A COMPREHENSIVE REVIEW ON SELECTION OF LOST CIRCULATION MATERIALS FOR FRACTURED OIL RESERVOIRS

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Abstract - The problem of lost circulation have for long time occurred during the drilling operation. The massive loss of drilling fluid can cause various drilling problems, thus increasing drilling non-productive time, cost and also leads to improper removal of cuttings out of the wellbore, which causes stuck pipe. Different solutions have been used to overcome this problem, these include chemical sealants, hydratable pills, rigid-plugs, gel polymer, cement and conventional LCMs. Type, shape, particle size distribution (PSD) and concentration are key parameters in determining the effectiveness of the lost circulation materials (LCM) and lost circulation pills (LCP). The method to combine these parameters in an optimized way leads to reducing or preventing the lost circulation effectively and protect the production zone from liquid and solids invasion significantly. The objective of this paper is to present different materials, their applications and limitations, and their optimized combination in controlling the mud lost circulation into oil fractured zones.

Keyword - Lost Circulation Materials, Fractures Oil Reservoirs

I. INTRODUCTION

Lost circulation is a common drilling problem especially in highly permeable formations, depleted reservoirs, and fractured or cavernous formations. Lost circulation problems can begin in shallow, unconsolidated formations and extend into the well-consolidated formations. The industry spends millions of dollars every year to combat lost circulation and its associated detrimental effects such as loss of rig time, stuck pipe, blow-outs, and less frequently, the abandonment of expensive wells. Two conditions are both necessary for lost circulation to occur down hole:

- The pressure in the well bore must exceed the formation pore pressure
- There must be a flow pathway for the losses to occur.

The severity of lost circulation can be grouped into the following categories [1]:

- Seepage losses: up to 10 bbl/hr lost while circulating
- Partial losses: 10-500 bbl/hr lost while circulating
- Severe losses: more than 500 bbl/hr lost while circulating
- Total losses: no fluid comes out of the annulus

To prevent lost circulation, several approaches can be assessed depending on the severity. One type of method is the four-tiered strategy consisting of both prevention and remediation measures (Figure 1). The prevention tiers are: best drilling practices, drilling fluid selection and wellbore strengthening materials. Drilling fluid selection includes the selection of the best suited fluid with the proper rheological properties. The remediation tier (lost circulating materials), is devoted to reduce the lost circulation with materials such as cure or stop-loss pills. Experience has proved that it is more sufficient to prevent the occurrence of losses rather than to stop or reduce them when they have started, thus it is of importance to develop suitable drilling fluids [2].

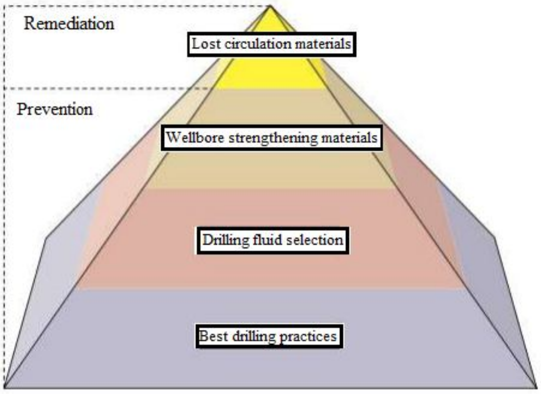


Figure 1. Four-tiered strategy

II. FEATURES FOR IDENTIFYING LOST CIRCULATION ZONES

Normally lost circulation zones can be identified to some extent, based on how fast the drilling mud is being lost and how drilling is affected once the formation starts losing mud. There are four basic types of formations that lead to losses and these are described as follows:

2.1 Natural Fractures

These can occur in any type of rock. The mud level decreases slowly in the pit and if the drilling is continued, more fractures become exposed to the drilling mud which can lead to a complete loss. The natural fractures in formation are represented in Figure 2. This figure demonstrates that for a natural fracture to exist, the overburden must be self-supporting

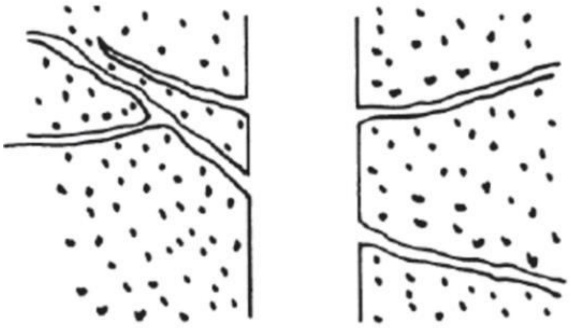


Figure 2. Natural Fracture

2.2 Cavernous Formations

These are most commonly limited to limestone formations. When these occur there is a sudden loss of mud and before the loss starts taking place the drilling bit drops anywhere from several inches to a few feet into a new zone. The drilling becomes rough before the loss starts taking place. Figure 3 shows that these are fractures of large proportions and the mud can flow from an upper zone to a lower zone, making the fracture more difficult to seal.

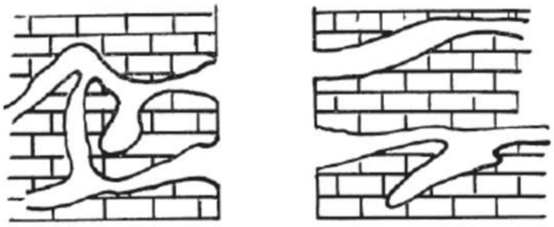


Figure 3. Cavernous Formations

2.3 Induced Fractures

These fractures can be induced in any type of rock but are typically a feature of weak formations such as shale. The loss of mud is rapid when drilling is carried out through this type of fracture. Normally, when the drilling mud weighs more than 10.5 lb/gal, the conditions lead to the formation of induced fractures in these weak formations. Figure 4 shows how induced fractures can be created because of high mud weight. Other causes can be well irregularities, excessive back pressure and rough handling of the drilling tools.

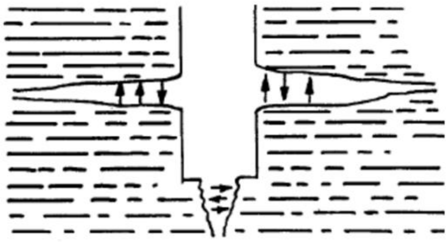


Figure 4. Induced Fracture

2.3 Unconsolidated Formations

These are highly permeable formations as shown in Figure 5. This results in a drop in the mud level in the pit. If drilling is continued, there can be a complete loss of drilling fluid. These formations need to have a permeability of 10-100 Darcy for the loss to occur. Shallow sands and gravels often have such permeabilities and, therefore, are prone to mud losses [3,4].

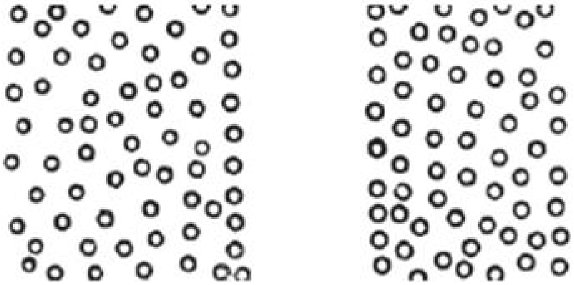


Figure 5. Unconsolidated Formations

III. TYPE OF LOSS ZONE FROM MUD LEVEL DROP AT THE PITS

While drilling in fractured formations, drilling fluid losses are common. By monitoring fluid losses, the formations that are fractured are identified. In order to differentiate between the types of mud losses, the mud losses at the mud tank can be observed closely. For mud loss through pores, the amount of loss occurring increases slowly as the flow of drilling mud increases; whereas for natural fractures there is a rapid initial loss of mud that declines with time. This is shown in the Figure 6.

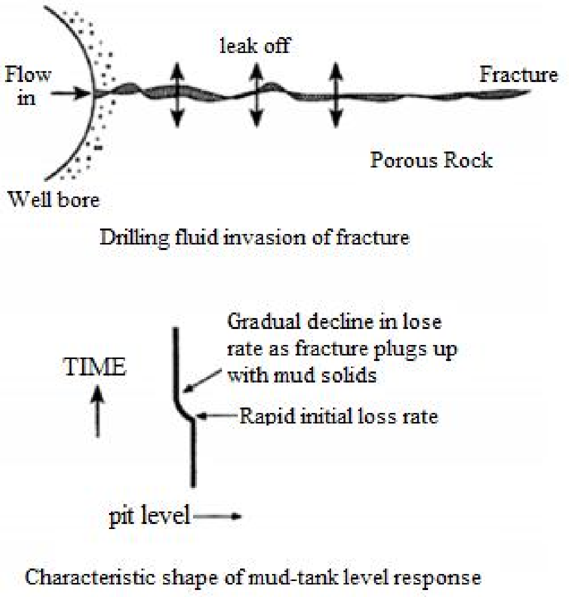


Figure 6. Mud losses into natural fractures

The type of loss zone can be identified by looking at the mud level drop in pits as shown in Figure 7. There are different models that describe the process of mud invasion into the fractures and they help in identifying conductive fractures present in the formation. After these problems are identified and the causes are known, methods are devised to rectify or reduce them [5].

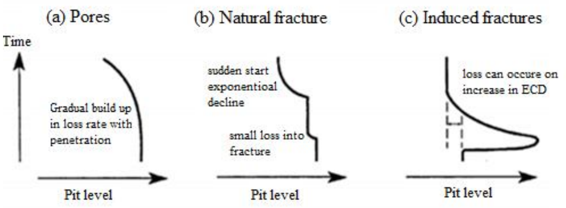


Figure 7. Type of loss zone from mud level drop at the pits

IV. FUNDAMENTALS OF LOST CIRCULATION CONTROL

A lot of effort has been done to understand the mechanics of lost circulation control. Lost circulation control during well construction is more than just selecting the right lost circulation material (LCM) but requires a complete engineered approach. Some of the approaches involve borehole stability analysis, equivalent circulating density (ECD) modelling, leak-off flow-path geometry considerations, drilling fluid and LCM selection to help minimize effects on ECD, on-site monitoring using annular pressure while drilling (APWD), connection flow monitoring techniques, and timely application of LCM and treatments [6].

Lost Circulation Materials (LCMs) Selection

LCMs are needed to stop fluid losses in order to drill ahead in most drilling operations. An LCM should react, block fractures, and form a bridge to provide a seal in a timely manner. The seal could be temporary or even permanent. Permanent seals are used to block thief zones in non-producing intervals while temporary seals are used to block loss zones in pay intervals. Previous studies have demonstrated that some products work better than others as lost circulation materials. LCMs are categorized into common groups along their physical and chemical characteristics. These groups are as follows: [7]

- Conventional Lost Circulation Materials (fibers, flakes, and granules)
- High Fluid Loss Squeezes (diatomaceous earth or clay blends)
- Gunk Slurries (diesel oil bentonite)
- Precipitated Chemical Slurries (silicate and latex)
- Resin-coated Sand
- Cross-linked Polymer Slurries
- Cements
- Barite Plugs
- Dilatant Slurries

4.1 Conventional LCMs

These LCMs can be classified as granular (ground walnut shells, pecan shells, almond shells, plastic, and calcium carbonate), flakes (ground mica, plastic laminate, cellophane, and polyethylene plastic chips), fibers (rice hulls, peanut hulls, wood, cane, etc.) or a mixture of the three [1]. The granular LCMs form two types of bridges; one at the formation face and one within the formation matrix. The latter sealing is preferred because it forms a more permanent bridge within the formation such that pipe movements in the wellbore cannot dislodge the granular particles. The effectiveness of granular LCMs depends on their particle size distribution, with larger particles first forming a bridge across or within the void and smaller particles bridging the openings between larger ones. Figure 8 illustrate the importance of getting the right PSD of LCMs for bridging and sealing loss zones.

Fibrous materials are best suited for controlling losses in porous and highly permeable formations because they form a mat like bridge over the pore openings. The mat reduces the size of the openings to the formation, permitting the colloidal particles in the mud to rapidly deposit a filter cake. Flake LCMs are also designed to form a mat on the formation face, which also provides the best results as fibrous materials when used to treat losses in porous and highly permeable formations. Blends of granular, flakes, and fibrous materials are used in solving actual field problems [1].

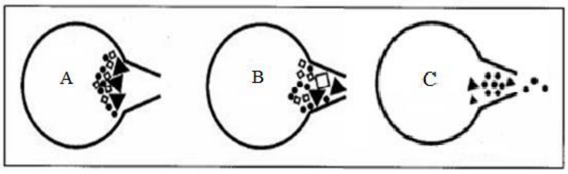


Figure 8. A: Results using LCM too large – forms a bridge on the wellbore and erodes away; B: proper bridging; C: result using LCM too fine- goes through the opening and does not form a bridge.

The key characteristics of the particulate materials that will affect their performance in the wellbore strengthening process have been provided in order of descending importance (Freidheim et al. 2008):

- Particle size
- Particle size distribution
- Concentration
- Shape (sheroidicity/aspect ratio)
- Others (surface texture, compressive strength, bulk density, resiliency, etc.)

4.2 High Fluid Loss Squeezes

These LCMs lose water quickly and deposit a thick cake of residual solids in the loss zone. This method is particularly useful for preventing the extension of natural or induced fractures, as the deposited solids prevent the transmission of pressure to the tip of the fractures. The two main high fluid loss pills are:

- DiaSeal M (diatomaceous earth)
- Attapulgite/Calcium Carbonate

4.3 Gunk Slurries

The gunk slurries consist of two or more fluids which upon making contact with the wellbore or the loss zone form a viscous plug which seals the zone. For partial losses, better results are achieved by using Mud-Diesel-Oil-Bentonite (M-DOB) plugs. When this mixture contacts water or water-based mud, a mass with high gel strength is formed. The DOB mixture is pumped down the drill string while the mud is pumped down the annulus. M-DOB plugs have several disadvantages:

- They break down with time
- They are difficult to apply in long open hole intervals
- When losses are severe, it is impossible to achieve reliable pumping rate down the annulus; therefore the degree of mixing cannot be controlled
- No compressive strength is developed [1, 8].

There are other gunk slurries that can be used with oil-based muds. For example, Reverse Diesel-Oil-Bentonite (R-DOB) is used for oil-based muds.

4.4 Precipitated Chemical Slurries

Both silicate solutions and commercial latex additives used for cementing can be made to precipitate and used to plug loss zones when pumped in combination with calcium chloride. The general idea is to pump a calcium chloride pill followed by the silicate of latex slurry. When these two slurries are mixed in the open hole, hopefully adjacent to the loss zone, they form a viscous plug which can slow and seal many loss zones.

4.5 Chemically Activated Cross-linked Pills (CACP)

Cross-linking is the linking of two independent polymer chains by cross-linking agents that links two chains. The advantage of these pills is that they can be used to stop losses in water, oil or synthetic-based drilling muds. However, their main limitation is that they are not biologically or chemically degradable in the wellbore and hence they must be used with caution near pay zones.

4.6 Cement Slurries

Cement plugs are often effective against complete losses. Especially in geothermal wells cement plug is the cure for lost circulation zones. Special cement formulations like magnesium-based cements and thixotropic cements are more common. Portland cements are also being used as LCMs only after other techniques have proven unsuccessful, or if experience has shown it to be the method of choice. Portland cement compositions have particle size distributions in the 30 to 100 micron range; which, for the most part, should not penetrate the permeability matrix near producing zones. Formation fractures can be created by rock stress which can accept whole fluid during the cement placement process and lead to formation damage. However, using cement recipes that combine an acid-soluble additive have proven to be viable alternatives to reduce formation damage near productive zones. Cement plus bentonite plug is also used in industry and it is capable of plugging vugular lost zones. Bentonite cement formed by adding cement to prehydrated Bentonite and This slurry formed has lower density and higher gel strength [8,9].

4.7 Dilatant Slurries

These LCMs are composed of specifically sized solids and polymers that are both water soluble and insoluble. The ability of these types of fluids to thicken irreversibly when they pass through the high shear zones in the drill bit make them suitable for stopping losses in any loss zone [8].

4.8 Gel type

An appropriate gel selection is important to lost treatment; it will affect treatment result directly. Gel with greater strengths can be applied in reservoir with large fractures, weaker gel will be used in reservoir with less extensively fracture or matrix with lower productivity. Polymer gel treatment is the most common and effective gel treatment application in reservoir. Polymer gel can flow through fractures and also strong enough to withstand high pressure difference near wellbore. It can be placed in high permeable with high water saturation, to reduce water permeability and block the water channels. Crosslinked polymer gel can be applied to production wells with excessive water or gas flow; it can also apply to injection wells with poor injection profile. Polymer goes through crosslinking fist and then forms a solid gel with time and temperature.

There have two type of crosslinker to polymer such as organic crosslinker and metal ions crosslinker, the most common use for metal ions crosslinker is chrome-based crosslinker. Metal ions crosslinkers contain Al^{3+}, Cr^{3+} and Cr^{6+}. Crosslinker with Al^{3+} is hard to control or delay the crosslinking time. Chromium (III) Carboxylate/Acrylamide-Polymer Gels is also known as CC/AP gels. CC/AP gel can be both used as water shutoff treatment. The disadvantage for chrome-based crosslinkers are less remaining time during injection and sometimes tend to set up earlier than desired, particularly at temperatures above 175°F. For high reservoir temperature or oxidative degradation, Metal ions crosslinked polymers are less likely to use [10]. Figure 9 shows a schematic of cross-linking polymer with chromium.

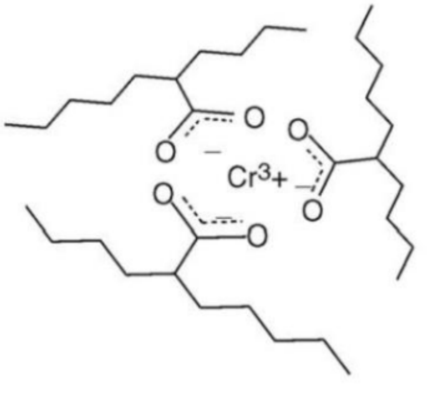


Figure 9. Cross-linked polymer by Cr^{3+}

Organic crosslinker polymer is an environmental friendly system. It took less job to mix and pump to the field. Organic crosslinker system reacts more predictable to change of reservoir temperature, component concentration, brine type, salinity and pH values. Those characters make organic crosslinking polymer gel easier to control and to understand during the treating process. Compared to chrome based polymer gel, organic crosslinkers last longer time than tradition polymer gel with it deep sealing properties. From the laboratory test data result, organic crosslinker can penetrate into the formation eight times as far as traditional chrome-based polymer; it can completely seal off the formation [10].

4.9 New developed severe LCMs

Today many changes have been made on different materials and compounds to achieve better applicable and more useful product to cure different types of mud losses. Due to high cost some times two or more companies joint together to reduce the risk of unsuccessful trials. Here some of these new recently developed materials are introduced; perhaps they change the future of extreme mud loss problem.

4.10 Shear Sensitive Plugging Fluid (SSPF)

The SSPF is a fluid designed to gel rapidly after passing through the BHA in normal drilling operations, thus forming a solid mass and curing heavy mud losses. The SSPF consists of a single ‘loose’ or ‘shear-sensitive’ invert emulsion (water-in-oil). The term ‘loose’ or ‘shear-sensitive’ is defined as meaning that the prepared emulsion has a degree of instability to high shear forces. It is this instability of the emulsion that is exploited to create the new technology.

The SSPF is fabricated from encapsulation of the crosslinker in the continuous oil medium and a water soluble polymer in the water phase. The emulsion is maintained by a low concentration of a lipophilic surfactant, or emulsifier. In this ‘loose’ state, the surface of the crosslinker is oil wet and remains in the oil phase. Although the water droplets are large, the surfactant enables good curvature around the water droplets. Therefore minimal transfer, or migration, of the crosslinker from the oil to the water phase occurs. The perceived release mechanism for an SSPF is that during the high shear trigger event, the large water droplets (Figure 10) are ruptured. This process crushes the large water droplets and, by virtue of the low concentration of emulsifier used in the emulsion, flips into a direct state. The emulsion now contains more stable, numerous and smaller diameter oil droplets (Figure 11).

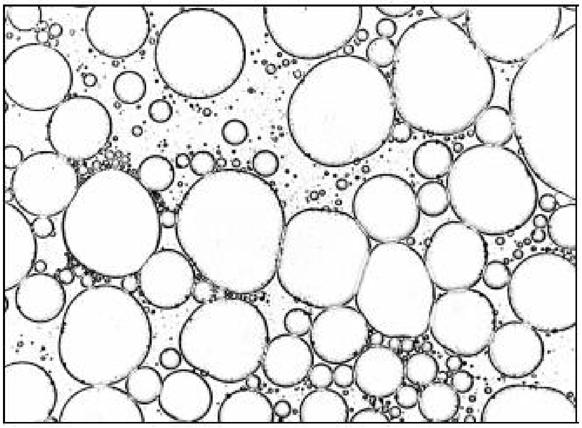


Figure 10. Image of ‘loose’ emulsion state before deformation by high shear

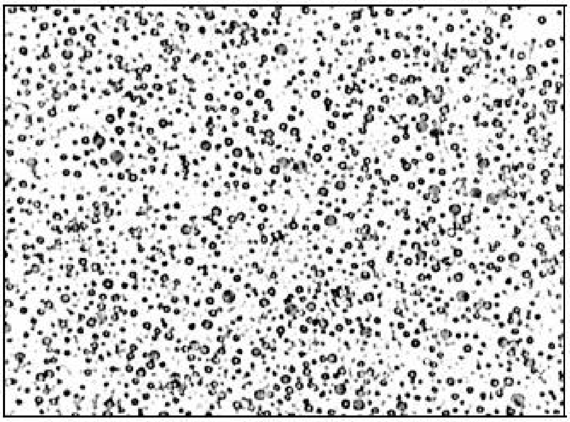


Figure 11. Image of emulsion state after deformation by high shear

To exploit this new fluid technology a minimum shear threshold must be achieved to initiate the chemical reaction between the two reactive species. Upon exposing the SSPF to a pressure drop greater than 400 psi across a small orifice, the ‘loose’ invert emulsion undergoes very rapid deformation. The high shear forces experienced as the emulsion is displaced through the drill bit triggers a rupture in the interfacial membrane of the emulsion, causing the emulsion to flip to a more stable direct state (oil-in-water). The emulsion inversion at this point releases the crosslinker into the now water continuous phase initiating the crosslinking reaction. Between 30 seconds to 30 minutes after this trigger event the fluid crosslinks into a rigid gel structure. The rapid setting of the crosslinked gel makes the setting time virtually temperature-independent. The shear-sensitivity is controlled by the concentration of emulsifier in the emulsion. Only a narrow range of emulsifier concentrations can be used in the design and application of an SSPF. If too much emulsifier is used, the SSPF is less shear sensitive, i.e. more stable to the shear forces at the drill bit nozzles. Consequently, it does not invert and no crosslinked gel structure is created. Conversely, if too little emulsifier is used, the SSPF is highly shear sensitive and may exhibit strong and rigid gel properties immediately after exiting the drill bit nozzles.

Consequently it may set before penetrating the loss zone.

The SSPF is a cement free, low solids fluid which has a rheology similar to many drilling fluids. Therefore it flows easily into the areas of high permeability (loss zones). The flipped emulsion quickly penetrates into the loss zone before demonstrating any properties of gelation. After the designated set time for the gel it is expected that the gel will have sealed the loss zone enabling normal drilling to continue. As a lost circulation treatment, this type of fluid offers Drilling operators many advantage [11]:

- No trips are required.
- Can be pumped through any BHA configuration.
- Can be stored for several weeks without reacting.
- Compatible with all known mud systems.
- Gelation is fast and temperature-independent.
- Gelation is triggered only after passing through the BHA.
- Requires no spacers.
- Weighting agents can be added.
- Tools can easily be pulled through the set gel.

V. PARTICLE SIZE SELECTION METHODS

The current bridging theories and their selection criteria (Table 1) were developed to optimize PSD for drill-in fluids based on the pore size distribution, which can be estimated from thin section analysis, scanning electron microscopy, mercury injection, or derived from permeability measurements (Dick, 2000; He and Stephens, 2011). The particle size distribution (PSD) of LCMs used depends on the permeability, pore size, fracture width of the loss zones. D_X implies X% of the PSD is less than a certain diameter size. The D_{50} is the primary PSD used to select LCMs used for bridging and sealing pores or fractures. Models that are available to select the optimum PSD in order to effectively form a bridge that will plug fractures and stop losses are presented:

5.1 Abrams' Median Particle-Size Rule (Abram 1977)

According to Abram, the median particle size of the bridging material has to be equal or slightly greater than 1/3 the median pore size/fracture size (λ) of the formation. $D(50) = \lambda/3$. This rule addresses the size of particle to initiate a bridge. It is important to note that the rule does not give an optimum size for ideal packing sequence for minimizing fluid invasion and optimizing sealing.

5.2 Ideal Packing Theory (IPT) (Dick 2000)

The IPT addresses either pore sizing from thin section analysis or permeability information, combined with particle size distribution of bridging material, to determine ideal packing sequence. The D90 value of the PSD should be equal to the fracture opening size.

5.3 The Vickers Method (Vickers 2006)

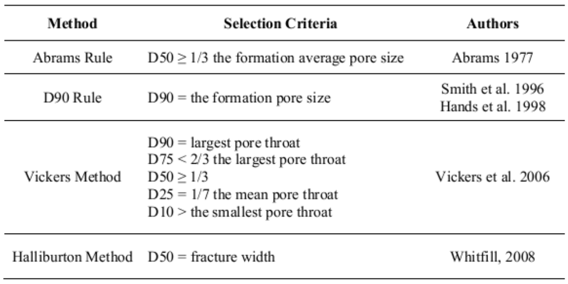
This method tries to exceed the bridging efficiency gained in IPT. It was decided to match target fractions. For minimal fluid loss in the reservoir, the following criteria should be met:

D(90) = largest pore throat
D(75) < 2/3 of largest pore throat
D(50) +/- 1/3 of the mean pore throat
D(25) 1/7 of the mean pore throat D(10) > smallest pore throat.

5.4 Halliburton Method (Whitfill 2008)

The D(50) of the PSD is set equal to the estimated fracture width to offset uncertainty in the estimation. In that situation, enough particles smaller and larger than the fracture are present to plug smaller and larger fracture width [12, 13].

Table1. Particle size selection methods



Method	Selection Criteria	Authors
Abrams Rule	D50 ≥ 1/3 the formation average pore size	Abrams 1977
D90 Rule	D90 = the formation pore size	Smith et al. 1996 Hands et al. 1998
Vickers Method	D90 = largest pore throat D75 < 2/3 the largest pore throat D50 ≥ 1/3 D25 = 1/7 the mean pore throat D10 > the smallest pore throat	Vickers et al. 2006
Halliburton Method	D50 = fracture width	Whitfill, 2008

VI. FORMATION DAMAGE

Loss of circulation into the productive zones is highly damaging. When invasion of the pay zones occurs, fluid-fluid and fluid- rock interactions are caused. These interactions are due to the invasion of mud filtrate, mud solids and in some cases, whole mud to the porous media. Solid invasion to the porous media can be classified into three main types: surface bridging, shallow plugging, and deep invasion. During the migration of fine solids through the rock, they begin to accumulate in the pore throats, forming an internal cake that irreversibly blocks the hydraulic flow channels. To avoid this internal blocking, it is necessary to create a surface mud cake in the pore in the near wellbore [14].

CONCLUSIONS

The objectives of this study were reviewing lost circulation control materials and methods that have been applied in the drilling industry. The following conclusions can be drawn:

- Loss of circulation into the productive zones is highly damaging. To prevent lost circulation, the choice of best drilling practices, drilling fluid selection and wellbore strengthening materials are vital.

- There are no guaranteed methods for solving lost circulation problems entirely but a lot of approaches can be used to prevent its occurrence, especially those that occur via induced fractures when drilling formations that are prone to losses.
- Determining the type of formations has a very important influence on the selection of lost circulation materials. The most difficult formation to controlling lost circulation are Cavernous Formations
- The type of loss zone can be identified by looking at the mud level drop in pits. Mud loss through pores, the amount of loss occurring increases slowly as the flow of drilling mud increases and for natural fractures there is a rapid initial loss of mud that declines with time.
- Particle size distribution in controlling lost circulation is important. The larger particles first forming a bridge across or within the void and smaller particles bridging the openings between larger ones.
- The ideal packing theory is more successful than other theories in the guidance of the particle size distribution selection for sealing the pore throats.
- Successful control or treatment of lost circulation depends on several factors such as borehole temperature, pressure, depth, and size of the thief zone.

REFERENCES

[1] Pilehvari, A. A., and Nyshadham, V. R., 2002. "Effect of material type and size distribution on performance of loss/seepage control material", International Symposium and Exhibition on Formation Damage Control, Society of Petroleum Engineers.

[2] Canson, B. E. “Lost Circulation Treatments for Naturally Fractured, Vugular, or Cavernous Formations”, paper SPE/IADC 13440 presented at the 1985 SPE/IADC Drilling Conference held in New Orleans, Louisiana, 6-8 March.

[3] Datwani, A., 2012. "Review of Lost Circulation Mechanisms". Society of Petroleum Engineers.

[4] Majidi, R., Miska, S., and Zhang, J., 2011. "Fingerprint of mud losses into natural and induced fractures", SPE European Formation Damage Conference, Society of Petroleum Engineers.

[5] Dyke, C., Wu, B., and Milton-Tayler, D., 1995, "Advances in characterizing natural fracture permeability from mud log data". SPE Formation Evaluation, 10(03): p. 160-166.

[6] Whitfill, D., 2008. "Lost circulation material selection, particle size distribution and fracture modeling with fracture simulation software", IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Society of Petroleum Engineers.

[7] Sanders, M.W., Scorsone, J.T., and Friedheim, J.E., 2010. "High-fluid-loss, high-strength lost circulation treatments", SPE Deepwater Drilling and Completions Conference, Society of Petroleum Engineers.

[8] Harrison, T.-F., 2011. "Practical Approaches for Solving Lost Circulation Problems while Drilling".

[9] Fuller, G.A., Serio, M.C., Trahan, J., and Langlinais, J.C., 2010. "A Novel Approach to the Control of Whole-Mud Losses While Encountering Productive Formations", SPE International Symposium and Exhibiton on Formation Damage Control, Society of Petroleum Engineers.

[10] Uddin, S., Dolan, J.D., Chona, R.A., Gazi, N.H., Monteiro, K., Al-Rubaiyea, J.A., and AlSharqawi, A., 2003. "Lessons Learned from the First Openhole Horizontal Well Water Shutoff Job Using Two New Polymer Systems-A Case History from Wafra Ratawi Field, Kuwait", Middle East Oil Show, Society of Petroleum Engineers.

[11] Quinn, D., Sunde, E., and Baret, J., 1999, "Mechanism of a novel shear-sensitive plugging fluid to cure lost circulation", SPE international symposium on oilfield chemistry.

[12] Abrams, A., 1977, "Mud design to minimize rock impairment due to particle invasion". Journal of petroleum technology, 29 (05), pp. 586-592.

[13] Dick, M., Heinz, T., Svoboda, C. and Aston, M., 2000, "Optimizing the selection of bridging particles for reservoir drilling fluids", SPE International Symposium on Formation Damage Control, Society of Petroleum Engineers.

[14] Restrepo, A., Osorio, G., Duarte, J. E., Lopera Castro, S. H. and Hernandez, J., 2010, "LCM Plugging Effect on Producing Formations During Drilling Naturally Fractured Sandston Reservoirs". SPE International Symposium and Exhibiton on Formation Damage Control, Society of Petroleum Engineers.

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