PRACTICAL APPROACHES FOR SOLVING LOST CIRCULATION PROBLEMS WHILE DRILLING

A THESIS
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PRACTICAL APPROACHES FOR SOLVING LOST CIRCULATION PROBLEMS WHILE DRILLING

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ABSTRACT

As the demand for petroleum resources increases, drilling of oil and gas wells are often carried out in challenging and hostile environments. Among the top ten drilling challenges facing the oil and gas industry today is the problem of lost circulation. Major progress has been made to understand this problem and how to combat it. However, most of the products and guidelines available for combating lost circulation are often biased towards advertisement for a particular service company. The purpose of this study is to develop practical guidelines that are general and not biased towards a particular service company product and which will also serve as a quick reference guide for lost circulation prevention and control at the well-site for drilling personnel.

DEDICATION

This work is dedicated to God for being my strength through all my challenging moments in Graduate School. To my mum, for giving me a different meaning to life. Finally, to my beloved sisters, Hilda and Rhodaline, for their encouragement and support.

AKNOWLEDGEMENTS

I would like to express my appreciation to Prof. Samuel Osisanya, my supervisor, for his immense contribution to the success of this work. When I approached him to work with him, he wholeheartedly accepted me despite his busy schedules; Dr. Sam, am very grateful for your time.

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CHAPTER 1

FORMULATION OF PROBLEM

1.1 INTRODUCTION

Lost circulation is a common drilling problem especially in highly permeable formations, depleted reservoirs, and fractured or cavernous formations. The range of lost circulation problems begin in the shallow, unconsolidated formations and extend into the well-consolidated formations that are fractured by the hydrostatic head imposed by the drilling mud (Moore, 1986). It can then be defined as the reduced or total absence of fluid flow up the formation-casing or casing-tubing annulus when fluid is pumped down the drill pipe or casing. 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: 1) the pressure in the well bore must exceed the pore pressure and 2) there must be a flow pathway for the losses to occur (Osisanya, 2011). Sub-surface pathways that cause, or lead to, lost circulation can be broadly classified as follows:

- Induced or created fractures (fast tripping or underground blow-outs)
- Cavernous formations (crevices and channels)
- Unconsolidated or highly permeable formations
- Natural fractures present in the rock formations (including non-sealing faults)

The rate of losses is indicative of the lost pathways and can also give the treatment method to be used to combat the losses. The severity of lost circulation can be grouped into the following categories (Abbas et al. 2004):

- 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

Circulation may be lost even when fluid densities are within the customary safety-margin; less dense than the fracture density of the formation. Stopping circulation losses before they get out of control is crucial for safe and economically rewarding operations (Abbas et al. 2004). According to Ivan and Bruton (2003), “Deepwater drilling has brought loss circulation control to a more critical level as it involves narrow pore-pressure/fracture-gradient windows, cold drilling fluid temperatures, high equivalent circulating densities (ECDs), high cost-per-barrel of synthetic-based fluids (SBM) and a high cost for rig time/non-productive time (NPT).” The reduction of the fracture pressure gradient in the deeper water is mainly due to the low stress regime as a result of the reduction in the overburden pressure gradient. Also, drilling through sub-salt zones poses a challenge to the operator because of the problem of lost circulation encountered in these zones. These wells have shear zones above and below the salt formations and also narrow margins between the pore and fracture pressure and hence these wells tend to register severe losses in circulation.

1.2 LITERATURE REVIEW

Lost circulation is a broad subject and several studies and measures have been introduced in the industry to combat it. For example, Moore, (1986) noted that in shallow, unconsolidated formations where the drilling fluid may flow easily into the formation, the most common method used to combat lost circulation is to thicken the mud. This may be done in fresh water muds by adding flocculating agents such as lime or cement. He also stated that in areas such as below surface casing in normal-pressure formations where natural fractures are common, the most common method used to combat lost circulation is to drill without fluid returns to the surface. The purpose is to remove the generated cuttings from the hole and deposit them at the lost circulation zone. However, this practice requires large volumes of water and close supervision as there is the possibility of encountering high drill-string torque and drag.

Current research on lost circulation has been focused on the use of Lost Circulation Materials (LCMs), especially chemical formulations which have been proven to be more effective. Hamburger et al. (1983) of Exxon Production Research Company developed a Shear-thickening Fluid (STF) which was tested successfully in 10 different wells that experienced severe lost circulation. A STF is a multi-component system composed of water-swellable material (usually clay) dispersed in an oil-external emulsion. The emulsion consists of liquid oil, an oil-soluble surfactant, and aqueous-phase droplets containing dissolved polymer. At the low shear rates encountered while it is being pumped down the drill pipe, the fluid is a low-viscosity, pumpable liquid. Yet as it passes through the drill-bit nozzles, the resulting high shear rates cause the fluid to thicken irreversibly into a high strength viscous paste.

Nayberg, (1987) conducted laboratory tests that compared the performance of conventional LCMs (granules, flakes and fibers) with a new high-performance material which is composed of thermoset rubber in controlling mud loss in simulated fractured formations using both water-based and oil-based muds. From field applications, he found out that the use of thermoset rubber was very effective in controlling severe mud losses in fractured formations. Also, Gockel et al. (1987) of Agri-Systems of Texas Inc. conducted a research on the use of Expanded Aggregates (EAs) as opposed to the use of convention LCMs. AEs are vitrified mineral-based materials that are made from several types of clay-bearing soils. The results obtained from six different field applications showed that AEs were efficient in solving several lost return problems as compared to conventional LCMs because they have high compressive strengths, do not change mud rheological properties, and have rapid lost return resolution properties. Vidick et al. (1988) also conducted a research into the use of internally activated silicate solution. Laboratory tests indicated that this solution has a low viscosity initially but after some time which depends on its design and temperature, its viscosity increases rapidly to form a gel. This gel is coherent, strong, and does not produce free water as a function of time. A high pressure experimental set up was used to plug cores of different permeabilities and different saturation fluids. They found out that the gel formed by this solution could withstand differential pressures greater than 1500 psi per foot of plugged formation.

Other researchers have worked on the use of specially formulated squeeze materials (reactive pills) as LCMs. Sweatman et al. (1997) studied the use of lost circulation material squeeze systems (LCMSS). These LCM squeeze systems were applied in wells after conventional materials/methods failed and they successfully cured the losses. Data from field trials indicated that losses were cured in wells having temperatures ranging from below 80 to over 325 ^{o}F, highly vugular or channel zones, weak zones that are easily fractured by oil-based and water-based drilling muds and other extreme conditions. Bruton et al. (2001) conducted studies on Chemically Activated Cross-linked Pills (CACP). These pills are activated by cross-linking agents, time and borehole temperature. When set, they produce a substance described as rubbery, spongy, and ductile. The setting time is fully controllable by using either a retarder or an activator based upon the thief formation or bottom hole temperature. However, laboratory tests and field trials suggest that these pills are not biologically or chemically degradable and hence they must be used with caution near pay zones.

Sweatman et al. (1999) also studied the use of mud-reactive-chemical-squeeze (MRCS) system and process, in especially subsalt zones, to cure losses. They observed that in 1996, during a problematic subsalt drilling operation in the Gulf of Mexico, the MRCS system and process successfully halted severe mud losses that, combined with a high pressure water influx, equalled 1200 bbl/hr. They noted that one reason this technology is successful in the subsalt zone is that the solidification of the mud and MRCS system downhole is accelerated before the mixture enters the thief zone. In addition, this system does not bridge the hole above the thief zone. Depending on the mud type, the solidification reaction is designed to occur after 10 seconds or after 5 to 7 minutes.

Suyan et al. (2007) researched the use of a novel sealant system consisting of an elastomer combined with cross-linking polymers, activator and bridging agents which provided a quick and a reliable control of loss returns. Initial low viscosity of this sealant allows it to be placed in the loss zone and then gel activated near the wellbore to set and form a stiff, rubbery gel stick with formation sediments to prevent further losses. The composition can be engineered to produce durable cross-linked polymeric gel across a wide range of densities (8.6 – 14 ppg) and temperatures (45 – 120 ^{0}C). Addition of accelerators or retarders during mixing controls setting time and eliminates premature setting inside the drill string while pumping. Another novel work was done by Darugar et al. (2011) where they researched into the use of single-sack fibrous pills as LCMs. This one-sack product does not require activators, retarders, set time calculations or temperature activation. It has been specifically designed for rapid mixing and pumping with minimal equipment. Laboratory studies have demonstrated the ability of the fibrous pill slurries to rapidly de-water/de-oil and form a sealing plug on both ceramic filter discs and slotted metal discs. Testing also shows that the product forms a sealing plug in depleted sand formations. The product is suitable, and has also been tested with a wide range of fluids including freshwater, brine, and base oils.

The use of cement as LCM has also become a common practice while drilling and many researches have investigated its use. Cement could provide a permanent cure for the problem and is irreversible in many cases. Therefore, it is generally applied to non-producing zones (surface drilling), in which mud loss is extremely severe, as a quick but permanent solution (Fidan et al. 2004). Vinson et al. (1992) did a study on the use of acid removable cement to stop losses in producing zones. This cement has been formulated to have moderate thixotropic properties, but with sufficiently small particle size and low rheologies to penetrate near-wellbore fractures and voids. The synthetic cement is readily mixed using conventional oilfield cementing equipment. It has been field tested in producing zones where losses occurred with success. Samsuri and Phuong, (2002) also designed a special cement formulation which is composed of 9 % local bentonite, 2 % calcium chloride, and 0.5 % sugar cane fiber with adequate shear bonding strength and formation permeability reduction of about 10 %. From their experimental work, they came out with the following: cement slurry suitable for controlling lost circulation must have light density, minimum free water and fluid loss content, compressive and bonding strengths must be enough to support casing, and shorter thickening time.

A recent work by Metcalf et al. (2011) in which they investigated the successful application of a new environmentally-friendly natural polymer to control lost returns during drilling and primary cementing operations in the Permian Basin of West Texas is also worth noting. This polymer consists of 30 pounds per barrel of conventional LCMs, a natural polymer, and silicate particles. They presented instances where this material was used to cure partial to total losses in more than 100 wells during drilling and primary cementing operations after other loss return control materials/methods have failed.

In summary, successful control or treatment of lost circulation while drilling depends on several factors such as borehole temperature, pressure, depth, and size of the thief zone.

The purpose of this study is to evaluate new methods being used in combating lost circulation in the drilling industry and develop practical guidelines that will serve as a reference material for lost circulation control at the well-site for drilling personnel.

1.3 RESEARCH OBJECTIVES

The objectives of this study are as follows:

- To review lost circulation control methods that have been applied in the drilling industry till date.
- To provide the successes and the failures of the methods presented above in field applications.
- To develop practical guidelines that will serve as a reference material for lost circulation control at the well-site for drilling personnel.

1.4 RESEARCH METHODOLOGY

The objectives of this study will be achieved through the following methods:

- Read various technical journals, papers and textbooks that talk on the subject of lost circulation control over the years in the drilling industry.
- Summarize these technical materials based on the various lost circulation control methods used over time, their success stories, and their failures in various field applications.
- Develop practical guidelines based on the above methods.

1.5 ORGANIZATION OF THESIS

This thesis is organized into five chapters. Chapter one focuses on formulation of the problem. Chapter two addresses the theoretical background to lost circulation control. Chapter three focuses on the review of lost circulation control materials/methods that have been applied in the drilling industry till date and their successes and failures in field applications. Chapter four involves the development of practical guidelines to solve lost circulation problems during drilling operations. Chapter five addresses summary, conclusions, and recommendations of the thesis.

CHAPTER 2

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 (Whitfill, 2008). 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. This chapter sheds light on the physics and chemistry of some of the lost circulation control approaches.

2.1 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 (Fidan et al. 2004). Previous studies have demonstrated that some products work better than others as lost circulation materials (Sanders et al. 2010). LCMs are categorized into common groups along their physical and chemical characteristics. These groups are as follows (Onyekwere, 2002):

- 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

2.1.1 *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. 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. 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 (Pilehvari and Nyshadham, 2002).

2.1.2 *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: 1) DiaSeal M (diatomaceous earth) and 2) Attapulgite/Calcium Carbonate (Onyekwere, 2002).

2.1.3 *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 (Pilehvari and Nyshadham, 2002):

- 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.

There are, however, 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.

2.1.4 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 ideal is to pump a calcium chloride pill followed by the silicate of latex slurry. When these two slurries mix in the open hole, hopefully adjacent to the loss zone, they form a viscous plug which can slow and seal many loss zones (Onyekwere, 2002).

2.1.5 Chemically Activated Cross-linked Pills (CACP)

Cross-linking is the linking of two independent polymer chains by a grouping (cross-linking agents) that spans or links two chains. (Bruton et al. 2001). 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.

2.1.6 Cement Slurries

Special cement formulations like magnesium-based cements and thixotropic cements are more common (Onyekwere, 2002). 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 (Suyan et al. 2007). 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 (Fuller et al. 2010).

2.1.7 Dilatant Slurries

These LCMs are composed of specifically sized solids and polymers that are both water soluble and insoluble (Onyekwere, 2002). An example is a Shear-thickening Fluid (STF) which was developed by Exxon Production Research Company in 1983 (Hamburger et al. 1983). 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.

In summary, the theories and observations raised from years of experience fighting lost circulation can be boiled down to five pertinent points (Bruton et al. 2001):

- A lost circulation material should be equally effective in sealing unconsolidated formations and fractures or vugs in hard formations.
- It should form an effective seal under both low and high differential pressure conditions.
- Final plug shear strength should be high enough to support fluid column, but low enough to ensure removal by washing or jetting (low side-track risk).
- The plugging seal has to withstand both negative (swab) and positive (surge) pressures applied during drilling, drill pipe trips, and casing runs.
- It should have workable/controllable set time and should be functional in oil, synthetic or water based mud systems.

2.2 BOREHOLE STABILITY ANALYSIS

To effectively prevent and cure losses resulting from borehole stability issues, it is important to understand the fundamental principles of this process.

2.2.1 Fractures and Fracture Identification

Lost circulation in fractured formations is one of the biggest drilling problems. Drilling fluid losses to a formation can be through a fracture which has been induced through drilling operations or a pre-existing natural fracture. If pre-existing, the fracture may be permanently open in which case losses to the formation may occur at mud pressures only in excess of the formation pressure. Induced fractures occur when the mud weight, required for well control and to maintain a stable wellbore, exceeds the fracture resistance pressure of the formation (Majidi et al. 2011). Identification of the type of fracture responsible for the losses is an important step in combating the lost returns problem. Figures 2.1 and 2.2 are examples of natural and induced fractures respectively.

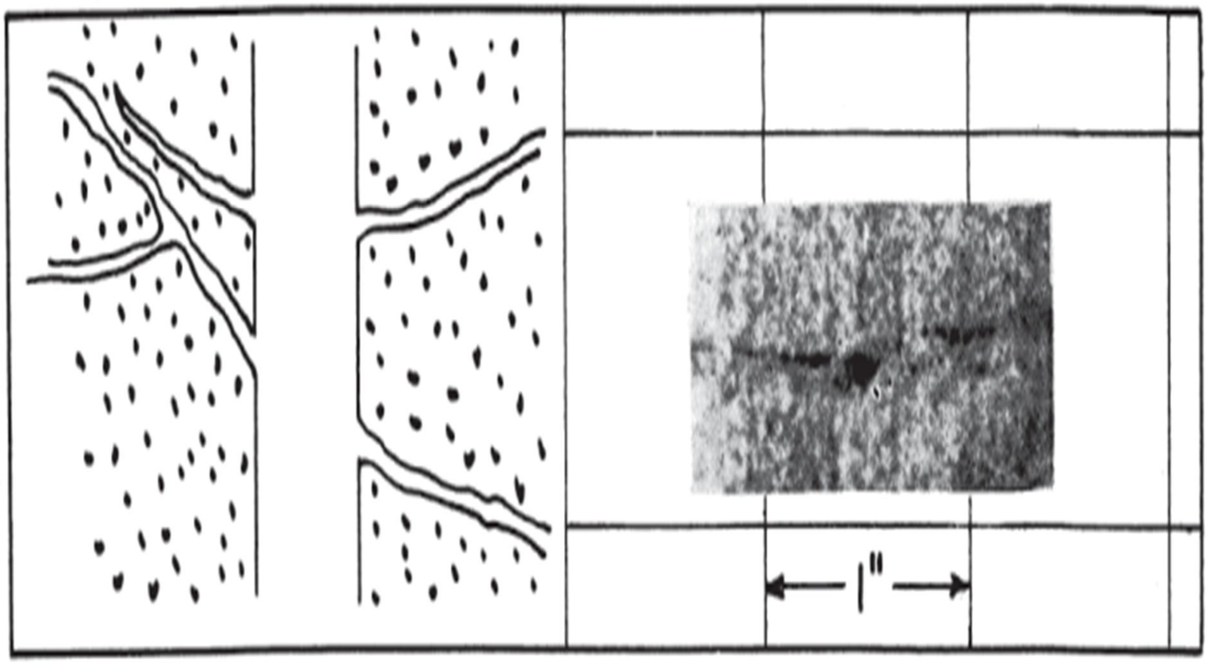

Fig. 2.1 – Natural or Intrinsic Fractures (After Howard and Scott, 1951).

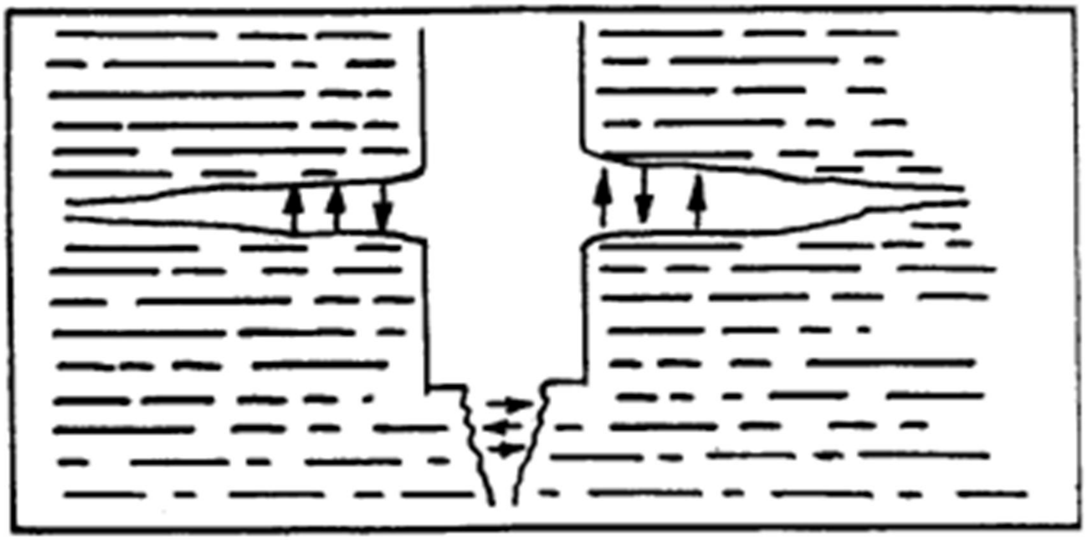

Fig 2.2 – Induced Fractures (After Howard and Scott, 1951).

Acoustic, electrical, and optical wellbore images provide means of detecting and distinguishing natural fractures from induced fractures. The direct measurement of mud loss flow rates and the downhole annular pressure while drilling (APWD) can also be used as an indication of a fracture as well as the type of fracture (Majidi et al 2011). High resolution flow-meters can accurately measure the rate of fluid flow into and out of the wellbore. The characteristic response of the rate of losses can be used to interpret the fracture characteristics. A useful technique for identifying the type of lost circulating zone is the utilization of plot of variation of mud pit levels. Figure 2.3 shows a qualitative response of mud losses in terms of the mud pit level changes with time.

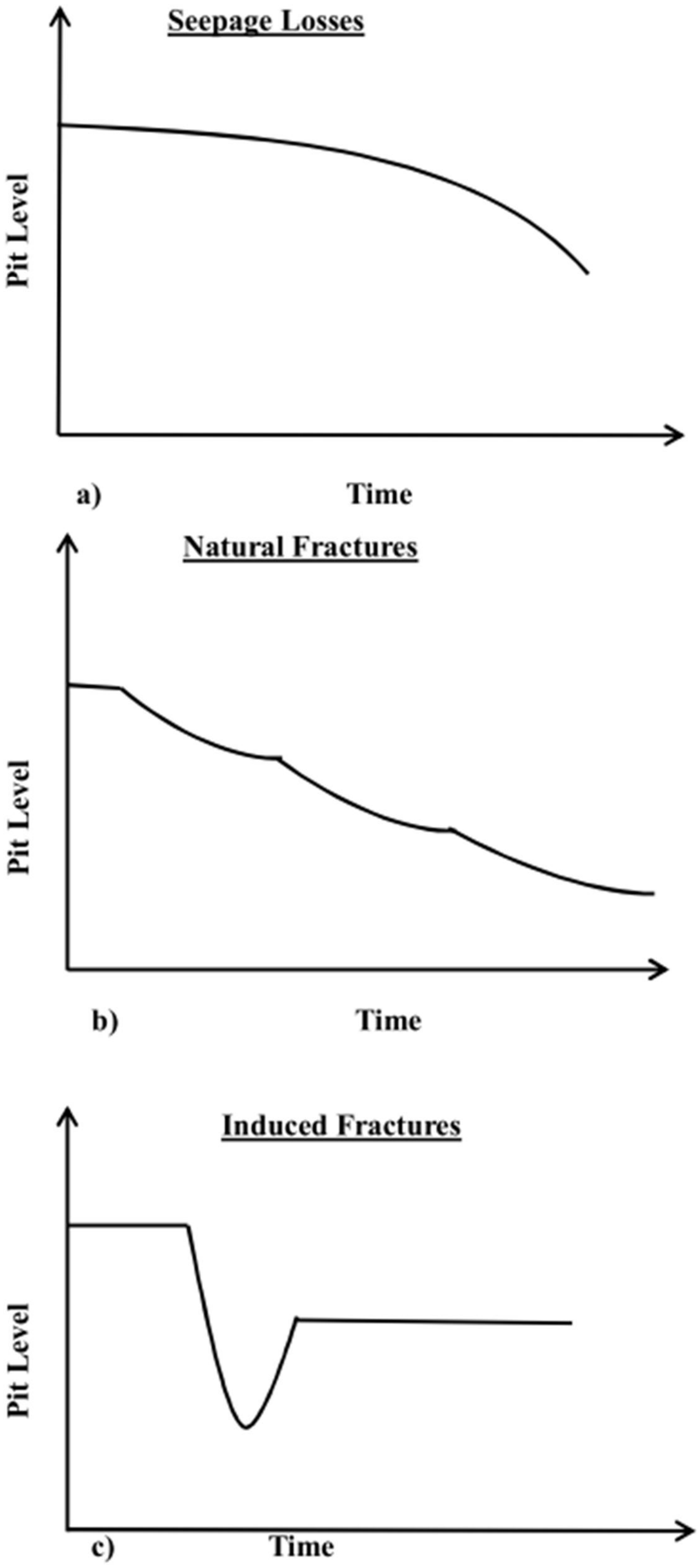

Fig. 2.3 – Losses from Pit Level (After Majidi et al. 2011)

Losses through pores are initially slow and gradually increase whereas losses through natural fractures are rapid initially and then they decline with time. It is important to note that fractures are not the only cause of mud losses during drilling operations and caution must be exercised when evaluation the causes of mud losses. The following causes of fluctuating mud-tank levels during drilling have been provided by Dyke et al. (1995):

- Downhole losses through matrix permeability
- Downhole losses into induced and natural fractures
- Volume change owing to temperature and pressure effects
- Surfaces mud losses
- Hole collapse and enlargement
- Change in bottom hole lithology

Table 2.1 summarizes some important identification features used to distinguish between natural and induced fractures.

Table 2.1 - Identifying Features of Fractures (After Howard and Scott, 1951).

Natural Fractures	Induced Fractures
May occur in any type of formation.	May occur in any type of rock but would be expected in formations with characteristically weak planes such as shale.
Loss is evidenced by gradual lowering of mud in pits. If drilling is continued and more fractures are exposed, complete loss of returns may be experienced.	Loss is usually sudden and accompanied by complete loss of returns. Conditions are conducive to the forming of induced fractures when mud weight exceeds 10.5 ppg.
	Loss may follow any sudden surge in pressure.
	When lost circulation occurs and adjacent wells have not experienced lost circulation, induced fractures should be suspected.

2.2.2 Mechanics of Fracturing

Induced fractures normally occur at the weakest part of formations. The requirements for forming fractures are pressure and surfaces upon which the pressure may act so that the resultant forces are of sufficient magnitude and are exerted in such a manner to part the formations (Howard and Scott, 1951). Depending upon depth, the fractures created will either be vertical or horizontal. If the depth is around 2,500 feet or less, horizontal pancake fractures are usually produced because the vertical stress (overburden) is lower than the horizontal stresses. At depths greater than 3,500 feet, vertical fractures are created because the overburden is higher than the horizontal stresses (Ramirez et al. 2005). Figure 2.4 shows a typical stress distribution in a wellbore.

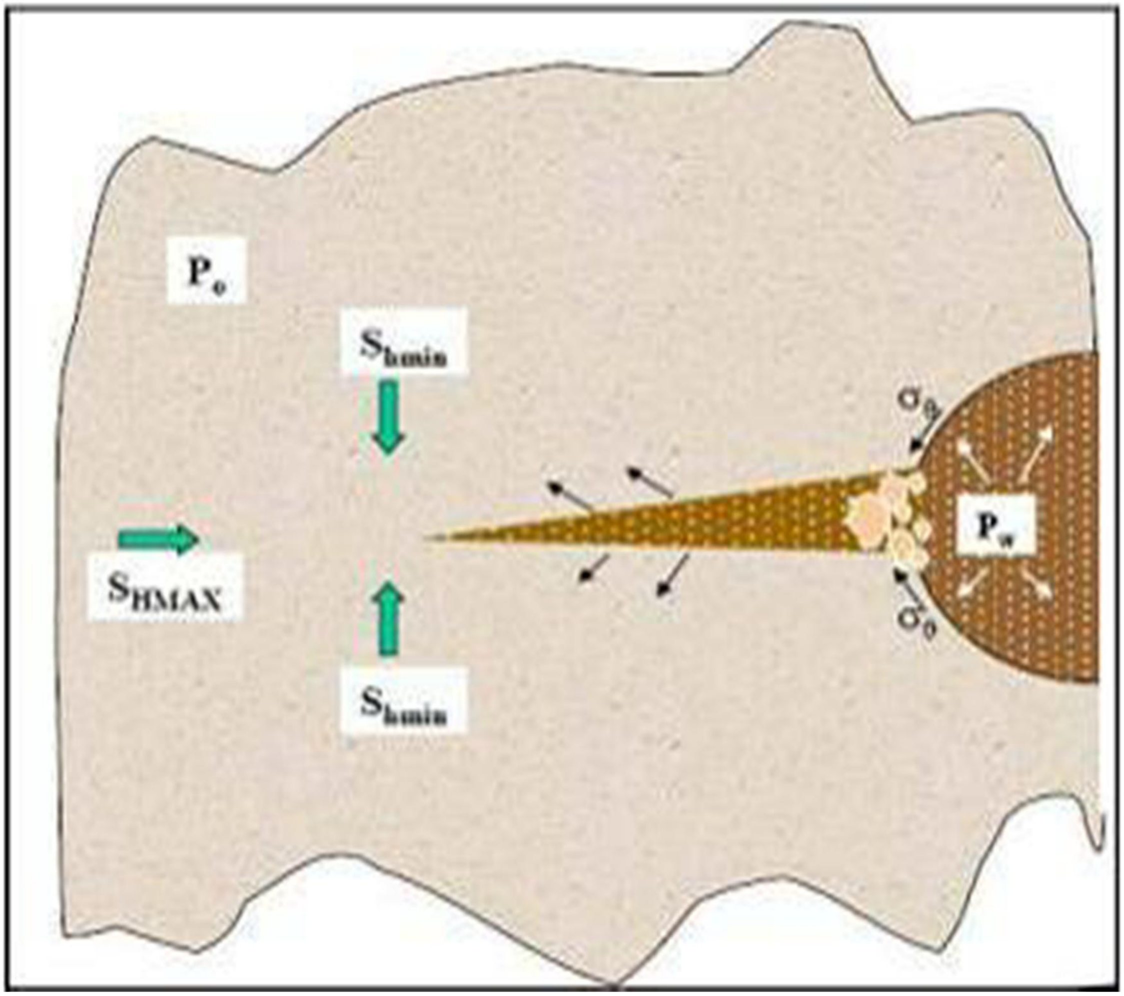

Fig. 2.4 – Stress Distribution in a wellbore (After Kumar et al. 2011)

Where,

P_w = Wellbore Pressure;

P_o = Pore Pressure;

S_{hmin} = Minimum Horizontal Stress;

S_{HMAX} = Maximum Horizontal Stress; and

δ_θ = Effective Tangential (Hoop) Stress

The minimum horizontal stresses are inherent in a particular rock and cannot be altered while the effective tangential stresses are the near wellbore stresses acting on the periphery of the wellbore which are caused by drilling operations.

2.3 MANAGEMENT OF EQUIVALENT CIRCULATION DENSITY (ECD)

Drilling programs are designed to control downhole pressures in order to eliminate high ECDs that lead to induced fractures. The control can be achieved through manipulating mud properties such as density, viscosity, and fluid loss. The ECD is the measure of the combined effect of the hydrostatic pressure of the fluid in the wellbore plus the created friction pressure while the fluid is being circulated (Metcalf et al. 2011):

$$\mathrm{ECD} = \frac{P_{\mathrm{Total}}}{(0.052 \times \mathrm{TVD})} \quad \text{..........} \quad (2.1)$$

Where,

PTotal = Phydrostatic + $P_{friction;}$

P_{Total} = Total Annular Pressure;

$P_{hydrostatic}$ = Hydrostatic Pressure;

$P_{friction}$ = Annular Friction Pressure; and

TVD = True Vertical Depth.

Equivalent Circulating density (ECD) is a function of the following (Fidan et al. 2004):

- Annular space: the smaller the annular area, the greater the ECDs will be.
- Fluid rheology: higher viscosities will increase the ECDs.
- Pump rate: the higher the rate, the higher the ECDs.

Apart from manipulating mud properties to controlling the generation of excessive ECDs, knowledge of the fracture gradient in an area is an important step towards combating lost returns during drilling operations.

The fracture gradient is determined through a leak-off test (LOT). The LOT provides a safe method to determine the amount of pressure (equivalent mud weight) that a wellbore will withstand without fracturing and losing returns (Carlton and Chenevert, 1974). In this test, the borehole immediately behind the casing shoe is pressurized until fluid begins to leak into the formation which means that a fracture has been created. The leak-off pressure (LOP) is the first deviation from a linear pressure-volume curve as shown in Figure 2.5.

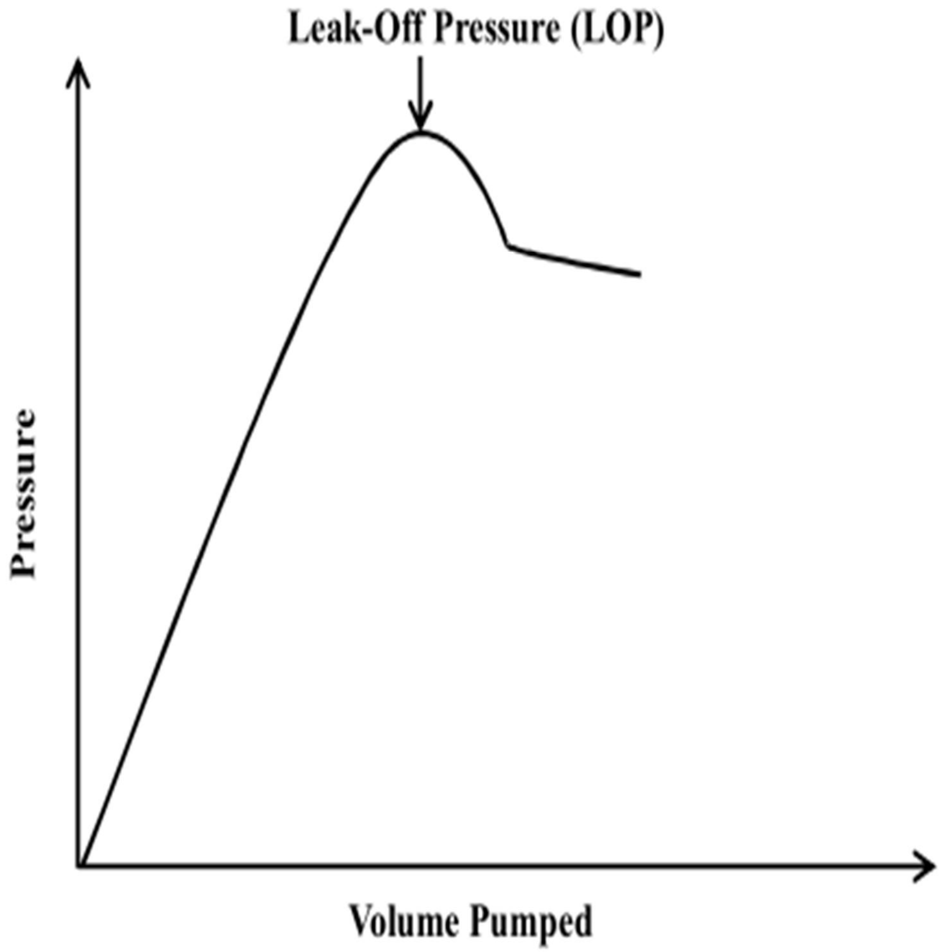

Fig. 2.5 – Leak-Off Test (After Carlton and Chenevert, 1974)

If the local fracture gradient is sufficiently known at a certain casing shoe depth, a simpler formation integrity test (FIT) is often performed instead. FIT is performed by pressurizing the formation to a predetermined pressure without fracturing the formation; this is used to test cement integrity. Combination of LOTs is used to generate local and regional depth trends which are used to predict fracture gradients in other wells. However, the following limitations are associated with using LOTs to generate a fracture gradient curve (Okland et al. 2002):

- Individual tests may be difficult to interpret when no clear or unique deflection/deviation point exists.
- Test data is often recorded manually at a coarse sampling rate, disallowing raw data scrutiny.
- Some bias towards higher interpretations may even be introduced by the drilling team's eagerness to drill ahead.
- Leak-Off Pressures (LOPs) from a group of neighbouring wells are often scattered, giving considerable room for subjective interpretation of local trend.

An extended leak-off test (XLOT) which has striking similarities with the early stages of a lost circulation event can be used to overcome the limitations associated with LOT (Okland et al. 2002). XLOT was designed mainly to measure the minimum in-situ stress (i.e. the fracture closure pressure, FCT). However, it can be used to capture additional fracture events that will serve as a valuable tool in designing drilling programs to combat lost circulation. Some of the additional events captured by XLOT are:

- FIP: Fracture Initiation Pressure
- FRP: Fracture Re-opening Pressure
- FCP: Fracture Closure Pressure
- ISIP: Initial Shut-in Pressure
- FPP: Fracture Propagation Pressure

The decision to perform an XLOT at the casing shoe should take into account both the cost of breaking the near-well barrier and the benefit of knowing what stress and FPP lies behind that barrier. The near-well barrier is the volume of rock whose stress state is affected by the presence of the borehole, usually 1-2 hole diameters into the formation.

Figure 2.6 shows an example of an XLOT from the Norne field in offshore Norway.

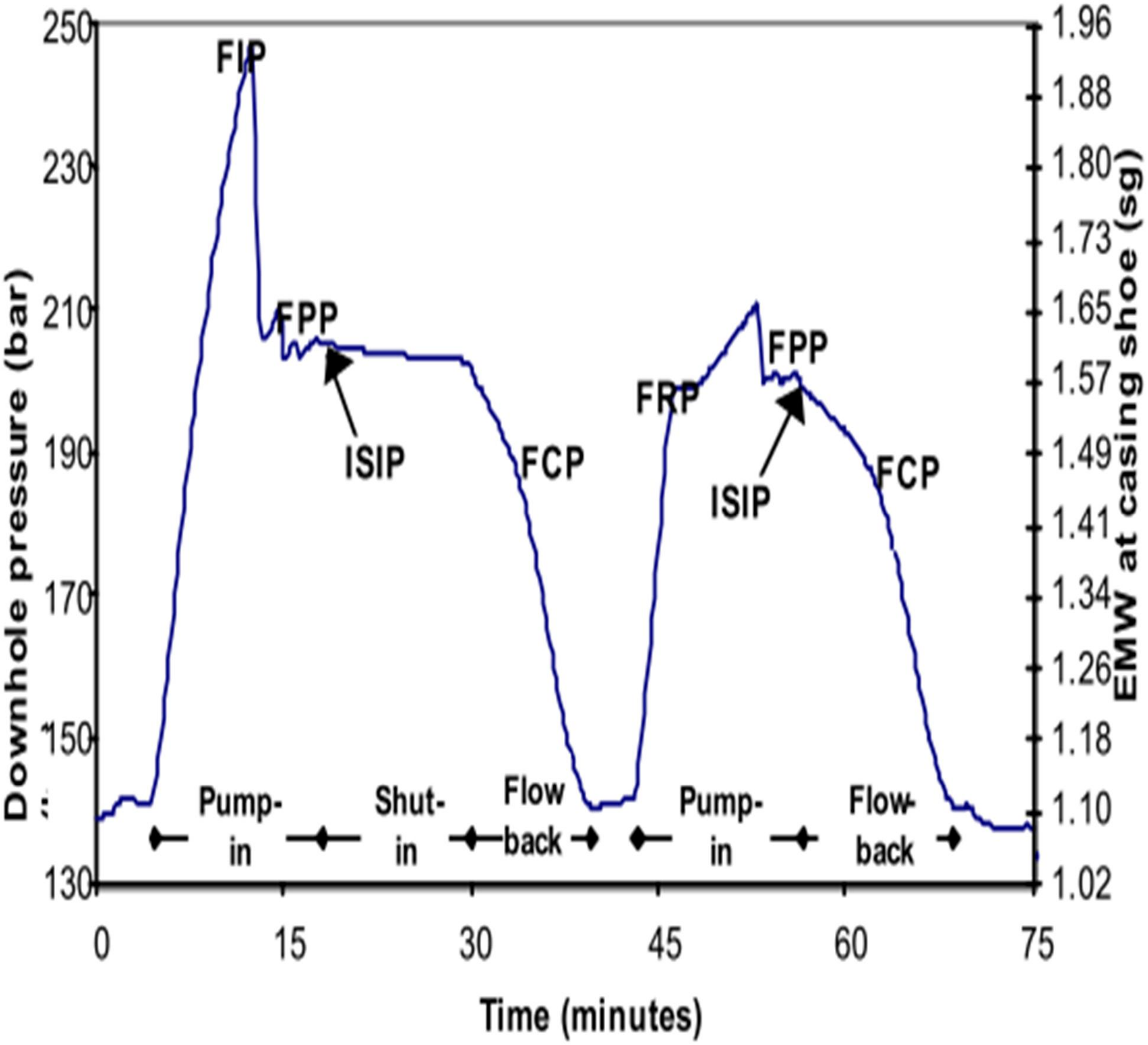

Fig. 2.6 – Extended Leak-off Test (After Okland et al. 2002)

CHAPTER 3

REVIEW OF LOST CIRCULATION CONTROL METHODS/TECHNIQUES

Lost circulation solutions may be applied before or after the occurrence of the problem (Wang et al. 2009). The solutions are therefore grouped into preventive and remedial respectively. This chapter highlights some of the lost circulation control methods/techniques that are used in the petroleum industry.

3.1 USING LOST CIRCULATION MATERIALS (LCMs)

A wide range of bridging or plugging materials is available for reducing lost circulation or restoring circulation while drilling or cementing a well (Nayberg and Petty, 1986). The choice of LCM to use in a given case depends on cost and availability in a given drilling area (Pilehvari and Nyshadham, 2002). LCMs are designed to accomplish two goals (Jiao and Sharma, 1996):

- To bridge across the face of fractures and vugs that already exist.
- To prevent the growth of any fractures that may be induced while drilling.

Lost circulation materials can be broadly classified into the following groups (Suyan et al. 2007; Pilehvari and Nyshadham, 2002):

- Granular: these LCMs form bridges at the formation face and within the formation matrix, thus providing an effective seal which depends on the particle size distribution (PSD).
- Fibrous: these groups of LCMs are used in drilling muds to lessen mud loss in fractures and vugular formations.
- Flakes: flaky types of LCMs are used to plug and bridge many types of porous formations to stop the mud loss or to establish an effective seal over many permeable formations.
- Mixtures: these are combinations of granular, flaky and fibrous materials that will penetrate fractures, vugs, or extremely permeable formations and seal them off effectively.
- Encapsulated fluid-absorbing particles: these are materials that are highly absorbent and form spongy mass in contact with water.

Detailed classification of LCMs has been covered in chapter 2 of this thesis. From a review of various literatures on lost circulation, it can be inferred that a combination of LCMs rather than one is effective in combating losses. Table 3.1 provides some commonly used LCMs.

Table 3.1 – Lost Circulation Materials (After White, 1956).

TYPE	MATERIAL
FIBROUS	Raw cotton, Bagasse, Flax shive, Wood fiber, Bark fiber, Textile fiber, Mineral fiber, Leather, Glass fiber, Peat moss, Feathers, Beet pulp.
GRANULAR	Perlite, Coarse bentonite, Ground plastic, Nut shells, Nut hulls, Ground tires, Asphalt, Wood, Coke.
FLAKE	Cellophane, Cork, Mica, Corn cobs, Cotton-seed hulls, Vermiculite.
MIXTURE	Film, fiber and sawdust; Textile fiber and sawdust; Cellulose fiber and sawdust; Perlite and coarse bentonite.

3.2 WELLBORE STRENGTHENING

Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al. 2005). To address these issues, new lost circulation solutions such as wellbore strengthening has evolved. The process of propping and plugging fractures with LCMs induced in the formation is referred to as wellbore strengthening (Kumar et al. 2010).The overall effect of using wellbore strengthening is to increase the fracture gradient of the formation. This provides an opportunity to use higher mud weight windows for drilling, especially, weaker and depleted formations. Wellbore strengthening methods, generally, rarely target strengthening the rock matrix but are mostly applied to (van Oort et al. 2009):

- Enhance the near-wellbore stress, thus raising the threshold for fracture re-opening and growth.
- Increase the formation's resistance to fracture propagation.

However, there are chemical methods that enhance rock matrix strength in permeable and depleted formations. There are a number of approaches to wellbore strengthening, one of which is the stress cage approach (van Oort et al. 2009). This approach aims at creating an additional hoop stress (a "stress cage") in the near-wellbore region, adding to the already existing hoop stress riser when a wellbore is created. Near-wellbore fractures of specific sizes are deliberated created and packed with specially sized LCMs in a frac-and-pack type of operation. Because of the presence of the packed LCMs, an additional tangential stress (hoop stress) is created in the near-wellbore zone, which raises the threshold for fracturing and fracture propagation. The stress cage approach can be applied while drilling into the weak zone to obtain the strengthening effect instantaneously (Wang et al. 2009). An important step in this approach involves using log analysis to identify fracture location and determine its geometry, especially its width, and then determine a mixture of particulates materials that will seal the calculated fracture width (Song and Rojas, 2006).

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.)

Some of the particulate materials used for wellbore strengthening include sized resilient graphitic carbon and ground marble ($CaCO_3$). Figures 3.1 and 3.2 are show images of these particulate materials.

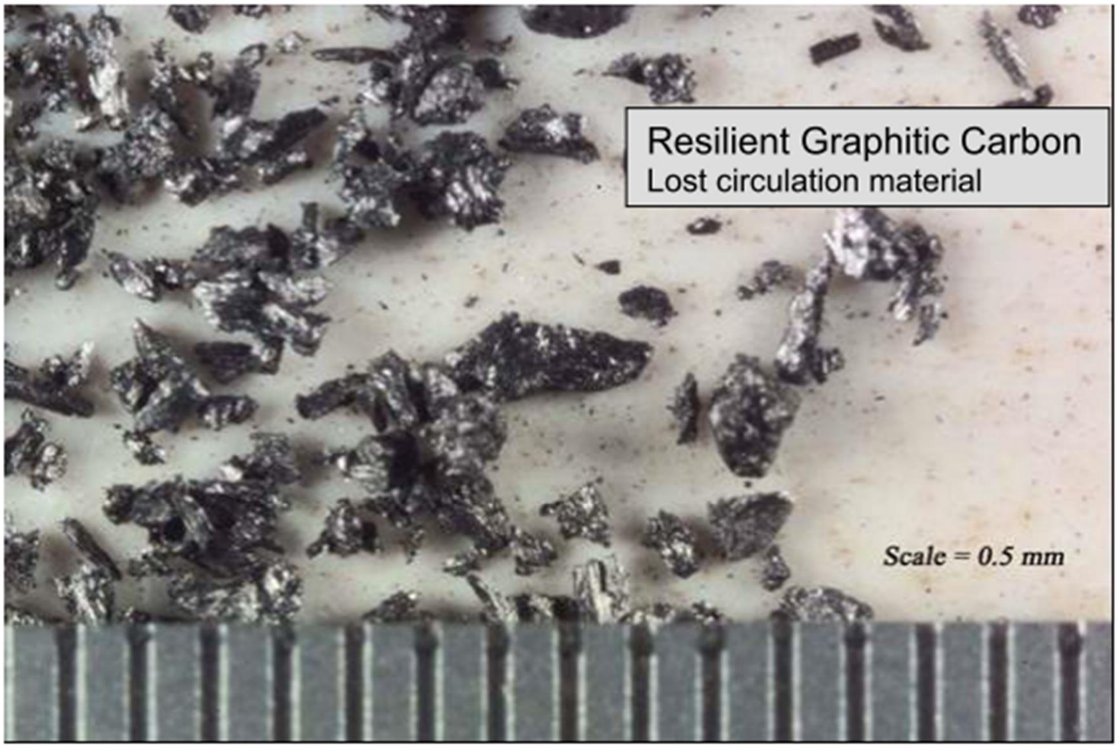

Fig. 3.1 – Particulate LCM for Wellbore Strengthening (After Wang et al. 2009).

Fig. 3.2 – Particulate LCM for Wellbore Strengthening (After Wang et al. 2009).

3.3 USING DRILLING TECHNIQUES/PROCEDURES

The drilling techniques/procedures described in the subsequent paragraphs may be used to prevent or remedy lost circulation problems.

3.3.1 Aerated Mud Drilling

Aerated mud is defined as a fluid (in the form of mists and foams) consisting of liquid (usually water), air, and drill cuttings (Guo and Rajtar, 1995). Aerated muds are low density fluids that can be used to maintain a minimum overbalance while drilling probable loss zones such as depleted formations that are competent and low-pressured. Aerated mud drilling is recognized as having many advantages over conventional mud drilling; such as higher penetration rate, less formation damage, minimized lost circulation, and lower drilling cost. Foams are highly structured fluids of air bubbles contained in a continuous network of liquid films. The structured nature of the fluid and the wide size distribution of the air bubbles means that foams have the ability to bridge a wide range of pore sizes, and even small fractures. However, foams have the following disadvantages (Reid and Santos, 2003):

- Specialized equipment is required to generate them. This may be costly, and in offshore locations, deck space may limit the use of foams.
- Foams are compressible and so lose some or all of their structure (and hence bridging properties) under downhole conditions. Downhole densities and rheology become difficult to predict and control.

To address the limitations of foams, a new class of aerated fluids, known as aphrons, has been developed. The aphron system is an at-balance technique that uses micro bubbles that are non-coalescing and can be re-circulated (Redden et al. 2011). Aphrons are engineered to occur within the drilling fluid without the need to inject air or gas. They exist as independent spheres where a multiple layer film encapsulates a gas or air core. This film is the key to maintaining the bubble strength that allows aphrons to function as bridging agents. A surfactant is used to produce the surface tension to contain the aphron as it is being formed, build the multi-layer bubble wall, and create interfacial tension that binds the aphrons into a network capable of creating downhole bridges.

3.3.2 Floating Mudcap Method

A Floating mudcap is a column of drilling fluid floating on the annulus side of the drillstring to hold back formation fluids/pressure. This method is used only as a final option when massive and total lost circulation has occurred and all attempts to regain circulation have failed. This is because the operation can be very expensive and hazardous. The floating mudcap method involves pumping water down the drillstring to clean, cool, and lubricate the bit. Drilling fluid is added on the annulus side and it is weighted to exert hydrostatic pressure on top of the formation to keep the well under control. The drill water carries the cuttings into the loss zone where it disappears into the formation. The density of the drilling fluid in the annulus must be heavy enough to keep the well under control and must also be light enough to prevent any further losses.

The floating mudcap method is hazardous and requires rigorous safety procedures and only experienced crew to handle it. When the formation pressure equals the hydrostatic pressure of the drilling fluid, the well is in equilibrium. The drill water will exert an additional pressure against the fluid column which will force the drilling fluid back out the top of the column. This reduces the hydrostatic pressure which forces formation fluids to migrate into the annulus. This is a kick and needed to be handled (Redden et al. 2011).

3.3.3 Drilling Blind

When loss zones are too large and difficult to be filled and sealed by lost circulation materials, the recommended approach is to drill blind until competent formations are encountered , after which casing is set (Redden et al. 2011). When drilling blind, it is important to maintain a pumping rate equal or greater than the pumping rate normally used to clean the hole. Otherwise, there is a risk of sticking the drillstring. Therefore, adequate source of water is a necessity when this technique is to be carried out efficiently (Canson, 1985).

3.4 USING ADVANCES IN DRILLING TECHNOLOGY

Developments in new drilling technology such as expandable tubulars and casing-while-drilling (CwD) can serve as long term methods that will mitigate the costly effects of lost circulation while drilling (Davison et al. 2004). Expandable tubulars permit a number of mud weights to be used for different sections without losing hole size due to the telescoping effect of casing.

Casing-while-drilling employs downhole and surface components to provide the ability to use normal oilfield casing as the drillstring so that the well is simultaneously drilled and cased (Tessari et al. 1999). The casing is rotated from the surface with a top drive. Drilling fluid is circulated down the casing internal diameter (ID) and up the annulus between the casing the wellbore. The objective of this technology is to reduce the non-productive time (NPT) and the casing running times where partial and total fluid losses make conventional drilling practices difficult and expensive (Gallardo et al. 2010). Two types of CwD exist: retrievable and non-retrievable systems. The retrieval system uses a drillpipe or wireline to retrieve the bottom hole assembly (BHA) assembly attached to the casing or liner. The non-retrievable system is designed to leave the casing drill shoe (CDS) on bottom if the last section of the well is being drilled to total depth (TD) or is to be drilled afterwards to continue with the following hole sections. Figures 3.3 and 3.4 are pictures of part of the CwD assembly.

Fig. 3.3 – Top Drive and Internal Casing Drive (After Tessari et al. 2006).

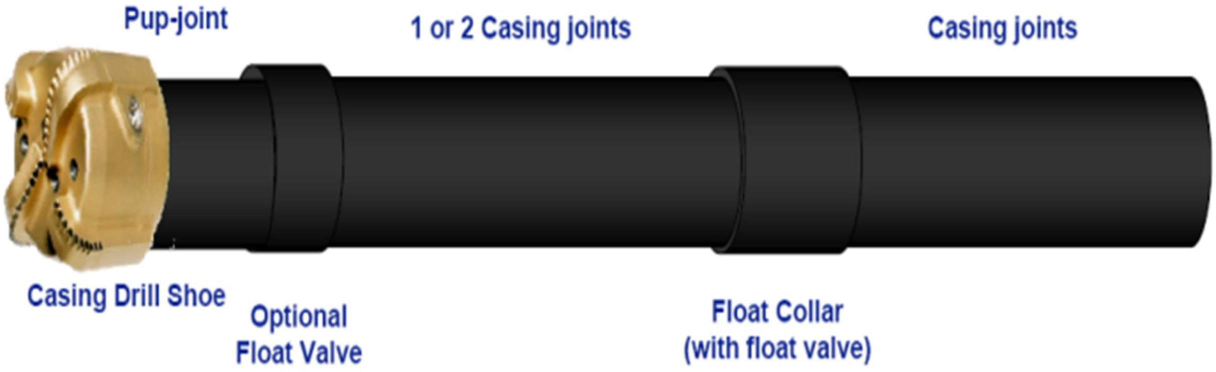

Fig. 3.4 – BHA Components of CwD Assembly (After Gallardo et al. 2010).

CHAPTER 4

PRACTICAL GUIDELINES TO COMBAT LOST CIRCULATION WHILE DRILLING

4.1 GENERAL GUIDELINES

- The drilling program must include contingency plans (additional casing strings, adequate water source etc.) for known problems such as that associated with infill drilling and unknown problems such as those encountered in wildcat drilling.
- The following information is required about the loss zone before an effective treatment could be achieved:

a) The location of the loss interval – preferably the top and bottom.

b) Estimate the pressure within the loss zone.

c) Estimate the size of the openings into the loss zone; use borehole electronic images.

d) Knowledge of whether or not there is cross-flow into the loss zone because of the reduced pressure in the wellbore. Cross-flows into the loss zone can complicate the treatment process.

- A quick economic evaluation should be made of how much investment would go into curing the lost returns problem before a decision is made to case the zone off, or side-track the loss interval or even abandon the project.
- It is important to reduce human error, to a tolerable minimum, as a contributing factor to lost circulation. The following drilling practices were identified as contributing to lost circulation:
- Generation of excessive ECDs caused by high circulation rates (Prevention strategy: Use the lowest circulation rate that will clean the hole adequately).
- Failure to break circulation frequently while tripping (Prevention strategy: Break circulation several times on the way into the hole and rotate the pipe; when on the bottom, break circulation slowly, and raise the pipe while doing so).
- High pipe running speeds (Prevention strategy: Run pipe slowly, and above all, do not ream down rapidly with the pumps on).
- Monitor downhole annular pressure and make sure that the ECD and equivalent static density (ESD) always stay within the safe mud weight window during drilling, connection, and tripping by optimizing mud weight and drilling operations.
- It is advisable to include properly sized LCM in the drilling mud when drilling formations that are prone to losses (depleted formations). This practice can help in preventing seepage

losses and also prevent induced fractures from propagating beyond their initiation stages.

- Graphitic carbon and sized calcium carbonate have proven to be effective primary LCMs if included in the drilling mud in the course of drilling through depleted and weak formations.
- Avoid the use of coarse LCMs that require by-passing the solids control equipment as this will result in fines build up in the mud and increase viscosity and ECD which may induce more losses.
- LCMs come in many different forms; each possesses a specific advantage such as cost, availability and effect or lack of it on drilling fluid properties. However, the performance of a LCM is based primarily on its concentration, particle size distribution (PSD), and shape.
- Size LCMs to restrictions in Bottom Hole Assembly (BHA); consult the manufacturer or Directional Drilling Services Company if necessary.
- When circulations are lost temporally due to pressure surges induced while running casing or because bottom hole pressures are exceeded while breaking circulation after a trip, it is recommended to reduce the solids content or reduce the yield point (YP) value of the drilling mud rather than using LCMs.
- Overall well economics can influence whether to pre-treat the system with LCM or deal with the problem when/if the problem occurs.
- Get ready for well control situations when handling losses.

4.1.1 Locating the Loss Zone

Drilling through a low pressure, naturally fractured formation is normally signalled by a sudden severe loss of returns which is accompanied by a notable increase in drilling torque and relative drilling roughness. This signature is a reliable indication that the loss zone is at the bottom when no previous incident of lost circulation had occurred (Canson, 1985). When drilling through vugs, channels, and caverns, apart from the drilling conditions experienced in low pressure naturally fractured formations, the drill-string can advance to a particular depth unrestricted without taking any weight.

Since rock strength generally increases with depth, the location of an induced fracture is closer to the previous casing shoe than total depth (Ramirez et al. 2005). To accurately locate the loss zone, a temperature survey is employed. Circulation of drilling fluids will alter the static geothermal gradient in a borehole because of the injection of cooler mud (Sweatman et al. 1997).

A base temperature log is run to establish the normal temperature gradient in the well under static conditions. Then a volume of mud (equal to 1000 – 1500 feet of open hole) is pumped into the hole from the surface and a second temperature log is run. The two logs are compared to determine the location of the loss zone. A cooler gradient is observed on the second log from the surface to the point of mud exit into the loss zone. However, below the loss zone, higher temperature gradient should be observed on both logs. Figure 4.1 shows a temperature survey used to locate a loss zone.

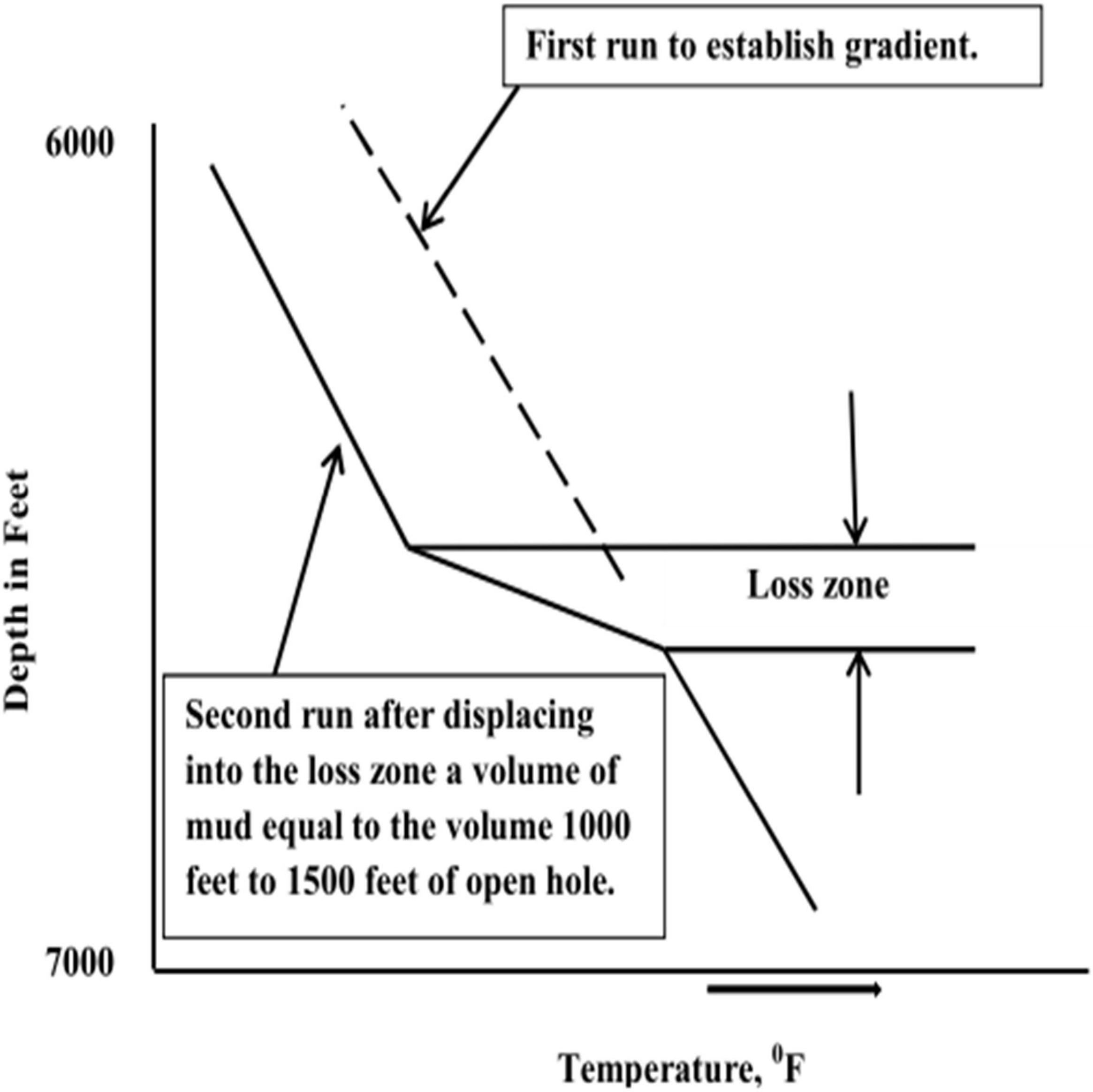

Fig. 4.1 Temperature Survey (After Canson, 1985).

Radioactive logs, noise logs, and mechanical devices (flowmeters) can also be used to locate the loss zone (Canson, 1985). The above methods are useful when the loss zone is off the bottom of the well. When the loss zone is at the bottom of the well, it is advisable to drill through the loss interval until the top and bottom of the loss interval can be established.

4.1.2 Estimating Pressure in the Loss Zone

This information is especially useful when total loss of returns is experienced. Without this information, the control of the flow of treatment material into the loss zone is left to trial and error work, and as such the treatment might not be successful (Canson, 1985). To estimate this pressure, knowledge of the static fluid level in the wellbore is a requirement. A number of methods are available to estimate static fluid level in the well; echometer determinations as well as counting pump strokes to fill the annulus are two of the methods used (Gray and Darley, 1980). Another method used is described below (Ferron et al. 2011):

A one inch diameter ball is formed with soft clay. A stopwatch is started when the ball is released over the wellbore and stopped when the ball hits the static fluid level in the wellbore. It is advisable that the ball does not hit the sides of the wellbore when it is released otherwise it will take a longer time to hit the fluid level. From figure 4.2, tracing the time along the vertical until it hits the curve, the distance to the top of the fluid level in the wellbore can be estimated. From this estimated distance and knowing the depth of the loss zone, the pressure in the loss zone can be estimated using a simple formula:

$$P_{\text{loss zone}} = D_{\text{static fluid column}} \times MW \times 0.052 \quad \text{...(4.1)}$$

Where,

$P_{\text{loss zone}}$ is the pressure in the loss zone (psi);

$D_{\text{static fluid column}}$ is the static fluid column above the loss zone (feet); and

MW is the mud weight (lb/gal).

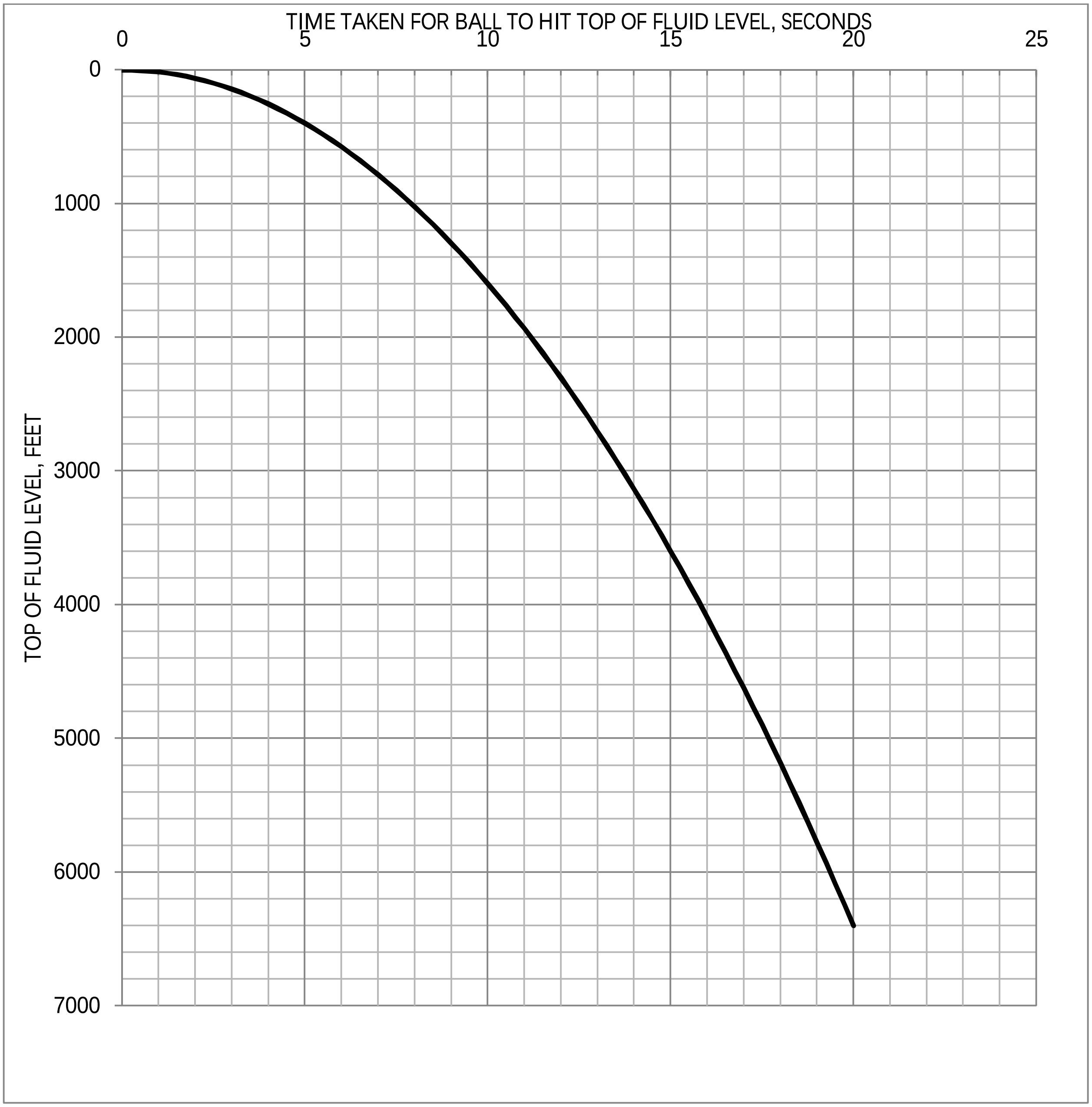

Fig. 4.2 – Approximate Distance to Top of Fluid Level in Wellbore (After Ferron et al. 2011)

4.1.3 How to Detect Cross-flows in the Loss Zone

One of the methods used to detect cross-flows is oxygen activation (Sweatman et al. 2004). Oxygen activation logging tools such as pulse-neutron capture (PNC) or pulse-neutron spectroscopy (PNS) can detect downhole water flows. When oxygen is irradiated with neutrons with energies greater than 10 Mev, the following reaction occurs:

$16\ O + n = 16\ N^{*} + p$ …………………………………………………………………………(4.2)

The nitrogen is left in an excited state which beta-decays back to the oxygen with a 7.35-second half-life. The oxygen immediately emits a gamma ray which the logging tool uses to detect oxygen activation. For water to be detected, its fluid velocity must be greater than the speed of the logging tool.

4.2 SEEPAGE LOSSES

A lost circulation incident can be classified as seepage loss when the rate of loss is in the range of 1-10 bbl/hr. They occur in any type of formation. Seepage loss can be caused by a number of factors resulting from the drilling operations or it may be a perceived loss. For example, drilling through competent formations with fast drilling rates can result in perceived losses when they did not actually exist. Some of the causes of perceived seepage losses are (Ferron et al. 2011):

- Normal displacement of drilling mud with drilled solids; a certain amount of drilling fluid is required to fill the new hole being drilled.
- Drilling fluid retained on drill solids that have been removed from the system; the allowable upper limit is 1 bbl of fluid per 1 bbl of drilled cuttings removed.

Therefore, it is important to analyze the seepage loss based on the above factors before any treatment is commenced. Monitoring the mud level in the mud pit with floating sensors or acoustic reflectors and measuring the cumulative volume of mud lost over a period of time provides a way of differentiating actual losses from perceived losses (Beda and Carugo, 2001). The subsequent paragraphs provide some seepage loss control techniques and guidelines.

4.2.1 Ignore the Problem and Drill Ahead

This technique can be applied depending on the severity of the seepage loss. The technique is in two folds:

- Depending on what stage the drilling operation is and the severity of the seepage loss, the loss may be ignored entirely. That is, when the drilling operation is good and close to a casing setting depth with an in-expensive drilling mud, simple economic analysis may dictate that the loss may be ignored entirely.
- Ignore the problem and drill ahead with the intention that the accumulated solids would seal the loss zone and stop the seepage loss. This technique must be applied with caution as it can lead to other hole problems. For example, the accumulated fine-solids may alter the rheology of the drilling mud and render it ineffective.

4.2.2 Pull up and Wait

This technique can be used to solve seepage losses resulting from induced vertical fractures. While circulating, if the increased pressure due to circulation (ECD) is higher than the fracture initiation pressure of the formation, induced fractures may be created (Tare et al. 2001). These induced fractures open and accept fluid but when circulation is stopped many of these fractures may close and heal and the fluid is released back into the wellbore provided that the increased ECD has not exceeded the fracture propagation pressure of the fractures. The healing process can take about two hours. To reduce non-productive time (NPT), this period is normally used for rig maintenance.

4.2.3 Pretreat the Active Mud System with LCM

This technique is applied either as a preventive method (i.e. before drilling through zones that are prone to lost circulation) or as the problem arises (remedial). When pretreating the drilling fluid system with LCM, special considerations must be made to optimize the solids control equipment (Ferron et al. 2011). This is important to maintain the LCM in the fluid system. Research shows that combinations of LCMs rather than a single type give the best results in combating losses (Savari et al. 2011). Graphitic carbon and sized calcium carbonate ($CaCO_3$) have proven to be effective primary materials when carried as a pretreatment in the drilling fluid (Whitfill and Wang, 2005). The particle size distribution (PSD) of these LCMs used depends on the permeability/pore size/ fracture width of the loss zones. 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:

- Abrams' median particle size rule (Abrams, 1977): the median particle size (D50) of the bridging material should be equal or slightly greater than 1/3 the median pore size of the formation.

- Ideal Packing Theory (Dick et al. 2000): the D90 value of the PSD should be equal to the fracture opening size.
- Vickers Method (Vickers et al. 2006): In order to achieve minimal fluid loss into the formation, the following criteria for the bridging blend must be met:
- D90 = largest pore size
- D75 < 2/3 of largest pore size
- D50 = +/- 1/3 mean pore size
- D10 > smallest pore size
- Halliburton Method (Whitfill, 2008): the D50 of the PSD is set equal to the estimated fracture width to offset uncertainty in the estimation. In this way, sufficient particles both larger and smaller than the estimated fracture width are present to plug a smaller or larger fracture width.

Where 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/fractures (Kumar et al. 2010). Figures 4.3 and 4.4 illustrate the importance of getting the right PSD of LCMs for bridging and sealing loss zones.

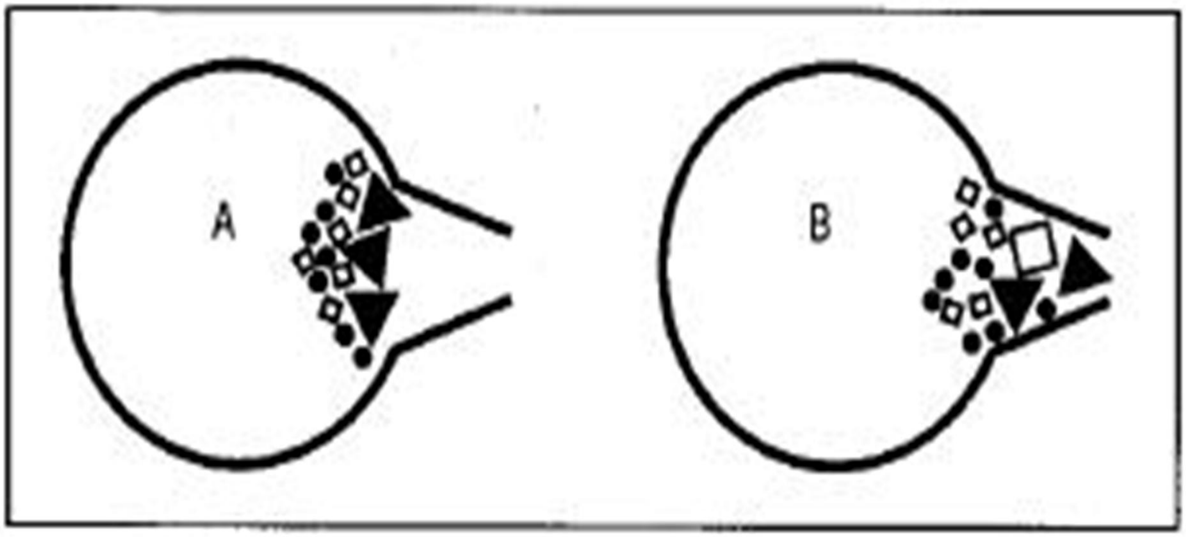

Fig. 4.3 – A: Results using LCM too large – forms a bridge on the wellbore and erodes away; B: Proper bridging (After Ivan et al. 2002).

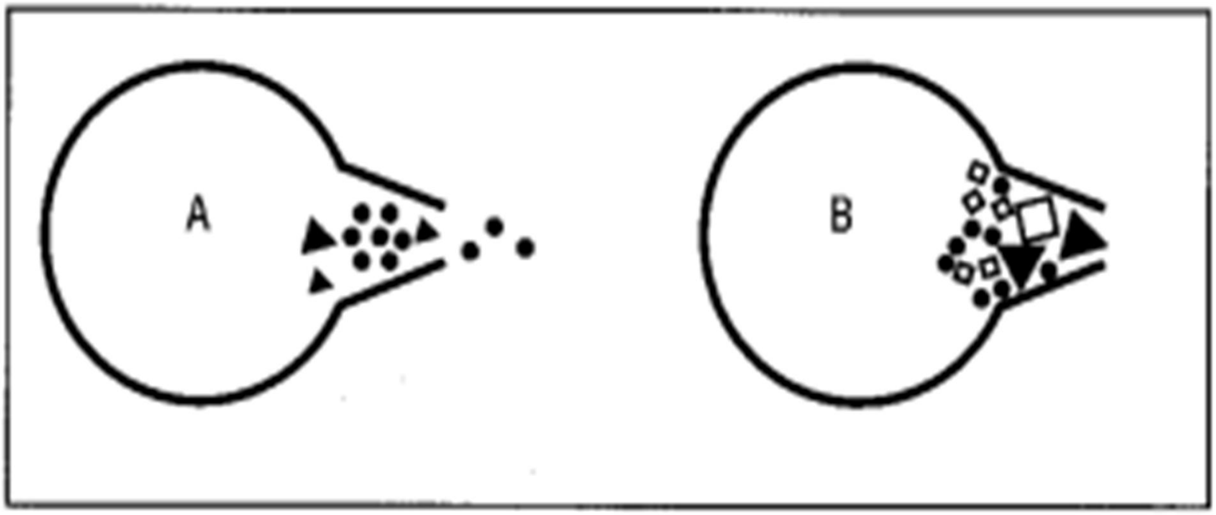

Fig. 4.4 – A: Results using LCM too fine – goes through the openings and does not form a bridge; B: Proper bridging (After Ivan et al. 2002).

Higher concentration of LCMs delivered in sweeps can aid in fracture tip screen-out and prevent fracture propagation (Whitfill and Wang, 2005). As the drilling progresses, additional make-up LCMs should be added to maintain pretreatment levels. Table 4.1 provides a guideline on the amount of LCMs to be added to the mud, based on the weight of mud (Ferron et al. 2011):

Table 4.1 – Seepage Loss Quick Reference Guide to Pretreat Active Mud System with LCMs

LCMs		MUD WEIGHTS (lb/gal)				COMMENTS
		7.0 to 12.5	12.5 to 15.0	15.1 to 17.0	17.1 +	Add recommended amounts to active mud system.
GRAPHITIC CARBON (FINE)	LCM CONCENTRATION (lb/bbl)	5-10	5-10	5-10	5-10	
$CaCO_3$ (FINE)		5-10	5-10	5-10	5-10	
TOTAL LCM CONC. (lb/bbl)		10-20	10-20	10-20	5-10	

4.3 PARTIAL LOSSES

Partial losses occur when the severity of the loss is in the range of 10-500 bbl/hr. They occur in gravels; small, natural horizontal fractures; and barely opened induced vertical fractures (Nayberg, 1987). The use of LCMs in the mud can be used to prevent and cure partial losses in all the formations mentioned above. The guidelines discussed in the previous sections on selecting the optimum PSD of these bridging materials must be adhered to. Table 4.2 provides guidelines on the amounts of LCMs to be added to the active mud system to prevent and cure partial losses (Ferron et al. 2011).

Table 4.2 – Partial Loss Quick Reference Guide to Pretreat Active Mud System with LCMs

LCMs		MUD WEIGHTS (lb/gal)				COMMENTS
		7.0 to 12.5	12.5 to 15.0	15.1 to 17.0	17.1 +	Pump sweeps as needed. Do not over treat as this can lead to a build-up of solids which will increase ECDs.
Micro-Fiber (Fine)	LCM CONC. (lb/bbl)	10	10	10	10	
Micro-Fiber (Medium)		10	10	10	10	
Micro-Fiber (Coarse)		10	10	10	10	
$CaCO_3$ (Fine)		10	10	10	10	
$CaCO_3$ (Coarse)		10	10	10	10	
TOTAL LCM CONC. (lb/bbl)		30-50	30-50	30-50	30	

4.4 SEVERE AND TOTAL LOSSES

Mud losses are said to be severe when the rate of loss is greater than 500 bbl/hr. Total losses occur when no fluid returns is seen through the annulus. These types of losses occur in long, open sections of gravels; large, natural horizontal fractures; caverns; interconnected vugs; and widely-opened induced fractures (Nayberg, 1987). Losses into large caverns occur only at very shallow depths and are difficult to treat. Sometimes, a cure may not be possible and may require other actions (Ferron et al. 2011). Some of the actions that may be taken include: 1) Drilling Blind 2) Drilling with Aerated Mud

4.4.1 Blind Drilling (Drilling Without Returns)

This technique is used in severe total lost circulation events, where a cure might not be possible or where economic analysis of the treatment process is not favorable, to cross the loss zone in order to set casing. Concerns of drilling blind should include: possible stuck pipe, insufficient hole cleaning, loss of well control, sloughing formations, etc. (Johnson et al. 2000). When drilling without returns, it important to maintain a pumping rate equal or greater than the normal pumping rate used for hole cleaning. Otherwise, there is a risk of sticking the pipe string. This makes practical access to an adequate water source a necessity if the technique is to be completed efficiently (Canson, 1985).

Chemical systems that form flexible ultra-viscosity treatments may be necessary to solve the most severe lost circulation problems (Whitfill and Hemphill, 2003). The most commonly used chemical systems are Reactant Pills. These pills are used to regain circulation from either lost circulation or kicks and they have been successfully used for many years to seal off zones or pathways to underground flows allowing the flowing zone to be killed. Reactant means that the pill’s final properties will be much different after it has been spotted in the wellbore (Ferron et al. 2011). There are many pill treatments available, including cements, gunk squeezes, cross-linked gels, and graded particulates (Reid and Santos, 2003). It is important that the operator carries out a careful study in order to select a pill that will offer several technical and operational advantages.

Figure 4.5 provides a summary of the techniques and guidelines on how to combat the different types of lost circulation cases. When used in combination with the above guidelines, the problem of lost circulation will be reduced if not totally stopped.

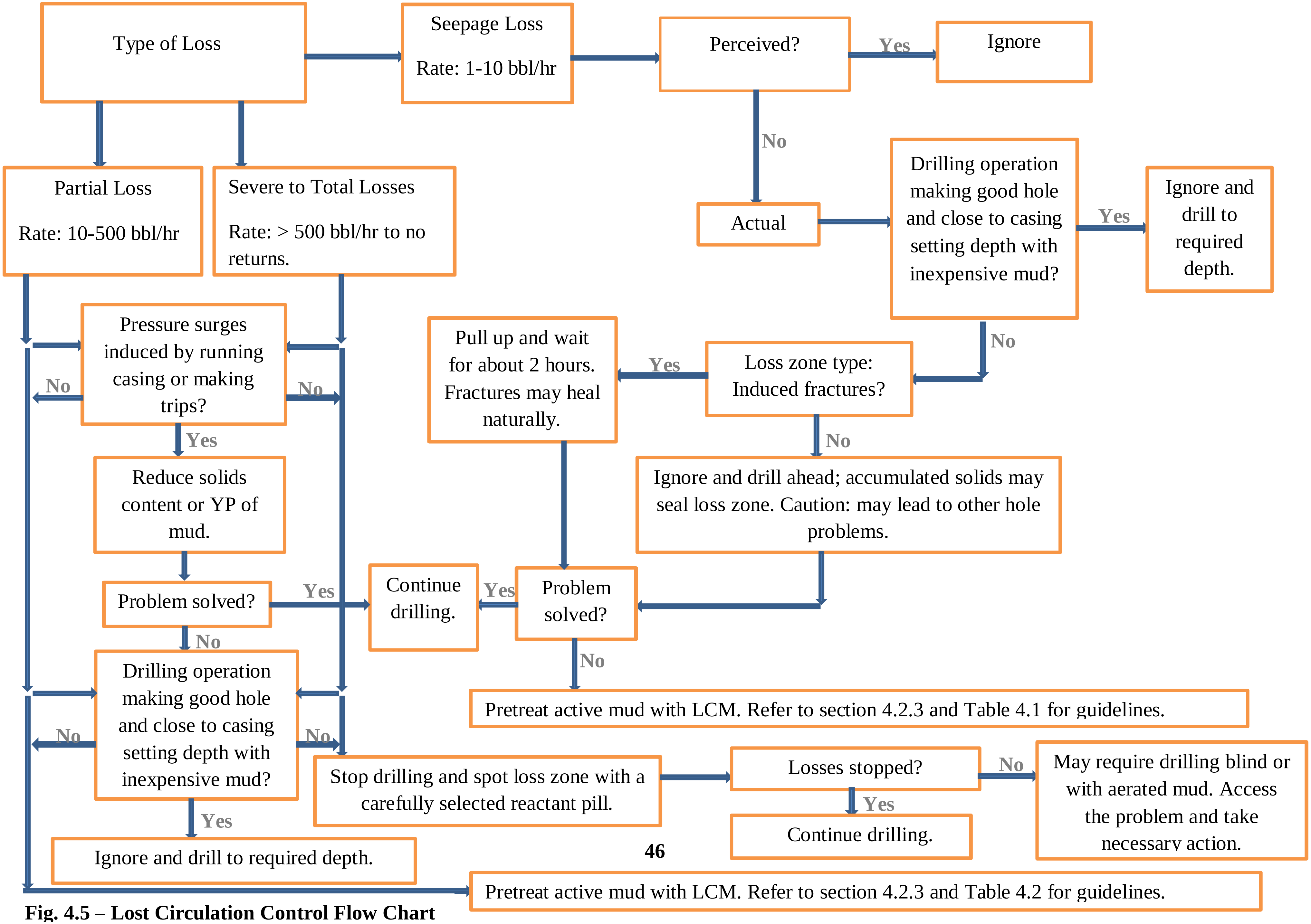

Fig. 4.5 – Lost Circulation Control Flow Chart

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY

Lost circulation presents a lot of challenges while drilling. To address these problems, a number of methods/techniques have evolved over the years. The objectives of this study are: 1) to review lost circulation control methods that have been applied in the drilling industry till date 2) to provide the successes and the failures of these methods in field applications and 3) to develop practical guidelines that will serve as a reference material for lost circulation control at the well-site for drilling personnel.

To achieve these study objectives, a selected number of technical journals, papers, textbooks, and manuals that address the problem of lost circulation were carefully reviewed and summarized. The results of this study are practical guidelines that are not biased towards a particular service industry product but are general to the mitigation of the problem of lost circulation while drilling. A flow chart has also been developed that will serve as a quick reference guide for drilling personnel at the well-site.

5.2 CONCLUSIONS

Based on this study, the following conclusions were made:

- Successful control or treatment of lost circulation depends on several factors such as borehole temperature, pressure, depth, and size of the thief zone.
- 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.
- Practical guidelines have been developed that when used with the accompanying flow chart will serve as a quick reference guide to prevent and minimize the problem of lost circulation while drilling.

5.3 RECOMMENDATIONS

For future work in this study area, the following recommendations may be considered:

- The effect of lost circulation materials (LCMs) on reservoir productivity may be considered when selecting these materials for lost circulation control.
- Since the subject of lost circulation control is very broad, a study may be conducted in a particular formation type, such as depleted reservoirs, for in-depth understanding of control measures.

NOMENCLATURE

APWD	Annular Pressure while Drilling
bbl/hr	barrels per hour
BHA	Bottom Hole Assembly
CACP	Chemically Activated Cross-linked Pills
CDS	Casing Drilling Shoe
CwD	Casing while Drilling
DOB	Diesel-Oil-Bentonite
D_{static}	Static Fluid Column above Loss Zone
EAs	Expandable Aggregates
ECD	Equivalent Circulating Density
FCP	Fracture Closure Pressure
FIP	Fracture Initiation Pressure
FIT	Formation Integrity Test
FPP	Fracture Propagation Pressure
FRP	Fracture Re-opening Pressure
ID	Internal Diameter
ISIP	Initial Shut-in Pressure
lb/bbl	pounds per barrel
lb/gal	pounds per gallon
LCM	Lost Circulation Material
LCMSS	Lost Circulation Material Squeeze Systems
LOP	Leak-off Pressure
LOT	Leak-off Test
M-DOB	Mud-Diesel-Oil-Bentonite
Mev	Mega-electron Volts
MRCS	Mud-Reactive-Chemical-Squeeze
MW	Mud Weight
NPT	Non-productive Time
$P_{friction}$	Annular Friction Pressure

$P_{hydrostatic}$	Hydrostatic Pressure
$P_{loss\ zone}$	Pressure in Loss Zone
PNC	Pulse-neutron Capture
PNS	Pulse-neutron Spectroscopy
ppg	pounds per gallon
P_o	Pore Pressure
PSD	Particle Size Distribution
psi	pounds per square inch
P_{Total}	Total Annular Pressure
P_w	Wellbore Pressure
R-DOB	Reverse-Diesel-Oil-Bentonite
SBM	Synthetic-based Mud
S_{HMAX}	Maximum Horizontal Stress
S_{hmin}	Minimum Horizontal Stress
STF	Shear-thickening Fluid
TD	Total Depth
TVD	True Vertical Depth
XLOT	Extended Leak-off Test
^0C	Degree Celsius
^0F	Degree Fahrenheit
δ_θ	Effective Tangential (Hoop) Stress

REFERENCES

1. Aadnoy, B.S., Belayneh, M., Ariado, M., and Flateboe, R.: "Design of Well Barriers To Combat Circulation of Losses," paper SPE 105449 presented at the 2007 SPE/IADC Drilling Conference and Exhibition held in Amsterdam, The Netherlands, 20-27 February.
2. Abbas, R., Jarouj, H., Dole, S., Effendhly, Junaidi, H., El-Hassan, H., Francis, L., Hornsby, L., McCaith, S., Shuttleworth, N., van der Plas, K., Messier, E., Munk, T., Nadland, N., Svendsen, R.K., Therond, E., and Taoutaou, S.: *A Safety Net for Controlling Lost Circulation*. Oilfield Review (winter, 2003/2004) 20.
3. Abrams, A.: *Mud Design to Minimize Rock Impairment Due to Particle Invasion*. JPT (May, 1977) 586.
4. Beda, G., and Carugo, C.: "Use of Mud Microloss Analysis While Drilling to Improve the Formation Evaluation in Fractured Reservoir," paper SPE 71737 presented at the 2001 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, 30 September – 3 October.
5. Bell, R.J., and Davies, J.M.: "Lost Circulation Challenges: Drilling Thick Carbonate Gas Reservoir, Natuna D-Alpha Block," paper SPE/IADC 16157 presented at the 1987 SPE/IADC Drilling Conference held in New Orleans, LA, 15-18 March.
6. Bruton, J.R., Ivan, C. D., and Heinz, T.J.: "Lost Circulation Control: Evolving Techniques and Strategies to Reduce Downhole Mud Losses," paper SPE 67735 presented at the 2001 SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 27 February – 1 March.
7. 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.
8. Carlton, L.A, and Chenevert, M.E.: "A New Approach to Preventing Lost Returns," paper SPE 4972 presented at the 1974 49th Annual Fall Meeting of the Society of Petroleum of AIME held in Houston, Texas, 6-9 October.

9. Darugar, Q.A., Szabo, J.J, Clapper, D.K., and McGuffey, G.: "Single-Sack Fibrous Pill Treatment for High Fluid Loss Zones," paper SPE 149120 presented at the 2011 SPE/DGS Saudi Arabia Section Technical Symposium held in Al-Khobar, Saudi Arabia, 15-18 May.
10. Davison, J.M., Leaper, R., Cauley, M.B., Bennett, B., Mackenzie, A., Higgins, C.J., Shuttleworth, N., and Wilkinson, D.: "Extending the Drilling Operating Window in Brent: Solutions for Infill Drilling in Depleting Reservoirs," paper IADC/SPE 87174 presented at the 2004 IADC/SPE Drilling Conference held in Dallas, Texas, U.S.A, 2-4 March.
11. Dick, M.A., Heinz, T.J., Svoboda, C.F., and Aston, M.: "Optimizing the Selection of Bridging Particles for Reservoir Drilling Fluids," paper SPE 58793 presented at the 2000 SPE International Symposium on Formation Damage held in Lafayette, Louisiana, USA, 23-24 February.
12. Dyke, C.G., Wu, B., and Millton-Taylor, D.: "Advances in Characterizing Natural-Fracture Permeability From Mud-Log Data," paper SPE 25022 presented at the 1992 SPE European Petroleum Conference held in Cannes, 16-18 November.
13. Ferron, D.J., Smiley, B.E., Reneau, W.P., Ledbetter, S.B., Stephens, M.L., Murray, D., Griggs, J., Esparza, C., Goldwood, D.S., Moses, P., and Matthiesen, M.*: Lost Circulation Guide*. Drilling Specialties Co. (2011).
14. Fidan, E., Babadagli, T., and Kuru, E.: "Use of Cement As Lost Circulation Material – Field Case Studies," paper IADC/SPE 88005 presented at the 2004 IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition held in Kuala Lumpur, Malaysia, 13-15 September.
15. Freidheim, J., Sanders, M., and Roberts, N.: "Unique Drilling Fluids Additives for Improved Wellbore Stability and Reduced Losses," paper presented at the 2008 SEFLU Conference held in Margarita Island, Venezuela, 19-23 May.
16. Fuller, G.A., Serio, M., Trahan, J., and Langlinais, J.: "A Novel Approach for the Controlling of Whole Mud Losses while Encountering Productive Formations," paper SPE 127718 presented at the 2010 SPE International Symposium and Exhibition on Formation Damage Control held in Lafayette, Louisiana, USA, 10-12 February.

17. Gallardo, H., Cassanelli, J.P., Barret, S., Romero, P., and Mufarech, A.: “Casing-Drilling Technology (CwD) Mitigates Fluid Losses in Peruvian Jungle,” paper SPE 139065 presented at the 2010 SPE Latin American & Caribbean Petroleum Engineering Conference held in Lima, Peru, 1-3 December.
18. Gockel, J.F., and Brinemann, M.: “Lost Circulation: A Solution Based on the Problem,” paper SPE/IADC 16082 presented at the 1987 SPE/IADC Drilling Conference held in New Orleans, LA, 15-18 March.
19. Gray, G.R., and Darley, H.C.H.: *The Composition and Properties of Oil Well Drilling Fluids*. Fourth Edition. Gulf Publishing Company, Houston, Texas (1980).
20. Guo, B., and Rajtar, J.M.: “Volume Requirements for Aerated Mud Drilling,” paper SPE 26956 presented at the 1994 SPE Latin America/Caribbean Petroleum Engineering Conference held in Buenos Aires, 27-29 April.
21. Hamburger, C.L., Tsao, Y., Morrison, B., and Drake, E.N.: “A Shear-Thickening Fluid for Stopping Unwanted Flows While Drilling,” paper SPE 12122 presented at the 1983 SPE Annual Technical Conference and Exhibition held in San Francisco, 5-8 October.
22. Howard, G.C., and Scott, P.P.: “AN ANALYSIS AND THE CONTROL OF LOST CIRCULATION,” paper SPE 951171 presented at the 1951 Annual Meeting of the AIME held in St. Louis, Mo., 19-21 February.
23. Ivan, C.D., Bruton, J.R., Thiercelin, M., and Bedel, J.: “Making a Case for Rethinking Lost Circulation Treatments in Induced Fractures,” paper SPE 77353 presented at the 2002 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, 29 September – 2 October.
24. Ivan, C., and Bruton, R.: “How Can We Best Manage Lost Circulation?” paper AADE-03-NTCE-38 presented at the 2003 AADE National Technology Conference, Houston, Texas, 1-3 April.
25. Jiao, D., and Sharma, M.M.: “Mud-Induced Formation Damage in Fractured Reservoirs,” paper SPE 30107 presented at the 1995 European Formation Damage Control Conference held in The Hague, The Netherlands, 15-16 May.

26. Johnson, L., Murphy, P., and Arsanious, K.: "Improvements in Lost-Circulation Control During Drilling Using Shear-Sensitive Fluids," paper PETSOC-2000-062-P presented at the 2000 Petroleum Society's Canadian International Petroleum Conference held in Calgary, Canada, 4-8 June.
27. Kumar, A., Sharath, S., Whitfill, D.L., and Jamison, D.E.: "Wellbore Strengthening: The Less-Studied Properties of Lost-Circulation Materials," paper SPE 133484 presented at the 2010 SPE Annual Technical Conference and Exhibition held in Florence, Italy, 19-22 September.
28. Majidi, R., Miska, S.Z., and Zhang, J.: "Fingerprint of Mud Losses into Natural or Induced Fractures," paper SPE 143854 presented at the 2011 SPE European Formation Damage Conference held in Nordwijk, The Netherlands, 7-10 June.
29. Metcalf, A.S., Nix, K., and Martinez-Guedry, J.: "Case Histories: Overcoming Lost Circulation During Drilling and Primary Cementing Operations Using an Environmentally Preferred System," paper SPE 140723 presented at the 2011 SPE Production and Operations Symposium held in Oklahoma City, Oklahoma, USA, 27-29 March.
30. Moore, P.L.: *Drilling Practices Manual*. Second Edition. PennWell Publishing Company. Tulsa, Oklahoma (1986).
31. Nayberg, T.M.: "Laboratory Study of Lost Circulation Materials for Use in Both Oil-Based and Water-Based Drilling Muds," paper SPE 14723 presented at the 1986 IADC/SPE Drilling Conference held in Dallas, 10-12 February.
32. Nayberg, T.M., and Petty, B.R.: "Laboratory Study of Lost Circulation Materials for Use in Oil-Base Drilling Muds," paper SPE 14995 presented at the 1986 Deep Drilling and Production Symposium of the Society of Petroleum Engineers held in Amarillo, TX, 6-8 April.
33. Okland, D., Gabrielsen, G.K., Gjerde, J., Sinke, K., and Williams, E.L.: "The Importance of Extended Leak-Off Test Data for Combating Lost Circulation," paper SPE/ISRM 78219 presented at the 2002 SPE/ISRM Rock Mechanics Conference held in Irving, 20-23 October.
34. Onyekwere, C.: *Lost Circulation Material Training Manual*. Schlumberger (2002).

35. Osisanya, S.: *Course Notes on Drilling and Production Laboratory*. Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Oklahoma (Spring 2002).
36. Pilehvari, A.A., and Nyshadham, V.R.: "Effect of Material Type and Size Distribution on Performance of Loss/Seepage Control Material," paper SPE 73791 presented at the 2002 SPE International Symposium and Exhibition on Formation Damage Control held in Lafayette, Louisiana, 20-21 February.
37. Ramirez, M., Diaz, A., Luna, E., Figueroa, Y., and Per-Bjarte, T.: "Successful Application of Synthetic Graphite to Overcome Severe Lost Circulation Problem in the Troublesome Foothills of Colombia," paper AADE-05-NTCE-30 presented at the 2005 AADE National Technical Conference and Exhibition held at the Wyndam Greenspoint in Houston, Texas, 5-7 April.
38. Redden, J., Carpenter, B., Polnaszek, S., Bloys, B., and Headley, J.: *Lost Circulation Manual*. MI-SWACO (2011).
39. Reid, P., and Santos, H.: "Novel Drilling, Completion and Workover Fluids for Depleted Zones: Avoid Losses, Formation Damage and Stuck Pipe," paper SPE/IADC 85326 presented at the 2003 SPE/IADC Middle East Drilling Technology Conference and Exhibition held in Abu Dhabi, UAE, 20-22 October.
40. Samsuri, A., and Phuong, B.T.N.: "CHEAPER CEMENT FORMULATION FOR LOST CIRCULATION CONTROL," paper IADC/SPE 77216 presented at the 2002 IADC/SPE Asia Pacific Drilling Technology Conference held in Jakarta, Indonesia, 9-11 September.
41. Sanders, M.W., Scorsone, J.T., and Friedheim, J.E.: "High-Fluid-Loss, High-Strength Lost Circulation Treatments," paper SPE 135472 presented at the 2010 SPE Deepwater and Completions Conference held in Galveston, Texas, USA, 5-6 October.
42. Savari, S., Kumar, A., Whitfill, D.L., and Jamison, D.E.: "Improved Lost Circulation Treatment Design and Testing Techniques Minimize Formation Damage," paper SPE 143603 presented at the 2011 SPE European Formation Damage Conference held in Noordwijk, The Netherlands, 7-10 June.

43. Shun Chang, W., YiMing, J., ChunJiang, Z., BaiLin, W., XinQuan, Z., JiPing, T., JinHai, Y., and HongHai, F.: “Real-Time Downhole Monitoring and Logging Reduced Mud Loss Drastically for High-Pressure Gas Wells in Tarim Basin, China,” paper IPTC 12865 presented at the 2008 International Petroleum Technology Conference held in Kuala Lumpur, Malaysia, 3-5 December.
44. Song, J.H., and Rojas, J.C.: “Preventing Mud Losses by Wellbore Strengthening,” paper SPE 101593 presented at the 2006 SPE Russian Oil and Gas Technical Conference and Exhibition held in Moscow, Russia, 3-6 October.
45. Suyan, K.M., Dasgupta, D., Sanyal, D., Shama, V., and Jain, V.K.: “Managing Total Circulation Losses With Crossflow While Drilling: Case History of Practical Solutions,” paper SPE 109898 presented at the 2007 SPE Annual Technical Conference and Exhibition held In Anaheim, California, USA, 11-14 November.
46. Sweatman, R.E., Kessler, C.K., and Miller, J.M.: “New Solutions to Remedy Lost Circulation, Crossflows, and Underground Blowouts,” paper SPE/IADC 37671 presented at the 1997 SPE/IADC Drilling Conference held in Amsterdam, The Netherlands, 4-6 March.
47. Sweatman, R., Faul, R., and Ballew, C.: “New Solutions for Subsalt-Well Lost Circulation and Optimized Primary Cementing,” paper SPE 56499 presented at the 1999 SPE Annual Technical Conference and Exhibition held in Houston, Texas, 3-6 October.
48. Tare, U.A., Whitfill, D.L., and Mody, F.K.: “Drilling Fluid Losses and Gains: Case Histories and Practical Solutions,” paper SPE 71368 presented at the 2001 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, 30 September – 3 October.
49. Tessari, R., Madell, G., and Warren, T.: *Drilling with casing promises major benefits.* Oil and Gas Journal (May, 1999).
50. Tessari, R.M., Warren, T.M., and Jo, J.Y.: “Drilling with Casing Reduces Cost and Risk,” paper SPE 101819 presented at the 2006 SPE Russian Oil and Gas Technical Conference and Exhibition held in Moscow, Russia, 3-6 October.

51. van Oort, E., Friedheim, J., Pierce, T., and Lee, J.: “Avoiding Losses in Depleted and Weak Zones by Constantly Strengthening Wellbores,” paper SPE 125093 presented at the 2009 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 4-7 October.
52. Vickers, S., Cowie, M., Jones, T., and Allan, J.T.: “A New Methodology that Surpasses Current Bridging Theories to Efficiently Seal a Varied Pore Throat Distribution as Found in Natural Reservoir Formations,” paper AADE-06-DF-HO-16 presented at the 2006 AADE Fluids Conference held in Houston, Texas, USA, 11-12 April.
53. Vidick, B., Yearwood, J.A., and Perthuis, H.: “How To Solve Lost Circulation Problems,” paper SPE 17811 presented at the 1988 SPE International Meeting on Petroleum Engineering held in Tianjin, China, 1-4 November.
54. Vinson, E.F., Totten, P.L., and Middaugh, R.L.: “Acid Removable Cement System Helps Lost Circulation in Production Zones,” paper IADC/SPE 23929 presented at the 1992 IADC/SPE Drilling Conference held in New Orleans, Louisiana, 18-21 February.
55. Wang, H., Sweatman, R., Engelman, B., Deeg, W., Whitfill, D., Soliman, M., and Towler, B.: “Best Practice in Understanding and Managing Lost Circulation Challenges,” paper SPE 95895 presented at the 2005 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 9-12 October.
56. Wang, H., Soliman, M.Y., Towler, B.F., and Shan, Z.: “Strengthening a Wellbore with Multiple Fractures: Further Investigation of Factors for Strengthening a Wellbore,” paper ARMA 09-67 presented at the 2009 43rd US Rock Mechanics Symposium and 4th US-Canada Rock Mechanics Symposium held in Asheville, NC, 28 June – 1 July.
57. White, R.J.: “Lost-Circulation Materials and their Evaluation,” presented at the 1956 Panel Discussion on Lost Circulation held at the Spring Meeting of the Pacific Coast District, Division of Production, Los Angeles, in May.
58. Whitfill, D.L., and Hemphill, T.: “All Lost-Circulation Materials and Systems Are Not Created Equal,” paper SPE 84319 presented at the 2003 SPE Annual Technical Conference and Exhibition held in Denver, Colorado, U.S.A., 5-8 October.
59. Whitfill, D., and Wang, H.: “Making Economic Decisions To Mitigate Lost Circulation,” paper SPE 95561 presented at the 2005 SPE Annual Technical Conference held in Dallas, Texas, U.S.A., 9-12 October.

60. Whitfill, D.: “Lost Circulation Material Selection, Particle Size Distribution and Fracture Modeling with Fracture Simulation Software,” paper IADC/SPE 115039 presented at the 2008 IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition held in Jakarta, Indonesia, 25-27 August.