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Effects of Lost Circulation Material Retention on Drilling Fluids and Drilling Waste Management

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Abstract

The drilling industry has recently seen an increase in usage of LCM retention equipment for the separation and reuse of LCM in the active mud system. The main driver for LCMR originated with operators desiring to reduce the total volume of LCM products necessary when drilling through problematic zones, by retention of LCM that would normally be removed and discarded by the shale shakers. The LCM, being a desired and necessary solid, is retained in the active mud system, thus reducing the cost associated with continued maintenance additions of LCM.

LCMR can be achieved by simply bypassing the solids control equipment, using fine screens on shale shakers to capture the LCM, or by utilizing specialized shakers that attempt to separate a specific size range of LCM from the solids to be discarded.

This application has become increasingly popular as operators continue to look for economically beneficial ways to minimize downhole losses and strengthen the wellbore. However, since shale shakers separate by particle size, the recovery process returns undesirable particles such as drilled solids to the mud system along with the desired LCM. In addition, the particle size of both LCM and drilled solids will degrade with each circulation, primarily from bit shear and downhole grinding, thus returning finer drilled solids to the active system over time. These fine drilled solids returned to the active mud system then require additional dilution or whole mud displacement, significantly increasing the cost for drilling fluid maintenance.

This paper will identify the variables associated LCMR and overall economic effect on drilling fluid cost and drilling waste management. An economic analysis comparing dilution, LCM maintenance additions and whole mud disposal versus the retention of drilled solids and LCM in the active mud system along with reconstitution of the drilling fluid will be addressed.

Introduction

The intentional addition of sized particles into water-based and non-aqueous fluids has been a practice for many years to minimize/mitigate downhole losses. More recently, specifically sized LCM has been incorporated into the drilling fluids to preferentially plug pore throats and fractures for wellbore strengthening, reduction of lost circulation events and even skin damage minimization to the reservoir.

Common additives include, but are not limited to, calcium carbonate, graphite, walnut shells, and fiber. In advanced applications, large concentrations are required (at times, in excess of 50 lb/bbl). With large hole sections and modern drilling rigs, the active fluid volumes can exceed several thousand barrels. The needed replacement rates to maintain the desired LCM loading can be significant and at times can pose logistical problems.

Conventional solids control practices dictate using the most efficient and economical removal of as fine a particle size of drilled solids as possible from the fluid system. The removal efficiency is a function of the particle sizes of the insoluble solids. With each circulation, solids tend to degrade in size as they pass through the pumps and bit and due to grinding action from the rotation of the drilling assembly. The solids that are too small to be removed by the solids control equipment accumulate over time. The accumulation of these smaller solids skews the PSD in the drilling fluid towards the finer sizes. While the total LGS in the system may not significantly increase, these fine LGS can have an increasingly detrimental effect on drilling performance. This phenomenon requires frequent monitoring of the PSD to properly size the shaker screens for economic retention of LCM while discharging the economic maximum amount of drilled solids.

Shale shakers are the primary solids removal devices and they remove solids based on the minimal particle size that will not pass through the screen. The practice is therefore to outfit the shakers with the finest possible API mesh size screen available for a given flow rate. This maximizes the solids removal efficiency, but unfortunately, tends to remove the desired LCM in the fluids system. Additional solids control equipment such as hydrocyclones and centrifuges separate by mass and will tend to also remove LCM along with the drilled solids from the fluid as the specific gravities can be similar.

Even with the most efficient solids control equipment available, (removing particle with sizes down to 5-7 µm) low gravity solids will build up in the fluids system. The only effective way to reduce the concentration of these solids below the desired threshold is to dump and dilute as needed. This increases the waste volumes and also requires continuous additions of LCM for maintaining the desired concentration. Depending on the concentration of the LCM in the system, the logistics can be problematic.

With conventional shale shakers, one option to maximize LCMR is to size the screens so that the LCM can pass through and be retained in the fluid system. This strategy reduces the need for LCM additions but increases the retention of similarly sized drilled solids in the fluid system. As a result, more dilution is required. However, if the rate of generation of drilled solids is small compared to the required rate of LCM addition, this option may be economically and logistically justifiable.

One issue with LCMR is maintaining the desired particle size distribution. Most LCM will degrade with circulations in a similar manner as with drilled solids to the point of becoming colloidal solids. These can lead to poor filter cake quality and undesirable rheological properties. Unfortunately, the rate of degradation varies on operational parameters and LCM type. Without particle size analysis on location, it is difficult to determine whether the LCM is within the desired PSD after one circulation.

Functionality of Shale Shakers for LCMR

Shale shakers have evolved over time with respect to an increase in solids control efficiency. Additionally, this evolution has increased the capability of providing an engineered fluid with regards to LCMR in a specific size range as well as extending the LCM loading when desired.

Several scenarios exist pertaining to the ease and efficiency of separating and discarding the drilled solids generated from the LCM that would be desirably retained. These scenarios are dependent upon the size of the drilled solids generated relative to the PSD of the LCM utilized. For example, when large LCM material is used and fine drilled solids are being generated, it is easier to separate these solids based on particle size. This ideal scenario is not a typical case, especially since a broad PSD range is the normal recommendation for LCM material. In reality, a more likely scenario would be as the fluid is circulated, the PSD of the LCM and the drilled solids would overlap, making the separation difficult, and at times, impossible.

Recently, some solids control manufacturers have introduced triple deck shakers that can be used for increased flow rates or LCMR, known as operating in parallel or series. The exact choice of screens for the different decks can vary depending upon the PSD of the LCM and drilled solids as well as the expected flow rates and rheological properties. While triple deck shakers simplify LCMR operations, it is possible to achieve the same effect by placing standard shakers in a series arrangement with different sized screens, or simply by using a standard configuration and choosing screens such that they capture the majority of the desired LCM size. Furthermore, LCMR can be maximized by bypassing the shakers altogether and returning the drilling fluid directly to the active system.

With a triple deck shaker, ideally the screens will be chosen so that the top deck captures the larger drill cuttings, but allows the desired size of LCM to pass through to the middle deck along with finer drilled solids. The API mesh size on the middle deck should be fine enough to capture the desired percentage based on the LCM PSD and return it to the active system. Fines, both LCM and drilled solids, that pass through the middle screen may be caught on the bottom deck and removed from the system. The selection of top and middle screens impacts not only the LCM recovery efficiency, but the buildup of drilled solids in the active system. If the size difference between them is large, a significant amount of solids may accumulate, but if the screen sizes are too close to each other, the amount of recovered LCM may not justify the expense of a dedicated recovery system. There is no clear guidance on the best screen sizes for LCMR, though selecting the top screen to permit the D90 of the LCM to pass through and a middle screen to catch the D10 of the LCM has been suggested. This will still result in discarding 20% of the LCM being circulated.

It is worth noting that even a perfect LCMR system will not eliminate the need to continue adding product. As the hole volume increases and LCM becomes part of the filter cake and plugs the formation, additions will be needed. Furthermore, the LCM may degrade in a circulation cycle and necessitate the addition of properly sized LCM to achieve the desired loss control properties. Particle degradation is also a function of the material properties of an LCM. Calcium carbonate could be expected to degrade more rapidly than most graphite products, and some fibers may not degrade at all. In many operations where LCMR might be considered, the LCM has usually been chosen for a specific PSD. If the middle deck screen size is too fine, the needed LCM concentration may be present in the fluid system, but it will no longer be of the desired size and may not function as designed. Without particle size analysis, it will be difficult to determine this in the field.

Basic Economics Calculations of LCMR

To examine the economics and logistics of LCMR, two simple examples have been calculated. Both cases consider the cost of maintaining a desired LCM loading over a 20 hour drilling interval. Dilution is used to limit the buildup of drilled solids to a maximum of 5%. Three solids control options are calculated; no solids removal, selective (3 deck) screening that removes 60% of the solids and 10% of the LCM, and fine screening that removes 90% of the cuttings and 90% of the LCM. No degradation of the particles is considered and the dilution and LCM addition is considered to be continuous. For simplicity, the volume of the active system on surface is not considered for the dilution requirements. LCM is assumed to be in 50 pound sacks and is added to match the amount discarded by the shakers. The results can be seen in table 1 through 4. These examples illustrate a few of the considerations to make LCM retention economic.

- When the ROP and hole size is small, LCMR may be cost effective to maintain the desired LCM concentration.

- When the ROP and hole size is large, LCMR may not be cost effective.

- With high flow rates, LCMR may provide a solution to logistics and waste management issues.

Theoretical Modeling

To better analyze the effects of various parameters on the economics and performance of any lost circulation material (LCM) recovery system, a mechanistic model based on particle size distributions (PSD) of drilled solids and LCM was created. The model requires basic equipment and operational inputs; namely flow rate, well depth and hole size, rate of penetration (ROP), and available fluid volume on the surface. From this, total system volumes and transport rates are calculated. A drilled solids PSD is assumed and this represents the fraction of LGS that enters the system based on the rate of penetration. Obviously, it is difficult to guess what a representative PSD of cuttings generated by the bit would be, furthermore the PSD would constantly change as a function of drilling parameters such as weight on bit, pipe rotation, mud weight, and so on. As a result, an arbitrary Gaussian distribution was used as a first approximation to study its impact on LCM recovery. However, any distribution may be entered into the model. A PSD of the LCM is also required. This is available through physical testing of various products and through the manufacture's literature. Again, a bell curve distribution was used based on the D50 and D90 of various commercial products. To determine what size cut is removed or returned to the system, the model requires that three screen sizes to be entered, representing a three deck shaker LCM recovery configuration. If the screen sizes are all the same, it represents a conventional shaker configuration.

The model proceeds in a time-stepwise fashion. For each iteration, a new depth and hole volume are calculated. From the increase in hole volume, a volume of cuttings is generated. This volume is converted into a flow rate from the surface pumping rate, which is the multiplied by the probability function across 10 µm increments to create a flow rate PSD for the drilled cuttings generated in the time step. The bin sizes range from 10 to 1000 µm, with the assumption being that anything over 1000 µm (either cuttings or LCM) will always be removed. This can result in a truncated distribution, but, as physical cuttings normally include pieces that are in excess of 1000 µm, this seems necessary for physical realism.

The generated drilled solids flow rate is combined with a flow rate of drilled solids that already exist in the active fluid system. At this point the PSD is subjected to a degradation function. Solids, both LCM and cuttings, must pass through the mud pumps and usually through the bit nozzles. In addition, they may be subjected to grinding or pounding actions by the drill pipe while being transported out of the hole. As a result, a PSD will tend to shift toward smaller sizes as circulation continues. The model represents this by giving each flow rate size bin a probability to move some or all of its content to a smaller bin. The probability of this happening is independently adjustable for the LCM and cuttings to allow representation of different formation types or different constituent particles in the LCM.

The degraded flow rate bins now pass the shaker function. This function assumes that the screens have no holes, are sealed properly and are 100% efficient so that everything above the specified cut point is removed. In the case of LCM recovery, all flow rate bins above the size of the top screen are zeroed and thus removed. Bins between the middle and top screen sizes are allowed to remain. Those between the middle and bottom size are removed, while those below the bottom also remain. These non-zero flow rates bins are then multiplied by the time step, giving a volume, which is then added to the volume already in the active system, corrected for the portion of the active system that was pumped downhole. After a few circulations, the shift in cuttings PSD becomes clear, figure 2 shows the volume PSD based on the cuttings PSD from figure 1 after 300 circulations through an LCM recovery system with API 20, 100, and 140 screen sizes for the top, middle and bottom screens, respectively.

LCM is handled in a similar manner, except that while it is assumed that there are no drilled solids in the active system at the first time step, the system is loaded with LCM to a specified amount. This LCM will degrade and be screened out in the same way as the cuttings. Additional LCM with a non-degraded PSD can be introduced at a fixed flow rate by adjusting a model parameter.

The drilled solids and cuttings volumes can now be tracked against time and depth for a given system. By specifying a maximum allowable drilled solids percentage and assigning a cost to dilution and the LCM material, it is possible to determine relative costs.

The model suffers from some obvious limitations, namely the representativeness of the drilled solids PSD and the assumptions required for the degradation function, but these are both arbitrary and replaceable in the model. The same problems exist in the field if it is assumed that the screen sizes will never need to be changed to maximize the retention of LCM while minimizing the retention of drilled solids.

The values in the example were chosen to represent an intermediate hole section drilled with a synthetic based drilling fluid. The screen sizes were chosen to try and capture between the D10 and D90 of a $CaCO_3$ based LCM product centered on a D50 of 250 µm, which corresponds to some commercial products. Regardless, 20% of the LCM will have to be replaced along with whatever percentage of LCM has been claimed by the wellbore. It is assumed that the LCM is harder than the drilled rock and thus degrades less. The results were calculated out for 5,000 feet of additional hole and for 300 circulations, or approximately 2 weeks. Dilution volumes and costs are calculated, but dilution is not factored into the particle concentrations or PSD.

The initial result of this simulation can be seen on figure

3. To quantify the results of the sensitivity analysis for each parameter, the following criteria is used; cost of LCM addition and dilution, and percentage of drilled solids and LCM that are below the bottom screen size. The last category is important as LCM of this size is significantly smaller than the desired size and is probably not assisting in lost circulation control, while very fine drilled solids are difficult to remove with other solids control equipment and can cause additional drilling problems.

The calculated cost and volumes may not be accurate predictions, but they are indications of the trends dictated by the parametric changes.

Discussion

It is clear from the sensitivity analysis, that the economics of LCM recovery is heavily dependent on the choice of top and middle screen sizes. The larger the gap, the more LCM retained, but more drilled solids are retained in the system in this cut point range. The LGS PSD is relatively insensitive to a change in the rate of drill cuttings generation, assuming similar particle degradation. The results of the sensitivity analysis based on the assumptions in tables 5,6, and 7 can be seen in table 8.

The economics of LCMR does dramatically change based on drill solids generation rate. The difference between a 12 1/4" and a 22" hole with a 20 mesh top screen and a 100 mesh middle screen is striking. In the model, this increase in bit size raises the ratio of dilution to LCM cost ratio from roughly 1:1 to more than 10:1. As the rate of cuttings generation increases compared to the rate of LCM addition, it becomes more economical to screen out as much LGS as possible.

Clearly, the higher the degradation rates, the larger the quantity of LGS that cannot be removed through mechanical action. Accordingly, assuming the LCM has been chosen for a specific size range, and that the rate of LCM addition is based only on the total LCM concentration, it is quite possible to end up with the desired LCM concentration, but with most of the particles significantly smaller than intended. Given that many LCM applications are designed with a specific LCM size range, a degraded PSD may defeat the purpose of LCMR. The problem is exacerbated by a large, pre-loaded active system and low LCM addition rate. If this was a concern, a remedy would be to run a PSD on the fluid in the active system and basing the LCM addition rate on this.

Drilled solids degradation has some interesting effects. A small amount of degradation can improve cuttings removal, as larger particles that are recovered with the LCM start to become small enough to pass through the middle screen and be caught by the bottom screen. However, larger amounts of degradation lead to significant increases in the amount of irremovable fines that must be diluted out. Degradation of LCM, from a retention standpoint, is only detrimental, as the particles move from the desired size; they should be stripped from the mud and require replacement.

While LCMR economics is strongly affected by the mesh size of the top and middle screens, it is relatively independent of the bottom screen mesh. Unless the LCM has a high proportion of particles in the size between the middle or bottom screen size, or the degradation rate is such that many particles fall in this range during circulation, the size of the bottom screen does not change the LCM cost or addition rate. It does, however, impact the required dilution.

It should be noted that in some of the examples, it makes more economic sense to bypass the shakers. In others, it seems to be better to discard as many solids as possible regardless of type, although the model does not examine the logistics of mixing LCM or waste disposal.

Conclusions

The potential effectiveness of LCM recovery is highly dependent on having an LCM with a relatively tight PSD that does not degrade; otherwise, it appears to be difficult to achieve sufficient recovery rates of the correct size of LCM to justify recovery. In practice, this would require onsite particle size monitoring of the drilled solids and LCM. Additional variables can be added to the model to improve its use as a decision making tool. This can only be accomplished by further research in the lab combined with data collection from the field.

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Nomenclature

LCM	*=Lost circulation material*
ROP	*=Rate of penetration*
LCMR	*=Lost circulation material retention*
PSD	*=Particle size distribution*
LGS	*=Low gravity solids*
µm	*=micrometer*

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Tables

Table 1: Assumptions for Offshore ExampleRig Type	Offshore
Hole Size	12 1/4"
Rate of Penetration	100 ft/hr
Pumping Rate	1000 gpm
Drilling Time	20 hrs
Drilling Fluid Type	Non-aqueous Fluid
Fluid Cost	250 $/bbl
Desired LCM Concentration	30 lb/bbl
LCM Cost	29 $/50 lb sack of graphite LCM
Maximum Drilled Cuttings Volume	5%
Hole Drilled	2000 ft
Volume Drilled	291.6 bbl
LCM Circulated per minute	714 lb/min

Table 2: Calculations for Offshore Example

Case	**Bypass Shakers**
LCM Additions Required	0 lb
LCM Addition Rate	0 sacks / min
LCM Cost	$0
Dilution Rate	193.9 gpm
Dilution Cost	$1,385,100
Total Cost	$1,385,100
Case	**Coarse Screening**
LCM Additions Required	85,700 lb
LCM Addition Rate	1.4 sacks / min
LCM Cost	$49,706
Dilution Rate	77.6 gpm
Dilution Cost	$554,040
Total Cost	$603,746
Case	**Fine Screening**
LCM Additions Required	771,300 lb
LCM Addition Rate	12.9 sacks / min
LCM Cost	$447,354
Dilution Rate	19.4 gpm
Dilution Cost	$138,510
Total Cost	$585,864

Table 3: Assumption for Onshore Example

Rig Type	Onshore
Hole Size	7 1/4"
Rate of Penetration	2 ft/hr
Pumping Rate	275 gpm
Drilling Time	20 hrs
Drilling Fluid Type	Water Based
Fluid Cost	100 $/bbl
Desired LCM Concentration	10 lb/bbl
LCM Cost	29 $/50 lb sack of graphite LCM
Maximum Drilled Cuttings Volume	5%
Hole Drilled	40 ft
Volume Drilled	2.044 bbl
LCM Circulated per minute	41.1 lb/min

Table 4: Calculations for Onshore Example

Case	**Bypass Shakers**
LCM Additions Required	0 lb
LCM Addition Rate	0 sacks / min
LCM Cost	$0
Dilution Rate	1.36 gpm
Dilution Cost	$3,883.60
Total Cost	$3,883.60
Case	**Coarse Screening**
LCM Additions Required	4,932 lb
LCM Addition Rate	0.082 sacks / min
LCM Cost	$2860.56
Dilution Rate	1.04 gpm
Dilution Cost	$1,553.44
Total Cost	$4,414.00
Case	**Fine Screening**
LCM Additions Required	44,388 lb
LCM Addition Rate	.74 sacks / min
LCM Cost	$25,745.04
Dilution Rate	0.136 gpm
Dilution Cost	$388.36
Total Cost	$26,133.40

Table 5: Assumed Well Parameters for Sensitivity Analysis

Parameter	Units	Value
Flow Rate	gpm	1,000
Bit Size	in	12 1/4
Drill Pipe OD	in	5 1/2
Drill Pipe ID	in	3
Measured Depth	ft	10,000
Drilling Interval	Ft	5,000
ROP	ft/hr	100
Surface Active Volume	bbl	1000
Maximum Drilled Solids in Drilling Fluid Cost	%	5
Drilling Fluid Cost	$/bbl	250
LCM Cost	$/50lb sack	10
Initial LCM concentration in active system	ppb	40
LCM addition rate	Sacks/24hr	587

Table 6: LCM Recovery System

Top Screen Cut Point	µm	780	API 20
Middle Screen Cut Point	µm	140	API 100
Bottom Screen Cut Point	µm	100	API 140

Table 7: LCM and Cuttings PSD Functions

LCM mean	µm	500
LCM standard deviation	µm	250
LCM degradation probability	%	.1
Drilled solids mean	µm	1200
Drilled solids standard deviation	µm	800
Drilled solids degradation probability	%	.25

Table 8: Sensitivity Analysis Results

Scenario	LCM Cost	Dilution Cost	Fine Drilled Solids %	Fine LCM %
Base Case	$30,281	$39,385	17.0%	22.7
Increase Flow Rate to 1500 gpm	$29,999	-	14.6%	12.7 %
Increase Bit Size from 12 1/4" to 17 1/2"	42,318	370,522	12%	6%
ROP increased to 200 ft/hr	24,145	106,681	11%	5.8 %

Figures

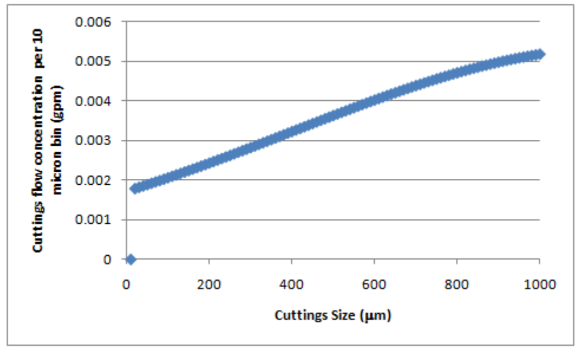

Figure 1: Example Drilled Solids PSD as generated at the bit

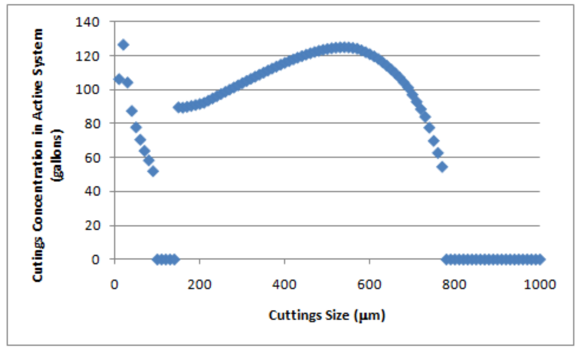

Figure 2: Example Drilled Solids PSD after 300 circulations through LCM recovery

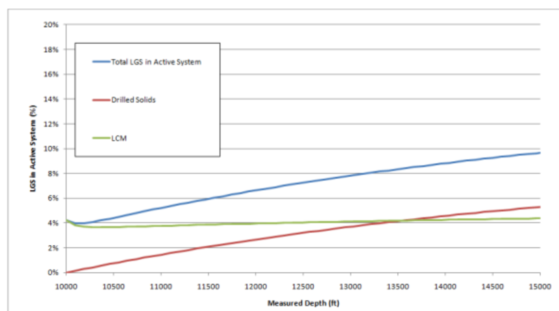

Figure 3: LGS concentrations generated by model for 12 1/4" hole with LCM recovery, 100 ft/hr ROP, and 0.95ppb per minute LCM addition