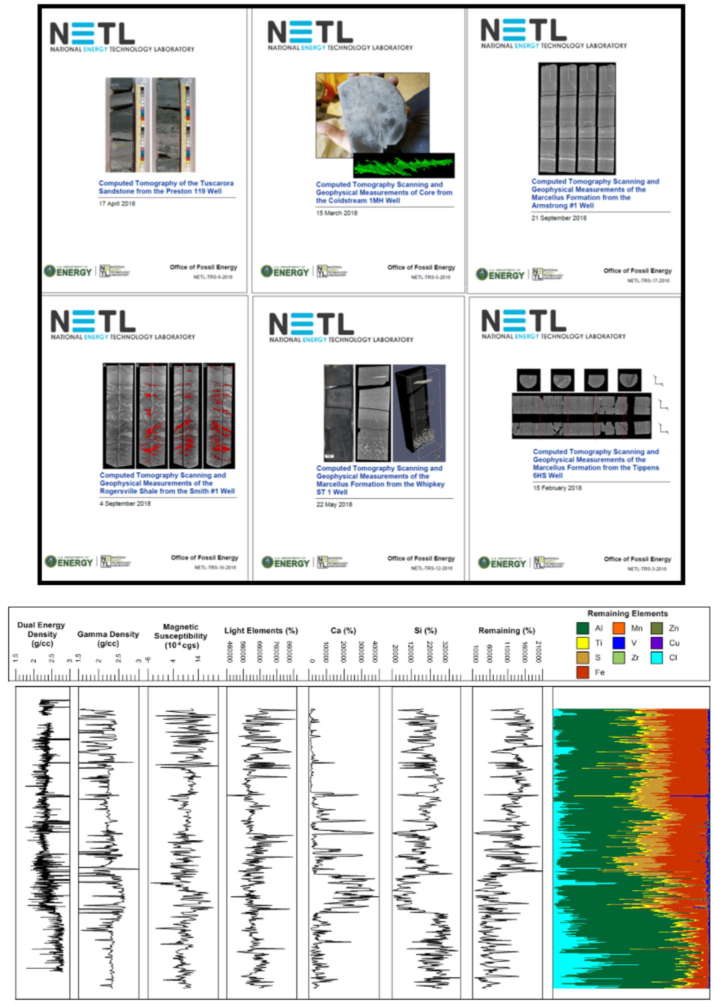


Figure 9. Covers of technical reports of non-destructive core characterization published by NETL and an example of data on one of these cores obtained with the multi-sensor core logger.

PAST AND PRESENT RESEARCH

NETL researchers work with many regional, international, university, and industry partners on projects ranging from carbon storage, to improving the production from unconventional shale formations, to material characterizations. The following are a few examples:

- Analysis of foamed cements used to seal wells in the oil and gas industry with the goal of improving well safety; featured on the cover the Journal of Petroleum Technology

- Detailed characterization of super-critical CO_2/brine relative permeability cures in depositional environments expected to be critical for wide spread geologic carbon sequestration. Data available at https://edx.netl.doe.gov/hosting/co2bra/

- Non-destructive core characterization of thousands of feet of core from carbon storage, shale formations, and NETL sponsored field laboratories. Data available at https://edx.netl.doe.gov/group/core-characterization. Descriptive video of capabilities available at https://www.youtube.com/watch?v=dll8B4AgbAc

- Development and use of in-house fracture shearing mechanism to understand coupled geomechanical and flow behavior of fractured rock. Please see the following for more details:
  - Crandall, D., Moore, J., Gill, M., and Stadelman, M. (2017) CT scanning and flow measurements of shale fractures after multiple shearing events, International Journal of Rock Mechanics and Mining Sciences. 100, 177-187. https://doi.org/10.1016/j.ijrmms.2017.10.016
  - Moore, J., Crandall, D., Gill, M., Brown, S., and Tennant, B. (2018) Design and implementation of a shearing apparatus for the experimental study of shear displacements in rock, Review of Scientific Instruments¸89(045107), doi:10.1063/1.5018419
  - Gill, M., Moore, J., Brown, S., Mackey, P., Tennant, B., Crandall, D. (June 2019) Complex influences on the behavior of sheared Eau Claire formation: insights from computed tomography, ARMA 19-1785, 23-26 June, New York, NY

- Use of micro-CT and virtual reality systems to quantify the contact angle of super-critical CO_2 inside of pore space under representative subsurface conditions. Please see the following for more details:
  - Tudek, J., Crandall, D., Fuchs, S., Werth, C.J., Valocchi, A.J., Chen, Y., and Goodman, A. (2017) In situ contact angle measurements of liquid CO_2, brine, and Mount Simon sandstone core using micro-CT imaging, sessile drop, and lattice Boltzmann modeling, J. Petrol Science, 155, 3-10
  - Dalton, L.E., Klise, K.A., Fuchs, S., Crandall, D., and Goodman, A. (2018) Methods to Measure In-Situ Contact Angles in scCO2-Brine-Sandstone Systems, Adv. Water Res 122 278-290. https://doi.org/10.1016/j.advwatres.2018.10.020

- Pore scale visualization and characterization of methane hydrate bearing sediment retrieved from natural hydrate reservoir.
  - Seol, Y., Lei, L., Choi, J., Jarvis, K., Hill, D. (2019) “Integration of triaxial testing and pore-scale visualization of methane hydrate bearing sediments.” Review of Scientific Instruments, 90(12), 124504. https://doi.org/10.1063/1.5125445

CAPABILITIES AND GOALS

NETL’s suite of geoimaging technologies provides researchers with access to comprehensive non-destructive testing and evaluation of a wide variety of geomaterials, including but not limited to sandstones, limestones, carbonates, coals, gas shales, and cements. The facilities enable the experimental examination of complex processes, such as enhanced oil recovery, carbon storage, sealing formation integrity, wellbore safety, geothermal energy production, hydrate formation, and shale gas development. Many of these real-world applications can be examined in the laboratory using actual core samples and fluids from specific target formations at pertinent temperature and pressure conditions, thus allowing researchers to study the changes within both the geologic samples and the fluids they contain.

The resulting data can then be used to improve numerical simulations, leading to more realistic models, economic valuations, and field characterization efforts. Ultimate goals include improving oil recovery techniques, furthering research on carbon storage, addressing safety concerns in the oil and gas industry, reducing oil costs, extending domestic oil supplies, and reducing dependence on foreign oil, while also informing policy makers in the energy field.

For more information on evaluating geologic materials at NETL, we invite you to see our Geomaterials Research Facilities Fact Sheet (R&D176). https://netl.doe.gov/sites/default/files/rdfactsheet/R-D176_0.pdf

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