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A Pragmatic approach to Lost Circulation Treatments: What every Drilling Engineer Should Know

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Abstract

Lost circulation is a common problem encountered when drilling and completing wells. Cost to the industry has been estimated to be billions of dollars. This paper will present a pragmatic approach to lost circulation treatments and will present information to give drilling engineers a better understanding of lost circulation and lost circulation material (LCM) treatments.

Common misconceptions will be discussed along with common deficiencies in lost circulation research, testing, and applications. A short review of significant historical technical literature findings will be made to refute common misconceptions and guide the reader to more effective treatments. The authors will also propose an improved classification system and performance criteria ranking for LCM products.

Introduction

For over 60 years the industry has had a wealth of technical knowledge around lost circulation and lost circulation materials (LCM) (Howard 1951, White 1953, Green 1959) but much of that information is not effectively transferred to field practice and most drilling engineers.

Lost circulation is the loss of whole mud from the circulating system to a subsurface formation. For lost circulation to occur, the wellbore hydrostatic pressure must be greater than the lowest pore pressure in communication with the wellbore.

Lost circulation types are generally divided into:

1) natural features, such as naturally occurring conductive fractures/faults/channels, cavernous or vugular formations, and high matrix permeable zones, or

2) induced fractures

Most field muds have the larger particles that are around 100 microns and can seal matrix formation permeabilities to 75 Darcies or more (Bugbee 1953, Gatlin 1961). Losses to high matrix permeable zones, such as shallow coarse gravel, are likely to occur only if the drilling fluid was water or had ultra-low solids. Matrix permeability of this magnitude would only be anticipated at shallow depths.

Generally conductive fractures/faults, carbonate formations with caverns/vugs, and shallow loss zones are known or easy to identify from drilling or loss rate data. Excluding these, lost circulation is usually caused by induced fracturing in weak sands or sand shale interfaces. Sandstone or sand/shale interfaces are most prone to mud losses from induced fracturing and depletion makes it more likely to happen. Two recently published books about lost circulation have as much information about rock mechanics as useful information on solutions for curing lost circulation (Lavrov 2016, Feng 2018).

It is a misconception that lost circulation frequently occurs due to whole mud invasion of matrix permeability and that combatting losses requires bridging matrix permeability. This misconception leads many to mistakenly recommend small sized LCMs, like fine calcium carbonate or finely ground cellulose. These types of LCMs are usually smaller sized than the larger particles already in a field mud, ineffective at stemming losses, increase low-gravity solids and the need for dilution, and can be detrimental to drilling fluid properties. Given that losses are rare to a permeable formation matrix and more often related to induced fractures or large openings, HTHP or PPT testing on ceramic disks and sand bed tests are generally not applicable to understanding or evaluating lost circulation remedies. This confusion between filtration and lost circulation can be seen in both industry and academic testing and publications (Alkinani 2018)

Particle Bridging

For remedial lost circulation treatments, it is essential to bridge the loss zone permeability regardless of whether it is a fracture, vug or pore. The size of material that can be realistically used is limited by several factors such as bit nozzle size, MWD/LWD tool sizes and their screens/filters, and rotary steerable restrictions. Often the size of LCM that may be used it limited to granular material only, below 2 mm (Alsaba 2016, Aston 2014). MWD/LWD tools are frequently qualified and rated using 40 to 50 lb/bbl of medium nut shells with a D100 just below 2 mm. Often the tool manufacturers prohibit fibrous or flake LCM. Downhole by-pass circulation subs are available which allow larger materials to be used.

Particle bridging theory is not complicated. Since the earliest published technical work on lost circulation and bridging (Howard 1951, Green 1959), it has been known that for a stable high-pressure bridge to be established, strong granular materials are required. Fibrous, laminated/flake shaped materials do not perform as well as granular materials (Fig. 1).

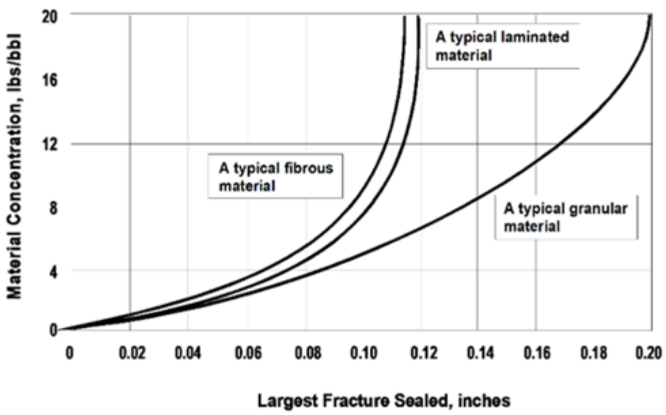

Figure 1: Effect of LCM Type on Sealing

When fibrous and flake materials can be used and in situations where larger granular materials are not effective at establishing a bridge, LCM treatments can benefit from blends of material types. There were several early developments regarding optimized blends and the development of a commercial product using walnut shells, two types of fibers, and flake cellophane in equal amounts (Lummus 1967, Messenger 1981). In these blends, the fibers and flaked material help form a seal. Reticulated foam particles most likely function in a similar manner. As will be discussed later, the strength and character of materials varies greatly and the components in blends will affect performance. Similar blends are widely available from a variety of companies, these blends may allow a bridge to be formed where granular products alone will not, but generally offer a much lower level of allowable pressure differential. This early work on blends also identified the beneficial sealing capability of barite sized material when testing LCMs, something that is often overlooked when testing or recommending LCMs.

Regarding size and concentration, one of the best scientific studies of bridging mechanics was done by Sandia National Labs (Loeppke 1990). This work can be summed up by stating that for a stable high-pressure bridge to form, the larger particles needs to be "equal or slightly larger" than the opening. And the concentration of these larger bridging particles needs to be in the 10-20 lb/bbl range. One conclusion from the Sandia work is that "allowable pressure differential increases sharply with increasing particle lengths slightly larger than the fracture width" and "concentrations of granular LCM particles as high as 20 lbm/bbl [57.1 kg/m^3] can reduce filtrate loss and improve the probability of forming a high-pressure-plug" (Fig. 2). Similar results have been obtained by other researchers.

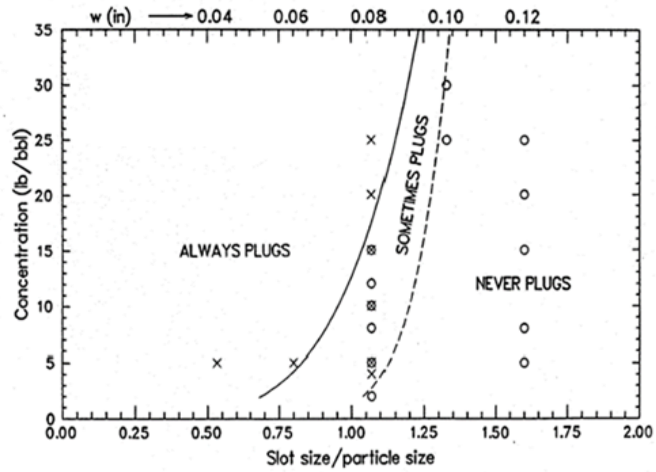

Figure 2: Particle Size and Concentration Required for Effective Bridging

Given that particles above 2 mm are often not able to be used due to the risk of plugging tools, this leads to the conclusion that fracture apertures and openings greater than 2 mm cannot be sealed with conventional LCMs for many drilling situations. Many practical considerations limit the size of LCM that can be used; suspension and settling, rig equipment, nozzle/BHA/tool plugging, attrition, and solids control. It is not uncommon to have loss zones with faults, fractures, or vugs with opening above 2 mm where remedial treatments other than conventional LCMs would be needed. For higher loss rates that cannot be corrected with conventional LCMs, treatments such as high-fluid loss high-solids squeezes, reactive squeezes or settable squeezes would be applicable. Alternatively, finding ways to continue drilling with losses is also often necessary.

It is a misconception that the size of bridging solids can be as small as 1/3 of size of the loss zone opening and still affect a strong bridge. This has been demonstrated many times (Loeppke 1990, Alsaba 2016, Kageson-Loe 2009). Yet this so-called "Abrams rule" is often mentioned in industry technical and academic literature concerning lost circulation. This often-cited rule says that to reduce formation damage, the median particle size needs to be greater than 1/3 of the median pore size of the formation and these >1/3 bridging solids need to be 5% by volume of the solids in the final mixture (Abrams 1977). It does not apply to bridging a loss circulation opening. If the reader examines the Abrams paper it has nothing to do with lost circulation and only deals with formation damage.

Lost Circulation Treatment Particle Size Distribution

Many of the drilling fluid service companies and some operators recommend using "optimized particle size distribution techniques" for blends of LCMs. According to particle bridging theory, an optimized bridging distribution is not needed for sealing lost circulation zones. The only thing that is important is that the bridging materials form a bridge at or within the loss zone opening, that can then be sealed by the particle size distribution (PSD) of the mud or of the formulated treatment (Jeennakorn 2017).

Like the Abrams method above, the following LCM optimized sizing methods and their associated software are not necessarily applicable to bridging and sealing lost circulation zones. They are based on obtaining good surface coverage for paints, minimizing voids within the filter cake, or having a fluid with minimal filtration to a permeable matrix and are applicable to minimizing formation damage: Ideal Packing Theory (Dick 2000), Vickers Method (Vickers 2006), and Sharma (Suri 2004). Lost circulation, induced fracture bridging, and the sealing of bridging materials are not covered in these references. These approaches and many drilling fluids technical advisors often recommend blends of products to achieve a special particle size distribution based on these methods believing that they are beneficial to remedial lost circulation treatments. While idealized PSDs may be applicable to “stress cage” squeezes, they are not applicable to remedial bridging and sealing treatments. There is no evidence that these special PSDs are more effective at solving losses. If bridging of an opening can be achieved, the pore spaces in the bridged materials can almost always be effectively sealed by the PSD of most field muds. Using these sizing optimized approaches makes it difficult to formulate treatments that have the required volume of larger bridging solids without using excessive concentrations of LCM.

An example of effective bridging and sealing without a special PSD is shown in Figures 3 to 5. In this example, 20 lb/bbl of a 250-600 micron nut shell loss prevention material (LPM) is blended into a field mineral oil based mud (MOBM) and tested on a 500 micron slot using a high pressure slot tester at ambient temperature. Figure 3 shows the PSDs of the untreated field MOBM, the LPM, and the field mud treated with LPM. The treated mud PSD is bimodal with very few particles between 100 and 200 microns.

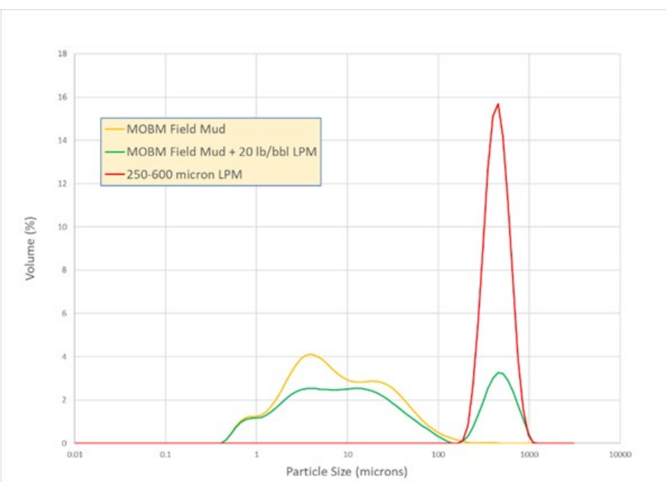

Figure 3: Particle Size Distribution MOBM field mud, LPM, and MOBM LPM Fluid

Figure 4 shows the same treated field mud plotted on an Ideal Packing Theory type graph, illustrating that the PSD is significantly different. The ideal packing theory rule as applied for lost circulation recommends the percent of cumulative volume vs the $D^{½}$ forms a straight-line relationship, where $D^{½}$ is square root of the particle diameter and that the D90 be the square root of the opening.

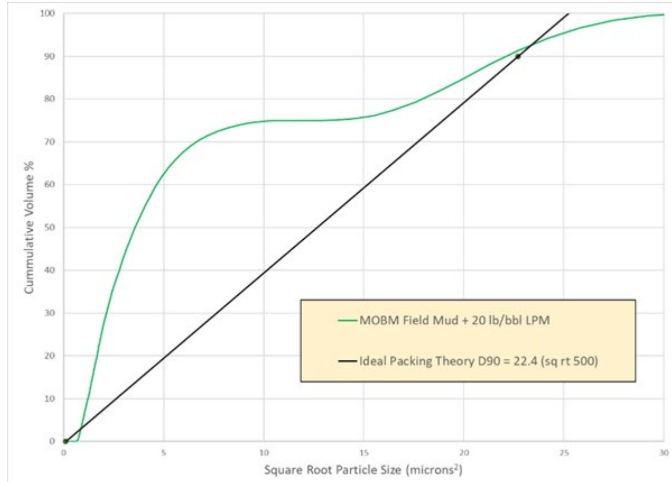

Figure 4: Comparison of Ideal Packing Theory with MOBM LPM Fluid

Figure 5 shows the results of the slot test for the not optimized fluid where excellent sealing is achieved to 3500 psi (which is the operational limit of the equipment) with minimal fluid lost of only 11 mL

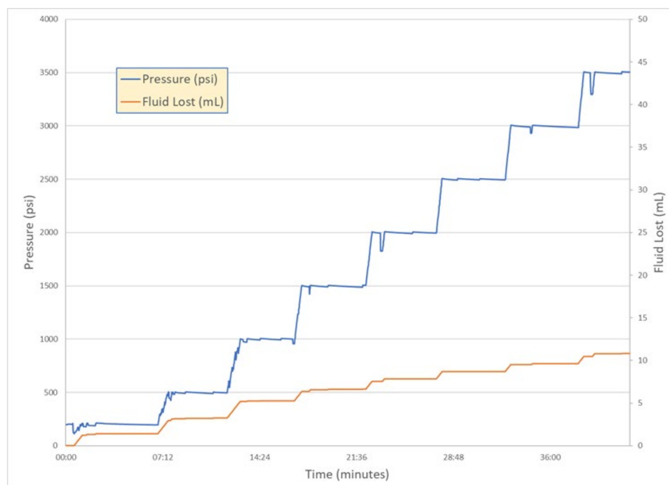

Figure 5: Slot Test Sustained Pressure and Fluid Lost for MOBM with LPM

A simplistic but conservative approach to determine what minimum size particle is needed in a bridging slurry yet which can still be sealed with a field mud is to assume tetrahedral uniform particle packing (Fig. 6).

For a field mud having particles up to 100 microns the bridging material would need to have the smaller end solids 645 microns or smaller (100 ÷ 0.155 = 645). For systems using micronized barite and finer mesh screens, only slightly smaller particles around 400 microns would be needed.

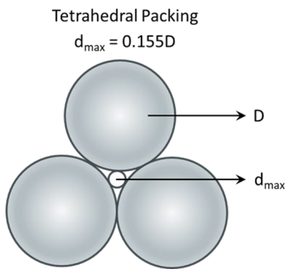

Figure 6: Pore Space Diameter of Tetrahedral Packing of Bridging Solids

It is a misconception that the PSD for an effective lost circulation treatment needs to have an optimized broad even distribution of solids. This is not necessarily more effective than particle bridging based distributions. If the drilling fluid PSD can seal the largest pores within the bridging solids, an effective seal will be achieved. It was this concept that was used to develop the two originally patented LPM (Fuh 1992, Fuh Conoco 1993).

PSD of field muds

The size of the larger solids in most field muds is in the 75-150 micron range, depending on the shaker screen size openings (Table 1), not the additives used in the mud formulation.

Table 1: Sieve (mesh) Opening Diameters in microns

U.S. Sieve Number	Opening µm
50	300
60	250
70	212
80	180
100	150
120	125
140	106
170	90
200	75
230	63
270	53
325	45
400	38
450	32
500	25

Even when centrifuges or other solids control equipment are used, these larger bridging solids are still present because that equipment does not make a 100% cut. It is these larger solids that govern what opening size can be bridged and sealed. Also weighted muds often start with solids that are as large as 150 microns because API sized barite contains particles in this range with the upper end specification being <3% above 75 microns (Fig. 7). Figure 8 and 9 are example PSDs for two field muds. Figure 8 is a 14.5 lb/gal MOBM which used API sized barite and 140 mesh shaker screens and Figure 9 is a 14.3 lb/gal micronized barite MOBM system (starting fluid with a D50 of about 2 microns) and 230 mesh shaker screens, both have larger bridging solids regardless of the starting fluid distribution.

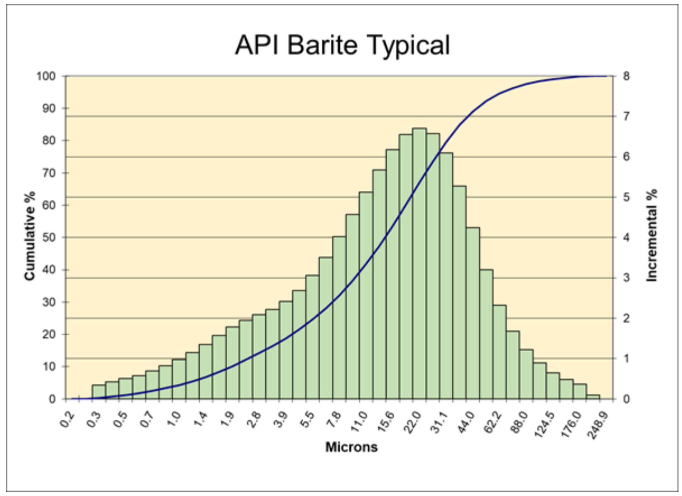

Figure 7: Typical API Barite PSD

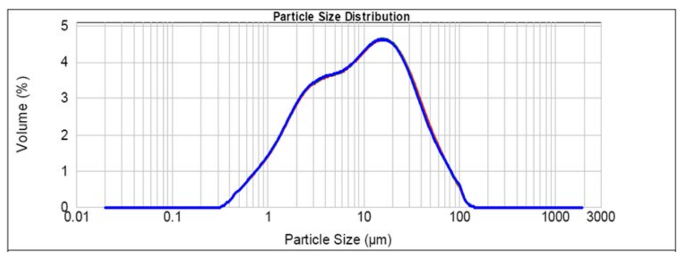

Figure 8: Field 14.5 lb/gal MOBM using API Barite 140 mesh screens

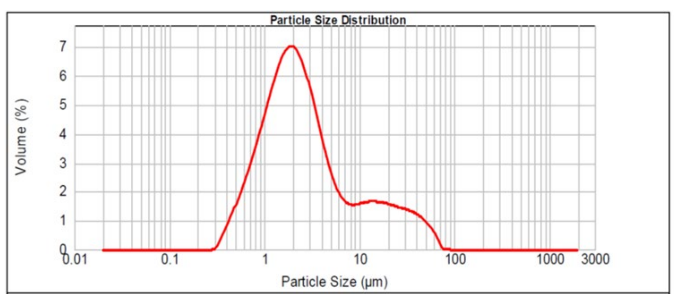

Figure 9: Field 14.3 lb/gal MOBM using micronized barite using 230 mesh screens

Confusion due to LCM naming practices

One of the most important aspects of granular LCM is size, not only for selecting the best product to solve losses but also to prevent plugging of the drill string. However, there are no industry standard concerning naming conventions for LCMs which causes great confusion and difficulty in selecting products (Amer 2017). A naming convention for one product may not apply to other LCM products within one company's product offerings and rarely between different suppliers. For instance, fine nut shells are often 3 times larger than other lost circulation material products named coarse. Another example is that one company's fine walnut shells has a D50 six times larger than another company's fine walnut product. There are more than 300 different LCM products offered by at least 50 different companies. Clearly the industry could benefit from adopting a sizing and naming convention, especially for granular materials.

Other naming conventions can be misleading too. For instance, within the major drilling fluid suppliers, calcium carbonate is often named according to the D50 of the product which is particularly helpful when designing minimally damaging drill-in fluids. Other products may be named using the D90 instead of the D50. One company uses a number in the name of their LCM products that is related to developmental code of the product and is unrelated to size. Many LCM manufacturers use the screen size used in manufacturing to designate products. As an example, one product named "calcium carbonate 300" is manufactured using the material that passes a 325 mesh screen and has a D50 of 15 which is similarly sized to other products named "calcium carbonate 15". Even for screened products using the screen size number in the name, some products are made where all of the solids that pass through that size are used and others are sized with the solids between the screen size used in the name and the next screen size down in their product line – so one product has fine particles and the other does not. For products that are made using two screen sizes, some manufacturers use both numbers in their name similar to gravel pack sand sizing (ex. product 40-200) but the drilling fluids industry does not carry over this naming convention and would most likely market the product according to the D50 designation or names like "fine", "medium", or "coarse".

Table 2 has examples that illustrate the range of sizes that are called "fine" or of similar size with different number designations. The same situation exists for products named with "regular", "medium", "superfine", "coarse", and "extra coarse".

On top of not having industry standard sizing and naming conventions, the plugging capability of different types of LCM makes size information less important. For instance, for strong granular materials, diameter is a good indication of sealing, as shown in Figure 2. However, for fibrous and flake materials with different shapes and from materials which are quite flexible and weak (cellophane, paper, spun mineral fiber, rubber, etc.) dimensional data is less relevant to a product's plugging capability, both for solving losses and for potential plugging of the drill string.

Table 2: Range of sizes for "fine" LCM products

Name	D50 (microns)	D90 (microns)
Fine Calcium Carbonate 1	15	120
Fine Calcium Carbonate 2	18	57
Fine Calcium Carbonate 3	75	155
#200 Calcium Carbonate 4	7	40
#200 Calcium Carbonate 5	20	100
#300 Calcium Carbonate 5	15	75
Fine Flake Calcium Carbonate	400	900
Fine Cellulose 1	50	150
"Super" Fine Cellulose 2	75	250
Fine Cellulose 3	300	1100
Fine Mica 1	160	220
Fine Mica 2	350	850
Fine Walnut Shells 1	210	700
Fine Walnut Shells 2	400	700
Fine Walnut Shell 3	600	850
Fine Walnut Shell 4	730	1400
Fine Walnut Shell 5	1250	1900
Fine Graphite 1	30	90
Fine Graphite 2	100	300
Fine Blend Seal 1	600	900
Fine Blend Seal 2	300	1200
Coarse Calcium Carbonate	200	650

For guidance on methods for determining the size of granular materials, the API Subcommittee 13 recently published a technical report on methods for sizing granular particulates and is looking at additional standard methods for sizing LCMs (API 13TR3 2018).

LCMs often lack good quality control. Products should be tested to ensure that the largest particles (D100) do not plug a given BHA or bit. It is not uncommon for drill string plugging to occur due to poor quality control of LCM products or from poor mixing equipment and practices. Many LCMs tend to clump or agglomerate when mixed quickly or with inefficient equipment. Premixing in a concentrated slurry is one best practice to prevent this from happening and aids in being able to add LCM more quickly.

Oversized LCM can create a hazard for downhole MWD/LWD equipment, which may lose function due to LCM plugging. Directional drilling firms routinely publish maximum allowable concentrations of LCM and type that may be used with directional tools. These limitations are typically based on the LCM names of fine, medium, and coarse along with the type of material used. Based on this poorly controlled criteria and qualification, it is the authors' opinion that MWD/LWD tool LCM reference material limitations are very conservative and need to be more specifically defined. The maximum allowable concentrations should include the actual size, shape, and type of LCMs that are acceptable.

Particle size information is not always provided on product bulletins for LCM or with recommendations for lost circulation in mud programs. When it is provided by the supplier it is usually presented in a tabular manner. Graphic representations make the data much easier to comprehend and help make product selection more obvious, particularly for bridging materials. An example that the authors find useful is shown below (Fig. 10). Mud programs and LCM decisions would benefit from having this format of the data available at the wellsite.

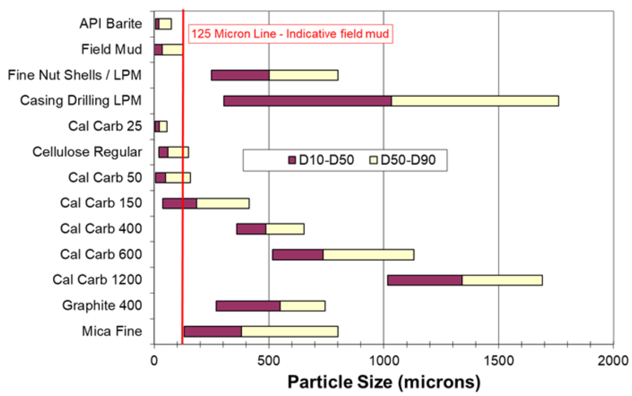

Figure 10: Example of graphical representation of LCM PSDs

It is a misconception that the LCM product names like fine, medium, coarse or numbers are useful for selecting the size of products. Given that there are no standards for naming materials and that the plugging behavior of a product may be unrelated to size, LCM names can be misleading and are not particularly useful for selecting a remedial product. Similarly, it will be shown later that classifications for LCM type are also misleading. There have been instances where naming and size information have led to ineffective LCMs being used.

A Pragmatic Approach

Preventative vs Remediation Treatments

Treatments for lost circulation can be divided into remedial treatments, where losses have already occurred, or preventative treatments, where fluids or products are used to prevent losses. Examples of remedial treatments are the post loss application of conventional LCM, high-fluid loss high-solids squeezes, and reactive or settable slurries. Examples of preventative treatments are pre-loss routine additions of LCM or methods often referred to as wellbore strengthening techniques (WBS), such as stress cage type squeeze treatments or drill ahead methods where LPM is maintained in the circulating drilling fluid.

Remedial treatments

When possible, it is recommended to try to identify the type and location of the loss zone, examples can be found in several references (ARCO-Baker Hughes 1999, Majidi 2010, Lie'tard 1999, Huang 2011, Civan 2002, Aston 2014). The analytical techniques that relate loss rate and type curve to loss zone fracture aperture can be particularly helpful at sizing an appropriate bridging material. Table 3 shows a generalized categorizations of lost circulation treatments.

Table 3: General Categories of Lost Circulation Treatments

General Categories of Lost Circulation Treatments

Type of Treatment	Method	Examples	Key Feature
Conventional LCM: Granular, fibrous, or flaked particles	Plug or bridge permeability or fracture/faults	Nut Shells, graphite, calcium carbonate, plant or textile fibers, mica or cellophane flakes, and LCM blends	Size & strength matter but BHA tools limit sizes
Fracture Packing: High-fluid loss high-solids squeezes & Stress Cage squeezes	Deposit a large volume of compacted solids into a fracture	Diatomaceous earth high-fluid loss slurries and Stress Cage LCM Blends	Time consuming to mix/spot/squeeze & must be squeezed to work
Reactive High Viscosity Slurries	High viscosity fluid increases pressure in loss zone to limit or stop losses	Gunk & shear activated treatments	Often a treatment of last resort & often temporary
Settable Slurries	Fluid sets to form a rigid plug or semi-solid gel plug	Thixotropic cements, crosslinked polymers & resins	Time consuming for rig, can be difficult to spot, often adversely affected by mud contamination
LPM Wellbore Strengthening	Particles form fracture tip bridge near wellbore preventing fracture propagation	30/60 mesh nut shell LPM at 20-50 lb/bbl	Preventative not remedial and difficult to manage at the rig

Lost circulation can be a challenge in mature depleted fields, as well as exploratory prospects. While the challenge is similar, the underlying causes of lost circulation and the availability of relevant information is different. Thus, the process of selecting the best lost circulation material (LCM) or treatment design may be different. It is recommended to have a lost circulation decision tree based on local experience using readily available products (Figure 1-2 in ARCO-Baker Hughes 1999). While these decision trees are normally based on loss rate, they can be augmented with special treatments for specific known formations where losses often occur.

Lost circulation is often classified according to the rate of loss, similar to Table 4, and treatments recommended based on loss rate. While the term seepage is often used for low loss rates, it implies that the losses are to a permeable matrix which may not be the case and may be misleading with regard to selecting the best LCM product. Many other factors may cause the loss rate to be low, low differential pressure being one.

The following sections on remedial treatments are a general guide provided as an example of common recommendations.

Table 4: Lost circulation Treatments often selected based on loss rate

Low (seepage) Losses	1 - 10 bbl/hr
Medium (partial) Losses	10 - 50 bbl/hr
High (severe/total) Losses	>50 bbl/hr

Low loss rates

A good starting point is to begin continual additions of granular materials larger that the solids in the mud. This is usually fine nut shells or calcium carbonate with a D50 around 400. A recommended rate would be 8 to 12 - 50 lb/sacks per hour and go up or down based on results. It is the author's experience that the continuous addition of materials is considerably more effective than pumping LCM sweeps.

For low loss rates, it is common to find decision trees or have recommendations for mixing and pumping LCM sweeps of fine calcium carbonate or fine ground cellulose products that are <200 microns. Unless the drilling fluid is water or an ultra-low solids fluid, the use of these smaller materials is rarely successful as they are smaller than the solids already in most muds or too small to seal the loss zone. These smaller products will increase low-gravity solids, are often detrimental to drilling fluid properties, and increase the required dilution to maintain good properties.

Nut shells are preferred to other materials due to cost, availability, and performance. Their irregular shape has been shown to outperform more spherical calcium carbonate and graphite materials (Alsaba 2016). Calcium carbonate shear degrades quickly and should not be used for situations where the LCM is being recirculated (Scott 2012).

Medium loss rates

Reduce mud weight/ECD if possible. Screen down to retain some LCM and begin additions of the largest granular materials that is allowed for the drill string and bit nozzles. This is usually a combination of medium and large nut shells or other granular LCM up to 2 mm, some situations may allow particles up to 4 mm. A recommended rate would be 15 to 20 - 50 lb/sacks per hour and go up or down based on results.

If this treatment is not effective, if possible, begin to use a medium sized blended LCM product that contain fibers and flaked material.

If this treatment is not effective and the situation requires additional remedial treatments, a high-fluid loss high-solids hesitation squeeze would be appropriate.

High loss rates

Clearly this is the most difficult lost circulation situation. Reduce mud weight/ECD if possible. Slow or stop circulation and work the pipe. Mix and spot a pill of the largest sized LCM blend allowed adjacent to the suspected loss zone, pull up above it and wait a period of time, circulate above it to judge effectiveness.

If positive results are achieved continue with conventional LCM treatments. If conventional LCM treatments are not effective and rig operations allow, prepare a high fluid loss squeeze and perform a hesitation squeeze.

Other Loss Circulation treatments

Fracture packing high-fluid loss high-solids squeezes are available from most mud companies and specialty lost circulation companies. While the industry does not keep statistics on treatments, anecdotal evidence and our experience is that that the high-fluid loss high-solids hesitation squeezes are more effective than other non-conventional LCM treatments. Hesitation squeezes require careful spotting, pressure monitoring, and slow circulation rates to stop losses and build pressure that allow drilling to continue (CP Chem 2014). Having rigsite supervision from someone experienced in this technique is recommended.

For losses with oil based muds (OBM), it is reported in literature and our experience is that water-based high-fluid loss high-solids hesitation squeezes are effective (Clancey 1981, Onyia 1994, Radenti 1969), even more effective than similar treatments formulated in base oil. A lab evaluation of settable treatments indicated that DOB2C and magnesium-based cements were considerably more effective than other treatments, partially because of their resistance to mud contamination, something often overlooked during testing (ARCO-Baker Hughes 1999). High loss rate natural fault/fracture loss zones with apertures of 3 and 5 mm have been successful sealing using high-fluid loss high-solids squeezes.

One region over time has developed the use of thixotropic cement to cure losses in weak pressure-depleted zones. It is the backup treatment used when conventional LCM does not work and when losses are above a rate that would allow drilling to continue. This has been used on 39 wells with a 74% success rate. This treatment is pumped through directional BHAs without tripping and many of these wells have continued drilling to interval total depth without tripping and without losses after the treatment.

Preventative Treatments

Examples of preventative treatments are routine additions of LCM or a variety of methods often referred to as wellbore strengthening techniques, such as stress cage squeeze treatments or the drill ahead LPM method where LPM is maintained in the circulating drilling fluid.

While the routine additions of LCM is a common practice and often recommended by suppliers, there is no definitive evidence that routine additions of LCM, such as LCM sweeps, are effective at preventing lost circulation. It would be coincidental if a routine LCM sweep were to circulate past a loss zone as it was being penetrated and it is hard to believe that a sweep that contacts the formation for a few minutes would have a lasting sealing effect. In fact, many wells where routine LCM is added, still experience lost circulation. When preventative routine LCM treatments are used and a well does not experience lost circulation it is never really known whether it would have had losses if the treatments had not been used. In addition, routine LCM additions often increase mud viscosity and ECDs, increasing the potential for inducing a fracture and having losses. The more pragmatic approach is to wait until measurable losses are observed and then begin adding LCM.

In addition to preventative LCM treatments, other drilling practices can minimize the potential for having losses by reducing ECD. These include using low-ECD drilling fluid systems, low viscosity micronized weight material systems, managed pressure drilling, controlled ROP drilling, having good hole cleaning practices, and conservative tripping practices. LCM Settling and buoyancy is a special concern for low viscosity systems. The use of mud coolers and cold mud temperatures after trips can increase the potential for lost circulation (Gonzalez 2004).

Wellbore Strengthening Techniques

Wellbore Strengthening techniques allow a higher differential pressure in the well than would be possible without the treatment (Feng 2017). As stated above LCM treatments and other remedial treatments are used after losses have occurred. Post loss it is common to maintain LCM in the system or to convert to some form of WBS, normally with a much lower efficacy than the pre-loss WBS approach.

LPM Drill Ahead method

The LPM drill ahead wellbore strengthening method is to maintain 25-50 lb/bbl of granular LPM sized 250-600 micron (30/60 mesh) in the circulating drilling fluid system (Fuh 1992, Fuh 2007). Recirculation is accomplished most frequently by utilizing three deck shakers. Occasionally very coarse single deck shaker screens have been used to keep the LPM from being removed yet to remove the very large drill solids. This is usually only done for a short distance at the end of an interval where a weak zone must be drilled.

The LPM application is for induced fracture losses to weak permeable formations. It is not a remedial technique and is not intended to be used after a well has had measurable losses, even though there have been times where it works for these situations. It is not applicable to losses in vuggy formations or to conductive channels, fractures, or faults. It works by a phenomenon that has been described as fracture tip screenout, where the LPM forms a bridge within the fracture to isolate wellbore pressure from the fracture tip such that further propagation is arrested (Fig. 11) (Fuh 1992).

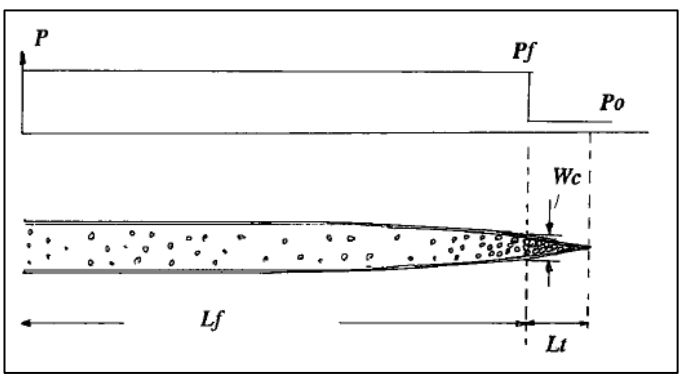

Figure 11: Wellbore Pressure Profile Fracture Tip Screenout

The drill ahead LPM method has been used on over 100 wells in a variety of locations around the world. Both LOT and FIT tests have shown a typically increase in fracture gradient of around 3.5 lb/gal, but increases as high as 8.0 lb/gal and overbalance pressures of 4600 psi have been achieved (Fuh 2007). The success rate for the drill ahead LPM method is over 90%. For squeeze treatments, similar to stress cage, success rates are only about 60%.

The drill ahead wellbore strengthening method is simple from a fluids standpoint and is extremely effective, but it is not easy to do. Three deck shakers not widely available as installed rig equipment. The process of separating LPM sized solids, cleaning the mud of finer drill solids, and reintroducing the LPM sized solids is mechanically difficult and inherently reduces solids control efficiently. Obtaining good removal efficiencies utilizing triple deck shakers, requires LPM with a relatively narrow PSD and a product does not degrade quickly. There have been several cases where the size or concentration of LPM drops below the desired levels and losses occurred, but where increasing the LPM restored full circulation. For that reason, it is important to monitor the concentration of target sized LPM in the fluid daily using a simple field sieve test. Depending on the type of LCM used and the solids control equipment, the daily attrition of target LPM is often in the 5 to 10% range.

Recirculating LCM during WBS or remedial LCM treatments can be problematic for other rig equipment. It and the associated higher levels of LCM size drill solids can cause plugging and lead to higher rates of erosion. Mud coolers and automated mud measuring devices may not be capable of circulating LCM laden mud.

The origin of the LPM drill ahead method was the DEA-13 joint industry project from 1985 to 1988. This research performed fracture testing on 30-in. cubes of sandstone. The information from this project showed that the that fracture initiation pressures are higher than anticipated when mud is used. An analysis of this data resulted in the “theory of lost circulation pressure” which accounted for the effects of drilling fluids on fracture initiation and propagation pressures (Morita 1990). From this same data it was observed that water based muds (WBM) and OBM have the same fracture initiating pressure but that OBM has a lower fracture propagation pressure due to the differences in filtration and filter cake deposition (Onyia 1994). This review also concluded that water based high-fluid loss high-solids treatments are effective for remedial treatments after losses with OBM. Post DEA-13 additional large sandstone block testing by Conoco showed that LPM in the 250-600 micron range (30/60 mesh) could be sealed by simple muds and would increase fracture propagation pressure 1700 to 4000 psi (Fuh Conoco 1993). LPM was field tested and showed a 3.0 to 8.0 lb/gal increase in borehole breakdown pressure (Fuh 1992). Additional research on the subject expanded on the original concept, yet concluded “A unifying picture of great clarity and simplicity thus emerges, where the different "strengthening" effects observed all finding their origin in fracture tip screenout and isolation, which was already identified as the source of wellbore strengthening by the scientists (Morita, Fuh, Onyia, Black, etc.) that guided the DEA-13 investigation in the late 1980 's.” (van Oort 2014).

Since this technique was first introduced, the PSD of the preferred LPM has not changed from the 250-600 micron size (30/60 mesh) regardless of target loss zone. This size is a narrower PSD than is found in most LCMs, like fine nut shells. Nut shells have been used more than any other material due to cost and availability. Over time, the concentrations have been reduced to the 25 to 30 lb/bbl range without a significant change in success rates. This was done partially due to field efforts to reduce cost and to make the process more manageable and because concurrent additional research using the University of Texas MudFrac device indicated that the lower concentrations would still be effective (Razavi 2016).

LPM Type

The selection of an appropriate LPM involves balancing availability, cost, and performance. However, for LPM or LCM that will be recirculated, it should be resistant to size degradation from shear or impact. Calcium carbonate is a poor choice (Fig. 11). First it degrades quickly and second it has been shown to be a poor performer. (Scott 2012, Dudley 2000). Another consideration is buoyancy, it is preferred that the LPM be as neutrally buoyant as possible, such that it does not tend to settle or float in the drilling fluid, especially in low viscosity muds. Nut Shells have a specific gravity around 1.4 and graphite has a specific gravity of 1.7 to 2.1, depending on the product. Both are resistant to degradation, making them good choices for drill ahead wellbore strengthening applications.

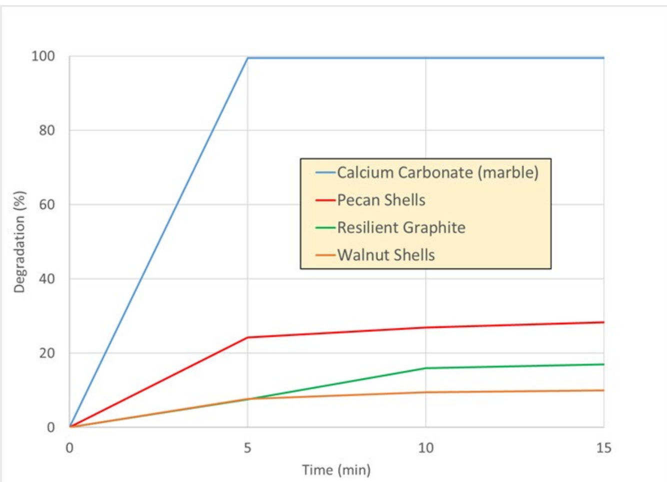

Figure 11: Size Degradation <60 mesh of 30/60 Mesh LPM on Silverson @ 7000 rpm

Nut shells are often a preferred LPM due to cost, availability, hardness, and good resistance to size degradation. However, the interaction with the drilling fluid over time and at temperature should be considered. Nut shells have been shown to perform well in WBMs after heat aging up to 72 hours at 200°F but completely ineffective after 24 hours of heat aging at 400°F, where a sealing pressure of 200 psi was not attainable (Jeennakorn 2017). Similarly, as shown in Figure 12 and 13, the performance of nut shell LPM in MOBMs is greatly reduced after being heat aged 16 hours at 248°F. When tested on a 500 micron disk prior to heat aging, a 3500 psi pressure is attained with 14 mL of mud lost. This same fluid after heat aging 16 hours at the relatively low temperature of 248 °F would only maintain 1500 psi.

There is limited data on the interaction of LCMs with muds and the performance after time and exposure to temperature. This aspect of performance should be built into LCM testing, more thoroughly evaluated, and communicated widely so that better decisions can be made. It should be expected that the performance of many plant-based products will be degraded by similar interactions with the drilling fluid over time and exposure to temperature.

Other products like thermoset rubber soften at temperatures <200°F and do not perform well at higher temperatures. Without performance-based data, it is unclear how material properties, like compressive strength, compressibility, plastic or elastic deformation, or resiliency, will affect performance.

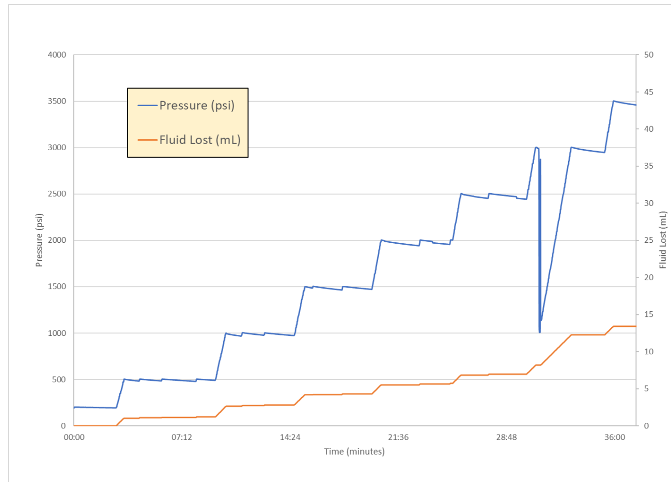

Figure 12: 20 lb/bbl Nut Shell LPM No Heat Aging 500 micron slot 248°F

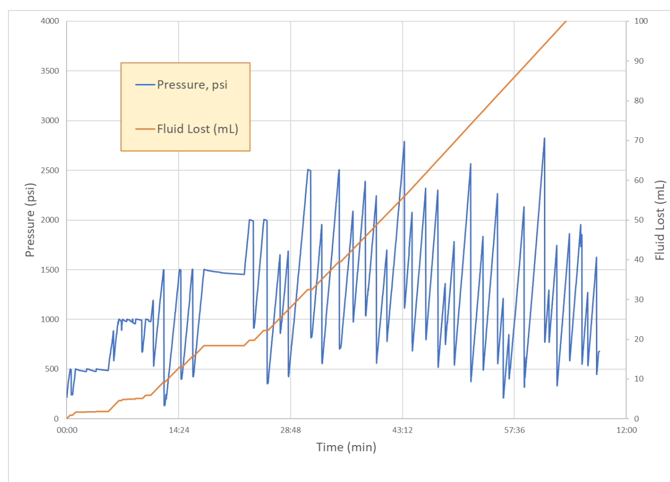

Figure 13: 20 lb/bbl Nut Shell LPM Heat Aged 16 hrs @ 248°F 500 micron slot 248°F

Defining Success

Defining success and understanding the reason for success can be difficult. Even when a LCM product is used and losses are reduced or eliminated, it is difficult know the extent to which the product was effective. Often when lost circulation occurs, drilling continues and drill cuttings assist in sealing loss zones, in both conventional and in casing drilling. One regional evaluation at successful LCM treatments identified ten successes where LCM had been used and losses healed. However, in six of these ten successes, the mud weight/ECD was also reduced, so it was impossible to how much each contributed to the success.

For preventative approaches, if lost circulation is not experienced it is never really known if losses would have occurred had the technique not been used. This is true for not only routine preventative LCM additions but also for the drill ahead LPM method. For the LPM technique there have been several leak-off and FIT tests that clearly show the benefit and efficacy of the method (Fuh 2007, Fuh 1992).

For many situations where circulation cannot be fully restored, it is necessary to find a way continue drilling with some level of acceptable loss rate or change the well plan. These include things like; mud cap drilling, drilling blind, bypassing the shaker and loading the system with LCM, having an adequate resupply of mud so that drilling can continue with losses, managed pressure drilling, underbalanced drilling, changing the well design (running pipe early or changing casing design on subsequent wells), and casing drilling (Watts 2010).

LCM Classification

One difficulty with classifying LCMs is that there are more than 300 products offered by at least 50 vendors. LCMs are often locally sourced low-cost plant or mineral based materials, waste streams, or byproducts from other industries and often lack good quality control.

The standard industry categorized has been according to appearance as granular, fibrous, flake, or blends. Recent efforts have been made to improve on these and to add new designations (Alsaba 2014, Alkinani 2018) but even these do not really help with product selection. Little mechanical property, performance, or mud reactivity information is available for most LCMs. In addition, no industry wide standard test methods exist to evaluate the important features of LCM products.

To illustrate the deficiency in this classification system based on appearance, within flaked material classification, cellophane is flexible and weak, mica and flaked calcium carbonate are stronger, and chips of laminated phenolic resin materials are extremely strong. In general, stronger materials will provide a stronger seal and these examples would be expected to have a wide range of performance. For the fibrous material classification, stiff rod like fibers (cedar fiber, carbon fiber) should allow a bridge to be established for larger openings as compared to more flexible fibers (fiberglass, polypropylene, nylon) or string-like fibers that tend to matt or ball up (spun mineral fiber, hemp, cotton fibers, textile fibers) and some products labeled as fibrous materials actually look and perform more like fine granular particulates (Amer 2017). This difference in stiffness is an important property of fibrous materials for bridging and is rarely evaluated for LCMs (Shindgikar 2010). An example of the range of materials that are labeled as fibrous is shown below in Figure 14.

Figure 14: Examples of LCM Products All Described as Fibers

Within the conventional classification for LCMs, improvements could be made with additional subclasses of information (Table 5). For each subclassification a testing protocol and specification would have to be established. Or a classification system could be designed according to function (Table 6). High-fluid loss high-solids squeezes, reactive fluids, and settable slurries would not fit well into an extended classification system for conventional LCMs as there aresimply too many variables for those products.

Another classification often used is “acid soluble” products intended to be used in the reservoir. Care should be taken when selecting these products as the classification of a product as acid soluble can be as misleading as the fiber example above. Rarely are all aspects of the acid soluble LCM disclosed, such as the concentration and type of insoluble materials and actual reaction rates under downhole conditions or for weaker acids. In some cases, there are precipitants that can be formed that could be damaging. Any precipitants for reservoir friendly material should be either water or acid soluble. It is recommended that all acid soluble LCMs be tested at downhole temperature with the acid type and concentration planned for the operation.

Table 5: Classification of LCMs with additional Subclasses

Primary Classification	1st Subclass	2nd Subclass	3rd Subclass
Granular (diameter)	Strong or Weak	Durable or Friable	Inert or Water/oil sensitive
Flakes (max dia.)	Strong or Weak	Durable or Friable	Inert or Water/oil sensitive
Stiff Rod-like Fibers (stiffness)	Strong or Weak	Durable or Friable	Inert or Water/oil sensitive
Flexible String-like Fibers			
Particulates from Fiber Based Materials (diameter)			
Blends			

Table 6: Classification of LCMs according to function

Function	Subclass
Primary Bridging	Granular
	Strong flakes
Bridge Augmenting (Matting or Nesting)	Stiff Fibers
	String-like Fibers
	Flexible Flakes
	Reticulated foam

Given the wide variety of materials used for LCM, any classification system will still have inherent weaknesses. Standardized performance testing and the reporting of performance testing would be a significant improvement. Another improvement would be if the general industry or suppliers were to keep comprehensive statistics on successful applications of LCM treatment.

Lost Circulation Treatment Testing

Currently the industry lacks standard test methods and testing protocols for LCMs and lost circulation treatments. Reactive and settable treatments require equipment that is different than what would be used for conventional LCMs. It is important to evaluate a number of different attributes of these slurries to understand their functionality because different devices and environmental conditions will produce dramatically different results (ARCO-Baker Hughes 1999). In addition to performance testing for solving losses, it would be beneficial to have a standardized test for plugging drill string tool filters and screens so that LCM treatments other than granular products equivalent to or smaller than medium nut shells could be used. Plugging of the drill string is not only an issue with regard to having to stop drilling and trip but is also a safety issue in that the well cannot be circulated.

Slot testing using a modified high-temperature high-pressure filtration (HTHP) device or a modified permeability plugging tester (PPT) is the most common method in use today. Most often the pressure is increased in stages and the fluid loss at each stage measured. Examples are shown on Figures 5, 12, and 13 where both sealing pressure and fluid loss are shown. These results are to gain confidence that an effective seal would be generated within fractures or porous formations that have similar sized apertures.

Testing where actual rocks are fractured, such as in DEA-13, GPRI, and the MudFrac system generate useful information, but are expensive, time consuming, and technically complex such that only limited data can be generated plus utilizing the data to make decisions may not be straightforward. Slot and other type of lab testing do not fully replicate the real-world situation, but they are used because they are capable of generating more data in a shorter amount of time under controlled conditions.

Common Deficiencies in Lost Circulation Treatment Testing

- Field muds or lab muds with PSDs (D90) like field muds not used
- LCM treated fluids are not heat aged prior to testing
- Tests only performed at low pressure
- Tests only performed at ambient or low temperature
- Tests on filtration devices, such as HTHP, PPA, or proppant/sand bed tests
- Comparisons between testing with too many variables; different sized material (D90), different concentrations, and significantly different LCM types
- Blends are tested but not individual products, making the determination of which product is working or failing impossible.
- Settable slurries not tested after contamination with mud or in test devices that can evaluate the effect of mud deposits on permeable formations
- Making conclusions from test data with high variability or having limited results
- Lack of standard equipment and test methods

API Bridging Materials For Regaining Circulation

The API subcommittee on drilling fluids in 1965 adopted a standardized LCM testing device and procedures. However, over time the equipment became obsolete and the old information is being removed from API documents. The tests were performed to 1000 psi and utilized 3 types of test media in both static (open valve initially) and dynamic tests (closed valve initially) tests which were to be run for 10 minutes if a seal was achieved. The base fluid was an unweighted 5-8% wt. bentonite slurry. The three types of test media were; 1) square edged slots in 1 mm increments from 1 mm to 5 mm, 2) 9/16 in (14.3 mm) diameter brass or stainless marbles, and 0.173 in. (4.39 mm) diameter brass-clad or stainless BBs. For tetrahedral packing, the 9/16 in marbles would have pore throats of 2215 microns and the 4.39 mm BBs would have pore throats of 681 microns. For each product, the slot test was supposed to be re-run at progressively larger slots until no permanent seal was achieved. The volume of mud lost at each pressure step and the maximum pressure for having a seal were recorded as results (Lummus 1967). Having standardized LCM testing information available on all products would be helpful in selecting the most effect LCM.

The API test protocol is a reasonable approach to comparing materials and was used to develop the first widely marketed optimized LCM blend. An updated version of a standardized test method and media, with modern equipment, would serve the industry well and assist with making better decisions when choosing LCMs. The API or International Association of Oil and Gas Producers task groups should take on standardization and testing of lost circulation material products.

Currently each mud company and LCM supplier uses different equipment and test procedures. Some can test at higher temperature and higher-pressure differentials, but most do not.

Conclusions

- Loss treatments with LCMs smaller than 200 microns are not normally applicable for lost circulation
- LCM size for most loss situations should be LCM with a D50 400 microns (fine nut shells) or larger
- LCM testing on filtration devices like modified HTHP and PPT cells or sand bed tests are not applicable to evaluating lost circulation treatments
- Bridging requires 10-20 lb/bbl of particles equal or slight larger than the loss zone opening
- Many situations are limited to particles <2 mm which makes sealing larger openings difficult and other types of treatments necessary
- Optimized particle size distributions are not needed and may be detrimental
- API barite and field muds usually have solids bridging up to 75-100 micron, so products like fine calcium carbonate and fine cellulose are not normally applicable
- LCM naming and numbering conventions are misleading
- No definitive evidence routine additions of LCM as a preventative method work
- Wellbore strengthening with the LPM drill ahead method is effective for induced loss zones in permeable formations but not easy to do
- Standardized test methods and performance-based data for both conventional LCM and LCM treatment slurries would be helpful for selecting treatments
- Better industry wide and company specific statistical information on successes and failures for all lost circulation related treatments would be beneficial

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Nomenclature

API = *American Petroleum Institute*
BHA = *Bottomhole assembly*
D50 = *diameter where cumulative 50% vol. of the sample is smaller (median)*
D90 = *diameter where cumulative 90% vol. of the sample is smaller*
D100 = *largest particle size of a sample*
DEA = *Drilling Engineering Association*
GPRI = *Global Petroleum Research Institute*
MWD = *measurement-while-drilling tools*
LWD = *logging-while-drilling tools*

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