Seamless Fluids Programs: A Key to Better Well Construction

New insights into displacement mechanics inside casing and in the annulus, combined with integrated drilling and cementing fluid services, can improve primary cementing. This structured “fluids-train” approach also optimizes overall drilling and completion performance at lower cost for operators.

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In this article, CBT (Cement Bond Tool), CemCADE, CET (Cement Evaluation Tool), DeepSea EXPRES, EXPRES, MUDPUSH, SALT BOND, USI (Ultrasonic Imager) and WELLCLEAN are marks of Schlumberger.

Improvements in well construction are possible if long-standing boundaries between drilling and cementing can be eliminated, and if mud removal and displacement criteria are properly applied. Efficient slurry placement for complete and permanent zonal isolation relies on effective displacement of drilling fluids from the casing-borehole annulus—mud removal—and on avoiding bypassing, mixing and contamination of fluids in the annulus and casing during cement placement. Understanding displacement mechanics is essential to successful cementing, but an integrated drilling and cementing fluids approach is a first step toward overall wellbore optimization.

The consequences of poor primary cementing jobs can be severe. Incomplete mud removal may leave channels, allowing communication between subsurface zones or to the surface. Likewise, failure to properly separate fluids as they are pumped downhole can negate the most meticulous plans or the best designs and lead to ineffective mud removal or contamination that prevents cement from ever setting up (hardening). Approaching well construction as a series of interrelated events in which both mud and cement play important roles—total fluids management—results in a more controllable, structured process with optimal wellbores as the objective.

Traditionally, drilling fluids and cementing services have been provided separately and the lack of stated, common objectives has been a roadblock to optimizing these operations. Better management of fluid services requires drillers and cementers to work together from well start to finish to select muds that achieve drilling goals, but do not impede cementing success. Consideration must be given to providing gauge holes that allow casing centralization. It may be necessary to reduce rates of penetration—average to high instead of very high—during drilling if that means improved borehole conditions, lower-cost primary cement jobs and reduction or elimination of expensive repair workovers. Necessary elements are available and, in most cases, in place to do this; where efforts often fall short is in coordination and management of the entire process to realize maximum benefits. Success in terms of the final product—a safe, long-lasting wellbore at the lowest possible cost—should be an incentive to rethink and restate fluid objectives.

Better understanding of annular displacement is a key element that is already in place. By using physical and computer modeling, cementing criteria have improved. Simulation and design software allow the myriad of fluid factors and complicated interactions involved in primary cementing to be addressed quantitatively, and most of the time quantitatively as well. The total process (mud removal and cement placement) including conditioning, annular flow regimes, spacer—a buffer between drilling muds and cement slurries—selection and fluid displacement inside pipe can now be evaluated in planning and design stages, during mud maintenance and conditioning, and before or after jobs.
High flow rates effectively displace mud if turbulent flow is achieved around the entire annulus, but are viable only if casing and hole sizes are relatively small and casing standoff from the borehole is adequate. Lower flow rates can also successfully remove mud in many cases where higher flow rates are not practical, but more sophisticated designs and modified fluids are often needed to achieve laminar displacements.

Spacers with controllable properties—ability to suspend weighting agents, reasonable turbulent rates, adjustable rheology, compatibility, low fluid loss and a wide range of applications—are needed to meet and better apply mud removal criteria (see “Engineered, Fit-To-Purpose Spacers,” page 46).6

Finally, to close the fluids loop, displacements inside pipe must be understood because density differences may cause mixing of fluids or bypassing of mud by spacers, spacers by cement slurries or lead by tail slurrifies.7 Better understanding and application of fluid flow and displacement mechanics are required along with more careful

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3. Turbulent flow occurs at higher flow rates. Individual fluid particles swirl around, but their average velocity results in what is considered a flat velocity profile. Momentum is constantly transferring from one region to another, but overall flow is relatively constant.
   Casing standoff (STO) in percent is defined as STO = 2w/D - d x 100 or w/R-r x 100, where D is hole diameter, d is pipe outside diameter (OD), R is hole radius, r is pipe radius and w is the smallest annular gap. STO is 100% when casing is concentric—perfectly centered.
5. Laminar flow occurs at relatively low flow rates. Fluid particles move parallel to the casing axis or annulus walls along straight lines in the direction of flow, with a parabolic velocity profile. At the walls, where liquids wet the surface, fluid particles in contact with pipe or annulus walls are stationary and velocity is zero, increasing to a maximum—twice the average velocity for Newtonian fluids—at the center of the flow channel.
The design of mud systems, spacer fluids and cement slurries to avoid common cementing problems (above). This article gives an overview of integrated fluids services, and reviews mud conditioning and removal from the annulus by turbulent and effective laminar flow (ELF). A Dowell and Texas A&M University study defining downward flow in pipe and proposing methods to improve cement placement without sacrificing effective mud removal is also examined.

The Case for Total Fluids Management
In the past, drilling and cementing fluids were often provided under individual service contracts, often by different companies. All too frequently, the attitude seemed to be, “drill as fast as possible and worry about cementing after reaching TD.” Other needs and intentions, and deleterious effects that occur when some fluids commingle were often ignored. In principle, instead of segregating drilling and cementing fluid services, operations can be unified in a single, integrated process. Isolated service-line mentalities are replaced by a common goal of providing seamless fluids programs—“fluids trains”—to optimize overall performance and results. Territorial considerations are forgotten, and the two disciplines work together to maximize the efficiency and effectiveness of all well-construction fluids.

Good communications and coordination are a necessity. Cementing designs are performed before drilling is complete, so choices about flow regime—turbulent or laminar—and spacer properties are made assuming hole size and mud characteristics. Last-minute changes or unexpected variations in borehole conditions place cementers at a disadvantage. Irregular holes and washouts hinder mud removal and casing centralization, and may preclude use of preferred turbulent flow. Low standoffs result in large radial variations in annular fluid velocity around casing with higher velocity on the wide side and lower velocity on the narrow side. This leads to inefficient annular displacement and potentially poor cement bonds or channels. For cement jobs, casing OD to hole diameter ratio is close to unity, so annular flow can be calculated using a basic slot model (next page, top).

Drilling fluid designs also influence cement job quality. For example, zonal isolation cannot be achieved unless mud and cuttings are removed from the annulus. Drilling fluids must be designed, maintained and treated to provide optimum final hole conditions, and ultimately be conditioned before cementing for easy removal by spacers and cement. Ideal muds for efficient displacement are nonthixotropic and have reduced gel strengths, plastic viscosities and yield points; low density to facilitate removal by buoyant forces; minimal fluid loss to prevent thick filter cakes and differential sticking; and are chemically compatible with cements. Perfect muds, however, cannot be achieved in practice, so efforts must be made to get close to ideal characteristics during selection, maintenance and precementing circulation.

Drilling fluid density and rheology must be kept low to meet mud-removal requirements. Displacing fluid weights and viscosities become higher with each successive interface, which can lead to unacceptably high cement densities and viscosities, and possible lost circulation if initial mud weight is too high. Just circulating and conditioning mud before cementing is not enough; effective solids and chemical control of rheology are required throughout drilling operations. If drilling fluids are not properly designed or deteriorate during drilling or logging, gelled mud that is difficult to remove may be left in washouts or on the narrow side of the annulus.

Fluids compatibility also impacts annular displacement. Fluid mixtures should have
lower rheologies than the individual fluids, but because this is difficult to achieve for muds and spacers, designs need to minimize mixture viscosities. Problems also arise if cement and mud mix inside or outside casing. Some drilling fluid additives accelerate or retard cement thickening times. But more commonly, cement-mud combinations result in high-viscosity mixtures and corresponding friction pressure increases that lead to excessive surface pump pressures and premature job termination as well as inefficient displacement. Washes and spacers isolate these potentially incompatible fluids, but unexpected variations in composition leave cementers unprepared to maintain this separation. This can be avoided by using bottom wiper plugs to separate fluids inside casing and liners.

In addition to displacement considerations, cementing cost is an issue as hole sizes increase from washout or enlargement. The cost of larger cement volumes is obvious, but additional centralizer cost to achieve adequate standoff for effective mud removal is often overlooked (right).

Spacer cost is also important. As hole size increases, higher flow rates are needed for turbulent flow and spacer volumes must be increased. For example, if hole diameter increases from 6.5 to 8.0 in., the rate to achieve turbulent flow goes from 4 to 14 bbl/min and cost of standard spacers goes from about $6500 to $15,500.

Workovers are another often overlooked cost component when drilling and cementing services are segregated. Typically, if a primary cement job is unsuccessful and a cement squeeze is necessary, more than one attempt is needed to achieve zonal isolation. Remedial cementing costs, including cement, perforating, packers and rig time, can be as much as, or more than, the primary cement job.

Integrating Fluids Services in Canada

A managed fluids approach proved successful in western Alberta, Canada, where vertical wells are drilled to between 6888 and 7544 ft [2100 and 2300 m] through unconsolidated formations. Historically, drilling and cementing fluids had been provided by one company, but individual services were not working to meet common goals. Drilling fluids services tried to minimize expenditures directly related to mud use, and cementers did the best job possible with resulting hole conditions. Managed separately, drilling fluids cost on four wells drilled with bentonite mud and three with partially hydrolyzed polyacrylamide (HPHA) fluids was $26,600/well, or $3.58/ft [$11.75/m] drilled. Average hole enlargement was 113% by volume and typically 23 days were spent drilling. Lost time due to hole problems and backreaming was about 24 hr/well.

Some elements of drilling fluids performance were acceptable, but hole geometries that cementers had to address were not. Bentonite mud was not conducive to drilling gauge holes and a HPHA fluid failed to prevent washouts that were responsible for major cementing cost over-runs. Enlarged holes were compensated for by pumping extra cement, knowing that there was risk of channeling due to reduced fluid velocities in washouts. Cementing on these seven wells cost $103,750/well or $13.96/ft [$46/m] drilled, about four times drilling fluid costs. Total fluids averaged over $130,000/well, or $17.56/ft [$57.60/m] of hole.

8. Thixotropic fluids are highly viscous when static, but become more fluid-like and less viscous when disturbed or moved by pumping.
Engineered, Fit-to-Purpose Spacers

The primary functions of spacers are fluid separation to avoid compatibility problems and ensuring flow under a specific regime—turbulent or laminar—while maintaining hydrostatic well control. Improved mud removal guidelines require preflushes for either turbulent flow or effective laminar flow (ELF) techniques, so weighted MUDPUSH spacers were developed for use with WELLCLEAN optimal mud removal services (right). XT and XS spacers are for turbulent flow. Viscous XL is used with ELF. All three can be adapted for use with oil- or water-base muds—XTO, XSO and XLO spacers.

Turbulent spacers were designed to overcome settling problems experienced with thin spacers. Weighting agents are suspended at surface or bottomhole temperatures to maintain fluid rheology that eliminates free water and particle settling over a wide range of densities while allowing turbulent flow at reasonable pump rates. The XT spacer is for turbulent flow regimes in low-salinity environments (fresh or less than 10% salt by weight of mix water) and the XS spacer is for high-salinity applications (30% salt by weight of mix water). Both can be formulated at 10 to 19 lbm/gal [1.2 to 2.3 specific gravity (SG)] densities.

Laminar-flow spacers have higher viscosities than turbulent-flow spacers, so good particle-carrying capacity ensures that weighting agents to achieve required densities do not settle out. To meet ELF friction-pressure hierarchy criterion, spacer rheology can be adjusted so that apparent viscosity across the range of pumping shear rates falls between drilling mud and cement slurry apparent viscosities. Spacer density can also be designed halfway between mud and cement slurry weights at any density from 10 to 20 lbm/gal [1.2 to 2.3 SG].

In addition to proper spacer rheology and particle-carrying capacity, fluid-loss control and compatibility are important. Fluid-loss control must be considered because water lost during displacement increases the spacer solids-to-liquid ratio, density, and to a greater extent, apparent viscosity. Excessive fluid loss introduces the possibility of spacers coming out of turbulent flow at design rates, which can lead to channeling of spacer through the mud. Fluid loss for these spacers is low and few compatibility problems have been encountered. Some mixtures of these spacers and cement slurries develop weak gel strengths when left static at low temperature, but these gels are broken by shear rate or small temperature increases.

Consistent performance under field conditions is also an advantage in effective mud removal. Spacers must perform under variable conditions from low-quality barite or brackish or high-salinity water to low-shear mixing without major changes in properties and effectiveness. Spacers should also have adequate viscosity and fluid-loss control at field conditions. MUDPUSH spacers perform successfully under a wide range of operational conditions, and rheological properties are consistent with laboratory measurements made prior to jobs.

These spacers are limited to maximum bottomhole circulating temperatures of 300°F [149°C], but the new XEO spacer, a polymer-modified, oil-in-water emulsion spacer, extends applicability to 450°F [232°C] for oil-base mud removal only. The WHT spacer is a water-base spacer developed for these same higher temperature applications and oil- or water-base mud removal to complement the XEO spacer. However, it exhibits less fluid-loss control, especially when seawater is used as mix water. MUDPUSH spacers can also be used for other cementing applications where weighted spacers are needed, such as plug or squeeze cementing, even when WELLCLEAN services are not directly applicable.

Overall improvement was the goal of a unified fluids approach on two subsequent wells. Total fluids cost were targeted to be reduced by improving hole gauge and reducing cement volumes. Unconsolidated formations in these wells were identified as the cause of washouts, so because of the lack of success with even a moderately inhibitive PHPA system, mixed-metal-hydroxide (MMH) mud with unique fluid rheology was chosen to minimize hole enlargement.

After the revised fluids program was implemented, gauge holes allowed for better casing centralization and improved displacement designs—a laminar flow regime was chosen for these wellbore geometries. Spacers effectively removed MMH fluids from the annulus and logs indicated good cement placement and successful zonal isolation. Cement returns compared to cement volume pumped in excess of caliper hole volume indicated minimal if any channeling in both the wells drilled with MMH fluid. But severe channeling was likely in three of the previous seven offset wells, and one had significant losses during cement placement.

Water flow—the first in this field—occurred while drilling the initial test well. Although most of the 57% washout was over the interval where flow occurred on this well, this still compares well with over 100% average washout on offsets. Drilling fluid cost exceeded average offset cost because dilution, borehole instability and the need to increase density resulted in excess product use that skewed cost. Positive results, however, were seen in improved hole gauge and cement cost, which fell to 64% of the average.

The second test well had no losses or flow and was drilled in the least number of days, despite moderate rates of penetration. Lost drilling time on this well was the lowest for this field and washouts were reduced to 29%. Drilling fluid cost at $43,000 was above the $25,000/well average, but cementing costs of $45,000 were less than half those of previous wells.

Total fluids cost was the lowest on record for this field—a 32% savings over the average for offsets. The objective of reducing overall well construction fluid costs was achieved by reducing washouts, and higher drilling fluid costs to minimize hole enlargement were more than offset by cement savings. Proper drilling practices cannot assure cementing success, but poor drilling practices may make cementing success unachievable.

1. Courturier et al, reference 6, main text.
2. Tehrani et al, reference 6, main text.
Circulation: Mud Conditioning
Primary cementing operations often have multiple objectives. On long intermediate casing strings, a complete cement sheath from bottom to top is preferred, but a good seal near the bottom of the string and around the casing seat is all that may be required, making the casing seat the primary and the full cement sheath the secondary objectives. For liners, isolation a way from bottom to top is preferred, but a good asphalt as a seal at the liner-casing overlap (top). Cementing goals dictate job designs. To solve cementing problems, better understanding and application of fluid flow, displacements and placement are required along with careful design of mud systems, spacer fluids and cement slurries. Cement placement is important in most cases; mud removal is critical on all cementing jobs.

The accepted procedure is to circulate and condition before cement jobs. However, in the past, there were few guidelines for these procedures, except generally to reduce mud viscosity, gel strength and fluid loss; maximize standoff—casing centralization; use preflushes—chemical washes and spacers to separate mud and cement; move the pipe—rotate or reciprocate; circulate a minimum of two hole volumes and pump at high rates. Also, until a few years ago, critical flow-rate calculations assumed that casing was perfectly centered in the hole. However, the critical flow rate correction to account for casing eccentricity is significant and must be taken into consideration (top).

In the early 1990s, eccentricity was first taken into consideration in designs and in the field by using WELL-CLEAN optimal mud removal service in CemCADE cementing design and evaluation software. This comprehensive software is used to evaluate all well parameters, including casing standoff, and to recommend flow regimes, preflushes and volumes, and pump-rate sequences for optimum fluid displacement.

- **Cementing versus drilling geometries**: the importance of standoff. At lower standoffs, the decrease in frictional pressure drop in a cementing geometry—large casing in open hole—is significantly greater than in a drilling geometry—smaller drill pipe in open hole. Standoff, therefore, has a double effect on annular displacement in a cementing geometry. Both wall shear stress and pressure drop are lower for poor standoffs in an eccentric annulus, which further compounds mud removal and cementing problems. In the past, most cementing designs used drilling simulators that assumed a concentric annulus.

- **Optimizing mud removal.** In the early 1990s, pipe eccentricity was first taken into consideration in designs and in the field by using WELL-CLEAN optimal mud removal service in CemCADE cementing design and evaluation software. This comprehensive software is used to evaluate all well parameters, including casing standoff, and to recommend flow regimes, preflushes and volumes, and pump-rate sequences for optimum fluid displacement.

- **Adjust standoff or flow rate.**

- **Evaluate Mud Removal Criteria**
  - Determine if mud removal criteria are met across all zones of interest.

- **Evaluate U-Tubing that occurs while pumping at the selected rate.**

- **Select pump rate that meets criteria for the chosen flow regime, hole size and standoff.**

- **Select centralizers appropriate for hole dimensions and desired standoff.**

- **Evaluate flow regimes and range of flow rates versus hole size; select flow regime and standoff.**

- **Eccentered Flow Screen**
  - Evaluate flow regimes and range of flow rates versus hole size; select flow regime and standoff.

- **Centralizer Calculation**
  - Select centralizers appropriate for hole dimensions and desired standoff.

- **Pump Rate Selection**
  - Select pump rate that meets criteria for the chosen flow regime, hole size and standoff.

- **U-Tube Calculation**
  - Evaluate U-tubing that occurs while pumping at the selected rate.

- **Evaluate Flow-rate Ratio**
  - Circulation: Mud Conditioning
  - Frictional pressure drop, Pa/m

<table>
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<th>Flow-rate Ratio</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
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<th>60</th>
<th>70</th>
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<tr>
<td>API standoff, %</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
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- **Cementing geometry:**
  - Drilling geometry: 0.55 diameter ratio
  - Annular pressure, kPa

- **Flow-rate ratio corrections versus casing eccentricity.** The critical flow rate to achieve turbulent flow completely around a casing-borehole annulus doubles as casing standoff (STO) decreases from 100 to 70% and there is almost a tenfold increase if standoff drops to 30%.

- **Cementing problems.** In the past, most vertical wells, and frequently no higher than 85%. At low flow rates, drilling mud with high yield stress and gel strength can be static in the narrow gap of an eccentric annulus because of distorted velocities, lower frictional pressure drops and uneven wall shear stress distribution (left). This is undesirable because stationary mud may gel or dehydrate by static filtration at permeable zones and be difficult to mobilize during mud removal and cement placement.

- **Conditions leading to zero flow in narrow annular gaps need to be defined by account-


Annular flow regimes. Fluids calculated to be in turbulent flow, assuming perfectly centered casing, are now known to be turbulent only in part of the annulus. In fact, three flow regimes—no flow, laminar and turbulent—can coexist in an annulus, which means that mud may be removed effectively on the wide side, while on the narrow side mud is static, resulting in a channel. Between the extremes of no flow on the annulus narrow side and full turbulent flow around the annulus, mud removal may be poor, unless laminar flow displacements are properly designed.

Another consequence of uneven velocity profiles is coexistence of different flow regimes. In an eccentric annulus, mixed flow regimes are possible if critical flow rate for turbulence is calculated, as in the past, based on a concentric annulus, a common assumption in drilling hydraulics models. For fluids exhibiting yield stress and gel strength like muds and cements, it is possible for three annular flow regimes to coexist—no flow if wall stress is less than fluid yield strength on the narrow side of the annulus, turbulent on the wide side and laminar in between.

Mud, spacer and cement distribution for various displacement rates, standoffs and spacer properties. In the base case (far left), mud and spacer channels were left along the length of a simulated annulus in this full-scale flow loop. As displacement rate was increased, mud was displaced from the annulus narrow side, but full cement placement did not occur because interfacial velocity was low. Increasing standoff (STO) had a dramatic effect on mud displacement and cement placement (middle and bottom), but further rate increase under these conditions did not significantly improve cement placement. Rate is, therefore, important in mud displacement, but less influential in cement placement. Better standoff, higher rate and a thin spacer for more effective turbulent flow also had a positive impact on cement placement, highlighting the importance of proper fluid rheology designs, especially for spacers (far right). (From Lockyear and Hibbert, reference 2 and Tehrani et al, reference 6.)
The Annulus: Removing Mud, Placing Cement

A better understanding of annular displacement emerged in the late 1980s and early 1990s.\(^{10}\) Previously, casing eccentricity, or standoff, was not considered in designs, even though it was known to be a factor in channeling and primary cementing failures. Competent cement sheaths and a good seal depend on effective mud removal by turbulent or, under certain conditions, laminar flow. But fluids calculated to be in turbulent flow assuming perfectly centered pipe might actually bypass mud in an eccentric annulus because fluid velocities vary radially around eccentric casing. Now CemCADE cementing design and evaluation software can be used to make mud circulation, annular displacement and cementing recommendations based on actual well geometry, casing standoff and fluid rheologies (right).

Even if mud gel strength is broken during circulation and conditioning, the question of whether cement will flow into the narrow annulus gap needs to be answered. If cement flows primarily on the annulus wide side and leaves a slow-moving mud or spacer channel in the narrow side, good cement placement and zonal isolation will not be achieved. Cementing, therefore, can be considered in two parts: mud removal and cement placement—uniform cement flow without channeling—which both depend on proper displacements up the annulus and down casing. Increasing standoff improves mud displacement and cement placement; displacement rate is important for effective turbulent mud removal (previous page, bottom).

Displacing mud with spacers in turbulent flow is one of the most effective and widely accepted cementing techniques. Turbulent-flow mud removal dates back to the 1940s. It was subsequently recognized that turbulent scavenger displacing fluids—pre-flushes—placed in contact with formations for about 10 minutes improved mud removal.\(^{11}\) Increasing displacement rate improves turbulent mud removal. And thin, less viscous spacers like water and surfactants that can easily be placed in turbulent flow at low pump rates work best, probably because of combined drag, erosion and


dilution at interfaces due to turbulent eddies (below left). Chemical washes should always be used, but weighted spacers designed for turbulent flow—low rheologies and temperature stability—can be used under some conditions if required. The maximum wash or spacer volume without compromising well control should be recommended or the 10-minute annular contact time should be used. Even moderate chemical wash volumes used with spacers reduce mud viscosity and are preferable to spacers alone.

Pump rates to achieve turbulence on the annulus narrow side depend on hole dimensions and casing standoff. However, achieving turbulence around the entire annulus, even on the narrow side, requires high pump rates in large casing that may not be practical because of surface equipment limits or fracture gradients. Achieving mud removal by turbulent flow becomes harder as hole sizes get larger and standoff decreases, and is even more difficult when weighted spacers are used. Turbulent flow criteria for annular mud removal require turbulence around the entire annulus, including the narrow side, thin preflushes in contact with formations for 10 minutes, and similar displacing and displaced fluid densities (above).

When turbulent flow is not an option, there is a need for properly designed mud displacements with spacers and cement in laminar flow. These designs are more complicated, but criteria have been established to ensure displacement efficiency (below right). Effective laminar flow requires positive density contrasts—10% is recommended whenever possible—a minimum pressure gradient (MPG) to overcome mud yield stress and positive rheological hierarchies to maintain increasing friction pressure and minimize differential velocity between fluids. Positive density differential, which is independent of hole geometry, helps generate a flatter, more stable interface and is the first condition to check. In cases where cement slurry density is close to mud density and mud weight cannot be modified, spacer density range is limited and it may not be possible to meet this criterion.

Yield stress of fluids being displaced must be exceeded by wall shear stress. Minimum pressure gradient defines the force needed to move drilling fluids in the annulus narrow gap and should also be applied prior to cementing during mud circulation to ensure that all the mud is moving and reconditioned. Below this force some mud remains immobile on the narrow side of the annulus. When mud is displaced by heavier fluids in laminar flow, a density differential helps meet this condition by contributing to wall shear stress (next page, top left). MPG verifies fluid mobility and defines a lower flow-rate limit to ensure that flow occurs all around the annulus.

The differential between frictional pressures generated by fluids should be at least 20% to increase interfacial stability. Otherwise the displacing fluid tends to bypass fluid ahead. Under laminar flow, spacers with higher rheologies—thicker or more viscous than the mud—are most effective (next page, top right). This is equivalent to having apparent mud viscosity lower than that of the displacing fluid for a given flow rate and annular geometry. The frictional
pressure criterion is important and an initial check should be always made. If there is not at least a 40% friction pressure differential between mud and cement, both spacer and cement cannot meet this condition and rheological properties must be changed by reducing mud yield point, density and solids contents to a minimum during mud conditioning prior to cementing or by increasing spacer and cement rheology (plastic viscosity and yield point). Improving casing standoff and increasing density differentials also helps satisfy this criterion. Friction pressure hierarchy and MPG establish minimum flow rates.

Differential velocity around the annulus at fluid interfaces must be minimized to establish a relatively flat interface. The combination of density and frictional pressure differentials helps generate a relatively flat and stable interface and reduce the possibility of one fluid fingering or channeling through another. The sum of gravitational and friction forces for displacing fluids in the wide side must be greater than those of the fluid being displaced on the narrow side of the annulus to balance forces so flow is uniform around the annulus. This condition can be satisfied if annular flow rate is below a critical value (right).

Annular velocity differential can be minimized by reducing mud yield point during conditioning, maximizing standoff, meeting density and friction pressure hierarchy conditions by using viscous weighted spacers, displacing at low pump rates and moving the pipe. When displacement rates are too high, displacing fluids tend to flow faster in the wide side of the annulus, regardless of gravitational effects that tend to flatten the interface. Therefore, differential velocity criterion is important and an initial check should be always made. If there is not at least a 40% friction pressure differential between mud and cement, both spacer and cement cannot meet this condition and rheological properties must be changed by reducing mud yield point, density and solids contents to a minimum during mud conditioning prior to cementing or by increasing spacer and cement rheology (plastic viscosity and yield point). Improving casing standoff and increasing density differentials also helps satisfy this criterion. Friction pressure hierarchy and MPG establish minimum flow rates.

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teria establish maximum annular flow rates and contradict “pump-as-fast-as-you-can” philosophies.

Unlike turbulent displacements in which annular flow is maintained above a critical rate, displacements by ELF must be maintained between maximum and minimum rates. In turbulent flow, preflush volume is determined to be at least 500 ft (150 m) of annular fill, with a 60 bbl (10 m³) minimum. Increased wellbore inclination reduces displacement efficiency by decreasing gravitational effects, but this reduction can be compensated for by optimizing pump rates and fluid rheologies. Complicated laminar displacements highlight how properly designed spacers are essential in annular mud removal.

Down Casing: Displacing Cement

Much effort goes into selecting proper fluids, flow regimes and displacement mechanics to remove mud from the annulus and place cement. This usually means pumping fluid stages with increasing densities. For downward flow inside pipe, however, a positive density hierarchy is counter to effective displacement. Mixing and contamination occur when interfaces between fluids are unstable or displacing fluids bypass—fall through—fluids ahead, problems that can be overcome by using wiper plugs for mechanical separation. Sometimes only one bottom wiper plug is run, but more often, none is used.

After investigation of primary cementing failures in which fluid mixing inside casing was a possible cause, P. Valkó performed an in-depth study of frictional and gravitational forces on fluids flowing downward in pipe. The mechanics of heavier fluids displacing lighter fluids down casing when wiper plugs are not used were defined, and methods were developed to calculate displacement efficiency and interfacial boundary shapes. This project was based on earlier work involving upward flow in annuli and packed, fluid-filled columns (above). The software to make these calculations uses fluid densities and rheologies along with gravitational effects, assuming vertical, laminar flow and no mixing. This software is only qualitative and not a simulation, and cannot determine when bottom wiper plugs should not be run.

Subsequent work with this software shows that there may be three forms of displacement inside pipe (next page, top). Fluid interfacial boundaries may form smooth parabolas with moderate displacement efficiency or there may be an outer cylinder of the first fluid that is not moving, so efficiency is lower. It is also possible to have a region where the first fluid tends to move upward, in opposition to primary flow, so displacement efficiency is quite low. In cementing applications it is not possible for fluids in the casing to flow up because of the cementing head, but this force can lead to a high degree of mixing at fluid interfaces. As expected, displacement is never completely effective, demonstrating the need for mechanical separation—bottom wiper plugs.

Incomplete fluid displacement inside casing is likely to mean an unsuccessful cement job (left). The tendency for upward flow at interfaces can cause spacer or cement leading edges to be contaminated or complete mixing of mud, spacer and cement, leading to inefficient mud removal. Extreme viscosity increases and corresponding high pump pressures can also result if slurries and muds are incompatible. Fluid mixing can have disastrous results, including appearance of premature set if incompatibility is severe enough. It is also possible for displacing fluids to bypass fluids that were pumped ahead. This is often evident on pressure charts in the form of early lift pressure and from returns at the surface as heavier fluids bypass lighter fluids and “turn the corner”—U-tube—from the casing into the annulus sooner than expected.

Cement contamination by spacer or mud can change slurry rheology or retard thickening time, as evidenced by friction pressure increases during displacement or apparent lack of set cement on evaluation logs. In some cases, mixing may be only at the slurry leading edge and result in lower than expected cement tops or low-strength cement up hole. It is also possible for tail
slurries to fall through lead slurries; in this case, cement evaluation logs may show good cement bond across most of the interval, but poor cement at the bottom, where good, strong tail cement should be. There may also be spotty occurrences of good and bad cement. In some cases, no evidence of cement may be found even after several days because of complete mixing and retardation of cement by spacer.

Two common problems are failure of cement to provide a seal at the shoe and lack of hardened cement in shoe tracks (float joints) during drill out. Shoe failure may be related more to formation characteristics where casing is set than to cement job quality, but there are cases when slurries bypass spacers and the cement seal is actually being tested.

Displacement efficiency also affects cement quality in shoe joints. If bottom plugs are not run and cement bypasses spacer or mud, the top wiper plug can push bypassed spacer and mud into the shoe joint. Since wiper plugs stop at float collars, there may also be low-quality cement or mixed fluids between the float collar and float shoe. Even when bottom plugs are run, cement may bypass other fluids in the shoe tract. Also, float collar outlet orifices establish a thin fluid jet through casing or liner joints below float collars, compounding a difficult situation.

Sensitivity analyses using this new software indicate that effective displacement inside casing cannot be achieved by modifying fluids without adversely affecting annular displacements. Properties that might influence interface shape and displacement efficiency include average velocity, yield point, density, plastic viscosity and pipe size. Displacement efficiency improves as flow velocity and yield point difference between bottom and top fluids increase. Efficiency decreases as fluid-density differences increase; even at similar densities, displacement is only 70% after a pipe volume of fluid is pumped. Differences in plastic viscosity have little effect on displacements in the range of geometries and shear rates studied. As pipe sizes increase, displacements become more inefficient, and in larger pipe sizes, reverse flow of lighter fluids causes unstable conditions.

Although there are often acceptable results when bottom plugs are not used, theory and field data indicate that mechanical separation at each interface is the only way to ensure that competent fluids leave the casing and enter the annulus. This work suggests that bottom plugs should be used whenever possible and that many undesirable results can be explained by the phenomenon of heavier fluids “falling through” or mixing with fluids being displaced ahead in the casing. Running bottom wiper plugs is strongly recommended and, in critical cases, bottom plugs should be run at each interface (see “Using Multiple Wiper Plugs,” next page).


Use of the EXPRES Extrusion Plug Release System, a next generation cementing head, continues to expand. This innovative design automates release procedures and gives a positive indication of plug launch. Plugs are held in a basket below the head and inside casing so that cementing fluids—chemical washes, spacers and cement slurries—can flow around the basket (right). Over 2000 lb of force from a hydraulic ram launches the plugs, minimizing chance of premature or accidental release. Mechanical stops in the launcher provide an end to each phase of the job. An oil-level gauge indicates launcher-rod position and gives a clear indication of plug departure. Top plug departure is verified by sensors mounted on the casing that detect drillable magnets in the plug, sounding a horn and sending a signal to the cementing unit.

Modular design, quick-latch connectors and remote operating capability save rig-up and job execution time. This means better mud conditioning prior to cementing and the unique ability to launch plugs on the fly—without interrupting pumping—which reduces U-tube effects and improves mud removal. High pressure ratings allow pressure-integrity testing immediately after cementing, saving rig time and reducing possibility of forming a microannulus. An exclusive wiper plug fin design ensures complete fluid separation and effectively wipes casing walls, so cement slurry reaches the float collar without being contaminated. Exposure to high pressure is minimized by remote control and light, well-balanced modules make the EXPRES system easy and safe to handle.

The concept, developed several years ago, of preloading plugs in a basket has been expanded from two plugs to three plugs and to subsea cementing using a Surface Dart Launcher (SDL) and Subsea Tool (SST) (next page). The first DeepSea EXPRES prototype was used off the west coast of Africa in mid-1994 and two other prototypes were placed in service in the Gulf of Mexico earlier this year. Over 28 jobs have been performed with these tools. The SDL holds identical darts, which are individually released from surface during cementing jobs. These darts launch the wiper plugs when they reach the downhole SST, but unlike free-falling balls, are pumped down drillstrings to separate fluids and wipe pipe walls. Other advantages over dropping balls include positive fluid displacement and elimination of the time and uncertainty of waiting for balls to reach bottom.

The heart of DeepSea EXPRES, the downhole SST, allows use of high-performance, easily drillable EXPRES plugs with simplified designs that eliminate problems associated with pumping fluids through wiper plugs. The tool retains wiper plugs, preloaded in a basket with over 2000 lb force, until they are launched by arrival of a dart from the SDL. Friction holds plugs in place during pumping operations. The current design accepts up to three 8 5/8- to 13 5/8-in. plugs, or two 16- to 20-in. plugs that are under development. During circulation, mud flows down the drillpipe, through a sliding sleeve and out two orifices into the casing-SST annulus. When a dart reaches the tool, drillpipe pressure forces the sliding sleeve down, ensuring that each dart travels a full length. Continued pumping forces the dart and rod down, pushing a plug out of the basket. After a dart reaches its final position, a spring retracts the sliding sleeve to ensure complete, unobstructed flow through the orifices. Darts remain in the holder and are retrieved with the tool after the job.

Rod travel is slowed by a shock absorber filled with hydraulic oil that flows past a small gap...
between the rod piston and bore. The resulting pressure differential resists rapid movement and stops the rod after plugs are released. Combined with plug friction, this causes a 1500 psi [10,350 kPa] pumping pressure increase and provides a positive indication of plug launch. Three brass shear pins increase top-plug release pressure to 3000 psi [20,700 kPa]. A sleeve holding these pins slides down, but remains inside the basket after the top plug leaves the tool. Spacers that keep plugs from sticking together also slide down the basket and are retrieved with the tool.

Systems are also available to improve liner cement jobs. In the past, one pump-down plug and a top plug were used, but new top and bottom, four-plug systems prevent cement contamination inside liners. Spacer is pumped down drillpipe followed by a pump-down plug, cement slurry, another pump-down plug and displacement fluid. The first pump-down plug passes through the top wiper plug and into the bottom wiper plug at the top of the liner where it latches into a catcher. Pressure shears pins attaching the bottom wiper plug to a mandrel and the plug is pumped down the liner to the float collar. A further increase in pressure shears the catcher from the bottom wiper plug, allowing it to move into a circulating tube, which permits cement slurry to pass through float equipment into the annulus. The second pump-down plug latches into the top wiper plug, which is displaced through the liner until it reaches the bottom wiper plug where it forms a seal.

was well below 50% (above left). Running a bottom wiper plug only between mud and spacer allowed cement to fall through and mix with spacer.

Tail Bypassing Lead Slurry
In Balikpapan, Indonesia, Unocal cemented a long, 7-in. liner with two slurries—12.5 ppg lead and 15.8 ppg tail. The liner top was at 2240 ft [683 m] and the bottom was at 9844 ft [3000 m]. In liner applications, of course, an added difficulty is dropping bottom plugs, and in this case, the problem was compounded because viscosities had to be kept low to avoid fracturing the well due to high friction pressures. During displacement, high frictional pressures resulted in the premature termination of the job, leaving cement in the liner. Evaluation of displacements for this liner cement job indicated that lead slurry fell through spacer and tail slurry fell through the lead.

Interfacial boundary shapes between spacer and lead slurry, and lead and tail slurries show a tendency for reverse flow of lighter fluids at the interface in both cases, indicating high likelihood of fluid mixing between stages. Calculations also show low displacement efficiencies—10 and 20% (above right). Tests on cement and mud mixtures resulted in high viscosities that correlated with high displacement pressures during the actual job.

Integrating Fluid Services
Quality cement jobs depend fundamentally on the ability to predict and manage fluids and displacement performance over a wide range of conditions. Personnel training, from management through engineering to field operations, is high on the list of issues that must be addressed to properly integrate drilling and cementing fluids and implement total fluids management. Mud engineers do not have to run cement pumps and cementers do not have to supervise drilling fluids programs, but it is helpful if each understands the other’s needs. If the entire fluids process is to be optimized, cooperation must develop through appreciation of needs and intentions of the other discipline. Formal cross-training must be supplemented by practical experience, with the goal of establishing wellsite “fluids-engineering” teams dedicated to optimizing all fluid operations.

Rather than view other services from afar, drilling fluids engineers and cementers need to cooperate in designing structured fluid sequences—fluids trains—for wells. At wellsites, cementers should gain hands-on fluids experience as backup mud engineers and act as mentors to mud engineers during cementing operations. At offshore and remote locations where engineers reside on location, this approach can be formalized with one service-line specialist acting as team leader in addition to performing primary product-line responsibilities. Effective team leaders must be experts in their primary field, familiar with other disciplines and be good communicators. With available fluids technology, efficiencies can be found in cooperation and interfacing between fluids services, and between fluids teams and operators. By restructuring the approach to well construction fluids, savings are available with no up-front increase in either cost or risk.

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