Optical Sensing Systems

Reliable permanent downhole optical monitoring provides the necessary data to accelerate production and increases ultimate reservoir recovery.
Optical Sensing Systems

Optical Downhole Permanent Monitoring: Life-of-Well Solutions

Key Applications

Commingled production from multiple zones

- Optical sensing provides simultaneous production, rather than sequential zone production or separate wells, to allocate accurately from each zone.
- Intelligent well technology allows the producer to monitor and control each zone independently.

High-rate gas wells

- Optical pressure transducer can handle extreme pressure.
- Vibrations from high-rate production or injection do not affect the sensor performance.

HT/HP wells

- Optical sensing systems can withstand temperatures to 347°F (175°C).
- All electronics are at the surface and more easily accessible for upgrades and maintenance; high-reliability, passive components remain downhole.

Hydraulic fracturing

- Optical sensing systems monitor hydraulic fracturing to optimize stimulation operations and to determine fracture growth.

Sand control

- Monitoring across perforated intervals and open-hole sections.
- Sensors deployed inside or outside the sand screen.

Optical permanent monitoring systems provide downhole measurement and control that play a critical role in both the short-term characterization and long-term management of the reservoir. They offer clear advantages in terms of performance, reliability, cost, and ease of installation. Problems can be identified sooner than with other technologies and remedied before they become too costly to fix. In fact, for multi-zone and other challenging well environments, optical systems deliver capabilities that no alternative technology can match.

These systems provide real value in all well phases, including mid-to-late field life, and particularly in hostile environments where well intervention is costly, if not altogether impossible. Optical sensing technology is robust in high-temperature/high-pressure (HT/HP) and high-rate gas wells. Vibrations from high-rate wells do not affect the performance of the sensors, and the sensors can withstand extremely high temperature and pressure combinations.

Simple, single-gauge installations have now evolved into multi-zone intelligent wells with integrated pressure and multi-phase flow rate measurements, distributed temperature sensing, downhole seismic, and remote flow-control capabilities.
Why Optical Sensing?

Companies are finding that data from permanent downhole monitoring systems helps improve production operations and reservoir management. The advantages have already paved the way to general acceptance within the industry.

- Increase reservoir recovery
- Reduce the need for well interventions, resulting in benefits of reduced cost, downtime, and operational, safety, and environmental risks
- Provide information for more efficient development and operation of complex reservoirs, thus improving field economics
- Eliminate compensations for drifting gauges because optical in-well gauges demonstrate zero or negligible drift over time

Technology Traction

The technology is now more robust and sophisticated. It has gone through the crucial “new technology” incubation stage and been refined. In slightly more than a decade, the acceptance and adoption of optical fibers in downhole production monitoring has grown significantly. Initial systems were expensive, complicated to install, and able to support only limited applications.

Early progress was incremental as the enabling technology was developed. Flexible, scalable surface instrumentation had to be designed to receive and process the large volumes of data arriving, literally, at the speed of light from multiple optical sensors and sensors of various types. Simple, single-gauge capabilities have now evolved into multi-zone intelligent wells with integrated pressure sensing, in-well flow measurements, distributed and array temperature sensing, and downhole 4D seismic measurement capabilities all in one well.

Simplicity Is Key

Rather than putting complex electronic devices into the caustic downhole environment, optical sensors rely on nothing more than coated glass downhole. The more delicate parts of the sensors are at the surface, easily accessible for upgrades or maintenance. Since the sensor itself is all glass, it can withstand high temperatures, pressures, and vibration. The glass is also immune to interference from local radio or electrical transmission sources.

Minimal Footprint

Optical cable requires a minimal footprint. A single multi-fiber cable can include integrated pressure/temperature (P/T), multi-phase flow, distributed or multi-point temperature, and multi-station seismic sensing. In addition, each zone’s flow can be measured without obstruction in multi-zone commingled wells.

Long-Term Value

Optical systems typically pay for themselves within a year in the form of improved recovery rates and decreased workover interruption. They provide reservoir and production engineers with a stable, reliable, high-quality data stream throughout the life of the asset.

Weatherford optical solutions have no downhole electronics and few moving parts leaving fewer things that can go wrong downhole.
Weatherford has more than a decade of experience with optical sensing and intelligent well technologies. In fact, we recently announced achieving milestones of 1 million ft (305,000 m) of fiber-optic cable and 3 million ft (915,000 m) of optical fiber installed in wells. These achievements reflect more than one million cumulative in-well operating hours for our optical systems.

Cumulative optical installations including P/T, DTS, flow and seismic applications.

Weatherford has developed an entire suite of measurement systems around optics-based technology. In addition to P/T gauges, we provide permanent, in-well fiber-optic sensors for measurement of multiphase flow rates, distributed temperature and seismic properties. To complete the information loop for the downhole sensors, our surface equipment interrogates the sensors to provide high-bandwidth data and data trends. This meaningful information can be accessed by the operator through the Weatherford Reservoir Monitoring System (RMS) or transferred to legacy SCADA systems.

Weatherford’s RMS provides integrated information to operators from multiple optical tools. It can operate as a stand-alone data-acquisition, management, display and communication system, or it can seamlessly interface with legacy SCADA, secure Intranets, Internet or communication systems.

Our offering responds to two of our clients’ more important needs: real-time downhole information (part of the concept of intelligent completions) for reservoir optimization and technology that can consistently deliver accurate data from even the harshest downhole environments.
The Weatherford Suite of Optical Sensors

**P/T gauge.** This optical tool boasts the industry’s highest mechanical shock and vibration survivability. The rugged glass microstructure features two Bragg gratings that measure strain associated with pressure and temperature. Integration of the single-piece pressure and temperature transducer with a simple transducer pressure housing delivers the smallest part-count solution and highest reliability for a P/T gauge.

**Single-phase and multiphase flowmeter.** Weatherford’s optical flowmeter delivers accurate, real-time measurements of downhole oil, gas, and water flow rate. Optical fibers monitor dynamic strain in a section of the production tubing without any obstruction to the flow. They determine flow rates by measuring the velocity and speed of sound of the flowing stream, using an array of sensors mounted on the outside of the flow tubing. When this sensor is combined with the other sensors to quantify fluid density and the speed of sound transmission, three-phase flow (gas, oil, and water) can be accurately determined.

**Temperature measurement systems.** Weatherford offers two technologies to provide distributed temperature measurements along the wellbore.

- **Distributed temperature sensing (DTS).** The length of the entire fiber acts as the sensor, yielding a continuous temperature log along the length of the fiber-optic cable. A time-lapse profile of the temperature changes across the production zone.

- **Array temperature sensing (ATS).** This system integrates an array of discrete optical temperature sensors into a fiber-optic cable to provide high-resolution temperature measurement points. Stable, high-resolution measurements from the sensor array enable production analysis of applications where changes in temperature are minute, such as profiling oil and water production from long horizontal wells.

**Clarion™ seismic sensor system.** This permanent system enables production optimization and enhanced reservoir management by making high-resolution, on-demand reservoir imaging possible through the use of low-profile, high-performance accelerometers. These incredibly sensitive sensors use only fiber and a proof mass. The Clarion system was designed specifically for hostile wellbore environments. Its sensors decrease uncertainty by providing consistent, unchanging reference points in the subsurface and eliminate repeatability errors that frequently result from redeployment of temporary sensors.

Weatherford World Firsts for Downhole Optical Installations

- **1993** First in-well optical P/T gauge
- **1996** First subsea optical P/T gauge
- **1999** First in-well Bragg grating P/T gauge
- **1999** First in-well seismic accelerometer
- **2000** First non-intrusive in-well fiber-optic flowmeter
- **2001** Optical P/T gauge and DTS in single completion
- **2002** Multiple optical P/T gauges in single completion
- **2003** Full three-phase fiber-optic flowmeter with P/T gauges
- **2003** Multi-zone optical P/T gauges and remote flow control
- **2004** Multi-zone optical P/T gauges and flowmeters with remote flow control
- **2004** Casing-conveyed, multi-station, seismic with P/T gauge
- **2005** Multiple optical P/T gauges and DTS integrated with sand control
- **2006** First successful multi-station, multi-component, tubing-conveyed optical seismic array in an offshore environment

More than 100 optical systems have been installed to date
How They Work

All optical sensors use light transmitted from the surface down an optical fiber. The sensors interact with the light and reflect a portion of it back up the fiber to the surface unit for analysis. Bragg grating technology allows incorporation of sensors directly in the optical pathway, simplifying the sensor to a single monolithic glass structure.

When the temperature, pressure, or strain on the fiber changes, the reflected wavelength changes, providing a direct measurement. The all-glass downhole sensor can withstand high temperatures, pressures and vibration while the electronic components of the system are at the surface, unexposed to the hostile downhole environment and easily accessible for upgrades or maintenance.

Silica with high-temperature fiber coatings enables the development of sensing systems for applications with operating temperatures in excess of 347°F (175°C). The optical sensors overcome issues of sensor deterioration because the glass has no unstable mechanical transducer sensor components. There simply is no wear-out phase.

Testing to validate the sensor’s stability at 302°F (150°C) and 5,000 psi (34.5 MPa) began in June 1999. After more than five years of testing, the pressure gauge still has demonstrated no detectable drift. (Typical pressure gauge technology exhibits drift of ±2 psi [13.8 kPa] per year.)

Single Cable

Our intelligent well systems integrate P/T, multi-phase flow, distributed temperature, and multi-station seismic capabilities on a single optical cable. A single optical cable can support multiple sensors. The number and type of sensors can be tailored to address specific downhole information requirements.

Weatherford currently offers two sizes of in-well optical cable: 1/4-in. and 1/8-in. Both have been designed for maximum durability and longevity. To simplify rig-site deployment, the final packaging is identical to that of most in-well hydraulic and electronic control lines. A complete integrated system of dry- and wet-mate connectors enables the cables to pass through packers, safety valves, and other in-well equipment. Weatherford’s standard cable contains three strands of fiber, one commonly used for distributed temperature sensing, and the other two for all other types of sensors. This fiber combination, however, can be modified for application requirements.
Typical Applications

**P/T sensors** can be used effectively during well startups, not only to measure real-time reservoir pressure, but to manage initial drawdown. In-well P/T sensors are also useful for conducting well connectivity or interference tests as well as pressure transient analysis. Weatherford’s proprietary software, such as the PanSystem™ and PanMesh™ programs, is used to aid with this analysis and provide reservoir boundary information.

In horizontal completions, P/T gauges are useful for defining drainhole production efficiency. When coupled with flow-control valves or inflow control devices, these gauges can ensure uniform production across a long horizontal section. This technique can prevent the excessive flow from the “heel” of the completion that kills production from the “toe.”

**DTS** and **ATS** monitor the thermal profile of the entire well, giving an indication of the production or injection profile across the reservoir sections and helping to identify flow anomalies, such as tubing or casing leaks, thief zones, and flow obstructions. A DTS array can detect water, gas, or steam breakthrough. DTS has also been useful in determining completion effectiveness and the performance of gas lift valves. DTS systems monitor each gas lift valve as it comes onstream, providing both individual and cumulative performance information. Weatherford works with clients to find which distributed measurement technology best fits their application and data requirements.

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<thead>
<tr>
<th>Completion Types</th>
<th>P/T</th>
<th>DTS</th>
<th>ATS</th>
<th>Flowmeter</th>
<th>Seismic</th>
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* Instrument can be contained in canister in subsea control module or located on surface if fiber is in umbilical.
** Instrument must be linked to surface via fiber in umbilical.
Optical Sensing Systems

Typical Applications (continued)

Real-time downhole flow measurement is critical for optimizing production from many of today’s complex well designs, including intelligent, multi-zone, and multilateral completions. In multilateral completions and wells with commingled production from stacked reservoirs, optical flowmeter data can help resolve production allocations issues and determine productivity index for individual zones or the entire well. Data from a downhole flowmeter can be used to reduce or eliminate the need for surface well testing and the resulting operational, safety, and environmental effects.

Unlike conventional flowmeters, optical flowmeters have no borehole restrictions or intrusions into the flow path, like a Venturi throat or a spinner. They are bidirectional, scalable to any pipe size and feature a control-line bypass for use in intelligent well systems. These flowmeters can be configured for single-, two- or three-phase flow and are applicable to production and injection wells.

Permanent in-well seismic monitoring performs time-lapse vertical seismic profiling (VSP), cross-well seismic imaging and surface seismic calibration. Additionally, seismic monitoring has been used to map fracture propagation during well stimulation. Recently, geoscientists have been listening to microseismic activity that is associated with injection, production, or subsidence—adding a new dimension to dynamic reservoir characterization. The seismic stations can be installed in a production well or injector or a nearby observation well.

One-component or three-component optical seismic accelerometers are mounted in robust sensor carriers, linked in an array along the fiber-optic cable. Sensor array configuration and placement is dependent on the application. A group of sensor stations can be placed above the reservoir for reflection imaging purposes or can be placed close to the reservoir for production-induced microseismic monitoring or hydraulic fracture mapping. Coupling of the seismic sensors can be achieved either by an active clamping mechanism or by passive means. Sensor carriers can be deployed on the production tubing or outside the casing and can even be cemented into place.

Flexible Solutions

Weatherford provides an integrated optical architecture for virtually all measurements you may need. With the cable as the optical “backbone,” sensor architectures can be reconfigured as required.

For example: one fiber can accommodate four P/T gauges or one flowmeter and two P/T gauges; another can act as a DTS; and the third can be dedicated to seismic monitoring.

These systems can be designed around your needs, your project parameters. Fully integrated, reliable optical sensing systems can be designed to solve reservoir management problems over the life of the reservoir. With this flexibility, optical monitoring sensors can be configured for innumerable production zone applications. With the advent of optical seismic monitoring, a new generation of life-of-asset management capabilities is here.

Hydraulically actuated in-well flow controls, such as our ROSS® and ROSS V tools, can be combined with optical monitoring systems for a truly robust and reliable intelligent well system. Weatherford also offers a wide range of non-optical downhole gauges, packers, liners, screens and gravel-pack systems for advanced completions. From simple well architectures to the most complex reservoirs, optical monitoring systems can improve field development and management.
Additional Applications

Management of startup to minimize formation damage
• Downhole P/T gauges are used to accurately control startup without formation damage from a rapid pressure drop downhole.
• Users can monitor drawdown and control the choke at the surface to minimize the time for starting the well without exceeding the maximum allowable pressure drop.

Reservoir pressure and pressure transient analysis without intervention
• Near-well measurements provide data for reservoir analysis.
• Reducing interventions addresses safety concerns and possibilities of malfunctions such as leaks. Shutdown for interventions results in deferred production, reducing revenue for that period.
• Downhole pressure measurements enable use of unscheduled shutdown to perform transient analysis and enables on-demand permeability, skin, and reservoir boundaries analysis.

Measurement for productivity or injectivity index
• Use of a downhole flowmeter, coupled with a P/T gauge provides operators with instant displays of changes in the productivity or the injectivity index.

Flow measurement for subsea wells
• Flowmeter identifies individual well flow before fluid reaches the seafloor manifold.
• An integrated subsurface P/T-flowmeter combination replaces the need for separate downhole P/T gauge and seafloor flowmeter.
• The multiphase flowmeter can eliminate the need for a test facility on the platform.
• The flowmeter is downhole; therefore, slugging that typically occurs at or near the wellhead is eliminated.

Seismic imaging and monitoring
• Borehole seismic is the key link between surface seismic and well information, reducing both uncertainties and risk in exploration and production.
• Permanent, reliable optical in-well seismic arrays can be used to obtain detailed time-lapse reservoir imaging around the well to track fluid movement and help locate bypassed hydrocarbons.
• Optical in-well seismic arrays can also be used to image thermal fronts and injections, such as carbon dioxide (CO\(_2\)).
• The time-lapse (4D) surface seismic response can be calibrated to better process and understand the data. Stress changes in the reservoir caused by production or injection are continuously monitored to help delineate faults and understand flow paths. Compaction, which can induce well or casing damage, can be monitored as well.

Diagnostics
Installing optical sensors often results in unexpected well diagnostic capabilities.
• Rather than waiting for a disparity in the expected production amounts, the operator can use a permanent downhole pressure gauge to determine immediately when a safety valve is not opened completely and thus avoid unnecessarily production delays.
• When used with production well testing, the downhole flowmeter provides a diagnosis of the well test facility.
• The operator can determine the highest and lowest points of production or injection in the production or injection zone.
• DTS/ATS provides information that can be used to monitor water, gas and steam breakthrough.
• Distributed temperature measurement can tell you which gas lift valves are open or closed.
• Temperature data can be used to manage production to maintain temperature above the point where formation of paraffin or asphaltene will occur.

Pressure gauges and flowmeters can be multiplexed on a single fiber. Multiple sensing point and measurement types on a single fiber reduce system complexity by replacing multiple electrical sensors, instrument types, and associated electrical wiring. A downhole cable splitter can be used to interconnect several sensors in complex completion designs. Custom fiber configurations are also available upon request.
Above-the-Packer Sample Well Profile

Simple Well: P/T

Additional Options
- DTS
- Subsea with instrument in a subsea pod
- Subsea with fiber in umbilical and instrumentation on the surface
- Flowmeter
Below-the-Packer Sample Well Profiles

Multi-Zone Well: Flowmeter, P/T and Flow Control

Additional Options
- DTS
- Subsea with fiber in umbilical

Used for production or injection wells

Multi-Zone Well: P/T with Flow Control

Additional Options
- DTS
- Subsea with instrument in a subsea pod
- Subsea with fiber in umbilical and instrumentation on the surface

Used for production or injection wells
Fiber Across the Reservoir: DTS or ATS

Additional Options

- P/T, either single or multiple units
- Subsea with instrument in a subsea pod (ATS only)
- Subsea with fiber in umbilical and instrumentation on surface

Used for production or injection well
Multi-zone, horizontal or multilateral well
Sand Control Options for All Well Profiles

The Intelligent Screens™ system combines two highly effective and successful Weatherford technologies—well screens and optical sensing—to enable safe, easy, permanent monitoring across perforated intervals and open-hole sections in sand-control completions.

- Outside conventional screen
  - Fiber fits into a channel, integrated into a shrouded screen
  - Virtually no flow obstruction

Using a special groove, incorporated in a sand screen protective shroud, a fiber-optic cable and sensors can be deployed along the screen to measure production profiles.

- Inside ESS® expandable sand screen, using a stinger to deploy. This sand screen design complements Weatherford’s proven ESS plus expandable zonal isolation (EZI™) completion technique

- Inside gravel pack. Stinger systems enable integration with third-party gravel-pack systems without requiring complex interfaces

When distributed production monitoring is combined with P/T and optical flowmeters and/or flow-control valves, an intelligent multi-zone sand screen completion is possible.

Applications include monitoring of completion effectiveness and well start-up; continuous production and well profiling; wellbore diagnostics; and special analysis during normal well operations, such as the warm-back that accompanies shut-ins of injection wells.
Multi-Component Seismic Array Within or Above the Reservoir

Additional Options
- P/T above or below the packer
- DTS
- Flowmeter

Casing-conveyed seismic deployment.

Tubing-conveyed seismic deployment.