Focusing on Downhole Fluid Sampling and Analysis

A new focused-sampling device allows acquisition of downhole fluid samples of unprecedented purity, and in a fraction of the time needed with conventional sampling technology. The method also gives superior results for downhole measurements of formation-fluid properties.

Understanding the properties of fluids contained in a hydrocarbon reservoir requires measurements on fluid samples. Sample analysis helps identify fluid type, estimate reserves, assess hydrocarbon value and determine fluid properties, so production can be optimized.

Using fluid-analysis results, oil companies decide how to complete a well, develop a field, design surface facilities, tie back satellite fields and commingle production between wells.

Fluid analysis is also important for understanding the properties of formation water, which can have significant economic impact. Often, the most crucial goals are to identify the corrosive properties of the water for the purpose of selecting completion materials and to measure scaling potential for avoiding flow-assurance problems. In addition, log analysts want to quantify the salinity of the water for petrophysical evaluation, and geologists and reservoir engineers want to establish the water source for evaluation of reservoir connectivity.

Formation-fluid samples can be acquired using one of three main techniques. First, wireline formation testers deployed in open hole can acquire fluid samples and also perform downhole analysis of fluids, ensuring optimal sample acquisition and the possibility of analyzing fluids early in the life of the well. These testers provide a cost-effective method of acquiring early fluid samples, with performance now often equal to or above that achievable with the second method, drillstem tests (DSTs). In the past, DSTs, typically designed to test production and investigate reservoir extent, have produced samples with less contamination than openhole sampling. DSTs require early planning and a well completion that can withstand production pressures, and can cost much more than openhole sampling, especially in offshore wells. In a third method, samples can be acquired by wireline tools deployed in a cased, producing well.

An important aspect of fluid sampling is analysis of the fluids at reservoir conditions. This helps validate sample quality during the sampling process, but also enables the mapping of vertical variations in fluid properties, allowing interpreters to determine zonal connectivity and define reservoir architecture early in field life. Uncontaminated fluid samples allow accurate measurement of fluid properties both downhole and at the surface.

After samples are acquired, they typically are analyzed in laboratories, where they undergo a series of tests depending on what the client needs to understand. Standard analyses for hydrocarbon samples include chemical composition to C30+, gas/oil ratio (GOR), density, viscosity, and phase properties such as saturation pressure, bubblepoint, pour point and stability of asphaltenes. Several measurements can now be performed downhole, using optical spectroscopy to characterize formation fluids under reservoir conditions. These include density, optical density, GOR and chemical composition to C6+.

Laboratory and downhole fluid measurements both require pure, uncontaminated samples. Contamination occurs when miscible drilling-fluid filtrate that has invaded the formation mixes with the formation fluid being sampled. For instance, hydrocarbon samples are contaminated by oil-base mud (OBM) filtrate, and water samples are contaminated by water-base mud (WBM) filtrate.

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To reduce contamination during sample collection, engineers rely mostly on increasing the volume of fluid pumped from the reservoir by pumping longer or at a higher rate. Downhole analysis of contamination level can determine when fluid flowing through the sampling-tool flowline is clean enough to be collected. However, long pumping time increases rig time and associated costs, and may increase the risk of downhole tool sticking. Depending on the reservoir permeability, high pumping rates can cause the reservoir fluid to drop below saturation pressure. If this happens, the downhole samples will not be representative of the reservoir fluid. In the case of unconsolidated formations, high pumping rate may induce sand production. Also, in settings involving high vertical permeability, even long pumping times and increased pumping rates do not guarantee clean samples.

Fluid-analysis experts have worked to understand and mitigate the effects of contamination on samples. Some methods attempt to derive the composition or GOR of a pure sample knowing the composition of the OBM contaminating the collected sample. However, uncertainties and errors accompany fluid properties estimated in this manner. Researchers have quantified the errors caused by contamination on some measurements. For example, the pressure at which asphaltenes precipitate from solution in crude oil decreases in the presence of OBM contamination. In one case, just 1% OBM contamination by weight caused asphaltene-
Thus, measurements on contaminated samples underestimate asphaltene-precipitation onset pressure, and may negatively affect flow-assurance and production predictions. These results emphasize the need for extremely low-contamination samples.

A new sampling apparatus designed to reduce filtrate contamination focuses fluid intake so that reservoir fluid flows into one sampling line while filtrate flows into a separate line. With this innovative tool, mud-filtrate contamination can be separated efficiently from formation fluid in the early stage of the sampling process. A clean reservoir-fluid sample can be acquired much faster than with conventional sampling techniques. This article describes the advantages of the new, focused-sampling tool through field examples of hydrocarbon and water sampling from the Gulf of Mexico, the North Sea, India and the Middle East.

Quicker and Cleaner

To fully appreciate the advantages of the new sampling method requires a brief overview of conventional downhole fluid-sampling technology. In the typical scenario, overbalanced drilling into a permeable formation will facilitate invasion of drilling-fluid filtrate into the formation and the creation of filtercake on the borehole wall. During conventional formation-fluid sampling, a wireline formation tester deploys a packer against the borehole wall to isolate the sample probe from borehole fluids and hydrostatic pressure. The probe is then pressed through the mudcake and against the formation. Formation fluid is blue-gray and filtrate is light brown. The probe has a single intake port. When pumping begins, fluid is highly contaminated (graph inset), but decreases gradually with time. However, even with long pumping times, the contamination level may not reach an acceptable limit in some formations.

extended periods of time—many hours—which can be expensive in terms of rig time and increased exposure to sticking in open hole.

Seeking ways to improve sample quality and reduce sampling time, researchers investigated the effects of different probe configurations. To test the idea that focused flow into a probe could reduce sample contamination and shorten sampling time, a scientist at Schlumberger Cambridge Research in England simulated flow into modified probes. The modeling results helped determine optimal probe size. Researchers at Schlumberger-Doll Research in Connecticut, USA, conducted 2D experiments on laboratory models to determine the potential benefits in sample cleanup (above). The modified probes had three openings: side openings, called guard probes, drew contaminated fluid away from the central area of the probe, and a central opening, called a sample probe, collected low-contamination fluid. Experimental results indicated that cleanup with the guard probes active proceeded much more quickly than without, achieving lower contamination levels with less fluid volume pumped (right).

▲ Setup and visual results of laboratory experiments simulating focused flow. The experimental setup (top right) consisted of a 2D formation made of glass beads, surrounded by a single oil with an optical index identical to that of the glass beads, all held between two vertical glass plates. A bottom portion of oil was dyed red to represent the filtrate-invaded zone. Above this, the oil was left transparent. A sample and guard-probe assembly at the bottom of the formation extracted fluid (inset). A camera monitored the cleanup in the formation directly in front of the probe assembly. After image processing, the time-lapse visual images (left) show large differences in the area cleaned up by the sample probe alone (left) and the sample and guard probes together (right). The sample and guard probes clean up a large area in front of the sample probe, ensuring that only uncontaminated fluid enters the sample probe.

▲ Contamination reduction with and without guard probes. Laboratory measurements detected decreasing contamination levels with increasing volume of fluid pumped, corresponding to increasing pump time. Sampling without the guard probe (blue) never achieved contamination levels less than 1%.
Formation and filtrate fluid (supply side)

Sampling and conductivity (measurement side)

Engineering experimental setup to investigate the feasibility of focused sampling. A formation interface tester, containing a 15.5-in. diameter, 12-in. tall sandstone core, is in contact with two fluid manifolds and a laboratory-prototype focused-sampling probe. Simulated formation fluid is supplied at the base of the core, and simulated filtrate is supplied in a ring around the core. Flow into and from the tester is controlled and monitored by pumps and valves, and contamination level is calculated from electrical conductivity measurements on the flowlines. (Adapted from Dong et al, reference 8.)

Focused-sampling experimental data. The decrease in contamination inferred from electrical conductivity measurements on the guard and sample flowlines demonstrates fluid cleanup in this sampling test. The contamination level in the sample flowline (green) decreased rapidly, while the contamination level in the guard flowline (red) decreased gradually. Summing the flow from both flowlines produces the total flow (blue), the flow that a traditional probe would have measured. (Adapted from Dong et al, reference 8.)

Further engineering tests at Sugar Land Technology Center in Texas extended the 2D results in simulated formations to three dimensions and actual rock formations. In these experiments, a downhole probe prototype of a new focused-sampling tool drew fluids from a large sandstone core in a test apparatus (left). The 15.5-in. diameter, 12-in. tall core contained aqueous sodium chloride [NaCl] formation fluid and mud-filtrate fluid of different known conductivities. Fluid flow to the guard and sample flowlines was controlled and measured with metering valves and high-pressure flowmeters. Calibrated electrical conductivity meters on the flowlines leading from the guard probe and the sample probe recorded the cleanup history of each sampling test. With focused sampling, the contamination levels of the fluid in the sample flowline decreased rapidly, while the contamination level in the guard flowline decreased gradually (below left). A traditional probe would have measured the combined flow, and would not have achieved contamination less than 10%.

The key to acquiring such low-contamination samples is the focusing effect achieved by the multi-intake probe. This innovative design has been implemented in the Quicksilver Probe wireline sampling tool, a new module of the MDT Modular Formation Dynamics Tester tool. In some ways, the configuration of the Quicksilver Probe module is similar to that of traditional samplers, in that a packer seal isolates the fluid-sampling zone from the borehole. However, within the fluid-sampling zone, a cylindrical guard probe on the periphery of the sampling zone surrounds the innermost sampling area (next page, left). An additional packer seal separates the guard intake from the sample intake. The inner and peripheral areas are connected to separate flowlines, called the sample and guard flowlines, respectively. Two pumps in the tool, one above the probe and one below, can draw fluid into the two flowlines at different rates, and spectroscopic analyzers determine the composition of fluid in each flowline (next page, right). The focusing effect of the method is somewhat analogous to the way laterolog devices use guard electrodes to focus current into a formation to measure resistivity.

The Quicksilver Probe focused-sampling tool pumps fluid from the formation through the central and peripheral areas of the sampling zone simultaneously. Initially, commingled contaminated fluid flows into both areas, but this...
Fluid is not collected. Fluid flow is then separated, or split, between the guard and sample flowlines. Fluid flow into the guard intake can be increased, and in a short time, all contaminated fluid is drawn into the guard flowline, allowing low-contamination formation fluid to flow into the sample flowline. This technique accentuates the difference in contamination level between clean and contaminated fluid, making it easier to identify a time at which a clean sample can be collected. Case studies from several environments show the sample quality that can be obtained using the new focusing technology.

Exploring in the Gulf of Mexico

In 2004, Chevron drilled an exploration well into the emerging Lower Tertiary play in the deepwater Gulf of Mexico. These wells are typically difficult to drill and complete, with water depths down to 10,000 ft [3,000 m] and total well depths exceeding 25,000 ft [7,600 m]. More than 20 exploration and appraisal wells have been drilled so far in this play, and more than half were discoveries, many with thick oil columns. However, in such conditions, well tests usually are extremely expensive, typically costing US$ 70 million or more. For this reason DSTs are rarely performed in this region.

Drilling in this play in Walker Ridge Block 759, Chevron and partners announced discovery of more than 350 ft [110 m] of net-pay oil sands in Jack 1, the first well of the Jack prospect, in September 2004. The subsalt prospect is...


The Quicksilver Probe toolstring. Fluids enter the tool at the focused-sampling probe. Contaminated fluids flow downward through the guard fluid analyzer and pump. Clean fluids flow upward through the sample fluid-analyzer and pump modules to the sample-bottle module. The configuration may change for different sampling jobs. For example, the pumps may be located upstream of the fluid analyzers for some applications. (Adapted from Del Campo et al, reference 9.)
approximately 270 miles [430 km] southwest of New Orleans and 175 miles [280 km] offshore (right).

To further evaluate the prospect, Chevron drilled a second well, Jack 2, in Walker Ridge Block 758 to a total depth of 28,175 feet [8,588 m]. Departing from typical procedures, Chevron planned a well test, which would make Jack 2 the only Lower Tertiary well ever tested in the Gulf of Mexico. Acquiring a pure sample of the formation fluid prior to the production test would aid significantly in reducing the fluid uncertainties in the test design and therefore enhance the value of this expensive endeavor.

A unique MDT sampling toolstring configuration allowed collection of traditionally acquired fluid samples at two stations with an extralarge-diameter (XLD) probe, and focused samples at two stations with the Quicksilver Probe module. Real-time analysis of flowline fluid acquired at one station with the XLD probe shows GOR increasing but not leveling off, even after 8 hours of pumping (below left). Nevertheless, samples were collected at 30,000 seconds.

Cleanup plot of flowline fluid acquired with a single extralarge-diameter probe in the Chevron Jack 2 well. The volume of fluid pumped during sampling is shown in the top track. Real-time analysis of optical density measured with the LFA Live Fluid Analyzer tool leads to quantification of the volume fraction of C6+ components, essentially liquid hydrocarbons (second track), and gas/oil ratio (GOR) (third track) as flowline fluid becomes cleaner. GOR (blue) continues to increase, indicating cleaner sampling, but does not level off, even after 8 hours of pumping. Laboratory analysis of samples collected at 30,000 seconds showed the contamination level to be greater than 10%. A data-quality flag track (bottom track) is green when data quality is high, and brown when data quality is lower.

Pumpout volume, volume fraction and GOR plots for sample-line (left) and guard-line (right) fluids obtained with Quicksilver Probe focused sampling. As seen in the pumpout-volume track (top), only the guard-line pump (red) operates from 0 to 7,340 s. Then, the sample-line pump (brown) is activated and pumps until 11,500 s, at which time both pumps operate synchronously but at different rates. Cleanup can be seen by the increase in GOR (blue) in the guard flowline from 0 to 7,340 seconds, while the sample line is idle. Then, the guard pump stops and the sample-line pump starts. The GOR seen by the sample-line LFA module increases gradually at first, and then, when flow is split at 11,500 s, the sample-line GOR increases dramatically and reaches a plateau, indicating that the fluid is clean. The sample acquired at 14,000 s had a contamination level that was too small to measure.

The Lower Tertiary play in deepwater Gulf of Mexico, where Chevron discovered the Jack field in 2004. Other wells in the Lower Tertiary play are shown as dots.
Laboratory analysis later showed that these samples had more than 10% OBM contamination.

Samples acquired with the Quicksilver Probe module were less than 1% contaminated after 4 hours of pumping. Pumpout volume and GOR plots from the guard and sample flowlines show the stages of fluid cleanup (previous page, bottom right). From 0 to 7,340 seconds, the lower pump initiated fluid movement into the borehole by pulling commingled fluids through the guard flowline. Pumping early fluids through the guard-line pump helps optimize sample acquisition. Fluids that flow early are most likely to contain mud solids that might potentially plug the pump. If plugging is going to occur, field engineers prefer the guard pump to plug instead of the sample pump. Although flow will not be focused if pumped with a single pump, samples can still be taken if the sample pump is functioning. Samples cannot be collected with only the guard pump operating.

In this example, the guard pump stopped at 7,340 seconds and the sample-line pump started. The GOR seen by the sample-line LFA Live Fluid Analyzer module started to build. The GOR seen by the guard-line LFA tool is ignored, since no fluid is flowing through it.

At about 11,500 seconds, the flow splits. The sample-line GOR increases rapidly, indicating fast cleanup as the contaminated filtrate is directed away from the sample probe. Additionally, the GOR flattens immediately, indicating that the fluid is as clean as it can be. The GOR on the guard line is still increasing; its fluid is still cleaning up. The sample acquired at 14,000 seconds was later analyzed in the laboratory and found to have a contamination level that was too small to measure.

Use of the Quicksilver Probe device allowed high-quality fluid samples to be compared with those of the discovery well, and provided improved viscosity estimation compared with samples obtained from more conventional tool configurations. The lower contamination samples also improved the DST design by quantifying GOR for separator and surface-facilities requirements, predicting PVT behavior and enhancing reservoir characterization.

The Jack 2 production test, completed in September 2006, was the deepest successful well test in the Gulf of Mexico. During the test, the well sustained a flow rate of more than 6,000 bbl/d [950 m³/d] of crude oil from about 40% of the well’s net pay. Chevron and partners Statoil ASA and Devon Energy Corporation plan to drill an additional appraisal well in 2007.

**Sampling at High Pressures and Temperatures**

High-pressure and high-temperature (HPHT) conditions present a challenging environment for all aspects of drilling, logging, completing and producing a well. HPHT wells are often deep and require the use of the most capable rigs, which can be costly. Wireline logging generally requires multiple runs to obtain the necessary information, and often encounters tool sticking, so expensive and lengthy fishing operations are potential risks. Pipe-conveyed logging is often not the best option because it subjects tools to longer exposure to high temperature.

Traditional wireline logging with standard cables may not provide enough pull to deploy long toolstrings in deep wells, and may lack the extra pull necessary to get a tool out if sticking occurs. A recently developed deployment method using a high-tension cable and a high-tension reduction unit, or capstan, can be effective in these cases (above). This allows for the rapid deployment of the logging string and much higher overpull, which reduces the risk of tool sticking.

Proven technologies to overcome difficulties in Sea, ConocoPhillips (UK) Ltd applied new and improved samplers in North Sea wells. High temperature is a primary challenge to fluid sampling, as it can yield unsatisfactory results. The use of high-strength cable and high-strength tooling can optimize results while mitigating risks associated with tool failure.

PVT Express fluid-analysis experts identified 600 to 900 ppm of hydrogen sulfide (H2S) in the shallower sand layer, which would be incompatible with the completion design. These levels of H2S in the first sandstone led the ConocoPhillips (UK) Ltd subsurface team to upgrade their equipment. The onshore laboratory analysis of samples collected from the four shallow sand layers showed contamination in later laboratory analysis. The fluid samples collected here showed 1% contamination in later laboratory analysis.

In this near-field exploration well, ConocoPhillips (UK) Ltd planned to log the well and acquire pressures to determine mud weights for drilling deeper and to characterize the formation fluid. Sampling would not be required in the primary reservoir, but the fluids in the nearby productive fault blocks were known. Bottomhole temperatures were expected to reach 365°F (185°C) and formation pressures could exceed 14,000 psi (97 MPa). SlimXtreme slimhole HPHT logging tools, including the analog borehole seismic tool, were run on high-strength tubing. The high-strength tubing could withstand the high temperatures.

The focus was on collecting samples from the first sand and the shallowest sand layer, which would have been H2S prone. Fluid samples were collected from the four shallow sand layers. In all, 27 fluid samples were collected. The fluid samples collected here showed 1% contamination in later laboratory analysis. Normal levels of H2S were found here and in the remaining layers. In all, 27 fluid samples were acquired with good-quality results in every layer.

In one HPHT example from the central North Sea, ConocoPhillips (UK) Ltd applied new and proven technologies to overcome difficulties in this hostile environment. Experience has shown that in addition to high temperatures and pressures, wells in the area are prone to sticky hole conditions; the effects of depth, filtercake properties, hydrostatic overbalance and wellbore tortuosity combined to hinder wireline-conveyed reservoir evaluation. Obtaining any data under these conditions requiredassuring the drilling team that appropriate steps would be taken to reduce the risk of logging tools becoming stuck in the hole. Studies were conducted to confirm that any hydrocarbon fluids pumped into the borehole during fluid analysis would not destabilize the mud column. Pipe-conveyed wireline logging was ruled out for safety reasons.

ConocoPhillips (UK) Ltd had successfully logged other challenging HPHT wells in the region with a high-tension logging package. In these cases, wireline logging tools were lowered into and raised from the wells using high-strength cable and a capstan. The capstan, placed between the drill floor and the wireline unit, increases the wireline pull from 9,700 to 15,500 lbm (4,400 to 7,030 kg), ensuring that even long, heavy toolstrings can be retrieved.

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The well encountered an unanticipated secondary reservoir above the primary target, introducing uncertainty into the understanding of fluid properties. The logging program was immediately modified to include fluid sampling in these newly discovered zones. A Quicksilver Probe module was readied to run in the hole and a PVT Express onsite well fluid analysis system was installed on the platform to perform surface analysis of samples collected from the four new zones.

In the first sand sampled using the Quicksilver Probe focusing device, the tool operated smoothly, and flow through the tool began in commingled mode. Flow was split between the sampling and guard probes after 2,600 seconds of pumping, giving rise to an abrupt GOR increase from 850 ft³/bbl to around 1,500 ft³/bbl (bottom track). PVT Express fluid-analysis experts on site identified 600 to 900 ppm of hydrogen sulfide (H2S) in the shallower sand layer, which would be incompatible with the completion design. These levels of H2S in the first sandstone led the ConocoPhillips (UK) Ltd subsurface team to upgrade their equipment.

At another station, Quicksilver Probe operation began and remained with the tool bypass valve in the open position. This means that the guard and sample flowlines were hydraulically connected inside the tool, mimicking traditional, single-probe sampling. Pumping continued for more than 14,000 seconds—about 4 hours—at which point samples were collected, because the fluid was not getting any cleaner (next page, top). Wellsite analysis determined contamination to be 22%, which was confirmed by the onshore laboratory result of 23% three weeks later.

Before moving away from this sampling station, the field engineer managed to close the bypass valve and establish focused flow. Fluid flow split into the guard and sampling flowlines, GOR increased dramatically, and contamination decreased. PVT Express onsite analysis indicated that contamination levels fell from 22% to 1.5%. The fluid samples collected here showed 1% contamination in later laboratory analysis. Normal levels of H2S were found here and in the remaining layers. In all, 27 fluid samples were acquired with good-quality results in every layer.

The well was subsequently completed, perforating only those layers that had been shown to have low H2S levels compatible with the tubing metallurgy. Being able to acquire a suite of uncontaminated downhole samples as part of a rapidly evolving logging program was vital to the success of the development of this secondary reservoir. If high-quality samples had not been taken and the well completion had proceeded without this data, high concentrations of H2S would have damaged the production tubing and entered the production facility. Mitigating that would have required shutting in production and performing a costly workover to identify and shut off the H2S-prone zone.
**HPHT Sampling Instead of DST**

BG, drilling in another HPHT area of the central North Sea, made a discovery with multiple hydrocarbon-bearing zones. This exploration well was designed not to have a DST, saving costs on two levels. First, a DST in this region would have cost US$ 10 to 20 million. Second, additional savings came from installing a less expensive completion. A DST would require heavier 9$\frac{7}{8}$-in. casing to withstand the pressures of the well test, and a different well-test tree for supporting the well-test equipment, totaling an additional US$ 4 million. Also, producing no reservoir fluids to surface would avoid environmental risks.

Since no DST would be run, it was crucial to acquire high-purity samples by wireline. To allow real-time analysis of formation fluids, the Quicksilver Probe tool was configured with LFA and CFA Composition Fluid Analyzer modules on the sample flowline. A PVT Express system installed on the rig analyzed contamination at the wellsite. Shore-based experts were able to participate in logging and sample analysis in real time through the InterACT real-time monitoring and data delivery system. By confirming sample purity at the wellsite, engineers would know if the quality of the acquired sample was adequate, or if a new sample was required. BG fluid experts were hoping for samples with less than 5% OBM contamination. In addition to hydrocarbon samples, the tool would acquire water samples if it could sustain the high temperatures deeper in the reservoir. Pressures were anticipated to be at least 13,000 psi [90 MPa], and temperature was expected to surpass the 350°F [177°C] stated limit of LFA and CFA operability.

In the first and shallowest hydrocarbon interval sampled, the temperature was already 340°F [171°C]. Quicksilver Probe operation proceeded normally, starting with the guard probe and sample probe connected through the inner bypass valve. The upper pump was used to pump fluid through the sample line. The flow was split into guard and sample lines after 3,050 seconds of pumping, at which time a jump in GOR on the LFA plot indicated a significant decrease in contamination of the fluid in the sample line (right). Less than two minutes later, when contamination reached an estimated 10%, the one-gallon sample bottle opened to collect a safety sample—a standard practice in difficult wells. This proved prudent, because soon afterward, the sampling-flowline pump stalled, but started again.

Contamination continued to decrease, and when GOR leveled off, a single-phase sample bottle was opened, filled and retrieved to surface. PVT Express analysis on the rig quantified extremely low contamination, indicating that the sample was sufficiently pure, and the tool could be redeployed to the next deeper and hotter level. Independent onshore laboratory testing conducted a few weeks later detected no contamination in this sample.

Three low-contamination samples were successfully acquired at the next hydrocarbon-bearing zone, but after that, mud-check valves in the sample flowline started to show signs of plugging. However, the deepest and hottest zone remained to be sampled. There, at the watersampling station, slugs of borehole mud and OBM filtrate were detected by the LFA module, indicating that unexpected fluid movement was occurring through the fluid-exit port. After some time, this movement of fluid from the borehole had cleared the mud-check valve, and synchronized pumping to the guard and sample lines proceeded normally—despite the 361°F [183°C] bottomhole temperature—allowing acquisition of formation-water samples.

[^Quicksilver Probe operation in a ConocoPhillips (UK) Ltd North Sea well, with the tool bypass valve in the open position (left). With the guard and sample flowlines hydraulically connected inside the tool, the effect is the same as conventional single-probe sampling. The pumpout-volume track (top) shows only the sample pump operating (blue). Cleanup is gradual, as seen by the slow increase of the GOR with time (third track). After more than 14,000 seconds, the fluid was not getting any cleaner, so samples were collected. According to PVT Express wellsite analysis, contamination was 22%. After the field engineer closed the bypass valve (right), fluid flow was split into the guard and sampling flowlines at around 15,500 seconds. Both the sample-line pump (blue) and the guard-line pump (brown) were pumping (top track), with the guard-line pump operating at a higher rate. GOR (third track) jumped to about 1,500 ft$^3$/bbl, indicating a reduction in contamination. Onsite analysis with the PVT Express system quantified a contamination drop from 22% to 1.5%.

[^Quicksilver Probe operation in BG's HPHT North Sea well. Before 3,050 s, fluid flowed through the sample-line pump (blue, top track). At 3,050 s, the guard-line pump (brown) and sample-line pump operated synchronously, with the guard-line pump operating at a higher rate. This split the flow, giving rise to an abrupt increase in GOR (blue) at 3,050 s (second track). The sample acquired at 8,700 s was found to contain no contamination.]
Determining OBM contamination level of water samples downhole relied on interpreting data from the color channels of the LFA module (left). Borehole mud, OBM filtrate and formation water each have distinctive signatures in the visible and near-infrared frequency ranges measured by the tool. The two water samples collected at this level contained some OBM filtrate, but this was not a problem, because the OBM is immiscible in formation water.

BG estimates savings of up to US$ 24 million by using the Quicksilver Probe focused-sampling method instead of a drillstem test to acquire zero-contamination samples.

Sampling Viscous Oils

Viscous oils can be especially difficult to sample using traditional sampling technology. With its relatively lower viscosity, OBM filtrate flows preferentially to sampling devices, increasing sample contamination and often leaving high-viscosity formation fluids in the formation.

Cairn Energy India Pty Ltd experienced such problems acquiring oil samples in their Bhagyam field in northwest India. The Bhagyam field is one of 19 fields in the Barmer basin tapping the high-permeability Fatehgarh sandstone. Oil reserves in the reservoir are currently estimated at 1.5 billion bbl (240 million m³). Oil properties vary from field to field within the basin, and oils within the Bhagyam field exhibit compositional grading from crest to oil/water contact. With a better understanding of oil properties, Cairn plans to optimize field development and surface facility design.

Bhagyam oils have high wax content, giving them high pour point and high viscosity at reservoir temperature. Acquiring representative, PVT-quality samples has been a challenge. Before the arrival of focused-sampling technology in India, most samples acquired by Schlumberger and other service companies using traditional openhole formation testers were too contaminated to yield correct PVT properties during laboratory analysis.

To obtain contamination-free samples, Cairn had resorted to collecting samples from cased wells using monophasic wireline-deployed samplers. Samples acquired in this way may have low levels of contamination, but can be collected only after the well has been completed.

In a campaign designed to improve sample quality, the Quicksilver Probe device collected samples in two Bhagyam wells. Of the 18 samples acquired, 15 were of PVT quality. Six of these showed no contamination. One such
sample was analyzed for chemical composition and compared with a sample acquired at the same location by a traditional openhole formation tester and one obtained in cased hole (previous page, bottom). The traditional openhole method produced a sample that was clearly contaminated with several OBM components. The sample acquired in cased hole showed an overall composition that was similar to the uncontaminated Quicksilver Probe sample, with small concentration variations in a few components.

Following the successful acquisition of contamination-free samples and the availability of detailed fluid PVT data, Cairn has better fluid-property data for carrying out field-development studies that involve reserves estimation, facilities design and flow assurance. These studies will make a significant contribution to production at Bhagyam and demonstrate the potential for improved field-development studies worldwide.

**Sampling in Mature Fields**

The Quicksilver Probe device is also a valuable tool for evaluating the efficiency of hydrocarbon recovery in mature fields. Examples from complex, mature fields in the Middle East show how focused sampling acquired pure samples in high- and low-permeability formations and helped assess gas-sweep efficiency.

The first well is in a reservoir that is under gas-cap expansion drive and water drive. Recently, several evaluation wells were drilled to monitor sweep efficiency. The wells were drilled with OBM and logged with the Platform Express integrated wireline logging tool and nuclear magnetic resonance tools for openhole analysis. The Quicksilver Probe module of the MDT tool was used to collect fluid samples.

The objective was to evaluate the efficiency of the gas-cap expansion in the main reservoir—a heterogeneous sandstone formation with permeability exceeding 1 darcy. Although low oil saturations from MRX Magnetic Resonance eXpert measurements indicated highly efficient sweep of the oil by expansion of gas, the formation tester was run to confirm that there was no mobile oil in the swept zone. The identification of any remaining mobile oil would indicate incomplete sweep. The Quicksilver Probe module identified and sampled fluids at four stations in the gas zone and one station in the oil column (below). All zones show the characteristic increase in GOR when flow through the guard line is split from the sample line. Several gas samples were captured with no OBM-filtrate contamination and with no mobile oil, indicating highly efficient recovery.

In the oil zone, the GOR measured by the LFA module was within 1% of the GOR already known for the field. The pumping time required for a clean oil sample in this zone was about 1,600 seconds, roughly one-third of the time normally

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19. PVT-quality samples are those that have sufficiently low contamination, such that PVT properties measured in the laboratory correspond to those of an uncontaminated sample. The maximum allowable contamination varies by company and laboratory. A general rule is 7% contamination for this basin.
Comparison of pumping times to acquire clean oil samples in a Middle East field using the Quicksilver Probe module and a traditional probe. In this high-permeability sandstone, it took the Quicksilver Probe tool (red) only about 1,600 seconds of pumping time to draw low-contamination fluid into the sampling line, while the traditional probe (blue) pumped about three times as long to obtain a low-contamination sample.

In a second Middle East example, an evaluation well penetrated six reservoirs, including a discovery. The objectives were to obtain pressure profiles, identify fluids downhole and acquire clean fluid samples. In addition, the operator wanted to establish flow from low-porosity zones that previously had not been directly tested for their potential producibility. The operator selected the Quicksilver Probe device because its large probe area was better equipped than conventional large-diameter probes to establish flow and obtain samples from the low-porosity, low-permeability formations.

The well was drilled with OBM, and caliper data showed good hole condition. Fluid sampling points were selected using free-fluid porosity readings from the nuclear magnetic resonance log. On the first pressure and sampling run, the MDT tool, deployed on wireline, acquired pressure profiles using the large-diameter probe. On the second descent, the Quicksilver Probe module and sampling units were run on drillpipe, and sampled at five stations (next page, top).

At the second sampling station, downhole fluid analysis identified oil in a previously untapped interval. Fluid mobility was so low in this tight zone that a pressure measurement could not be acquired. However, the LFA module in the Quicksilver Probe tool successfully monitored formation-fluid cleanup and found a low GOR for the liquid, leading to additional oil reserves.

**Downhole Fluid Analysis**

In most reservoirs, fluid composition varies with location in the reservoir. Fluids may exhibit gradations caused by gravity or biodegradation, or they may be segregated by structural or stratigraphic compartmentalization. One way to characterize these variations is to collect samples for surface analysis. Another way is to analyze fluids downhole, without bringing them to surface. Downhole fluid analysis (DFA) is emerging as a powerful technique to characterize fluids downhole. DFA helps determine the best intervals for sample collection, if necessary. Analyzing fluid composition while the tool is still in the hole also allows more detailed fluid characterization, because interpreters can modify the fluid-scanning program in real time to investigate unexpected results.22

The ability of the Quicksilver Probe module to supply uncontaminated fluids ensures optimal DFA results, and the faster cleanup time allows several DFA fluid-scanning stations to be conducted efficiently without the long station times associated with conventional sampling. A combination of DFA and sample collection helped a Norwegian operator understand fluids in a well drilled on the Norwegian Continental Shelf.23

The well was drilled as a final appraisal before development of an oil field. Because of environmental restrictions, a production test was not planned, so it was critical to obtain uncontaminated samples and fully characterize fluid variations within the reservoir. The fluid analysis would be used in the material selection of subsea pipeline and surface facilities, process design and production planning. Because of the high priority to capture representative hydrocarbon samples without miscible contamination, the well was drilled with water-base mud (WBM).

The Quicksilver Probe tool was run in the 12\(\frac{1}{4}\)-in. and 8\(\frac{1}{2}\)-in. sections to collect samples of gas condensate, oil and formation water, and filled 19 sample chambers from many levels. An example from one of the more challenging zones, sampling oil in a relatively tight zone with mobility of 17 mD/ft, shows how the focusing technology results in an uncontaminated sample.

Fluid cleanup began with commingled flow first through the guard flowline, then through the sample flowline. After 1,300 seconds, flow is split and focusing is achieved by increasing the flow rate in the guard probe (next page, bottom). The real-time GOR detected by the CFA module stabilized at around 2,900 seconds, indicating that the fluid was clean. However, pumping continued, and a sample was acquired at 2,800 seconds. The spikes in the GOR curve indicate the presence of produced fines from the formation, confirmed later when the sample was analyzed at surface. Wellsite analysis showed some sand in the samples, but no detectable level of WBM filtrate.

In the same well, the focusing method created optimal conditions for DFA. The spectroscopic analyzers that indicate when fluid in the flowline is pure enough to sample also characterized the fluid composition in terms of three component groups: methane (\(C_1\)), ethane to pentane (\(C_2\) to \(C_5\)), and hexane and heavier (\(C_6^+\)). This allows in-situ compositional analysis without collecting a sample and retrieving it to surface.

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Sampling a new discovery in a mature Middle East field. This evaluation well penetrated six reservoirs, including a discovery. In addition to obtaining pressure samples, the operating company performed tests in bypassed low-porosity zones. Formation pressures appear in Track 1, with oil identified as green circles and water as blue circles. Open circles indicate pressure measurements that do not fall on any gradient. Stars are pressures measured with the Quicksilver Probe tool. Track 2 contains drawdown mobility. Track 3 plots porosity and pore-fluid content with red for oil and blue for water. The second sampling station, at X,300 ft, was a discovery. LFA volume fraction and GOR results are plotted to the right of the porosity track (top right). Pump rates and GOR values for the third station are also shown to the right of the porosity track (middle right). A low-contamination sample was also acquired at the fifth station, at Y,100 ft—the first time oil had flowed from this low-porosity formation. The GOR from this interval (bottom right) was found to be 250 ft³/bbl.

Fluid cleanup in an oil well offshore Norway. Quicksilver Probe tool operation began with commingled flow through the guard flowline, as seen by the increase in guard-flowline pumpout flow rate (light green, top track), then through the sample flowline (dark green, top track). After 1,300 s, flow is split and focusing is achieved by increasing the pumping rate in the guard probe. The GOR (bottom track) responds by stabilizing at around 2,300 s, indicating that low-contamination fluid is flowing through the sample flowline. Sample flowline GOR is red, and guard flowline GOR is blue. A sample was acquired at 2,800 s, and was found to contain no detectable WBM. The spikes in the GOR curve indicate the presence of produced fines from the formation sand. (Adapted from O'Keefe et al, reference 23.)
Two DFA fluid-scanning stations straddled the gas/oil contact within 0.5 m, which was a higher accuracy than could be achieved using pretest pressure gradients in this well. The focusing capability of the Quicksilver Probe tool ensured that the fluids being analyzed were representative of reservoir fluids, adding confidence to the DFA results. Similar measurements at 15 additional DFA stations helped quantify reservoir-fluid composition and delineate fluid contacts. To facilitate quantification of WBM filtrate contamination, tritium, a naturally occurring isotope of hydrogen, was added to the WBM as a tracer. Formation waters do not contain tritium in measurable amounts, so tritium levels detected by laboratory testing could be easily converted to contamination levels. The first sample was taken with the Quicksilver Probe focused-flow tool. Flow was split after 18,700 seconds, and the sample was collected after 24,960 seconds of pumping. Laboratory analysis of tritium content showed the sample to have 0% contamination. The well was then cased with a 7-in. liner and perforated over the zone of interest. A wireline formation tester was run inside the liner, along with inflatable dual packers to isolate the flow interval. The increased flow area provided by the packers would minimize the drawdown required to extract samples and so reduce the risk of tool sticking.

After a long cleanup time—24 hours—during which 1,700 liters [450 galUS] of fluid were pumped from the formation into the borehole, the formation tester collected two samples. Laboratory analysis indicated that the samples contained elevated concentrations of tritium, potassium, calcium and bromide, indicative of contamination by completion brine and mud filtrate.

The operating company then performed a DST to test a gas zone above the water zone. Water flowing with the gas was collected for analysis, but was found to be heavily contaminated with completion brine and also contained 46% hydrate inhibitor.

The Quicksilver Probe samples proved to be the purest water samples ever collected from the field, surpassing the quality obtainable from conventional-probe sampling, cased-hole sampling or a DST. Analysis of the samples revealed unexpected compositional characteristics that were difficult to believe at first, but further analysis of core and logs corroborated the new water-composition results. In another water-sampling example from offshore Norway, both focused and conventional methods applied to the same formation helped compare cleanup performance. This exploration well was drilled with water-base potassium chloride [KCl] drilling fluid, adding difficulty to the water-sampling program. Because the formation water and the WBM had similar optical properties, real-time quantification of contamination relied not on spectroscopic measurements but on resistivity differences. For quantitative determination of contamination levels, the concentration of potassium in the sample, corrected by subtracting the level assumed present in the formation water, was divided by the known concentration in the WBM filtrate at each depth.

In the first sampling sequence, samples were collected at three times during focused flow, at 1,050 seconds, 7,050 seconds and 7,800 seconds, and showed 8.35%, 0.02% and 0% contamination, respectively. Temporarily switching off the guard pump shows the corresponding effect on contamination (next page, top). An additional sample collected at 1,550 seconds, after the guard pump had been stopped, yielded 33.4% contamination.
For the next run, the field engineer shifted the toolstring 3.5 m [11.5 ft] higher in the same formation and used a conventional single-probe tool with a large-diameter packer to sample formation fluid without focusing (above). Sampling at this station was designed to allow direct comparison between the performance of the focused probe and the conventional probe. Three sample bottles were filled at this station after the same cleanup times as the three samples in the focused-sampling sequence. The conventionally acquired samples showed contamination levels of 26.2%, 8.6% and 8.2%. Not only were the focused samples cleaner at every time comparison, but the focused sample acquired at 1,050 seconds (17.5 minutes) was cleaner than the conventional sample after 7,050 seconds (2 hours).

**Focusing on the Future**

The focused-sampling capability of the Quicksilver Probe tool provides higher purity fluid samples in much less time than traditional sampling tools. Benefits include higher quality fluid-property data, access to accurate fluid information earlier in the reservoir-characterization process, reduced risk of tool sticking, enhanced capabilities for downhole fluid analysis and all the savings associated with getting the fluid characterization right the first time.

For some E&P operators, especially those involved in deepwater activities, the technology represents the best existing substitute for prohibitively expensive or environmentally unfeasible DSTs. The tool can be run without the extensive upfront planning required for DSTs. Other operators have used high-quality Quicksilver Probe results to optimize DST plans. In either case, the focused-sampling approach increases efficiency, quality and safety in these demanding environments.

In several cases, Quicksilver Probe sampling has yielded surprising results. The technology is encouraging some operators to review current plans and resample zones where other technologies have given unsatisfactory answers. Operating companies that have had to drill with WBM for the purpose of obtaining clean oil samples can now confidently drill with OBM, safe in the knowledge that pure samples can be obtained downhole with no miscible contamination.

As a result of the high purity of new, incoming samples, some laboratories have had to create a new classification for such low contamination, called “too small to measure,” or TSTM. Now that such pure samples are available for laboratory analysis, researchers and experimentalists may be able to perform additional analyses and devise new measurements to better understand fluid behavior.

An important consequence of the ability to obtain zero-contamination samples downhole is the improvement in accuracy of real-time downhole measurements. This will encourage companies to perform downhole fluid analysis for a more complete mapping of reservoir fluids than is done today, and will also promote the addition of new DFA measurements. —LS