

Impact of Lost Circulation Materials on Fracture Initiation and Propagation

by Fred Growcock.

Naturally occurring lost circulation (loss of whole mud) can often be mitigated through adjustment of the properties of the drilling fluid. Usually this entails adding a Lost Circulation Material (LCM) – either to the whole mud or as a pill -- that will seal off the loss zone, which is generally a fractured or high-permeability section. Induced lost circulation, on the other hand, is generally thought to be controllable only by maintaining the equivalent circulating density (ECD) of the fluid at a level which is less than the fracture gradient. This is not always possible, especially when drilling through zones of variable or rapidly changing pore pressure and/or mineralogy.

However, recent work at Conoco and Halliburton suggests that the effective fracture gradient of rock may be increased through the use of LCM. Let us look at induced lost circulation more closely, with particular emphasis on its prevention and mitigation through the use of LCM.

Prevention of Induced Lost Circulation

Until recently, the potential for inducing fractures has been thought to be relatively independent of the nature of the fluid. Indeed, a recent DEA study appears to confirm that Water-Based Mud (WBM) is just as apt to initiate a fracture as Oil-Based Mud (OBM).¹ In addition, there seems to be no reliable evidence that additives in either kind of fluid can affect fracture initiation.

However, this same study showed that in rock containing water-sensitive minerals, WBM tends to promote healing of previously fractured rock and mitigate crack propagation. Thus, in a system with existing fractures, the pressure required to reopen the fractures is generally less with OBM than with WBM. Experiments performed by Conoco² provide additional confirmation that WBM usually generate higher fracture reopening pressures than do OBM. In this work, the difference between WBM and OBM is attributed to the amount and nature of the filter cake deposited along the fracture surface. The ease of fracture propagation is also attributed to the properties of the filter cake, so that both fracture reopening and fracture propagation are more difficult with WBM than with OBM. A consequence of this is the rule of thumb that the wellbore can generally tolerate an ECD as much as 1 to 2 lb/gal higher with WBM than with OBM.

There is now other evidence which strongly suggests that not only the nature of the base fluid, but also the presence of certain additives – especially particulates – can affect the apparent fracture gradient. By controlling the fracture propagation process, these additives can appear to increase the pressure required to initiate fractures. Recent experiments conducted by Conoco^{2,4} indicate that borehole breakdown pressure is strongly influenced by the presence of solid components that can seal potential loss zones and incipient fractures. Fracture models based on conventional linear wellbore stability theory do not take into account this sealing effect.³

Introduction of particles with a size distribution that matches the geometry of incipient cracks can seal the wellbore quite effectively. LCM can protect the wellbore by

directly plugging minute surface flaws and gravel-size pores. If this protection system fails and breakdown of the borehole occurs, LCM will accumulate in the fracture and bridge near the fracture tip. Through bridging, or screen-out, of incipient fractures, resistance to fracture propagation can be increased, thus providing a secondary level of protection to the wellbore.

Both theoretical treatment and experimental evidence indicate that fracture propagation resistance increases with elastic modulus of the formation and net in-situ stress, but that it decreases with fracture size and fracture toughness. High fluid loss of the mud also will tend to create a quicker screen-out. Fracture reopening pressure depends upon how much mud cake is left along the fracture walls.

Characteristics of Effective LCM⁵

- Large and uniform, so that it prevents mud leaks after being packed, yet does not significantly change mud properties and can be removed easily (and perhaps recycled). Typical materials would include nut shells and calcined petroleum coke.
- Not buried in filter cake, so that its concentration increases with fracture propagation as mud is lost through a fracture or microfracture.
- Similar density to the base mud, so that phase separation is minimal.
- Not abrasive or easily crushed while drilling.
- Available at the surface at a high concentration, so that it induces screen-out while an induced fracture is still small.

Limitations of LCM

- Some filtration loss and formation of filter cake is required. Thus, impermeable shales and limestones are not suitable substrates, unless they have a tendency to form microfractures.
- Formations with low Young's modulus and high pressure zones should be avoided, unless they also have high permeability or high in-situ stress from high pore pressure.
- If fractures are formed in the absence of LCM, addition of LCM to the mud will not cure the induced fracture, though it may mitigate fracture propagation.

Modelling^{3,5}

An analytical solution has been obtained for fracture initiation and propagation of a fracture which incorporates various properties of the formation, the wellbore, fracture geometry and nature of the drilling fluid. With the assumption that a pressure seal is formed at the inlet of the zone containing dehydrated gel (filter cake), a model was developed for a fractured, inclined borehole in a general plane strain condition which predicts that when drilling fluid is used as an injection fluid, borehole breakdown pressure is highly dependent on Young's modulus, in-situ stress, wellbore size and the sealing ability of the mud. Less important are thermal cooling, hole inclination and pore pressure build-up.

Borehole breakdown pressure tends to be low under the following conditions:

Low Young's Modulus	Low In-Situ Stress
Large Fracture Width	High Toughness
Low Fluid Loss	Large Wellbore
High Thermal Cooling/High Young's Mod.	High Hole Angle/Low Young's Mod.
High Pore Pressure/Low Permeability	

Field Tests

Conoco chose some wells near Newkirk, Oklahoma and Venture, California for testing of the concept that LCM can increase apparent or effective fracture gradient.⁴ Using ground calcined coke in a simple WBM at a concentration up to 100 lb/bbl, borehole breakdown pressure was increased by 8 lb/gal. At the same time, fracture propagation pressure was increased by 3 to 6 lb/gal. In these tests, the LCM was sized to provide a sufficiently broad particle size distribution that it could function both by (a) plugging minute surface flaws and gravel-size pores, and (b) screening out at the fracture tip of induced fractures. A similar approach has been taken by Amoco Trinidad Oil Company with a blend of three products of different size and shape distribution: 15 lb/bbl QUIK SEAL (fine) / 15 lb/bbl QUIK SEAL (med) / 10 lb/bbl ULTRA SEAL XP.⁶

Mitigation of Induced Lost Circulation

Sometimes induced lost circulation can be fixed by plugging the zone with a pill or squeeze treatment. With the right material, the plug may also increase the apparent fracture gradient.

Data obtained recently by Halliburton suggests that FLEX-PLUG (also called the "new" Lost Circulation Material Squeeze System, or LCMS)⁷ can function in this manner. When mixed thoroughly at a prescribed shear rate, the latex-laden FLEX-PLUG quickly forms a semi-solid mass that can be made to travel directly to the loss zone. The rapid development of high consistency in the formulation permits it to travel through fluids to the weak zones and plug the zone completely.

FLEX-PLUG appears to work in almost any kind of fluid, either oil-based or water-based at temperatures up to at least 325 °F. The consistency of the material may also be adjusted from soft to rubbery to semi-hard. For example a rubbery, semi-hard material may be desired when swab/surge pressures are expected to bypass or dislodge a hard cement, which would again start losses to that (weak) zone. A hard material may be desired when no drill-out is anticipated and a permanent seal is necessary to meet regulatory requirements.

Generally, the new flexible plugging materials tend to be self-diverting, which allows them to seal zones sequentially from weakest to strongest in a single treatment. The wedging effect which is thought to occur in plugged fractures may increase the integrity of the formation, effectively increasing the fracture gradient. This is also thought to be the case for a competing treatment, POLY-PLUG (M&D Industries), which is a mixture of a cellulosic fiber and a cross-linked polyacrylate polymer.

The generality of this effect is not known. Conventional plugging agents can effectively seal off loss zones, but we have seen no evidence that they can also increase the apparent fracture gradient. Conventional treatments include barite plugs (barite/water solutions containing a thinning agent), which are often used before running casing (the pill is spotted across the loss zone and the barite is allowed to settle); mica; wood chips; walnut hulls; and, in extreme cases, cement.

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