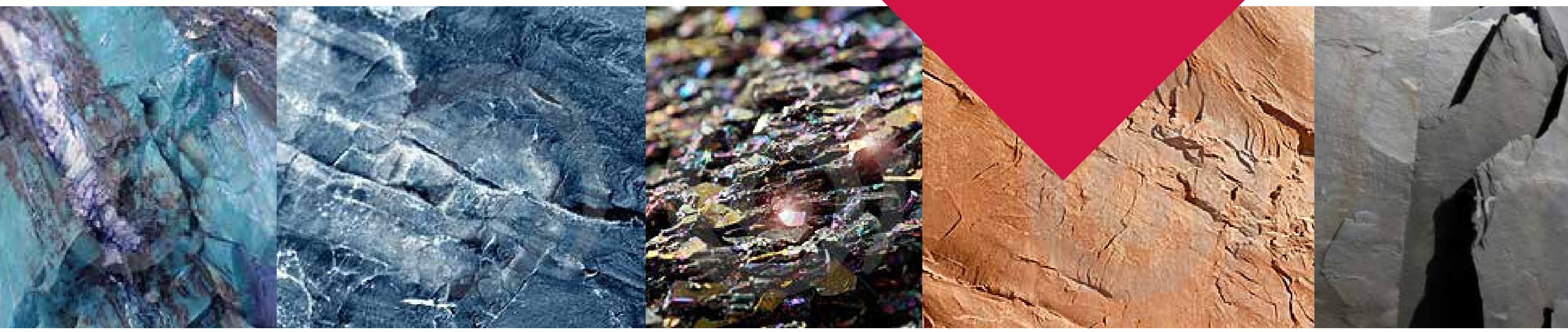
Weatherford®
LABORATORIES

higher standards

Special Core Analysis

**Special Core Analysis –
getting to the heart of the reservoir.**

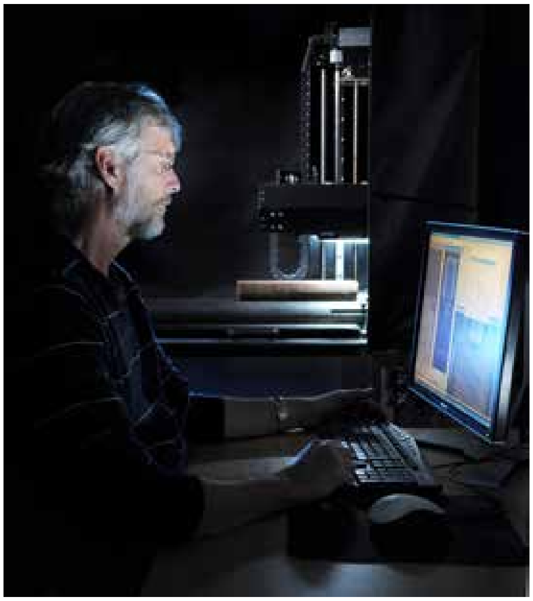


Core samples truly represent the ground truth in the search for oil and gas. Only by understanding the petrophysical properties, geological makeup and geomechanical attributes of rocks – will the operator realize the production potential of a reservoir and map out the best well construction scenarios for optimal field production.

Weatherford Laboratories' array of special core analysis services goes beyond routine core analysis techniques, with a comprehensive suite of advanced tests specifically designed to assess:

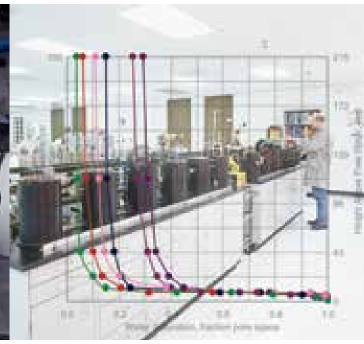
- Petrophysics
- Fluid Flow Properties
- Enhanced Oil Recovery
- Formation Damage
- Rock Mechanics

These analyses help operators more accurately **define reservoir estimates, improve their reservoir modeling and identify and remediate any formation damage.** The end result: more informed well construction and production decisions will help optimize the long-term production and profitability of their fields.



petrophysics






Petrophysics is the study of the physical and chemical properties that describe the occurrence and behavior of rocks and fluids; ultimately shedding light on the reservoir rock's composition and structure. The most common instructive properties in Petrophysics include lithology, porosity, permeability, water saturation and reservoir thickness. Reservoir models are built upon these measured and derived properties to estimate:

- **the amount of hydrocarbon present in the reservoir**
- **the optimal rate at which hydrocarbons can be produced from the reservoir**
- **the fluid flow properties of the reservoir rock**
- **enhanced oil recovery potential**

Weatherford Laboratories offers a full suite of petrophysical laboratory tools and techniques to measure these production properties. We also report the results in ways that guide informed decisions for subsequent well operations. Our standard suite of petrophysical analysis methods include:

Capillary Pressure

Capillary pressure is a key parameter in determining distribution of fluids in the reservoir. Methods for measuring capillary pressure include:

Mercury Injection (MICP)

- Fastest method to obtain results
- Range of pressure is higher compared to other methods
- Provides additional information in the form of pore throat size distribution
- Independent of wettability
- Shale samples for clay effect

Ultra-centrifuge Method

- Increasingly favored for measuring capillary pressures
- Obtain a complete curve in a few days
- Produces high pressure difference between phases
- Rapidly reaches equilibrium and has good reproducibility

Porous Plate Method

- Much slower method, one full curve can take in excess of 180 days
- Highest pressure achieved equals the threshold pressure of the plate
- Electrical properties can be conducted concurrently with this method
- Representative confining pressure and temperature conditions

Electrical Properties

Laboratory measurements of electrical properties from core samples can be used to relate a reservoir rock's porosity, brine and hydrocarbon saturations to its in-situ electrical conductivity. Advantages:

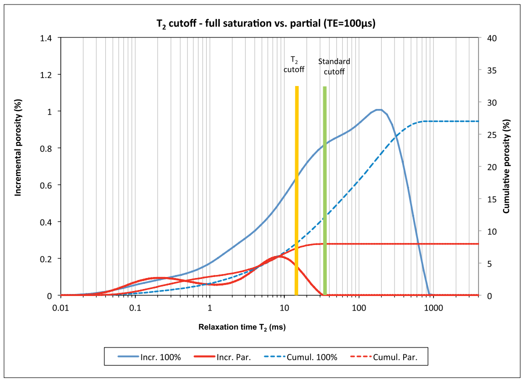
- Understand and calculate oil and gas reserves
- Understand and interpret electrical resistivity logs related to the overall assessment of oil and gas in place

Weatherford Laboratories has the knowledge and practical experience to extend the range of electrical property and capillary pressure testing on rock samples with low water saturations, such as tight gas sands and shale. Our petrophysical experts helped develop and refine specific capillary membrane and vapor desorption techniques to investigate the ultra-high pressure conditions for this prolific and economically important class of unconventional reservoir rocks.

NMR

Weatherford Laboratories routinely conducts nuclear magnetic resonance (NMR) studies on core samples. These tests not only provide useful core analysis data, deduced from the fluid within the pores, but also enhance data interpretation of NMR results from logging-while-drilling (LWD) tools. The core-based NMR studies provide an array of useful information, including:

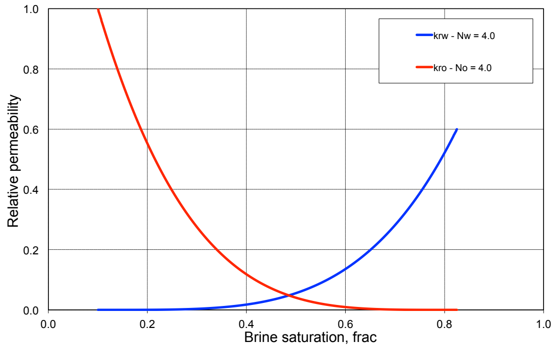
- Determination of reservoir thickness and net pay
- Verification of formation's liquid-filled porosity and log response
- Calculation of a formation-specific permeability relationship
- Determination of formation-specific parameters to determine BVI (irreducible) from the downhole tool
- Determination of movable fluids from log responses



fluid/flow measurements

Relative Permeability

In multiphase flow in porous media, relative permeability is a dimensionless measure of the effective permeability of that particular fluid phase. Weatherford Laboratories employs a full complement of both steady- and unsteady-state methods to measure relative permeability.



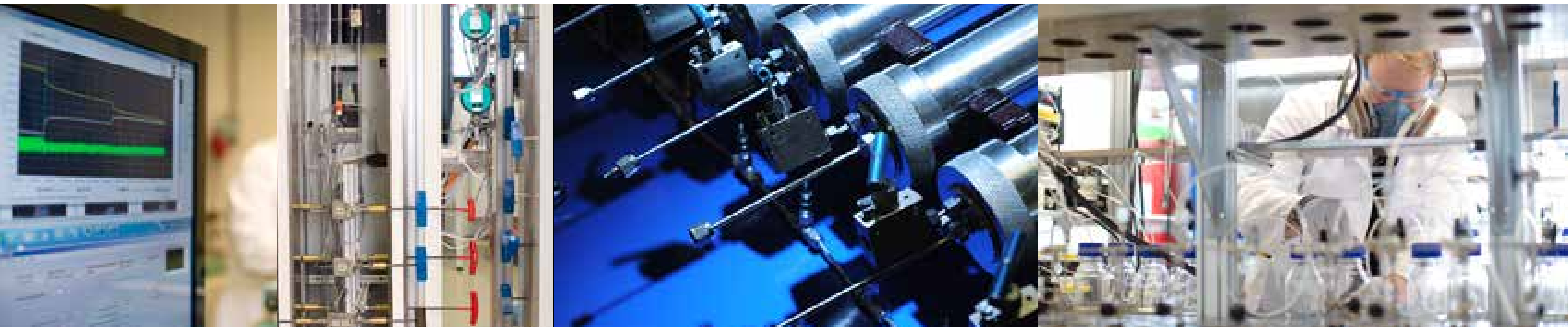
- Steady-state techniques produce reliable relative permeability data, and consist of simultaneously injecting two phases (oil and water) at constant rates for extended durations to reach equilibrium. Parameters such as saturation, flow rate and pressure gradient are measured for each phase and used in Darcy's law ($q=-\frac{kA}{\mu}\frac{\Delta P}{L}$) to derive an effective permeability. While inherently time-consuming, steady-state methods are highly reliable and allow for the determination of relative permeability at a wide range of saturation levels, even early in the life of the field.
- Unsteady-state techniques provide relative permeability curves by production history matching. These experiments use reservoir conditions of temperature, pressure, net overburden and live fluids on restored state core. Relative permeability curves are generated from effluent volumes and differential pressure data recorded as a function of time, during a constant rate (or constant pressure) injection of a displacing fluid. Another unsteady-state method that only measures the produced phase relative permeability data is done with the centrifuge.

Wettability

Wettability measurements, the analysis of one fluid's tendency to spread on or adhere to a solid surface in the presence of other immiscible fluids, play a key role in understanding basic reservoir properties like relative permeability, capillary pressure and resistivity.

Weatherford Laboratories employs a range of lab methods, including Amott, Modified Amott/USBM and contact angle measurements, to measure the wettability of the rock formation in the presence of different reservoir fluids.

enhanced oil recovery



Enhanced Oil Recovery (EOR)

Weatherford Laboratories is the industry's leader in applying integrated analytical capabilities to define the feasibility and compare the value of EOR techniques. From gas injection, complex water floods to steam flooding and chemical floods, we incorporate proven standards of interpretation with field experience to improve hydrocarbon recovery.

Weatherford Laboratories' experience includes a variety of plays in a range of reservoir types worldwide; therefore we can apply our science and technology to support you from the pore-scale to field-scale, wherever you are.

Our suite of EOR special core analysis methods include:

Initial screening for an appropriate EOR process specific to your reservoir

Constant interfacial tension (IFT) core flooding

- This technique, which uses equilibrium phases obtained from multi-contact studies between injected fluids and reservoir oil, provides high definition of EOR sensitivity to interfacial tension, pore geometry, gravity effects, wettability, mobility effects and fluid phase behavior

Chemical flood testing

- Thorough screening and optimization methodology for chemical flood reservoir candidates

Low-and high-temperature multi-phase and heavy oil core flooding

- The industry's only true laboratory model of actual reservoir conditions

Sour service analysis methods

- Operating in a certified sour gas facility allows us to perform all core flow and fluids phase behavior studies under a wider range of real-world reservoir conditions, including H2S and acid gas conditions

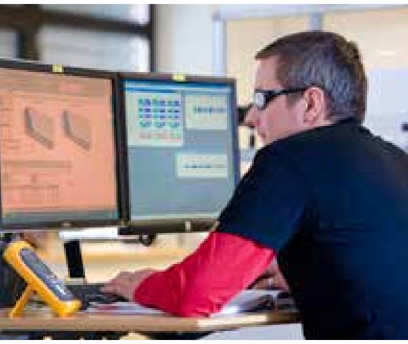
Gas Injection

- Immiscible and miscible gas injection (CO_2) are potentially attractive methods of improving oil recovery, because they can result in lower residual oil saturations than water flooding alone

Low Salinity Water Injection

- Low salinity water flooding can alter wetting properties of oil reservoirs, optimizing fluid flow and oil recovery during production

formation damage




E&P processes may cause formation damage if they reduce the natural inherent productivity of the formation, or reduce injectivity of a water or gas injection well. Formation damage can take place at all stages of a well's life, from drilling on through to its production decline. Our formation damage studies are custom tailored to identify a problem and offer the appropriate solution that will allow the well to be drilled, completed and produced in the safest and most efficient manner possible. A few examples of well operations that commonly encounter formation damage issues include:

Drilling

During the drilling of a well, the improper design of drilling mud composition and cuttings may result in plugging of pore throats, clay swelling, or adverse fluid-fluid interactions that may result in organic scaling or water block.

Fracture Stimulation

In well stimulation operations in shale and other low permeability formations, a well-connected fracture network between the productive zones of the reservoir and the well bore is essential. There are a myriad of formation damage challenges that threaten the fracture network, and the overall production of the well. These challenges include:

- Inorganic/organic scales in the well bore
- Expose pore filling clays
- Wettability changes
- Fracture conductivity decline due to proppant embedment and crushing
- Plug perforations from remnant debris
- Release of fines
- Collapse of the formation during acidizing or inadequate breakers for high viscosity fracture fluids may cause blockage of propped fractures

Completion

The improper planning of completion operations can have a number of serious impacts on the long-term integrity and production potential of the formation. Excessive overbalance pressure can force both solids and fluids into the formation. Incompatibility between circulation fluids and the formation can result in clay swelling/reduced pore throats, invasion of the perforating fluid solids and explosives debris into the formation with resultant pore plugging or wettability alteration from completion fluid additives.

Production

Adverse effects from chemical injection, incompatible waters or steam injection can cause reductions in injectivity and overall production. A multitude of remedies and prevention testing is available.

Weatherford Laboratories deploys a wide range of formation damage laboratory test methods, including but not limited to:

Capillary Suction Time (CST)

- Measures the affinity rock has to hold onto fluid. In filter-cake evaluations, CST measures reactivity permeability of water-base drilling muds (WBMs) or completion fluids. This test may also be used to study how clays and shale react in filter cakes, or be a quick look for rock/fluid sensitivity.

Rock/Fluid Sensitivity

- Various dynamic flow tests allow us to understand if the permeability changes are related to mobile fines or to changes in chemical composition, pH, or salinity.

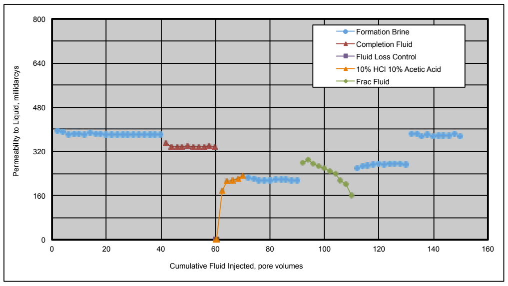
Critical Velocity

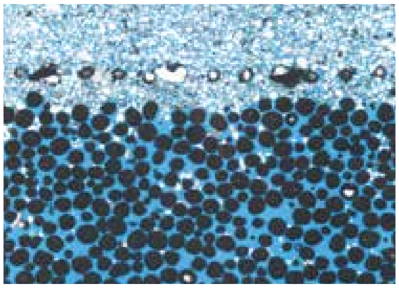
- Core flow tests are carried out at various flow rates to determine at which velocity certain clay minerals may become dislodged and reduce permeability.

Regained Permeability

- Determines the effects of a drilling or completion fluid on the reservoir rock under dynamic (flowing) conditions. Once the baseline flowing properties of the core are established with non-damaging fluids, a treatment with a test fluid is performed. The amount of permeability regained after the treatment is presented as a percentage of the baseline/treated permeability.

Fluid Fluid Compatibility and Scaling Tendency





rock mechanics

In unconventional oil and gas plays such as shales, understanding rock mechanics is essential to success.

Rock mechanics is the study of how formation rock responds to forces imposed by their physical environment. Rock strength affects essentially every aspect of reservoir development including well placement, drill bit selection, high-angle and horizontal drilling, deepwater drilling, hydraulic fracturing, completion operations and production.

Failure to properly measure rock mechanic properties can cause a number of wellbore problems such as borehole instability, casing shear, subsidence, stuck pipe and sand control issues. Together, these issues are estimated to cost the E&P industry billions of dollars each year in the form of lost or deferred production, expensive remediation and intervention operations.

Weatherford Laboratories has the experience and analytical tools to understand a core sample's rock mechanics, and how these translate to better well construction decisions in the field. Our rock mechanics laboratory methods include:

Triaxial Compressive Tests and Acoustic Velocities

We conduct triaxial compression strength tests on cylindrical core samples to understand how the rock responds to compressional stress. Such information guides where and how the operator will place hydraulic fracturing stages. Axial and radial strains are measured while increasing axial stress at constant confining pressure. We also perform the unconfined compression test, which is done with zero confining pressure. Combined, this information helps determine the compressive strength, failure envelope, Poisson's ratio and Young's Modulus. In determining the Mohr-Coulomb failure envelope, 3-4 triaxial tests on samples recovered from the same depth are recommended to obtain trustworthy results.

When core material is limited, a multi-stage triaxial test can be conducted on a single sample at several different confining pressures for Mohr-Coulomb failure analysis. Acoustic velocities can be determined during compressive tests. Dynamic elastic parameters are provided from compressional and shear wave velocities along with sample bulk density and can be compared with static values.

Proppant Embedment Tests

Weatherford Laboratories conducts proppant embedment tests to evaluate proppant behavior with increasing stress. Different types of proppants and concentration can be tested to characterize proppant embedment with stress.

Uniaxial Strain Pore Volume Compressibility Measurements

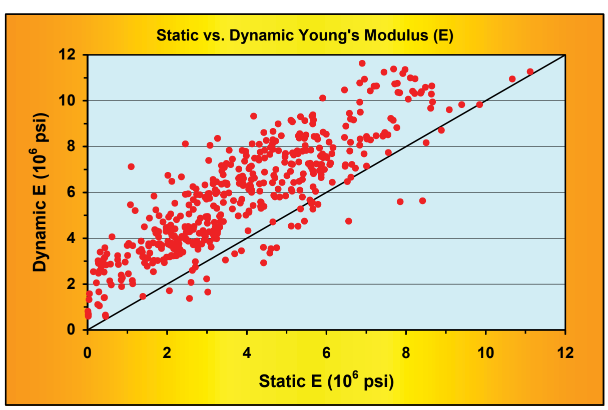
Weatherford Laboratories evaluates core samples for the compressibility that reservoir rock is commonly exposed to in the field. We measure core samples for bulk compressibility (the relative change in bulk volume due to unit change in applied stress), and pore volume compressibility (representing the relative change in pore volume). To measure the representative in-situ compressibility of the core under reservoir production conditions, we conduct drawdown tests under both uniaxial strain and constant axial stress conditions. This test can also be conducted using an overburden ramping method by increasing axial stress while maintaining uniaxial strain condition.

Thick-Walled Cylinder Testing (TWC)

Weatherford Laboratories routinely conducts this test, in which a rock sample in the form of a hollow cylinder sample is externally stressed to failure. The test configuration produces non-uniform stress and strain distributions around the central hole, thus closely mimicking field conditions of near wellbore or near perforation production stress and strain regimes. Such information is vital in helping to characterize openhole stability and the potential for sanding or solids production.

Indirect (Brazilian) Tensile Strength

Measurement of the maximum tensile strength that the rock can withstand is an important parameter in planning a fracture stimulation job. Weatherford Laboratories has the expertise to conduct indirect testing of the tensile strength of core samples by subjecting the sample to line load until failure, and then using well-established equations to determine the corresponding tensile strength.



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