Reservoir monitoring requires dependable downhole data-acquisition systems. Products based on sound reliability engineering and failure testing, essential to building durable permanent monitoring systems, are responsible for an impressive track record for permanent gauge installations worldwide. Gauges supply data useful for both short-term troubleshooting and for long-term development planning.

Downhole Monitoring: The Story So Far

Nothing lasts forever. To many of us, “forever” is our life span, which can vary widely among individuals. The “permanence” of inanimate objects also varies in absolute time and importance. For example, commercial communication satellites are expensive to fabricate, difficult to deploy and generally inaccessible for repair, so it is important that they function properly for a long time. Replacement valves and pacemakers for human hearts can be replaced or repaired, but not without considerable risk to the recipient. Equipment sent to the remote research stations of Antarctica is expected to stand up to harsh conditions. Buildings, bridges and monuments are also built to endure, but they have finite lifetimes. Intelligent completions, which combine production monitoring and control, are becoming more common, and require reliable downhole gauges and flow-control valves.

Downhole equipment in the oil field also must stand the test of time. The productive life of an oil or gas well may be 10 or more years, so “permanent” downhole equipment must last at least that long to satisfy operators’ expectations. Because it is impractical to conduct equipment tests of such long duration, reliability engineering and failure testing have become mainstays of those people who develop permanent monitoring systems. The result has been an impressive reliability track record for permanent monitoring installations worldwide.

In this article, we begin by examining the challenges in permanent monitoring. Next, we consider how engineers develop robust permanent gauges to provide a continuous stream of data for the life of a well. Finally, we present examples that demonstrate how the use of permanent gauges adds value by helping to optimize production and forewarning operators of problems so that preventive or corrective action can be taken.

FloWatcher, NODAL, PQG (Permanent Quartz Gauge), PressureWatch, PumpWatcher, Sapphire and WellWatcher are marks of Schlumberger.

Challenges in Permanent Monitoring

From the perspective of reliability, permanent downhole gauges used in oil and gas wells are similar to commercial communication satellites, although other industries, such as the automotive industry, confront similar reliability challenges. Each system must endure a long life under harsh environmental conditions. Once in place, the devices are not routinely repaired, replaced or recovered. Parts may never return to surface for lab analysis of what worked and what didn’t; it is difficult to determine what failed without retrieving and examining a malfunctioning device.

A typical approach to these challenges is to include redundant components in the hope that if one part fails, its backup will function. When used wisely, redundant designs can improve reliability significantly. However, in both downhole gauges and satellites, redundant components occupy valuable, limited space and consume precious power. Common failure modes must be avoided when specifying redundant components. For example, if a particular component is prone to failure in a particular environment, its backup part should be made from different material so that it too won’t fail under the same conditions.

The annals of aviation include numerous episodes of common-failure-mode disasters. Charles Lindbergh undertook a transatlantic flight in the single-engine Spirit of Saint Louis in 1927 only after careful study convinced him that the lack of backup systems would not put him at risk.2

In addition to fabricating durable permanent downhole equipment, engineers and designers work together to address the complexity of equipment installation and conditions at the wellsite. Competent field engineers and robust equipment are both essential for reliability. For example, it is difficult to maintain a high level of manual dexterity for hours at a time in an icy downpour or a fierce wind. It is important for the field crew to install a monitoring system using well-designed installation tools that ensure installation consistency, especially in remote locations. Simplifying the installation process as much as possible also improves success rates. Early failure of permanent monitoring systems decreases when a well-prepared crew performs the installation with familiar tools.

Operators have used permanent downhole pressure gauges since the 1960s.3 The vast body of experience is paying off in the latest generation of gauges, for which statistically valid reliability data are now available. There are now thousands of gauges deployed worldwide, over 800 of which have been installed by Schlumberger since 1973 (above and next page, top). A significant increase in installations occurred after a new generation of more reliable gauges was developed in the early 1990s.

1973 First permanent downhole gauge installation in West Africa, based on wireline logging cable and equipment
1975 First pressure and temperature transmitter on a single wireline cable
1978 First subsea installations in North Sea and West Africa
1983 First subsea installation with acoustic data transmission to surface
1986 Fully welded metal tubing-encased permanent downhole cable

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Dependability, the *Sine Qua Non*

A basic permanent downhole gauge consists of sensors to measure pressure and temperature, electronics and a housing [previous page, right]. A mandrel on the production tubing holds the gauge in place. A cable, enclosed in a protective metal tube, is clamped onto the tubing. The cable connects the gauge to the wellhead and then to surface equipment, such as a computer or control system. Because acquiring and transmitting good data depend on proper functioning of each part, such systems are only as reliable as their weakest component.

A complete monitoring and communication system, such as the WellWatcher system, handles diverse sensors, including a FloWatcher sensor to measure flow rate and fluid density, a PumpWatcher sensor to monitor an electric submersible pump and a PressureWatch gauge to measure pressure and temperature [below]. Surface sensors measure multiphase flow rate and pressure and detect sand production. In addition to surface controls for valves and chokes, there is a computer to gather data, which

![Image](image_url)

*A complete permanent monitoring system for measuring pressure, temperature, flow rate and fluid density downhole. Surface sensors measure flow rate and pressure. A data-retrieval and communications system facilitates data transfer to the office of the end user.*
are stored at the wellsite or transmitted to the office (below).1

Permanent downhole systems must be dependable throughout their lifetimes—they must be reliable and stable. "Dependability" conjures different meanings for different people, but is used in this article to refer to the combination of reliability and stability. "Reliability" in the context of downhole gauges refers to proper installation and ongoing delivery of data from the gauge. It can be defined as the probability that the gauge will perform as specified without failure for a certain amount of time under the required environmental conditions.

"Stability" refers to the actual measurement. Measurements from an unstable or excessively drifting gauge might prove more troublesome to an oilfield operator than outright failure of the gauge. It is important to know whether gradual variation in a measurement with time indicates an actual change in the reservoir or reflects a drift problem with the measuring device.

To ensure a dependable product, it is essential to maintain strict quality control throughout the entire engineering process. Quality is the degree to which the product conforms to specifications. To truly achieve world-class reliability and stability entails systematic product development and qualification testing, use of qualified components and proven design methods, strict audits and tracking of generic parts, failure analyses and consultation with industrial and academic peers. Reliability and stability cannot be tested into a product after it is built, but instead must be considered throughout the entire process, from design and production to installation.

The Road to Reliability

During the past 10 years, Schlumberger has enhanced the dependability of its permanent monitoring systems through improvements in engineering and testing processes, system design, risk analysis, training and installation procedures (next page, top). Like other tools and systems developed by Schlumberger, permanent gauge development follows a logical sequence of engineering phases. Dependability concerns are paramount during each phase.

The engineering phase begins with development of a mission profile, or a verbal description of the technical concept that serves as an engineering framework. The mission profile defines the role of each component and the environmental conditions components will encounter during the entire process, from design and production to installation.
their expected lifetime. All components of the system are screened and qualified to withstand the expected conditions. Accelerated destructive tests subject components to conditions much more extreme than expected over their lifetime, such as greater mechanical shocks and vibrations and higher-than-downhole temperatures and pressures. This type of testing helps determine failure causes and failure modes. Long-term testing of the system enables engineers to validate reliability models and quantify measurement stability.

A drawback to accelerated testing is that failure can occur simply because of the stressful test procedure, and the test might not be a good predictor of actual performance. It is impossible to test everything, but it is important to test as much as possible to increase confidence that the product will perform as required in commercial operations. Feedback from field engineers is a critically important complement to laboratory testing.

> Permanent monitoring system development. From the initial mission profile to failure analysis, collaboration between engineers, field personnel and operators contributes to continual improvements in permanent monitoring systems.

Permanent gauge stability test. This plot of pressure versus time represents testing of a PQG Permanent Quartz Gauge system at elevated pressures and temperatures for more than two years. The initial test conditions were 140°C [284°F] and 7000 psi [48.2 Mpa]. Testing was then accelerated, with the temperature increased to the maximum rated temperature of 150°C [302°F], and then to 160°C [320°F] and 170°C [338°F], to make the gauge fail. Each time the temperature was increased, there was a brief period of measurement drift before the gauge reached stability. The gauge drifted less than 3 psi/yr [20 kPa/a]. During the test, the gauge performed as expected, but the test cell had to be repaired twice!


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**Table: Product engineering, Training and personnel development, Project engineering, Reliability and data quality management**

<table>
<thead>
<tr>
<th>Product engineering</th>
<th>Training and personnel development</th>
<th>Project engineering</th>
<th>Reliability and data quality management</th>
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<tbody>
<tr>
<td>Mission profile and requirements</td>
<td>Training with development and field engineers</td>
<td>Reservoir engineering and production requirements</td>
<td>Collect field track records into database</td>
</tr>
<tr>
<td>Prototype product design</td>
<td>Well completions installation training</td>
<td>Well completions design and installation planning</td>
<td>Analyze results and feedback for improvement</td>
</tr>
<tr>
<td>Risk analysis and test plans</td>
<td>Performance evaluation and growth plan</td>
<td>Well construction, installation and operation</td>
<td>Review with operators, development and field engineers</td>
</tr>
<tr>
<td>Components qualification testing</td>
<td>Technique improvement</td>
<td>Project improvement</td>
<td></td>
</tr>
<tr>
<td>Reliability qualification testing</td>
<td>Technical reviews and audits</td>
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<tr>
<td>Sustaining, product improvement</td>
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</tbody>
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![Diagram: PQG Stability Test at 10,000 psi](image-url)
Tests for susceptibility to mechanical shock and vibration, such as those expected during transport and installation, are also performed. These tests are similar in concept to those developed by Sir Henry Royce, the engineer behind the success of the Rolls-Royce automobile. By repeatedly bumping the car on an apparatus that simulated bumps in a road, Royce determined which parts of the chassis were not strong enough and developed better ones (right). The changes included replacing rivets with bolts and using a few large bolts rather than many small ones.

In the system-design phase, engineers ensure proper interfacing between the completion components. Communication with completion engineers and third-party vendors has resulted in continual improvement in downhole cable connections and protection of the system.

Both experts and end users provide input during the development phase, as engineers perform simulations and build mock-ups. Conducted frequently, design reviews include field personnel. Design rules have been prepared to address the need for low stress on components, minimal external connections and other concerns.

Once the system is built and is ready for installation, a specially trained crew reviews detailed installation procedures and project plans with operations personnel and third-party vendors. Performance of the field installation crew plays an important role in system reliability, so formal training programs for both system design engineers and field installation technicians are conducted. Whenever possible, system design engineers attempt to simplify installation requirements because factors such as frigid temperatures, gusty winds and long hours may present additional challenges to the crew. A design that allows fast, easy installation relieves some of the burden on the field crew and minimizes risk and rig time.


8. We thank Philip Hall for information about the "bumping test" machine. Mr. Hall retired from Schlumberger after 22 years of service, both in the oilfield and in electronics. He is Chief Executive of The Sir Henry Royce Memorial Foundation, The Hunt House, Paulerspury, Northamptonshire, NN12 7NA, England.

Torturing tools. By exposing an automobile chassis to repeated mechanical shocks (top), Sir Henry Royce observed which parts were prone to failure and built better ones for Roll-Royce, beginning around the turn of the last century. Today, highly specialized testing machines and accelerated test techniques developed by Schlumberger verify the endurance of downhole equipment against mechanical shocks (bottom).
Learning from Experience
If a permanent downhole gauge fails, engineers analyze the circumstances and sometimes attempt to reproduce the failure modes in the engineering center or other testing facility. Failure mechanisms are not random; in most cases there are underlying causes at work that must be uncovered, such as design problems, faulty materials or improper installation. Schlumberger has established an on-line database to capture data about system installations, including details about environmental conditions, to identify any patterns in failures (right). The database allows statistical analysis of the data by region, operator, environmental conditions and other operational parameters. Careful analysis of the worldwide database increases confidence that the appropriate lessons are learned from field experiences and helps focus efforts on possible areas of improvement.

From August 1, 1987, to the present, the performance of 712 permanent gauge installations has been tracked. The oldest system is more than 16 years old, having been installed a few years before the database was established. Analysis of 572 new-generation digital technology installations made since their introduction in March 1994 indicates that over 90% of these PressureWatch Quartz and Sapphire systems were still operating after 2.5 years (below). The analysis, based on methods introduced by

From the graph, it is evident that since record-keeping began in 1987, Schlumberger has installed more than 700 permanent gauges worldwide.

Analysis of 572 new-generation digital technology installations made since March 1994, shown by the purple line, indicates that over 88% of these PressureWatch Quartz and Sapphire systems were still operating after 4 years. The lavender trend line begins at 97% and decreases by 3% per year, a higher failure rate than that of the actual data. The photograph shows the production facilities of the Baldpate field, operated by Amerada Hess.
Møltoft, helps reveal the key factors influencing the reliability of permanent monitoring systems (above right). The Møltoft method addresses a system’s actual operational time rather than its calendar time, a key advantage when studying field installations over a long time period. The method helps pinpoint areas for improvement in system design and deployment.

Operating companies have independently studied the reliability of permanent gauges. Different manufacturers and operators measure performance according to their own standards. Schlumberger has chosen to focus on the whole system rather than a single component because it is vital that the entire system operate properly and provide usable data.

### Downhole to Desktop: Using the Data

After the equipment has survived the ordeal of testing and installation, the real challenge begins once a permanent monitoring system is placed securely in a well. A system that takes a measurement every second of the day produces over 31 million data points per year. Coping with the volume of data from permanent monitoring systems is an issue that operators and service companies continue to address. Some operators have chosen to sample their data at specific times or when the change in a measurement exceeds a predetermined threshold. Others sample their data at greater time intervals, such as 30 seconds, to reduce data volume.

Once reaching the end user, the data are applied to two general production issues: reservoir drainage and well delivery (right). Reservoir-drainage aspects include pressure monitoring, pressure maintenance, material-balance models and simulation models. Well-delivery issues, such as skin and permeability, affect production engineering.

When a well is shut in for maintenance, a pressure gauge offers the small-scale equivalent of a pressure buildup test. Subsequent well shut-ins allow engineers to analyze the repeatability of accumulated failures.

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
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<tbody>
<tr>
<td>Pressure monitoring</td>
<td>Static bottomline pressure survey</td>
</tr>
<tr>
<td>Pressure maintenance</td>
<td>Future development plans (reservoir repressurization: install injection facilities?)</td>
</tr>
<tr>
<td>Well test interpretation and analysis (buildup, drawdown, multirate and interference well testing)</td>
<td>Reservoir boundaries, well spacing requirements, interwell pressure communication</td>
</tr>
<tr>
<td>Water and gas injection monitoring</td>
<td>Evaluate degree of pressure support from injector wells; Appraise performance of injection program</td>
</tr>
<tr>
<td>Reservoir simulation model refinement and validation</td>
<td>Historical database for pressure history matching; Calibration tool for simulation model</td>
</tr>
<tr>
<td>Complement or corroborate other reservoir monitoring measurements</td>
<td>Corroboration of information provided by innovations such as 4D seismic surveys, time-lapse well logging</td>
</tr>
<tr>
<td>Material balance model updating</td>
<td>Input data for continuous update and refinement of material balance model</td>
</tr>
</tbody>
</table>

## Reservoir drainage

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well test interpretation and analysis (buildup, drawdown, multirate and interference well testing)</td>
<td>Skin, permeability and average reservoir pressure</td>
</tr>
<tr>
<td>Production engineering</td>
<td>Input for NODAL analysis; Productivity Index (PI) and long-term variation in PI measurement; generation of water, gas and sand production rate correlation as a function of pressure</td>
</tr>
<tr>
<td>Flowing bottomhole pressure survey to determine maximum offtake — Flow well at optimal pressure above bubblepoint pressure to avoid liberation of free gas</td>
<td></td>
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<tr>
<td>Real-time fracturing and stimulation operation monitoring</td>
<td></td>
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<tr>
<td>Appraisal of injection and production profile along the well</td>
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</table>

*Typical applications of permanent downhole gauge data. Data from downhole gauges can be used to improve both reservoir drainage and well delivery.*
of the tests and improve confidence in selecting a reservoir model. If all the wells in a field are shut in, downhole gauges can measure the average reservoir pressure. The average reservoir pressure measured this way is a key component of decline rate and reserve estimations and a parameter for reservoir simulations.11

In fluid-injection projects, permanent downhole pressure gauges can be used to better maintain pressure, displace oil, arrest subsidence and dispose of fluids. By monitoring a continuous stream of pressure data, operators can control reservoir performance by injecting fluids to keep reservoir pressure above bubblepoint pressure to ensure production of oil rather than gas. Permanent gauges can also help determine the optimal production rate when there are concerns about sand production or water coning at high flow rates.

Downhole pressure gauges allow engineers to allocate production to specific wells. Knowing the downhole pressure, the wellhead pressure and the general properties of the produced fluids allows calculation of the flow rate for a well and calibration of flow rates with test data. Offshore satellite fields tied back to platforms and fields owned by multiple partners are good candidates for this particular application of downhole pressure gauges.

In artificial-lift applications, downhole pressure gauges help engineers determine how well the artificial-lift system is performing. For example, a prolific, highly permeable, unconsolidated oil reservoir might have high deliverability, but the bottomhole pressure of the well might be inadequate to produce the fluid to surface. If an electric submersible pump or gas-lift system is installed in the well, the operator can add a downhole gauge to assess the performance of the lift system.

Gauges in Action

The permanent monitoring applications that follow come from widely separated regions with different operational challenges and operator priorities. In each case, the operator might measure the value of permanent monitoring systems in a variety of ways, such as additional barrels of oil recovered through more efficient reservoir drainage or delivery from individual wells, or in cost savings through decreased well interventions. Appraisal of a deep, sour, high-pressure, high-temperature (HPHT) discovery in the Middle East presented numerous operational and interpretation challenges. Unlike the prolific shallow oil fields nearby, the discovery well produced anomalously high API gravity oil for the region from a fractured carbonate reservoir with limited microporosity. A thick salt layer above the reservoir complicated interpretation and operations. Nevertheless, the accumulation presented fascinating opportunities to evaluate fracture fairways below structural spillpoints and hydrocarbon self-sourcing in a kerogen-rich reservoir rock.

Data from the initial discovery well were inadequate to calibrate reservoir simulations or to plan development. A deep appraisal well, drilled over the course of a year with mud weights exceeding 20 pounds per gallon [2.4 g/cm³], provided core, mud log and wireline log data. An extended well test generated enough data for engineers to decide how to proceed.

The extremely high formation pressures and use of kill-weight mud in wellbores meant that wireline-conveyed pressure measurements were not possible. Instead, the operator selected a FloWatcher system to measure pressure, temperature and flow rate continuously. This installation was the first use of the FloWatcher system at a pressure of 15,000 psi [103.4 Mpa], so advance preparations were necessary. The wellhead, which had already been procured, was modified to allow an exit for the cable. A shed was built to accommodate surface monitoring equipment.

The permanent monitoring system was safely installed and an extended well test was conducted for four months, with oil flowing through a 70-km [43.5-mile] flowline. The FloWatcher system was selected in part because pressure measurements at the Venturi inlet and throat allowed determination of the absolute pressure, the pressure change across the Venturi and the flow rate. Despite a repairable seal failure in the Venturi, it was still possible to obtain pressure measurements from the pressure gauge, which functioned as expected throughout the test. Also, the mandrel design for the system was relatively inexpensive.

The permanent monitoring system enabled engineers to produce at the maximum rate while maintaining pressure above the bubblepoint, and to gather the data they needed to formulate development plans. Given the operational challenges of this particular well and area, the remote location and the importance of gaining useful data, an extended well test with a permanent downhole monitoring system proved to be the optimal approach.

Permanent downhole monitoring systems have been used in the Gulf of Mexico for several years. Shell Offshore, Inc., has installed permanent gauges in each of the 10 wells it operates in the Enchilada area in the continental Gulf of Mexico (above). The Enchilada area comprises thin-bedded turbidite reservoir sands located both...
above and below salt. The first gauge was installed in September 1997, and to date all of the gauges continue to operate without failure.

Permanent downhole pressure gauges fulfill two major requirements for Shell Offshore: daily operations improvements and better long-term reservoir management. In both cases, pressure data must be accessible to reservoir specialists in a format they can use efficiently. The system installed by Schlumberger stores the data for subsequent pressure transient analysis. Shell Offshore retrieves the data from the system and uses its own computer-assisted operations (CAO) system to manage the data stream on a long-term basis.

Shell’s CAO acquisition unit captures surface and downhole pressure measurements at approximately 30-second intervals for trend analysis and long-term archiving of pressure data. In the past, most decisions about daily operations were made on the basis of surface pressure or tubing pressure measurements with infrequent downhole wireline pressure measurements. A decline in surface pressure could indicate reservoir depletion or a downhole obstruction, but this ambiguity could not be resolved with surface data alone. Now, with both surface and downhole pressure measurements, it is possible to quickly diagnose production problems. For example, if both surface and bottomhole pressure curves track each other on a declining trend, then the probable cause is reservoir depletion. On the other hand, if the surface pressure is dropping but the downhole pressure remains constant or increases, then the engineer might suspect that salt, scale or paraffin is plugging the tubing (right). Therefore, engineers for the Enchilada area use surface and downhole measurements to diagnose production problems and optimize remediation treatments.

Permanent downhole pressure gauges are especially important for effective reservoir management in the Enchilada area and areas like it. Thin-bedded reservoirs, such as turbidite sands, can be difficult to evaluate by wireline methods. Producers want to determine if the reservoir is continuous. During the initial development, few appraisal wells had been drilled and the subsalt location of several prospects made it difficult to define the reservoir geometry and extent. Gathering early reservoir pressure data from each well aided development planning. In addition, the long-reach, S-shaped wells in the Enchilada area are expensive to drill and not easily accessed by wireline methods. Furthermore, the mechanical risk of running wireline pressure devices into these high-rate wells is unacceptable. Therefore, the permanent gauge system allows frequent reservoir pressure monitoring without mechanical risk and with minimum deferred production. Frequent pressure measurements help optimize production rates, and enhance understanding of ultimate reserve potential.

The Enchilada area example affirms that data from permanent gauges are valuable throughout the life of the well. Run time is a major concern for Shell Offshore because the Enchilada wells are expected to produce for at least 10 years. The reliability and durability of these permanent gauges have a direct impact on the asset’s value. The successful application of permanent monitoring technology convinced Shell to install gauges in two wells on their deepwater Ram-Powell platform, offshore Gulf of Mexico. The second of these installations, a PQG Permanent Quartz Gauge system set at a depth of 23,723 feet [7230 m], is the deepest installation by Schlumberger to date.

> Diagnosing production problems. Plots of both bottomhole, $P_{\text{bhp}}$ and surface pressure, $P_{\text{surface}}$, versus time help engineers diagnose production problems. In the top example, surface and bottomhole pressures are declining, but the curves track each other, suggesting reservoir depletion. In the bottom plot, the surface pressure diverges and drops at a faster rate than the bottomhole pressure. One possible conclusion is that scale is plugging the production tubing.
Complicated deepwater developments, such as the Baldpate field in Block 260 of the Garden Banks area of the Gulf of Mexico, challenge operating companies (above). The first downhole gauge in the Baldpate field was installed in August 1998. Seven of eight wells have downhole gauges. The field is expected to produce for 6 to 10 years.

Baldpate field comprises two major Pliocene reservoirs at depths of 15,500 to 17,500 feet [4724 to 5286 m]. Original reservoir pressures exceeded 13,000 psi [89.63 MPa]. Production from the sands in the Baldpate North area is commingled in a seventh well. The field reached peak production of 58,000 BOPD [9216 m³/d] and 230 MMscf/D [6.5 MMm³/d] by June 1999.

Installation of permanent downhole gauges is particularly demanding at the well depths and pressures of Baldpate field. Success depends on a thoroughly trained, competent wellsite crew. For example, the crew must avoid potential pitfalls such as damaging the cable and making bad splices. Extensive prejob planning allows the entire team to anticipate problems and work out solutions before installation. Having many of the same crew work on every installation builds experience and carries lessons learned from one job to the next.

Amerada Hess Corporation, operator of Baldpate field, elected to install permanent downhole pressure gauges for both mechanical and reservoir management purposes. Expensive gravel-pack completions and tubing in high-rate wells are prone to damage if there is excessive drawdown or if the erosional velocity is too high. The as flow rates were ramped up during the initial stages of production, pressure data helped avoid damage by ensuring that predetermined limits on drawdown and erosional velocity would not be exceeded. By measuring the pressure drop across the completion, engineers calculated the mechanical efficiency, or mechanical skin, of the completion.

Acquiring a constant stream of pressure data enables reservoir engineers to fine-tune compositional models for reservoir simulation, perform history matching of pressure depletion of the reservoirs over time, test secondary recovery scenarios and predict ultimate recovery. The pressure data are also used for frequent pressure-transient analysis. This analysis provides calculations of effective permeability, mechanical skin, non-darcy flow effects, average reservoir pressure and approximate distance to various reservoir boundaries.

Interference tests can be performed because there are permanent downhole pressure gauges in all the wells. Each well responds to rate adjustments in offset wells within hours. The pressure responses can be used to assess reservoir continuity. Data from pressure gauges confirmed the geologic model of laterally continuous basin floor fan sands.

Of seven gauges installed in the Baldpate field, six are working. The lone failure—the only failed gauge out of 43 gauges installed by Schlumberger in North America—appears to have resulted from a problem within the gauge itself, although it has not been recovered for postmortem analysis. The installation of gauges in all the wells meant that the loss of one gauge was an inconvenience rather than a major difficulty. It was not worth retrieving or repairing the failed gauge because of the cost and mechanical risks of pulling tubing. Data from the gauges in the other wells are sufficient for ongoing reservoir management.

Amerada Hess carefully manages the high volume of data from permanent downhole pressure gauges. The data are stored in the hard drive of a personal computer on the production tower. From the office, an engineer can control sampling rate and electronically retrieve data from the remote production tower and move them to the office. Eventually, however, Amerada Hess expects to move and store the complete data volume elsewhere. Data can be downloaded into a pressure-transient software package and analyzed within minutes.


14. Erosional velocity is the velocity at which an impinging fluid degrades a metal at the molecular level. In this case, the operator was concerned about the possibility of high-flow rate wells producing sand from the unconsolidated reservoir and damaging the production tubing.

An example from Africa demonstrates other applications of downhole gauges. Since 1992, Mobil Producing Nigeria Unlimited has installed permanent downhole pressure gauges in 12 of its fields offshore Nigeria: Usari, Oso, Mfem, Ubit, Iyak, Enang, Asasa, Ekpe, Asabo, Unam, Edop and Etim (above).\textsuperscript{16}

Mobil has used continuous pressure measurements from downhole gauges in many ways. The most basic applications include determining the reservoir drive mechanism, assessing depletion patterns and reservoir discontinuities, and planning pressure maintenance programs. Permanent downhole gauges measure downhole pressure in wells whose high wellhead pressure precludes use of wireline pressure measurement techniques. Mobil can avoid the costs of shutting in wells with high flow rates solely for gathering data. In fields with many wells, data from strategically placed pressure gauges allow reservoir engineers to calibrate pressure measurements gathered by wireline methods with those from permanent gauges.

In the Edop field, 7 of approximately 40 wells have downhole pressure gauges. Mobil expected to inject gas to maintain reservoir pressure, so the initial plan was to place a downhole pressure gauge in a well in each of four fault blocks in the Edop field and assess the connectivity of the reservoir across fault blocks. Results from the gauges showed no communication across the fault blocks, and that separate injectors would be required for each fault block. The downhole pressure gauges also indicated that the planned injection patterns needed to be changed, so the downhole pressure gauge data were then integrated with the 3D geological model to modify and optimize producer and injector locations.

\textsuperscript{16} Ogunlowo RF, Ewherido UJ and Oyewole AA: "Use of Down-hole Permanent Gauges in Reservoir Description and Management of a Gas Injection Project in Edop Field, Offshore, Nigeria," prepared for the 23rd Annual International Conference and Exhibition, Abuja, Nigeria, August 4-6, 1999.

\textsuperscript{17} Algeroy et al, reference 1.


Pressure data provided by downhole gauges were critical in determining communication efficiency around shale baffles that had escaped detection by seismic and well logging methods. Also, the continuous data provided by the gauges led to better reservoir simulation results than single data points from wireline measurement methods. As the injection project proceeded, instantaneous pressure responses within the continuous stream of data enabled engineers to determine how much compressor downtime their injection project could accommodate (right).

In other fields operated by Mobil offshore Nigeria, 20 to 25% of the wells have downhole pressure gauges. Approximately 95% of the gauges provided by Schlumberger are still operating. The rare instances of failure have been attributed to problems in control lines, bad cable splices, failure at the wet connector or problems with the Christmas tree rather than problems with the gauges themselves. However, these are still considered failures of the system. Improvement beyond the current 95% success rate is expected.

Outlook for Reservoir Monitoring
Permanent reservoir monitoring is vital to intelligent completions, a modern approach to improving reserve recovery.17 Efficient, beneficial operation of downhole flow-control valves depends on understanding reservoir dynamics, so the combination of acquiring downhole data and using flow-control valves is essential. At present, knowledge of the reservoir comes from analyzing pressure and production data and, in some cases, data from downhole flowmeters. Ongoing research and development of flowmeters are expected to provide accurate measurement of flow rates as well as multiphase fluid properties. In addition, researchers are addressing the challenges of accurately measuring flow rates in directional and horizontal wells.

Improved links between data acquisition systems and operators will facilitate real-time data transmission and display. Permanent monitoring allows engineers to get a sense of the reservoir, but to "see" the reservoir requires that the data be transformed into a usable format. If data access or display is too cumbersome, downhole pressure gauge data are in danger of being ignored.

The costs and economic benefits of permanent monitoring must be considered together. Success stories from around the world, such as those presented in this article, should serve to bolster confidence in permanent downhole pressure gauges. As confidence in the dependability of permanent gauges and other systems continues to grow, the value of the data will overcome short-term concerns about cost in many cases.

Today, operators are venturing into remote areas and water depths approaching 10,000 ft (3048 m) and are completing wells subsea with the expectation of limited or no interventions.18 Optimal production in these areas will necessitate permanent monitoring systems that are compatible with other completion equipment. As with permanent downhole pressure gauges and flow-control valves, dependability of downhole flowmeters and other permanent equipment in wells will remain the key criterion for choosing to deploy these devices in expensive, inaccessible wells.

The successful application of rigorous product development and testing processes with concurrent reliability engineering and field service quality control has set the standard for dependable permanent monitoring systems. This reflects a long-term commitment of people and resources. Employing these engineering processes enhances future permanent monitoring systems. For operators, these enhancements translate into early diagnosis of problems, fewer well interventions, reduced risk and greater reserve recovery. —GMG