GEOIMAGING CHARACTERIZATION
CT SCANNERS

BACKGROUND

Traditional petrographic and core-evaluation techniques typically aim to determine the mineral makeup and internal structure of rock cores. Special techniques also analyze fluid migration in rocks to understand the properties influencing flow. This type of evaluation is frequently destructive, physically sectioning the core to capture details of the sample's internal composition. NETL's geoimaging facility provides a non-destructive alternative to these traditional methods. The lab hosts four computed tomography (CT) X-ray scanners, an assortment of flow-through instrumentation and a multi-sensor core logging unit.

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NATIONAL ENERGY TECHNOLOGY LABORATORY

These technologies work in tandem to provide characteristic geologic and geophysical information at a variety of scales:

- NETL's medical CT scanner images bulk dynamic flow (sub-cm resolution).
- NETL's GeoTek Multi-sensor Core Logger analyzes rock properties along cores (mm resolution).
- NETL's industrial CT scanner images pore and fracture networks undergoing alteration (μm resolution).
- NETL's dynamic micro-CT scanner enables rapid examination of processes (μm resolution).
- NETL's micro-CT scanner allows evaluation of microscopic structure and static fluid distribution (sub-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 CT scanners are equipped with temperature and pressure controls to enable in-situ flow testing during non-destructive visualization.

FACILITIES

MEDICAL CT SCANNER: CORE-SCALE CHARACTERIZATION AND FLUID FLOW

Figure 1

The state-of-the-art **Toshiba Aquilion™ RXL medical CT scanner** (Figure 1) is used for bulk core characterization and in-situ fluid flow experiments. The the scanner's resolution of 100 to 500 µm is the lowest of NETL's CT scanners, but 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 energy producing 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 the 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.

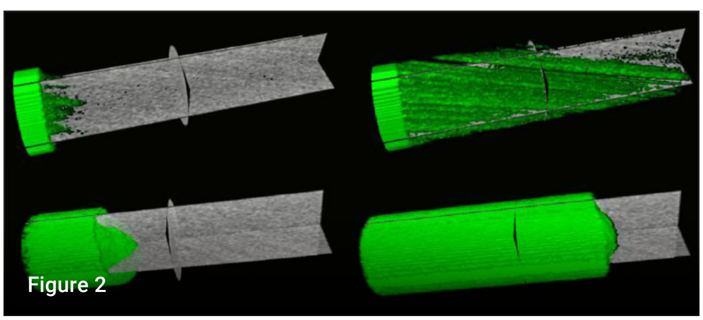

Figure 2

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 coarse- and fine-scale CT scanners. 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

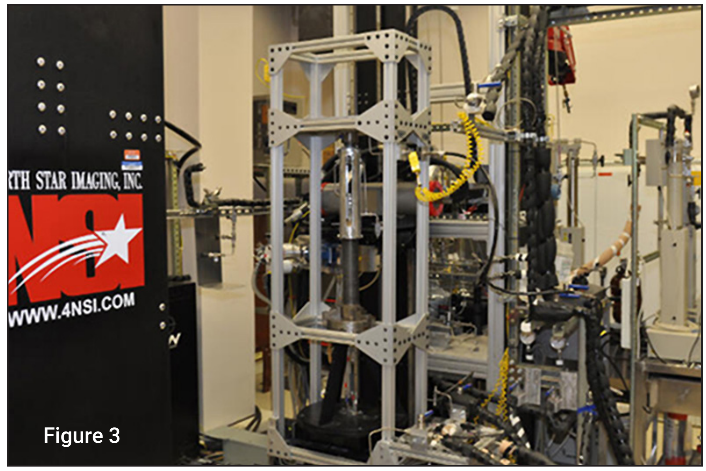

Figure 3

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 flow 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 fractured rock undergoing shear while under confining pressure; fluid flow properties were measured in tandem with this imaging (see the Past and Present Research section for references to work with this shearing apparatus).

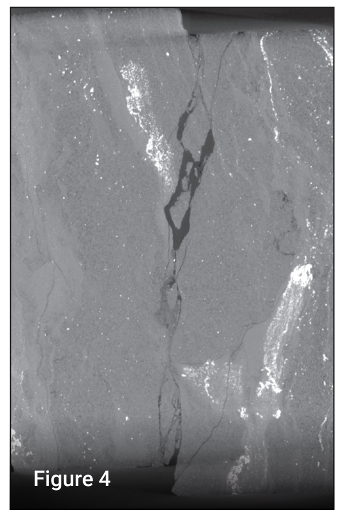

Figure 4

DYNAMIC MICRO-CT SCANNER: RAPID IMAGING OF SMALL-SCALE PROCESSES

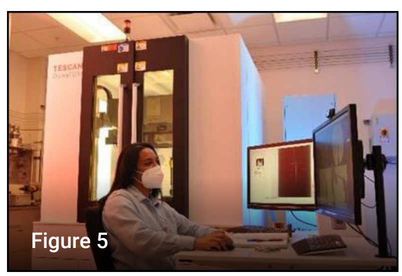

Figure 5

The **TESCAN DynaTOM micro-CT scanner** is NETL's newest scanner. This system obtains images at the three to tens of micron scale, but is unique in that it has a gantry system and integrated reconstruction software that enables sub-minute 3D image captures of samples. NETL's TESCAN DynaTOM (Figure 5) also hosts an in-situ loadcell capable of up to 5 kN tensile compression during X-ray CT applications. Coupling this system with the ability to control temperature, pressure and flow in rocks is currently underway, with full-scale operations anticipated in 2025.

MICRO-CT SCANNER: SUB-PORE-SCALE CHARACTERIZATION AND FLUID FLOW

The **ZEISS Xradia micro-CT scanner** operates at the highest resolution, scanning samples ranging from the size of a piece of thread up to 25mm. This resolution, which is 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 allow 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 the Past and Present Research section for references to work on residual fluid trapping behavior captured with this system.

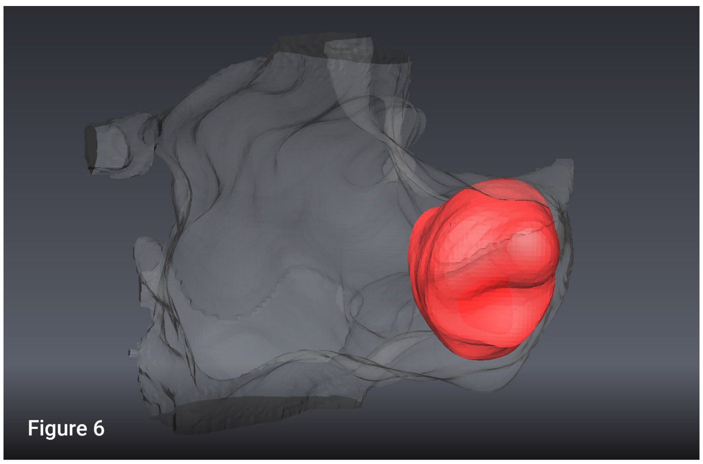

Figure 6

FLOW-THROUGH CAPABILITIES: LONG-TERM FLUID FLOW

Experiments conducted to examine long-term chemical and morphological changes can last many months, but NETL's CT scanners are typically in constant use and downtime 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

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- and s-wave velocity, gamma-density, natural gamma, magnetic susceptibility and chemical composition using VIS/VNIR/SWIR/ Labspec 4HR and 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. edx.netl.doe.gov/group/core-characterization

Figure 8

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 some recent examples:

- Analysis of foamed cements to improve well safety; featured on the cover of the Journal of Petroleum Technology.
- Detailed characterization of supercritical CO_2/ brine relative permeability curves in depositional environments expected to be critical for widespread geologic carbon sequestration. Data available at 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 edx.netl.doe.gov/group/core-characterization. Video of capabilities available at www.youtube.com/watch?v=dIl8B4AgbAc

- 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). https://doi.org/10.1063/1.5018419
- Use of micro-CT and virtual reality systems to quantify the contact angle of supercritical CO_2 inside of pore space under representative subsurface conditions. Please see the following for more details:
  - Dalton, L.E., Klise, K.A., Fuchs, S., Crandall, D., and Goodman, A. (2018) Methods to Measure In-Situ Contact Angles in $scCO_2$-Brine-Sandstone Systems, Adv. Water Res 122 278-290. https://doi.org/10.1016/j.advwatres.2018.10.020
  - Dalton, L.E., Tapriyal, D., Crandall, D., Goodman, A., Shi, F., Haeri, F. (2020) Contact Angle Measurements Using Sessile Drop and Micro-CT Data from Six Sandstones, Transport in Porous Media, 133, 71-83. https://doi.org/10.1007/s11242-020-01415-y
- Dynamic CO_2 Flow Measurements
  - Moore, J., Holcomb, P., Crandall, D., King, S., Choi, J.-H., Brown, S., and Workman, S. (2021) Rapid determination of relative permeability curves for brine and supercritical CO_2 systems using CT and unsteady state flow methods, Advances in Water Resources. https://doi.org/10.1016/j.advwatres.2021.103953
- Pore-scale visualization and characterization of methane hydrate-bearing sediment retrieved from a 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 capture and storage; addressing safety concerns in the oil and gas industry; reducing oil costs; and reducing dependence on foreign oil. We aim to accomplish these goals over the next decade while keeping our nation's policymakers informed.

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