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The Top 10 Mud-Related Concerns in Deepwater Drilling Operations – Revisited After 10 Years

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Abstract

By any standard of measurement, exploration activities in the world's deepwater and ultra-deepwater environments have changed appreciably over the past decade. New records for water depth and measured depth in deepwater are being set regularly. Exploration and production activities continue to expand into less-traditional deepwater basins, bringing with them new sets of technical, operational, environmental and economic challenges. Many of those challenges focus on the engineering and application of drilling and completion fluids.

Accordingly, this paper revisits the top 10 mud-related concerns in deepwater drilling put forward in SPE 59019[1] ten years ago. The intrinsic subsurface environment of cold water temperatures, narrow operating windows, gas hydrates and other characteristics has remained unchanged with the passage of time. However, over the past decade, a number of technological advancements and operational approaches have helped mitigate many of the associated concerns.

The authors revisit those top 10 concerns and discuss the corresponding technology and operational solutions that have since been introduced and applied to lessen their adverse influence. The discussion will focus on advancements in managing (1) lost circulation, (2) mud properties, (3) solids transport, (4) stuck pipe, (5) wellbore stability, (6) shallow gas hazards, (7) gas hydrates, (8) reservoir productivity, (9) environmental issues, and (10) fluid-related logistics. Also discussed are some emerging technologies that hold promise in further management and control of these deepwater issues.

Introduction

Typically, discussions on deepwater and ultra-deepwater arenas focus on the Gulf of Mexico, Brazil, and West Africa. In recent years; however, less-traditional areas like India,[2] East Africa, New Zealand, Eastern Mediterranean, and parts of the North Sea and Eastern Canada also have launched major initiatives to explore their versions of deepwater. Over the past 10 years, wells have been drilled in 10,000 ft of water and only last year, India, a relative newcomer to deepwater, constructed a well in 9,035 ft of water. Also, in late 2009, New Zealand announced that the results of a seismic program examining 10 unexplored deepwater basins and sub-basins revealed a conservative reserves base of 20 and 25 billion bbl of oil equivalent.[3]

The geographic expansion of the last decade, likewise, has brought with it different characterizations of what constitutes deepwater. For well-construction purposes, deepwater today generally is considered as any water depth greater than 1,500 ft, while waters deeper than 7,000 ft move into the ultra-deepwater category. Brazil's Petrobras classifies deepwater as starting at 3,281 ft (1,000 m).

Clearly, the enormous prospects for deepwater and ultra-deepwater exploration in tandem with steady increases in daily rates for floating drilling rigs (**Fig. 1)** provide sufficient impetus for the continual advancement of R&D efforts directed at improving the safety, economics and efficiencies in this environment. Plainly, the bulk of those resources continue to focus on minimizing the enormous costs associated with unscheduled events and downhole non-productive time (NPT), which has been said to collectively cost operators annually more than $1 billion in the Gulf of Mexico alone.

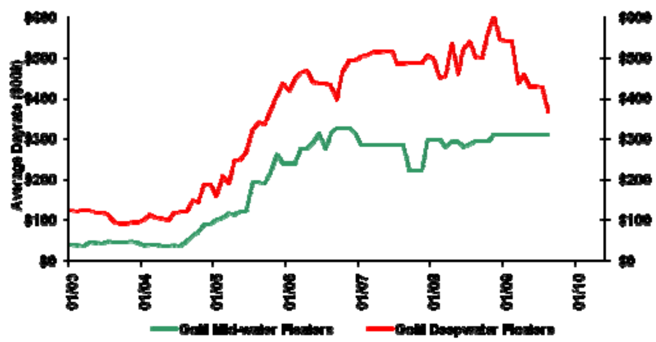

Fig. 1 – Day rates for Gulf of Mexico floating drilling rigs, 2003-2010.

As presented in an SPE conference[1] in 2000, the deepwater environment places serious demands and constraints on both the engineering and application of drilling fluids employed in well-construction operations. Recognizing that failure to adequately address these concerns can result in excessive costs or even loss of the well, industry has devoted considerable resources over the past decade to develop new or improved mud-related technologies and processes.

Consequently, a re-examination of the original top 10 list is in order with a focus on the subsequent technical advances and the resultant effects on both reducing costs and improving operational efficiency. As in the previous publication, discussion in this paper focuses on advancements over the past 10 years to mitigate or prevent issues with (1) lost circulation, (2) mud properties, (3) solids transport, (4) stuck pipe, (5) wellbore stability, (6) shallow gas hazards, (7) gas hydrates, (8) reservoir productivity, (9) environmental issues, and (10) fluid-related logistics.

Some of the downhole characteristics continue to be interrelated, meaning that developing technology to address one concern can affect others. For instance, many of the efforts undertaken to reduce and prevent lost circulation likewise have helped improve wellbore stability. On the other hand, the most difficult challenges still occur when multiple concerns are encountered in the same well, for example when a directional well with hole-cleaning and sag issues is drilled in a deepwater environment with narrow drilling windows.

1. Lost Circulation

Perhaps no single mud-related concern has received more concerted attention over the past 10 years than lost circulation. Inherently low fracture gradients, narrow drilling windows, tight casing/hole clearances, and ill-effects of cold water temperatures on rheological properties contribute to a problem that over the years has accounted for as much as 40% of NPT costs. Operators understandably have intensified pressure to minimize NPT associated with lost returns. Notably, efforts to manage lost circulation have shifted to proactive prevention measures from reactive approaches that rely on lost-circulation materials (LCM) to control losses after they have occurred.

Although lost circulation remains an ever-present concern in deepwater drilling, significant advancements have helped move it down the priority list from its perennial top position. Industry has responded with a portfolio of solutions, including wellbore-strengthening technology, flat-rheology synthetic-based mud (SBM) systems, wide-spread use of annular pressure-while-drilling (APWD) measurements, and advanced hydraulics modeling software, among others. Operationally, dual-gradient and managed-pressure drilling (MPD) technologies have emerged as viable approaches to reduce lost circulation and maintain wellbore stability. In addition, better understanding of leakoff tests and formation-integrity tests have led to developing new fluid additives to improve leakoff values and breakdown pressures in deepwater.[21]

By far, inherently low fracture gradients are the bases for severe lost circulation in deepwater. Drilling fluid density requirements to address downhole pressures and wellbore stability issues can create very narrow drilling margins. Accordingly, pre-spud planning for deepwater wells should include accurate pore-pressure and fracture-gradient predictions, both of which have been widely discussed in the literature.[13,14,15]

Fig. 2 is an example of a Gulf of Mexico fracture gradient plot generated through pre-spud calculations and specialized software modeling. The plot depicts mud weights that are 90% of the overburden weight equivalent. In most cases, lost returns occur when the mud weight is increased above this threshold.

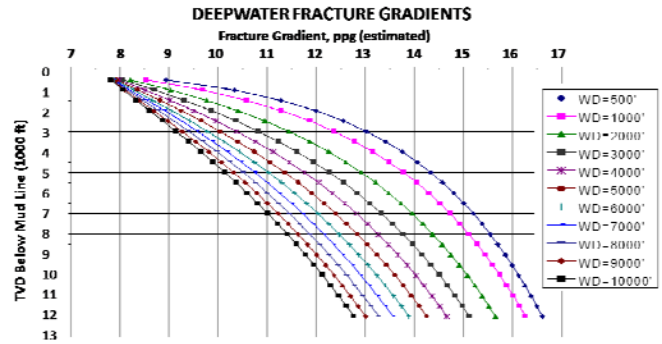

Fig. 2 – Deepwater fracture gradients, depicting mud weights that are 90% of the overburden weight equivalent.

While new technological advancements in LCM have been applied successfully, efforts became more proactive by mid-decade with a focus on developing materials and techniques engineered to prevent lost circulation after identifying potential loss zones. Use of chemically activated pills[5] that combine crosslinking polymers and fibrous materials is but one example of wellbore-strengthening materials (WSM) that allow use of higher mud weights without losing returns.[6,7,8] These efforts primarily have taken an integrated approach to wellbore strengthening, encompassing an extension of historical concepts surrounding fracture propagation resistance and investigations to identify suitable WSM and appropriate concentrations.

Flat-rheology SBMs[10,11,12,33] developed for deepwater applications have proven in the field to exhibit much less sensitivity to wide temperature and pressure variations. Cold temperatures in deepwater risers can exponentially increase viscosity of conventional systems, thereby increasing equivalent circulating density (ECD) and endangering lost circulation. Steps to control this viscosity increase can impede hole cleaning efficiency and barite sag mitigation downhole where temperatures and pressures are greater. The goal of flat-rheology systems is to provide a balance between low ECDs and good hole cleaning and barite suspension.

Minimizing lost circulation also has been a driving force behind intensified interest in dual-gradient and managed-pressure drilling.[16-19] **Fig. 3** compares the equipment and configuration of dual-gradient drilling with conventional riserless drilling and drilling with a marine riser. Basically, dual-gradient drilling involves the introduction of two fluid pressure gradients to extend the initial casing depth, thus making it a highly attractive option for deepwater. Further, MPD in tandem with automated dynamic pressure control and accurate modeling of drilling-fluid hydraulics has exhibited its capacity to allow re-entry of highly depleted deepwater structures.[18] The technology has been shown to create a stable wellbore with a mud density lower than that typically required to control the formation under normal drilling conditions, thereby effectively reducing ECD and resultant lost circulation incidents.

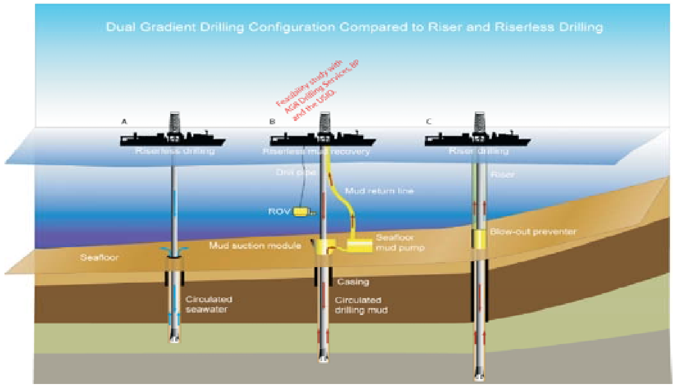

Fig. 3 – Comparison of dual gradient drilling with conventional riser and riserless drilling techniques.

Finally, computer modeling and simulations have successfully captured downhole drilling-fluid behavior and provided this useful information to fluid-system developers and drilling personnel at all levels. Perhaps the most interesting advancement in this subject area over the past decade has been the increasing use of real-time data interpretation.[4] In many applications, the most important use has been to provide virtual ECD values to the driller while running casing. This has significantly reduced lost circulation problems during these operations that cannot take advantage of APWD sensors.

2. Mud Properties (Density and Rheology)

Synthetic and low-toxicity-oil muds, for the most part, have become the systems of choice for most deepwater drilling operations. Best practices to monitor and minimize the dramatic effects of wide variations in temperature and pressure on density and rheology have been largely successful. These efforts have been significantly helped by development of flat-rheology synthetic-based mud (SBM) systems less sensitive to temperature and pressure variations. Further, introduction of micronized weight materials (including barite, manganese tetroxide, and ilmenite) for both aqueous and non-aqueous drilling fluids likewise has helped maintain proper rheological properties, especially in extended-reach, deepwater applications.

Maintaining reasonably consistent rheological parameters is difficult, in part, because of water temperatures that can be below 40°F in the Gulf of Mexico and West Africa, and 25°F in the North Sea. **Fig. 4** illustrates the relationship between Gulf of Mexico seafloor temperatures with water depth. Moreover, deeper waters mean that the drilling fluid will be exposed to these cold temperatures for longer periods. As such, flowline temperatures in the North Sea are roughly 60 to 65°F, while those in the Gulf of Mexico average 55 to 65°F.

Little can be done to mitigate temperature and pressure effects on drilling fluids density, especially those with non-aqueous external phases, so it follows that extra care must be taken to determine downhole densities by APWD measurement or computer simulation. Equivalent downhole densities (ESD) depend on the pressure-volume-temperature (PVT) characteristics of its liquid components and the compressibility of solid constituents. **Table 1** lists PVT values of sample base fluids as published in API RP 13D[9] released in 2006 to address key issues encountered in critical wells drilled today.

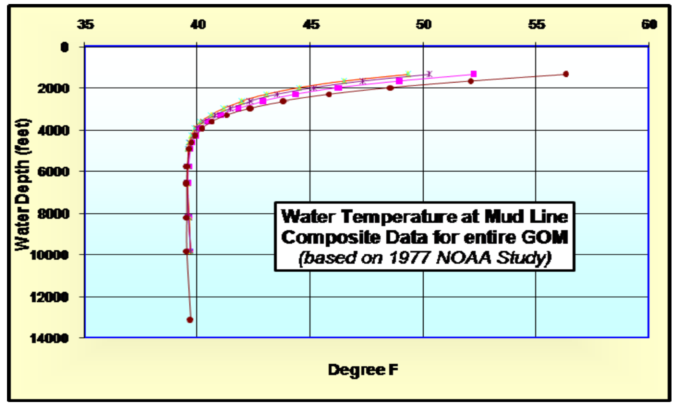

Fig. 4 - Gulf of Mexico seafloor temperatures versus water depth (from National Oceanic and Aquatic Administration).

Table 1- Pressure and Temperature Coefficients for Determining Fluid Density[9]

	Calcium Chloride 19.3 wt %	Diesel	Mineral Oil	Internal Olefin	Paraffin
Pressure Coefficients					
a_1 (lb_m/gal)	9.9952	7.3183	6.9912	6.8358	6.9692
b_1 (lb_m/gal/psi)	1.77 E-05	5.27 E-05	2.25 E-05	2.23 E-05	3.35 E-05
c_1 (lb_m/gal/psi^2)	6 E-11	-8 E-10	-1 E-10	-2 E-10	-5 E-10
Temperature Coefficients					
a_2 (lb_m/gal/ºF)	-2.75 E-03	-3.15 E-03	-3.28 E-03	-3.39 E-03	-3.46 E-03
b_2 (lb_m/gal/psi/ºF)	3.49 E-08	7.46 E-08	1.17 E-07	1.12 E-07	-1.64 E-08
c_2 (lb_m/gal/psi^2/ºF)	-9 E-13	-1 E-12	-3 E-12	-2 E-12	2 E-13
Fitting Statistics for Modeled Data					
Avg. Error %	0.135	0.237	0.166	0.194	0.214
r^2 coefficient	0.998	0.997	0.998	0.998	0.999
Range of Validity					
Maximum Applied Pressure (psi)	20,300	20,000	20,300	24,000	14,500
Minimum Temperature (ºF)	77	40	77	56.4	68
Maximum Temperature (ºF)	392	400	392	392	302

Base fluid and brine density as functions of temperature and pressure can be calculated using the following equation where constants for several fluids are listed in **Table 1** and densities ρ are in lb/gal, pressure P is in psi, temperature T is in °F:

$$\rho_{\text{base}} \text{ or } \rho_{\text{brine}} = [(a_1 + b_1P + c_1P^2) + (a_2 + b_2P + c_2P^2)\ T]$$

The form of this equation is similar but not identical to the one published previously,[1] so care must be taken to correctly match the curve-fit constants. ESD at a given depth is then the numerical integration of local fluid densities determined from:

$$\rho_i = \frac{\left(\text{Vol}_{\text{base}} \times \rho_{\text{base}} + \text{Vol}_{\text{brine}} \times \rho_{\text{brine}} + \text{Vol}_{\text{ds}} \times \rho_{\text{ds}}\right)}{\text{Vol}_{\text{total}}}$$

Computer simulations in concert with APWD measurements have proven valuable for estimating downhole densities and rheological properties, and even essential for addressing critical concerns. Data from downhole APWD tools clearly demonstrate the high-pressure transients that can be impressed upon the borehole when the mud pumps are turned on and off. Conventional, steady-state computer solutions routinely used for planning, analyzing, and evaluation have now been augmented by transient and real-time interpretations that incorporate the impact of density and rheology profiles on downhole drilling operations and concerns.

Achieving flat-rheology profiles is a function of a re-designed package of emulsifiers, rheology modifiers and viscosifiers that reduce key viscosity parameters at low temperatures while raising them when temperatures increase. The general concept is illustrated in **Fig. 5**. Field results have demonstrated that elevated, but flat rheological profiles, including low-end rheology, yield point and 10-min gel strength, can lower ECDs.

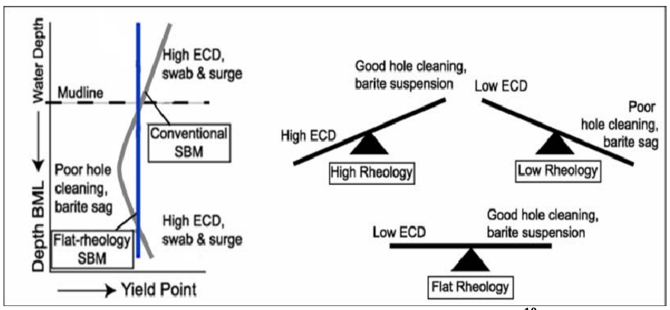

Fig. 5 - Illustration of flat-rheology concept.[10]

Fig. 6 compares rheograms for conventional and flat-rheology SBMs at 40°F and 150°F. Note the temperature effects and the close proximity of the 40°F flat-rheology and 150°F conventional system rheograms.

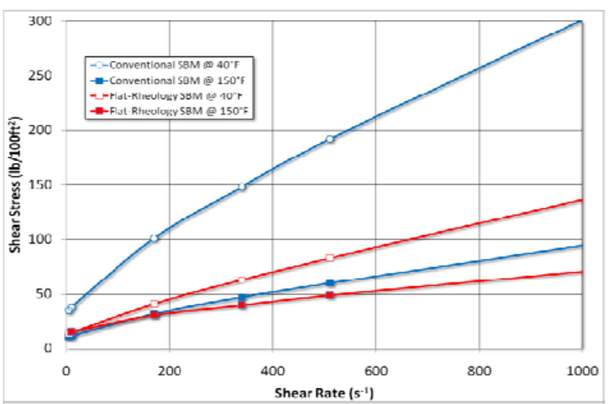

Fig. 6 - Rheogram comparison between conventional and flat-rheology synthetic-based muds.[11]

Rheological parameters of both invert emulsion and water-based drilling fluids also have been optimized with the introduction of micronized weight materials. One technology[22] involves reducing barite particles from the API median size of 25 microns to less than 2.5 microns. Field results have shown the micronized technology to reduce ECD and surge/swab pressures. Improved hole cleaning and reduced instances of barite sag also have been documented.

Fig. 7 compares rheograms for two different drilling fluids, one weighted with micronized barite and the other weighted with API barite.

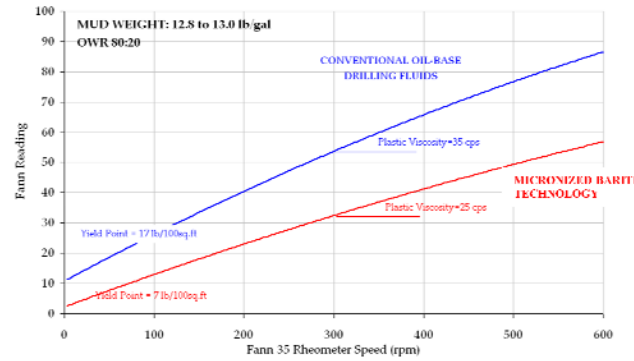

Fig. 7 - Comparison rheograms for oil-based muds weighted with conventional and treated micronized barite.

3. Solids Transport (Hole Cleaning and Barite Sag)

Problems with hole cleaning and barite sag in deepwater drilling persist despite general agreement on fundamentals and best practices to mitigate or eliminate the issues. Despite advancements over the past decade, solids-transport technology continues to be tested by increasingly complex and demanding deepwater wells, especially those drilled directionally and for extended-reach purposes.

Improved engineering of rheological properties and the introduction of micronized weight materials have made the biggest impact from the fluids perspective, but rotary steerable systems[34] (RSS) and enhanced computer modeling have also contributed significantly. As before, drilling practices ideal for addressing solids-transport issues can still be detrimental to other concerns. As such, fluid properties, hydraulics, and practices selected in the field often represent engineering compromises.

Annular velocity, rheological properties, and pipe rotation remain among the key physical parameters for efficient hole cleaning[23] and sag mitigation. Velocity and rheology options have to be tempered in the presence of narrow drilling windows created by low fracture gradients, higher mud weights required to maintain wellbore stability in high-angle holes, and low temperatures.

Pipe rotation in combination with eccentricity and proper rheological properties has now been proven to be a viable operational practice. Wide use of RSS, which permit continuous rotation of the drill string during directional control, has significantly enhanced transportation of cuttings to the surface, barite suspension, and erosion of existing cuttings and barite beds.

Low-shear rheology (expressed as a viscosity or yield stress) is now firmly entrenched for hole cleaning and sag mitigation, as demonstrated in API 13D.[9] Unfortunately, consensus still has not been achieved on the best method to measure or determine a representative parameter. LSYP (low-shear yield point) based on 6 and 3-rpm viscometer reading may have the best chances for gaining traction. Perhaps consideration for viscoelastic effects may offer new opportunities.[24] Regardless, there is no evidence at this time that any given parameter will be the proverbial "magic bullet" that can eliminate solids-transport issues without concern for drilling practices.

Micronized weighting agents have made major inroads in deepwater applications where sag is particularly difficult to manage due to operational restrictions. Fundamentally, this approach greatly minimizes the mass of the weight-material particles and reduces sag tendencies under dynamic and static conditions. Continued refinement of this technology is expected in order to address more demanding wells in the future.

Finally, persistent issues related to lack of standardization on sag measurement and reporting have moved the API to develop a new bulletin primarily devoted to wellsite considerations.[35] A major contribution is the recommendation that sag be reported as the difference between maximum and nominal mud weights while circulating bottoms up after a period where the mud has been static.

4. Stuck Pipe

Stuck pipe is one of those persistent concerns that realistically cannot be eliminated in deepwater operations. Any number of downhole conditions can cause stuck pipe, including differential sticking, hole packoff and bridging caused by an unstable wellbore or key seats, doglegs and other well geometries can initiate sticking. Rotary steerables, wellbore strengthening and stability initiatives, non-aqueous drilling fluids, and improved drilling practices have been instrumental in minimizing the problem. For the case differential sticking, some have suggested that prevention should not be a design objective. Instead, operational practices should be such that differentially stuck pipe can effectively be pulled free.[25]

Escalating rates for floating drilling vessels make stuck pipe a serious concern in deepwater drilling. Consequently, operators drilling in areas known or suspected to be prone to stuck pipe prefer to use invert-emulsion fluids with their high lubricity characteristics. This also assists while running casing, an activity highly vulnerable to stuck pipe. While the typically slow running speeds may alleviate lost circulation, it raises the risk of stuck pipe. Real-time measurements and data interpretation have proven particularly useful in this regard.[4]

Rotary steerable systems proven to benefit hole cleaning, also reduce wellbore tortuousity and incidents of stuck pipe. RSS have been shown to lessen dramatically the impact of vibration when drilling subsalt wells.[34] The ability to rotate 100% throughout the drilled interval can provide a high quality wellbore with smoother build rates, lower dog legs and fewer ledges. A smoother and less tortuous wellbore is important since experience has shown that ovalized holes are more prone to casing deformation and cementing issues.

Operationally, new and notable recommendations[25] for addressing differentially stuck pipe include:

- For weight on the bit in vertical and low-angle holes, use heavy weight drill pipe in compression; in intermediate and high-angle wells, use conventional drill pipe in compression
- Use stand-off subs on drilling jars run above stabilized bottomhole assemblies
- Conduct progressive pipe sticking tests before connections
- Run API particle-plugging tests to assist design of improved filter cakes
- Consider pipe-sticking risks associated with wear grooves in high-angle wells, even if non-aqueous drilling fluids are in use.

5. Wellbore Stability (Shale Problems and Wellbore Stresses)

Most problems resulting directly from wellbore instability and exacerbated in deepwater are related to unstable or chemically reactive shales, unconsolidated formations and/or reservoir depletion. Over the past few years, much of the research emphasis has expanded from a focus on shale inhibition to a broader view encompassing wellbore strengthening and optimization of wellbore integrity.

From a conventional fluids perspective, industry has continued to refine guidelines for optimum water-activity levels in synthetic- and oil-based drilling fluids. This has markedly improved wellbore stability while drilling water-sensitive shale formations.

While casing and cement arguably provide the most effective pre-emptive strategy for wellbore strengthening, their costs and logistical issues often outweigh potential benefits. Hence, throughout much of this decade, interest in artificially strengthening the wellbore has intensified, as reflected in the literature.[26,27,28,29,30]

The fundamental difference between dealing with simple lost circulation and those targeted towards wellbore strengthening is that remedies for whole mud loss are concerned only with mitigating the losses. Conversely, wellbore strengthening focuses on avoiding losses at the onset by isolating the fractures from the wellbore and in so doing enable safe drilling to proceed with mud weights that exceed the local fracture gradient.

Various methods have been proposed to strengthen formations and to help stabilize the wellbore and to allow use of higher mud weights, including fracture closure stress, stress cage, and fracture propagation resistance. Other techniques include imposing a mechanical barrier such as expandable screens, using cross-linkable plugs or particulates to effectively seal the fractures, and heating the mud system.

A more recent multi-disciplinary approach has been introduced that essentially integrates chemical, mechanical and engineering to implement wellbore strengthening solutions. A key component is specially engineered wellbore strengthening materials (WSM) for plugging, bridging and sealing fractures, and thereby enhancing formation integrity and the apparent near wellbore fracture gradient.[31]

Design of the particulate treatment is carried out with proprietary software to calculate the width of induced stabilizing shallow fractures that are generated during treatment and the blend of particulates required to fill and hydraulically seal those fractures thus isolating the fracture interior and preventing further unstable fracture propagation. The software package initially calculates the width of induced shallow fractures that is required to achieve a desired wellbore pressure. **Fig. 8** is a sample fracture/bridging model generated with the software. In addition, the package is used to calculate the particle-size distribution (PSD) that will effectively seal the induced fractures, and it designs the WSM blend that provides that PSD. The engineering tool uses Monte Carlo simulations to generate a probability distribution for the maximum fracture width (fracture mouth) and particulate formulation using expected uncertainties in rock properties and drilling parameters.

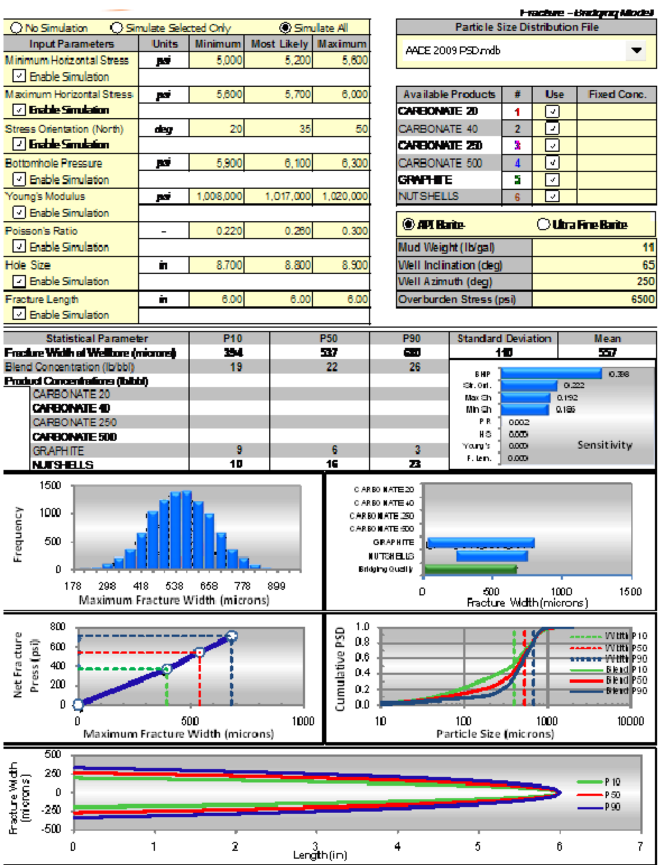

Fig. 8 - Sample output for wellbore-strengthening software.

Furthermore, the integrated approach also includes a specially engineered fit-for-purpose shaker (**Fig. 9)** and a managed-particle-size recovery system. The shaker can be used during drilling to recover valuable bridging solids and remove coarse cuttings and fines, thus minimizing waste and maintaining acceptable fluid rheological and filtration properties. The recovery system (**Fig. 10)** consists of a series of solids-control equipment arranged to enable continuous treatment of the drilling fluid with the desired WSM while effectively removing undesirable drilled solids from the drilling fluid to avoid adverse effects on rheology and ECD.

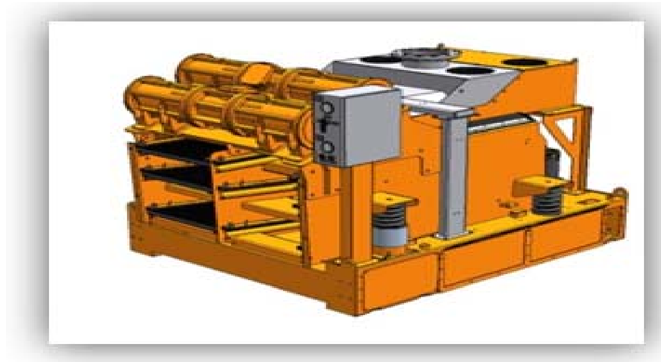
Fig. 9 - Triple-deck shaker used to recover bridging particles.

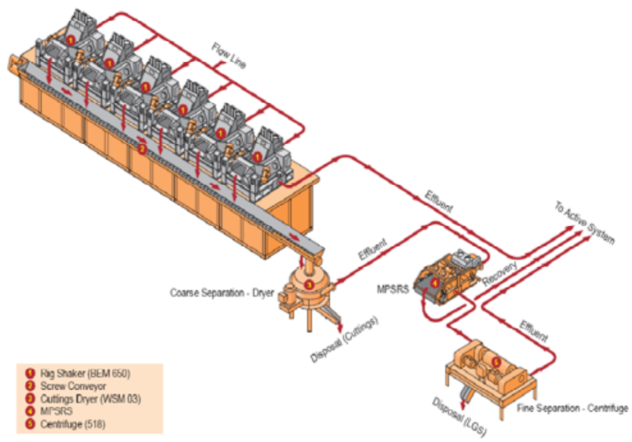

Fig. 10 - Managed Particle-Size Recovery Process.

6. Shallow Hazards

Identification of shallow water-flow and pressurized gas zones has always been a key to minimizing potentially catastrophic results. Logs of different types, geotechnical data, seismic surveys, seafloor surveys, and known mud volcanoes and shale diapirs are among the tools used by industry. Even when shallow hazards are expected, careful planning is required to ensure proper execution on demand.

Riserless drilling is typically used to contend with shallow water-flow zones, but this can present challenges:[31]

- Supplying enough weighted fluid at the wellsite to drill the interval
- Preventing bit balling and hole pack-off with cuttings
- Maintaining adequate hole cleaning in a large-diameter hole at reasonable drilling rates
- Maintaining well control by monitoring ECD at the suspected flow zone as well as at the bit while drilling ahead.

Drilling riserless with seawater with bentonite sweeps until the hazard is confirmed is still the accepted method. Thereafter, weighted muds are used to drill the interval, preferably with fifth or sixth-generation drillships with enormous mud storage capacities to handle the 10,000 to

30,000 bbl that may be required. Hydraulics software helps maintain the proper ECD values required to inhibit flow and prevent losses while drilling to casing point.[31]

In order to meet the volume requirements, mixing-on-the-fly techniques using vortex-type mixers have demonstrated their capacity to provide sufficient volume and density for drilling through shallow flow zones. Utilization of the "mix-on-the-fly" method has been shown to allow the 20-in. conductor string to be set comparatively deeper, thus allowing casing points to be extended.

7. Gas Hydrates

Deepwater presents a perfect storm of conditions for the formation of gas hydrates. While they can jeopardize the safe drilling and completion of a well by plugging the upper annulus, BOP stack and choke/kill lines, attention to the issue has diminished, largely because the wide use of synthetic-based drilling fluids in deep and ultra-deepwater environments. Though only a few serious problems with gas hydrates have been documented, the potential risk cannot be ignored and contingencies must be incorporated in the well plan.

While aqueous-based fluids incorporating kinetic hydrate inhibitors have been developed and shown to provide temperature suppression to a degree,[32] they do not have nearly the hydrate inhibitive characteristics of a properly formulated SBM. To provide a desirable level of inhibition, an aqueous-based fluid must be formulated to prevent hydrate formation at the lowest temperature it will be exposed to and the highest pressure anticipated at this lowest temperature point. Unfortunately, it is not always possible to avoid or even know the impact of each additive will have on stabilizing hydrates. Even products as common as clay, lignite, lignosulfonate, and polymers can promote and stabilize gas hydrates.

Oil-based and synthetic-based drilling fluids are preferred fluids when hydrates are expected to be encountered in deep and ultra-deepwater. Hydrates forming in non-aqueous fluid systems can cause phase separation, but they will only form in the water phase. Hydrate formation is inhibited in the water phase of these muds by the salinity of the internal (brine) phase. The internal phase is generally maintained at 20-25% by weight calcium chloride or higher. Moreover, since gases dissolve in oil and synthetic muds, they do not migrate up the wellbore to the mudline, resulting in kicks normally being contained at depths warm enough to prevent hydrate formation.

Hydrate zones and the associated gas and water sands usually can be identified from shallow seismic data before drilling commences. Ironically, over the past 10 years, interest has increased in looking at hydrates not as a geohazard, but as an abundant clean energy source. The USA, Japan, New Zealand and others have intensified efforts to examine the prospects of exploiting the plethora of methane gas in the deepwater as a clean energy source. The New Zealand Centre for Advanced Engineering, for instance, has undertaken a study to examine the options for developing and commercializing the methane hydrate potential of its deepwater basins that it estimates to be 20 times greater than its giant Maui gas field.[2]

8. Reservoir Productivity (Formation Damage and Evaluation)

The increased number of deepwater wells entering the development mode has generated more attention to the refinement of completion and reservoir drilling fluids that deliver minimal formation damaging characteristics. However, unlike many drilling environments, deepwater continues to be an exploratory province where one of the main objectives is to evaluate the future productivity of a reservoir. While freshwater and low-salinity WBMs provide the ideal log environment, their performance characteristics are less than those for SBMs. Unfortunately, the promising conductive SBMs mentioned in the original paper faded due to development of new logging tools.

Most of the attention over the past decade has focused on reservoir drilling fluids that deliver a minimally damaged production target. A notable example is the once fledging and now commonplace reversible emulsion drill-in fluid that exhibits the drilling benefits of conventional oil-based muds, but with the cleanup characteristics equivalent to or better than biopolymer calcium carbonate water-based drill-in fluids.[33] Conversion from a non-aqueous to a water-based system is accomplished by changing the pH to replicate WBM-like clean-up of the deposited filter cake.

An unwanted effect of the deepwater environment is the potential solidification of completion brines at a seabed temperature well above its atmospheric true crystallization temperature (TCT), which is defined as the point where salt could precipitate. An important consideration that has developed is the influence of pressure on TCT, a phenomenon commonly referred to as pressurized crystallization temperature (PCT). A completion fluid in a deepwater environment is influenced by the combination of high pressure and cold temperatures, due to the column of fluid between the seafloor and the surface and the cold seawater at sea bottom. Before these influences were understood and accounted for, several instances of sea floor completion fluid crystallization were reported. In those situations, the combination of pump pressure and hydrostatic column resulted in crystallization (PCT) at a temperature above the measured atmospheric pressure crystallization point (TCT). These concerns are now better managed by laboratory testing that considers pressure and temperature effects on the fluids in question.

9. Environmental Issues

Industry has responded to growing environmental issues with a number of innovative drilling waste management initiatives for deepwater, including pneumatic collection and transfer of cuttings and newly introduced offshore boat and tank cleaning technologies. Shore-based environmental centers that accept, treat and recycle spent drilling fluids also have become widespread over the past few years and efforts to move cuttings re-injection (CRI) technology to the deepwater, likewise, is gaining increased interest.

During the past decade, however, much of the attention has focused on SBMs used in deepwater, which most government regulators agree are preferred from an environmental standpoint as their high performance characteristics reduce the risks of ancillary pollution sources arising from extended time on location. Accordingly, while some offshore theaters have adopted strict zero discharge policies for contaminated cuttings, regardless of the source fluid, the controlled discharge of SBM-generated cuttings is allowed in many deepwater basins around the world.

In 2000, the US Environmental Protection Agency included synthetic base fluids in its Final Effluent Limitation Guidelines, thereby allowing controlled discharge, and followed a year later with its final modification of the general permit of the National Pollutant Discharge Elimination System for the Western Gulf of Mexico. For the first time, the federal agency had clearly authorized the discharge, albeit controlled, of SBM cuttings. These requirements have been addressed in the Gulf of Mexico by teams of drilling fluid specialists, whose responsibility is assisting operators in complying with the discharge regulations.

Regulations in the North Sea are markedly more restrictive with the OSPAR decision in 2000 that eliminated SBM discharges. In that theater, cuttings, therefore, must either be hauled to shore for treatment and disposal or injected in-situ. Elsewhere, South America, West Africa and the Far East currently allow controlled discharge, but cuttings must meet individual biodegradation and toxicity criteria.

10. Fluid-Related Logistics

Logistical challenges are magnified by the deep and ultra-deepwater environment. Clearly, the massive volumes of mud and equipment plus drilling locations far from the shore base means the pre-spud planning for a successful deepwater drilling operation requires even more attention to logistical issues, including vessel turnaround time from the liquid mud plant to the rig. Since fluids and other materials must be available at the rig when needed, capabilities and services necessary to handle large quantities of fluids and dry materials in a timely fashion are paramount. As such, both liquids and dry materials must be available at the distribution site and appropriate transportation must be available to deliver it to the rig, which, in turn, must have the capability to store and access the liquids and dry materials as needed. Therefore, the movement of this material must be carefully planned and coordinated. Since the drilling operation dictates the logistical requirements, logistical planning must be based on the drilling program.

Obviously, the scale of the rigs and support vessels used in deepwater projects bear little resemblance to their shallow water counterparts. Owing to the volume of mud required, most operators have adopted as best practice a requirement that a deepwater rig must have storage capacity for a minimum of 5,000 sacks of barite on location to increase the density of the active mud system 1.0 lb/gal if an emergency arises. In addition, new generation drillships also have been designed to handle a 6,000-bbl active mud system.

Vessels servicing a deepwater rig now should have a liquid capacity of at least 3,000 bbl, but some displacements may require more volume. Ideally, the support vessel also would have the capability to pump 1,000 sacks of bulk material onto the rig in one hour and possess high-output liquid pumps to off-load liquid mud and other liquids. The logistical challenge of deepwater operations was reflected in early 2010 with the introduction of the world's largest supply vessel in the Gulf of Mexico (**Fig. 11).**

Fig. 11 - At 370 ft, the HOS Centerline was introduced to the deepwater Gulf of Mexico in early 2010 as the world's largest supply vessel. (Photo Courtesy of Hornbeck Offshore).

The geographic expansion also has placed pressure on suitable shore-based locations to service deepwater operations. One alterative being examined is to station offshore drilling fluid support bases with sufficient inventory of drilling fluids, chemicals and bulk material.

Technical Challenges Going Forward

As deepwater operators continue to expand into more geographic areas and deeper depths, the industry must continue to adapt with technologies to meet increased technical, economic, and environmental demands. From a drilling fluids standpoint, research is continuing on new technical approaches to drilling the prolific subsalt/presalt structures, especially with respect to improving efficiencies in dealing with underlying tar and/or asphalts. Work also is continuing on developing improved versions of the flat rheology SBM, along with continuing research in reactive shale inhibition.

Finally, work continues in developing rig-based environmental solutions for processing cuttings for safe discharge. Deepwater-specific production chemicals represent an area where new products are being introduced for use on new floating production storage and offloading vessels.

Conclusions

Steady advancements in technology and operational efficiencies over the past decade have played significant roles in minimizing many of the mud-related deepwater concerns raised in 2000, including:

- New developments in wellbore strengthening and creation of integrated approaches to wellbore stability during drilling.
- Development of flat-rheology SBMs to address the adverse-effects of wide variations in temperature and pressure on rheological properties in deepwater.
- Introduction of micronized weighting agents to effectively mitigate and even eliminate barite sag, while helping improve hole cleaning and ECD management.
- Implementation of reversible reservoir drilling fluids for maximum drilling performance and improved cleanup.
- Environmental centers to treat potential waste for maximum recycling and minimum disposal.
- Expansion of shore bases to better service deepwater operations.
- Refinement of managed-pressure and dual-gradient drilling technology to better engineer downhole wellbore pressures.
- Introduction of rotary steerable systems to provide directional control and provide advantages of rotating drill strings.
- Improved software that improves simulation of the downhole hydraulics environment in steady state, transient, and real-time scenarios.

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