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Tackling Lost Circulation Challenges for Drilling the Depleted and Naturally Fractured Formations in Bakken

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Abstract

Drilling in the Beaver Lodge area in the Williston Basin has experienced severe lost circulation events that resulted in great capital loss, well kick, sometimes even well abandonment without reaching target. In order to tackle this challenge, reduce the drilling cost and shorten the drilling period, an analysis was performed to understand the mechanisms of lost circulation. The Rival member of the Mission Canyon formation in the Beaver Lodge area has been severely depleted from early production. The Bakken drilling has to penetrate this formation to reach Middle Bakken/Three Forks reservoir. Furthermore, below this depleted formation is the Lodgepole formation in which seismic images indicate development of natural fractures/faults.

Based on the analysis, a lost circulation prevention and remediation strategy was proposed by utilizing an innovative wellbore strengthening method – STRESS SHIELD Engineering. This new method uses hydraulic fracturing theory to seamlessly integrate the concentration of special fast-sealing lost circulation material with rock mechanical properties and defines a robust design process supported by quantitative rig site quality controls. Nevertheless, the design is straightforward and implementation is simple.

Among the 16 wells drilled so far in the area, 6 wells drilled with conventional lost circulation material had mud losses in the amount ranging from hundreds to thousands of barrels of oil-based mud. Of the other 10 wells drilled with the new technology, only one had downhole mud losses—about 280 bbl induced mud losses due to pack-off during reaming after the well had reached its section total depth. Comparing the success of the new technology with the failure of the conventional lost circulation material for the 16 wells on record, one can clearly see the substantial effectiveness of STRESS SHIELD method.

Introduction

Massive drilling operations have been initiated and executed in the past decade targeting the Middle Bakken/Three Forks formations **(Fig. 1)** of the North Dakota part of Williston Basin. Drilling in Bakken is pursuing time and cost efficiency to ensure the project economics, the key for any unconventional assets. Subsurface drilling troubles such as wellbore instability and lost circulation would lengthen drilling period substantially, greatly increase cost and sometimes cause environment, health and safety issues. In the Beaver Lodge area, the Rival member of the Mission Canyon formation, which lies above the target Bakken formation, has been highly depleted from early conventional oil production. The Lodgepole formation, which lies between Mission Canyon and Bakken, has developed natural fractures and faults due to its vicinity of the Nesson anticline. Drilling in this area can occasionally result in severe lost circulation which in turn results in large losses of capital.

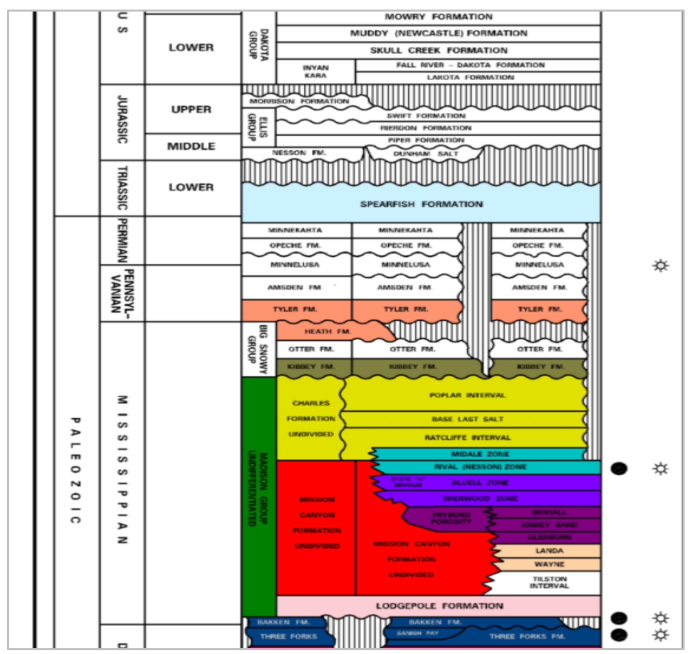

Figure 1. Williston Basin Stratigraphic Column

Bakken drilling is generally straightforward: surface casing is set at ~1,850 ft. Then an 8 ¾" vertical hole is drilled to the kick off point (KOP) at ~9,300 ft. A 10-12 degree build rate curve is then built until the well is 90 degree inclination in the Middle Bakken or Three Forks Formation (~10,000 ft TVD). The 8 ¾" hole section penetrates most of formations that could cause drilling troubles such as overpressured Amsden, creeping Charles Salt, unstable Upper and Lower Bakken shale. Commonly, 9.2 to 10 ppg oil-based mud (OBM) is used in this hole section. After setting 7" casing, a 5 $^{7}/_{8}$" lateral is drilled to ~20,000 ft measured depth (MD) and a 4 1/2" production liner is then set. **Fig. 2** illustrates a common well design.

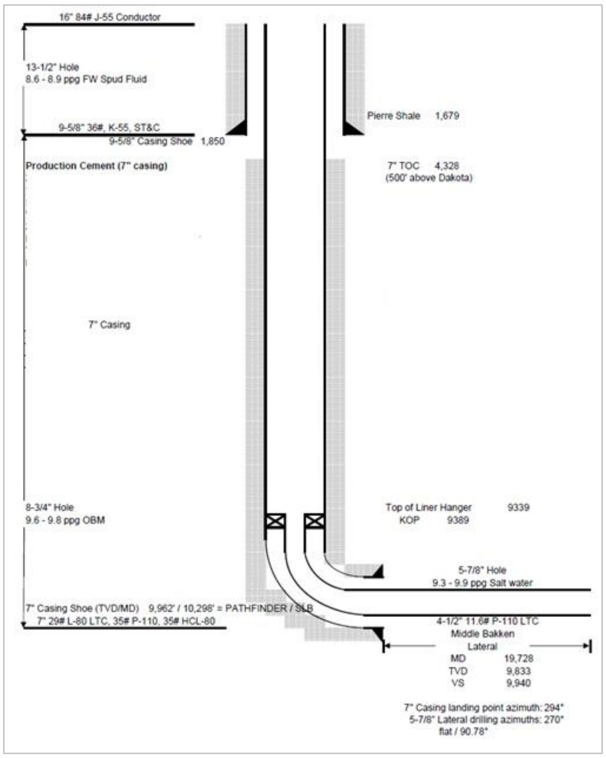

Figure 2. Typical Well Structure in Bakken

Not all Bakken wells are the same, however. Specifically when drilling the 8 ¾" hole section in the Beaver Lodge area, severe lost circulation events have occurred. Direct consequences of the lost circulation events are the loss of expensive OBM/SBM, rig time for treatments, cost of inefficient lost circulation material (LCM). Indirect consequences of the lost circulation includes stuck pipe due to loss of circulation rates and insufficient hole cleaning, well kicks and well control due to loss of hydrostatic pressure, plug-and-abandon of wells without reaching targets.

In order to tackle lost circulation challenges in the Beaver Lodge area, an analysis was performed to derive mechanisms by integrating geomechanics, reservoir, and seismic data. Based on the analysis, a fit-for-purpose wellbore strengthening method was adopted and applied. Ten wells have been drilled with this new method and the results are very encouraging. Especially for direct comparison, there are four wells drilled on the same drilling pad. The first two used conventional LCM, and the other two used the new method. These four wellbores are only 30 ft away from each other. The comparison of the four wellbores drilling experience is very self-evident.

Offset Wells Lost Circulation Events

Well A: This well was spudded in February 2012. Partial losses were observed when drilling the 8 ¾" hole at 8,505 ft, which is the top of the Rival member of the Mission Canyon formation. A conventional LCM pill was spotted on bottom and circulation was regained. Drilling then continued to 8,990 ft when losses recurred. While placing a stand of drill pipe in the derrick (annulus was not full), the well started to flow. Shut in well. A conventional LCM pill was mixed and spotted on bottom. Nitrogen gas, from the shallow, over-pressured Amsden formation, was circulated out. The well was eventually plugged and abandoned (P&A).

Well B: This well was immediately spudded on the same pad after P&A Well A. An 8 ¾" vertical hole was drilled to 5,908 ft with 9.8 ppg MW. Well kicked and took 30 bbls of gain. The well was shut in and 10 ppg mud weight was used to kill the well. (It is believed this event was related to the kick and shut-in that occurred in Well A). Prior to drilling into the Rival (lost circulation or 'thief' zone), the mud was pre-treated mud with 50 ppb conventional LCM and a 150 bbl conventional LCM pill was prepared ahead of time. Partial losses occurred when drilled to 8,500 ft. 1 to 2 bpm loss rate was reported when drilled to 8,971 ft. Pump conventional LCM sweeps for every joint. Losses subsided. The hole started to take fluid with no returns when drilled to 9,046 ft. Filled up on backside with trip tank. Pumped a 160 bbl of 60 ppb conventional LCM sweep. Spotted a 130 bbl of 100 ppb conventional LCM pill plus a 60 bbl of 80 ppb pill. Pumped a 100 bbl of 100 ppb pill. The losses continued. Finally a cement job was performed. Spotted and squeezed cement. Total loss of OBM was more than 7,000 bbl.

Well C: Drilled the 8 ¾" vertical section to 8,413 ft (top of Rival) and lost full returns. An 80 bbl pill containing 80 pound per bbl (ppb) of conventional LCM pill was pumped, resulting in partial returns. Pumped a 100 bbl of 80 ppb conventional LCM pill and performed hesitation squeeze. Losses stopped. Lost full returns again when drilled to 8,488 ft. Different conventional LCM pills were tried but all failed to stop losses. Managed to drill to 8,854 ft with partial losses. Stuck pipe and worked free. The well was eventually plugged and abandoned. Total loss of mud to hole was ~6,800 bbl.

In summary, conventional LCM neither prevented nor cured losses effectively, and two of the three wells were P&Aed because of massive losses. Events associated with the lost circulation were kicks and stuck pipe. We believed that the kick in Well A was due to loss of hydrostatic pressure. The kick in Well B happened at a shallow formation that was charged during Well A shut-in. Stuck pipe in Well C may be caused by inefficient hole cleaning limited by mud losses.

As a result of these drilling problems in the Beaver Lodge area, drilling was suspended until such time as a strategy to mitigate the drilling problems could be developed. Substantial reserves in Beaver Lodge area were at risk.

Lost Circulation Mechanism Analysis

Two mud loss zones (**Table 1**) are identified through the experience obtained from drilling these three wells.

Table 1. Mud Loss Zones

	Depth (ft)	Formation	Lithology	Likely Loss Mechanism
Zone 1	~8,500	Rival member of the Mission Canyon	Limestone	Induced fractures due to depletion
Zone 2	~8,900-9,400	Lodgepole	Limestone	Natural fractures

Depletion in Rival

For decades before Bakken Development, the conventional oil field was developed from the Madison reservoir, which lies at ~8,500 ft in the Beaver Lodge area. Production was dominantly from the Rival member of the Mission Canyon formation. **Fig. 3** is a map of horizontal wells in the Beaver Lodge Madison Unit (BLMU). Bottomhole pressure monitored from these wells indicates that Madison reservoir pressure has been depleted significantly from the virgin gradient of 8.5 ppg to less than 2.7 ppg in current days. The total depletion of pore pressure (P_p) is 5.8 ppg **(Fig 4)**.

Far-field horizontal stress generally decreases with the depletion of pore pressure during production. The driller's fracture gradient (FG), which may not be the same as the far-field horizontal stress (S_h) gradient, would also decrease with pore pressure reduction from depletion. Based on the poroelastic theory, the relation can be expressed as in **Eq. 1:**

$$\frac{\Delta S_h}{\Delta P_p} = A \tag{1}$$

where $A = \alpha(1 - 2\mu)/(1 - \mu)$.

μ is the Poisson's ratio and α is the Biot coefficient. For reasonable values of μ and α, the theoretical change in S_h with depletion is in the range of 0.5-0.7[1], which corresponds to observed values for many reservoirs. For example, for typical value $\mu = 0.25$ and $\alpha = 1$, A = 0.67.

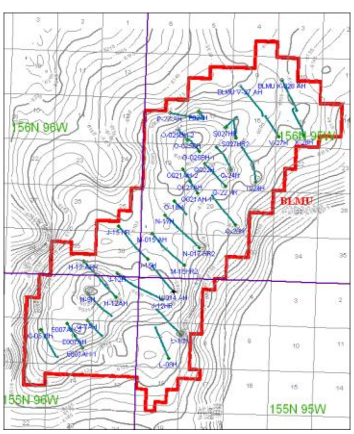

Figure 3. Horizontal Wells in the Beaver Lodge Madison Unit (BLMU)

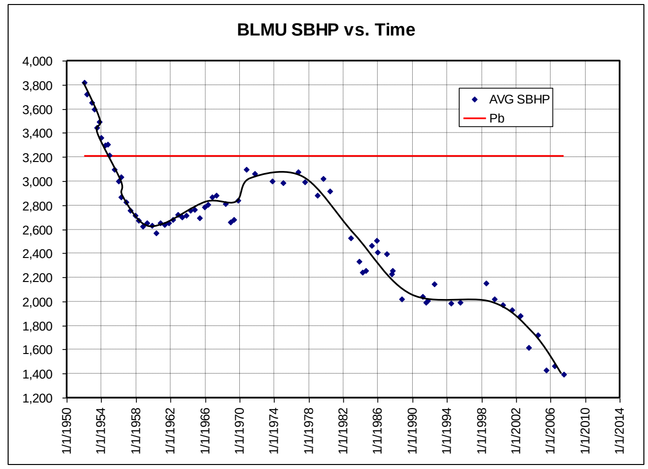

Figure 4. Beaver Lodge Madison Unit (BLMU) Reservoir Pressure Change with Time

Using A = 0.67, by substituting the depletion value of the Madison reservoir (5.8 ppg) to Eq.1, it is expected S_h would decrease by 3.9 ppg. Based on the same $\mu = 0.25$ and $P_p = 2.7$ ppg and assuming overburden gradient is 1 psi/ft or 19.25 ppg, the current S_h is estimated as 8.2 ppg, using **Eq. 2:**

$$S_h = \frac{\mu}{1-\mu}(S_v - P_p) + P_p \tag{2}$$

This estimated current S_h of 8.2 ppg for the depleted Rival could explain the lost circulation experience of the three wells when we drilled into the Mission Canyon formation at ~8,500 ft with a mud weight of 9.5-10 ppg.

When a vertical flawless wellbore is formed in the rock with a horizontal stress S_h, a near wellbore stress concentration naturally rises in a layer around the wellbore. Typically the hoop stress around borehole has a magnitude larger than S_h in vertical wellbore, increasing compression on the wellbore. When fluid pressure in wellbore increases, the magnitude of the hoop stress is equally reduced. In a wellbore without flaws, fluid pressure must increase to be high enough to offset this stress concentration and to put the wellbore in tension before a tensile fracture can be initiated. So the near wellbore stress concentration can shield the vulnerable far-field formations. Therefore, such a wellbore can hold more pressure. This high pressure to initiate such a tensile fracture is called wellbore fracture initiation pressure (P_{ini}). The P_{ini} defines the maximum pressure that a flawless wellbore can naturally hold and can be calculated as in **Eq. 3:**

$$P_{ini} = 2S_h - P_p \tag{3}$$

In the Rival case, due to the near wellbore stress concentration around the wellbore, a perfectly flawless wellbore could hold wellbore pressure up to 13.7 ppg even when the pore pressure has been depleted to 2.7 ppg and its far-field horizontal stress is only 8.2 ppg, calculated by Eq. 3.

However, the wellbore condition typically is not flawless and has been weakened. In a severe condition, if there is a crack at the wellbore wall which connects the wellbore to the far-field formation bypassing this stress concentrated zone, then the wellbore pressure can only be held by the far-field stress S_h. Such bypassing can be easily achieved from a small crack further extended by hydraulic fracturing with mud invasion or induced fracturing. Such a hydraulic fracture would keep growing as long as the far-field stress is not enough to hold the pressure from the mud weight or ECD. So, in reality, the pressure that a wellbore can hold is between S_h and P_{ini}. For drilling a long open hole interval, the chance to encounter large flaws at a wellbore is high. This is why a driller's FG is typically closer to S_h rather than P_{ini}. Wellbore weakening has been discussed elsewhere[2].

All drilling mud has particles which originated naturally from cuttings, weighting materials etc. Those particles have certain 'repairing' effect on the flaw. In the Rival case, the expected FG would be between 8.2 ppg and 13.7 ppg, depending on the repairing capability of drilling fluid to the wellbore flaws.

Natural Fractures in Lodgepole

AntTrack seismic data was used to correlate loss events with possible natural fractures and faults. According to the seismic data, this area seems to be highly fractured especially between Rival and Bakken. We surmise that development of natural fractures is related to the vicinity of the Nesson anticline in the Beaver Lodge area.

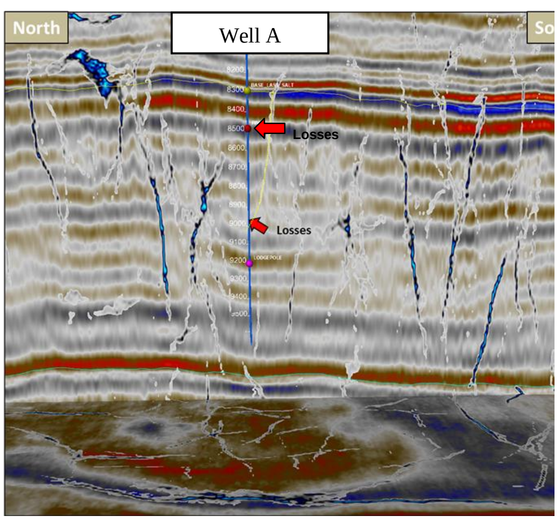

Figure 5. Seismic Image Section Related to Well A

Since Wells A and B were drilled on the same pad, **Fig. 5** applies for both wells. **Fig. 6** applies for Well C. From the seismic images in Fig. 5 and Fig. 6, no apparent correlation between visible seismic events and mud losses in Mission Canyon can be observed. This suggests that the lost circulation in Mission Canyon is primarily related to induced fractures rather than to natural fractures; admitting presence of natural fractures would aggravate lost circulation.

In Fig. 5, the yellow line shows a possible fault that intersects the wellbore of Well A at depth where losses recurred (~8,990 ft). This indicates that the major lost circulation mechanism in Lodgepole very likely is natural fractures/faults.

Based on all the above analysis, it is concluded that mud loss in Rival is primarily due to induced fractures while that in Lodgepole is due to natural fractures.

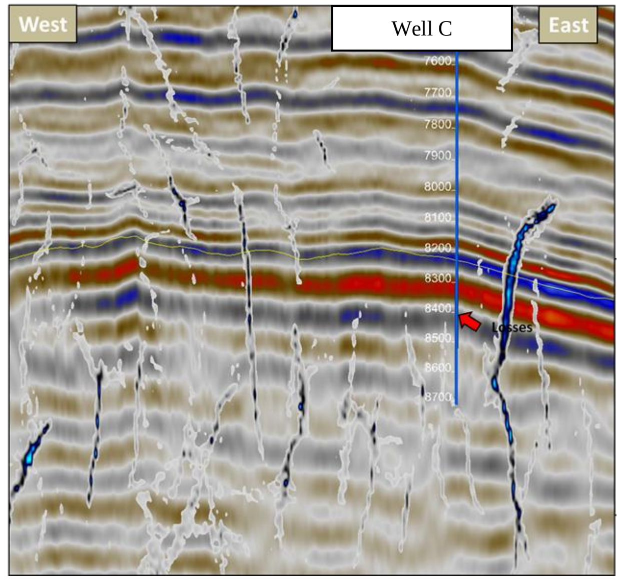

Figure 6. Seismic Image Section Related to Well C

The STRESS SHIELD Wellbore Strengthening Method

Two Wellbore Strengthening Mechanisms Both Requiring Sealing

Based on studies of wellbore strengthening[2-5], two mechanisms can be used to prevent induced fractures in a low fracture gradient formation with particulate LCM added to mud:

(1) Sealing the incipient fracture; and
(2) Sealing the incipient fracture and widening the fracture as well.

In the two mechanisms, sealing is necessary for either one. When sealing is achieved, no fluid can charge into the fracture anymore and the fracture propagation is arrested. When sealing is achieved, the near wellbore stress concentration can shield the wellbore and enable it to hold a much higher pressure than the far-field stress. Nevertheless, if effective sealing is not achieved, the fracture would continue to propagate with aperture widening, and wellbore strengthening would fail. When fractures have been sealed, further propping the fractures with particulates can induce more hoop stress around the wellbore, which would hold even more pressure.

Furthermore, based on similar studies[6], to maximize the strengthening effect, sealing should be achieved at the entrance of the fracture. When the sealing location is moved to inside a fracture, the strengthening effect reduces exponentially.

Effectively Sealing an Incipient-Induced Fracture

(1) Reliable Sealing Particulate Formulations

It is not easy to achieve an efficient seal with particulate formulation. Without a good formulation, a pill mixed at the rig site may not have a sealing effect. Sometimes, even if it has some sealing effect, its sealing efficiency may be low.

A typical particulate pill without sealing effects may demonstrate one or both of the following behaviors:

(a) The whole pill passes through a fracture without sealing; and

(b) The particulates are filtered out and accumulate at the fracture entrance, but the carrying drilling fluid is strained through the pile of the particulates and into the fracture freely.

For the first behavior, the particulates may be too small for the fracture. For the second, the particulates are large enough, but not of sealing effect. Over time, the drilling fluid keeps flowing into fractures and the particulates are piling up at the fracture entrance inside a wellbore.

This phenomenon can be easily experienced by scooping beach sand from water. Beach sand typically has little sealing effect. Though sand does not flow through your fingers, water will drain away and only sand is left in your hands. Imagine the pile of sand is in a wellbore. Although the loss rate decline somewhat due to the increased flow resistance, when the pile increases over time, mud losses are still not arrested on the surface. Furthermore, the pile may not last long. Soon the drill pipe may disrupt the pile, and massive losses start again.

Achieving efficient particulate sealing has been a challenge to mud engineers at the rig site. This is because particulates made of different materials have different sealing properties, and one may not have all the favorite components at the rig site. Furthermore, the particulate fragmentation is a random process and it is difficult to control the particle size distribution precisely. LCM products of a similar formulation may have largely varying sealing performances. Mud engineers typically do not have a standard means to test the sealing effect of a pill when it is mixed at the rig site.

To tackle that typical challenge and achieve a reliable sealing performance, a series of designated fast-sealing LCMs (FS-LCMs) are formulated to efficiently form a seal at a fracture entrance. The seal is checked by PPA slot disk tests. The sealing test results of one FS-LCM product **(Fig. 7)** are illustrated in **Fig. 8**. One can see that this particular product can efficiently seal a fracture when its aperture is 200 µm, 500 µm, or even 1000 µm wide. Efficient and preferred sealing would have just enough particulates at the seal but no more. **Fig. 9** shows seals formed on a slot disk with

Figure 7. FS-LCM

the FS-LCM in a synthetic-based mud tested on an offshore rig. Rather than forming a large pile inside a test cell with other inefficient LCM, this product formed a seal thickness comparable to mud cake. In a similar but different test, the seal formed by the FS-LCM was tested to 3000 psi.

Furthermore, efficient sealing is necessary not only

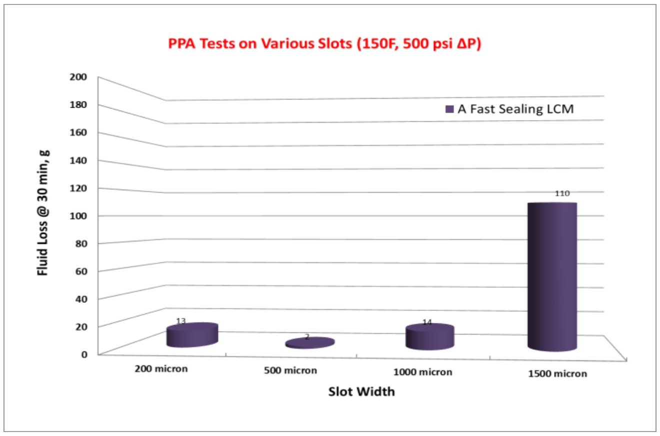

Figure 8. FS-LCM Seals Multiple Fractures

Figure 9. Efficient FS-LCM Seals Formed on Slots

because it is preferred to lose less mud, but, more importantly, because sealing an induced fracture requires it too. Efficient sealing means there can be little spurt fluid charging into an incipient fracture and it is small enough not to widen the fracture to propagate further.

The seal efficiency needs to be quantified by the spurt so we can know how much of the particulate LCM we have to add and how small the spurt has to be. But how can we know how small the spurt has to be?

(2) Criterion for Ensuring Sealing an Incipient Induced Fracture for Wellbore Strengthening – the STRESS SHIELD Engineering Method

STRESS SHIELD engineering is a new rock mechanics-based method of designing a particulate LCM formulation for pretreating mud to strengthen a weak wellbore while drilling to prevent mud losses into a depleted formation.

To seal an incipient induced fracture, the particulates have to have a fracture-sealing function. However, this is not enough. The seal also has to form before the fracture becomes too wide to seal.

Induced fractures are hydraulic fractures. The fracture widens when more of the drilling fluid charges into the fracture, which is the fracture propagation process. During this process, both the fracture width and length grow with the invasion of more drilling fluid. Due to the particle size selected, certain FS-LCM can seal only up a certain width of a fracture but no wider. This fracture width can be called the critical sealing width (W) for this particular FS-LCM. Different FS-LCMs can be designed and manufactured to have different critical sealing widths. For example, one FS-LCM has a W of 500 µm while another has a W of 850 µm. For an FS-LCM to seal, it is necessary to ensure that the incipient induced fracture would not be widened beyond the corresponding W for the selected FS-LCM before a seal has formed.

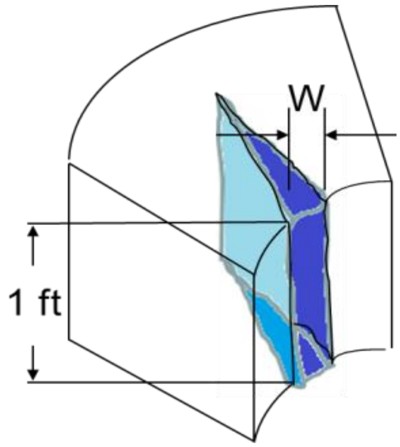

Figure 10. Calculating the Maximum Allowed Volume, V_{max}

The hydraulic fracturing theory indicates that the fracture width is controlled by the volume of mud charging into the fracture. Therefore, the W or the maximum width allowed is related to a maximum volume allowed to charge into the fracture. This maximum allowed volume (V_{max}) for every foot in height of a fracture, as indicated in **Fig. 10**, can be calculated when the rock mechanical properties and wellbore conditions are defined[6]. In a simple scenario for a near vertical wellbore in a low tectonic stress area, this V_{max} for every foot in height of the fracture can be calculated with **Eq. 4:**

$$\mathbf{Vmax = 0.5 \cdot H \cdot W\{\sqrt{\left(\frac{W \cdot E}{4(1-\mu^2)(P_w - S_{hmin})}\right)^2 + R^2} - R\}} \quad (4)$$

where the fracture height H = 1 ft. E is rock Young's modulus. P_w is the target wellbore strength or maximum wellbore pressure anticipated. R is the wellbore radius.

Controlling the fracture width, therefore, means controlling the mud volume charging into the fracture at less than this V_{max}. Evaluate this mud volume by measuring the spurt loss on a slot disk with the slot width equal to W. So the sealing criterion is that the spurt loss of pretreated mud over one-foot long slot (V_{spurt}) satisfies **Eq. 5** for a one-foot high incipient fracture to be sealed:

$$\mathbf{Vspurt \leq Vmax} \quad (5)$$

From this criterion, for sealing these induced incipient fractures, preventive particulate LCM added to mud has to be able to control the mud spurt so that it is low enough. Otherwise, whatever is added should have no effect and all are wasted.

The correlation between the spurt loss and the concentration of an FS-LCM has been predetermined by lab tests on a slot disk as shown in **Fig. 11**. The slots on the disk are to simulate the entrance of a fracture and of the same width as the corresponding W of the FS-LCM. Typically, the spurt loss is inversely related to the particulate concentration (C) of an FS-LCM as shown in Fig. 11. In other words, a higher concentration of the FS-LCM would generate a smaller V_{spurt} or would demonstrate a tighter control.

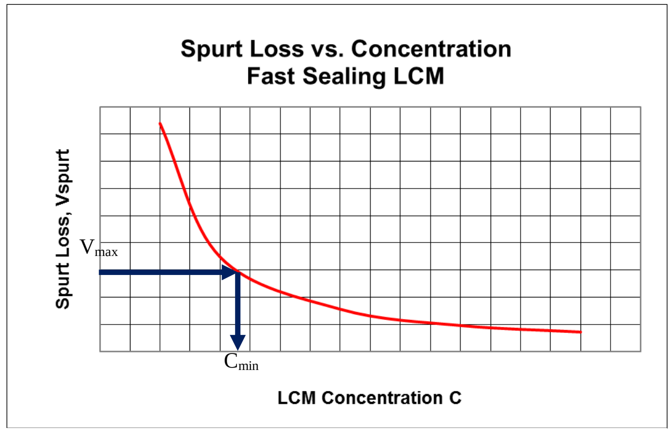

Figure 11. Correlation between Spurt Loss and Concentration of a FS-LCM

From Fig. 11, when a V_{max} is calculated for a specific project, use this V_{max} as the maximum V_{spurt} to find the corresponding minimum concentration of the FS-LCM, C_{min}. Then any concentration larger than C_{min} should yield smaller spurt, so that can be used for the project.

With the STRESS SHIELD Engineering method, one does not have to use a concentration exactly as C_{min}. Theoretically, any concentration above C_{min} could be used. As shown in Fig. 8, such an FS-LCM can seal large and small fractures. When the concentration is higher, the spurt is lower. This means the seal may form before the fracture opens to W due to the smaller fracture invasion volume ahead of the seal formation. This allows us to design a job without knowing exactly what the rock mechanical properties or other data are. We can select a conservative value in a reasonable range. Then the design will conservatively define a higher FS-LCM concentration for a tighter spurt loss control. Using this low value rather than the true value gives the design a safety factor, which is preferred when data is uncertain.

When this criterion is satisfied, the FS-LCM should seal the incipient induced fracture before it widens beyond the critical sealing width. When any incipient fractures are sealed and their propagation is arrested, the higher, naturally existing, near wellbore stress, which keeps the wellbore in compression, then can support the wellbore to hold the well pressure. In this sealing process, if the fractures are also propped by the particulates in the fractures, then the strengthening effect can be higher even if it is not necessary.

This process has been previously discussed elsewhere[7].

The STRESS SHIELD Engineering Design for Bakken – A "One Stone Kills Two Birds" Approach

The depleted Rival and fractured Lodgepole formations are in the same drilling interval. The strategy for mud loss prevention and remediation is to first focus on the loss prevention design for the depleted Rival formation. By applying the STRESS SHIELD method, we first came up with the designed FS-LCM concentration for drilling Rival. Due to the slot-sealing effectiveness of the FS-LCM, we can retain the same LCM in the mud system for drilling deeper in order to seal the natural fractures less than 1000 µm wide encountered in the Lodgepole formation. In addition, a contingency remedial plan was also in place to cure losses if encountered.

For Depleted Rival

The wellbore penetrating Rival zone at ~8500 ft is typically vertical and this Beaver Lodge area is not tectonically stressed. The bit size is typically 8 ¾" for drilling the Rival and Lodgepole formations. This will define a wellbore radius of 4.375 inch. Based on geomechanical data, it is believed the Young's modulus of the Rival formation is no smaller than 3×10^6 psi. A typical value of 0.25 is used as the rock Poisson's ratio, which has minor effect on the calculation. The critical fracture sealing width (W) is 850 µm, which is defined by the selected FS-LCM. (Although this FS-LCM can seal a fracture up to 1000 µm in width as shown in Fig. 8, the spurt loss does not show a good repeatability with slot width of 1000 µm.) A wellbore strength of ~10.2 ppg was targeted and this is to strengthen the wellbore by ~900 psi. This 10.2 ppg wellbore strengthening is still below 13.7 ppg, the fracture initiation pressure that is used as the upper limit for the strengthening. **Table 2** is a summary of the input data.

Table 2. Input Data for the Bakken Project

P_w, ppg	S_h, ppg	R, inch	W, µm	E, 10^6 psi	µ
10.2	8.2	4.375	850	3	0.25

With **Eq. 4**, the V_{max} can be calculated as 85 ml/ft. With this volume, from the spurt and concentration correlation as in Fig. 11, the required minimum concentration of the FS-LCM is defined as 10 ppb. In reality, for a safety factor, we may add 5 more ppb to this minimum concentration. So controlling the concentration of the FS-LCM in the range of 10 ppb to 15 ppb is determined by the STRESS SHIELD method. When the pretreated mud is bypassing the shale shakers to retain the material, a 10 ppb is considered to be sufficient. When the pretreated mud is running through an appropriate shale shaker screen, a 15 ppb is used to compensate the quantity lost over the shale shaker.

Furthermore, **Fig. 12** shows the sensitivity of the concentration to the target wellbore strengthening and rock Young's modulus for the project. This chart indicates that increasing wellbore strengthening target requires tightening spurt loss control and, therefore, increases the required concentration of an FS-LCM. Meanwhile, a wellbore with a larger Young's modulus can tolerate more fracture invasion and, therefore, requires less FS-LCM in mud.

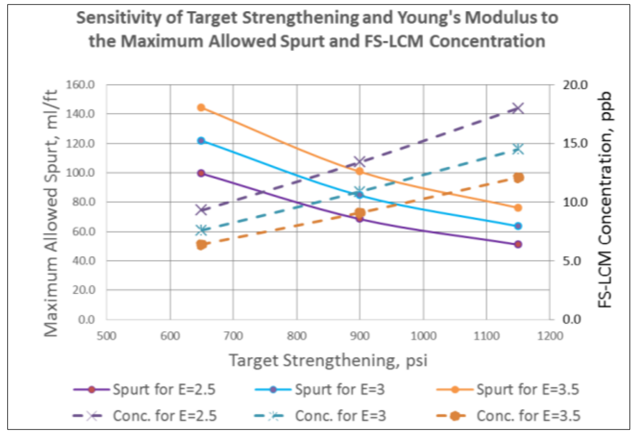

Figure 12. Required Spurt Loss Control Affected by Young's Modulus and Target Strengthening

In addition, to ensure that the mixture of FS-LCM and drilling mud meets the designed sealing capacity (85 ml/ft of the spurt loss), direct measurement of spurt loss tests with an appropriate slot disk were performed on the rig site of several wells. This is an important advantage over other LCM products in the sense of quantitative quality control.

For Fractured Lodgepole

Lab tests have indicated that the FS-LCM can seal fractures up to 1000 µm as shown in Fig. 8. This means mud containing the FS-LCM for the Rival depleted formation can also be used to control mud losses in the Lodgepole formation. As long as the natural fractures are narrower than 1000 µm, those can be instantaneously sealed without being noticed during drilling.

Contingency Plan for Remediation

However, the natural fractures in Lodegpole may be wider than 1000 µm. When these are encountered, mud losses would be observed and then remedial LCM pills are needed.

Secondly, natural fractures also may exist in the depleted Rival zone. In this case, the fracture may be already too wide before any mud charging into the fracture, and the STRESS SHIELD method may not be able to prevent the lost circulation.

Thirdly, below Lodgepole is the weaker Upper Bakken shale, which may be instable in high angle wells. Excessive cavings from this shale plus difficulty of hole cleaning in high angle wells may cause pack-off. Downhole pressure surge during pack-off could exceed designed wellbore strength and induce further losses.

To seal these wider fractures, a reticulated sponge LCM (sized as fine, medium and coarse) (**Fig. 13)** is planned to be added to a pill with an increased concentration (such as 50 ppb to 80 ppb) of the FS-LCM. Depending on the selected size of the sponge, such a pill can seal up to one-inch wide fractures.

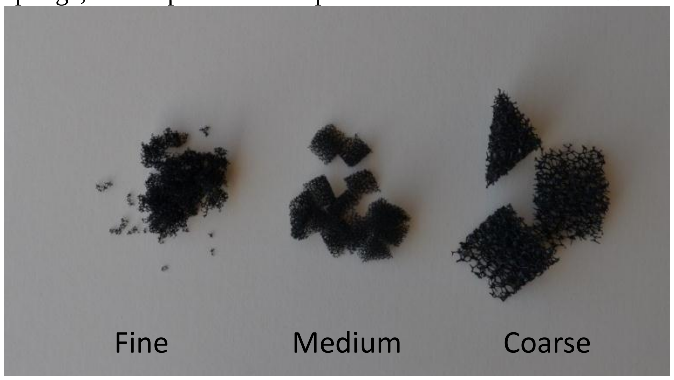

Figure 13. Reticulated Sponge LCM

To cope with severe mud loss situation, a high fluid loss squeeze product premixed with the sponge is also planned. This new technology has been discussed elsewhere[7].

Comparison of Applications and Results

Sixteen wells have been drilled in the Beaver Lodge area related to this topic. Among these 16 wells, 6 wells were drilled with conventional LCM. All 6 wells had mud losses ranging from hundreds to thousands of barrels and resulting in two wells abandoned. In contrary, 9 of the other 10 wells drilled with the application of STRESS SHIELD without mud losses. The mud losses in 1 well were induced by pack-off during reaming hole after reaching section TD.

First we drilled 3 wells (Wells A, B, and C) without STRESS SHIELD as we have stated. All of these had massive mud losses and two of them were abandoned.

Then, STRESS SHIELD was introduced and 5 wells were drilled with this technology. While drilling the first 3 wells, the spurt loss was tested at the rig site and the spurt loss of all the mud pretreated with the FS-LCM at 10~15 ppb met the design criterion (≤ 85 ml/ft). All these five wells were drilled without any mud losses.

Then another well (Well D) was drilled in the area without STRESS SHIELD but with conventional LCM. This well was initially drilled the 9 $^{7}/_{8}$" vertical section to 8,100 ft with 9.5 ppg MW and pretreated mud with conventional LCM. At 8,485 ft (top of Rival), the well immediately lost its full returns. Filling backside was attempted. A 40 bbl conventional LCM pill at 40 ppb was pumped. Returning flow increased. The rig then continued to drill with partial returns and kept pumping conventional LCM pills and sweeps. Cumulative mud losses were ~2,020 bbl before setting casing at 10,130 ft.

Seismic image cross section of Well D (**Fig. 14)** shows no visible seismic events in the Rival zone where total lost return occurred. This validates previous conclusion on the mechanism: loss in the Rival is due to induced fractures from depletion.

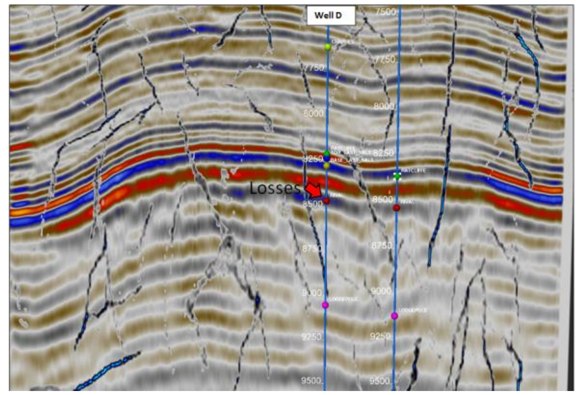

Figure 14. Seismic Image Section Related to Well D

Then we started batch drilling the 8 ¾" hole section for four wells (Well E, F, G, H) from a single drilling pad. The distance between surface locations as well as the vertical wellbores was only ~30 ft. The first (Well E) and second well (Well F) used 12.5 ppb to 15 ppb conventional LCM to pretreat the mud before drilling into Rival.

Well E was drilled to KOP (9,335 ft) without sustaining substantial losses. While drilling the curve, partial losses were reported at 9,652 ft. Conventional LCM pills were pumped. Total mud loss to the well was 500 bbls when the hole section was completed.

Well F inherited mud from Well E. The rig lost only 5 bbls through Rival zone (top at 8,526 ft), but sustained losses of 10 bph to 15 bph began at 9,220 ft in Lodgepole. Remedial pill with FS-LCM enhanced with reticulated sponge was pumped as a sweep. Loss was stopped. Curve section was landed, and 7" casing was run and cemented without further losses. Total mud loss to Well F was 238 bbls.

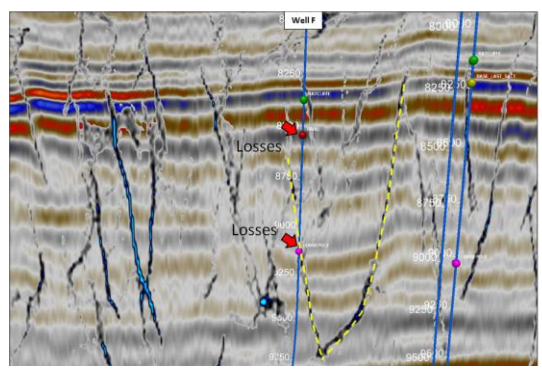

Figure 15. Seismic Image Section Related to Well F

Seismic image (**Fig. 15**) indicates good correlation between seismic events (natural fractures/faults) and the loss depth in Lodgepole along Well F trajectory.

Decision was then made to apply STRESS SHIELD again for the next two wells (Wells G and H). We considered this a great opportunity to test the effectiveness of the new technology due to the vicinity and similarity of those wells.

Typically, at around 200 ft before drilling to the Rival formation, the rig started to add the FS-LCM into mud while drilling ahead to make sure the predesigned FS-LCM concentration was reached before drilling into the Rival. When Rival is reached, it is preferred the spurt loss be tested to ensure that it meets the design requirement of 85 ml/ft or less. API 20 mesh screens were used to retain the FS-LCM and shake out coarse cuttings. Well G was drilled to section TD without mud lost to hole.

The same approach was applied to Well H, the last well on this pad. Again, it was drilled to section TD without any mud lost to hole. However, after reaching TD, while reaming the hole before running casing, pack-off and subsequent mud losses occurred. The presence of large chunks of shale cavings while circulating bottom up indicated that pack-off may be caused by wellbore instability in the Upper Bakken shale. It is also envisioned that downhole pressure surge during pack-off exceeded the designed target strength and induced mud losses. But this mud loss was cured by two pills of 25 bbl 50 ppb FS-LCM enhanced by the reticulated sponge. Eventually about 280 bbl OBM was lost.

After drilling these 4 wells, another 3 wells were drilled so far with STRESS SHIELD in the Beaver Lodge area and none of these experienced mud losses.

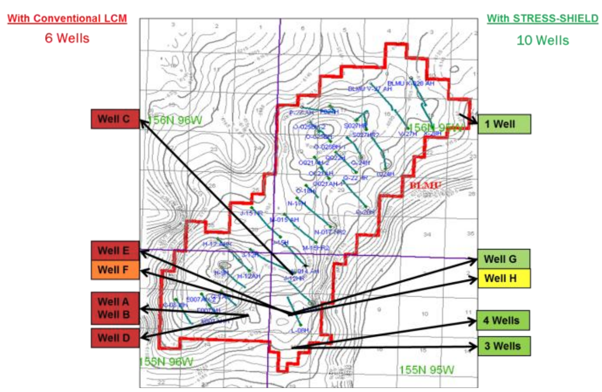

Figure 16. Well Locations in the Beaver Lodge Area

The map with the 16 well locations is shown in **Fig. 16**. On the left side, in red, are the 6 wells drilled without STRESS SHIELD but with conventional LCM. On the right side, in green, are the 10 wells drilled with STRESS SHIELD.

In summary, it is evident that the STRESS SHIELD method works very well so far. In all 10 wells using the STRESS SHIELD method, the pretreatment with FS-LCM sealed fractures and was compatible with the OBM. The remedial pills with high concentration of FS-LCM and reticulated sponge were effective to cure losses in 2 wells (Wells F and H). In those 6 wells without STRESS SHIELD, conventional LCMs were used at similar or higher concentration, but all failed to prevent or cure mud losses and sometimes led to well abandonment.

Conclusions

1. Integrated analysis of geomechanics, reservoir, and seismic data revealed that lost circulation in the Beaver Lodge area is due to induced fractures in the depleted Rival member of the Mission Canyon formation and natural fractures in the Lodgepole formation.
2. The drilling record of 16 wells has demonstrated that STRESS SHIELD is a substantially effective method of preventing mud losses in the depleted Rival formation. Quality control can be readily performed at the rig site by testing spurt with a slot disk tester. The rig-site tests indicated that the spurt loss control of the mixture met the designed requirement.
3. The selected FS-LCM at the designed concentration is also effective in preventing mud losses in the fractured Lodgepole formation.
4. When losses occurred either the result of ineffective conventional LCM or induced by pack-off, remedial pills of high concentration FS-LCM with reticulated sponge were effective to cure losses.
5. Conventional LCM was not efficient to either prevent or cure mud losses in all the 6 wells without STRESS-SHIELD applied.

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Nomenclature

μ = *Poisson's Ratio*
μm = *micron*
A = *Depletion Coefficient*
API = *American Petroleum Institute*
bbl = *barrel*
BLMU = *Beaver Lodge Madison Unit*
bpm = *barrel per minute*
C = *Concentration of a Fast Sealing LCM*
C_{min} = *The Minimum Required Concentration of a Fast Sealing LCM*
E = *Young's Modulus*
ECD = *Equivalent Circulating Density*
FG = *Fracture Gradient*
FS-LCM = *Fast Sealing LCM*
ft = *Foot*
H = *Fracture Height*
KOP = *Kick Off Point*
LCM = *Lost Circulation Material*
MD = *Measure Depth*
min = *Minute*
ml = *milliliter*
MW = *Mud Weight*
OBM = *Oil Based Mud*
P&A = *Plug and Abandon*
P_{ini} = *Fracture Initiation Pressure*
P_p = *Pore Pressure*
PPA = *Particle Plugging Apparatus*
ppb = *Pound per Barrel*
ppg = *Pound per Gallon*
psi = *Pound per Square Inch*

P_w	= *Target Wellbore Strength*
R	= *Wellbore Radius*
SBHP	= *Shut-in Bottomhole Pressure*
SBM	= *Synthetic Based Mud*
S_h	= *Far-field Minimum Horizontal Stress*
S_v	= *Vertical Stress*
TD	= *Total Depth*
TVD	= *Total Vertical Depth*
V_{max}	= *Maximum Allowed Volume for 1 foot of Fracture at W Wide*
V_{spurt}	= *Spurt Loss Volume for 1 foot of Slot at W Wide*
W	= *Critical Sealing Width*
α	= *Biot's Coefficient*

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