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Wellbore Strengthening – Continuous Application or Sweep as Needed?

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Abstract

Lost circulation can be one of the most time consuming and cost inflating events in the drilling operation. It costs the drilling industry hundreds of millions of dollars in rig time, materials, and other associated costs. Wellbore strengthening is one of the most popular lost circulation mitigation methods used in recent years. To effectively administer this strategy, a low concentration and specific size distribution of lost circulation material (LCM) must be maintained in the circulating system.

Wells drilled in a gas reservoir were studied for the cost and benefit using sized marble on a continuous basis for the purpose of wellbore strengthening. The methodology was utilized to quantify the costs for the different casing intervals and the benefits observed from the continuous addition strategy as well as evaluate an alternative strategy.

A study of the case history of these wells drilled in a gas carbonate reservoir demonstrates the importance of analyzing the specific requirements of the well before assuming a given strategy for mitigating an issue. This is an important lesson for applying strategies for lost circulation and can result in improving operational and engineering performance.

Background

Lost circulation is one the major drilling challenges in the industry. It results in significant nonproductive time and cost due to packoffs, stuck pipe, and most importantly well-control events. Of course, the loss of drilling fluid can be expensive but for the most part, it is the least significant of the potential impacts of lost circulation.

Lost circulation can have many causes, but it is a direct result of wellbore pressure that is too high and thus exceeds the fracture gradient. This increase in wellbore pressure can be the result of static drilling fluid weight that is too high and the resulting high equivalent circulating density (ECD) due to narrow annuli, increase in mud weight, increase in pump rate, and/or increases in viscosity which might result from solids loading. The problem is frequently exacerbated by production zones that are pressure depleted and the fracture gradient reduced. This scenario typically results in lost circulation.

Reducing drilling fluid density or mud weight, as it is commonly known, might seem to be a reasonable option, but non-depleted zones or normally pressured low-permeability zones, such as shales, will most likely minimize the ability to control lost circulation by such a dramatic option. Lowering the ECD is the most reasonable preventive measure that can be utilized. This can be done by lowering the pump rate which, will in turn, impact cuttings transport and make things worse, or lowering the drill solids content and thus reducing the overall viscosity.

Wellbore strengthening (WBS) techniques have been developed as a technique for mitigating lost circulation for many years (Alberty and McLean, 2004). The concept of WBS was initially to plug and seal incipient fractures by using sized particles that prevent fracture propagation. However, over the years, different mechanisms have been proposed. As suggested by Alberty and McLean (2004) plugging and sealing incipient fractures is one of those mechanisms.

Wellbore stress augmentation (WSA) functions by altering the hoop stress or closure stress near the wellbore by propping open the incipient fractures and thus maintaining a higher hoop stress that must be overcome before propagation of fractures from the wellbore can occur. The last mechanism is referred to as the Fracture Propagation Resistance – particles plug off leaks at the fracture tip and prevent pressure communication to the fracture, thus preventing propagation. van Oort and Razavi, 2014 have suggested that this is the most viable mechanism for mitigating fracture growth.

Understanding the width of the induced fracture is essential to achieving this goal. Alberty and McLean, 2004 and Zhang et al., 2016 attempted to calculate fracture width primarily utilizing mechanical loading, i.e., stresses and rock mechanical properties assuming isothermal conditions. These days most service providers and many operators have software packages which will not only estimate fracture width but also the particles sizes and quantities of LCM needed to control lost circulation. These calculations have multiple assumptions ranging from changing stresses as you move down the wellbore to changing drilling fluid parameters (e.g. static fluid weight, ECD), to various lithologies and, of course, temperature.

When designing particles size treatments, it is important to separately characterize each section of the hole to get the most engineering benefit possible from the particles. Regardless of the mechanism chosen for WBS, particle sizing is key but not the only requirement. To ensure reduced pressure communication to the tip of the fracture, it is important to have the appropriate distribution of particles to assure a good low permeability plug seals the fracture.

Wellbore strengthening materials (WSM) packages are typically designed with a particle size distribution (PSD) that accounts for the apparent fracture width and rate of drilling fluid loss. To maximize the impact of that package, the Ideal Packing Theory (Dick et al., 2000) must be included in the design. This theory has led to attempts to design (Wellbore strengthening materials (WSM) packages) a wellbore geometry model (WGM) package that would include coarse and fine particles. The coarse particles must be coarse enough to plug or bridge the mouth of the fracture or oversized pores of high permeability formation. The finer particles form a low permeability plug to plug or bridge the fracture. Together the distribution of particle sizes thus creates a seal that also provides good filtration control. This concept is the foundation of modern WSM packages as designed and executed today.

As stated above, initial models estimating fracture width were based on isothermal conditions. Most recently Ziheng and Alberty (2020) examined the effects of temperature on wellbore strengthening. They concluded that a contrast in temperature of the drilling fluid and the formation will affect the near wellbore stresses. In addition, in calculating incipient fracture widths, it is important to consider these thermal effects. This effect should be considered when designing WBS treatments which are based on expected fracture widths. Failure to do so can result in failure of the WBS treatment.

Hoxha, et al., 2016 demonstrated that a thermal effect might be used to improve the apparent fracture gradient thus minimizing the chance of lost circulation by using good thermal wellbore strategies. Hoxha and team designed coated exothermal particles that can be thought of as time-release capsules such that when a pill containing these time release capsules is placed at the interval most likely to fracture, the coated particles will enter the fracture and initiate an exothermic reaction. Thus, heating the wellbore and increasing the fracture gradient by several hundred psi.

Today there are two basic operational approaches to applying WBS, the first and usually the most desired is continuous addition of particles with appropriate size range and concentration, and the second is addition via pills that are pumped downhole as needed with the appropriate distribution and concentration. Both application techniques require a significant effort on the drilling fluid design, solids control system, and of course utilizing the best available data for determining fracture widths.

In summary, to do an adequate estimate of fracture width in the different lithology, it is important to obtain (most likely from offset wells):

- Principle Axial Stress
  - Vertical Stress, SV
  - Max Horizontal Stress, SH
  - Min Horizontal Stress, Sh
- Rock Properties
  - Young's Modulus
  - Poisson Ratio

Utilizing a proprietary software simulation package, the fracture width of the induced fracture can be calculated using the parameters just listed. With this information, the optimum blend and concentrations of the wellbore strengthening material can be calculated using on Monte Carlo analysis. This analysis can be confirmed, to some extent, by lab evaluation to establish if the particle size distribution and concentration are appropriate for the calculated fracture width. Enhancements or corrections can be made if needed.

The lab verification should include a complete mud check as per API RP 13B-2 to observe and record the effects on the drilling fluid properties and the tendency to plug the downhole tools with these materials. Because the addition of solids will alter drilling fluid parameters such as the rheological profile and/or fluid loss, it is important to optimize based on the drilling hydraulics needed to minimize ECD yet still maintain the appropriate PSD and concentration.

It is equally important to understand that whatever lost circulation material is used, it will grind down to smaller and smaller particle sizes with each circulation through the system. At some point, the LCM particles are small enough that the solids control equipment may not be able to remove the fine particles. This buildup of fines can result in altering the hydraulics such as the increase in ECD results in lost circulation.

This buildup of fines and potential ECD increase is especially the case in the continuous addition mode. If this mode is utilized, it requires a significant amount of dilution to keep the low-gravity fines from the ground-down LCM at as low a concentration as possible. These issues can be evaluated in real time while drilling. Data regarding particle size distribution, LCM concentration, rheological profile, and effectiveness on particle plugging can be used to establish the effectiveness of the system in real time.

The batch mode provides more control on additions since typically it is added in response to the real-time measurements. This approach helps minimize the chance for fines build up but still enables having particles in the fluid that can be beneficial. Both approaches require close attention to solids control and to ensure screening up when appropriate to minimize build up.

No matter the method or the mechanism, wellbore strengthening requires a serious engineering approach which encompasses the best estimate of average fracture aperture, optimized sized lost circulation materials, and intelligent dilution schedule which minimizes cost but ensures solids buildup does not occur, while proper sizing of the lost circulation material is maintained.

Problem and solution

To overcome severe lost circulation events drilling the 12-in. and 8⅜-in. intervals in some wells, a wellbore strengthening strategy using sized marble and fibrous bridging particles was implemented, The approach was not limited to the bridging strategy alone but extended to the reformulation of the fluid to reduce the ECD to the lowest value possible and minimizing the difference between equivalent circulating density and equivalent static density (Δ ECD-ESD).

At the start there were very little information available, while drilling and enquiring more information pre-existing industry practices were adopted. These practices included different lost circulation material pill designs with various ranges of particle sizes and concentrations. When these were not sufficiently successful, different types of plugs were evaluated (cement plus, resin plugs, high fluid loss plugs, and cross-linked polymer plugs) with mixed success rates.

Once the traditional industry approaches were proven insufficient, the focus turned to drilling parameters, such as pump rates and rate of penetration (ROP). ROP was reduced to lower ECD. None of these approaches were enough to reduce the occurrence of lost circulation events.

A wellbore treatment system was attempted. The method of execution was to pretreat the system with 50 to 70-lb/bbl sized LCM materials and utilizing coarse shaker screens to retain the LCM material in circulation. However, it was quickly observed that the ECDs increased (not decreased) and the lost circulation problem was still not resolved.

After collecting all data about the formation, it was clear that there was a very narrow window between fracture gradient and the fluid density required to control the well.

The team decided to approach the problem in more systematic manner by collecting data which included pore-throat sizes, Young′s modulus, Poisson's ratio, and better tracking of LCM pills performance.

Since the root cause for downhole losses is the very narrow mud weight (MWT) window, it was mandatory to minimize the pressure impact to the wellbore to avoid induced losses or fracture propagation.

Extensive lab work was done to reformulate the drilling fluid to use a brine-based fluid with a salinity of approximately 140,000 mg/L instead of a low salinity-based fluid. This helped to reduce the percentage of incorporated solids to about 5%, hence reducing both the PV and ECD.

Other changes in strategy included:

- Adapted more stringent solids control practices by running fine screens and proper dilution.
- Replaced old bridging strategy with a more engineered strategy based on formation and pore throat analysis.
- Avoided any excessive treatment with bridging either initially or with hourly treatment.
- Relied on LCM Sweeps rather than background LCM.

All these changes had a great impact on ECD.

Permeability plugging test was used as a good indicator for proper bridging concentration and enabled operations to avoid excessive treatment with solids.

The reengineered bridging formulation showed great improvement in PPT results over continuous hourly treatment, even with larger ceramic desk pore sizes being used and higher pressure applied.

Results

Significant improvements were shown on all aspects, either technically or economically. NPT for curing losses was significantly reduced after optimizing basic and bridging formulations.

Based on comparisons carried out between wells drilled with the old formulation and those drilled with the new formulation of LCM and bridging material (Table 1 vs Table 2), there was a significant drop in annular pressure loss (Δ ECD-ESD) shown in Figure 1. This was attributed to the reduction in percentage of incorporated solids and utilizing the brine-based drilling fluid. Table 3 compares the PPT results between the old and new formulations. Note that testing of the new formulation was conducted at a higher pressure with very similar fluid loss results.

As a result of these changes for solids and bridging concentrations, a 200-psi reduction was measured in SPP and ECD was reduced 2 to 3 lb/ft^3. Active mud volume lost and LCM pills volume pumped was reduced in both 12- and 8⅜-in. sections. Figure 2 shows the drop in losses for the 12-in. section and Figure 3 for the 8⅜-in. section.

This major improvement to reduce losses had a very positive impact on savings. Figure 4 shows the 75% drop in cost spent for LCM and bridging material for the 12-in. section and the even bigger 88% drop in cost shown in Figure 5 for the 8⅜-in. section.

Conclusions

- Background LCM treatment is a very engineering intensive work and requires considerable planning, however in recent years the trend has been over simplified as – “if losses are expected add x-lb/bbl LCM and maintain x lb/bbl as hourly treatment”.
- Lost circulation mitigation plans that are based on LCM pre-treatment and hourly additions should be scrutinized and challenged to ensure that the plan will add benefit and is based on correct engineering principles.
- Proper solids control must be observed and cannot be compromised unless the benefit can be clearly proven.
- Higher concentration of background LCM has adverse effect on fluid hydraulics.
- Running a properly designed and engineered system in this case study led to significant cost reduction (75% to 88%) with the new strategy of improved formulation, and “as needed” treatment tailored to real-time data.
- In addition to the saving on drilling fluids costs, the operation experienced significant savings on rig time.
- Indirect cost saving was also realized in logistics due to less LCM usage and less drilling fluid volume lost.

Nomenclature

ECD = *Equivalent circulating density*
ESD = *Equivalent static density*
LCM = *Lost circulation material*
MWT = *Mud weight*
NPT = *Non-productive time*
PPT = *Permeability plugging test*
PSD = *Particle size distribution*
PV = *Plastic viscosity*

SPP = *Standpipe pressure*
WBS = *Wellbore strengthening*

WGM = *Wellbore geometry model*
WSA = *Wellbore stress augmentation*
WSM = *Wellbore strengthening materials*

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Table 1: Background LCM and Bridging for 12¼-in. Section

Chemicals Name	Old Strategy		New Strategy	
	LCM and Bridging (50 lb/bbl)	Hourly Treatment (lb/hr)	Bridging (35 lb/bbl)	Hourly Treatment
$CaCO_3$ Flakes Fine	10	55	5	Nil
$CaCO_3$ Flakes Medium	10	55		Nil
Marble Fine		92	10	Nil
Marble Medium	10	92		Nil
Super Fine Fiber	10		5	Nil
$CaCO_3$-5			5	Nil
$CaCO_3$-25			10	Nil
Graphite Fine	5	50		Nil
Graphite	5	50		Nil

Table 2: Background LCM and Bridging for 8⅜-in. Section

Chemicals Name	Old Strategy		New Strategy	
	LCM and Bridging (50 lb/bbl)	Hourly Treatment (lb/hr)	Bridging (35 lb/bbl)	Hourly Treatment
$CaCO_3$ Flakes Fine	10	55	5	Nil
$CaCO_3$ Flakes Medium	10	55		Nil
Marble Fine		92	10	Nil
Marble Medium	10	92		Nil
Super Fine Fiber	10		5	Nil
$CaCO_3$-5			5	Nil
$CaCO_3$-25			10	Nil
Graphite Fine	5	50		Nil
Graphite	5	50		Nil

Table 3: PPT In Old and New formulation		
	Old Formulation	New Formulation
Spurt Loss, mL	< 3	< 4
30-min Fluid Loss, mL	< 16	< 20
Disc size, µm	35	55
Pressure, psi	2000	2500
Temperature, °F	270	270

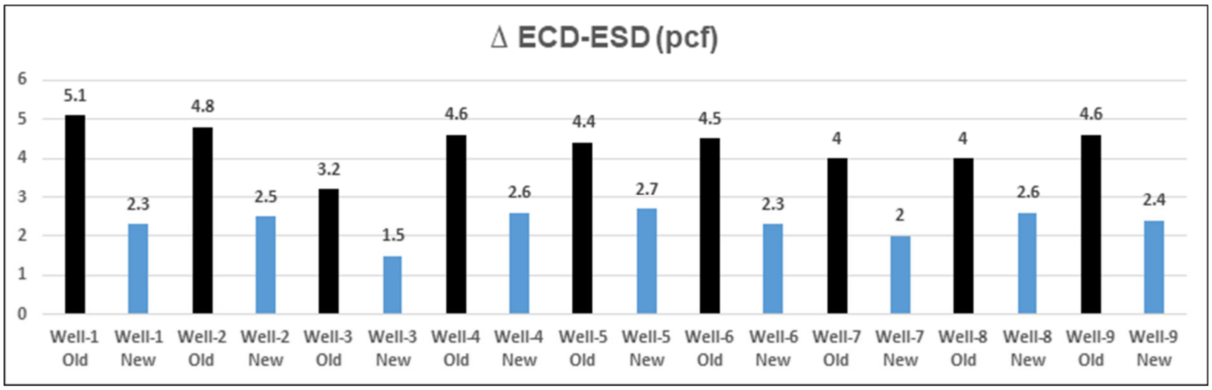

Figure1: ∆ ECD-ESD Comparison in lb/ft^3.

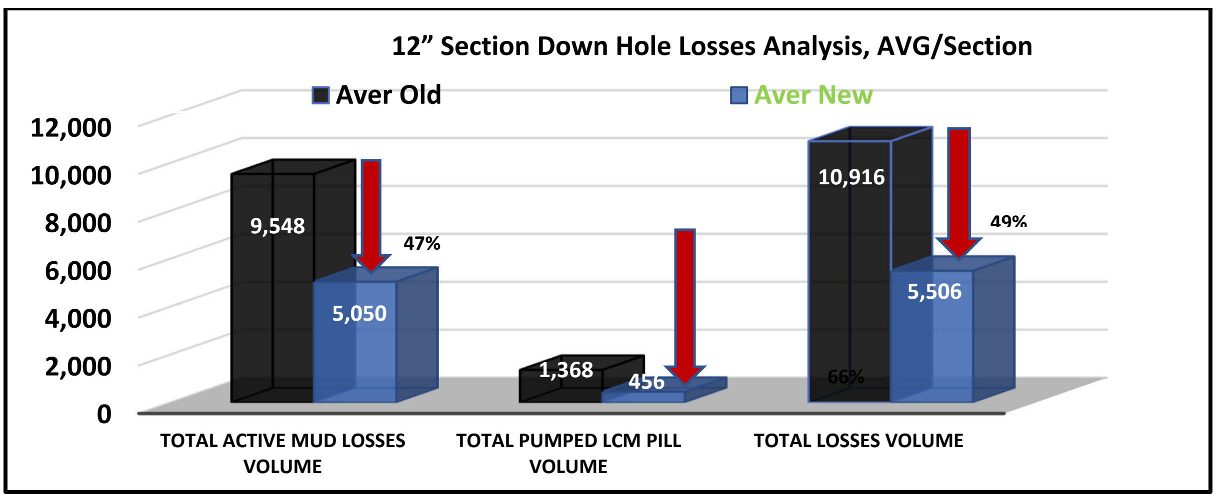

Figure 2: Analysis of 12-in. section downhole losses.

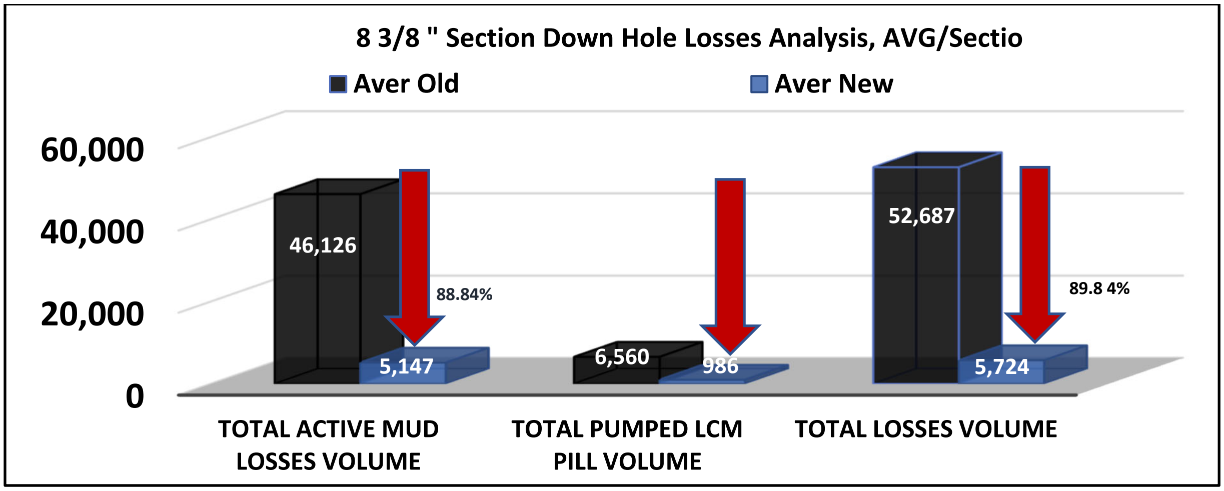

Figure 3: Analysis of 8⅜-in section downhole losses.

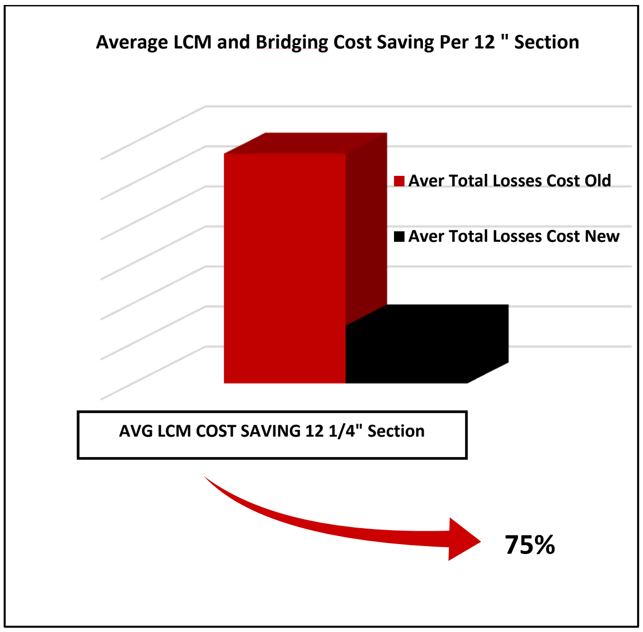

Fig. 4: Analysis of cost savings 12-in section.

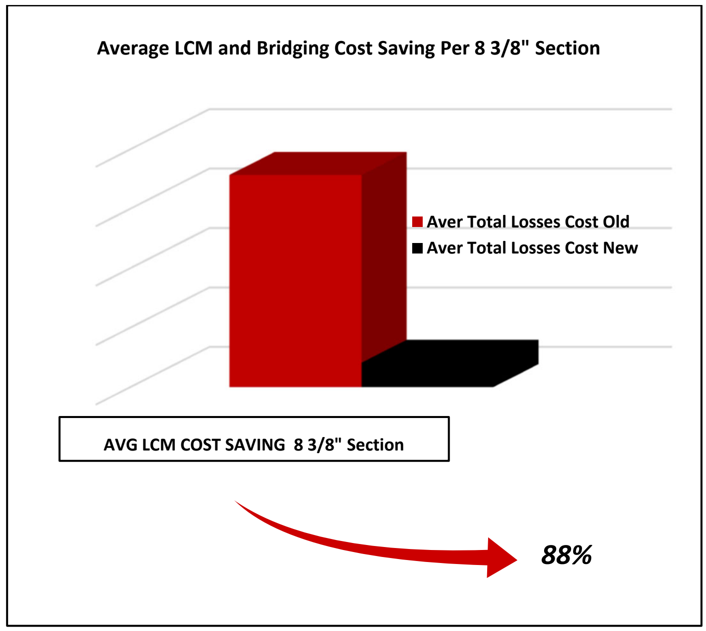

Fig 5: Analysis of cost savings for 8⅜-in. section.