Designing and Managing Drilling Fluid

Gone are the days when drilling fluid—or mud as it is commonly called—comprised only clay and water. Today, the drilling engineer designing a mud program chooses from a comprehensive catalog of ingredients. The aim is to select an environmentally acceptable fluid that suits the well and the formation being drilled, to understand the mud's limitations, and then to manage operations efficiently within those limitations.

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There are good reasons to improve drilling fluid performance and management, not least of which is economics. Mud may represents 5% to 15% of drilling costs but may cause 100% of drilling problems. Drilling fluids play sophisticated roles in the drilling process: stabilizing the wellbore without damaging the formation, keeping formation fluids at bay, clearing cuttings from the bit face, and lubricating the bit and drillstring, to name a few.[1] High-angle wells, high temperatures and long, horizontal sections through pay zones make even more rigorous demands on drilling fluids.

Furthermore, increasing environmental concerns have limited the use of some of the most effective drilling fluids and additives.[2] At the same time, as part of the industry's drive for improved cost-effectiveness, drilling fluid performance has come under ever closer scrutiny.

This article looks at the factors influencing fluid choice, detailing two new types of mud. Then it will discuss fluid management during drilling.

What Influences the Choice of Fluid?

Among the many factors to consider when choosing a drilling fluid are the well's design, anticipated formation pressures and rock mechanics, formation chemistry, the need to limit damage to the producing formation, temperature, environmental regulations, logistics, and economics (see "Critical Decisions," *next page*).

To meet these design factors, drilling fluids offer a complex array of interrelated properties. Five basic properties are usually defined by the well program and monitored during drilling: rheology, density, fluid loss, solids content and chemical properties (see "Basic Mud Properties and Ingredients," *page 36*).[3]

For any type of drilling fluid, all five properties may, to some extent, be manipulated using additives. However, the resulting chemical properties of a fluid depend largely on the type of mud chosen. And this choice rests on the type of well, the nature of the formations to be drilled and the environmental circumstances of the well.

1. For a comprehensive review of the role of drilling fluids:

   Darley HCH and Gray GR: *Composition and Properties of Drilling and Completion Fluids*, 5th ed. Houston, Texas, USA: Gulf Publishing Co.,1988.
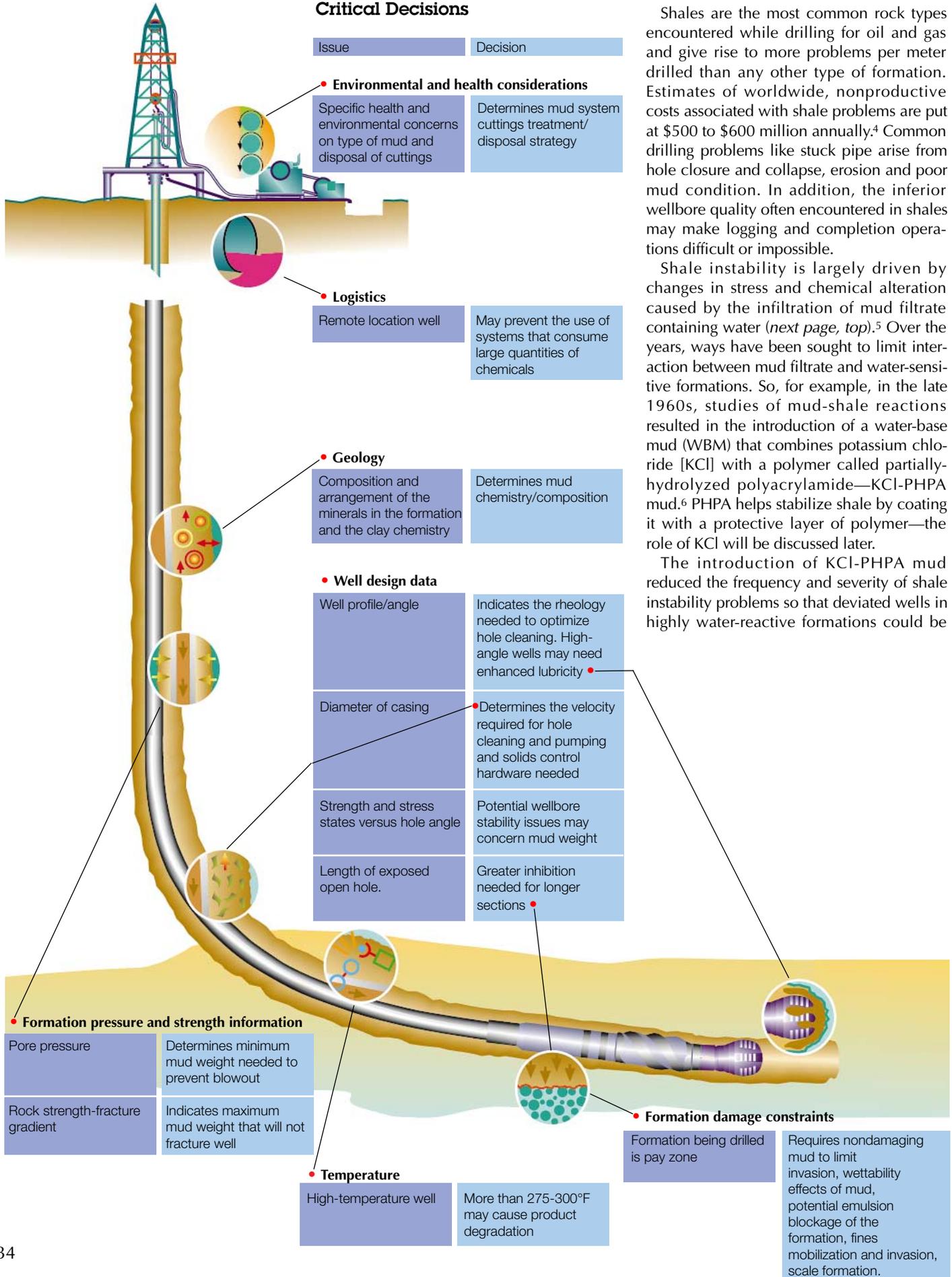
2. Geehan T, Helland B, Thorbjørnsen K, Maddin C, McIntire B, Shepherd B and Page W: "Reducing the Oilfield's Environmental Footprint," *Oilfield Review* 2, no. 4 (October 1990): 53-63.

   Minton RC, McKelvie DS, Caudle DD, Ayres RC Jr., Smith JP, Cline JT, Duff A, Blanchard JR and Read AD: "The Physical and Biological Impact of Processed Oil Drill Cuttings: E&P Forum Joint Study," paper SPE 26750, presented at the Offshore Europe Conference, Aberdeen, Scotland, September 7-10, 1993.

3. For a full description of these properties and their measurement:

   Geehan T and McKee A: "Drilling Mud: Monitoring and Managing It," *Oilfield Review* 1, no. 2 (July 1989): 41-52.

Critical Decisions

Issue	Decision

• Environmental and health considerations

Specific health and environmental concerns on type of mud and disposal of cuttings	Determines mud system cuttings treatment/disposal strategy

• Logistics

Remote location well	May prevent the use of systems that consume large quantities of chemicals

• Geology

Composition and arrangement of the minerals in the formation and the clay chemistry	Determines mud chemistry/composition

• Well design data

Well profile/angle	Indicates the rheology needed to optimize hole cleaning. High-angle wells may need enhanced lubricity
Diameter of casing	Determines the velocity required for hole cleaning and pumping and solids control hardware needed
Strength and stress states versus hole angle	Potential wellbore stability issues may concern mud weight
Length of exposed open hole.	Greater inhibition needed for longer sections

• Formation pressure and strength information

Pore pressure	Determines minimum mud weight needed to prevent blowout
Rock strength-fracture gradient	Indicates maximum mud weight that will not fracture well

• Temperature

High-temperature well	More than 275-300°F may cause product degradation

• Formation damage constraints

Formation being drilled is pay zone	Requires nondamaging mud to limit invasion, wettability effects of mud, potential emulsion blockage of the formation, fines mobilization and invasion, scale formation.

Shales are the most common rock types encountered while drilling for oil and gas and give rise to more problems per meter drilled than any other type of formation. Estimates of worldwide, nonproductive costs associated with shale problems are put at $500 to $600 million annually.[4] Common drilling problems like stuck pipe arise from hole closure and collapse, erosion and poor mud condition. In addition, the inferior wellbore quality often encountered in shales may make logging and completion operations difficult or impossible.

Shale instability is largely driven by changes in stress and chemical alteration caused by the infiltration of mud filtrate containing water (*next page, top*).[5] Over the years, ways have been sought to limit interaction between mud filtrate and water-sensitive formations. So, for example, in the late 1960s, studies of mud-shale reactions resulted in the introduction of a water-base mud (WBM) that combines potassium chloride [KCl] with a polymer called partially-hydrolyzed polyacrylamide—KCl-PHPA mud.[6] PHPA helps stabilize shale by coating it with a protective layer of polymer—the role of KCl will be discussed later.

The introduction of KCl-PHPA mud reduced the frequency and severity of shale instability problems so that deviated wells in highly water-reactive formations could be

drilled, although often still at a high cost and with considerable difficulty. Since then, there have been numerous variations on this theme as well as other types of WBM aimed at inhibiting shale.

However, in the 1970s, the industry turned increasingly towards oil-base mud (OBM) as a means of controlling reactive shale. Today, OBM not only provides excellent wellbore stability but also good lubrication, temperature stability, a reduced risk of differential sticking and low formation damage potential. OBM has been invaluable in the economic development of many oil and gas reserves.

The use of OBM would probably have continued to expand through the late 1980s and into the 1990s but for the realization that, even with low-toxicity mineral base-oil, the disposal of OBM cuttings can have a lasting environmental impact. In many areas this awareness led to legislation prohibiting or limiting the discharge of these wastes. This, in turn, has stimulated intense activity to find environmentally acceptable alternatives and has boosted WBM research.

To develop alternative nontoxic muds that match the performance of OBM requires an understanding of the reactions that occur between complex, often poorly characterized mud systems and equally complex, highly variable shale formations.

Requisites for a Successful Drilling Fluid

Most OBM is an invert emulsion comprising droplets of aqueous fluid surrounded by oil, which forms the continuous phase. A layer of surfactant on the surface of the water droplet acts like a semipermeable membrane, separating the aqueous solution in the mud from the formation and its water. Water will pass through this membrane from the solution with the lowest concentration of a salt to the one with the highest—osmosis (right).

A key method of maintaining shale stability using OBM is to ensure that the ionic concentration of the salts in the aqueous—internal—phase of the mud is sufficiently high, so that the chemical potential of the water in the mud is equal to or lower than that of the formation water in the shale.[7] When both solutions have the same chemical potential, water will not move, leaving the shale unchanged. If the water in the internal phase of the mud has a lower chemical potential than the fluid in the formation, water will travel from the shale to the mud, drying out the rock. Unless dehydration is excessive, this drying out usually leaves the wellbore in good condition.[8]

□ *Shale instability. In this example, Pierre shale has been exposed to a mud comprising fresh water and bentonite gel. Because this fluid contains no inhibitors, water has entered the shale causing it to swell and weakening the formation. Continuous flow of mud has eroded the borehole leaving an enlarged hole that would be hard to log and complete. This simulation was carried out using the small wellbore simulator at Schlumberger Cambridge Research, Cambridge, England.*
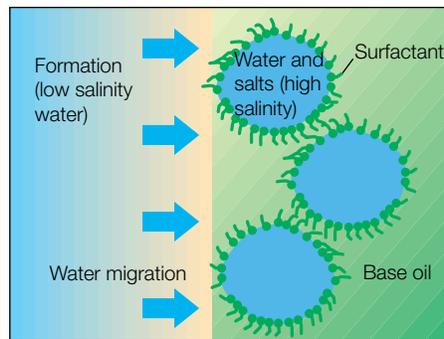
□ *How oil-base mud's semipermeable membrane works. OBM comprises droplets of aqueous fluid surrounded by oil. A layer of surfactant on the surface of each water droplet acts like a semipermeable membrane, separating the aqueous solution in the mud from the formation and its water. Water passes through this membrane from the solution with the lowest concentration of salt to the one with the highest.*

In WBM, there have been many efforts to protect a water-sensitive formation from mud filtrate. One technique is to introduce a buffer in the form of blocking and plastering agents, ranging from starches and celluloses, through polyacrylamides to asphalts and gilsonites. Total control cannot be achieved in this way so specific inhibiting cations—chiefly potassium [K^+] and calcium [Ca^{2+}] ions—are traditionally added to the base water to inhibit the clay from dispersing—to stop it from breaking up when attacked by aqueous solution. This is

4. Boll GM, Wong S-W, Davidson CJ and Woodland DC: "Borehole Stability in Shales," paper SPE 24975, presented at the SPE European Petroleum Conference, Cannes, France, November 16-18, 1992.

5. Allen D, Auzerais F, Dussan E, Goode P, Ramakrishnan TS, Schwartz L, Wilkinson D, Fordham E, Hammond P and Williams R: "Invasion Revisited," *Oilfield Review* 3, no. 3 (July 1991): 10-23.

6. Bailey L, Reid PI and Sherwood JD: "Mechanisms and Solutions for Chemical Inhibition of Shale Swelling and Failure," presented at the Royal Society of Chemistry 5th International Symposium, Chemistry in the Oil Industry, Ambleside, Cumbria, UK, April 12-14, 1994.

   Steiger RP: "Fundamentals and Use of Potassium/Polymer Drilling Fluids to Minimize Drilling and Completion Problems Associated With Hydratable Clays," *Journal of Petroleum Technology* 34 (August 1982): 1661-1670.

   O'Brien DE and Chenevert ME: "Stabilizing Sensitive Shales With Inhibited, Potassium-Based Drilling Fluids," paper SPE 4232, *Journal of Petroleum Technology* 25 (1973): 1089.

7. Chemical potential can be though of as an increase in the internal energy of the system when one mole of substance is added to an infinitely large quantity of the mixture so as not to change its overall composition.

   For more information about thermodynamic potentials:

   Fletcher P: *Chemical Thermodynamics for Earth Scientists.* Harlow, Essex, England: Longman Scientific & Technical, 1993.

8. Mody FK and Hale AH: "A Borehole Stability Model to Couple Mechanics and Chemistry of Drilling Fluid Shale Interactions," paper SPE 25728, presented at the IADC/SPE Drilling Conference, Amsterdam, The Netherlands, February 23-25, 1993.

   Chenevert ME: "Shale Control With Balanced Activity Oil-Continuous Muds," *Journal of Petroleum Technology* 22 (1970): 1309-1319.

Basic Mud Properties and Ingredients

Basic Mud Properties

Five basic properties are usually defined by the well program and monitored during drilling:[1]

Rheology—A high viscosity fluid is desirable to carry cuttings to surface and suspend weighting agents in the mud (such as barite). However, if viscosity is too high, friction may impede the circulation of the mud causing excessive pump pressure, decrease the drilling rate, and hamper the solids removal equipment. The flow regime of the mud in the annulus is also affected by viscosity.[2] Measurements made on the rig include funnel viscosity using a Marsh funnel—an orifice viscometer—and plastic viscosity, yield point and gel strength using a Fann 35 viscometer or equivalent.

Density—Sufficient hydrostatic pressure is required to prevent the borehole wall from caving in and to keep formation fluid from entering the wellbore. The higher the density of the mud compared to the density of the cuttings, the easier it is to clean the hole—the cuttings will be less inclined to fall through the mud. If the mud weight is too high, rate of drilling decreases, the chances of differential sticking and accidentally fracturing the well increase, and the mud cost will be higher. The most common weighting agent employed is barite. Density is measured on the rig using a mud balance.

Fluid loss—The aim is to create a low-permeability filter cake to seal between the wellbore and the formation. Control of fluid loss restricts the invasion of the formation by filtrate and minimizes the thickness of filter cake that builds up on the borehole wall, reducing formation damage and the chances of differential sticking. Static fluid loss is measured on the rig using a standard cell that forces mud through a screen, and also using a high-temperature, high-pressure test cell.

Solids content—Solids are usually classified as high gravity (HGS)—barite and other weighting agents—or low gravity (LGS)—clays, polymers and bridging materials deliberately put in the mud, plus drilled solids from dispersed cuttings and ground rock. The amount and type of solids in the mud affect a number of mud properties. A high solids content, particularly LGS, will increase plastic viscosity and gel strength. High-solids muds have much thicker filter cakes and slower drilling rates. Large particles of sand in the mud cause abrasion on pump parts, tubulars, measurement-while-drilling equipment and downhole motors. Measurement of total solids is traditionally carried out using a retort—which distils off the liquid allowing it to be measured, leaving the residual solids.

Chemical properties—The chemical properties of the drilling fluid are central to performance and hole stability. Properties that must be anticipated include the dispersion of formation clays or dissolution of salt formations; the performance of other mud products—for example, polymers are affected by pH and calcium; and corrosion in the well (see "Corrosion in the Oil Industry," *page 4*). Measurement rigside usually relies on simple chemical analysis to determine pH, Ca^{2+}, total hardness, concentrations of Cl^- and sometimes K^+.

Mud Ingredients

Water—In water-base mud (WBM) this is the largest component. It may be used in its natural state, or salts may be added to change filtrate reactivity with the formation. Water hardness is usually eliminated through treatment and alkalinity is often controlled.

Weighting agents—These are added to control formation fluid pressure. The most common is barite.

Clay—Most commonly, bentonite is used to provide viscosity and create a filter cake on the borehole wall to control fluid loss. Clay is frequently replaced by organic colloids such as biopolymers, cellulose polymers or starch.

Polymers—These are used to reduce filtration, stabilize clays, flocculate drilled solids and increase cuttings-carrying capacity. Cellulosic, polyacrylic and natural gum polymers are used in low-solids mud to help maintain hole stability and minimize dispersion of the drill cuttings. Long-chain polymers are adsorbed onto the cuttings, thereby preventing disintegration and dispersion.

Thinners—These are added to the mud to reduce its resistance to flow and to stifle gel development. They are typically plant tannins, polyphosphates, lignitic materials, lignosulfonates or synthetic polymers.

Surfactants—These agents serve as emulsifiers, foamers and defoamers, wetting agents, detergents, lubricators and corrosion inhibitors.

Inorganic chemicals—A wide variety of inorganic chemicals is added to mud to carry out various functions. For example, calcium hydroxide is used in lime mud and calcium chloride in OBM; sodium hydroxide and potassium hydroxide (caustic soda and caustic potash) are used to increase mud pH and solubilize lignite; sodium carbonate (soda ash) to remove hardness, sodium chloride for inhibition and sodium chloride has many uses—such as increasing salinity, increasing density, preventing hydrate formation and providing inhibition.

Bridging materials—Calcium carbonate, cellulose fibers, asphalts and gilsonites are added to build up a filter cake on the fractured borehole and help prevent filtrate loss.

Lost circulation materials—These are used to block large openings in the wellbore. These include walnut shells, mica and mud pills containing high concentrations of xanthum and modified cellulose.

Specialized chemicals—Scavengers of oxygen, carbon dioxide or hydrogen sulfide are sometimes required, as are biocides and corrosion inhibitors.

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1. For a complete description of the traditional mud check techniques:

   Geehan T and McKee A: "Drilling Mud: Monitoring and Managing It," *Oilfield Review* 1, no. 2 (July 1989): 41-52.

2. Plastic viscosity (PV) and yield point (YP) are related parameters and follow common oilfield conventions based on the Bingham rheological model. PV is largely dependent on the type of mud and its solids content. The lower the PV, the faster the drilling penetration rate. However, this is limited by the YP, which is a direct measure of the fluid's cuttings-carrying efficiency.

   For details of rheology:

   Bittleston S and Guillot D: "Mud Removal: Research Improves Traditional Cementing Guidelines," *Oilfield Review* 3, no. 2 (April 1991): 44-54.

achieved by providing cation exchange with the clays in the shale—the K+ or Ca2+ commonly replace the sodium ion [Na+] associated with the clay in the shale, creating a more stable rock that is better able to resist hydration. Hence KCl-PHPA fluids.[9]

The movement of WBM filtrate from the wellbore into the surrounding shale is controlled by the difference between the chemical potentials of the various species in the mud, and the corresponding chemical potentials within the formation. Chemical potential depends both on the mud's hydrostatic pressure in the wellbore and on its chemical composition.[10]

To design an effective WBM, it is necessary to know the relative importance of mud differential pressure versus chemical concentration and composition, and how this relates to the type of mud and formation. For example, if the rock is chemically inert to WBM filtrate (as is the case with sandstone), then invasion is controlled solely by the differences between the wellbore pressure and the pore pressure within the rock. But for shale, opinion varies. Some experimenters suggest that the shale itself can act as a semipermeable membrane, making the chemical components the key determinant.

Researchers at Schlumberger Cambridge Research tested Pierre shale and found that it behaves as an imperfect ion exclusion membrane and that the role of chemical differences between wellbore fluid and pore fluid is less significant than the difference in pressure between the mud and the formation.[11] This result is an oversimplification since it does not consider what happens after fluid invades the formation raising its pore pressure. However, it does suggest that mud weight should be kept as low as well safety and mechanical wellbore stability considerations allow.[12] These and other results are now being used to design more effective WBM systems and evaluate those that are already available (see "Strategies for Improving WBM Shale Inhibition," page 39).

A number of relatively new types of mud systems have been introduced. For example, one route is to substitute the oil phase in OBM with synthetic chemicals. In this way, the excellent characteristics of OBM may be reproduced with a more rapidly biodegraded continuous phase than was available before.

Typical synthetic base chemicals include esters, ethers, polyalphaolefins, linear olefins and linear alkyl benzenes. One of the chief disadvantages of these systems is that they tend to be relatively expensive compared to conventional OBM. However, such systems can still be cost-effective options compared

to WBM—particularly where OBM would have been used prior to the introduction of new environmental constraints.

The State of the WBM Art

This article will now concentrate on advances in WBM technology by looking at two distinct directions of development: the use of polyols for shale inhibition and the introduction of mixed-metal hydroxides to improve hole cleaning and help reduce formation damage.

Polyol muds—Polyol is the generic name for a wide class of chemicals—including glycerol, polyglycerol or glycols such as propylene glycol—that are usually used in conjunction with an encapsulating polymer (PHPA) and an inhibitive brine phase (KCl).[13] These materials are nontoxic and pass the current environmental protocols, including

those laid down in Norway, the UK, The Netherlands, Denmark and the USA.

Glycols in mud were proposed as lubricants and shale inhibitors as early as the 1960s. But it was not until the late 1980s that the materials became widely considered. Properly engineered polyol muds are robust, highly inhibitive and often cost-effective. Compared with other WBM systems, low volumes are typically required. Polyols have a number of different effects, such as lubricating the drillstring, opposing bit balling (where clays adhere to the bit) and improving fluid loss. Today, it is their shale-inhibiting properties that attract most attention. For example, tests carried out by BP show that the addition of 3 to 5% by volume of polyglycol to a KCl-PHPA mud dramatically improves shale stabilization (*below*). However, a significant gap still
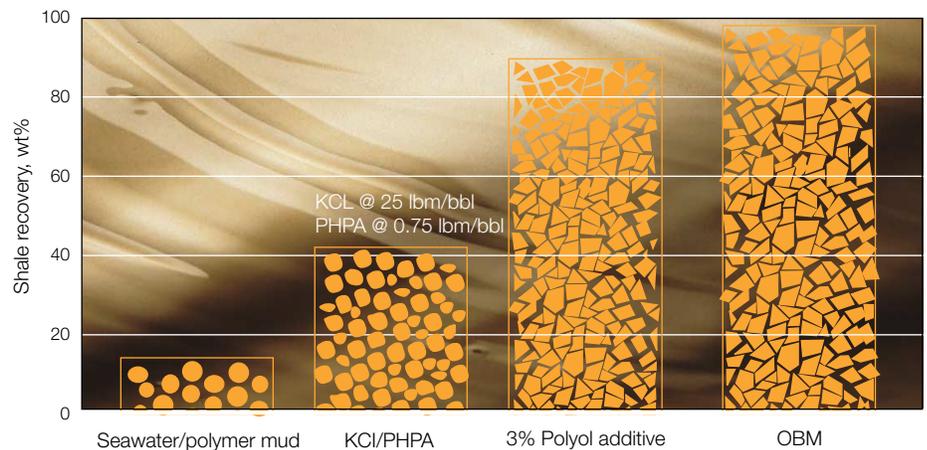
■ *Improving inhibition with addition of polyglycol. This chart shows the recovery of cuttings comprising Tertiary shale—London Clay that contains about 20% smectite—that have been exposed to different muds in an aggressive dispersion test. This test is an indication of a mud's shale stabilizing qualities rather than a simulation of downhole conditions. The weight of the cuttings before treatment is compared to the weight afterwards. Recovery increased from about 40% to 80% with the addition of polyglycol to a KCl-PHPA mud. Conventional seawater-polymer mud yields about 10%, while OBM showed almost 100% recovery.*

9. Hale AH and Mody FK: "Partially Hydrolyzed Polyacrylamide (PHPA) Mud Systems for Gulf of Mexico Deepwater Prospects," paper SPE 25180, presented at the SPE International Symposium on Oilfield Chemistry, New Orleans, Louisiana, USA, March 2-5, 1993.

Bol GM, "The Effect of Various Polymers and Salts on Borehole and Cutting Stability in Water-Base Shale Drilling Fluids," paper SPE 14802, presented at the SPE/IADC Drilling Conference, Dallas, Texas, USA, February 10-12, 1986.

10. Sherwood JD and Bailey L: "Swelling of Shale Around a Cylindrical Wellbore," *Proceedings of the Royal Society* 444, London, England (1994): 161-184.

Hale AH, Mody FK and Salisbury DP: "Experimental Investigation of the Influence of Chemical Potential on Wellbore Stability," paper SPE 23885, presented at the SPE/IADC Drilling Conference, New Orleans, Louisiana, USA, February 18-21, 1992.

11. See Bailey et al, reference 6.

12. For details of how mud weight affects mechanical stability:

Addis T, Last N, Boulter D, Roca-Ramisa L and Plumb D: "The Quest For Borehole Stability in the Cusiana Field, Colombia," *Oilfield Review* 5, no. 2/3 (April/July 1993): 33-43.

Steiger RP and Leung PK: "Predictions of Wellbore Stability in Shale Formations at Great Depth," Maury V and Fourmaintraux D (eds): *Rock at Great Depth*. Rotterdam, The Netherlands: A.A. Balkema (1990): 1209-1218.

13. Reid PI, Elliott GP, Minton RC, Chambers BD and Burt DA: "Reduced Environmental Impact and Improved Drilling Performance With Water-Based Muds Containing Glycols," paper SPE 25989, presented at the SPE/EPA Exploration and Production Environmental Conference, San Antonio, Texas, USA, March 7-10, 1993.

Downs JC, van Oort E, Redman DI, Ripley D and Rothmann B: "TAME: A New Concept in Water-Based Drilling Fluids for Shales," paper SPE 26999, presented at the Offshore Europe Conference, Aberdeen, Scotland, September 7-10, 1993.

Rheology Profile

Rheology Profile at 190°F and 2500 psi
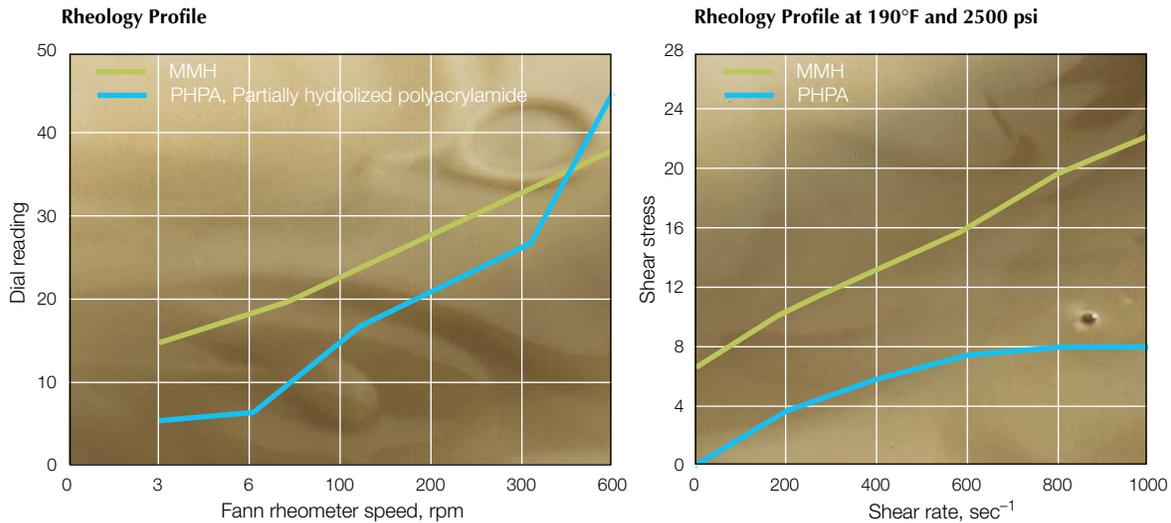
☐**Comparison of the rheologies of MMH and conventional PHPA mud. For MMH, the relatively high 3- and 6-rpm readings and low 300- and 600-rpm readings result in a flat rheology profile that is quite different from that of conventional PHPA mud. With use of a Huxley-Bertram rheometer to measure the rheologies at 190°F [88°C] and 2500 psi, the MMH shows a relatively high shear-stress intercept and a nearly linear rheologic profile. This contrasts with the downward curve of the PHPA mud.** *[Adapted from Sparling DP and Williamson D: "Mixed Metal Hydroxide Mud Improves Drilling in Unstable Shales,"* Oil & Gas Journal *89 (June 10, 1991): 29.]*

remains between the performance of polyol muds and that of OBM.

Field experience using polyol muds has shown improved wellbore stability and yielded cuttings that are harder and drier than those usually associated with WBM. This hardness reduces breakdown of cuttings and makes solids control more efficient. Therefore, mud dilution rates tend to be lower with polyol muds compared with other WBM systems (for an explanation of solids control and dilution, see mud management, *page 39*).

As yet, no complete explanation of how polyols inhibit shale reactivity has been advanced, but there are some clues:

• Most polyols function best in combination with a specific inhibitive salt, such as potassium, rather than nonspecific high salinity.

• Polyol is not depleted rapidly from the mud even when reactive shales are drilled.

• Many polyols work effectively at concentrations as low as 3%, which is too low to significantly change the water activity of the base fluid.

• Polyols that are insoluble in water are significantly less inhibitive than those that are fully soluble.

• No direct link exists between the performance of a polyol as a shale inhibitor and its ability to reduce fluid loss.

Many of these clues eliminate theories that try to explain how polyols inhibit shales. Perhaps the most likely hypothesis—although so far there is no direct experimental evidence supporting it—is that polyols act as a structure breaker, disrupting the ordering of water on the clay surface that would otherwise cause swelling and dispersion. This mechanism does not require the glycol to be strongly adsorbed onto the shale, which is consistent with the low depletion rates seen in the field.

Mixed-metal hydroxide (MMH) mud— MMH mud has a low environmental impact and has been used extensively around the world in many situations: horizontal and short-radius wells, unconsolidated or depleted sandstone, high-temperature, unstable shales, and wells with severe lost circulation. Its principal benefit is excellent hole-cleaning properties.[14]

Many new mud systems—including polyol muds—are extensions of existing fluids, with perhaps a few improved chemicals added. However, MMH mud is a complete departure from existing technology. It is based on an insoluble, inorganic, crystalline compound containing two or more metals in a hydroxide lattice—usually mixed aluminum/magnesium hydroxide, which is oxygen-deficient. When added to prehydrated bentonite, the positively charged

MMH particles interact with the negatively charged clays forming a strong complex that behaves like an elastic solid when at rest.

This gives the fluid its unusual rheology: an exceptionally low plastic viscosity-yield point ratio. Conventional muds with high gel strength usually require high energy to initiate circulation, generating pressure surges in the annulus once flow has been established. Although MMH has great gel strength at rest, the structure is easily broken. So it can be transformed into a low-viscosity fluid that does not induce significant friction losses during circulation and gives good hole cleaning at low pump rates even in high-angle wells (*previous page*). Yet within microseconds of the pumps being turned off, high gel strength develops, preventing solids from settling.

There are some indications that MMH also provides chemical shale inhibition.

This effect is difficult to demonstrate in the laboratory, but there is evidence that a static layer of mud forms adjacent to the rock face and helps prevent mechanical damage to the formation caused by fast-flowing mud and cuttings, controlling washouts.[15]

MMH is a special fluid sensitive to many traditional mud additives and some drilling contaminants. It therefore benefits from the careful management that is vital for all types of drilling fluid.

Mud Management—Keeping the Fluid in Shape

Selecting a reliable chemical formulation for the drilling fluid so that it exhibits the required properties is one part of the job. Maintaining these properties during drilling is another.

Circulation of drilling fluid may be considered a chemical process with the well-bore acting as a reactor vessel. In this reactor, the composition of the drilling fluid will be changed dynamically by such factors as filtration at the wellbore and evaporation at surface; solids will be added and taken away by the drilling process and the solids-control equipment; chemicals will be lost as

14. Fraser L and Enriquez F: "Mixed Metal Hydroxide Fluids Research Widens Applications," *Petroleum Engineer International* 63 (June 1992): 43-45.

Fraser LJ and Haydel S: "Mixed Metal Hydroxide Mud Application in Horizontal Wells—Case Studies Under Diverse Drilling Conditions," presented at the 5th International Conference on Horizontal Well Technology, Houston, Texas, USA, November 9-11, 1993.

15. Fraser LJ: "Unique Characteristics of Mixed Metal Hydroxide Fluids Provide Gauge Hole in Diverse Types of Formation," paper SPE 22379, presented at the SPE International Meeting on Petroleum Engineering, Beijing, China, March 24-27, 1992.

Lavoix F and Lewis M: "Mixed Metal Hydroxide Drilling Fluid Minimizes Well Bore Washouts," *Oil & Gas Journal* 90 (September 28, 1992): 87-90.

Strategies for Improving WBM Shale Inhibition

Researchers at Schlumberger Cambridge Research, Cambridge, England, have proposed a number of strategies for developing mud formulations with improved shale inhibition.[1]

Preventing Filtrate Access

Creation of a semipermeable membrane—If an effective membrane can be produced on the surface of the shale by adding suitable surfactants to WBM, then water ingress could be controlled using chemical activity as in OBM. This effect was obtained, to some degree, with the direct-emulsion WBM used occasionally in the 1980s. The challenge is to identify effective surface active molecules that are environmentally acceptable, do not unduly affect other mud properties and, ideally, show low depletion rates.

Provision of fluid-loss control—Conventional fluid-loss control polymers produce mud filter cakes that are typically one or two orders of magnitude higher in permeability than shales. Even if fractures are present, such polymers may be effective at plugging these relatively large holes, but filter cakes are otherwise unlikely to form on shale. If they did, the shale—the less permeable of the two solid phases—would still control the rate of fluid transport. Given the small dimensions of pores in shales—on the order of

nanometers—fluid loss control is likely to be best achieved either by chemical reactions that greatly reduce, or even eliminate, permeability or by molecules small enough to block pore throats.

Increasing the viscosity of the filtrate— By increasing the viscosity of the filtrate (using for example, silicates or glycols) the rate of ingress is reduced. However, this slowing may not be sufficient to control wellbore stability and the mud may have an infeasibly high plastic viscosity.

Minimizing Subsequent Swelling

If invasion of a WBM filtrate cannot be avoided, appropriate design of the filtrate chemistry may be used to minimize the swelling response of the shale. However, even if swelling is effectively inhibited, filtrate invasion of the shale will increase the pore pressure and add to possible mechanical failure of the rock.

Control of ionic strength—The salinity of the filtrate should be at least as high as that of the pore fluid it replaces.

Choice of inhibiting ion—Cations such as potassium should be incorporated into the formulation. These will replace ions such as sodium found in most shales to produce less hydrated clays with significantly reduced swelling potential. Any inhibitors added to the mud should have sufficient

concentration to remain effective as the filtrate travels through the shale.

Although potassium ions reduce clay swelling, they rarely eliminate it. Recently, there have been attempts to find more effective cations—for example, aluminium complexes or low molecular weight, cationic polymers.

Use of cementing agents—An alternative approach may be to use mud additives that react with the clay minerals and/or pore fluids present in shales to produce cements that strengthen the rock and prevent failure. In field trials, silicate and phosphate salts have demonstrated the potential to cement the formation, although some drilling difficulties unrelated to wellbore stability have been reported—for example, hole cleaning.

1. Bailey L, Reid PI and Sherwood JD: "Mechanisms and Solutions for Chemical Inhibition of Shale Swelling and Failure," presented at the Royal Society of Chemistry 5th International Symposium, Chemistry in the Oil Industry, Ambleside, Cumbria, UK, April 12-14, 1994.

they adhere to the borehole wall and to cuttings, and they will be added routinely at surface; formation fluids will contaminate the mud, perhaps causing flocculation or loss of viscosity, and oxygen may become entrained. Temperature, pressure and possible bacterial action may also have significant effects.

Under these circumstances effective management is not trivial. Nevertheless, basic process control techniques have been applied rigside for some years to aid in the selection and maintenance of the fluid formulation and to optimize the solids-control equipment—such as shale shakers and centrifuges (*next page*).[16] This approach is often linked to incentive contracts, where savings in mud costs are shared between contractor and operator, and has led to remarkable savings in mud costs.

For example, with a systems approach to drilling fluid management for 16 wells offshore Dubai, mud costs were cut in half and reduced as a proportion of total drilling costs from 6% to 3%. At the same time, hole condition remained the same or better—this was assessed by looking at hole diameter, time to run casing and mud usage per foot of well drilled.[17]

Such an approach is based on three premises:
• More frequent and more precise measurements, for example five mud checks per day and the introduction of advanced measurement techniques (more about these later)
• Efficient data management using mass balance techniques—which track the volumes of chemicals, hole and cuttings—and computerized data storage and acquisition
• Integration of the management of the solids control equipment with that of the drilling fluids.

Solids-control efficiency—the percentage of drilled solids removed versus the total amount drilled—is central to drilling efficiency and is a function of the surface equipment, drilling parameters and mud properties. For example, muds that have a lower tendency to hydrate or disperse drilled cuttings generally give higher solids-control efficiency.

The significance of solids control is that penetration rate is closely linked to the volume of solids in the fluid. The greater the amount of solids, the slower the rate of drilling (*below*). Mud solids are divided into two categories: high-gravity solids (HGS) comprising the weighting agent, usually barite; and low-gravity solids (LGS) made up from clays, polymers and bridging materials deliberately put in the mud, plus drilled solids from dispersed cuttings and ground rock.

The volume of HGS should be maximized, so that the total volume of solids in the mud is minimized, while still achieving the density required to control formation pressures. Therefore, drilled solids must be removed by the solids-control equipment. However, some solids become dispersed as fine particles that cannot be removed effec-

□*Mud solids versus rate of penetration. The greater the quantity of solids in the mud, the slower the rate of drilling.*

tively. In this case, the fluid must be diluted with fresh mud containing no drilled solids.
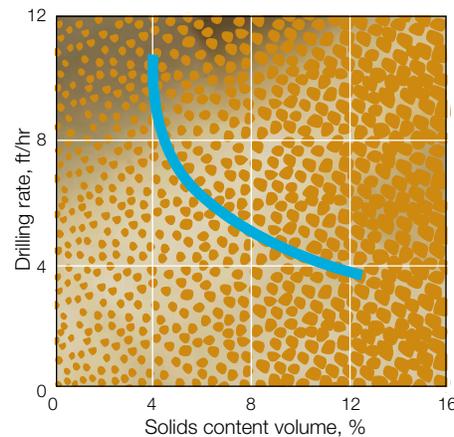
But desirable properties are not always optimum ones. For instance, zero drilled solids at the bit is desirable. However, achieving zero drilled solids would increase mud costs dramatically.[18] It is the job of mud management to plot the optimum course. To do this successfully requires accurate and regular input data.

Traditional field practice is to measure mud density and viscosity (using a Marsh funnel) about every 30 minutes at both the return line and the suction pit. Other properties—such as rheology, mud solids, fluid loss, oil/water ratio (for OBM), pH, cation-exchange capacity, and titrations for chloride and calcium—are measured once every 8 or 12 hours (depending on drilling conditions) using 1-liter samples taken from the flowline or the active pit. These determinations are then used as a basis for mud treatment until the next set of measurements is made.
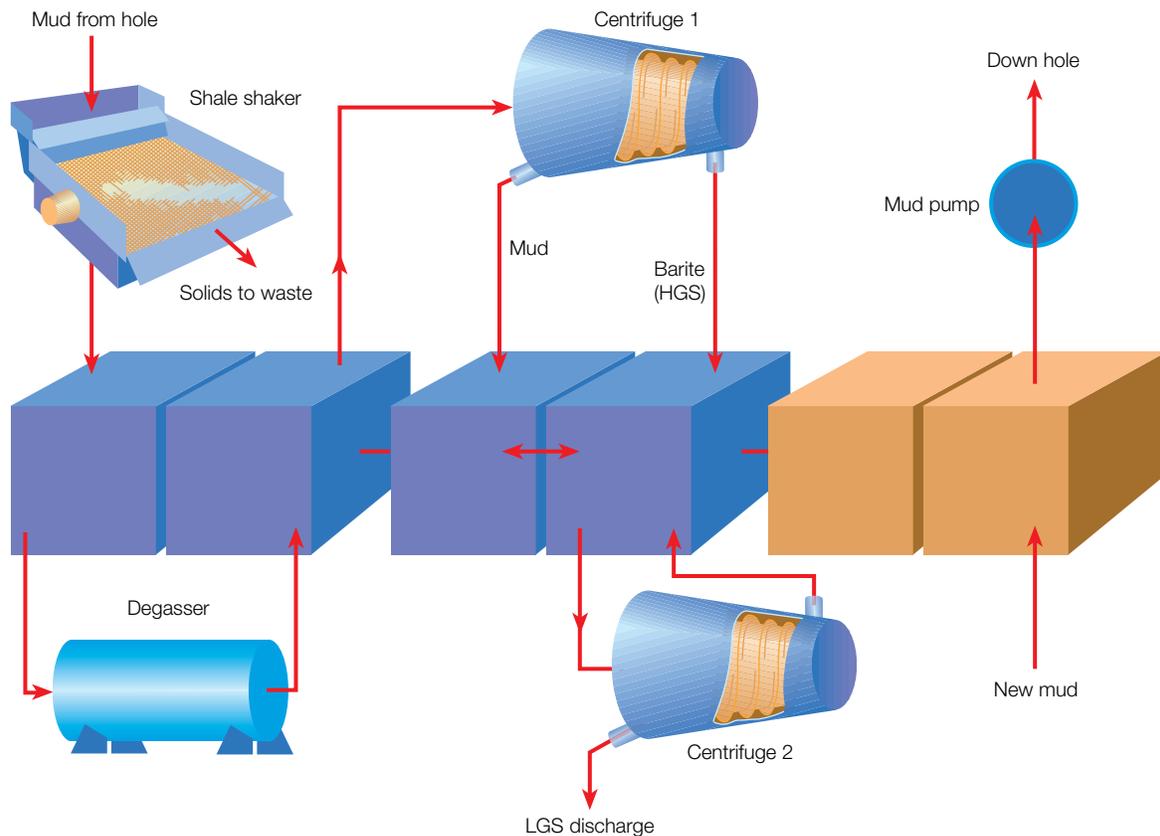
To gain better control over the mud system, a more meaningful monitoring strategy may be required. Simply increasing the frequency of traditional measuring techniques to at least five times a day and making sampling more representative of the whole mud system has improved control and significantly reduced the amount of chemicals used to drill a well.[19] However, new types of measurement are now available. Two new monitoring systems developed by Dowell are the MSM mud solids monitor and the FMP fluids monitoring package.

Mud Solids Monitor—A common indicator describing the solids content in the mud is the LGS-HGS volume ratio. This is traditionally measured using the retort, a technique that requires good operator skills, takes at least 45 minutes and often has an error margin of more than 15%.

The Dowell MSM system takes the place of the retort. Without complicated sample preparation, it offers a 10-minute test with an accuracy of more than 95%. The basic measurement uses X-ray fluorescence (XRF). A standard software package uses the barium fluorescence and backscattering intensity from XRF spectra, together with the fluid density to predict the concentrations of barium and water. From these primary outputs the LGS concentration is also determined. As an off-line measurement, XRF has the

Mud from hole

Shale shaker

Solids to waste

Centrifuge 1

Mud

Barite
(HGS)

Down hole

Mud pump

Degasser

Centrifuge 2

LGS discharge

New mud

□ *Cleaning the mud. The cuttings-removal performance of solids-control equipment depends on many factors, including the size of the mesh for the shale shaker screen, flow rate and density of the drilling fluid, and the size of the cuttings. Deciding how to use the surface equipment also depends in part on the type of mud run.*

With the shale shakers, the aim is to choose a screen mesh size that sieves out as much of the drilled solids as possible, leaving barite, which is finer, in the system. However, the finer the screen, the lower the throughput of mud and the more shale shaker capacity required. In this case, the choice is either to install an extra shale shaker or to fit a wider mesh screen *allowing more of the solids to remain in the fluid that must then be diluted with new, clean mud.*

Centrifuges may be used to control fines. For a low-density mud containing mostly drilled solids, the aim is to strip away as much of the solids as possible. However, if the mud is weighted, fines-control strategy depends on the liquid phase. If the liquid phase is relatively cheap (for example, a seawater-lignosulfonate mud), the barite is the most valuable part of the fluid. In this case, the centrifuge is used to remove all the barite while the rest of the fluid may be dis- posed of. However, if the liquid phase is *also valuable (such as in OBM, KCl-PHPA or glycol muds), both phases are worth keeping. In this case, two centrifuges may be used. First, to remove the barite, which may be reused. Then, the remaining larger solids—assumed to be drilled solids—may be removed and disposed of and the liquid returned to the active system. Clearly, treating mud with the centrifuge is a lengthy process and centrifuges can typically handle only about 15% of the active system.*

16. The MUDSCOPE service was originally developed by Sedco Forex, but has subsequently been offered by Dowell IDF Fluid Services.

   Geehan T, Dudleson WJ, Boyington WH, Gilmour A and McKee JDA: "Incentive Approach to Drill Fluids Management: An Experience in Central North Sea," paper SPE18639, presented at the SPE/IADC Drilling Conference, New Orleans, Louisiana, USA, February 28-March 3, 1989.

17. Moore DJ, Forbes DM and Spring CR: "A Systems Approach to Drilling Fluids Management Improves Drilling Efficiency: A Case Study on the NN Platform in the Arabian Gulf," paper SPE 25646, presented at the SPE Middle East Oil Technical Conference and Exhibition, Bahrain, April 3-6, 1993.

18. Beasley RD and Dear SF: "A Process Engineering Approach to Drilling Fluids Management," paper SPE 19532, presented at the 64th SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, October 8-11, 1989.

19. Geehan T, Forbes DM and Moore DJ: "Control of Chemical Usage in Drilling Fluid Formulations to Minimize Discharge to the Environment," paper SPE 23374, presented at the First International Conference on Health, Safety and Environment, The Hague, The Netherlands, November 10-14, 1991.

FMP Fluid Monitoring Package sensor skid and control rack. This is the first prototype skid which was developed in France, is a complete package comprising a sensor skid, feed pump, control rack, workstation with monitor and printer, and the software.

advantages of more frequent measurement, greater precision and less dependence on operator skills (*right*).[20]

These data provide the basis for informed mud management decisions. For example, using the MSM package offshore Congo, inflows and outflows through the desander and desilter were monitored. From these measurements, the amount of barite and LGS being dumped on an average day was calculated. The MSM package showed that the desander and desilter were removing a lot of valuable barite and not enough of the unwanted LGS.

Analysis of the MSM data showed that in eliminating 11.5 tons [10,430 kg] of LGS per day—the capacity of the desander and desilter—some 45 cubic meters [1590 ft³] of mud were lost, requiring a maintenance treatment including 41.65 tons [37,800 kg] of barite. Based purely on the cost of the barite, it was found to be more cost-effective to dispose of 60 cubic meters [2120 ft³] of mud and dilute the remaining system with new mud requiring only 23.25 tons [22,900 kg] of barite, saving $3339 per day. These findings may vary if mud component costs are included in the analysis—many inhibitive muds have high-value liquid phases—and if the environmental impact of dumping the mud is considered.

Fluid Monitoring Package—At the heart of the system is an in-line skid that continuously monitors the rheology, density, pH, temperature and electrical conductivity of the mud (*above*). Data are stored on hard disk and may be viewed on screen in real or deferred time and on hard copy. Data correlate with data obtained using standard rig equipment, but of course they are continuously delivered.

Measurement by Retort Method
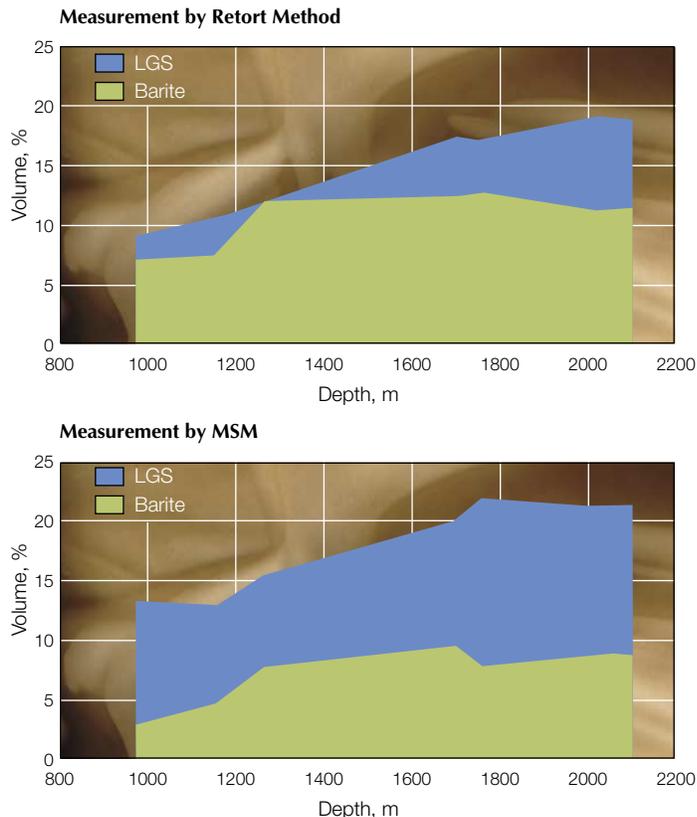
Measurement by MSM

Comparison of the solids content of muds using the traditional retort and MSM measurements. In this example the retort measurement overestimates the barite content, while the MSM measurement indicates a relatively larger amount of drilled solids. If decisions had been based on the retort measurement, necessary remedial action for the mud would not have been carried out and drilling efficiency would have suffered.

For example, rheology is measured using three pipe rheometers. Each of these coiled pipes has a different length and diameter and therefore exerts different shear on the sample of mud as it passes at a known rate through the pipe. Pressure drop on entering and leaving each pipe may then be equated to shear stress. So that data are presented in a form that is comparable to traditional information, shear rate and shear stress are converted to equivalent Fann 35 viscometer readings (*next page, left*). From these, plastic viscosity and yield-point readings may be derived. However, while mud rheology is traditionally measured at constant temperature, the FMP continuous measurement is made as the mud temperature fluctuates during drilling.

The FMP service is currently being field-tested in Europe and Africa. In one field trial lasting five weeks, the FMP was tested on two wellsites for over 915 hours. The system was exposed to three different mud systems —formate, KCl-gypsum, and NaCl saturated —and a wide temperature range—10°C to 79°C [50°F to 174°F]. The tests showed that the hardware is capable of withstanding the rugged demands of drilling, and yielded useful mud logs (*next page, right*).

Oilfield Review

**Comparison of PV Readings Using FMP and Fann Viscometer**
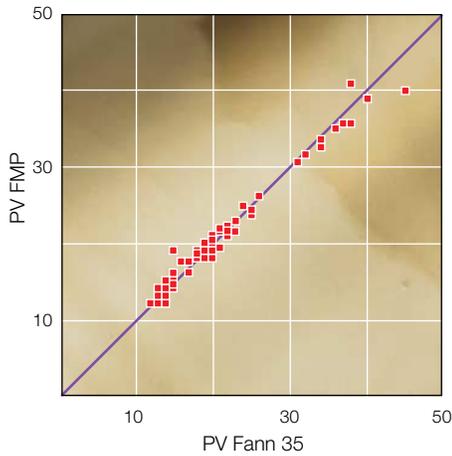
◻ *Comparing plastic viscosity (PV) data gathered in the field from KCl mud using the FMP skid with that generated the traditional way using a Fann 35 viscometer.*

Future Developments

It is still early days for these techniques, but such measurements, and others in development, will furnish the information required to help control a fully automated mud processing plant.[21]

Joint industry field trials are already under way to automate mud management. The aim is to deliver a system with automated solids-control equipment, automated addition of mud chemicals, continuous monitoring of key mud parameters, automated mud system valve control and tank lineup, and central monitoring of integrated process control. A demonstration system has been installed on the semisubmersible rig *Sedco 712*, working in the UK sector of the North Sea, to allow full-scale evaluation.[22]

However, it is clear that the driving force for automated mud processing, and other future developments, must be more cost-effective drilling, improved employee health and environmental compliance, and enhanced well performance.   —CF
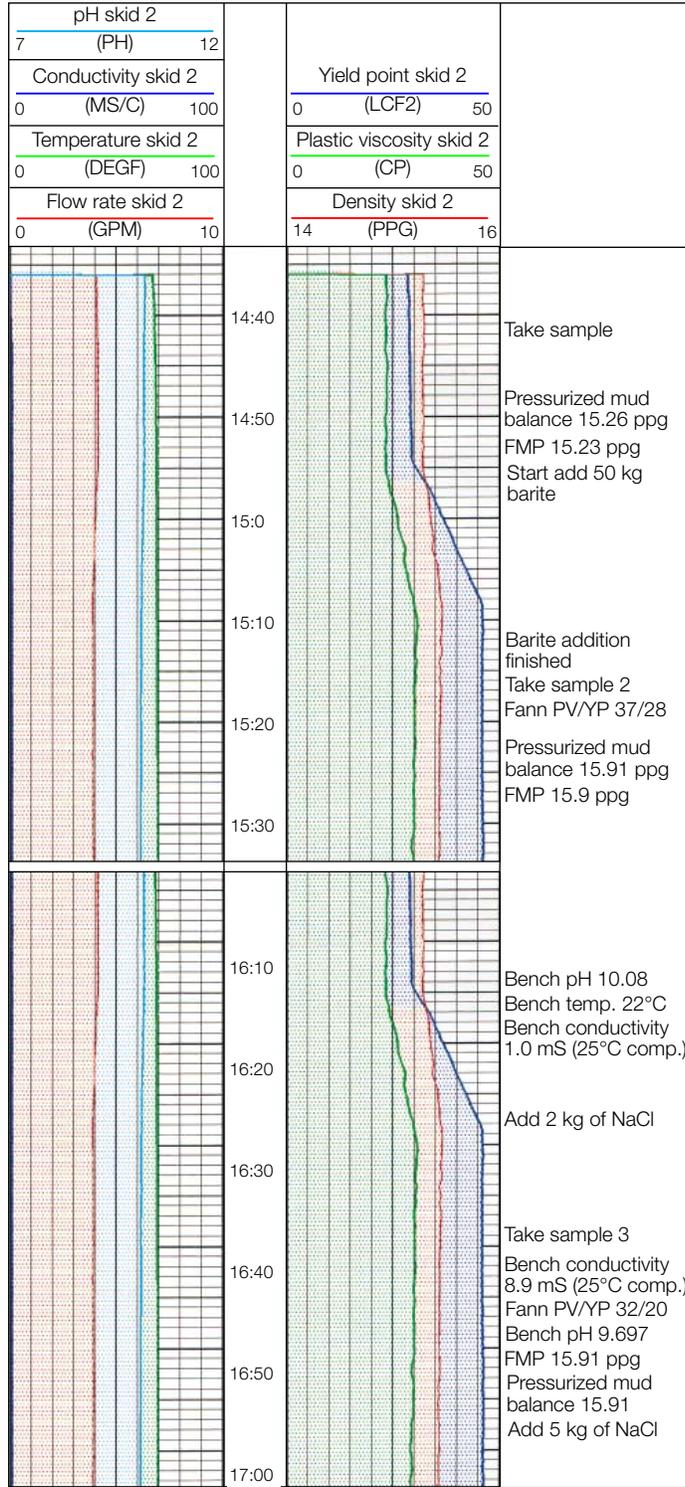
◻ *Minute-by-minute mud information. This example of an FMP log from pilot tests shows how the mud parameters change over 2 hours and 20 minutes. The right column includes bench tests carried out to validate the FMP measurements.*

20. Houwen OH, Sanders MW, Anderson DR, Prouvost L, Gilmour A and White DB: "Measurement of Composition of Drilling Mud by X-Ray Fluorescence," paper SPE 25704, presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February 23-25, 1993.

21. Hall C, Fletcher P, Hughes TL, Jones TGJ, Maitland GC and Geehan T: "Mud Analysis and Control for Drilling," presented at the 4th European Community Symposium on Oil and Gas in a Wider Europe, Berlin, Germany, November 3-5, 1992.

Hughes TL, Jones TGJ and Geehan T: "The Chemical Logging of Drilling Fluids," paper SPE 23076, presented at the Offshore Europe Conference, Aberdeen, Scotland, September 3-6, 1991.

Hughes TL, Jones TGJ, Tomkins PG, Gilmour A, Houwen OH and Sanders M: "Chemical Monitoring of Mud Products on Drilled Cuttings," paper SPE 23361, presented at the First International Conference on Health, Safety and Environment, The Hague, The Netherlands, November 10-14, 1991.

22. The demonstration project is being undertaken by Sedco Forex, Dowell, Thule Rigtech and Marine Structure Consultants (M.S.C.) bv. It is partially funded by The Commission of European Communities Thermie project, Shell UK Exploration and Production, Conoco (UK) Limited and BP International Limited.

Murch DK, White DB, Prouvost LP, Michel GL and Ford DH: "Integrated Automation for a Mud System," paper SPE 27447, presented at the SPE/IADC Drilling Conference, Dallas, Texas, USA, February 15-18, 1994.

Minton RC and Bailey MG: "An assessment of Surface Mud System Design Options for Minimising the Health, Safety and Environmental Impact Concerns Associated With Drilling Fluids," paper SPE 23362, presented at the First International Conference on Health, Safety and Environment, The Hague, The Netherlands, November 10-14, 1991.