Department of Petroleum Engineering - Chair of Drilling and Completion Engineering

Master Thesis

Lost Circulation Cure – An Evaluation Matrix to the Best Cure

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Kurzfassung

Lost Circulation ist ein Milliarden-Dollar-Problem, welches der Erdölindustrie wohl bekannt ist. In den vergangenen Jahrzehnten wurden unterschiedliche Ansätze und Abhilfemaßnahmen mit begrenztem Erfolg entwickelt.

Zur Klassifizierung von Problemen im Zusammenhang mit lost Circulation werden am Anfang dieser Arbeit die Schwere, die Mechanismen, Sonderfälle und besondere Belange charakterisiert. Zusätzlich wird eine Schritt-für-Schritt-Zusammenfassung einer effektiven Diagnose von lost Circulation vorgestellt.

Abhängig vom Schadensfall muss eine entsprechende Behandlung gefunden werden. Verfügbares Material gegen lost Circulation wird kategorisiert und spezifiziert. Dies geschieht mit Hilfe der verfügbaren Produktlinien der Hersteller. Anschließend werden die Behandlungsoptionen auf der Grundlage von Verlustmechanismen und Schwere diskutiert, um zu sehen, welche Behandlung unter bestimmten Umständen angewendet werden sollte.

Idealerweise ist dieses Vorgehen wissenschaftlich bewiesen. Gegenwärtig sind die meisten lost Circulation-Prüfstände dem Design des American Petroleum Institute (API) ähnlich und funktionieren daher wie Filterpressen. Ein verbessertes dynamisches Prüfstanddesign wird erstellt und diskutiert, um die verfügbaren Material im Kampf gegen lost Circulation anwendungsbedingt und vergleichbar zu bewerten. Das Prüfstanddesign ist rotierbar, kann verschiedene Risswinkel und Rissgrößen simulieren und verschiedene Durchflussraten bzw. Temperaturen anwenden.

Fünf Bohrungen von TAG Oil Ltd. Neuseeland, die am meisten anfällig für lost Circulation sind, bestätigen die empfohlene Auswahl der Materialien, indem sie zeigen, was getan wurde und was hätte getan werden können, um lost Circulation wirksamer zu bekämpfen.

In der Arbeit werden mehrere lost Circulation-Entscheidungsbäume der verschiedenen Unternehmen und deren Anwendungsgrenzen bewertet. Somit wird eine umfangreiche Bewertungsmatrix erstellt. Mögliche Verlustszenarien, die durch Mechanismus, Verlustrate, Neigungswinkel und Reservoir- bzw. Nichtreservoirbereich gekennzeichnet sind, werden auf die verfügbaren Behandlungsmöglichkeiten und Empfehlungen abgestimmt. Die Matrix soll eine Reaktion auf die Verluste erleichtern und eine schnelle Orientierung anhand vorhandener Optionen aufzeigen. Die unproduktive Zeit kann somit minimiert und bestmögliche Maßnahmen ergriffen werden.

Abstract

Lost circulation is a billion-dollar problem well known to the petroleum industry. During the previous decades, different approaches and remedies have been developed with limited success.

To classify lost circulation issues in a comprehensive way, severities, mechanisms, special cases and special concerns are characterised in the beginning of the thesis. Additionally, a step-by-step summary of how to effectively diagnose lost circulation is introduced.

Depending on the loss scenario, a corresponding cure must be found. Available lost circulation material (LCM) and settable material are categorised and specified. This is carried out with the help of available product lines of manufacturers. Subsequently, the treatment options are discussed based on loss mechanism and severity to see which treatment must be applied under certain circumstances.

Ideally, the latter is scientifically proven. Currently, most lost circulation material testing apparatuses are akin to the American Petroleum Institute (API) design and therefore function like filter presses. An improved dynamic test stand design is created and discussed to comparable evaluate LCM and settable material under certain conditions. The test stand design is rotatable, can simulate different fracture angles and sizes while various flow rates and temperatures can be applied.

Five wells from TAG Oil Ltd. New Zealand most prone to lost circulation confirm the recommended selection of LCM and settable material by showing what was done and what could have been done to combat lost circulation more effectively.

Several lost circulation decision trees of various companies and their limitations are assessed in this thesis. Consequently, an extensive evaluation matrix is created. Possible loss scenarios characterised by mechanism, loss rate, inclination and reservoir vs. non-reservoir are matched to available treatment options and recommendations result. The matrix is intended to be a first-action-tool when losses happen and give rapid guidance to the available options. Non-productive time (NPT) can be minimised and best possible actions can be taken.

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Abbreviations

bbl/hr	Barrels per hour
m^3/h	Cubic meter per hour
lb/bbl	Pounds per barrel
ft/hr	Feet per hour
lb/gal	Pounds per gallon
kg/m^3	Kilogram per cubic meter
ECD	Equivalent Circulating Density
LCM	Lost-circulation materials
CPP	Cross-linked Polymer Pill
NPT	Non-productive time
ROP	Rate of penetration
IPT	Ideal Packing Theory
PSD	Particle size distribution
LOT	Leak-off test
ROP	Rate of penetration
WBM	Water-based mud
OBM	Oil-based mud
SBM	Synthetic-based mud
ESD	Equivalent static density
ID	Inner diameter
DVCS	Deformable, viscous and cohesive system
LCMSS	Lost circulation material squeeze systems
BHP	Bottomhole pressure
HPHT	High-pressure high-temperature
FIP	Fracture initiation pressure
FBP	Formation breakdown pressure
MD	Measured depth
TVD	True vertical depth
APL	Annular pressure loss
PSD	Particle size distribution
UCS	Unconfined compressive strength

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1. Introduction

During well construction lost circulation related non-productive time (NPT) occurs during estimated 20 to 25% (Fidan et al. 2013) of all wells drilled and is one of the major contributors to well construction and well service NPT. Decision making during loss events and selection of loss control measures ahead of and while drilling is often exacerbating the total effect of lost time. Not always are operators in a position to judge which of the available alternatives is the most effective. As in many other trouble situations loss prevention is more effective than loss cure. Prevention comes at a price and a risk that may not always be justified, budget pressure can be one reason. In many cases, unpredicted or unforeseen losses occur while drilling.

The petroleum industry has invested a significant effort into understanding the mechanisms behind lost circulation, developing new tools to help locate the thief zone and implementing new steps to minimize or eliminate this problem. Many drilling teams develop a loss decision strategy ahead of drilling. The intent of these loss treatment strategies is to improve the decision-making time and reduce overall NPT by pre-selecting a loss control measure based on severity of losses by hole section and formation.

Current industry data suggests that loss related NPT remains one of the top-ranking loss time causes. This suggests that either loss strategies are not always chosen adequately or their implementation is not sufficiently.

Despite best efforts to plan for loss contingencies, operators and service companies often experience severe rig delays as planned strategies fail. Not only are loss mechanisms poorly categorized, they also change in character based on loss cause and well and string geometry. Loss events change with hole exposure time and become hard to treat, especially if a loss interval escalates in severity once it is off bottom. Similarly given lost circulation solutions will not be applicable to every well, string geometry and loss type the same way. Loss strategies often fail to recognise these changed requirements.

The purpose of this thesis is to investigate and categorize loss causes and well configurations. It will also categorize loss remediation measures currently available based on remediation mechanism, procedures, limitations and rig time involved.

In the end a treatment matrix will be proposed that attempts to match loss cure methods with various loss situations based on intended design of loss cure and loss mechanism, well and string configuration. The matrix is intended to provide recommendation on how to treat losses in the most effective way. And assist drilling engineers in defining loss control strategies and contingencies as well as assist in decision making during loss events while drilling.

This thesis shall provide a detailed recommendation of the best available cure. State-of-the-art methods and tools are being stored in a database and characterised and matched to loss type, loss rate, complexity to implement, risk profile and chance of success.

2. Loss Classification

Loss of circulation is an uncontrolled, total lacking or reduced surface return flow when pumps are active. It happens when highly permeable formation is drilled with significantly overbalanced mud weight. Loss severity increases the more the bottom hole pressure of the drill fluid exceeds the pore pressure and can become catastrophic if it exceeds the formation break down pressure. In a lost circulation case the pressure of the fluid column is greater than the formation-fluid pressure. The pumped fluid fills the freshly available space, flowing into geological formations as opposed to recirculating back to the surface. Phenomena like caving, washing out, bridging or sloughing are often accompanied and problems like slow drilling rates, damaged bits, stuck drill pipe and collapsed wells can be faced. Even though definitions may vary, there is a general classification of the reduction of flow. Losses are considered to be classified as seepage when they are below 10 bbl/hr (1,6 m^3/h), partial when greater than 10 bbl/hr (1,6 m^3/h) but below 100 bbl/hr (16 m^3/h), severe when greater than 100 bbl/hr (16 m^3/h) and total when there are no returns at all (100% losses). (Lavrov 2016)

Total losses can lead to a decreasing liquid level of the hole even when the pumps are stopped. Due to the reduced vertical height of the liquid column, the exerted pressure of other zones can exceed the hydrostatical pressure of the reduced fluid column, starting a flow into the well. The result is a highly complex well control situation with loss and kicking formations exposed. Even less severe seepage or partial losses affect drilling cost and operations significantly. As bridging and fibrous LCM is consumed and mostly discarded over shakers. It settles and accumulates in low flow areas of the circulation system, plugs narrow openings or significantly adds to erosion in high flow areas. Each drilling operation usually has its own financial and technically feasible severity barriers, which then comes to acceptable or unacceptable loss rates. Losses are technically acceptable if the rig can build mud faster than mud is lost. Chemical supply logistics and rig storage capacity play a significant role in how long high mud loss rates can be sustained. Allowance should always be made for the risk that loss rates can at any time change for the worse. (Schlumberger 2016)

2.1. Mud Loss Detection and Measurement

When speaking about mud losses, this mechanism should first be defined. The mud loss rate in this thesis will be defined as the mud flow rate entering the well minus the mud flow rate leaving the well. In practice, this is measured by flowmeters. Mud losses as a function of time then cause different signatures, which can be used to interpret and detect different kinds of lost circulation, as shown in the following figure and discussed later in this chapter. Figure 1 describes the fluid loss patterns of natural/induced fractures, matrix losses and caverns/vugs.

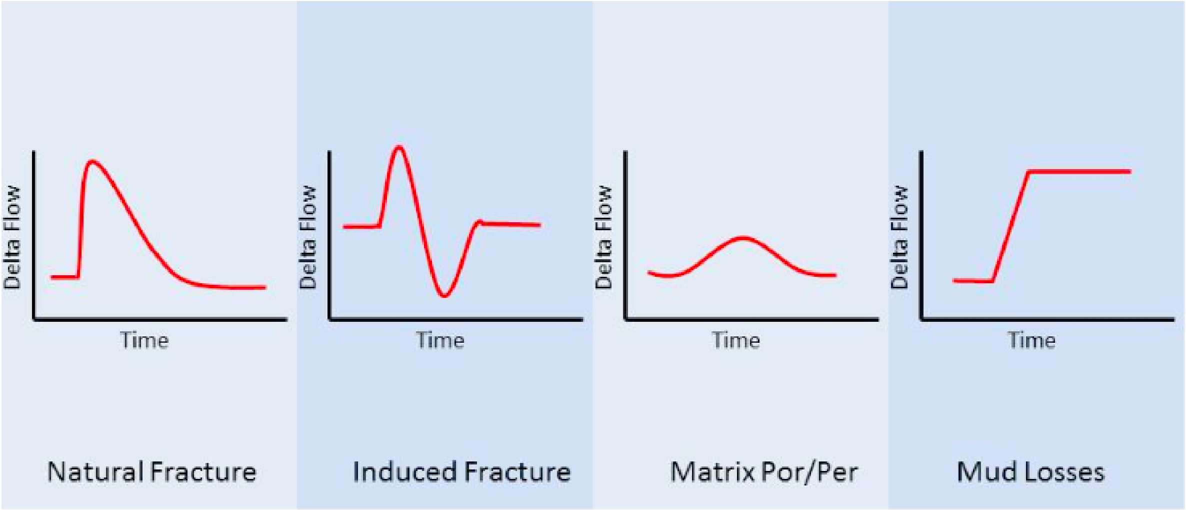


Figure 1: Patterns of Fluid Losses (Company 2012)

In general, the higher the frequency of the measurement is, the more detailed and resolute is the resulting curve. Electromagnetic flowmeters can have a frequency up to 5/s, with an accuracy of 10-15 l/min. On rigs with standard equipment a frequency up to 1/s is more common, even 1/5s happen.

The flowmeter measurement takes place on the standpipe or is measured by counting the mud pump strokes, calculating the number of strokes and assuming a pump efficiency. This is accurate enough for the extent and purpose. The flowmeter to measure the flow coming out of the borehole is situated upstream of the shale shakers. One drawback of using the more accurate and frequent electromagnetic flowmeters is that the mud has to be electrically conductive, which is restricting the usage to WBMs. Also, there are multi-phase flowmeters, which include a gas chromatograph to measure the amount of gas in the flow line. Moreover, sonic sensors are available, but of limited use when mud gets foamy. Also, flow paddles can be used, which are calibrated while circulating in cased hole against various pump rates. Unfortunately, they are also sensitive to changes in rheology and density. None of these sensors are faultless and all have to be fingerprinted over a flow rate range in cased hole.

In the field, the flow rate into the well is measured reliably, often depending on the pump strokes and therefore the calibrated pump efficiency. A standard mud system like this can be seen in the next figure. Due to poorer mud quality and contamination of the mud (cuttings, etc.) coming out of the well, the upstream flow rate is less accurate. In addition to flow rates, pit levels are used to evaluate losses. Pit level losses have to be corrected for hole drilled, evaporation or rain water additions, mud lost on cuttings by surface leaks, flooded shakers and mud transfers to and from the active system. Despite measuring the mud returns using the flow line paddles or flowmeters, there is another qualitative method to detect mud losses – the pit level. Monitoring the pit level with either floating or acoustic sensors provides a lost volume over a given time. On floating rigs the vessel motion, heave and riser storage effect have to be considered as well.

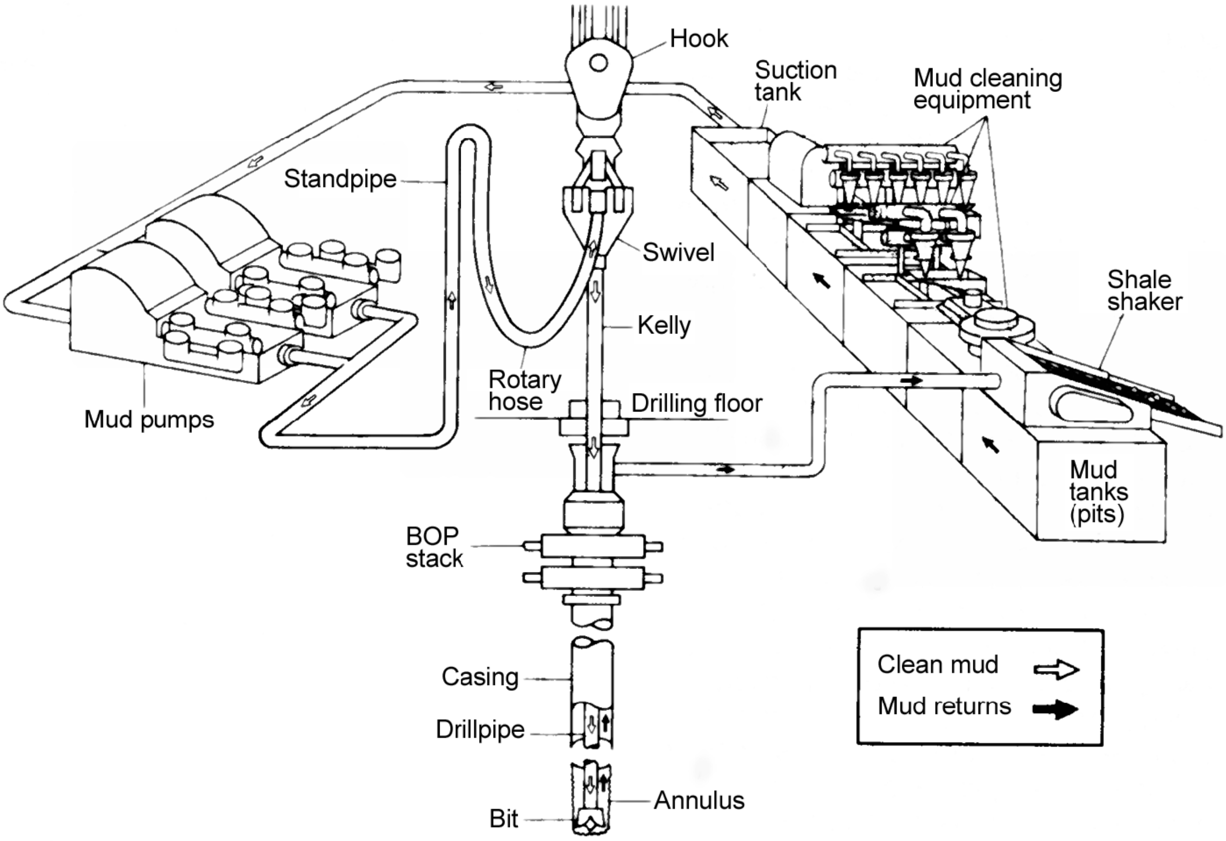


Figure 2: Mud System (Petrowiki 2016)

Unfortunately, the pit level measurement may be accurate but it is very delayed. Losses, on the other hand, are a less time sensitive event than kicks. In case of a kick, the well would need to be shut in within a few minutes. Losses can be seen on pits or evaluated with sufficient response time. If the loss rate is higher, this can be seen on flow in vs. flow out or the shakers. The shaker hand is turning his flow over the screens to optimum. If the flow out changes, he has to react. If the crew is trained well, the driller is informed and the pump rate potentially changed.

Moreover, the mud pit is influenced by losses on the surface, which can be draining and filling of the surface lines, shaker blinding, mud contraction or expansion (pressure/temperature related) and additional chemicals or water to the drilling fluid.

A more detailed view on the mud losses in the pit is below. The following figure provides a flow meter analysis. As soon as the cause is known, methods to resolve can be applied.

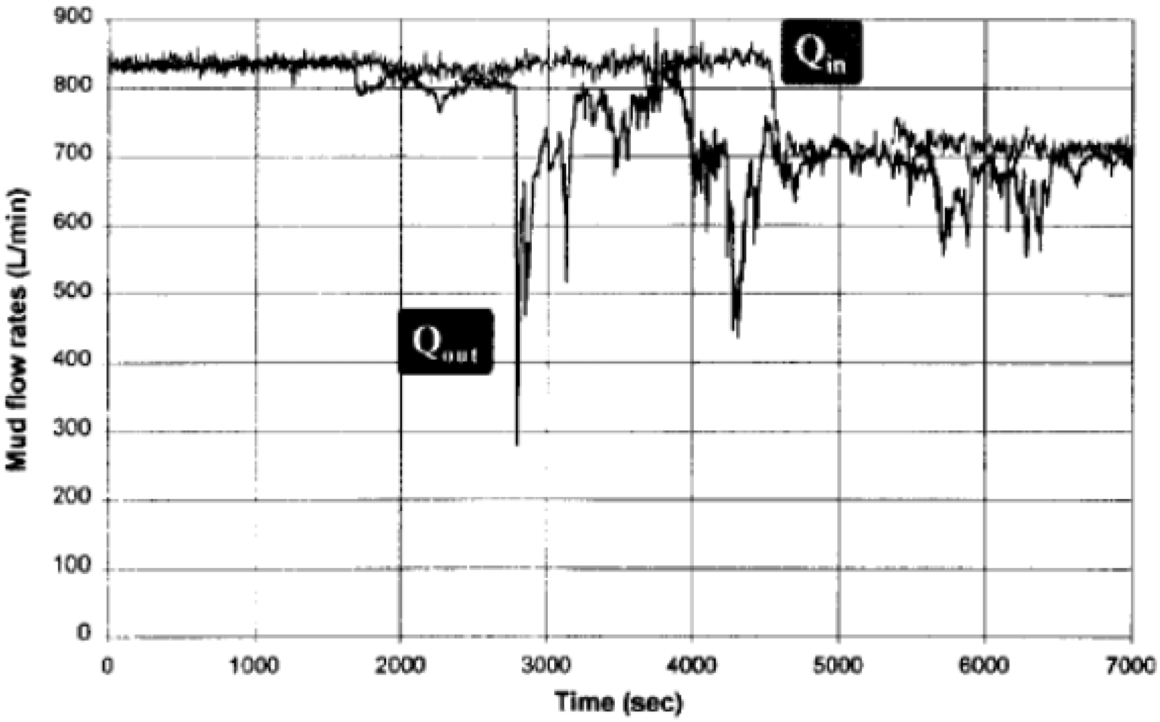


Figure 3: Flow Meter Analysis (Datwani 2012)

Ideally, the data from measuring the returns and monitoring the pit level is supported by more data. This can be logging data, mud properties (rheology, mud weight, particle size, solids content), specific information about the loss incident (ECD, duration, depth) and operational drilling data (torque, WOB, ROP, standpipe pressure, estimated fracture gradient). (Lavrov 2016)

2.2. Locating the Loss Zone

This paragraph is concerned with determining the loss zone at a certain depth. Although usually so reported, loss zones mostly do not appear at the depth of the bit (exception: first loss). Nine out of ten times the loss zone was reopened when drilling proceeded. Is the loss zone nowhere to be found in that range or the point of initial loss, it should be found by radioactive-tracer survey, spinner survey or temperature survey. Other tools and methods are open hole logs, hot wire surveys, pre-drill geological analysis and real-time geomechanical analysis. However, such tools are hardly available on standby.

A temperature survey can be run as follows. By circulating the cooler mud in a well, the geothermal gradient is altered. At first, an initial temperature log is executed to detect the temperature in static conditions. Then mud is pumped and the temperature log is repeated. Comparing this two logs, the loss zone can be determined by the temperature increase below the loss zone. One advantage of this approach is that LCM can be applied simultaneously in the mud pumped for the survey. A temperature survey like this can be seen in the following figure. Moreover, noise logs, radioactive logs and flowmeters are providing information to find a loss zone. In case the loss zone is at the very bottom of the borehole, drilling should be continued until bottom and top of the interval can be identified.

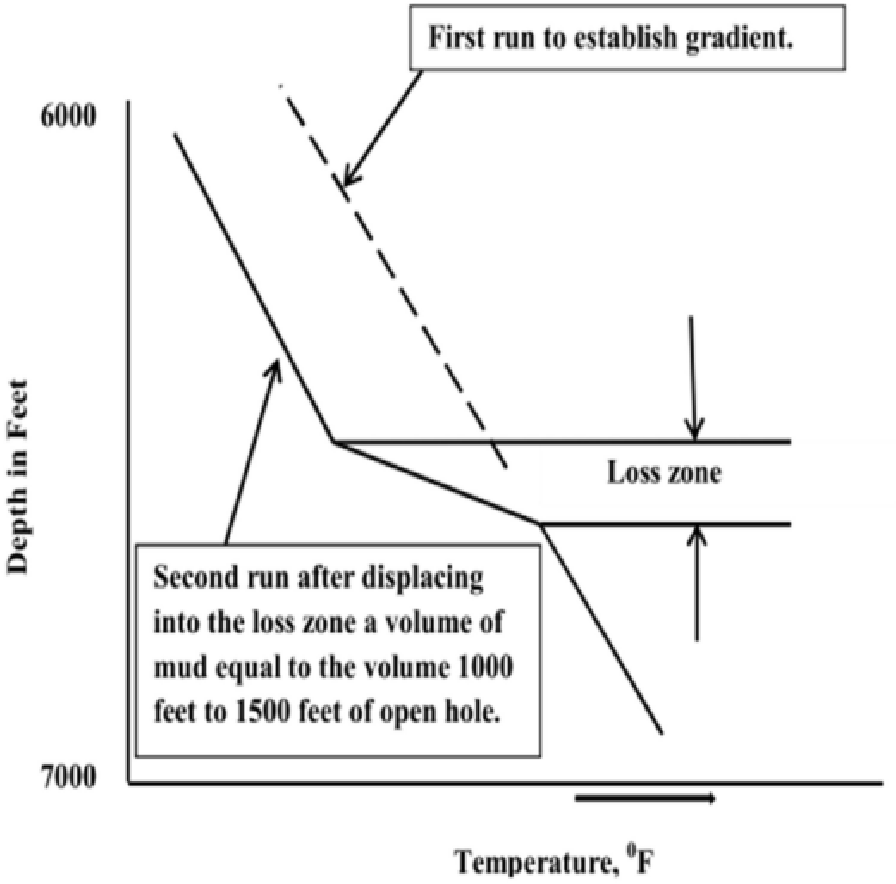


Figure 4: Temperature Survey (Tetteh-Fiagbor 2011)

Another method to locate the loss zone is a radioactive-tracer survey, which has some things in common with the temperature survey. A first gamma ray log is run to record the given radioactivity of the formation downhole under normal conditions to compare with a second gamma ray log run after a small portion of radioactive material was deployed. At the loss zone, a changed value of radioactivity can be noticed. Although this special equipment is very expensive, the precise location of the loss zone can be investigated.

As in the temperature survey, a temperature change in the mud gives clue about the location of the loss zone in hot-wire surveys. A temperature sensitive wire with calibrated resistance is run downhole. As fresh, cool mud is pumped and a temperature change is noticed, the tool is placed above the loss zone. If mud is pumped but no change is observed, the tool is located below the loss zone. A disadvantage of this method is that large volumes of mud are necessary to locate the loss zone precisely. Although many papers address surveys, a marginal loss or mud rate could not be found.

To run a spinner survey, a cable is let down to the suspected location of the loss zone. At the end of this cable, a little spinner is attached. The spinner can either turn or spin to respond to the movement of the mud. The speed of this movement is recorded. Near the loss zone, acceleration is noticeable, because mud streams into the fracture. Even though this method gives the most precise results, it needs a large amount of mud to be run.

The real-time geomechanical analysis integrates software tools, personnel, visualisation and data synchronisation to optimise the drilling process. Data is gathered for pre-drill analysis and updated on the fly while drilling, helping to interpret, recommend and report results.

Pre-drill geological analysis is often also used to locate thief zones:

- When losses are being encountered while drilling, a loss zone on bottom is probable and is typically caused by caverns, highly permeable formations or natural fractures
- An increased rotary torque and abrupt high losses indicates a problematic zone at the bit
- If losses are recognised during tripping or while raising mud weight, the lost circulation zone might not be on bottom, but likely because of induced fractures

Losses are very likely on bottom when:

- Losses occur after a change in torque, drilling vibration or rate of penetration (ROP)
- Losses are encountered while drilling ahead
- Losses obviously because of faults, vugs, natural fractures, high permeability sands and gravels or caverns

Losses are very likely off bottom when:

- Losses are encountered during raising mud weight or drilling fast
- Losses occur after shutting in the well or killing it
- Mud weight is higher than the fracture gradient of the last casing shoe, which can be referred to poor design (no safe drilling window)
- A weak zone is broken down

(Messenger 1981)

2.3. Lost Circulation Severity

Lost circulation events might be classified by their severity. As mentioned earlier, losses are classified as seepage when they are below 10 bbl/hr (1,6 m^3/h), partial when greater than 10 bbl/hr (1,6 m^3/h) but below 100 bbl/hr (16 m^3/h), severe when greater than 100 bbl/hr (16 m^3/h) and total when there are no returns at all (100% losses). This classification is convenient, but is not going into detail about the mechanism behind, the origin or the fracture properties. (Lavrov 2016)

2.3.1. Minor Partial Losses (seepage)

Seepage losses occur in any formation type and can appear as perceived losses or be induced by a couple of factors, usually from drilling operations. Perceived losses are losses which are actually non-existing, for example while drilling at a high ROP through competent rock. One cause can be for instance the displacement of cuttings, new drilling fluid is replacing the filtered solids. New hole volume can so easily be misread as minor loss. Before applying any treatment to seepage losses, it is therefore important to know the origin of the losses. The common guidelines and control techniques are as follows:

Drill Ahead and Track Losses

Depending on the mud cost and the distance until casing setting depth, seepage losses may be tolerated. Also drilling is often continued with the intention that cuttings will seal the interval.

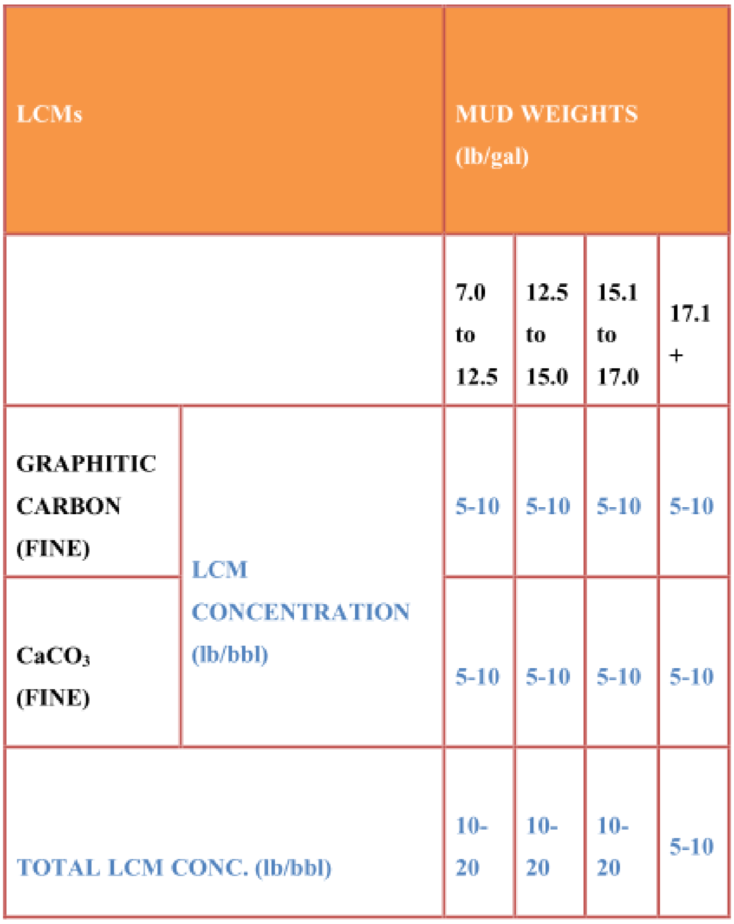
Pull Up and Wait

This technique is usually used to resolve minor losses due to induced fractures. Especially in this use case fractures may close after stopping circulation, depending on whether the fracture propagation pressure was exceeded. Drilling fluid is then “exhaled” into the borehole. This effect is called borehole breathing. Fracture closure and “healing” can take from two hours up to half a day. This NPT is can be potentially used for maintenance.

Pre-treat with LCM

Pre-treating with LCM can be applied either when the problem comes up or as a preventive measure. Proven primary materials are calcium carbonate and graphitic carbon. The used particle size will depend on pore size, possible fracture size and permeability of the current interval. A quick guideline regarding the recommended amount of LCM is shown in the following figure.

Table 1: Recommended Amount of LCM to Pre-Treat (Tetteh-Fiagbor 2011)



LCMs		MUD WEIGHTS (lb/gal)			
		7.0 to 12.5	12.5 to 15.0	15.1 to 17.0	17.1 +
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

Excursus: Find the Right LCM Size to Combat Seepage Losses

To control seepages losses, properly sized LCM is usually necessary. To figure out the correct size, knowledge of pore throat size or fracture size is ideal. Formation samples or wellbore-imaging are typically of great assistance. The Ideal Packing Theory (IPT) is then defining the proper particle size distribution (PSD) to work against seepage losses. This is to avoid that particles are too large.

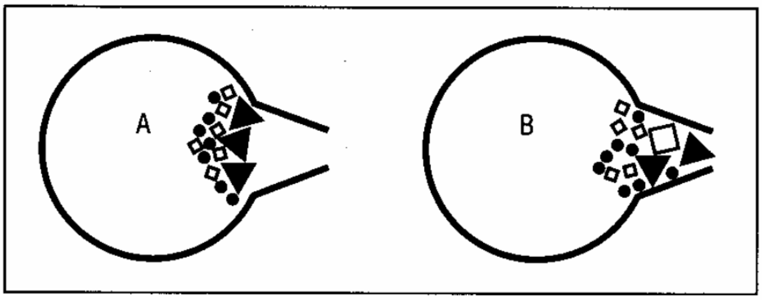


Figure 5: Results Using too Large LCM vs. Proper Bridge Forming (Power et al. 2003)

Too large particles would not enter the fracture completely and build up the bridge still in the wellbore, which leads to early erosion and a possible reopening of the fracture. Too fine particles go straight through the opening and do not build up a bridge. Not just the right treatment, but also the right mix/size decides, if a corrective measure is going to be successful.

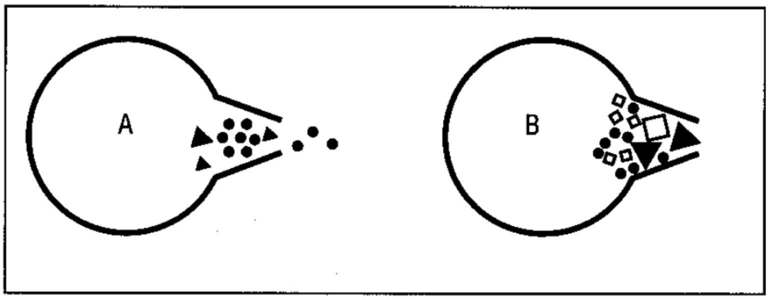
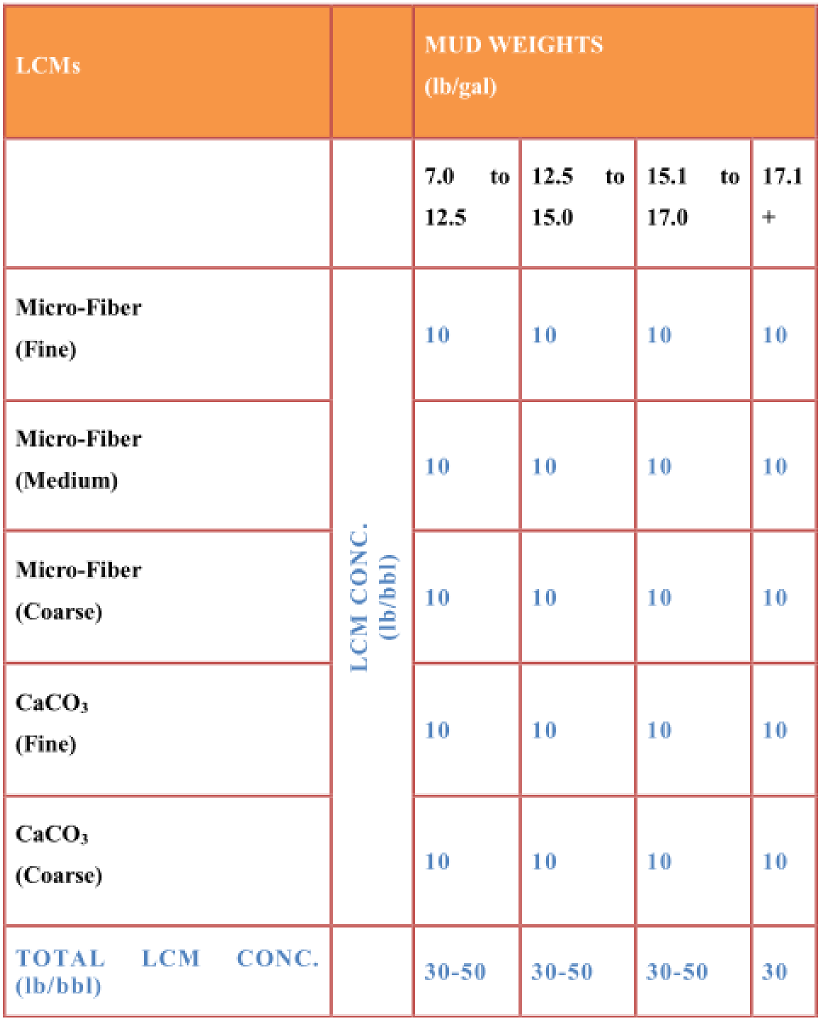


Figure 6: Results Using too Small LCM vs. Proper Bridge Forming (Power et al. 2003)

2.3.2. Partial Losses

Partial losses usually occur in natural, small fractures, gravels and slightly opened induced fractures. This kind of losses can mostly be cured and prevented with LCMs. A recommended amount of LCM can be seen below.

Table 2: Recommended Amount of LCM for Partial Losses (Tetteh-Fiagbor 2011)



LCMs		MUD WEIGHTS (lb/gal)			
		7.0 to 12.5	12.5 to 15.0	15.1 to 17.0	17.1 +
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

2.3.3. Severe and Total Losses

Losses are severe when exceeding 50 bbl/hr and are being considered total when no mud returns. This kind of losses usually happen in large natural fractures, interconnected vugs, caverns, long open gravel sections, wide apart induced fractures. Severe or total losses are hard to treat. A cure might be impossible. Possibilities can be drilling with aerated mud or drilling blind.

Drilling Blind

Used in severe or total loss events, drilling blind is typically applied when a cure is either not economical or has a minor chance of success. Drawbacks on drilling blind can be inadequate hole cleaning, sloughing formation, insufficient well control and stuck pipe. To best possible avoid stuck pipe, the pumping rate should not be lowered while drilling without returns. When drilling blind, the fluid is sacrificed. This sacrificial fluid can be even water. Depending on economy, infrastructure and storage on site, planned mud weight is sustained.

In the following decision tree, all types of losses are discussed regarding their severity.

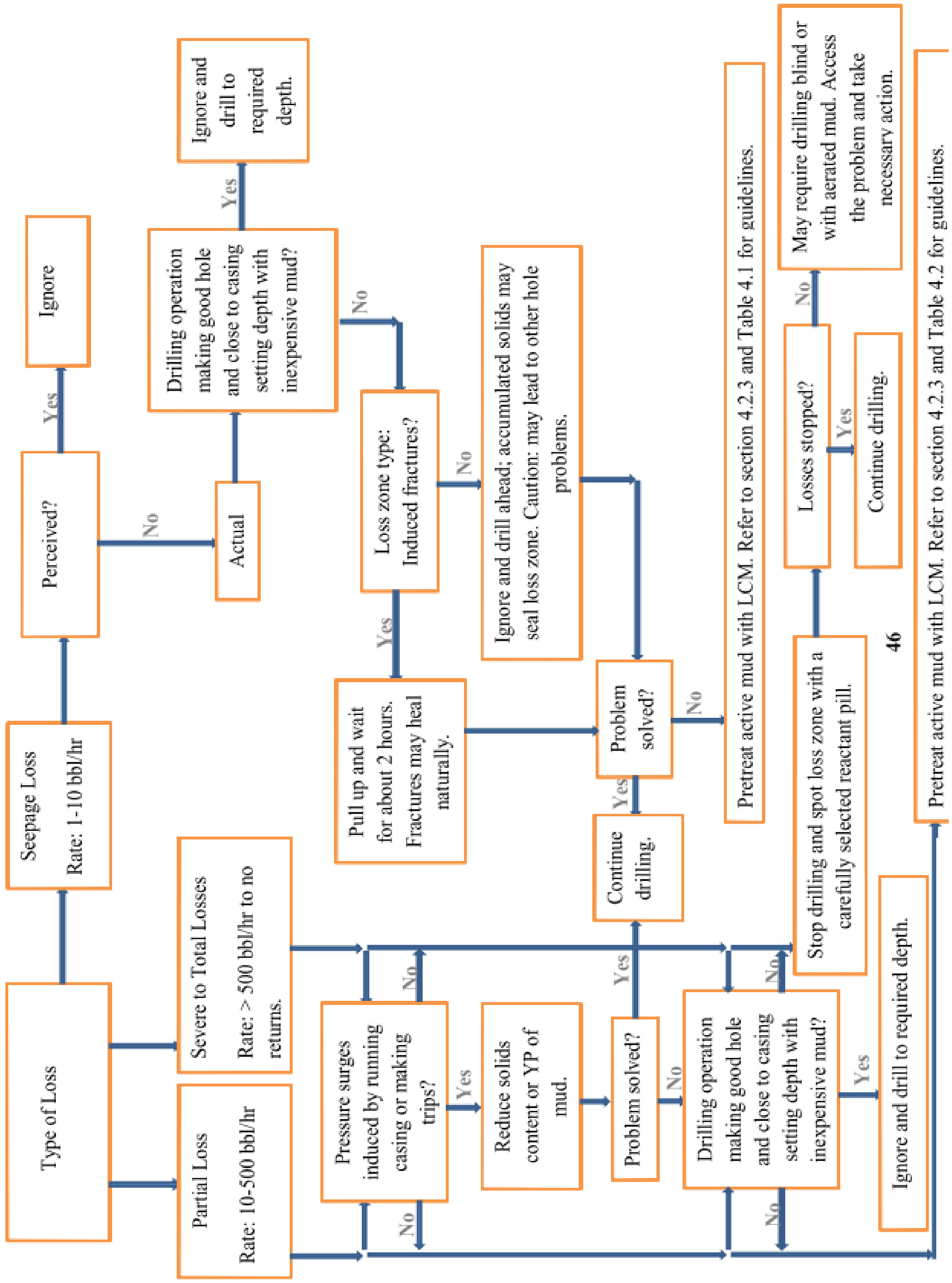


Figure 7: Decision Tree Regarding Severity (Tetteh-Fiagbor 2011)

2.4. Classification of Lost Circulation Zones

For losses to occur, two conditions must exist:

- Permeability in a formation so that drill fluid can pass from the borehole
- Pressure difference or overbalance between formation and borehole

Both conditions must exist concurrent, one may be predominating. In the following paragraph the most usual lost circulation zones are described. Those are in particular permeable zones, caverns, natural fracture zones and induced fracture zones. Moreover, this thesis will have a consider mature and depleted reservoirs, high-pressure high-temperature wells, long horizontal sections and deep-water drilling.

2.4.1. High-Permeability Matrix

This kind of formations nearly seem to provoke lost circulation events. Losses into permeable matrix happen when it is subjected to drilling mud. High-permeability formations can be for instance rubble zones, depleted reservoirs or unconsolidated formations, showing high permeability as displayed in the following figure. Since the permeability in these zones is usually between 10 and 100 Darcy, the drop in the mud pit is conspicuous. If drilling goes further, losses can be severe or total. Examples for this kind of formations are gravels and shallow sands.

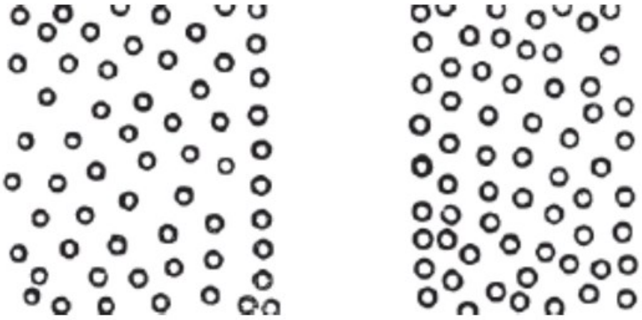


Figure 8: Unconsolidated Formations (Datwani 2012)

Typically, it takes time to reduce losses of this kind. Gradually, a filter cake is built up and mud losses start to decline. Usually losses will not fully stop until the end of the high-permeability interval is reached. The behaviour of the mud loss flow rate and the pit level can be seen in the following figure.

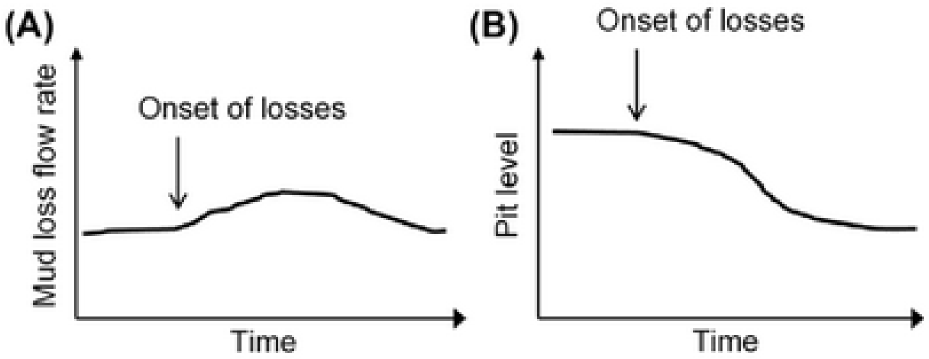


Figure 9: High-Permeability Matrix Losses (Lavrov 2016)

Excursus: Sub-Salt Rubble Zones

Rubble zones immediately below salt formations can be bothersome for many reasons. Often the zones directly below salt formations are either fractured or mechanically weaker, indicating a higher risk for losses. This so-called “thief zones” can be thin and are typically highly fractured rock, e.g. shale. A common problem in the Gulf of Mexico is that wells have a higher pore pressure just below salt formations, creating serious issues regarding well control, because the higher Equivalent Circulating Density (ECD) puts even more stress on this already weakened thief zones. Losses in these zones are often severe or total, typically above 100 bbl/hr (16 m^3/h), combined with the inability to keep the annulus full. A lot of different lost-circulation materials (LCM) were applied below salt formations to control the severe or even total losses. Pills containing gunk squeezes, sized solids, foamed cement and conventional cement squeezes have achieved good results. However, rubble zones typically feature a deep and wide network of fractures. Filling this network has ever been a gauntlet. The best available strategy on sub-salt rubble zones seems to be the Cross-linked Polymer Pill (CPP), consisting of fibrous material and cross-linking polymers. Activation of the agents is done by temperature and time. A fully controllable setting time is achieved by either a accelerator or a retarder. The CPP reduces non-productive time (NPT) and provides an effective sealing. (Power et al. 2003)

2.4.2. Cavernous Formations

Vugular or cavernous formations are mostly to be found in limestone formations that have been washed out by water, usually occurring with a sudden drilling fluid loss. Just before that loss is visible in the mud pit, the drill bit drops in to a new zone - typically between inches and some feet. When drilling becomes rougher just after the drop, the loss kicks in. Because those formations can vary a lot in proportions or can even be connected to other zones, it is often hard to seal them as the following figure shows.

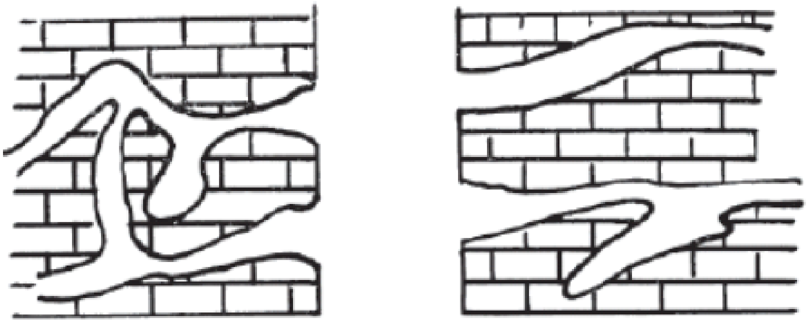


Figure 10: Vugular Formations (Datwani 2012)

The lost volume can be substantial, especially if multiple vugs are connected to each other. Even total losses can arise. A potential loss signature can be seen in the following figure. Losses start abruptly and mud loss flow rate is high.

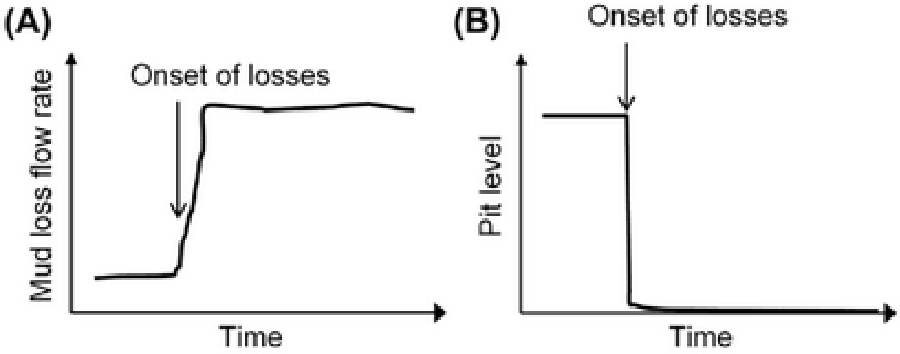


Figure 11: Vugular Formation Losses (Lavrov 2016)

The pit level in figure 11 (B) is showing an instant pit level loss. This loss is exaggerated and depends the pit volume and time frame. This kind of losses can also show less slope in pit loss.

2.4.3. Natural Occurring

Secondary permeability and porosity are advantageous to losses as well. Natural fractures typically occur in every rock type. Natural occurring fractures are either vertical or horizontal depending on mechanical characteristics, stress and depth. A slowly decreasing mud pit is a good indicator for horizontal natural fractures. Vertical natural fractures will take place progressively. Continued drilling then potentially leads to more fractures, which can cause a total loss of the drilling fluid. A usual type of natural fractures is shown in the following figure. For visualisation, this figure is not true to scale.

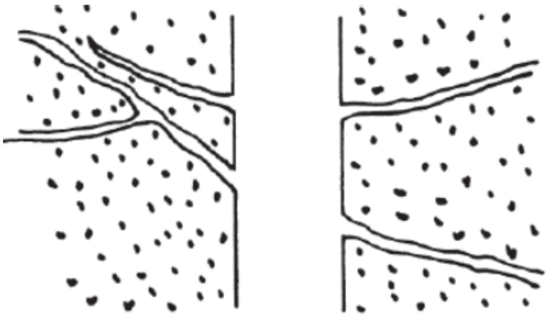


Figure 12: Natural Fractures (Datwani 2012)

Basically, losses due to natural fractures are depending on the following factors:

- Composition and rheology of the mud
- Filter cake build up and fracture wall leak off
- Hydraulic aperture
- Wellbore pressure
- Potential fracture network

A signature of mud losses due to natural fractures can be seen here:

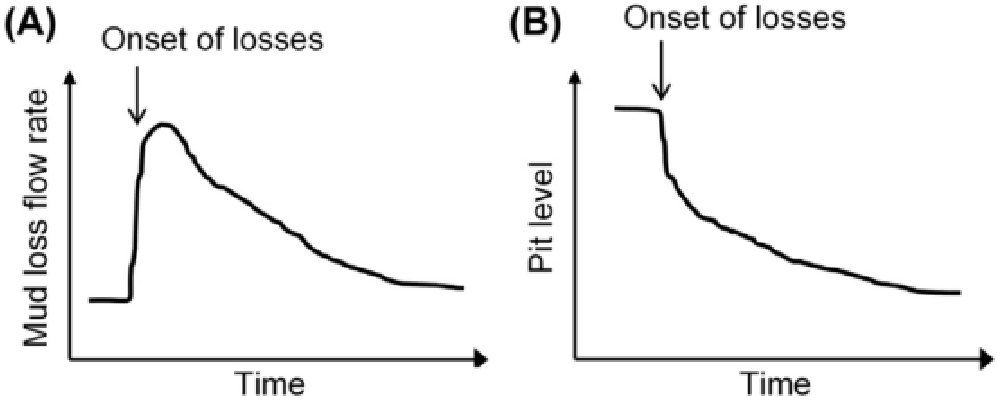
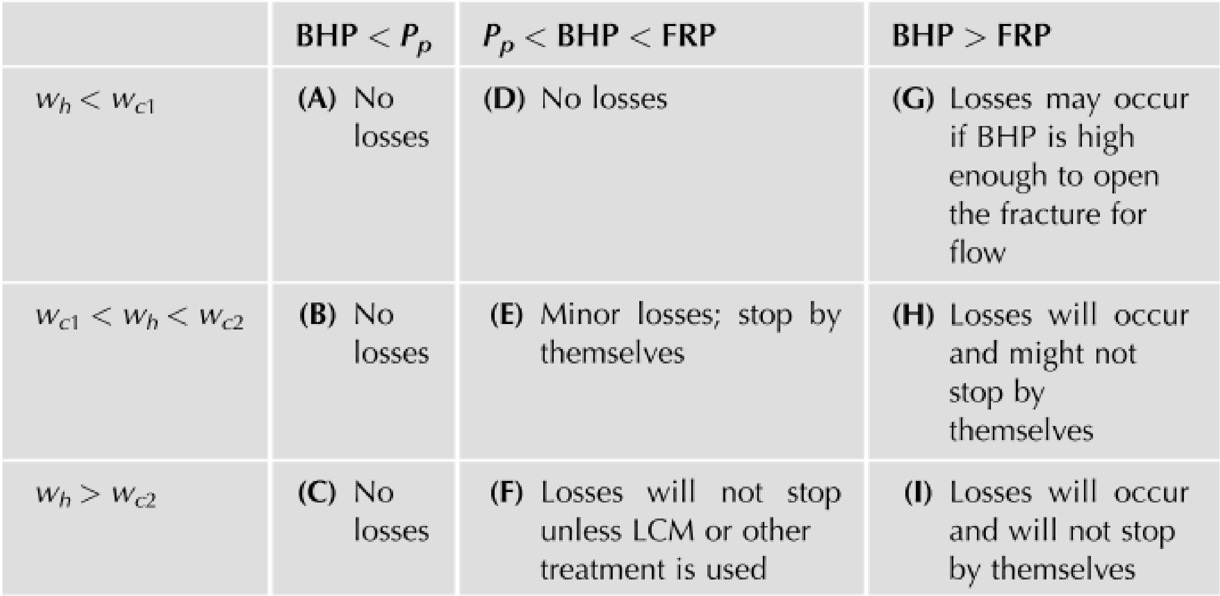


Figure 13: Natural fracture mud losses (Lavrov 2016)

Initially, the drilling fluid runs into the naturally open fracture. After this sudden loss, solids aggregate and gradually decrease the loss flow rate.

To actually cause losses, adequate permeability and width of the fracture must prevail. Also, not all natural fractures automatically cause mud losses. In case it is impermeable, too narrow, closed or filled it is not prone to losses. On the other hand, if natural fractures form a network their capacity for losses can be just about limitless. The main factors regarding drilling operations are the bottom hole pressure (BHP) and the hydraulic aperture. Possible cases are provided in the following table.

Table 3: Natural Fracture Loss Cases (Lavrov 2016)



	BHP $< P_p$	$P_p <$ BHP $<$ FRP	BHP $>$ FRP
$w_h < w_{c1}$	**(A)** No losses	**(D)** No losses	**(G)** Losses may occur if BHP is high enough to open the fracture for flow
$w_{c1} < w_h < w_{c2}$	**(B)** No losses	**(E)** Minor losses; stop by themselves	**(H)** Losses will occur and might not stop by themselves
$w_h > w_{c2}$	**(C)** No losses	**(F)** Losses will not stop unless LCM or other treatment is used	**(I)** Losses will occur and will not stop by themselves

w_h – Hydraulic Aperture

BHP – Bottom Hole Pressure

w_c – Critical Fracture Aperture

FRP – Fracture Reopening Pressure

P_p – Pore Pressure (fluid pressure in fracture)

2.4.4. Induced Fractures

Induced fractures are fractures, which were created while drilling. Those fractures occur if the BHP is greater than the fracturing pressure of the formation and fractures are induced in the direction of the least resistance. In the following figure, the formation and the zones of an induced fracture are shown oversimplified. In the field, an induced fracture would propagate in three dimensions.

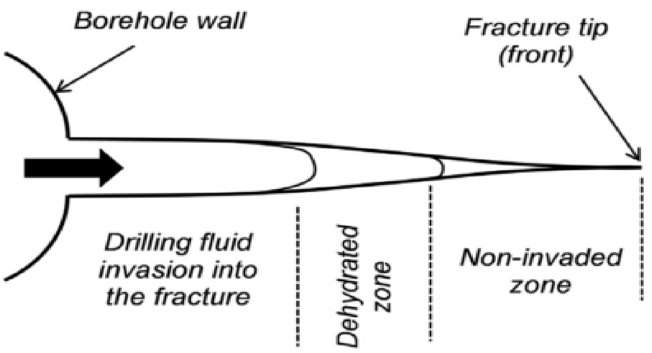


Figure 14: Induced Fracture Zones (Lavrov 2016)

Induced fractures can occur in every rock type but are basically common in weak formations. Losses can be described as rapid if drilling is continued. Typically, induced fractures appear drilling or cementing related. The following figure shows induced fractures because of heavy mud. Other reasons for this kind of fractures can be excessive or wrong handling of the tools, well irregularities and too much back pressure.

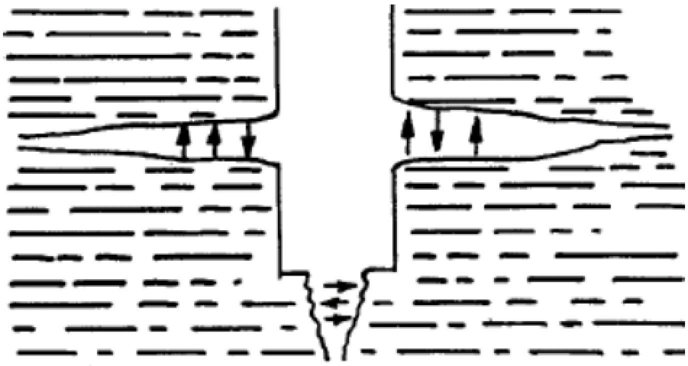


Figure 15: Induced Fractures (Datwani 2012)

2.5. Special Cases

Depleted Reservoirs

Certain formations and well types have a potentially higher risk for lost circulation. Starting with depleted reservoirs, several types will be discussed in this chapter.

Depleted reservoirs have a higher chance for lost circulation. This is mainly because of their decreased total stresses and pore pressure. Moreover, it is likely that there are depletion-induced fractures present. Because those reservoirs are depleted and the pore pressure is reduced, operating with the same mud weight as in the rest of the well will lead to higher overbalance, which can promote losses.

Since total stresses reduce during depletion and therefore the fracturing pressure is decreased, fractures can be easier induced. Furthermore, the reservoir can be depleted heterogeneously. In that case the pressure decrease, because of the already produced fluids, can vary within the reservoir. This is shown in the following figure. Case A describes a homogeneous depletion, whereas Case B displays heterogeneous depletion. In Case A, the depletion is consistent and equally over the sector. A safe drilling window can be applied.

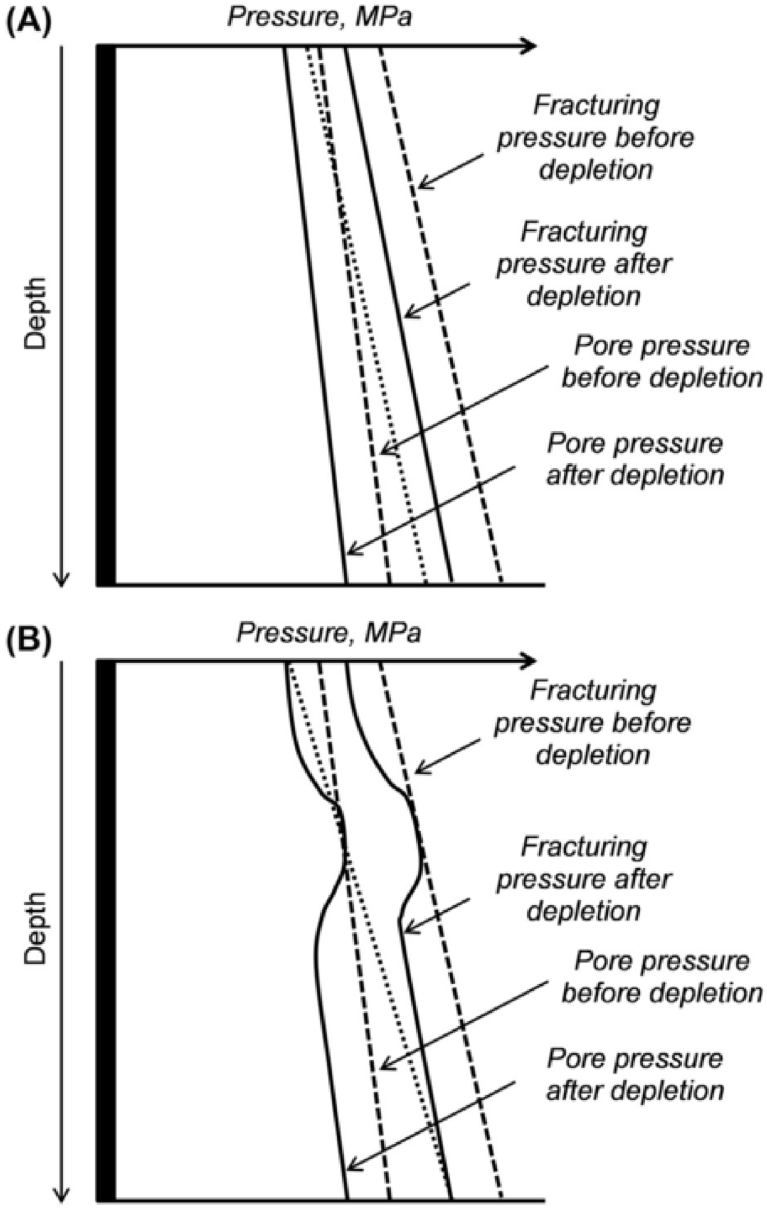


Figure 16: Pore and Fracture Pressure in a Depleted Reservoir (Lavrov 2016)

Case B shows an irregular pattern of depletion; a safe drilling window seems not possible. In Case B, it is therefore highly recommended to use either another casing point or to employ MPD. MPD in a long horizontal well can be a problem, though. MPD can just manage the pressure at one point and high pressure losses would move to ECD problems at another point in the well. Loss or gain at one of the points would be the consequence.

Deepwater Drilling

In deep-water drilling, there are a couple of reasons why lost circulation is more likely. In deep-water drilling a riser is used, which increases the risk for lost circulation. The narrow operating window and reduced rock strength on and just below the sea floor (sediments) are to consider as well. The fracturing pressure of it can be just over the hydrostatic pressure, as shown in the following figure.

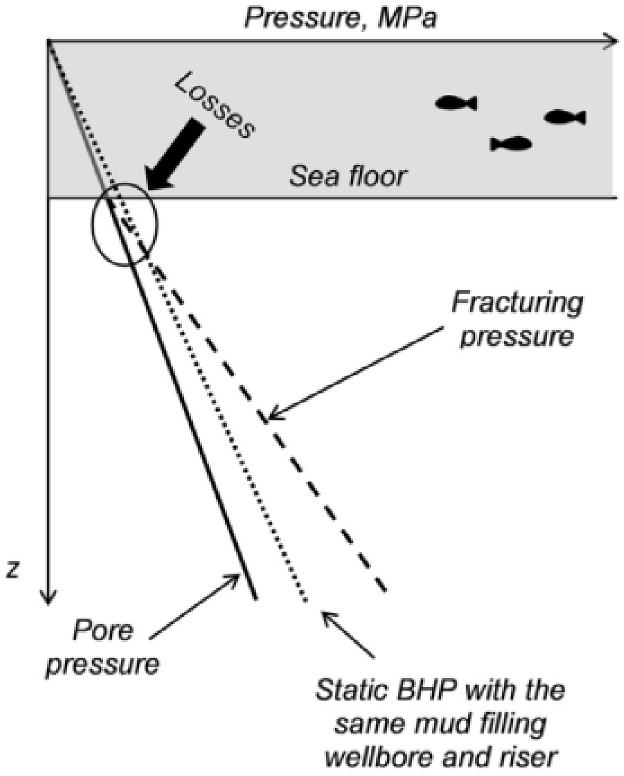


Figure 17: Operational Window Deepwater Drilling (Lavrov 2016)

A standard solution is the so-called “pump and dump” technique and includes releasing some of the up-streaming mud to lower the pressure. Also, MPD or a subsea pump are a possibility.

High-Pressure High-Temperature Wells

In high-pressure high-temperature (HPHT) wells lost circulation is more likely because of degraded mud properties and decreased drilling margins. The decreased margin is an immediate consequence of higher pore pressure.

One of the issues are the drill cuttings. Due to the high temperature, the mud might be thinner and unable to lift the solids sufficiently. Moreover, the ECD can be lowered by this effect. Consequently, solids settle down and cause a higher mud weight in the lower part of the annulus. This both conditions might be another treat for continuous circulation.

Another issue can be the cooling-effect of cold mud streaming downhole. The reduction of the hoop stress leads to an even narrower margin. Casing needs to be run more frequently, which pushes this issue in an economic direction, too.

Horizontal and Deviated Wells

Deviated and horizontal wells regularly experience problems with lost circulation because of higher frictional pressure losses, stress anisotropy and worse hole cleaning. A higher stress anisotropy leads to a more instable well. The lower mud weight therefore increases, resulting in a reduced margin up to the point of no margin at all, which is shown in the following figure.

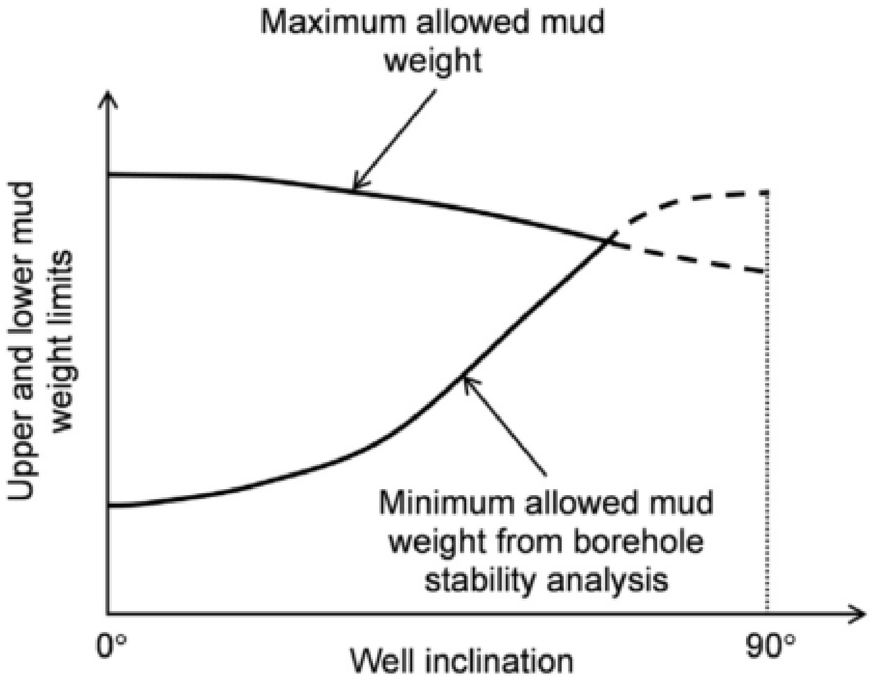


Figure 18: Mud Weight Window for Inclined Wells (Lavrov 2016)

As upper border either the fracture initiation pressure (FIP) or the formation breakdown pressure (FBP) could be chosen. The lower mud weight limit is influenced by the well stability. In case of parallel faults, the fracture propagation pressure (FPP) needs to be considered as well.

Another problem comes along with extended horizontal sections. While the true vertical depth (TVD) and the in-situ stresses remain almost constant, the measured depth (MD) increases. With that given, the fracturing pressure would only change because of geological heterogeneity. Simultaneously, the annular pressure loss (APL) increases, which consequently increases the BHP. At a given point, the BHP will pass the fracturing pressure and cause mud losses.

Furthermore, the worse hole cleaning keeps more cuttings downhole and decreases annular velocity. Moreover, the horizontal laying drill string interferes with hole cleaning and mobilising large volumes of cuttings can lead to crack openings. All this together can cause peaks in the BHP, consequently inducing mud losses.

2.6. Operational Concerns

Dynamic Losses

Dynamic losses only occur while circulating or when the drill string is creating surge pressure (either pumps or pipe movement). As soon as the pumps, respectively they pipe movement, are stopped, dynamic losses no longer take place. These ECD driven losses can be controlled by lowering the mud weight, also MPD can be an option in these particular zones. If dynamic losses are unstable, drilling should not be proceeded until losses are diagnosed and stabilised or cured. When dynamic losses happen, POOH can be possible.

Static Losses

Static losses occur when the well is not being circulated and the drill string is stationary (no pumps, no movement). Static losses can be a problem for well control, depending on the static loss rate. The operator may limit the ability to POOH, if well control is problematic. Having said that, the options to treat those losses are then limited to what is possible with the current BHA in place. The use of cement can jeopardise the expensive BHA, large particle sized treatments can block the BHA (e.g. nozzle size may be limiting). When static losses happen, POOH is not possible.

Excursus: Wellbore Breathing

The beginning of wellbore breathing is typically the indicator of upcoming lost circulation. Wellbore breathing is a phenomenon happening when a formation takes mud in case pumps are active and the ECD exceeds the formations pressure. After taking the pumps off, the mud returns as soon as the created micro fractures close again.

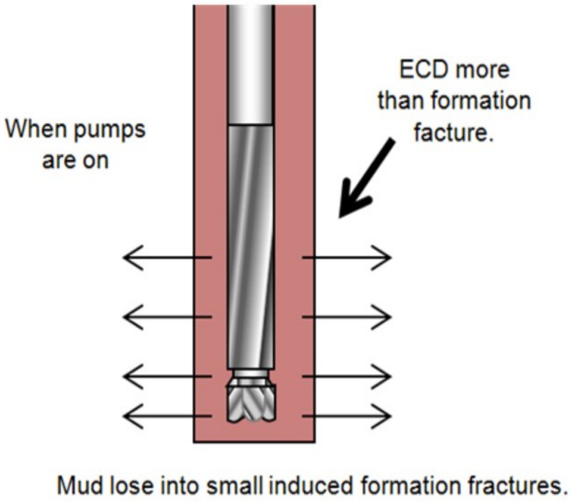


Figure 19: Pumps are Active (Power et al. 2003)

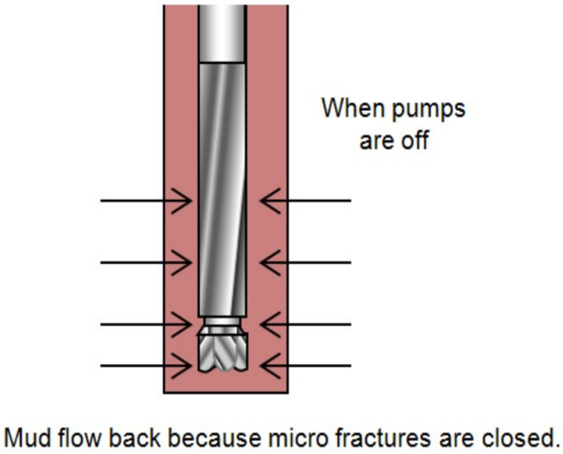


Figure 20: Pumps are Inactive (Power et al. 2003)

The flow back will be observed when the pumps are off. Wellbore breathing is possible to occur due to cold mud which alters the formations, producing fractures, pressure spikes or natural fractures. Returning mud must not be interpreted as kick. A more appropriate reaction would be to lower the mud weight or ECD. Monitoring the flow back, also during connections, can be of great help to diagnose wellbore breathing.

Typical volumes of wellbore breathing are 4-55 m^3 (25-350 bbl). Moreover, borehole breathing can occur due to the fluid compressibility, thermal contraction/expansion or by thermal fracturing (cooling effect). However, one barrel volume from the reservoir is not the same volume on surface anymore. That has to be considered.

In the following figure, the temperature difference between the mud and the formation is shown. As relatively cold mud is pumped, it is going to get warmer on its way downhole. However, the mud is colder than its surroundings when it exits the nozzles. On its way up in the annulus, it is still being warmed by the formation until, at some point, the mud temperature is equal to the formation temperature. While traveling further up, the mud is warmer than the formation.

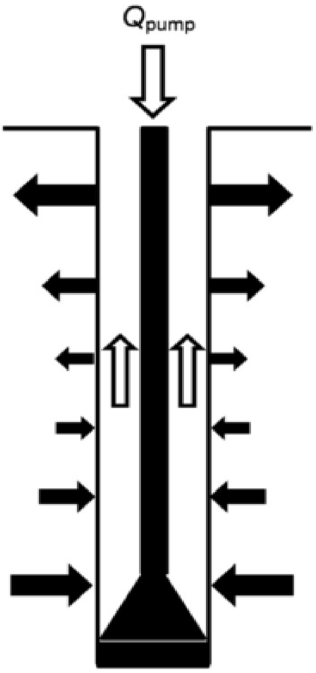


Figure 21: Thermal Difference of the Mud and the Formation (Lavrov 2016)

In case the pumps are stopped and the temperature of the mud equalises with the formation, the pit gain can be several per cent, but will temperature differences will become negligible after a few circulations again. A common temperature gradient in the industry is 2-3K/100m but can be up to 4K/100m in regions with volcanic activity. However, cold mud means thick mud, which increases the ECD when circulating again. All discussed effects of this excursus are illustrated in figure 22.

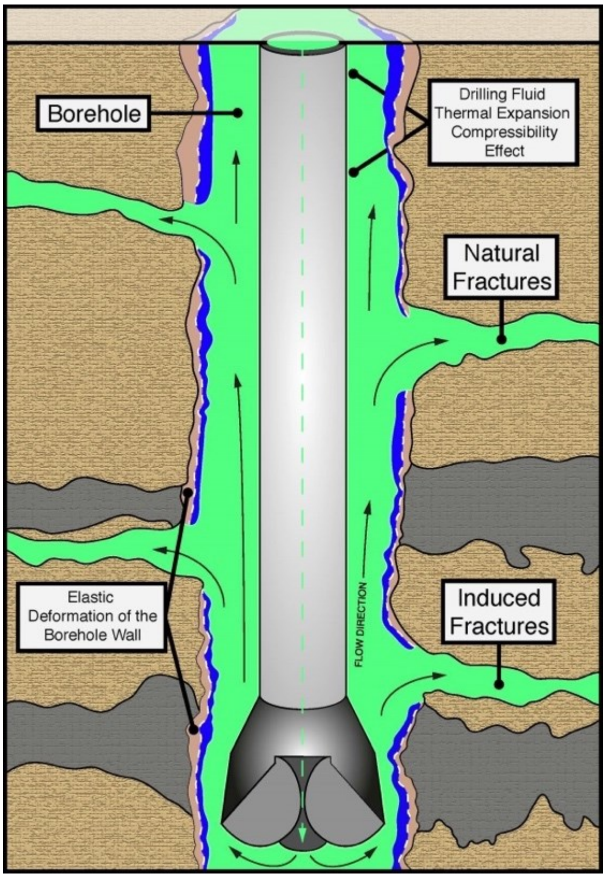


Figure 22: Borehole Breathing Main Causes (Elmgerbi et al. 2016)

Sustainable Losses vs. Unsustainable Losses

If it is established that losses are occurring down hole, the decision has to be made if the loss rate is sustainable. If inexpensive mud is being used or the losses occur near TD of the section, it may be deemed acceptable to 'live with the losses' even if loss rates are fairly high. The option to drill ahead with losses should always be considered, but it is a decision which has to be carefully made.

Distinguish between sustainable and unsustainable

- How long does the expected loss rate need to be sustained? (e.g. distance to TD)
- Are the losses economical tolerable? (e.g. cost of mud)
- Can the mud be built and supplied at the expected loss rate? (e.g. equipment)

To distinguish between sustainable and unsustainable losses in order to make a decision, these three questions should imply a first idea about which direction to take. Depending how far away from TD, these economical and technical concerns may give you the impression that the losses cannot be sustained long enough. Especially $300/bbl SBM can quickly become an economical limit. Also, the equipment on site can be limiting regarding a bbl/hr supply. The mixing rate might not be sufficient. Chemicals or replacements, even base oil for OBM can be the missing ingredient. Mainly logistics are depending on how remote the well is being drilled.

The primary concerns therefore are (drill ahead only if losses are dynamic):

- Distance to TD
- Economy
- Inventory and/or supply logistics
- Equipment

2.7. Other Lost Circulation Concerns

Initially, this paragraph should be distinguished between off- and onshore. In deep-water there many more challenges, like the close operating window between fracture gradient and pore pressure. Regardless of whether drilling, cementing or running casing, it usually results in more than minor fluid losses. Successful management is the most important objective in case lost circulation is encountered. To give a better idea about how lost circulation can happen, this part of the thesis addresses other lost circulation causes and drafts a recommended solution how to manage it.

Running Casing

Displacing the drilling fluid with heavier cement can lead to excessive displacement and so-called “u-tubing”. In worst case this can cause the breakdown of the shoe because of too high friction pressures and flow rates. Auto-fill equipment has evolved drilling to fewer losses while running pipe, directing the displaced mud along the way of least resistance and lowering the frictional pressure losses – minimising the breakdown risk of the shoe. Moreover, advanced models regarding the hydraulics have shown significant benefit, providing a schedule for running pipe at defined rates, maintaining the ECD in a controlled window and under the last leak-off test (LOT). This also includes alarms when approaching the LOT value – warning the driller to reduce speed.

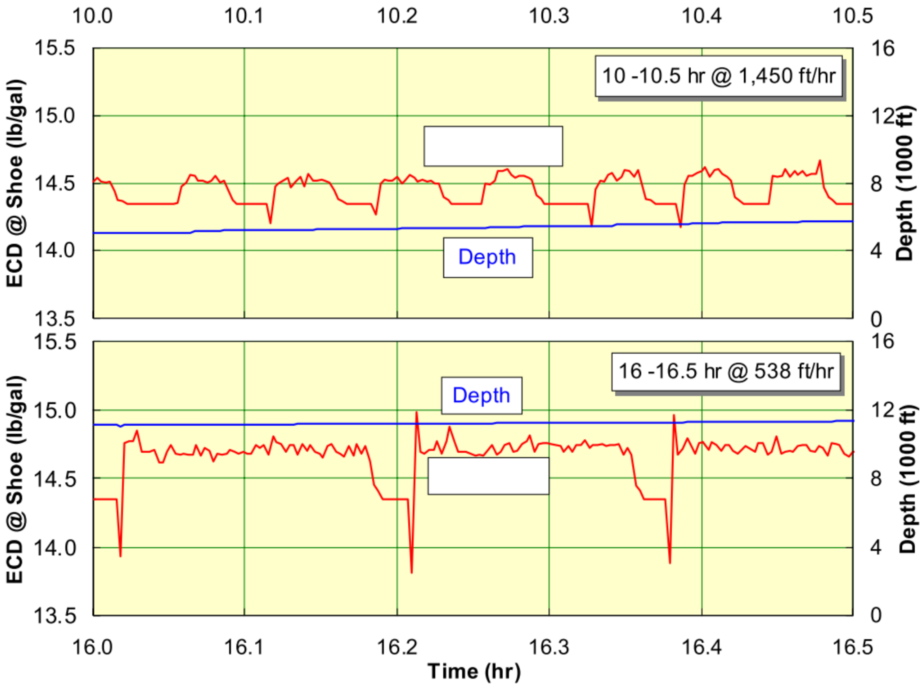


Figure 23: Exceeding ECD in a Real-Time Hydraulics Software (Power et al. 2003)

As reaching certain depths, the running speed should be lowered. In the shown example in figure 23, the running speed was reduced to 538 ft/hr as reaching the open hole section.

Excessive Rate of Penetration (ROP)

Especially in deep-water, a combination of powerful rigs, aggressive bits and softer formations can lead to excessive rates of penetration, which can result in problems regarding hole cleaning. Cuttings are faster generated as they can be removed from the very bottom. Formation breakdown and pressure spikes are possible consequences, which can initiate loss of circulation. Equipment should be adequate to the ROP. In this case, it should be kept a watching brief over hole cleaning.

One of the most obvious strategies to minimise the risk is controlled drilling in order to prevent over-generation of cuttings. Moreover, less aggressive bits can be chosen. Regarding field data, smaller cutters do not inevitably decrease ROP in synthetic-based muds. To act prophylactic, circulating before pumps down for brief periods can help to prevent lost circulation due to an over-generation of cuttings. In highly deviated wells high density sweeps and in vertical wells high viscosity sweeps have shown effective cleaning performance.

In the real world, with less than ideal conditions, a few things should be in mind when drilling with high ROP:

- Drill controlled
- Do not drill & circulate; avoid cuttings, surges (back reaming)
- Use a slow bit
- When drilling vertical – high viscosity sweep might be an option
- When drilling horizontal – high density sweep might be an option

However, both sweeps increase the ECD. The vertical high viscosity sweep increases the hydraulic pressure and therefore the ECD, the horizontal high density sweep increases the ECD directly. If losses appear in the horizontal section, most likely the reservoir is reached. A high-density sweep when experiencing losses is the last thing to apply – highly counterproductive. If losses appear and cuttings need to be cleaned out in order to stabilise the ECD in the mud window, cuttings could potentially be lifted with foam – no further ECD increase.

Low-Temperature Drilling-Fluid Rheology

For the purpose of preventing lost circulation, yield point, gel strength and viscosity should be maintained at the lowest possible level which still allow effective drilling. Moreover, borehole cleaning is a requirement for good progress and helps to avoid lost circulation. The ECD can be increased by high viscosity and could, consequently, crack the formation. Downhole temperatures can exceed 300°F (149°C) and this viscosity gap can significantly increase the expected ECD, also increasing the chance of fracturing the formation. This temperature related behaviour of the viscosity is shown by the table below.

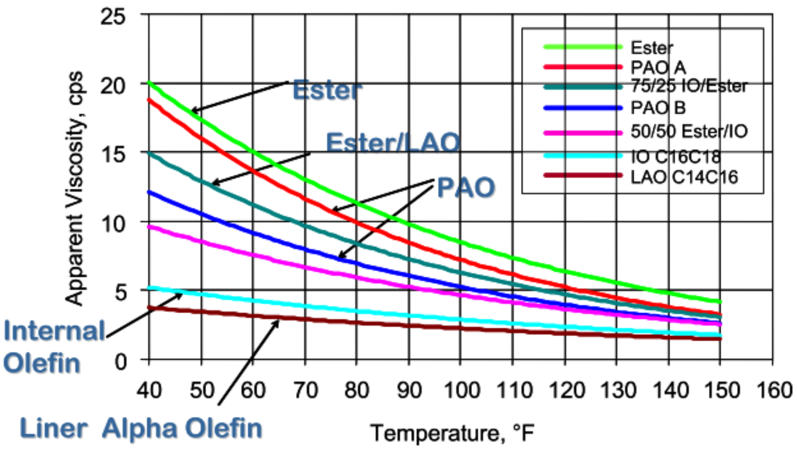


Figure 24: Temperature vs. Apparent Viscosity of Base Fluids (Power et al. 2003)

As presented in the table, Olefins can easily minimise temperature effects. Selecting a low kinematic drilling fluid ensures to maintain an acceptable rheology. Additionally, a modified drilling plan can take temperature effects in to account. This includes:

- Consistent gel breaking with pipe rotation and circulation
- Staged tripping (= breaking the circulation frequently when tripping in hole)
- Avoiding pressure spikes caused by rapid pump starts
- Avoid poor hole cleaning
- Replace solids laden mud with “new” mud would be another option

Synthetic-Based Fluid Compressibility

Not just temperature and viscosity influence the density of the drilling fluid. Also, the compressibility can be seen as a possible complication regarding lost circulation. While WBM hardly shows any pressure dependency and is supposed to be incompressible, SBM can vary strong. This behaviour automatically connotes a smaller margin to prevent lost circulation.

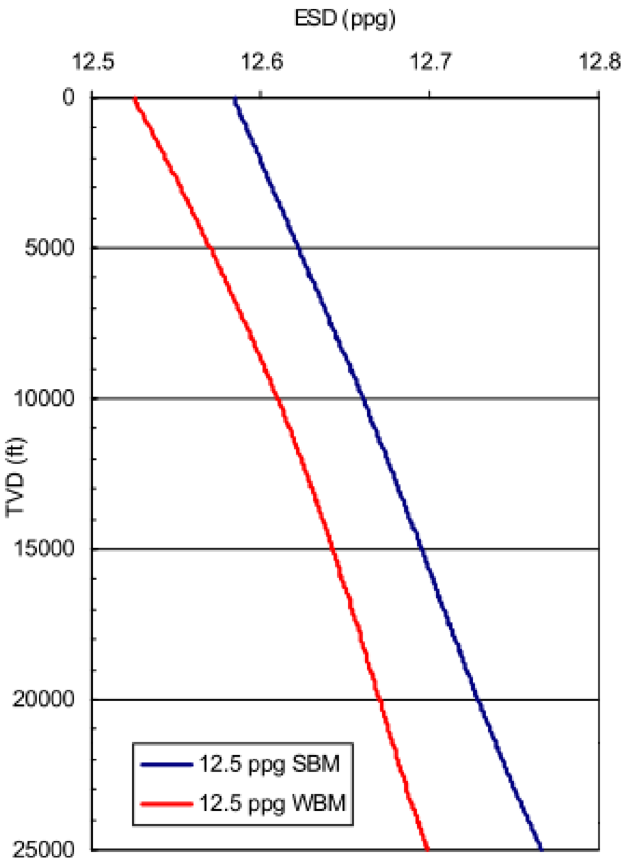


Figure 25: Equivalent Static Density WBM vs. SBM (Power et al. 2003)

The figure shows the different effects on SBM and WBM. While WBM just faces temperature effects, SMB changes its density with pressure and temperature. Thermal expansion and pressure compressibility form into a “net effect”, which needs to be compared with the WBM. Differences in behaviour should be modelled in the planning phase and minded in the drilling phase.

2.8. Summary

Typical causes for lost circulation can occur when favourable conditions take place. These conditions are for instance:

- Exposing a naturally fractured zone
- Induce fractures because of high-density mud circulating
- Smaller mud particles than pore openings
- Unconsolidated formations can fracture easily
- Channels provided by cavernous or vugular formations

Here is short summary how to diagnose a lost circulation situation step by step:

Step 1 “Establish the Loss Rate”

As a matter of routine, the monitoring of pit levels and returns should give early indications of losses. Once losses are observed, the loss rate should be carefully monitored as it could change rapidly. Loss rates are expressed in barrels per hour (bbl/hr). The definitions for loss rates are mentioned in this chapter:

Seepage losses:	< 10 bbl/hr
Partial losses:	10 – 100 bbl/hr
Severe losses:	> 100 bbl/hr
Total losses:	no returns or even unable to maintain the desired fluid level

Step 2 “Check on Surface”

It is important to confirm that the losses are occurring down hole and not at the surface. The following procedure would be recommended to do so:

- Check the solids control equipment to ensure that no new equipment has been placed online and that the discharge rates are normal
- Check to ensure that no mud has been dumped, transferred or otherwise removed from the system
- Check all flow lines, connections and valves for leaks and shakers

Step 3 “Is the Loss Rate Sustainable/Unsustainable?”

If it is established that the losses are occurring down hole, decide if the loss rate is sustainable. If inexpensive mud is being used or the losses occur near TD of the section, it may be deemed acceptable to ‘live with the losses’ even if loss rates are fairly high. The option to drill ahead with losses should always be considered, but it is a decision which should be carefully made. Consider well control and implications for cementing once the liner/casing has been run.

Step 4 “Characterise the Loss”

The following checks can be carried out to characterise the type of loss.

- Check the drilling program and check with personnel. Is this a potential zone for natural losses (e.g. natural fractures, porous formations)?
- Check for induced losses by considering the following options:
    - back off drill rate (ROP)
    - reduce pump rate
    - stop drilling and stop mud pumps for a short time
    - thin the mud
    - reduce mud density

Don’t experiment and jeopardize other well requirements (e.g. hole stability, well control, hole cleaning). If one of these methods cures the losses, the losses were induced by ECD effects and may not require LCM treatment. As another indicator, check PWD data and note if there was an increase in ECD just before the losses occurred. If so, this is indicative of induced losses. If losses are induced, consider reducing the mud density to get a permanent cure. If these methods fail to control the situation, LCM treatments will be required (static losses).

The following figure displays the mechanisms behind losses depending on the pit level. The upper left picture shows matrix losses:

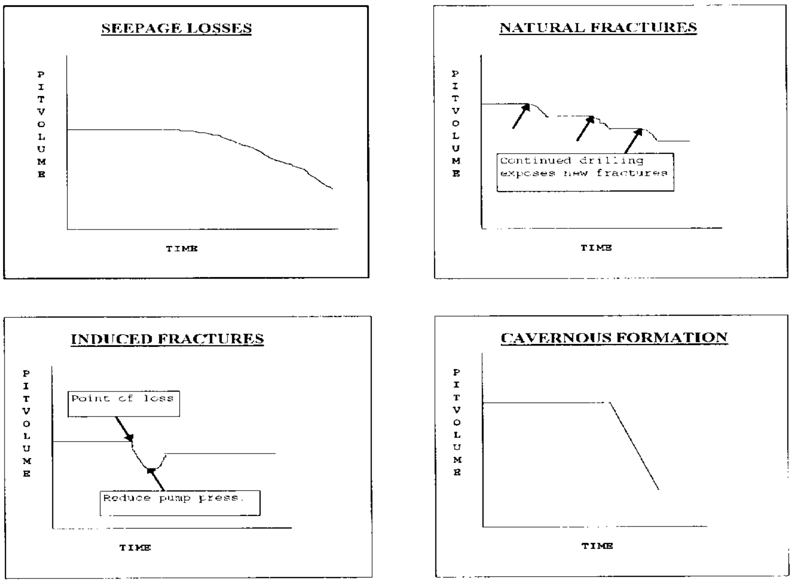
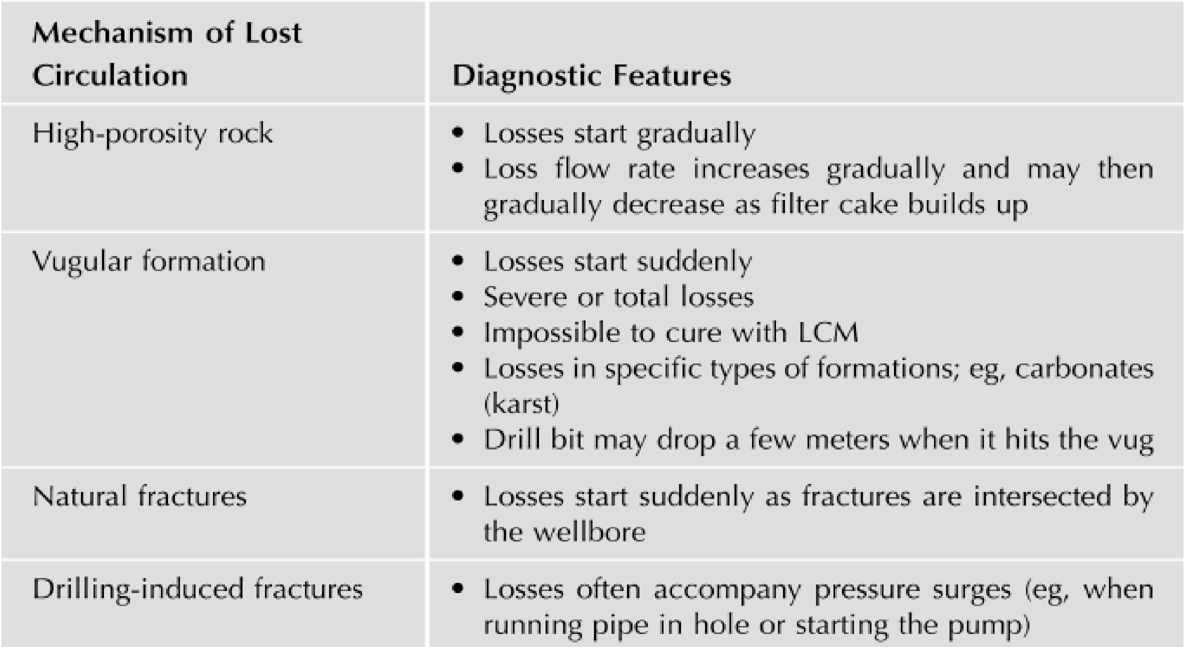


Figure 26: Pit Level Indicator Loss Mechanism (M-I SWACO, 2005)

The following table offers some diagnostic features for the most common mechanisms of lost circulation. Combatting mud losses requires awareness and a proper diagnosis of the location and the mechanism behind. Optimally, fracture properties are known as well.

Table 4: Diagnostics Loss Circulation Formations (Lavrov 2016)



Mechanism of Lost Circulation	Diagnostic Features
High-porosity rock	• Losses start gradually • Loss flow rate increases gradually and may then gradually decrease as filter cake builds up
Vugular formation	• Losses start suddenly • Severe or total losses • Impossible to cure with LCM • Losses in specific types of formations; eg, carbonates (karst) • Drill bit may drop a few meters when it hits the vug
Natural fractures	• Losses start suddenly as fractures are intersected by the wellbore
Drilling-induced fractures	• Losses often accompany pressure surges (eg, when running pipe in hole or starting the pump)

3. Cure Classification

During the last decades, lost circulation became more and more challenging. Big fields with thick reservoir opportunities are long gone. Now thin interlayered reservoirs are more in the focus. As the number of depleted reservoirs got higher and higher, the oil & gas industry uses already partially depleted or deeper reservoirs to keep production high. Some of them depleted, some of them virgin, but most of time the pore pressure is not fully understood. Drilling gets more difficult and lost circulation is more often encountered. Especially in long horizontal sections or extended reach wells. As this happens, more research is focussed on lost circulation developing further the available prevention and cure methods.

In order to apply the most suitable technique available, the loss zone should be evaluated in terms of its type, severity and location. The more accurately this is done, the better the technique can be matched.

When losses start, the usual way of dealing with it is to build up a seal to reduce the losses. Many, if not even hundreds, treatments are out on the market. The most important types are discussed in this chapter. This part of the thesis shall give an overview, which cure might or might not be effective against the most common situations.

3.1. Loss Cure Classification

Despite mechanical solutions, which are not an object of this thesis, measures against lost circulation can be classified into:

- LCM (flakes, walnut shells, calcium carbonate, synthetic graphite, fibres, etc.)
- Settable systems (cross-linked systems, cement, etc.)

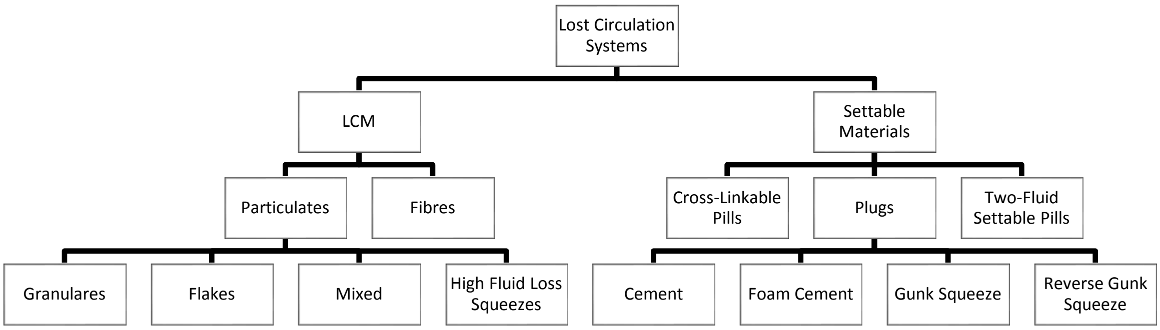


Figure 27: Loss Cure Classification

Settable materials basically form a semi-solid seal to prevent further losses. Including hardly any or no solids at all, settable materials are often easily pumpable and can get in any fracture width. Most of the materials used are insoluble, which restricts their application in or close to the pay zone.

LCM is available in wide variety. Even hog hair, chicken feathers, ground tires or alfalfa pellets have been used. The commercially used are for instance calcium carbonate, graphite, nut hulls and petroleum coke. Moreover, LCM has the advantage that it is possible to add it to cement, spacer and drilling mud. On the other hand, LCM is unable to enter fractures of every width, because it depends on the particle size used. LCM has also a maximum width to seal and bridge fractures. Thus, each LCM has an effective operating range depending on the product used to seal and bridge the formation.

Each mechanism has its weaknesses and strengths, making it work under specific conditions and surrender in another environment. Consequently, there is no universal treatment for lost circulation. Different conditions and formations require individual handling to cure losses. Developing or choosing a potential treatment usually happens with the help of operator depended decision tree. These decision trees reflect the current understanding and knowledge, individualised by the operators own experiences. There is currently no universally valid decision tree. Before developing the matrix to match the best cure, this thesis will discuss a few example decision trees, showing their strengths and potential weaknesses.

3.2. Lost Circulation Material

Before discussing how LCM actually works, the requirements for treatment systems should be stated and clarified.

The treatment should:

- Seal the loss zone
- Be compatible with the drilling fluids already in use
- Be easy to pump and without damage to the BHA
- Not damage the production zone, e.g. removable by acid
- Develop a strong seal to even withstand pressure differences in the wellbore
- Ideally resist back reaming

In order to seal and bridge the loss zone, fibrous and/or particulate LCM is pumped. The target hereby is to stop losses by plugging the pore throats and reducing permeability as much as possible. The following figures show which kind of LCM is able to seal which fracture size.

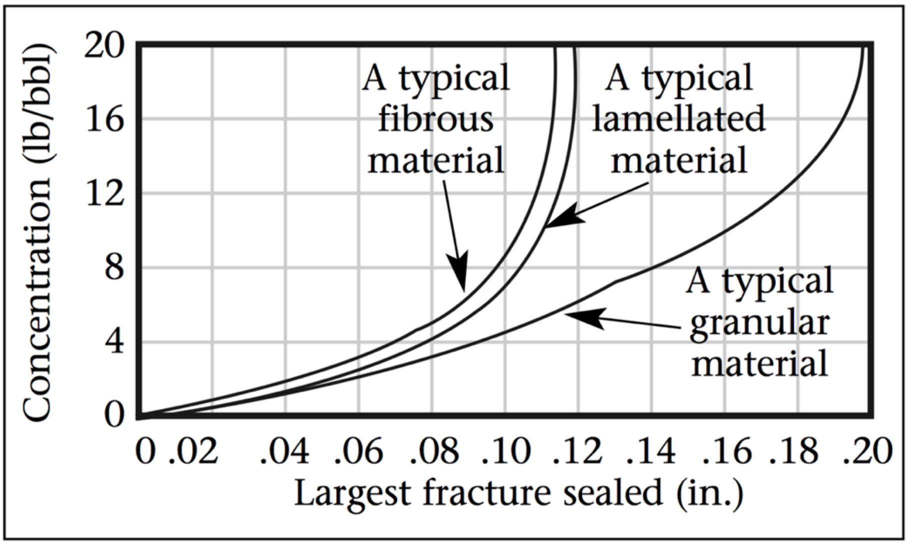
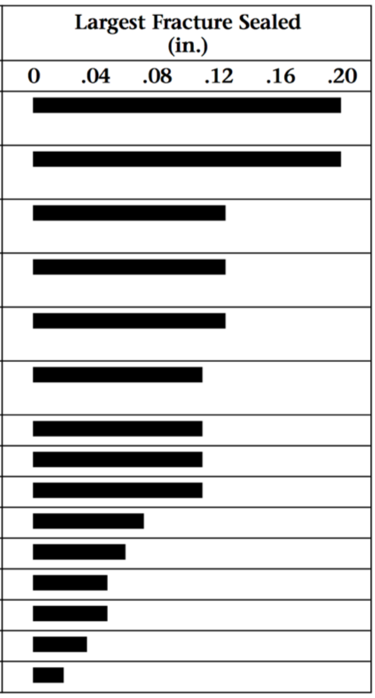


Figure 28: Type of LCM vs. Fracture Size (Messenger 1981)

This seal is typically build up near the mouth or in the actual fracture. The advantage of the seal being inside the fracture is that it cannot be destroyed by a simple drilling action. LCM particles should therefore be coarse enough to bridge but not too large to still be able to network with fibres and plugging agents.

Table 5: Material vs. Largest Fracture Sealed (Messenger 1981)

Material	Type	Description	Concentration (lb/bbl)
Nut shell	Granular	50% – 3⁄16+ 10 mesh 50% – 10+ 100 mesh	20
Plastic	Granular	50% – 3⁄16+ 10 mesh 50% – 10+ 100 mesh	20
Limestone	Granular	50% – 3⁄16+ 10 mesh 50% – 10+ 100 mesh	40
Sulphur	Granular	50% – 3⁄16+ 10 mesh 50% – 10+ 100 mesh	120
Nut shell	Granular	50% – 10+ 16 mesh 50% – 30+ 100 mesh	20
Expanded perlite	Granular	50% – 3⁄16+ 10 mesh 50% – 10+ 100 mesh	60
Cellophane	Lamellated	¾-in. flakes	8
Sawdust	Fibrous	¼-in. particles	10
Prairie hay	Fibrous	½-in. fibers	10
Bark	Fibrous	⅜-in. fibers	10
Cotton seed hulls	Granular	Fine	10
Prairie hay	Fibrous	⅜-in. particles	12
Cellophane	Lamellated	½-in. flakes	8
Shredded wood	Fibrous	¼-in. fibers	8
Sawdust	Fibrous	1⁄16-in. particles	20



The application of LCM has four stages. LCM firstly has to disperse, then to bridge, seal and lastly to sustain.

Dispersion is the first stage of the application of LCM. It means the delivery of the LCM to the intended position and preventing to get stuck or to plug the equipment.

Bridging means to develop a mechanical bridge across the aperture of the fracture. The bridge is supposed to provide enough mechanical strength for the upcoming sealing process. Yet, there is sufficient permeability to allow continued losses and more LCM to be supplied and deposited at the bridge.

Sealing is the process of forming a flow barrier with the help of fine particles. These fine particles create a filter cake and prevent further losses. This filter cake is on top of the bridge. Sealing reduces the permeability by filling the space within the bridge with fine particles.

Sustaining the loads is a crucial function the seal has to provide. Seal strength is characterised by the properties compressive strength and shear strength.

The following figure shows sealing as well as bridging. Stage A illustrates the fracture before LCM application. Stage B shows the bridge building process. In stage C fine particles form the final seal.

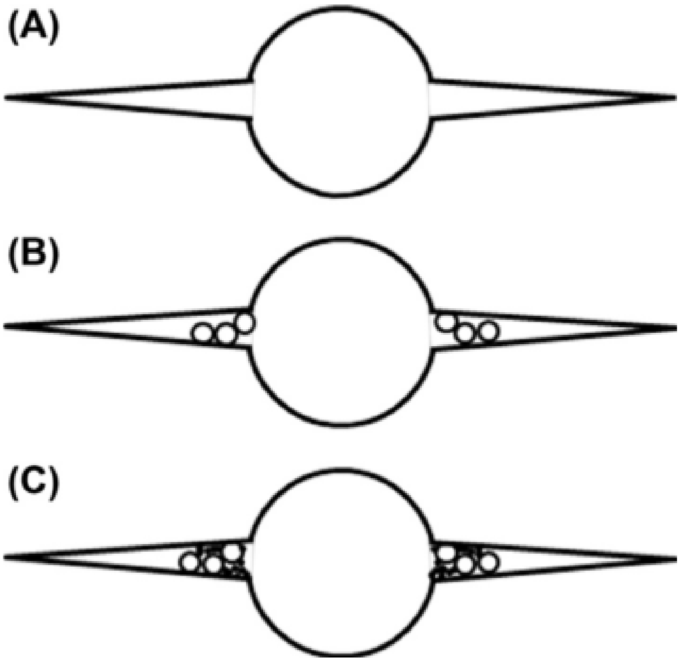


Figure 29: Sealing and Bridging (Lavrov 2016)

Additionally, effective LCM includes the following aspects:

- Safe to apply (e.g. personnel exposure chemical handling)
- Fast and easy to mix
- Seal sustains applied loads during the intended time
- Quickly reaches expected permeability (pump rate dependent)
- Does not block BHA (concentration and size dependent)
- Adequate thermal stability
- Mechanically robust during drilling and reaming operations

The basis for a filter cake, on the other hand, is a deposit on the borehole wall. One exception would be nano particles, which targets a permeability reduction by plugging pore throats. This LCM deposit on the surface of the borehole wall has a couple of risks:

- Fluid erosion
- Mechanical removal (e.g. back reaming)
- Thick filter cake (e.g. stuck pipe)
- Lift off during swabbing (e.g. pressure differential)

All the classic filter cakes require a positive pressure differential to stay in place, especially nano particle types.

3.2.1. Particulate LCM

Typically, sized solids are placed in the loss zone to stop the flow from the well into the thief zone. Those solids are commonly calcium carbonate, hackled walnut hulls, perlite, gilsonite, synthetic graphite, flake-type material (e.g. mica), asphalt and others, showing a particle size of 250-600 µm. Nanoparticle size is usually between 1-100 nm and is consisting of calcium carbonate, barium sulphate, silica or iron hydroxide. In order to bridge and seal sufficiently, different particle sizes are used to first create a bridge and then to seal the fracture. This is called particle size distribution (PSD).

Other properties affecting the output are size and shape of the fracture to be sealed as well as the particulate LCM, concentration and the base fluid itself. Blends of different LCMs in the right design can produce better results than separated.

Although LCMs can be very effective against lost circulation, overdosing them can have serious impact. A too high particle load can reduce the hole cleaning dramatically and even imply differential sticking. Poor hole cleaning may even lead to a higher BHP and therefore even more loss prone.

3.2.2. Granules

Granules are a sub-category of particulate materials and offer different degrees of size, rugosity and rigidity. These materials are fully capable of bridging and sealing formations. Good examples for granules are walnut hulls and calcium carbonate.

Calcium carbonate is commonly used against losses in production zones. It is acid soluble and recommended for seepage or partial losses. Calcium carbonate is made up of ground marble or ground limestone. Different grades help to prevent losses in the first place.

As calcium carbonate, walnut hulls are available in various grades: fine, medium, coarse.

3.2.3. Platelets or Flakes

Platelets or Flakes have usually no or limited rigidity and have a flat appearance. Examples would be cellophane or mica.

Mica can be compounded of several different silicates, but has equal physical characteristics. The material can also be ordered in fine, medium, coarse and tends to wedge apart into elastic and flexible thin sheets.

Cellophane are produced from pure cellulose are show an average size of 3/8”. Cellophane does not interact with any other mud components, is inert and is not impaired by brine or crude oil. However, Cellophane will plug the inflow screens and impair the reservoir.

3.2.4. Mixed

Mixes can consist of flaked, granular and fibrous material and offer the advantages of all three components, proper sizing assumed. Mixes are different for each manufacturer. Examples would be M-I Seal or KwikSeal.

M-I Seal is a mix consisting of all three components – fibrous, flake and granular. It is a very common product, particularly in water-based drilling fluids.

KwikSeal is primarily used to cure partial up to severe losses but can lower the stability of the emulsion of oil-based drilling fluids.

3.2.5. High fluid loss squeezes

A high fluid loss squeeze consists of dissolved barite (in oil or water), diatomaceous earth and bridging agents. High fluid loss squeezes form a seal as soon as reaching the fractures and stop losses from happening. They are most helpful for curing induced fractures and work best with a high pressure differential. For solid sealing, a fibrous LCM is added. High fluid loss squeezes are pumped through the jets.

3.2.6. Fibres

When talking about fibres, this typically includes the following materials: nylon, shredded paper, cellulose and polypropylene. The principle behind is that these materials form a network to bridge a fracture. Not to harm the formation in the pay zone region, acid-soluble fibres are used. Fibres have little rigidity and are intended to entangle to stop fluid loss.

The concentration when using fibres should be carefully considered. In order to create a proper bridging, the concentration needs to be adequately high. When this concentration is far exceeded, the viscosity increases and pumpability decreases a lot up to the point where bottom hole and surface equipment are endangered to getting plugged.

Fibres are often used together with particulates like graphite or calcium carbonate. The concept behind is that the fibres build up a bridge for the granular to deposit on. If a sufficiently chosen PSD is applied and the granular material can cover the voids in the fibre structure, a seal with low permeability is created, using the individual advantages of both materials.

The performance of fibrous LCM depends on many characteristics, e.g. concentration, viscosity, fluid type, fracture morphology, and mechanical properties. The strength can be increased by using a dual-fibre formulation, especially when used with WBMs. A dual-fibre material consists of rigid and soft fibres, improving the strength because of the increased stiffness. This system is able to seal fractures up to 5 mm. The created seal can sustain up 2000 psi pressure difference.

Moreover, fibres are frequently used while well cementing. Applied as additive, fibres can increase the cement strength due to their crack sealing impact. Fibres therefore also limit the crack propagation in the used cement, leading to a better hardening.

3.3. Settable Material

Settable material is typically liquid on the surface, is pumped downhole, solidifies at the loss zone and creating a seal. Settable material includes cement, bentonite-oil-mud, cross-linked systems and gunk. Before pumping settable material, it should be made sure that the viscosity of the material is sufficiently low. Moreover, the viscosity of the settable material should even be higher than the viscosity of the drilling mud to displace it.

After the material has been settled, the yield stress is a very important characteristic. It is a measure for the stability and determines, if a seal is able to withstand a certain pressure difference when applied to the seal.

3.3.1. Cross-Linked Systems

Linking different polymer chains with the help of an agent is called cross-linking. This cross-linking agent can be activated by shearing, temperature or simply time. After setting and linking, the system prevents additional losses. A typical setting time can be some hours and is shortened by accelerators or extended by retarders. Retarders might be of use, if the setting in the equipment needs to be impeded or more pumping time is necessary. If the formation features a relatively low temperature, accelerators quicken the setting.

Especially unconsolidated and depleted sands are treated with a blend consisting of LCM, polymers and cross-linking agents. Cross-linked systems are usually not used in producing intervals, since most of these systems are neither acid soluble nor degradable and the performance heavily depends on their surrounding temperature.

Form-A-Plug II is an example for a cross-linked system. This plug is a mix containing borate minerals and cross-linkable polymers. Setting can be timed and temperature controlled. Retarders and accelerators may help to provide optimal parameters. Moreover, this plug is almost completely acid soluble when suspended with HCl solution.

3.3.2. Gunk Squeezes

Gunk Squeezes or Oil/Bentonite use the swelling of the bentonite they are composed of to thicken and cure losses. Gunk Squeezes contain un-hydrated bentonite and are usually mixed with diesel. When interacting with a water-based drilling fluid or brine, they quickly gel. In many cases cement is added to add strength, which is then called OBC (Oil/Bentonite/Cement).

OBC forms a solid plug when contacted with brine or water. The cement increases the compressive strength of the plug. By changing the ratio between cement and bentonite the compressive strength can be altered. The standard ratio is 4:1 and forms a firm plug. The more bentonite the ratio contains, the softer the plug gets in the end.

OBC is a material for more severe lost circulation cases. It is usually applied when LCM could not cure the loss scenario.

3.3.3. Reverse Gunk Squeezes

Reverse gunk squeezes are another kind of bentonite squeezes. Employing the treatment is no different from a normal gunk squeeze. However, the reverse gunk squeeze must not be used with aqueous fluids. It is only used with non-aqueous fluids (NAF).

The treatment is pumped down the drill string and NAF simultaneously the annulus. Intermixing below the pipe, a gel/viscous mass forms is pressured into the formation. Because of the rapid swelling/gelling of the bentonite when contacted with NAF, the exposed formation becomes quickly impermeable.

Since cement does not hydrate in the presence of NAF mud, it is no element of a reversed gunk squeeze.

3.3.4. Two-Fluid Settable Pills

Settable pills are made of two different fluids, which are separately pumped. Both fluids mix downhole, set and create a gel that seals. To enable downhole mixing, either a spacer is used between both fluids or drill string (first fluid) and annulus (second fluid) are used for pumping. If a spacer is used, the following procedure is usually performed:

- First fluid is spotted at depth
- Pull clear above
- Circulate out spacer
- Run to bottom of first fluid
- Circulate second fluid at half the fill rate (pull double the fill rate)

Since activation and downhole mixing are necessary, flow rates need to be controlled at all times. Two-fluid settable pills are therefore risky while experiencing total losses.

Disadvantageous on this treatment is the poor control of spotting the pill in the right location. Also, environmental policies can be infringed and serious formation damage might be the result. This concerns have to be managed, especially the irreversible skin.

When WBM was used to drill the well, a system consisting of oil, possibly cement and bentonite as first fluid can be applied. An inelastic plug is created by the applied bentonite-oil system. The second fluid could then be WBM or water. Moreover, LCM can be added. When mixing the slurry, contamination between both fluids should be avoided to prevent premature gelation. Getting stuck or plugging the nozzles could be the consequence.

In case OBM was used to drill the well, a reversed squeeze is used. This is a pill consisting of organophillic bentonite and water. Mud gets downhole via the annulus and mixes to a plug, stopping the losses.

3.3.5. Cement

Cement is often used when other treatments could not achieve the expected effect. But especially the compressive strength of cement increases its sealing quality. Vugular formations and severe losses are mainly treated with cement. Depending on the kind of losses, even particulate LCMs, fibres and bentonite can be added to improve the performance.

Attention should be paid when using cement with non-aqueous mud. Since in that case the formation should be wetted and mixing of mud and cement prevented, a spacer is typically pumped. This secures a high-quality seal.

Thixotropic cements are especially appropriate for squeeze treatments. These cements are easily pumpable, but build up gel strength rather quick when the pumps are stopped. This gives the advantage that the cement could not fall back and inhibits gas migration. Moreover, rapid development of gel strength is preventing further formation damage. Certain cross-linked cements are even used in pay zones. These cements are acid-soluble and may contain magnesia, because the magnesia further improves the solubility of the cement slurry. In non-productive formations, regular cross-linked cements are preferred due to their economic efficiency. Despite the possible formation damages, the use of cement can cause significant non-productive time. Setting a plug and additionally wait for the cement to set can lead to multiple days of non-productive time.

3.3.6. Foam Cement

Pore pressure governs the decision of the fluid density. Especially in loss scenarios the density of the slurry is vital. To cure losses with cement, it might be necessary to lower the density of the applied treatment. One way is to add LCM to the slurry; another way would be to use foam cement. Foam cement is mixed of a cement slurry, a gas and foaming agents. Since nitrogen is inert, it is commonly used in foam cement slurries. The important fact here is that the gas bubbles are not linked-up and they form a solid cement slurry with low density. Once foamed cement is in place and fractures are sealed, regular cement can be pumped to consolidate and add strength. A big benefit of foamed cement is that it is energised by the N_2 charge. Therefore, foamed cement has the ability to expand and compensate for some drilling fluid lost. However, when expanding, the overall strength reduces. For that reason, it is recommended to pump high volumes of foamed cement.

3.4. Curing Losses Based on Mechanism

3.4.1. Matrix Losses

When pores are large enough, losses due to permeability can be caused. If 10 Darcy are exceeded, bentonite or barite particles will not reliably seal the loss zone anymore. More precisely, if the mud does not contain solids bigger than 1/3 of the pore throats, bridging and sealing of those pore throats will not be possible. Losses would continue in this case. Matrix losses can reach from seepage to total, which shows that this indicator alone would lead to poor decision making.

Gravels, shell beds and unconsolidated sands are good examples for formations prone to matrix losses. Washouts are possible in these formations, reducing the cementing quality wellbore stability significantly.

Individual PSD may be efficient in order to fight matrix losses. Too large particles would deposit inside the well and be removed by the drill string or BHA. Too small particles will not form a bridge and seal. Some estimates tell that 90% of the particles need to be littler than the average pore throat to give LCM a chance (Savari & Whitfill 2015). Other sources suggest that the median size is more relevant. Comparing the pore size and the LCM particle size, the latter should be similar or slightly bigger. Depending on the permeability of the rock, this median pore size can be estimated. Thus, a disadvantage of this simple technique is that just a median size is not sufficient enough for bridging and sealing particles in two stages.

Better information and advanced models give a more sophisticated approach to tailored PSD. So-called multimodal LCM is a fully optimised PSD (Savari & Whitfill 2015).

Synthetic graphite, calcium carbonate and fibre-based LCM have been effective in combating matrix losses. If there is no sufficient data available to estimate any pore size, a mix of LCM sizes can be pumped. Depending on the loss rate, these sizes can be suggested. The severer losses are, the coarser the sequence should start. In very severe loss conditions, the first grade to pump should be coarse. Depending on how much the loss rate improves, a medium to fine grade can be used to seal or a mix of all grades can be pumped to stabilise the situation.

3.4.2. Vugular Formations

Lost circulation in these formations are counted among the tersest loss problems. Drilling blind can be a strategy, but it needs to be assured that enough mud is available. Other methods like underbalanced drilling should be considered as well. Fibrous LCM and cross-linking pills have shown success. These are not acid-soluble and limits the application to non-reservoir zones.

3.4.3. Natural Fractures

As in vugular formations, losses in natural fractures are terser to treat. This kind of losses are common in geothermal wells, gas-bearing shales and carbonate formations. It is even more severe when the natural fractures turn out to be wide or interconnected. These interconnected networks are often coming up in high-permeability sedimentary rocks. Especially the unknown apertures make it a challenge to design a treatment in these formations. In formations with induced fractures it is at least possible to roughly estimate the aperture due to the research done in areas like hydraulic fracturing. In natural fractures, there are too many unknowns to estimate the aperture, e.g. orientation and magnitudes of stresses, fracture mineralisation and fracture orientation. It is hardly achievable to design the ideal PSD.

Generally, the application of LCM in formations with natural fractures is well debated, but there is no consistent approach defined and the best approach is argued over. There is a discrepancy between stopping losses and permeability damage in naturally fractured reservoirs. The dilemma is that stopping losses will harm permeability and productivity of the formation possible permanently. LCM treatments are often hard to remove. Therefore, it is important to prevent lost circulation in the best possible way, such as applying lost prevention material (LPM) or reducing overbalance with the help of managed pressure drilling (MPD) or underbalanced drilling (UBD). Alternatively, it is necessary to work closely with production and reservoir engineers to retain permeability and not to create excessive irreversible skin damage.

A possible solution for keeping the skin as low as possible while using LCM is, again, the right PSD, which is hard to achieve. Particle size should be chosen carefully. Particles need to be released close to the loss zone to achieve a best possible deposition. Treating near the loss zone has the advantage that less time and pill size is needed and faster treatment response is achieved. Pill size should be designed to sufficiently to bridge and seal, but also to keep the skin as low as possible. As a rough-and-ready rule, particles should be about 40% the size of the aperture to ideally bridge natural fractures. Thus, a wide-ranging PSD increases the chance to properly seal the fracture. In doing so, it should be considered that the particles do not reach the fracture in their initial shape and size when not designed resistant to grinding.

Although fibres are ineffective when combating large-aperture fractures, they can effectively be used in a mix with particulates. Both together perform better when released close and reaching inside the loss zone.

Another measure against natural fractures is synthetic graphite, which is sometimes preferred because it is inert. Moreover, cellulose flakes can seal fractures up to 3 mm width. One more option to treat would be cross-linking polymers, often used with fibres. This combination is effective in widely fractured loss zones, but it is not acid soluble or degradable, which is limiting it to non-reservoir zones.

To treat faults, a high LCM volume is necessary, which remains down hole. This raises the risk to expose the entire remaining open hole section to LCM. In case reservoir zones are exposed reversing out, this excess volume should be considered. This requires consideration during the planning phase.

3.4.4. Induced Fractures

Induced fractures present less variety, e.g. in their aperture or length, because they are drilling induced. Not pre-existing, but created during drilling operations. Many properties leading to their existence are known. In theory, their apertures can be estimated and therefore a design of effective LCM possible. In practice, however, this requires a model of the induced fractures, in situ stresses and the formation properties, which is general hardly available. On these grounds, classic estimation models are used.

Two of these classical models are commonly used:

- KGD (Khristianovitch-Geertsma-de Klerk) model
- PKN (Perkins-Kern-Nordgren) model

Both models base on research of hydraulic fracturing, but differ in terms of the position the actual maximum fracture aperture (w_{max}) is:

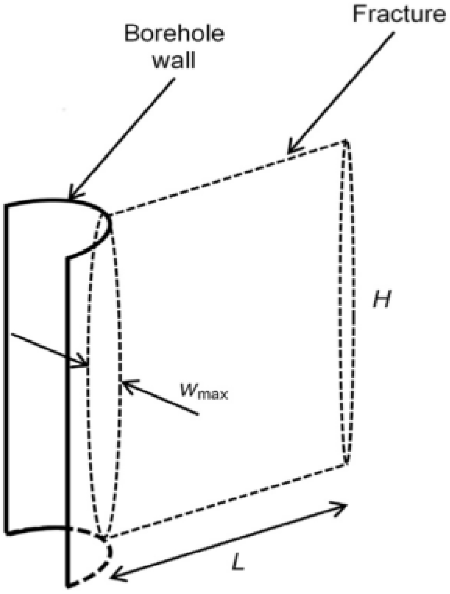


Figure 30: Fracture Geometry PKN Model (Savari & Whitfill 2015)

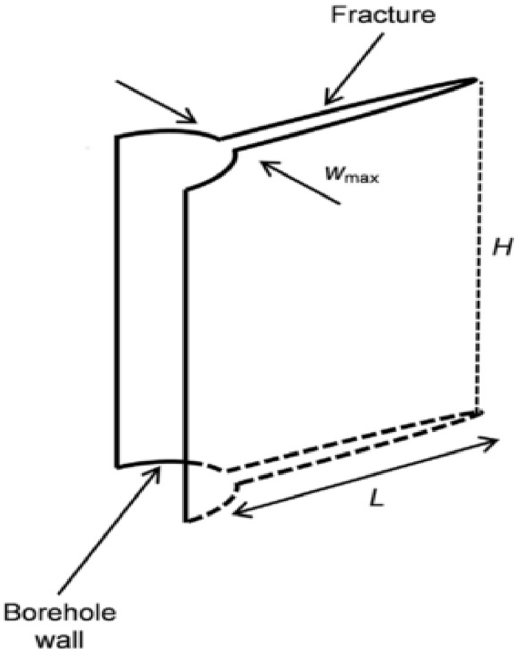


Figure 31: Fracture Geometry KGD Model (Savari & Whitfill 2015)

While the fracture aperture in the PKN model ranges between 0 (bottom and top) and w_{max} (midheight), the fracture aperture in the KGD model is constant along the borehole.

The fracture height is usually estimated by logging, the fracture length then by the lost mud volume into the formation.

Another issue on the fracture aperture is the fracture geometry in deviated wells, which is rarely planar. This reveals the limited capacity of the available models. Frequently, the fracture aperture is therefore a big uncertainty. Especially in designing a tailored treatment this is a problem.

Especially in the reservoir zone, a side-track could be good choice. Since the fracture aperture is often unclear and therefore a chance of success reduced, plugging back and performing a side-track might be a valuable option. But before that, the extent of the loss zone has to be identified. If the decision is made to destroy the permeability in the reservoir zone to drill to TD (economic decision), casing off, hydraulic fracturing or a stimulation/acid job are possible in order to maximise production again.

3.5. Different Severity

When losses happen, information is often unavailable. Best practice treatment is applied based on the current on-hand information, offset and experience from the previous wells. As soon as a loss rate and mechanism are clarified, designing and choosing a potential treatment is initiated.

Seepage losses are often handled with LCM, alternatively it is just drilled ahead when no other problems are expected during drilling (e.g. stuck pipe).

Partial losses are treated quite equally. Either they are treated or drilling goes ahead, if no problems are expected and the mud cost are not significant. If it is decided to treat and the first LCM pill is not sealing sufficiently, the decision can be made to use settable material (e.g. gunk, cross-linked pills, cement).

Severe losses happen in different formations and can be initiated by all four common mechanisms – vugs, induced fractures, natural fractures and a high-permeability matrix. Severe losses should generally be treated and stopped, because they can threaten well control. The first step into treating severe losses can be a LCM pill. If this pill fails to bridge and seal, settable materials can cure the losses. Alternatively, drilling ahead can be an option or mud-cap drilling might be considerable.

Total losses with no returns at all are hit hardest. Especially occurring in geothermal drilling, vugular formations, naturally fractured rocks and unconsolidated formations, total losses lead to an immediate threat to well control. Total losses can be hardly cured with LCM. Settable material may be able to cure losses or reduce loss rate. If all measures fail, mud cap drilling or drilling without any returns has been applied. Drilling blind without geological control and returns of cuttings increases pack off and stuck pipe risk. The last step of the escalation ladder would be abandonment.

Total losses in highly permeable loss formations respond significantly to reduction in overbalance. Before any of these treatments should be even considered, a reduction of the ECD might be of help. Sustainable loss rates may be achieved by lowering the pump rate or mud weight. If decided to do so, attention should be paid not to receive any influx. Moreover, hole cleaning should not be neglected. Static vs. dynamic losses is again an important issue. If the losses occurring are static, these losses have to be cured with the BHA in place. Limited or complicated procedures require extended planning before drilling.

There is always a risk that an existing loss scenario escalates in severity. When this occurs, additional uncertainty around the location of a single or multiple loss zones further complicate treatment approaches.

3.6. Summary

As described earlier in this chapter, there are three groups of treatments – settable materials, LCMs and a combination of both (blends). LCMs are usually the first of the three to consider. LCM pills can be added to the mud and easily pumped. The curing effect starts almost immediately after reaching the loss zone. In case LCMs are proven ineffective, settable materials may be the way to go, but need preparation and setting time before the treatment starts to work.

Only if the right cure and the right procedure are applied, lost circulation can be treated effectively and efficiently.

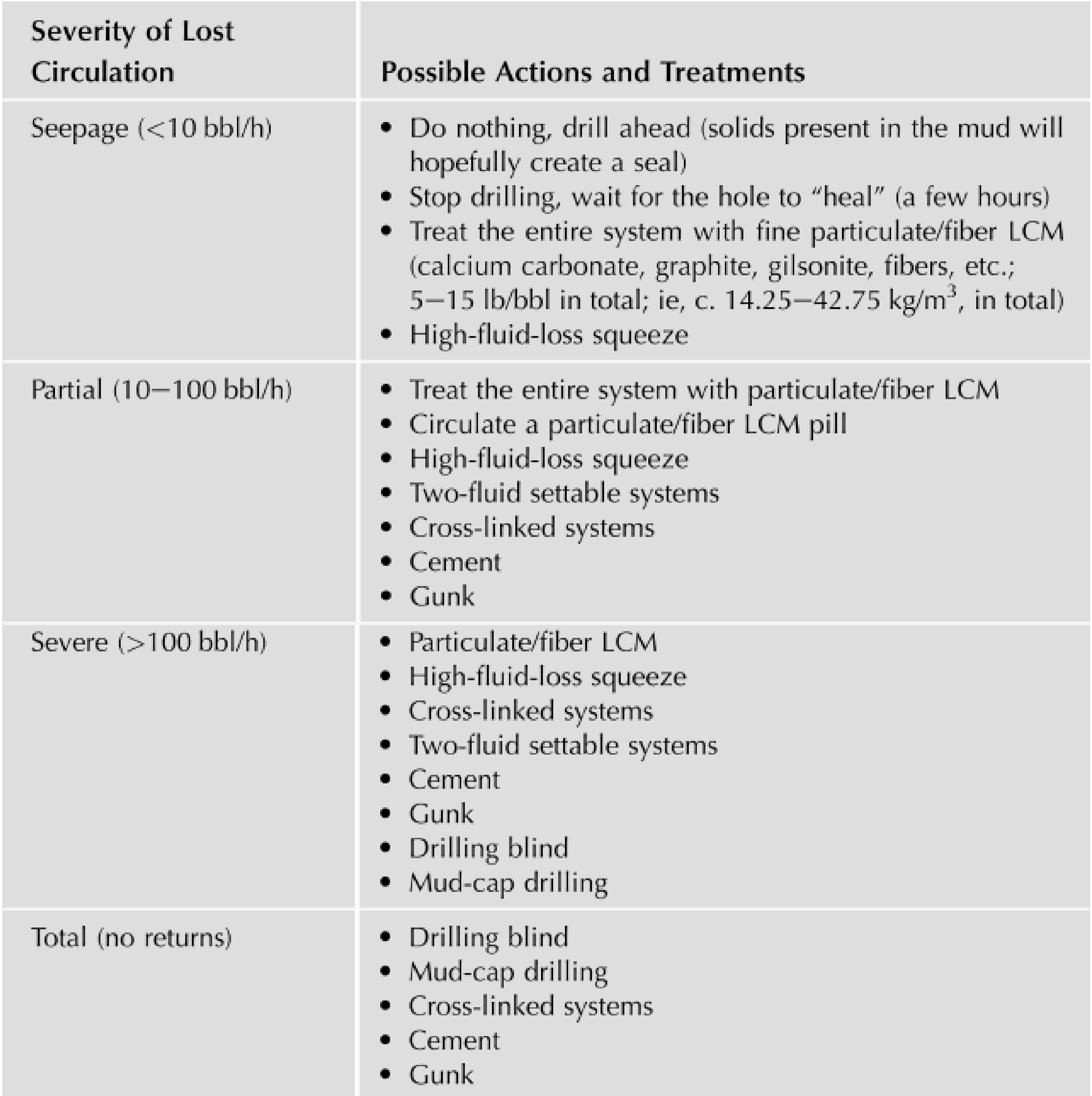
When it is about determining a potential treatment to combat occurring losses, information should be gathered, analysed and concluded. Working with this information, e.g. mechanism (e.g. vugs, high-permeability matrix, natural or induced fractures), severity (minor, partial, severe, total losses), geological setting (unconsolidated, caprock, pay zone, gravel, sand, etc.) and additional data about pores and fractures (throat size, spacing, fracture apertures, etc.), a more individual and effective treatment can be designed.

After losses are detected, the ECD is generally reduced. If a mud weight reduction or turning off the pumps does not work, LCMs are usually prepared. Graphite, nut shells, calcium carbonate or fibres are just a few options to mention. If a more severe loss scenario is detected, coarser particulates are applied. Different LCMs together (blends) may perform far better as single LCM. In the event of all LCM failing to cure, settable materials would be the next step to go (e.g. cross-linked pills, cement, gunk). One of the last treatments would be mud-cap drilling or to accept the losses and to drill ahead. Another highly disadvantageous possibility would be to place another casing string, which would have the consequence of losing the hole size. A lost hole size could, on the other hand, still be better than abandonment.

Only the right material and the right procedure succeed. If just one of them are right, the operation fails. The task is to run through all effective loss treatments and decide on the individual circumstances – not to waste time by trial and error or to repeat ineffective measures.

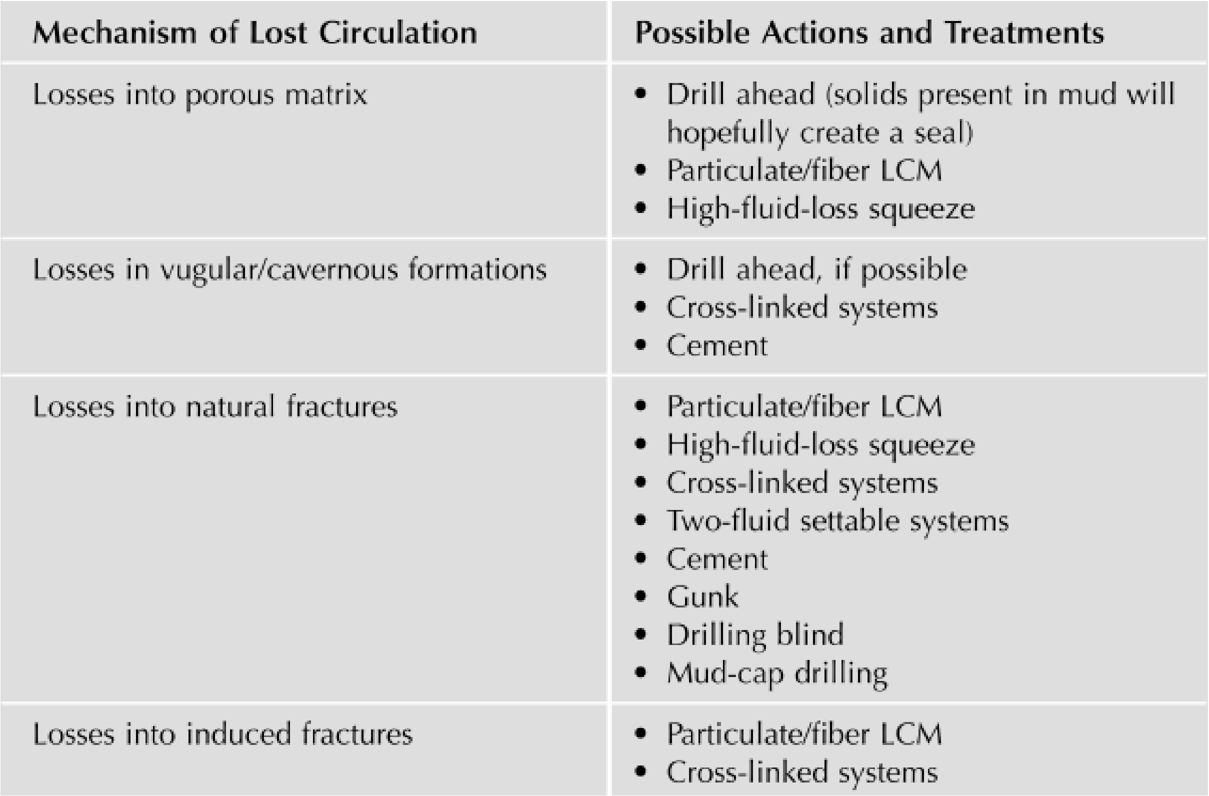
The following two tables give an overview what treatments are possible to apply, based on severity and mechanism.

Table 6: Possible Treatment Based on Severity (Lavrov 2016)



Severity of Lost Circulation	**Possible Actions and Treatments**
Seepage (<10 bbl/h)	• Do nothing, drill ahead (solids present in the mud will hopefully create a seal) • Stop drilling, wait for the hole to "heal" (a few hours) • Treat the entire system with fine particulate/fiber LCM (calcium carbonate, graphite, gilsonite, fibers, etc.; 5−15 lb/bbl in total; ie, c. 14.25−42.75 kg/m^3, in total) • High-fluid-loss squeeze
Partial (10−100 bbl/h)	• Treat the entire system with particulate/fiber LCM • Circulate a particulate/fiber LCM pill • High-fluid-loss squeeze • Two-fluid settable systems • Cross-linked systems • Cement • Gunk
Severe (>100 bbl/h)	• Particulate/fiber LCM • High-fluid-loss squeeze • Cross-linked systems • Two-fluid settable systems • Cement • Gunk • Drilling blind • Mud-cap drilling
Total (no returns)	• Drilling blind • Mud-cap drilling • Cross-linked systems • Cement • Gunk

Table 7: Possible Treatment Based on Mechanism (Lavrov 2016)



Mechanism of Lost Circulation	Possible Actions and Treatments
Losses into porous matrix	• Drill ahead (solids present in mud will hopefully create a seal) • Particulate/fiber LCM • High-fluid-loss squeeze
Losses in vugular/cavernous formations	• Drill ahead, if possible • Cross-linked systems • Cement
Losses into natural fractures	• Particulate/fiber LCM • High-fluid-loss squeeze • Cross-linked systems • Two-fluid settable systems • Cement • Gunk • Drilling blind • Mud-cap drilling
Losses into induced fractures	• Particulate/fiber LCM • Cross-linked systems

4. Lost Circulation Test Stand

Up to this point this thesis was reflecting the state-of-the-art theory in terms of lost circulation. Losses were classified and possible curing was discussed. Those treatments were matched to severity and mechanism of loss circulation situations. Having approached the theoretical side of lost circulation, this thesis is now diving deeper into the practical aspects of the issue. This chapter is dedicated to laboratory testing and shows the current methods to test lost circulation.

4.1. Previous Designs & Limits

To make progress in curing lost circulation, laboratory testing is necessary. Multiple methods are available to test LPMs and LCMs.

Commonly, the following two setups are tested:

- Fluid loss over 30min
- Required time to seal

Generally, these parameters are measured using a filter press, simulating the flow into a porous medium by a rock sample or a slotted ceramic disk. Additional assessments might be:

- Maximum pressure difference which the seal can withstand
- Resiliency and particle strength

To improve LCMs regarding their capability to bridge and seal, testing via a slotted disk or porous medium seems to be the most effective way. Examples for both are shown in the following figure.

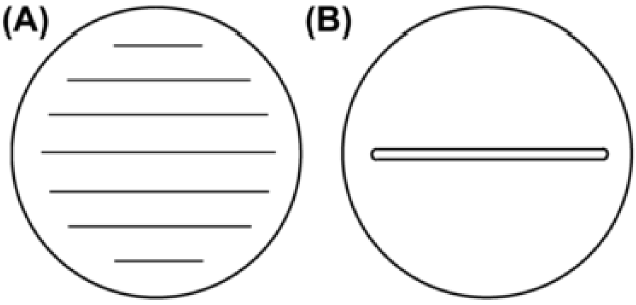


Figure 32: Slotted Disks to the LCMs. (A) Shows Multiple Slots and (B) One Single Slot (Lavrov 2016)

Fracture apertures should be variable. Tapered slots are more realistic when induced fractures shall be tested. Fluid flow should be kept upwards not to overestimate the materials capability to bridge and seal. Also, the roughness inside the slot should be considered. Surface roughness affects deposition and particle transport. A smooth surface would underestimate the materials capability.

While testing, the pressure gradient vs. the pumped volume is closely observed. This pressure gradient reveals, if bridging and sealing is successful. In the following figure this effect is shown.

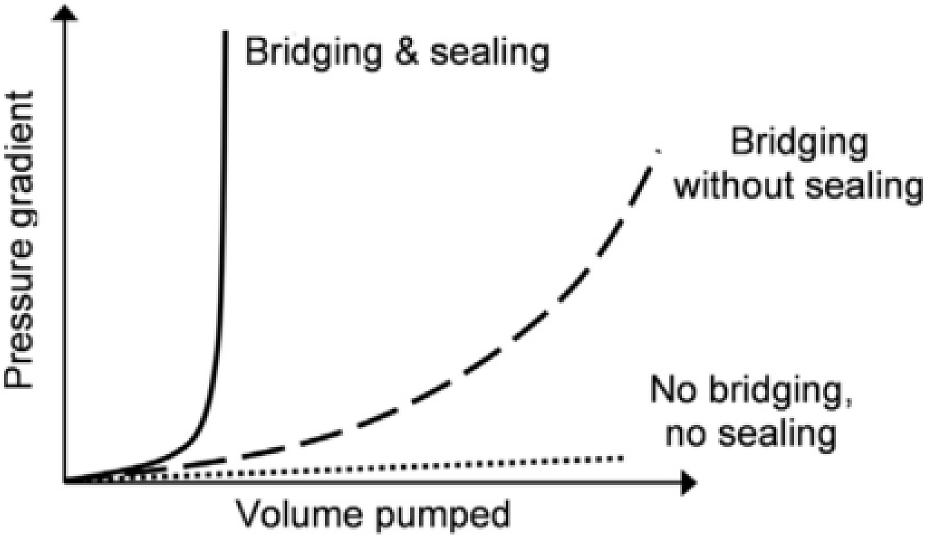


Figure 33: Bridging and Sealing Effect (Lavrov 2016)

The dotted line shows an insignificant pressure gradient, bridging failed and mud continues to flow through the slot – no pressure builds up. If bridging is successful, but sealing is not, mud is still flowing through and pressure builds up gradually – the dashed line shows solids aggregate slowly but continuously. If bridging and sealing is successful, the pressure builds up quickly. As soon as the seal is created, no more mud or solids can exit – the solid line shows proper sealing and proves the effectivity of the tested material.

A common way to test LCMs is to inject mud filled with LCM into a porous medium. Potentially that can be two porous layer with a variable gap, displayed in the following figure. In between the porous plates a fracture is simulated. This setup suits best for natural fractures.

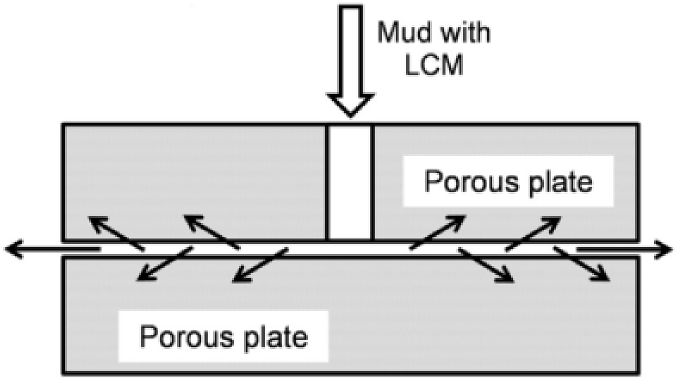


Figure 34: LCM Test Formation (Lavrov 2016)

Many different types of test stands were developed to measure the mechanical strength the seal can sustain. Mechanical loads and differential pressure need to be resisted. The seal must not break apart or crack. Two parameters are most important to characterise the seal – unconfined compressive strength (UCS) and shear strength.

To test the latter, different push-out tests can be used. A seal with defined thickness is created and placed into the test unit. An applied load pushes on the seal and induces shear. Depending on the peak load, the seals shear strength can be determined. The principle of this test unit is shown in the following figure.

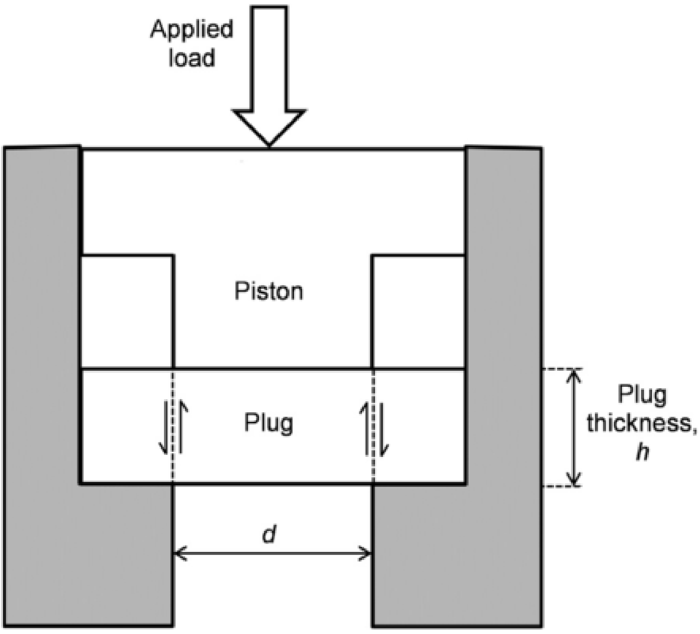


Figure 35: Push-out Test Unit (Lavrov 2016)

UCS represents the mechanical strength and is a similarly important characteristic of particulates. Performance of this materials is depending on for instance how adhesive their behaviour is. Controlled conditions in laboratory tests could improve their development before getting deployed into the field.

Additionally to these tests, the flow behaviour of LCM should be considered. Nozzles or BHA can restrict the flow or even get plugged. Several tests have evaluated the flow through such equipment. In a nozzle test for example, flow rates from 100 gal/min can be used to see possible problems. Similar tests are applied to prevent plugging of the BHA.

LCM testing apparatuses

Many specifications for testing LCM are available. One of the best known is the API specification. The test equipment to evaluate bridging material is shown below.

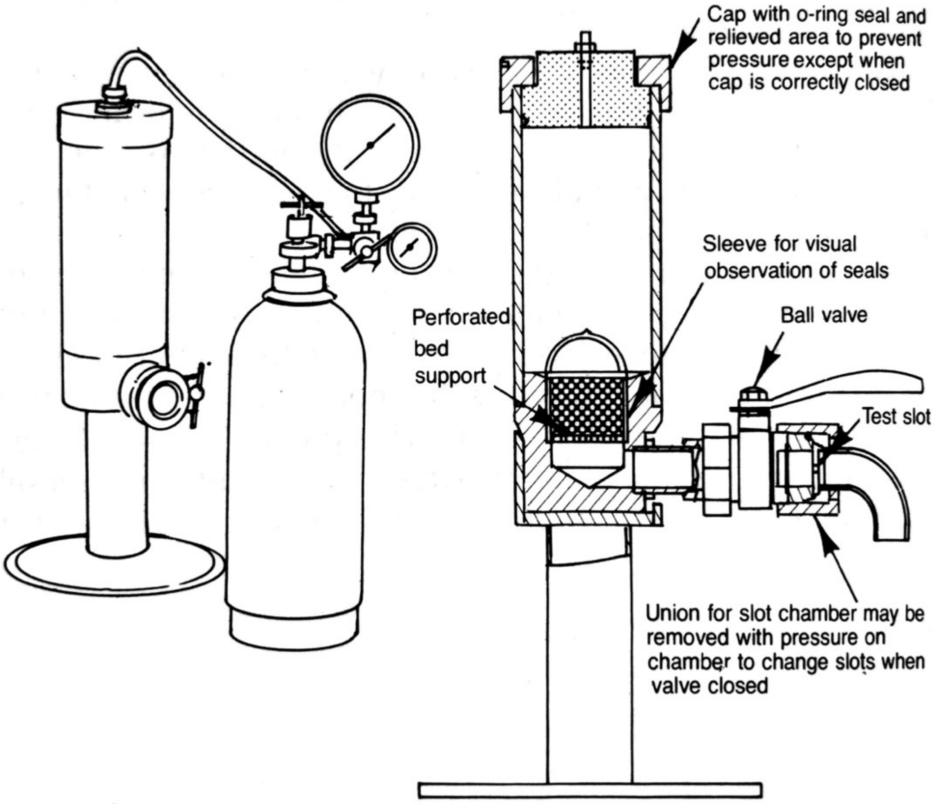


Figure 36: API Test Equipment (Messenger 1981)

The pressure is provided by a charged nitrogen bottle, regulating the necessary pressure during the procedure. The mud then flows through a perforated bed within the test cell via the ball valve to the actual test slot, where it passes the slotted steel disc.

In a static test, the pressure to evaluate the seal is raised to 1000 psi (10 psi per second). If it does not fail, the pressure can be raised until it does at the same rate. In a dynamic test, the pressure of 1000 psi is held steadily for 10 minutes. If the seal sustains, the slot size is increased and the test is repeated.

High-pressure high-temperature and particle plugging apparatuses are widely used to test LCM treatments. Slotted or tapered discs are then used to investigate induced or natural fractures, ceramic discs to investigate porous formations. In the below shown setup, the fluid loss is measured over a time frame of 30 minutes while applying a constant pressure. Since no pressure difference is applied during this kind of test, it lacks reality conditions. The newly created seal should be exposed to pressure changes.

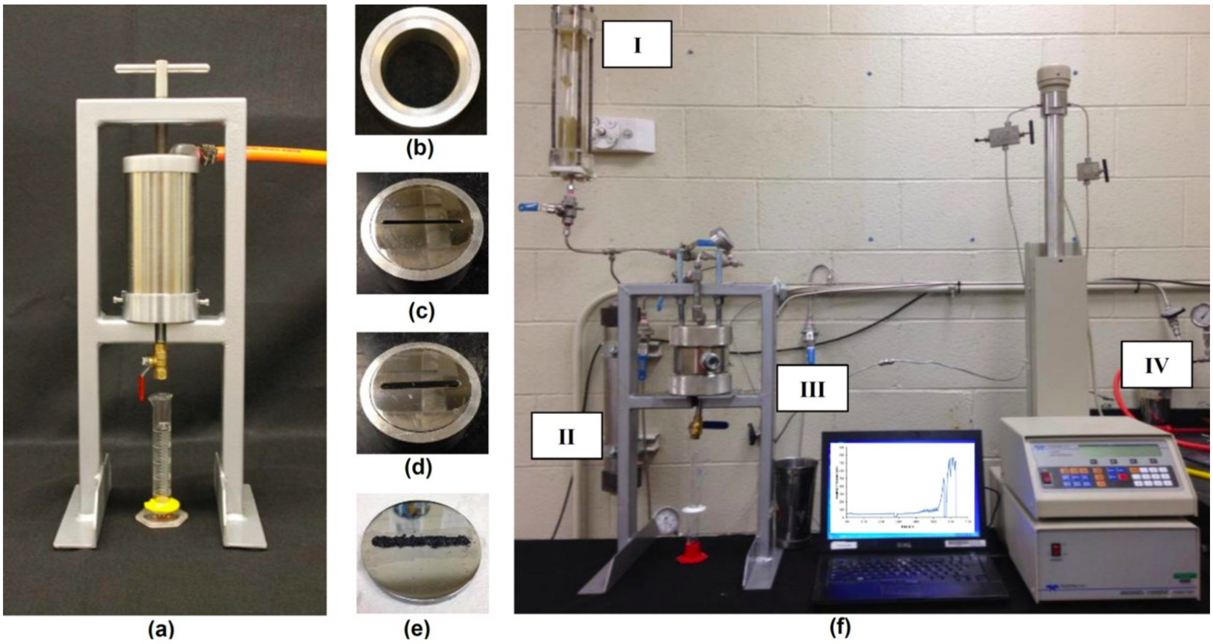


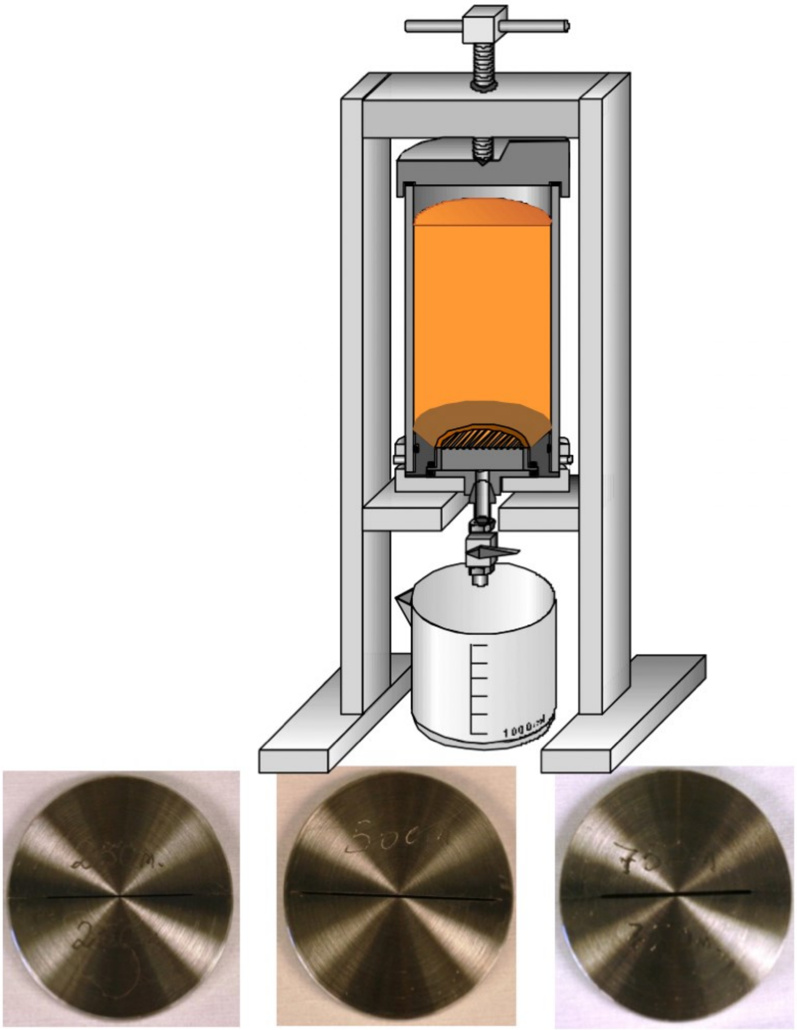
Figure 37: Low pressure / high pressure LCM laboratory equipment (Alsaba, Nygaard, Saasen, et al. 2014)

(a) Low pressure testing apparatus
(b) Snug-fit spacer
(c) Tapered disc 1
(d) Tapered disc 2
(e) Sealed tapered disc
(f) High pressure testing apparatus

(I) Plastic accumulator
(II) Metal accumulator
(III) Testing cell
(IV) Injection pump

Sealing efficiency is generally defined as the maximum pressure sustained by the seal, just before it breaks and fluid flow starts again.

This LCM testing setup is not just used in science, but can be seen in various companies.



250µm slot 500µm slot 750µm slot

Figure 38: Laboratory testing (M-I SWACO 2005)

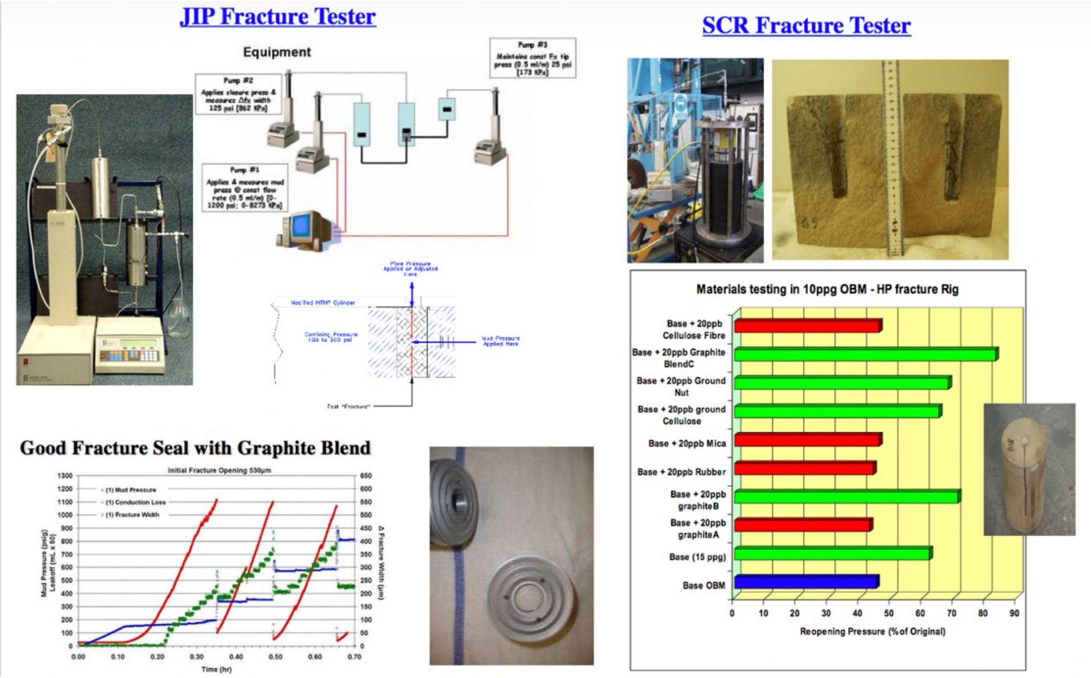


Figure 39: Laboratory Testing (M-I SWACO 2005)

Figure 40: Laboratory equipment (M-I SWACO 2005)

What all those setups lack is applicability in the field. Fractures are not adequately simulated. Geology, lithology, deviation, fracture aperture, fracture orientation, fracture length and pore size are usually not even remotely considered. Also, settable and mechanical solutions cannot be tested properly. In short, the common basic approaches to test LCM are far from reality and can hardly provide valuable insights regarding which LCM performs best under certain conditions. Therefore, a new way to test LCM is needed.

4.2. Improved Lost Circulation Test Stand

This improved way to test LCM is drafted in this chapter. The dynamic test stand shall be able to evaluate every possible solution to combat lost circulation. But not just the fighting lost circulation is important. Moreover, the mechanism behind needs more research. Only if the cause is undeniably clear, the best possible cure can be found. Finding the best cure needs input data, science, state-of-the-art products to resolve lost circulation and experience to match the best cure available.

To provide this kind of insight, the test stand would be a pipe-in-pipe design with a connected reservoir or rock sample and a pump to complete the cycle. The inner pipe, the inlet, has a prepared fracture. Three different inlets enable to simulate different fracture angels. 0, 15, 30, 45, 60, 75, 80, 85 and 90 degrees. Five fracture sizes help to determine the best product depending on the use case: 0,125”, 0,25”, 0,5”, 1” and 2”. Moreover, the whole pipe-in-pipe design is rotatable. Three temperature ranges shall be tested: 10-20°C, 40-50°C, > 75°C. In several series of tests, all available products in the discussed categories can be examined.

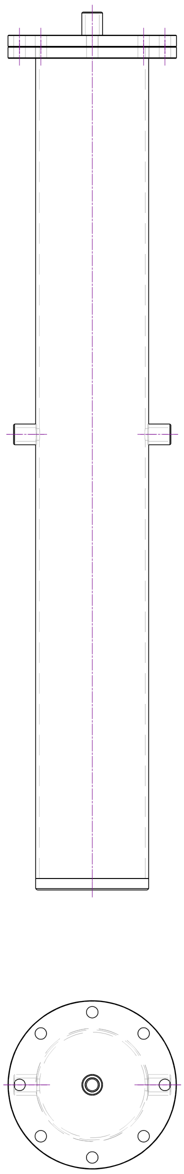


Figure 41: Outer Pipe

The shown medium being tested enters from the top via the pump, which is directly connected. It is then flowing through the inlet and reaching the prepared fracture. The inlets simulate either a diagonal, vertical or horizontal fracture.

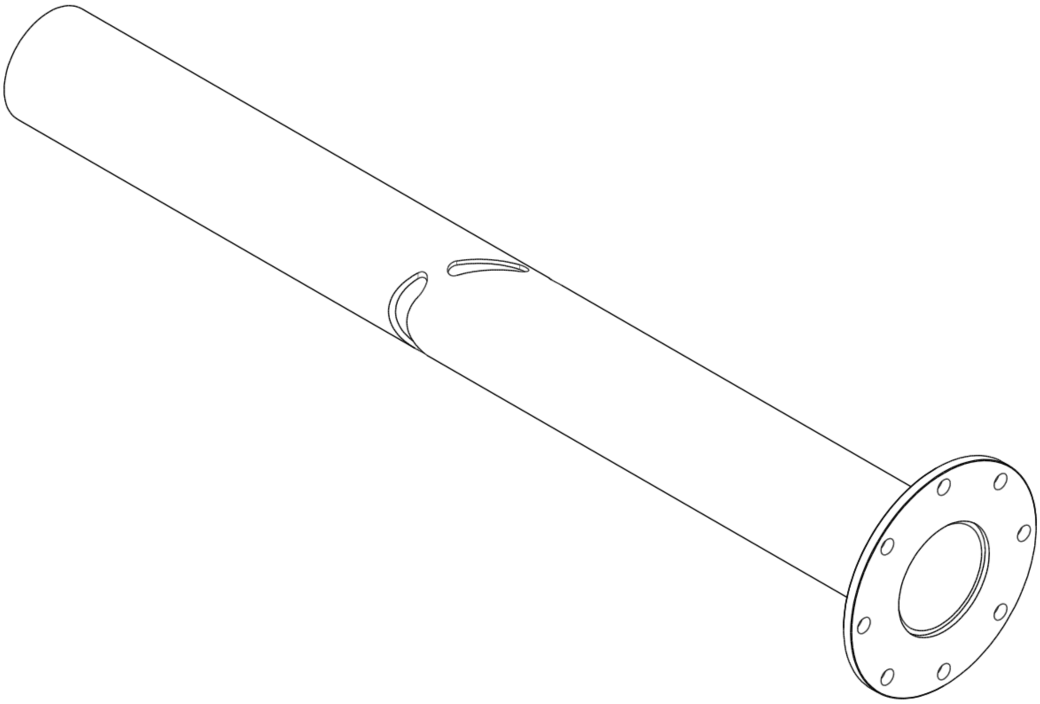


Figure 42: Inlet Pipe Diagonal Fracture

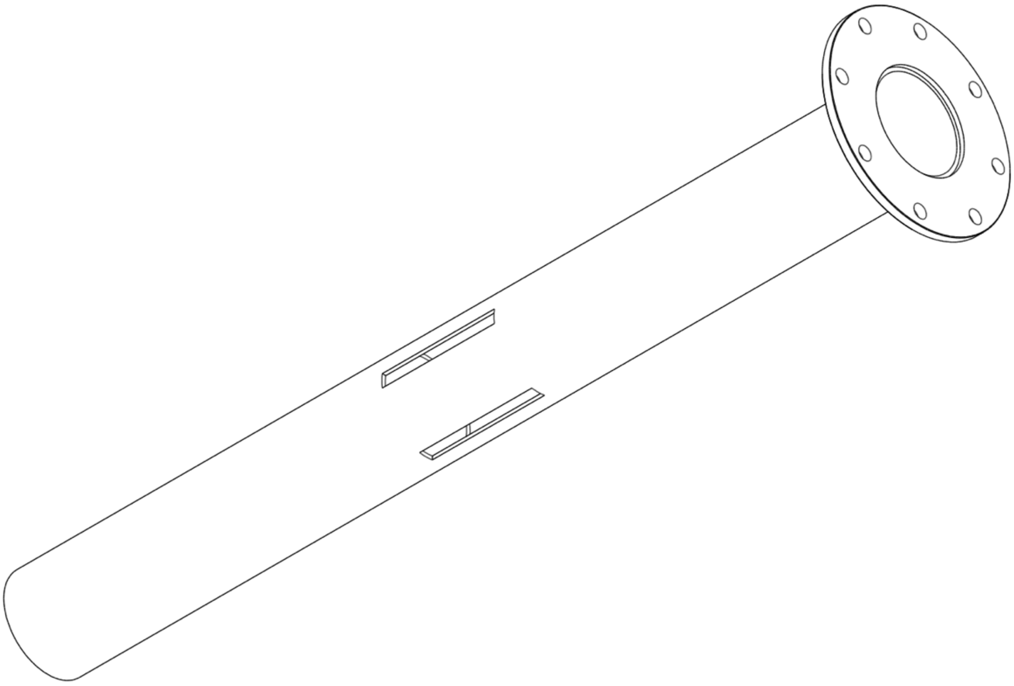


Figure 43: Inlet Pipe Vertical Fracture

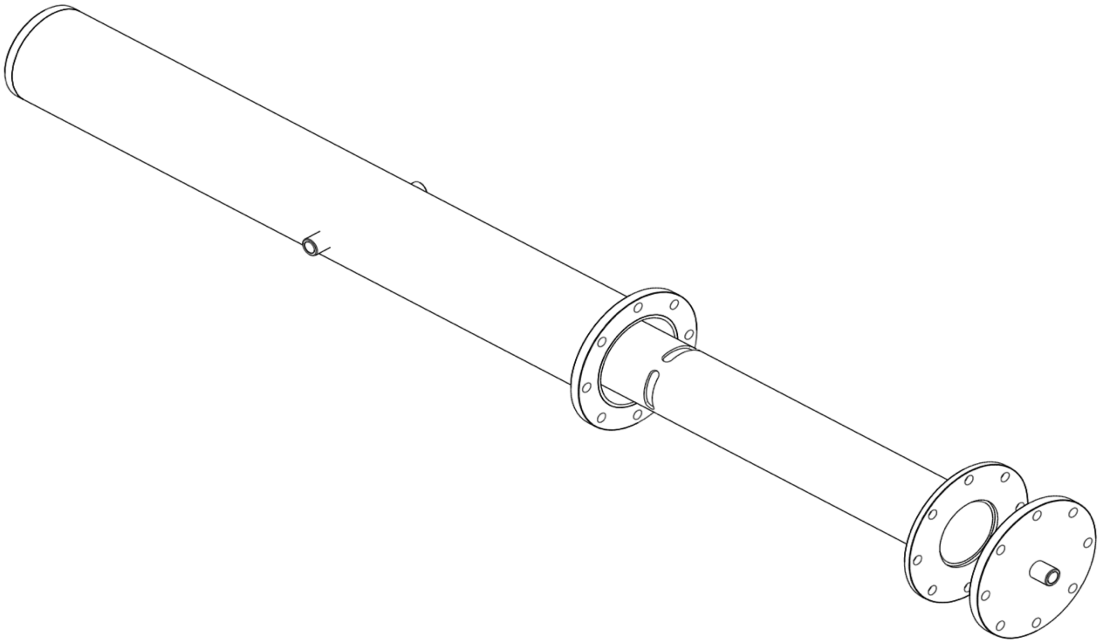


Figure 44: Pipe-in-Pipe Design with Vertical Inlet

After the testing medium flows past the fracture, it returns to the pit and is pumped again (loop). The medium can therefore enter the fracture continuously and deeply. Depending on the testing procedure, either a steady pressure over a certain time frame or a maximum pressure needs to be sustained by the seal, which closed the fracture when the testing medium was applied. The pressure is applied by the pump. A choke below the pipe can be closed and therefore the seal can be pressure tested.

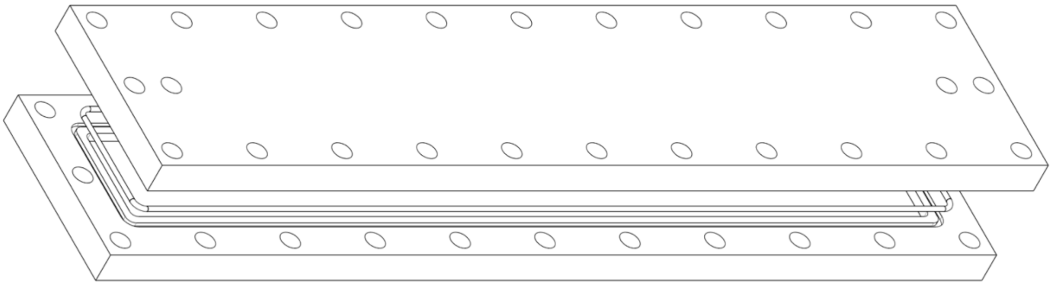


Figure 45: Simulated Reservoir

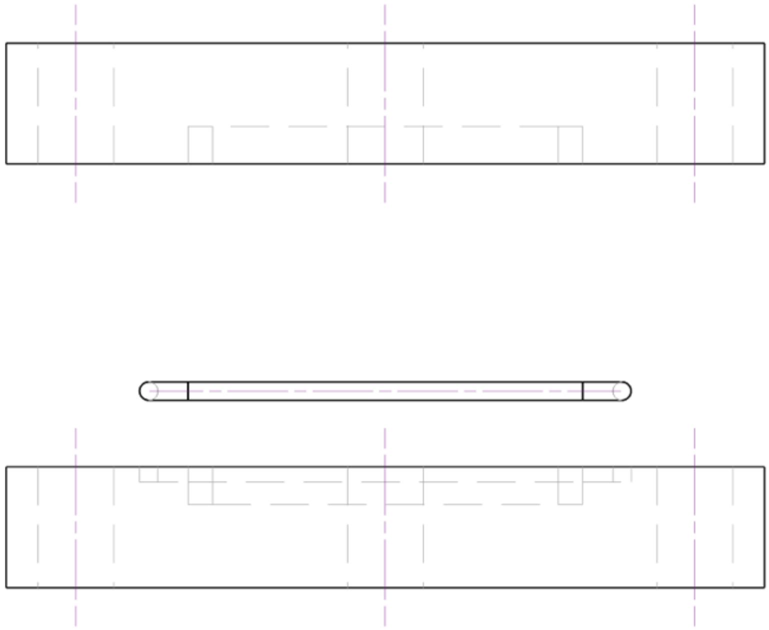


Figure 46: Simulated Reservoir

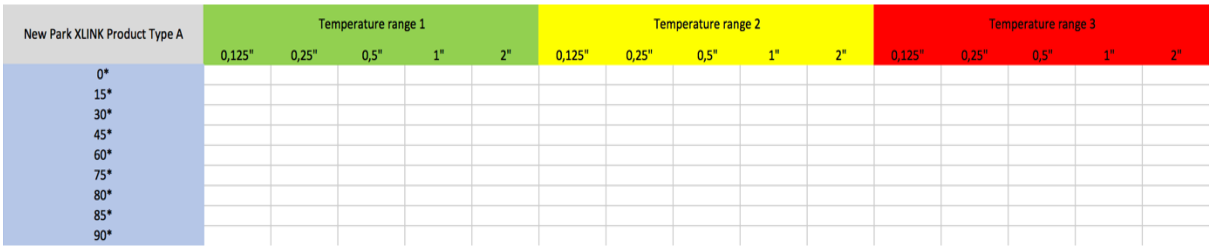
4.3. Testing Procedure

As described previously, the test stand shall be able to test the latest LCM. Therefore, a comparative testing method needs to be set up.

The test stand will be able to vary temperature, fracture aperture and angle as main parameters. There are three temperature ranges being tested. Temperature range 1 (10-20°C) will be tested at 15°C, range 2 (40-50°C) at 45°C and range 3 (> 75°C) at 85°C, if the material allows it. Different temperature ranges are examined to see chemical instabilities and changes in behaviour due to higher temperature. Five different fracture apertures will be tested: 0,125”, 0,25”, 0,5”, 1” and 2”. A wider fracture requires a coarser medium to cure losses. The limitation of each size and treatment shall examined. By changing the angle of the rock sample or simulated reservoir, different fracture angles are going to be tested. A higher inclination makes it more difficult for the treatment to reach the top. A critical angle for each treatment shall be figured out.

For all three inlets (vertical, diagonal, horizontal) and each medium, an excel file is saved.

Table 8: Excel Table Test Stand



New Park XLINK Product Type A	Temperature range 1					Temperature range 2					Temperature range 3				
	0,125"	0,25"	0,5"	1"	2"	0,125"	0,25"	0,5"	1"	2"	0,125"	0,25"	0,5"	1"	2"
0*															
15*															
30*															
45*															
60*															
75*															
80*															
85*															
90*															

In this table, the output data of the series of tests is organised. It will contain three major facts. The fluid loss over a critical time frame (e.g. 30 minutes), the actual time to seal the fracture until no further losses are happening and after the medium is applied as the manufacturer intends it, the differential pressure the seal can sustain.

With this output given, a comparison of the tested LCM can be achieved and recommendations can be made, which LCM to take under certain conditions.

5. Lost Circulation Case Studies

In this chapter, the five wells most prone to lost circulation of TAG Oil Ltd. are summarised. For each of the wells and at the end a recommendation is made how to avoid the losses happened during drilling those five wells.

5.1. Waihapa-1

Abstract

Mud losses during the drilling of Waihapa-1 when the well had been drilled to 1853 metres and 13 3/8“ casing set at 1849 metres. A total of 150 barrels of mud was lost during the displacement of cement.

Significant losses occurred after encountering the Tikorangi Limestone. At 2918 metres losses were 20-40 barrels per hour increasing to 60 – 70 barrels per hour. Losses were reduced but not eliminated by spotting LCM and Kocarb across the fracture zone. However, at 2969m metres, cement squeezes became necessary as well as LCM pills and Flocheck plugs. Loss continued through to 3599 metres, varying between 7 and 40 barrels per hour and during logging and the running of the 9 5/8” casing which was set at 3583 metres. Mud losses also became a problem while drilling the 8 ½” hole section and Kocarb was added to the mud in varying quantities.

Waihapa-1A was drilled without losses until the 7” liner was set at 4451 metres. A total of 298 barrels of mud were lost while cementing. There were also occasional losses following a drilling break in sandstone 4646 metres.

There were no mud losses during the drilling of Waihapa-1B.

Summary

Tikorangi Limestone once again stole large volumes of mud and resisted most attempts at sealing (whether with LCM or Cement). Mud cost escalated due to these attempts, losses and treating for cement contamination. Tikorangi limestone encountered at 2776m. Lost circulation became apparent from 2918m at 20 – 40 bbl/hr then total, lost all mud in system. Spotted 11 bbl of 25 lb/bbl Kocarb LCM slug across fracture zone without success. Spotted another 100 bbl 25 lb/bbl Kocarb plus 10 lb/bbl Kwikseal (medium) then pulled 15 stands and waited while building more volume of mud. Losses appeared to be healed.

Drilled ahead with losses of 5 – 35 bbl/hr to 2969m.

Cement squeeze no. 1 performed (50 bbl cement, squeezed 10 bbl), repeated above for squeeze no. 2. Cement tagged at 2815 m and drilling continued to 2969 m. Performed leak-off test – immediate drop off in pressure.

Ran in and drilled ahead, total loss of circulation at 2969.5m. Pumped LCM pill and spotted above loss zone (50 bbl). Circulation started slowly increasing pump stokes. Minor losses at 244 gpm.

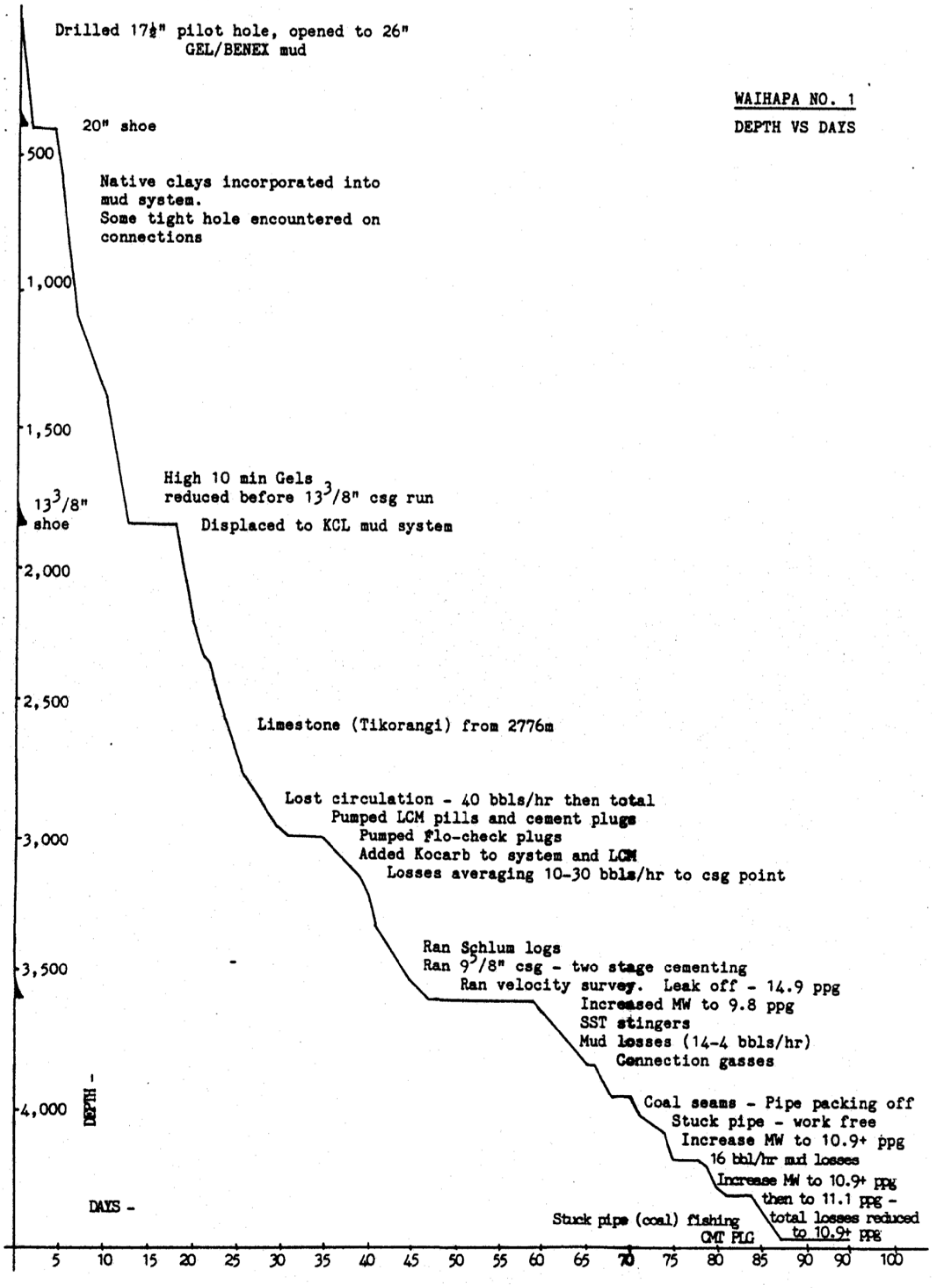


Figure 47: Depth vs Days Waihapa No. 1 (TAG Oil Ltd.)

Drilled ahead with reduced pump rate and minor losses, however major losses occurred while reaming. Losses of 60 bbl/hr at 100 gpm flow rate encountered.

Spotted 45 bbl LCM pill at 2953 m (Kwikseal at 20 ppb), pulled back six stands and circulated across well head monitoring losses for three hours – ok.

Reamed to 2982m losing 55 – 60 bbl/hr. Kwikseal was added to active mud system at approximately 2 - 3 ppb, some reduction but pulling pipe and reaming made situation worse. Pumped 130 bbl Flochek and squeezed, losses at approx. 15 bbl/hr. Spotted second Flochek pill and squeezed. Squeezed 3 bbl cement for 450 psi, continued squeezing cement at half hour intervals until 500 psi held.

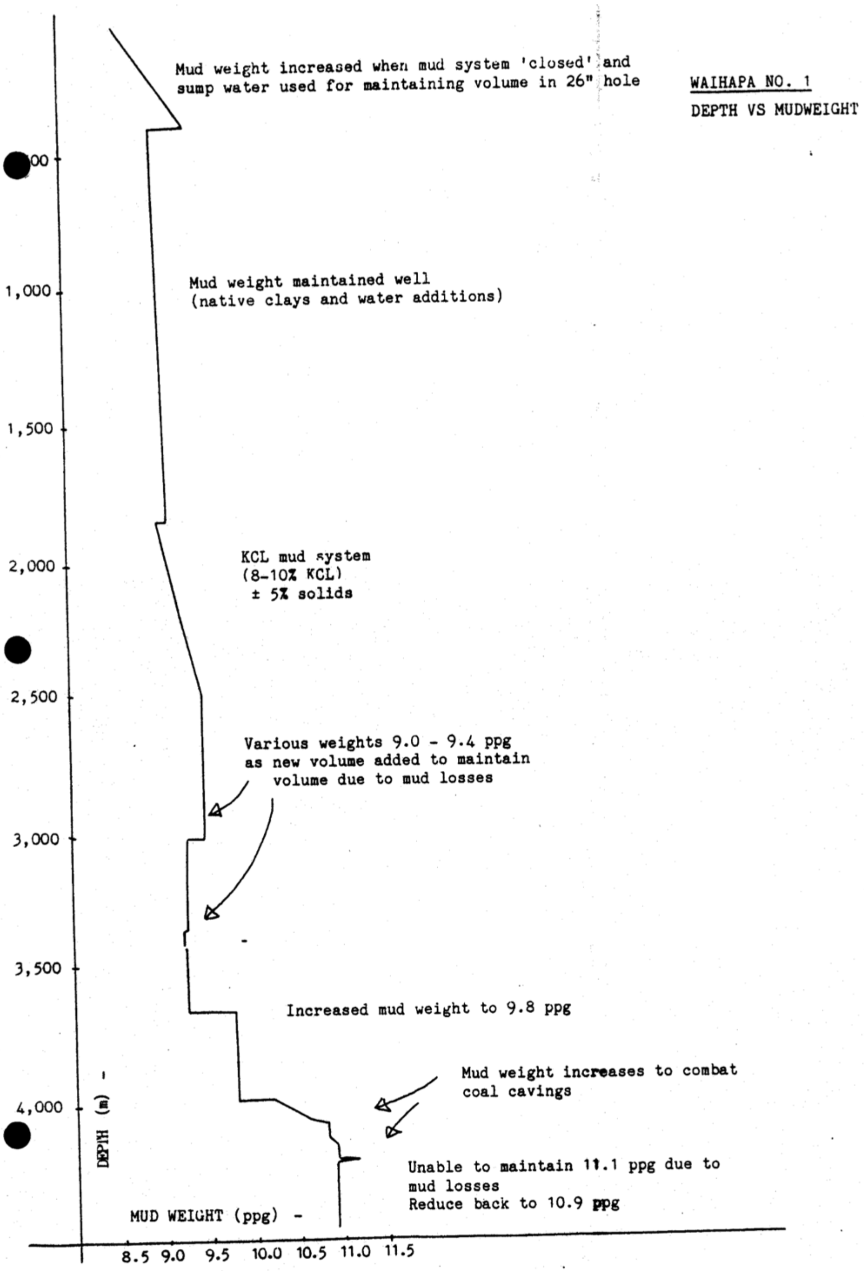


Figure 48: Depth vs Mudweight Waihapa No. 1 (TAG Oil Ltd.)

Drilled cement to 2982 m and drilled ahead with losses at 100 bbl/hr, up to 140 bbl/hr.

Then pumped 60 bbl LCM pill (Kocarb and Kwikseal) followed by continual additions of Kwikseal to mud system. Losses reduced to 5 – 10 bbl/hr, Kwikseal additions were stopped for one circulation but losses started increasing again. Kwikseal continued and losses averaged out at approx. 7 bbl/hr at 500 gpm flow rate.

When continuing drilling ahead, losses increased from 7 to 30 bbl/hr. Increased additions of Kwikseal and Kocarb averaged losses at 22 bbl/hr at 550 gpm flow rate. Constant additions of LCM required.

Drilling continued ahead with losses near zero but increased during reaming at 2833 m to 35 – 40 bbl/hr. Drilled to 3599 m, circulated high viscosity pill around then pulled out to log. Losses while logging 18 – 24 bbl/hr. Caliper log showed washout.

Reamed tight spot, added Mica to mud. Increased mud weight to 9.7 ppg and losses increased to 100 bbl/hr. Increased Mica additions. Made 40 bbl LCM pill (25 ppb) of Mica, Kocarb, Kwikseal and circulated around. Made another LCM pill of 50 bbl (45 ppb LCM) and spotted across loss zone. Pumped 50 bbl high viscosity pill and circulated hole clean. Cemented 9 5/8 casing without any problems.

Drilling continued to 3816 m when mud losses at 14 bbl/hr noted, reducing to 10.5 bbl/hr. Kocarb was added to the mud at 5 ppb (1:2 ration coarse to fine) and losses reduced to approx. 2 bbl/hr. Further drilling breaks at 3853, 3860, 3876 and 3888m noted, Kocarb additions were increased to 8 ppb.

Mud losses were a problem through this interval. The first record of mud losses was at 3816m after drilling breaks from 3745 – 3767m. Connection gasses were also noted over same interval so unlikely that losses were due to the sands. Initially it looked like losses were to fracture/vugs but no correlation to logs.

No further significant losses were encountered until the liner was set at 4451m (298 bbls mud lost while cementing).

Recommendation

The Tikorangi limestone continues to defy most attempts to stem drilling fluid losses. Some improvement was seen making continuing Kwikseal and Kocarb additions while drilling. The solids control equipment proved capable of minimising mud weights below 9,2 ppg where desired. Mud proved quite efficient – not any other hole instability problems.

The initial completion fluid was planned to be solids free sodium bromide – but as unavailable in New Zealand this option was not executed. Sodium chloride and sodium carbonate were used, giving a maximum density of 10,5 ppg. Calcium carbonate (Kocarb) would then be used as weighting agent to give the required 12,0 ppg. Also, the use of Kocarb as weighting agent was 30% cheaper than the use of Barite.

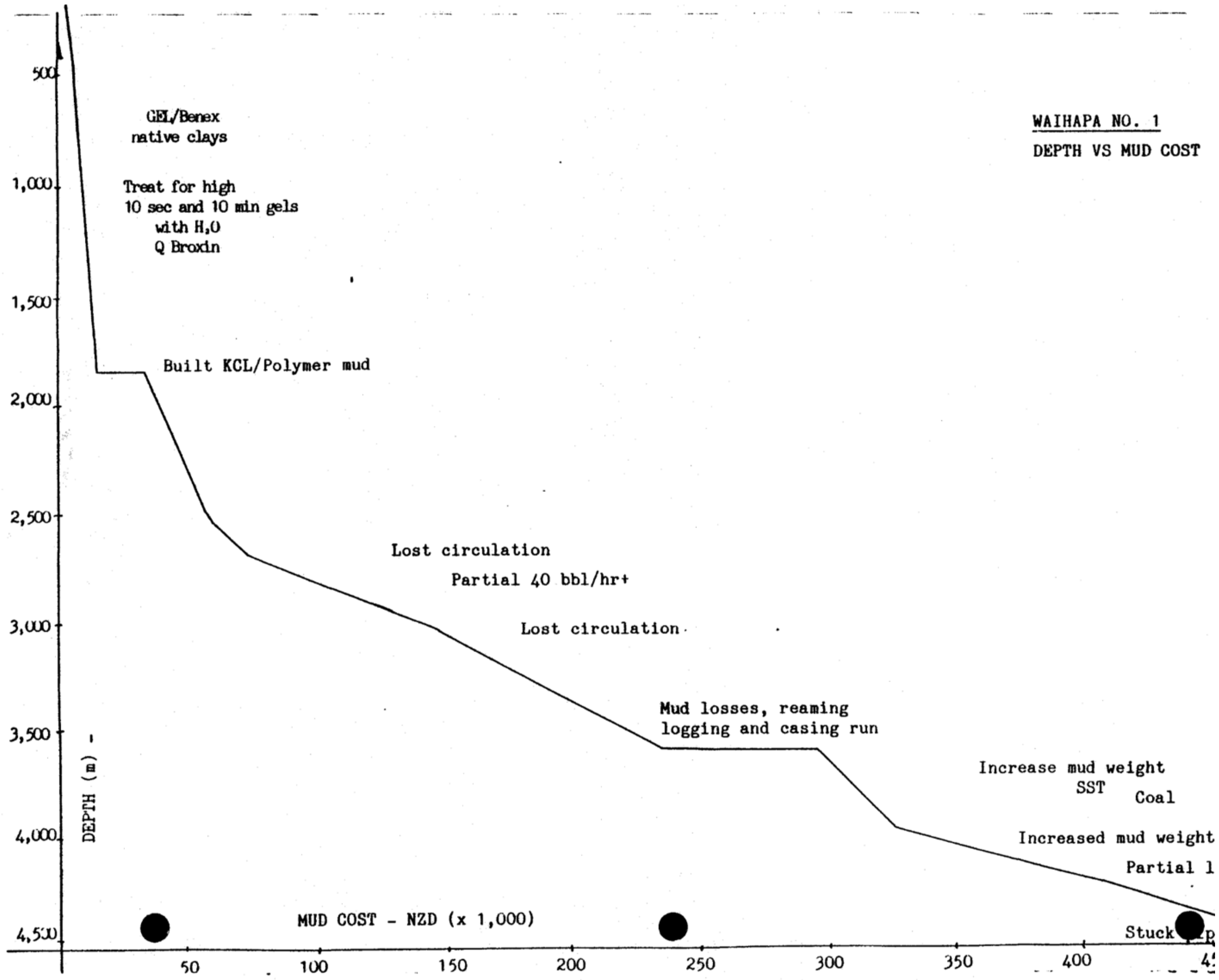


Figure 49: Depth vs Mud Cost Waihapa No. 1 (TAG Oil Ltd.)

Kocarb was added to the mud system for two specific reasons:

- Increase mud density
- Combat lost circulation

It was originally only programmed as an acid soluble lost circulation agent. The primary reason behind selecting Kocarb was indeed that it is acid soluble and hence minimises formation damage to productive formations. By using the correct grades of Kocarb it becomes an excellent bridging agent. Kocarb seemed to assist in the lowering of the API water loss but not the HPHT water loss. This would be achieved by the addition of bentonite, to give a compressible filter cake, or varying grades of Kocarb.

Kocarb would appear to be ideal in preventing “seepage” losses but as losses were total to partial it is unfair to say Kocarb is not a LCM. Certainly, in this case mixtures of fibre, flake and granular material would appear better but even they did not produce good results. Cement seemed the only solution.

5.2. Waihapa-6

Abstract

Waihapa-6 was a vertical appraisal/development oil well designed to evaluate the western part of the Waihapa Field. The primary objective was the Tikorangi Formation (limestone). Sandstone beds of the Mount Messenger and Moki formations were secondary objectives. Waihapa-6 was plugged back to 990m because two drill stem tests were unproductive. Waihapa-6A deviated to a target 360m northeast of the original well path. Waihapa-6A has a good fracture development, as inferred from electric and formation evaluation logs.

During the drilling of Waihapa-6A continuous losses occurred while drilling from 2885 metres to TD, during logging and until the liner was set and cemented. Over a period of eight days during which time LCM pills were pumped regularly to control the losses, the following daily subsurface losses occurred: 400, 2000, 2376, 6000, 3800, 5300, 3730 and 3525 barrels.

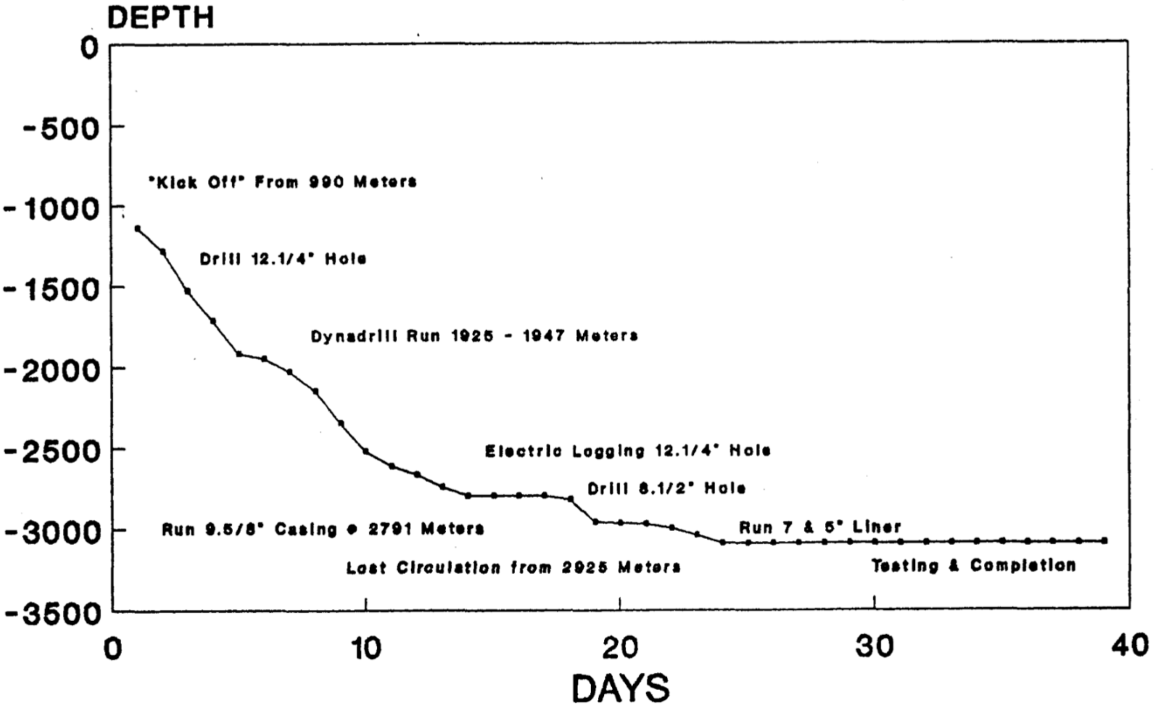


Figure 50: Depth vs. Days Waihapa-6A (TAG Oil Ltd.)

Summary

At 2925 metres, downhole mud losses were detected and a Kocarb pill was mixed and spotted on bottom. A wiper trip to shoe was made, where the well was monitored and found to be static.

After drilling ahead to 2958 m the mud weight was reduced to 8.8 ppg but losses increased to 60 bbl/hour and a further Kocarb pill was spotted on bottom. A short trip to the shoe was made and the well was monitored. Due to blocked jets a round trip was necessary. While tripping, the losses were approx. 30-35 bbl/hour.

Back to bottom and drilled ahead for 5m, total losses occurred and another Kocarb pill was pumped. Losses increased further after drilling from 2963 to 2965m. Another Kocarb pill was pumped to combat losses of 75 bbl/hour. Pulling back to 2781m made losses negligible and drilling continued then from 2965 to 2965.65m. Losses rapidly increased to 150 bbl/hour and another Kocarb pill was pumped. Two stands were pulled and mud circulated, losses were monitored at 280 bbl/hour. Two Kocarb pills were pumped and displaced at the shoe. The operation of pumping another Kocarb pill was repeated several times.

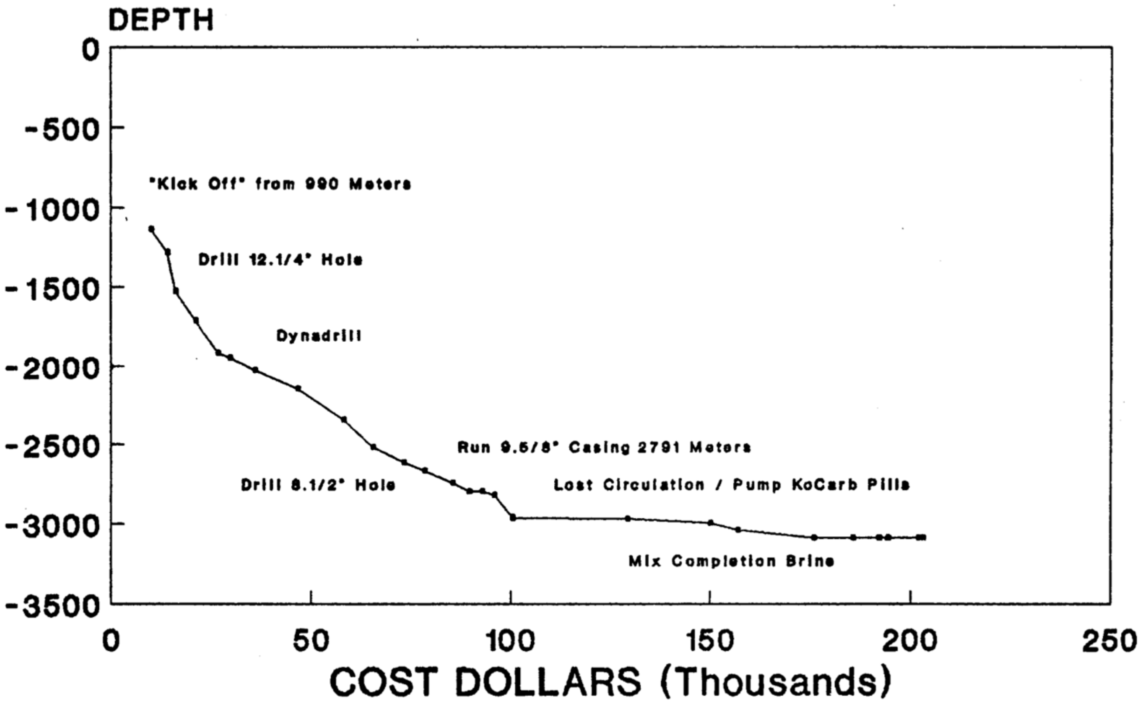


Figure 51: Depth vs. Cost Waihapa-6A (TAG Oil Ltd.)

With losses approx. 478 bbl/hour the bit was run back to bottom, 2944 metres where there was 21 metres of fill (Kocarb). The fill was drilled out and drilled ahead with partial returns to 2968 metres, where total losses occurred again. Two Kocarb pills were pumped. Drilled ahead to 2993 metres, losing approx. 250 – 300 bbl/hour, with reaming required due to tight hole. High-viscosity pills were used to clean the hole. Further Kocarb pills were pumped until the decision was made to change the bit and BHA. The hole was kept full during trip with losses of approx. 100 – 150 bbl/hour.

The new BHA was made up and bit re-run in hole, drilling continued to 3087 m, making regular hi-vis sweeps to clean the hole. Losses continued at 100 – 135 bbl/hour while drilling and further 100 bbl Kocarb pills were pumped and it was pulled back to the shoe. After 30 mins at the shoe losses were monitored at 132 bbl/hour. Another 100 bbl Kocarb pill was pumped and losses were monitored at 101 bbl/hour. Losses continued while completing the well.

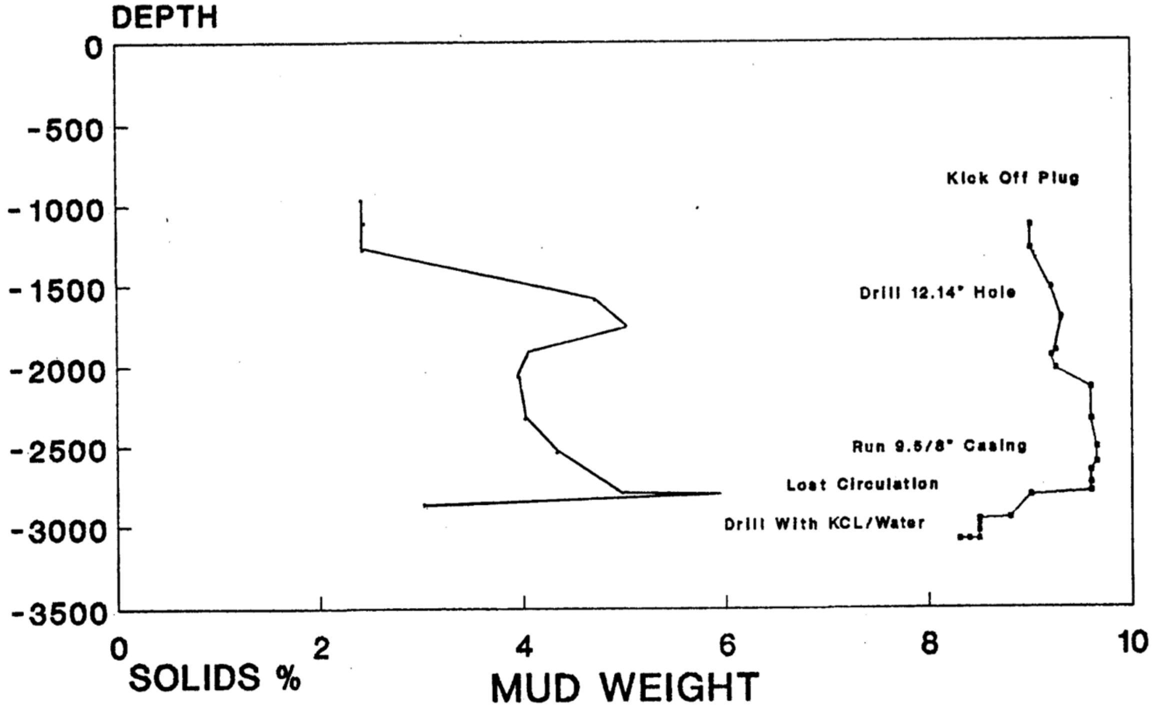


Figure 52: Depth vs. Mud Weight Waihapa-6A (TAG Oil Ltd.)

Recommendation

Efficient and effective solids control equipment is essential when utilising the solids. On this particular well both the desander and desilter were quite efficient with underflow discharges in the region of 9,9 – 10,1 ppg. The discharge of both units was wetter than expected, causing costly losses of mud in the region of 5 to 6 bbl/hour.

As 1200 bbl of old mud from Waihapa-6 was used in the 12 ¼” section a considerable cost saving was realised over mixing new volume.

The linear motion shakers should be monitored closely to ensure that correct screen sizes are being utilised. Care must be taken not to fall into the trap of increasing the angle of the decks to save going coarser mesh screens. The solids merely build up on the rear of the screen and cause it to tear allowing even more solids to enter the circulating system. With the utilisation of the Polyplus mud systems it has been found that an increase in Polyacrylamide content will bind the cuttings together causing a sweeping action in the hole and a matting effect over the shakers allowing the use of coarse mesh screens without the worry of drilled solids build-up in the mud.

Losses to the sands in the 8 ½” hole section proved costly and continued despite the partial success of Kocarb LCM pills. It has been found in some areas that by sizing the LCM according to the particular sands permability and mixing it in a 15 – 20 lb/bbl gel slurry and then adding 10 lb/bbl dry gel to the slurry prior to pumping that extremely good results in curing losses are possible. Instead of immediately sealing the sand with filter cake these pills invade the sand to a certain degree and the Kocarb or Calcium Carbonate along with the dry gel consolidate the sand and reduce permeability so that even with the loss of the protective filter cake during trips the previous losses do not manifest themselves again.

5.3. Waihapa-8

Abstract

Waihapa-8, a deviated appraisal/development well was drilled to appraise optimal well spacing and increase oil production and recovery from the Tikorangi Formation. Waihapa-8 was drilled vertically to a depth of approximately 900 m AHBKB. The well path was then deviated to an inclination of 35 degrees at 1700m AHBKB and then drilled conventionally to a total depth of 3618 m AHBKB. The Tikorangi Formation was penetrated at a depth of 3260 m AHBKB.

Waihapa-8 was completed as an Oil Producer. Mud losses occurred whilst drilling from 3275 m to TD. Total losses were experienced in the well.

Summary

At 3285m, losses of 60 bbls/hr were recorded and immediately the mud in the intermediate surface pits was isolated. The active system consisted of the one suction pit and water added to keep up with downhole losses. At this depth, the hole was circulated clean prior to pulling out. Losses during pulling out fluctuated from 30 to 90 bbl/hr. Surface supply water was treated with Bactericide and used to continuously fill the hole. A bit was run back in and drilling progressed using water and hi-vis sweeps. To TD, a 15 bbl sweep was pumped every 10 metres drilled. The production water supply was brought online, but an initial hiccup occurred when the plastic water pipe split due to the temperature of the production water. A metal water line was set up. As this production water did not need to be treated, it was used as much as possible. The sweep mud was formulated using old mud, prehydrated Gel and flocculated with Lime or Gypsum.

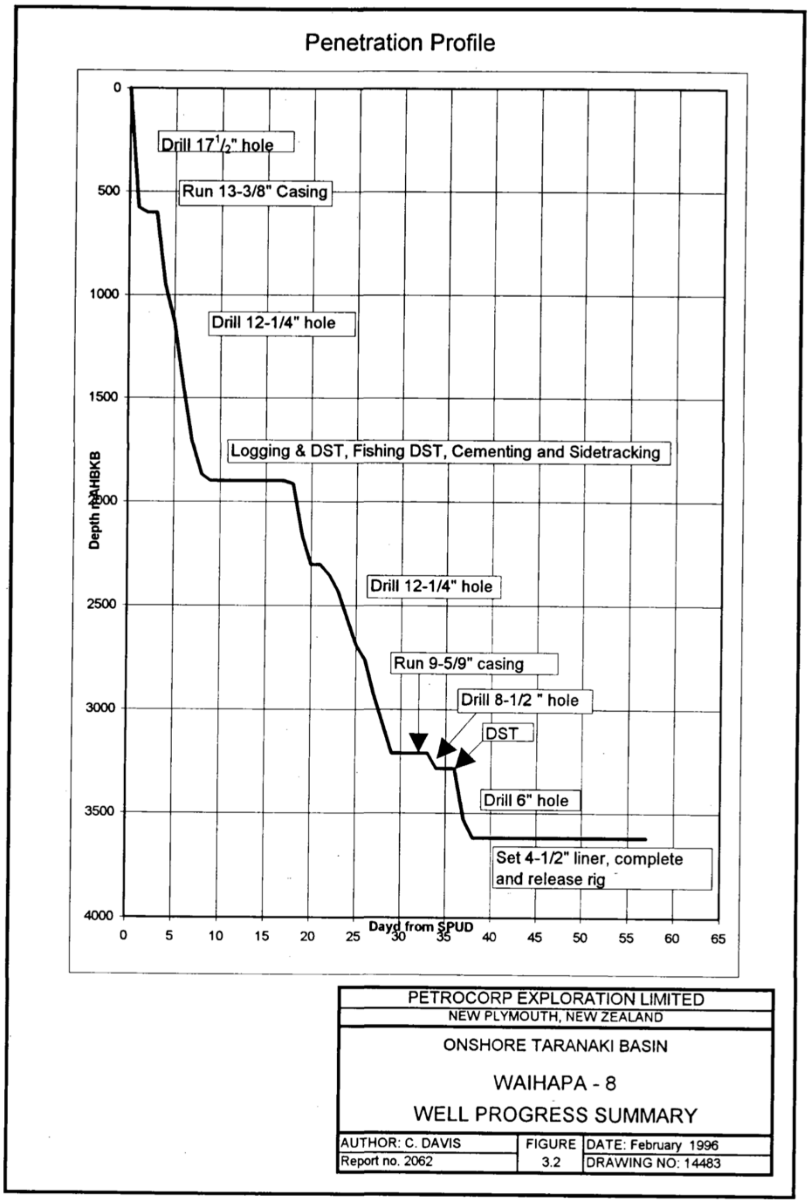


Figure 53: Depth vs. Days Waihapa-8 (TAG Oil Ltd.)

Drilling proceeded to 3490 m as losses increased from 120 to 240 bbl/hr and finally total losses were experienced. Initially, trucked water was brought in, but once everything was topped up, there were no problems keeping up with the production water supply.

The well was drilled to 3618 m, a 30 bbl hi-vis sweep was pumped – a wiper trip was made and the bit was POOH. It was necessary to ream near 3227 m. Wireline logging was attempted with BPB but they were unable to pass 3220 m. The logs did determine the fluid level to be at 420 m. Whilst logging, the hole was continually filled with 336 bbl/hr of water. A wiper trip was conducted, but a second attempt to log was held up again at 3220 m. Another wiper trip was performed but again logs were unable to pass. Logging was finally successful when the tools were passed through drill pipe.

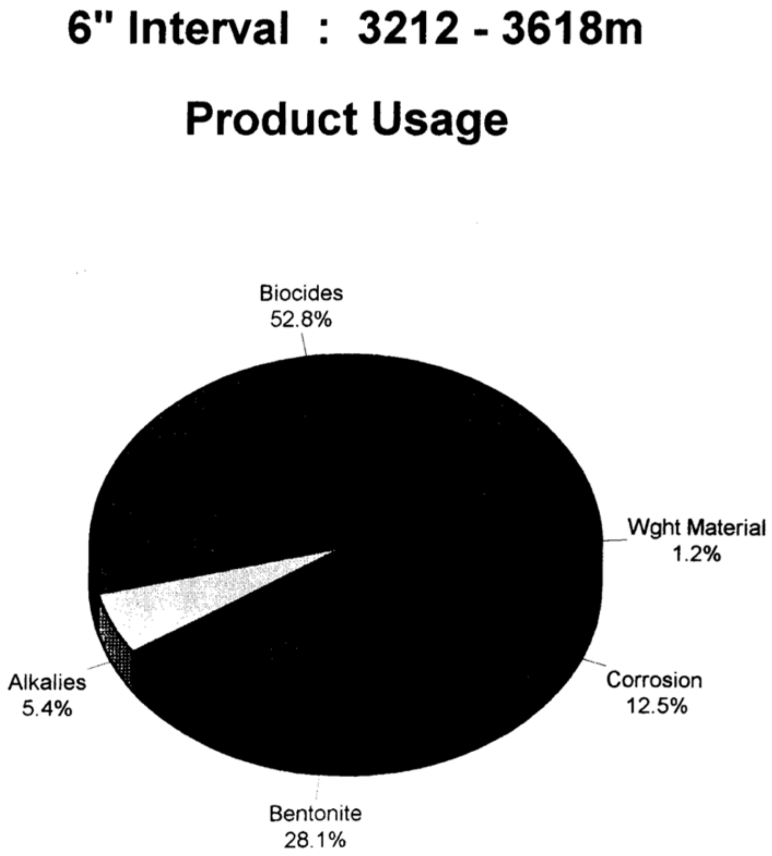


Figure 54: Product Usage Waihapa-8 (TAG Oil Ltd.)

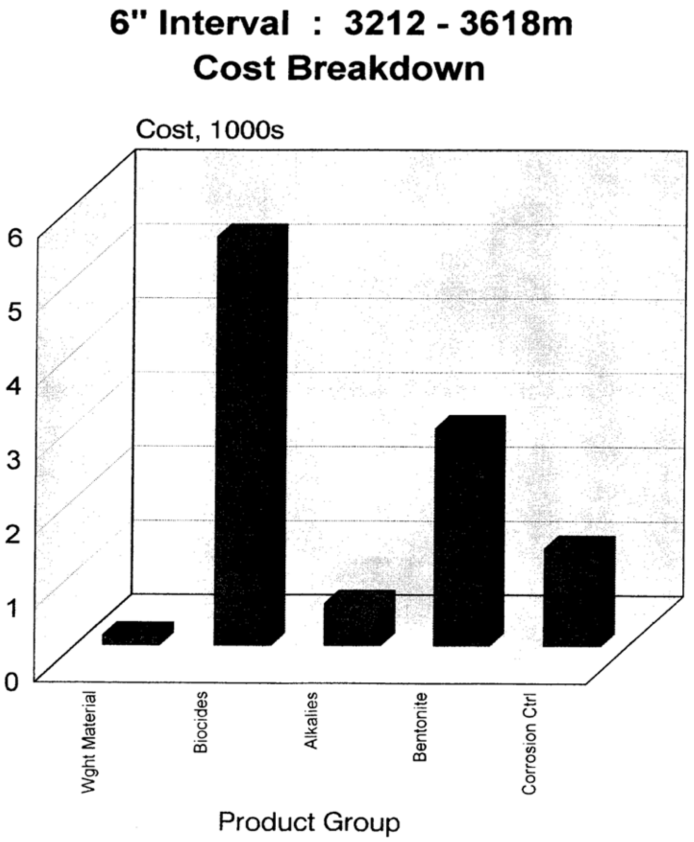


Figure 55: Cost Breakdown Waihapa-8 (TAG Oil Ltd.)

Recommendation

Circulatory returns deteriorated from 60 bbl/hr at 3285 m to 240 bbl/hr then to total losses at 3490 m. The KlaCure mud retained from the 8 ½” interval was used to drill to 3285m and as soon as expected losses were encountered, the mud in the intermediate surface pits was isolated for use in sweep mud formations. From 3285 m, the well was drilled with water and high viscosity sweeps, with 15 bbl of sweep mud circulated every 10 m drilled.

5.4. Sidewinder-2

Abstract

Sidewinder-2 was drilled as an exploratory well designed to evaluate the hydrocarbon potential of an Upper Miocene amplitude anomaly to the east of the Sidewinder-BS-1 discovery. At approximately 1387 m mud losses occurred, losing a total of 685 cubic meters.

Sidewinder-2 was plugged and abandoned as a result of drilling difficulties caused by extreme mud loss. The target was redrilled as side-track Sidewinder-2 ST-1. The majority of losses being at a rate of 12-16 bbl/hr while drilling from 1387 m – 1429 m MD. No drilling fluid losses were experienced during operations at Sidewinder – 2 ST1.

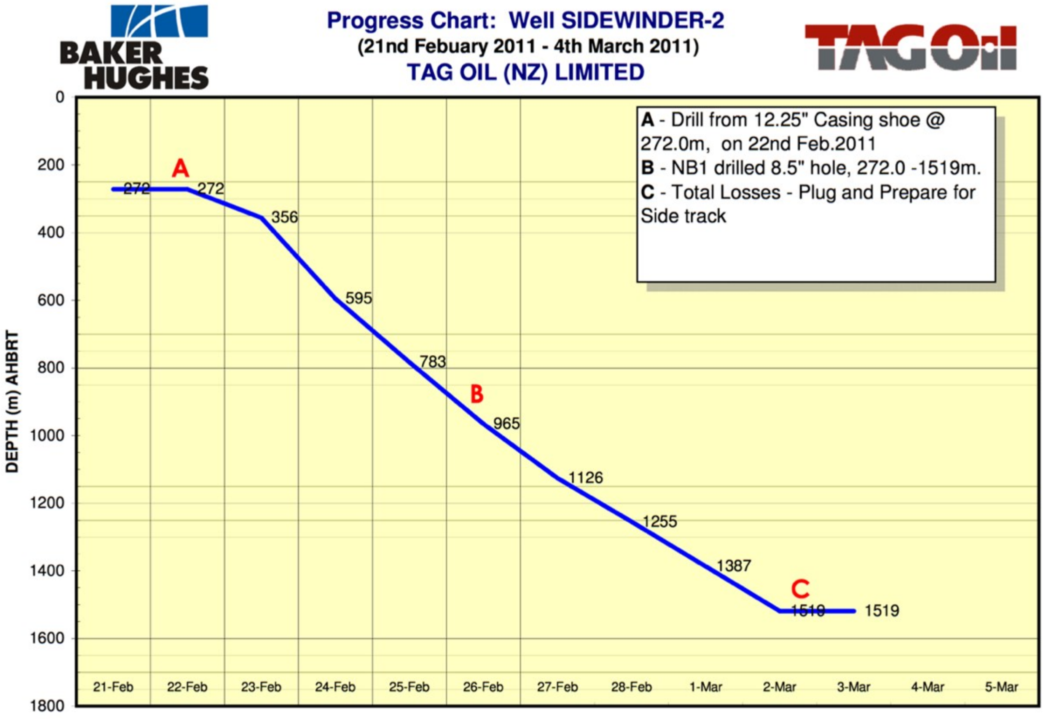


Figure 56: Depth vs. Days Sidewinder - 2 (TAG Oil Ltd.)

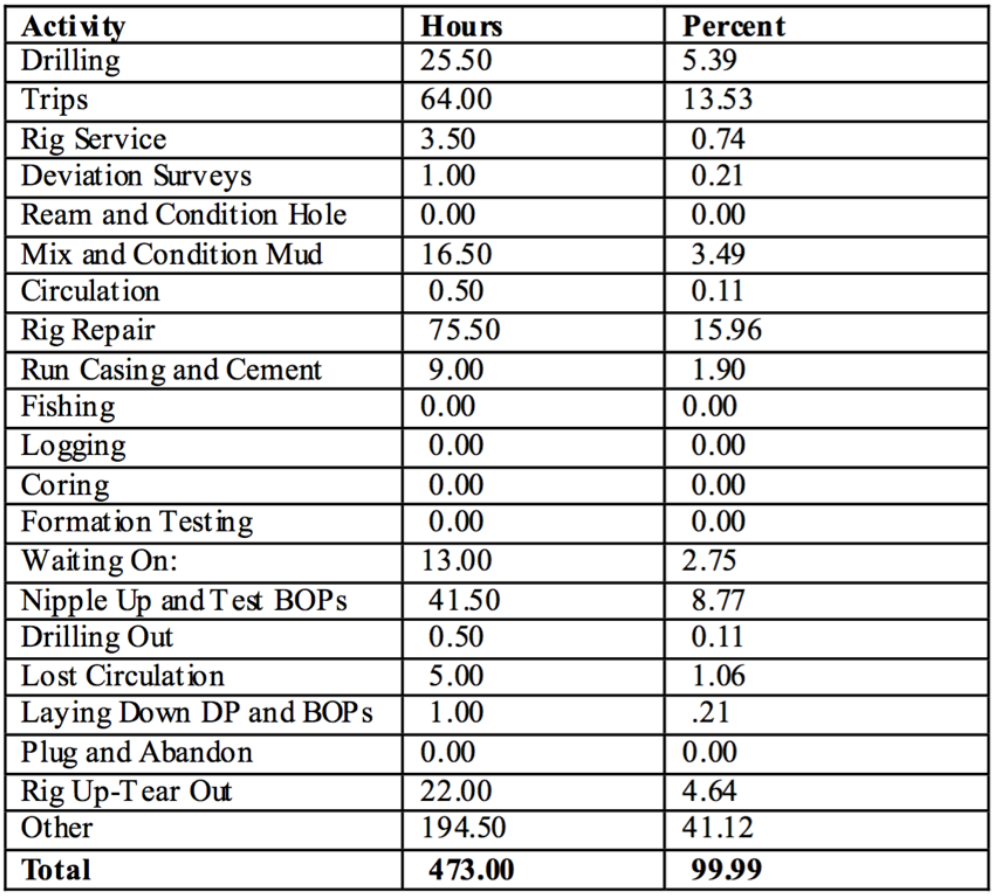
Summary

There were total losses on reaching 1387 m, space out and monitor well at 150 gpm, line up on trip tank while mixing LCM. Pumped 40 barrels of LCM and displace it with 55 bbl of drilling mud, pulled back from 1387 m to 1255 m and monitor losses via trip tank; no losses observed on trip tank. While circulating at 150gpm the annulus level drop was observed. Run in hole from 1255 m to 1353 m and pumped 40 bbl of LCM. Pulled back to 1255 m while waiting of LCM to soak and monitor well via trip tank, no losses observed during this operation. Staged up pumps to 38 strokes per minute, no losses observed.

Run back in hole from 1255 m to 1353 m and continue to drill ahead. Encountered loss of circulation at 1372 m, pumped 45 bbl LCM, monitor loss on trip tank, well observed static. Circulated the hole and staged up pumps from 150 gpm to 275gpm. Run back in after curing losses and drill ahead from 1372m to 1429m. Encountered loss circulation, upon which 40bbls LCM pill was spotted on bottom and pull back from 1429 m to 1235 m. Pumped 100 strokes every 10 minutes until well stabilized and static after which bring up pump rate to 150 gpm by staging up pumps by 50 gpm increments.

Run back in to 1429 m and drill down to 1448 m, well was observed to be flowing whilst performing a connection, shut in well. No casing pressure increment was observed, opened well and circulated bottoms up, upon which average loss rate of 15 barrels per hour was seen. Resume drilling with 15 barrel losses from 1448 m to 1519 m. On reaching 1519 m total loss of circulation was experienced. Pumped three 60 bbl LCM pill without much success and decision was made to pull out to surface and make up cement stinger to plug the well for side track. There were no losses while drilling Sidewinder – 2 ST1.

Table 9: Total Hours Spent on Sidewinder - 2 (TAG Oil Ltd.)



Activity	**Hours**	**Percent**
Drilling	25.50	5.39
Trips	64.00	13.53
Rig Service	3.50	0.74
Deviation Surveys	1.00	0.21
Ream and Condition Hole	0.00	0.00
Mix and Condition Mud	16.50	3.49
Circulation	0.50	0.11
Rig Repair	75.50	15.96
Run Casing and Cement	9.00	1.90
Fishing	0.00	0.00
Logging	0.00	0.00
Coring	0.00	0.00
Formation Testing	0.00	0.00
Waiting On:	13.00	2.75
Nipple Up and Test BOPs	41.50	8.77
Drilling Out	0.50	0.11
Lost Circulation	5.00	1.06
Laying Down DP and BOPs	1.00	.21
Plug and Abandon	0.00	0.00
Rig Up-Tear Out	22.00	4.64
Other	194.50	41.12
Total	**473.00**	**99.99**

Recommendation

Throughout production interval total losses were encountered at 1386 m / 1259 m TVD and again at 1519 m MD. LCM Pills were pumped, however a fault was observed and the production hole was required to be cement-plugged back to 342 m. Three cement plugs were set and a side-track was performed (Sidewinder-2 ST-1).

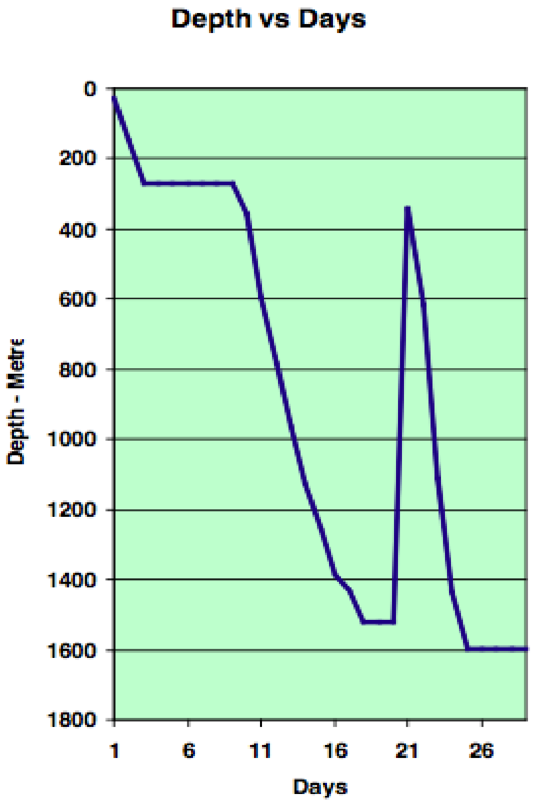


Figure 57: Depth vs. Days Sidewinder - 2 and ST1 (TAG Oil Ltd.)

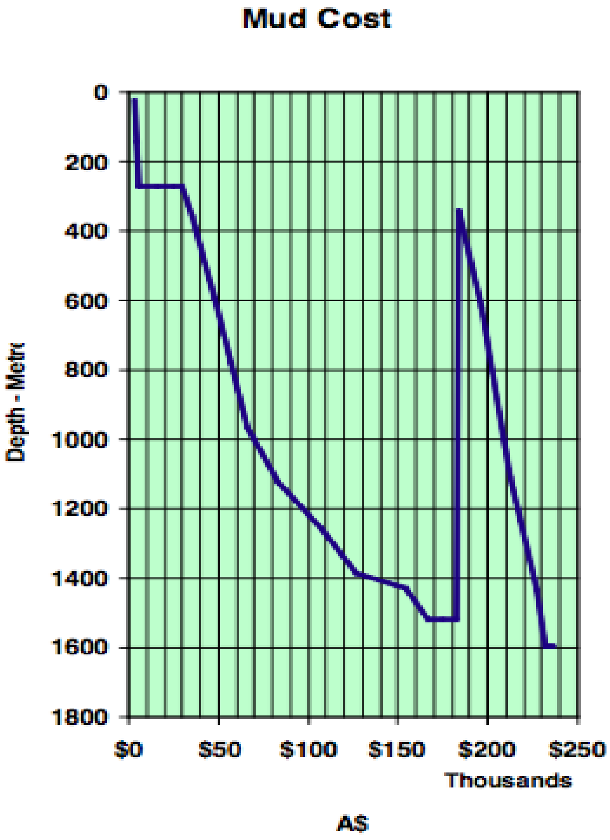
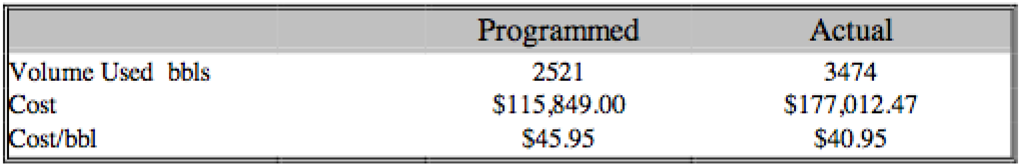


Figure 58: Mud Cost Sidewinder - 2 and ST1 (TAG Oil Ltd.)

High dilution rates required in an attempt to maintain mud density were a contributing factor for interval cost coming in over program costing. In conjunction with high dilution rates in this section, total downhole losses were experienced twice, therefore a significant amount of mud volume lost, and LCM product was used which was the predominant cost for the interval.

Table 10: Mud Cost Sidewinder - 2 and ST1 (TAG Oil Ltd.)



	Programmed	Actual
Volume Used bbls	2521	3474
Cost	$115,849.00	$177,012.47
Cost/bbl	$45.95	$40.95

Note: Costs/bbl include value of LCM used throughout section. No costing included for mud received at start of 8.5” interval.

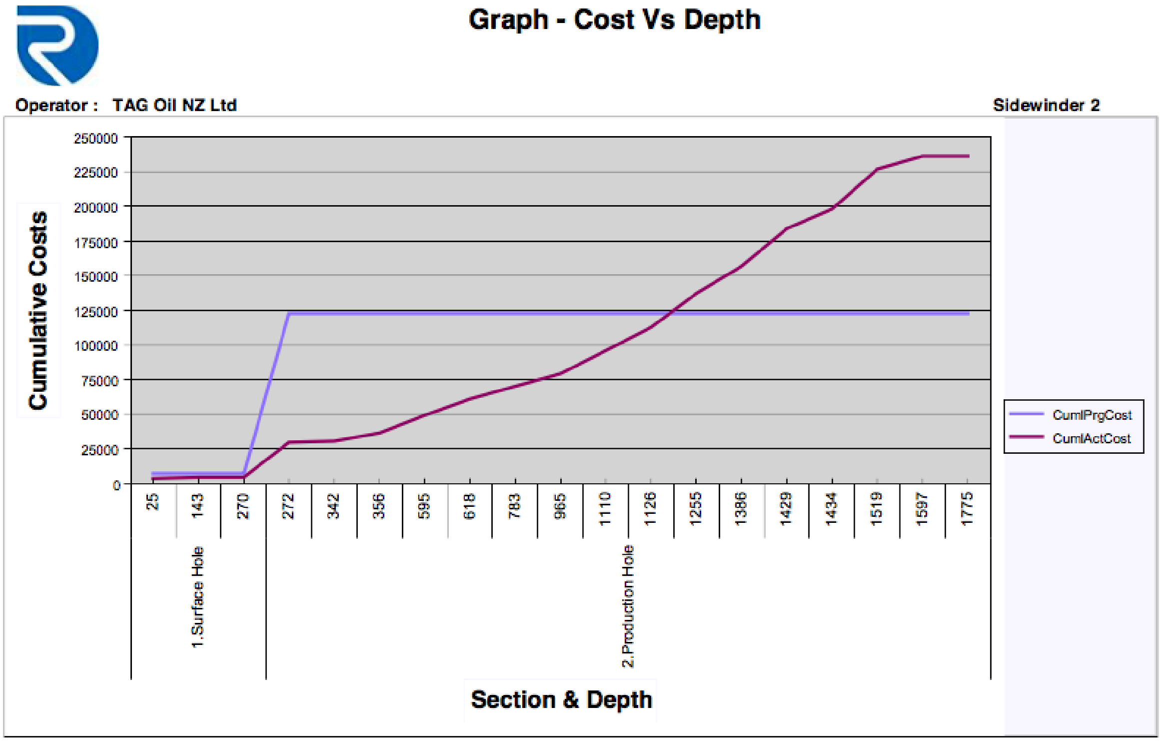


Figure 59: Cost vs. Depth Sidewinder - 2 and ST1 (TAG Oil Ltd.)

5.5. Douglas-1

Abstract

Douglas-1 targeted the open fracture system contained in a three-way dip closure of the Tikorangi Limestone sub-thrust against Murihiku basement. The Tikorangi Limestone was considered a principal target in this area as it has produced approx. 26 mmbbl oil from this fractured limestone in the adjacent Waihapa-Ngaere oil field.

The primary target, Tikorangi Formation, was intersected at 2548.5 m TVDss. This is 68.5 m deeper than prognosis. Encouraging oil shows (60 – 80%) and elevated wet gas was detected near the top of the limestone between 2816 – 2831 m (2554 – 2568 m TVDss) from fractures seen on the FMI log. Trace shows were noted in cuttings from 2871 – 2898 m before total losses occurred as a result of intersecting large open fractures up to 30 cm wide between 2909 – 2912.8 m.

Summary

At 2904 m, losses were taken and circulation was lost. This was anticipated as the Tikorangi Formation is highly fractured in the Eastern Margin of the Taranaki Basin. Drilling continued ‘blind’ to 2906 m when the pipe became stuck and required 60 klbs of overpull to free it during a connection. At 2912 m the surface pits had been completely drained and it was decided to pull back to the casing shoe while the tanks were filled with fresh water. Once at the casing shoe a 70 bbl LCM pill was pumped in an attempt to cure/slow losses, no pressure on stand pipe was recorded and it was decided to POOH and change the BHA from a directional to dumb rotary assembly that required lower circulation rates.

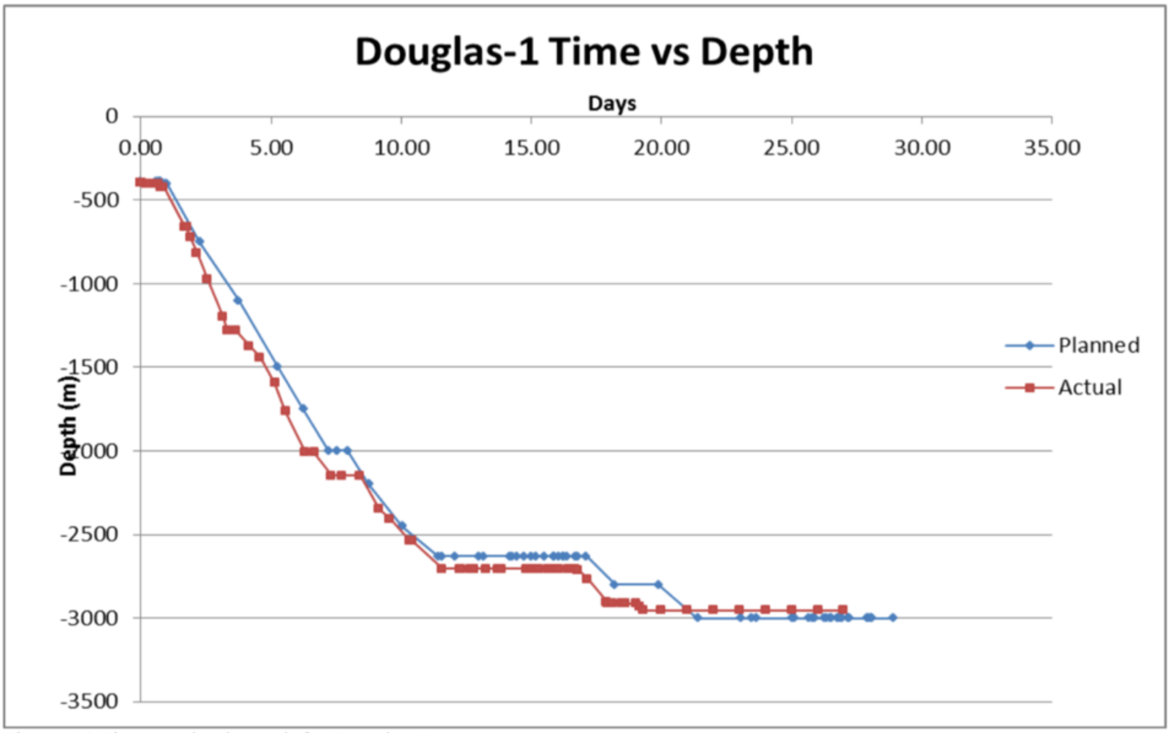


Figure 60: Time vs. Depth Douglas-1 (TAG Oil Ltd.)

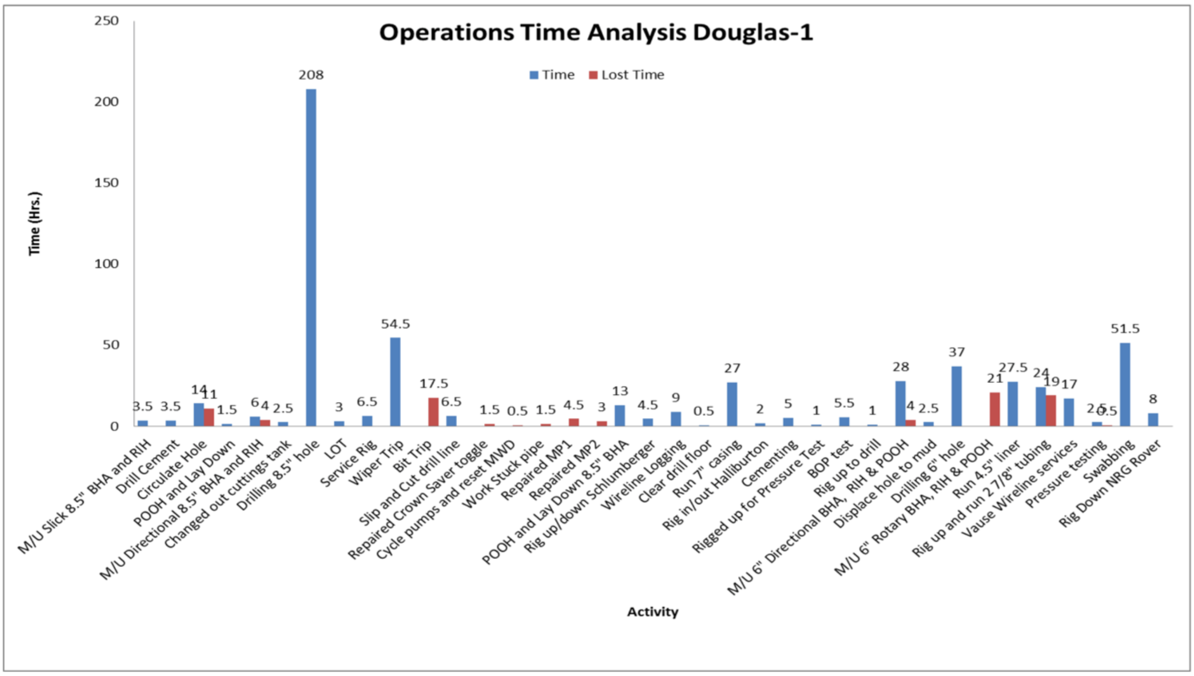


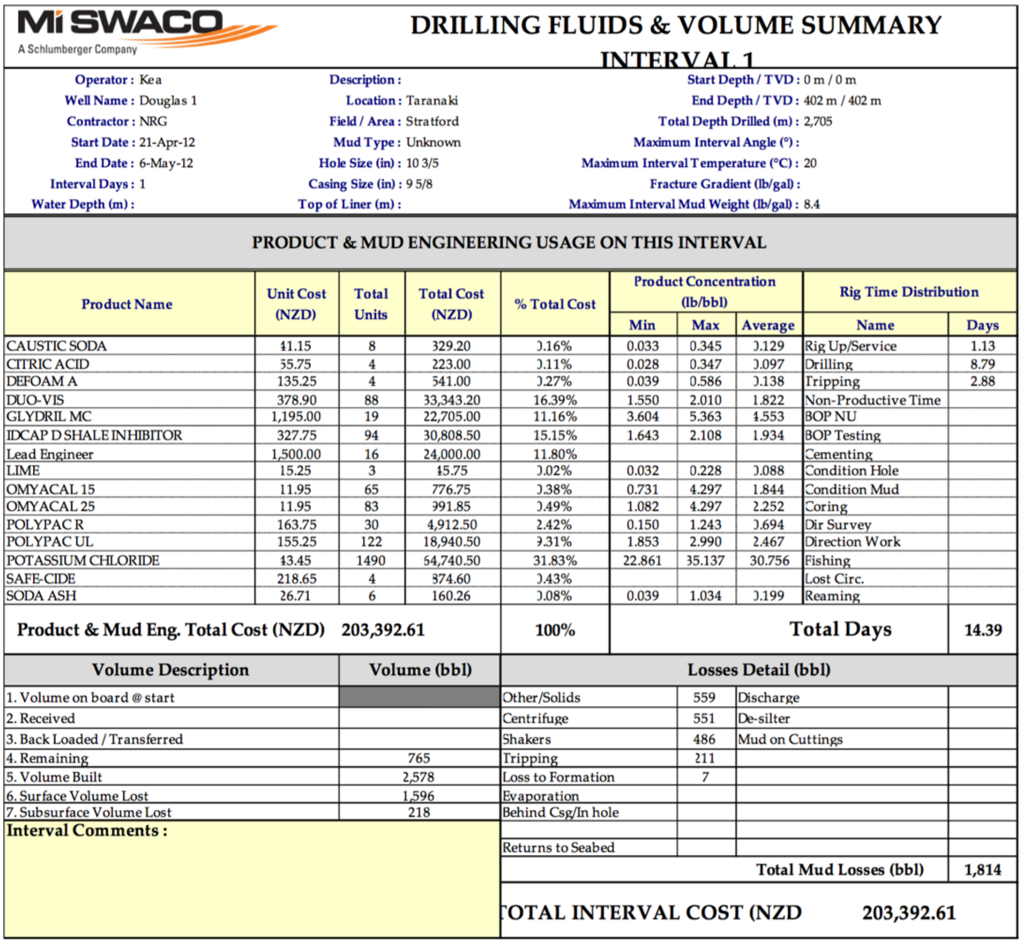
Figure 61: Operations Time Analysis Douglas-1 (TAG Oil Ltd.)

The BHA was pulled to surface and the directional tools laid down as the required pump rates couldn't be sustained due to fluid loss. A 'dumb-iron' assembly was run to drill to TD. Two further calcium carbonate LCM pills were pumped into the annulus before pulling out of hole, 60 bbl & 80 bbl, these had no visible effect. Following this the annulus was topped up with fresh water at 30 spm (0.7 bbl / minute) to keep the hole full. By the time the rotary BHA had reached bottom, 2129 bbl of drilling mud and water had been lost. The well was drilled ahead blind (total losses and pumping freshwater) to TD (2955 m) without any further issues, however, the drill string had to be back reamed out of the hole and over pull of up to 90 klbs was employed to pull the first 2 stands.

TD was reached at 10:30 on the 11 May 2012. The bit was pulled back to inside the shoe at 2700 m and a 290 bbl LCM pill (mixed grade Omyacal at 100 ppb concentration) was built and pumped down the backside in an attempt to reduce losses before wireline operations. No returns were seen from pumping LCM pills, but allowed to soak before a wiper trip was performed. Before the wiper trip was performed all surface fluid was treated with 0.5% KCl to allow for better conductivity during subsequent wireline logging run.

The bit tagged fill at 2920 m and had to be washed and reamed to TD. On bottom, an 18 bbl hi-vis sweep was pumped and circulated to take solids above the initial loss zone of 2905 m. Cumulative losses to formation by the end of the wiper trip had reached 4711 bbl.

Table 11: Drilling Fluids Summary Douglas-1 Interval 1 (TAG Oil Ltd.)



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DRILLING FLUIDS & VOLUME SUMMARY INTERVAL 1

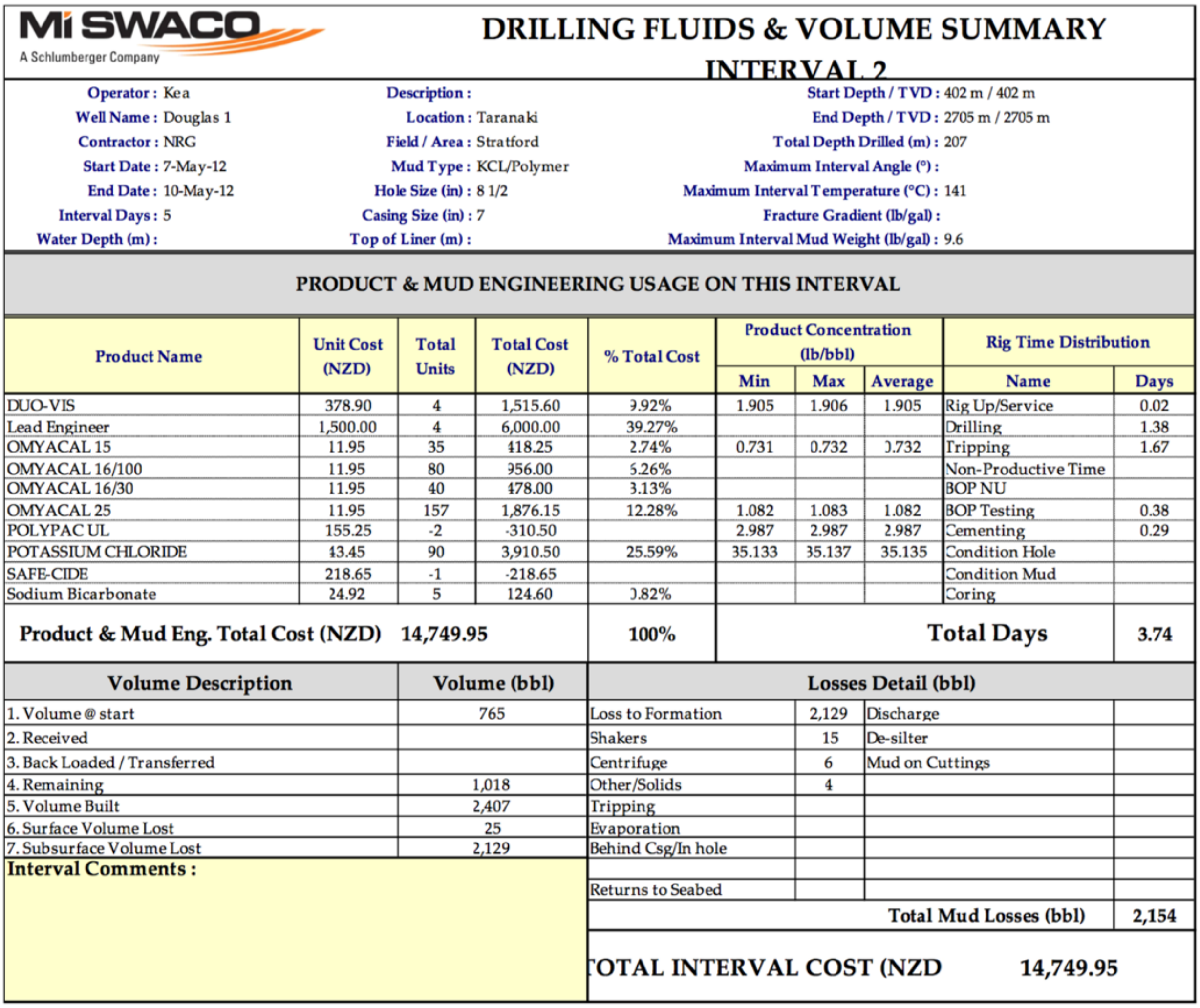
Operator : Kea	**Description :**	**Start Depth / TVD :** 0 m / 0 m
Well Name : Douglas 1	**Location :** Taranaki	**End Depth / TVD :** 402 m / 402 m
Contractor : NRG	**Field / Area :** Stratford	**Total Depth Drilled (m) :** 2,705
Start Date : 21-Apr-12	**Mud Type :** Unknown	**Maximum Interval Angle (°) :**
End Date : 6-May-12	**Hole Size (in) :** 10 3/5	**Maximum Interval Temperature (°C) :** 20
Interval Days : 1	**Casing Size (in) :** 9 5/8	**Fracture Gradient (lb/gal) :**
Water Depth (m) :	**Top of Liner (m) :**	**Maximum Interval Mud Weight (lb/gal) :** 8.4

PRODUCT & MUD ENGINEERING USAGE ON THIS INTERVAL

Product Name	Unit Cost (NZD)	Total Units	Total Cost (NZD)	% Total Cost	Product Concentration (lb/bbl)			Rig Time Distribution	
					Min	Max	Average	Name	Days
CAUSTIC SODA	41.15	8	329.20	0.16%	0.033	0.345	0.129	Rig Up/Service	1.13
CITRIC ACID	55.75	4	223.00	0.11%	0.028	0.347	0.097	Drilling	8.79
DEFOAM A	135.25	4	541.00	0.27%	0.039	0.586	0.138	Tripping	2.88
DUO-VIS	378.90	88	33,343.20	16.39%	1.550	2.010	1.822	Non-Productive Time	
GLYDRIL MC	1,195.00	19	22,705.00	11.16%	3.604	5.363	4.553	BOP NU	
IDCAP D SHALE INHIBITOR	327.75	94	30,808.50	15.15%	1.643	2.108	1.934	BOP Testing	
Lead Engineer	1,500.00	16	24,000.00	11.80%				Cementing	
LIME	15.25	3	45.75	0.02%	0.032	0.228	0.088	Condition Hole	
OMYACAL 15	11.95	65	776.75	0.38%	0.731	4.297	1.844	Condition Mud	
OMYACAL 25	11.95	83	991.85	0.49%	1.082	4.297	2.252	Coring	
POLYPAC R	163.75	30	4,912.50	2.42%	0.150	1.243	0.694	Dir Survey	
POLYPAC UL	155.25	122	18,940.50	9.31%	1.853	2.990	2.467	Direction Work	
POTASSIUM CHLORIDE	43.45	1490	64,740.50	31.83%	22.861	35.137	30.756	Fishing	
SAFE-CIDE	218.65	4	874.60	0.43%				Lost Circ.	
SODA ASH	26.71	6	160.26	0.08%	0.039	1.034	0.199	Reaming	
Product & Mud Eng. Total Cost (NZD)			**203,392.61**	**100%**				**Total Days**	**14.39**

Volume Description	Volume (bbl)	Losses Detail (bbl)			
1. Volume on board @ start		Other/Solids	559	Discharge	
2. Received		Centrifuge	551	De-silter	
3. Back Loaded / Transferred		Shakers	486	Mud on Cuttings	
4. Remaining	765	Tripping	211		
5. Volume Built	2,578	Loss to Formation	7		
6. Surface Volume Lost	1,596	Evaporation			
7. Subsurface Volume Lost	218	Behind Csg/In hole			
Interval Comments :					
		Returns to Seabed			
				Total Mud Losses (bbl)	**1,814**
		TOTAL INTERVAL COST (NZD		**203,392.61**	

Table 12: Drilling Fluids Summary Douglas-1 Interval 2 (TAG Oil Ltd.)



MI SWACO
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DRILLING FLUIDS & VOLUME SUMMARY INTERVAL 2

Operator : Kea
Well Name : Douglas 1
Contractor : NRG
Start Date : 7-May-12
End Date : 10-May-12
Interval Days : 5
Water Depth (m) :
Description :
Location : Taranaki
Field / Area : Stratford
Mud Type : KCL/Polymer
Hole Size (in) : 8 1/2
Casing Size (in) : 7
Top of Liner (m) :
Start Depth / TVD : 402 m / 402 m
End Depth / TVD : 2705 m / 2705 m
Total Depth Drilled (m) : 207
Maximum Interval Angle (°) :
Maximum Interval Temperature (°C) : 141
Fracture Gradient (lb/gal) :
Maximum Interval Mud Weight (lb/gal) : 9.6

PRODUCT & MUD ENGINEERING USAGE ON THIS INTERVAL

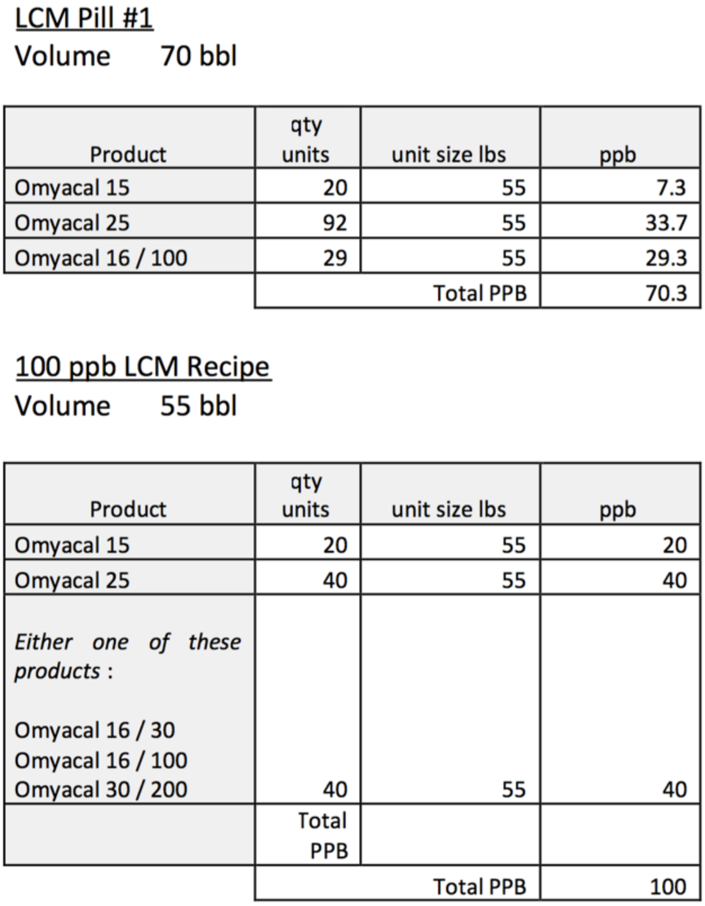
Product Name	Unit Cost (NZD)	Total Units	Total Cost (NZD)	% Total Cost	Product Concentration (lb/bbl)			Rig Time Distribution	
					Min	Max	Average	Name	Days
DUO-VIS	378.90	4	1,515.60	9.92%	1.905	1.906	1.905	Rig Up/Service	0.02
Lead Engineer	1,500.00	4	6,000.00	39.27%				Drilling	1.38
OMYACAL 15	11.95	35	418.25	2.74%	0.731	0.732	0.732	Tripping	1.67
OMYACAL 16/100	11.95	80	956.00	6.26%				Non-Productive Time	
OMYACAL 16/30	11.95	40	478.00	3.13%				BOP NU	
OMYACAL 25	11.95	157	1,876.15	12.28%	1.082	1.083	1.082	BOP Testing	0.38
POLYPAC UL	155.25	-2	-310.50		2.987	2.987	2.987	Cementing	0.29
POTASSIUM CHLORIDE	43.45	90	3,910.50	25.59%	35.133	35.137	35.135	Condition Hole	
SAFE-CIDE	218.65	-1	-218.65					Condition Mud	
Sodium Bicarbonate	24.92	5	124.60	0.82%				Coring	
Product & Mud Eng. Total Cost (NZD)			**14,749.95**	**100%**				**Total Days**	**3.74**

Volume Description	Volume (bbl)	Losses Detail (bbl)			
1. Volume @ start	765	Loss to Formation	2,129	Discharge	
2. Received		Shakers	15	De-silter	
3. Back Loaded / Transferred		Centrifuge	6	Mud on Cuttings	
4. Remaining	1,018	Other/Solids	4		
5. Volume Built	2,407	Tripping			
6. Surface Volume Lost	25	Evaporation			
7. Subsurface Volume Lost	2,129	Behind Csg/In hole			
Interval Comments :					
		Returns to Seabed			
				Total Mud Losses (bbl)	**2,154**
		TOTAL INTERVAL COST (NZD		**14,749.95**	

Recommendation

A total of 6142 bbl had been lost down the hole. Lost circulation was not cured with the LCM pills used, however this was expected and no 'formation damaging' materials were used in attempts to cure losses. A total volume of 500 bbl LCM was pumped into the formation during this section, mostly directly into the annulus. Calcium carbonate in fine to coarse grades was used to minimize losses in the fractured Tikorangi Limestone. This was non-damaging to the potential reservoir and should be used in future wells. Unfortunately, no returns were seen from pumping any LCM as the formation was highly fractured in this well. The initial pill was built to 70 ppb as below (Pill #1). All following pills were built to 100 ppb and consisted of a mix of materials as shown on the following table.

Table 13: LCM Content Douglas-1 (TAG Oil Ltd.)



LCM Pill #1

Volume 70 bbl

Product	qty units	unit size lbs	ppb
Omyacal 15	20	55	7.3
Omyacal 25	92	55	33.7
Omyacal 16 / 100	29	55	29.3
		Total PPB	70.3

100 ppb LCM Recipe

Volume 55 bbl

Product	qty units	unit size lbs	ppb
Omyacal 15	20	55	20
Omyacal 25	40	55	40
Either one of these products : Omyacal 16 / 30 Omyacal 16 / 100 Omyacal 30 / 200	40	55	40
	Total PPB		
		Total PPB	100

Pills were mixed in a 70 bbl pit in the tanks on top of existing dead volume and transferred to the pill tank before pumping down hole. The coarse components were mixed according to pallets available as there is little difference in their PSD's.

Potassium chloride (KCL) was used to provide a salinity of 2500 mg/l in the water. The logging tools run needed a minimum of 800 mg/l. This was equivalent to 0.5% potassium chloride concentration.

5.6. Summary

The Tikorangi limestone defies most attempts to cure drill fluid losses. This highly fractured limestone with up to 30 cm wide fractures requires highest attention in order to drill to TD efficiently and effectively. Total losses in the production interval were encountered frequently.

From the previous events happening, it is possible to compare all applied methods:

- Drill ahead “blind”
- Calcium carbonate
- Mixtures of fibre, flake and granular material
- Cement
- Side-track

When losses appear close to TD and appear to be severe or even total, drilling ahead “blind” can be an option. Drilling blind is usually applied, when a cure is either not economical or has a minor chance of success. Inadequate hole cleaning, stuck pipe and insufficient well control can be potential drawbacks. To avoid stuck pipe, the pumping rate should not be lowered while drilling without returns. Generally, fresh water or diluted mud is used as drilling fluid. Drilling ahead “blind” was successfully applied on Dounglas-1 with no further issues.

Some improvement was seen making continuing calcium carbonate additions while drilling. Calcium carbonate was added to the mud system for two specific reasons:

- Increase mud density
- Combat lost circulation

It was originally only programmed as an acid soluble lost circulation agent, which was the primary reason to select it. Moreover, it minimises formation damage in production intervals. By using the correct PSDs, calcium carbonate becomes an excellent bridging agent. Calcium carbonate successfully lowered API water loss and, when applied in varying grades, can also lower HPHT water loss. Calcium carbonate would appear to be ideal in preventing seepage losses but as losses were also total to partial it is unfair to say calcium carbonate is not a LCM. Calcium carbonate lacks alternative options and is mostly the only applicable LCM in production intervals.

Certainly, in this case mixtures of fibre, flake and granular material would appear better than calcium carbonate but even they did not produce good results. Moreover, formation damage needs to be considered, which makes this option obsolete when coming close to the pay zone.

Cement is often used when other treatments fail to achieve the expected results. But especially the compressive strength of cement increases its sealing quality. Severe losses are mainly treated with cement. Although certain cross-linked cements are even used in pay zones, formation damage needs to be considered, even if rapid development of gel strength is preventing unnecessary formation damage. As an alternative, acid soluble cements can be used, but there should be an economic assessment in advance, since these types of cement are relatively expensive. On top of that, the use of cement can cause significant non-productive time. Cement seemed the only solution for many Waihapa wells. Losses continued despite the use of calcium carbonate and cement was applied, usually after passing the loss interval and before reaching the production interval.

A side-track is a secondary well drilled with a different well trajectory. Side-tracks can be drilled for different reasons, one of them is drilling fluid losses. Production interval total losses were encountered while drilling Sidewinder-2. LCM pills were pumped but had no sufficient effect. However, a fault was observed and the production hole was cement-plugged and a side-track was performed (Sidewinder-2 ST-1). Particularly severe losses in the respective production interval of a well can therefore be eliminated with a side-track. In addition, severe or total losses in naturally fractured reservoirs, as the Tikorangi limestone, can imply extraordinary flow characteristics. For example, Waihapa-1, which had big loss issues, was the best producer in the whole field.

Eventually, the decision how to treat losses depends on what can be applied and the expectancy value behind it. Each step on the escalation latter should be well deliberated.

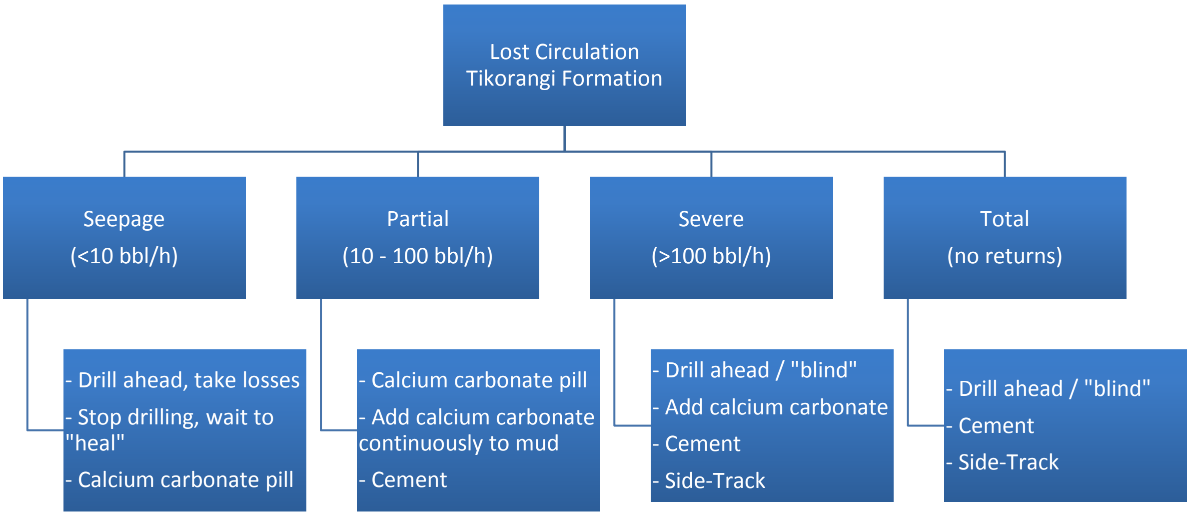


Figure 62: Tikorangi Formation Decision Tree

6. Lost Circulation Matrix

This chapter introduces a new approach to a first-action-tool against lost circulation. Conventional decision trees commonly offer specific procedures when losses are encountered and are not always generally applicable. The aim of this lost circulation matrix is to receive an overview of available options and to resolve loss situations more precise and quickly. All treatment options are categorised and matched to a step-by-step loss description to guide engineers through the dimensions of the occurring problem.

At the beginning of this chapter, common lost circulation decision trees are evaluated to see the best practice done by different companies in the industry.

6.1. Lost Circulation Treatment Decision Trees

When assessing lost circulation decision trees, it should be distinguished between decision trees created as a company guideline, for a specific field/well in the planning phase or decision trees, which were developed from service companies marketing their own products to resolve lost circulation. In this paragraph, all three types are reviewed.

The first decision tree reviewed is from M-I SWACO and was created in 2003. It is shown below in figure 63. It is one of the clearest, but also one of the shallowest decision trees available. The first decision to take is, if losses occur on surface or down hole. So-called “perceived losses” are discussed in chapter two of this thesis and cover the topic of surface losses. After a check if the well is flowing, the loss rate needs to be measured. This decision tree lacks the category “severe losses” completely. Just three pills are provided to cure losses. If none of the pills work, the decision tree recommends spotting a plug. As quick as this decision tree might work, it is missing many cure options. It does not even consider the loss mechanism or if losses appear in the reservoir section.

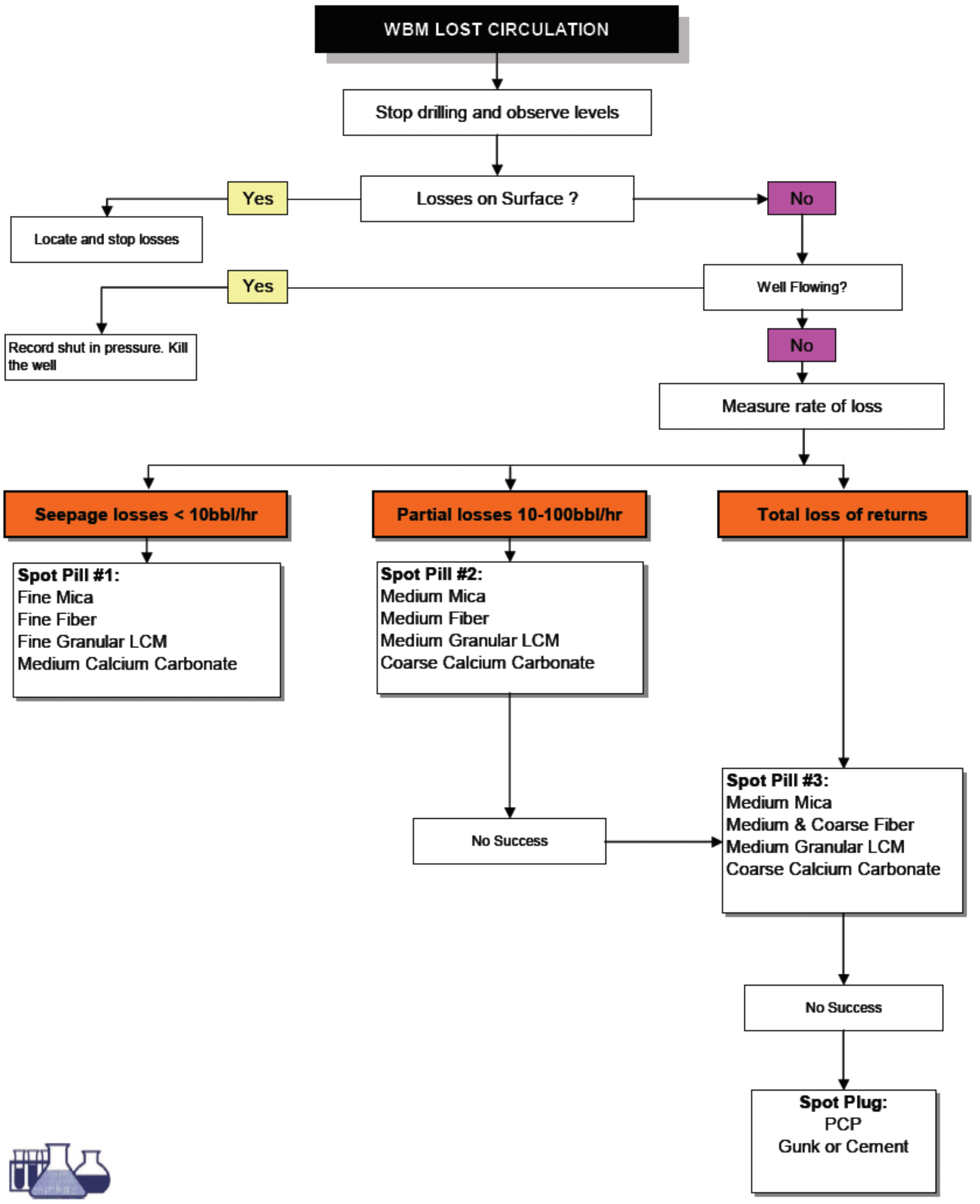


Figure 63: Lost Circulation Decision Tree WBM (M-I SWACO 2003)

M-I SWACO offer more decision trees as shown in figure 64. The decision tree is like figure 63, but categorises in OBM/SBM and WBM. In case of total losses, this decision tree does not start with LCM, but suggests a Form-A-Squeeze instead. The last option when encountering total losses is again spotting a plug. This tree is a little bit more detailed, but still far away from a general solution to fight losses the best possible way.

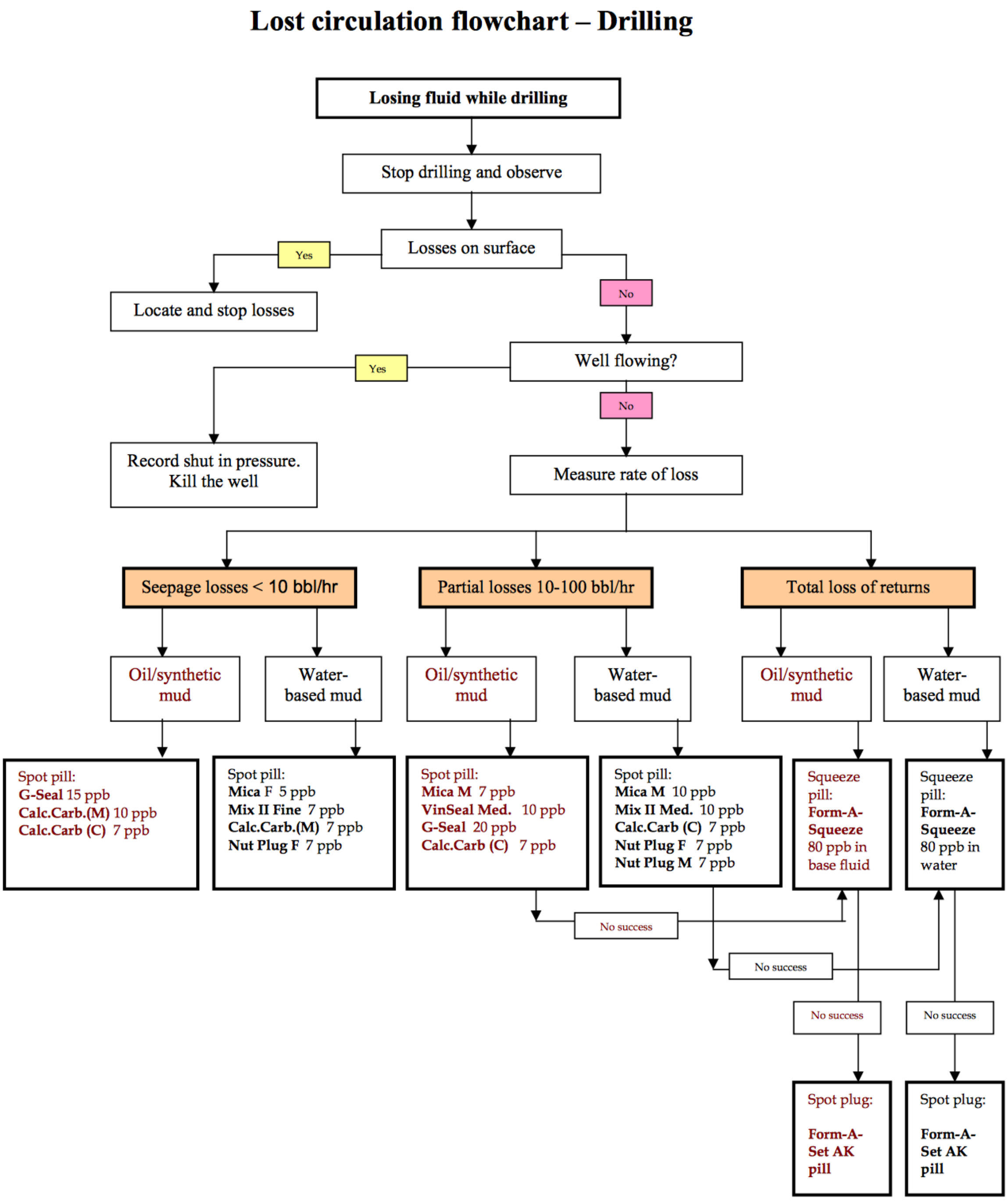


Figure 64: Lost Circulation Decision Tree Drilling (M-I SWACO 2003)

In figure 65, an improved decision tree of 2005 can be seen. On top of the two decision trees before, this version also suggests “VERSAPAC” and Reverse Gunk as plug options. But even the 2005 version has very limited options available and is not considering the loss mechanism or reservoir zone.

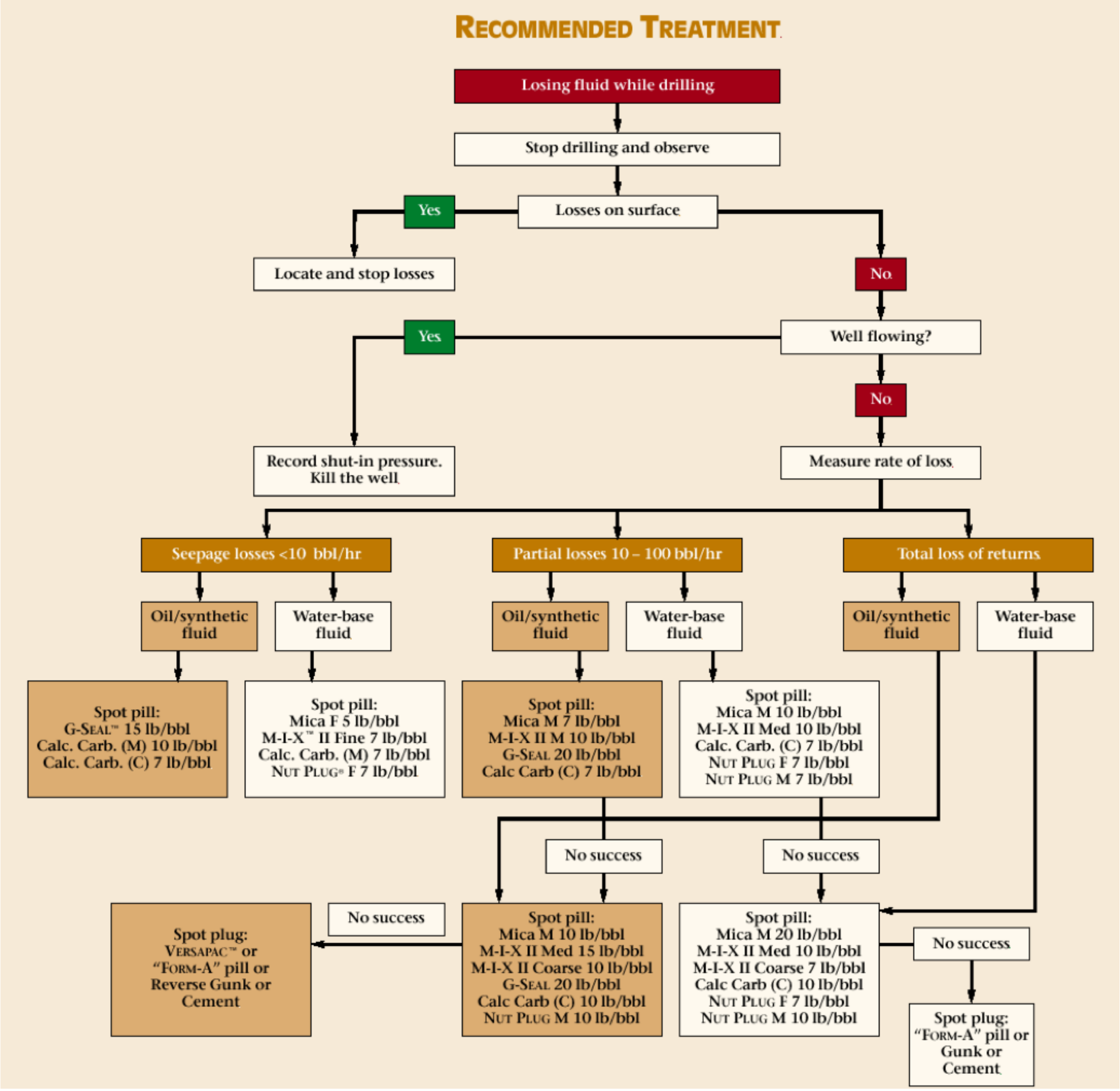


Figure 65: Lost Circulation Decision Tree Drilling (M-I SWACO 2005)

Figures 66 and 67 show decision trees including the underlying mechanism. Also, the question is asked, if the loss situation is sustainable. Two of the four mechanisms have a separate decision tree. Figure 66 shows natural losses and figure 67 presents induced losses. Decision trees for matrix losses or caverns were missing in the given document. What attracts attention in figure 66 is that total losses are not discussed. It may be unlikely that natural losses cause total losses, but it is not impossible. Having a look on figure 67, it turns out that severe and total losses in case of induced losses are cured with the same procedure. Furthermore, in case of induced losses, seepage losses are considered to be unlikely and not even mentioned. Again, predominantly M-I SWACO products are presented to resolve loss situations and no classification in reservoir/non-reservoir section was made.

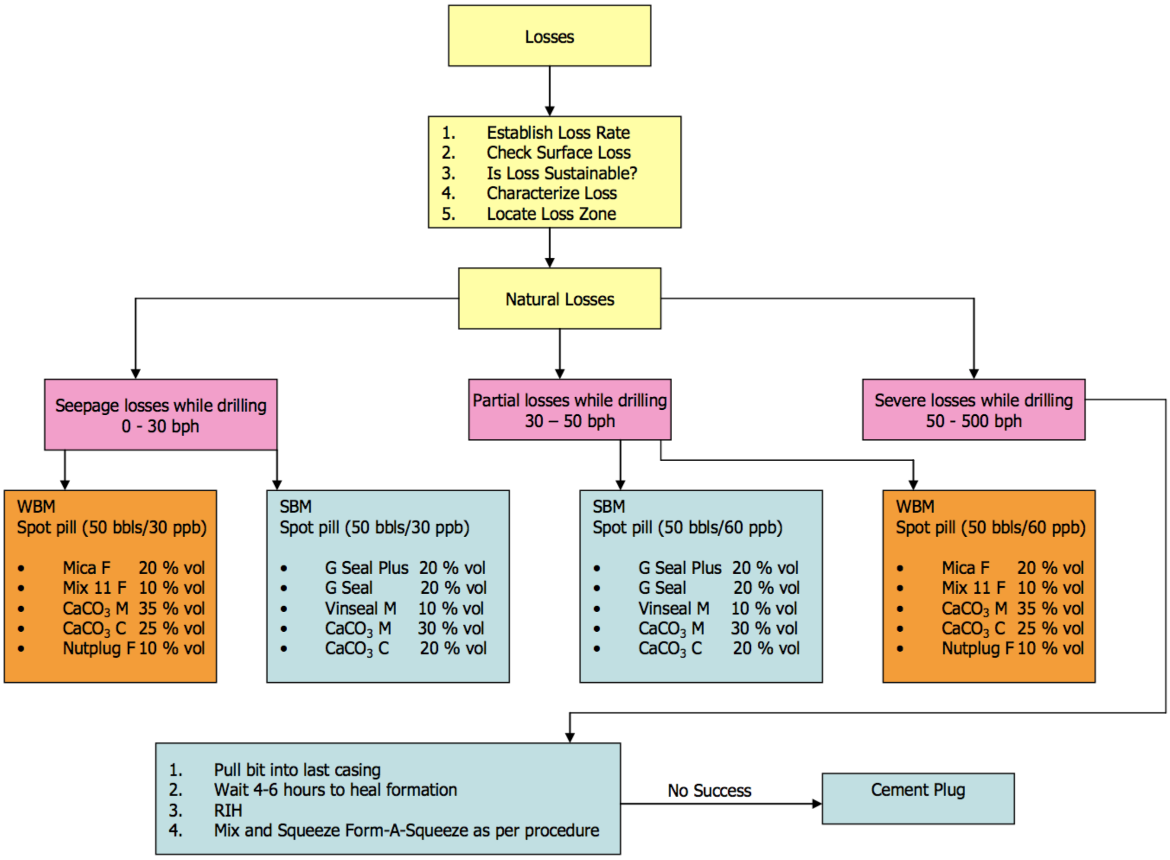


Figure 66: Lost Circulation Recommendation Natural Losses (M-I SWACO 2016)

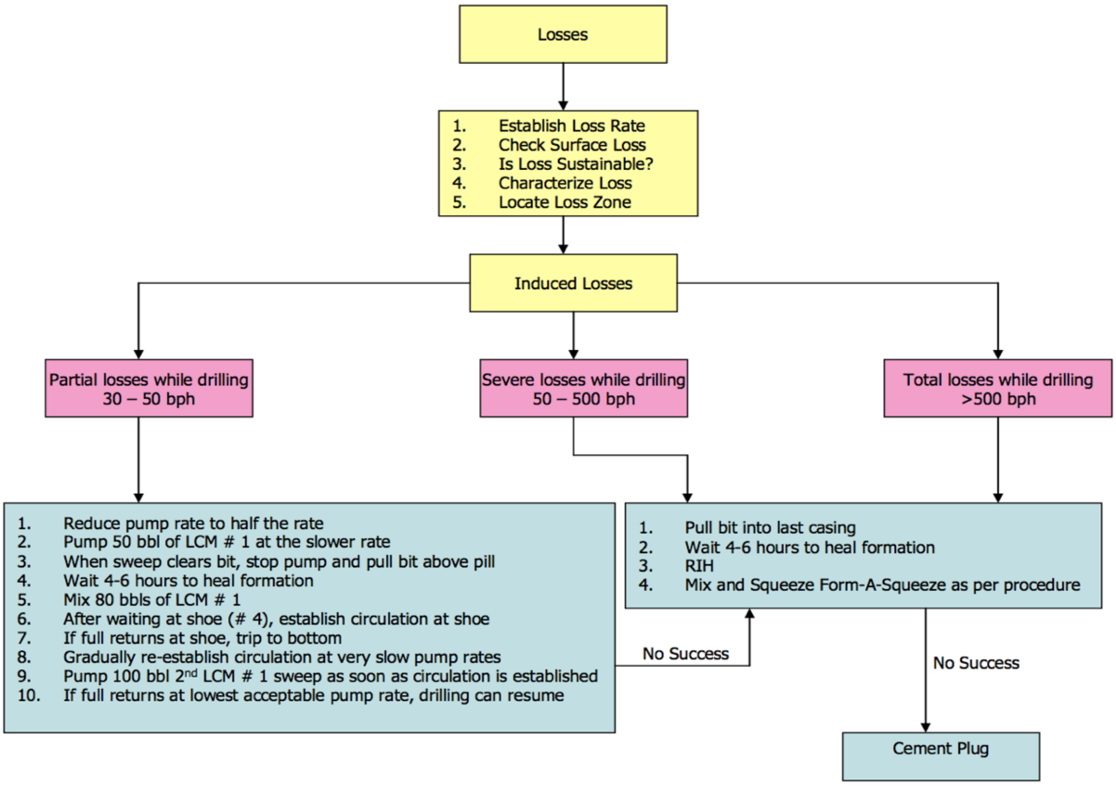


Figure 67: Lost Circulation Recommendation Induced Losses (M-I SWACO 2016)

Shown below are two decision trees from the Austrian company OMV designed for their operations in New Zealand. Figure 68 illustrates the lost circulation decision tree for the Manaia-2 well, which was created for this specific well. For every loss rate, the best solutions are listed, but this decision tree does not differentiate between reservoir and non-reservoir section or states, which options are applicable in the reservoir zone.

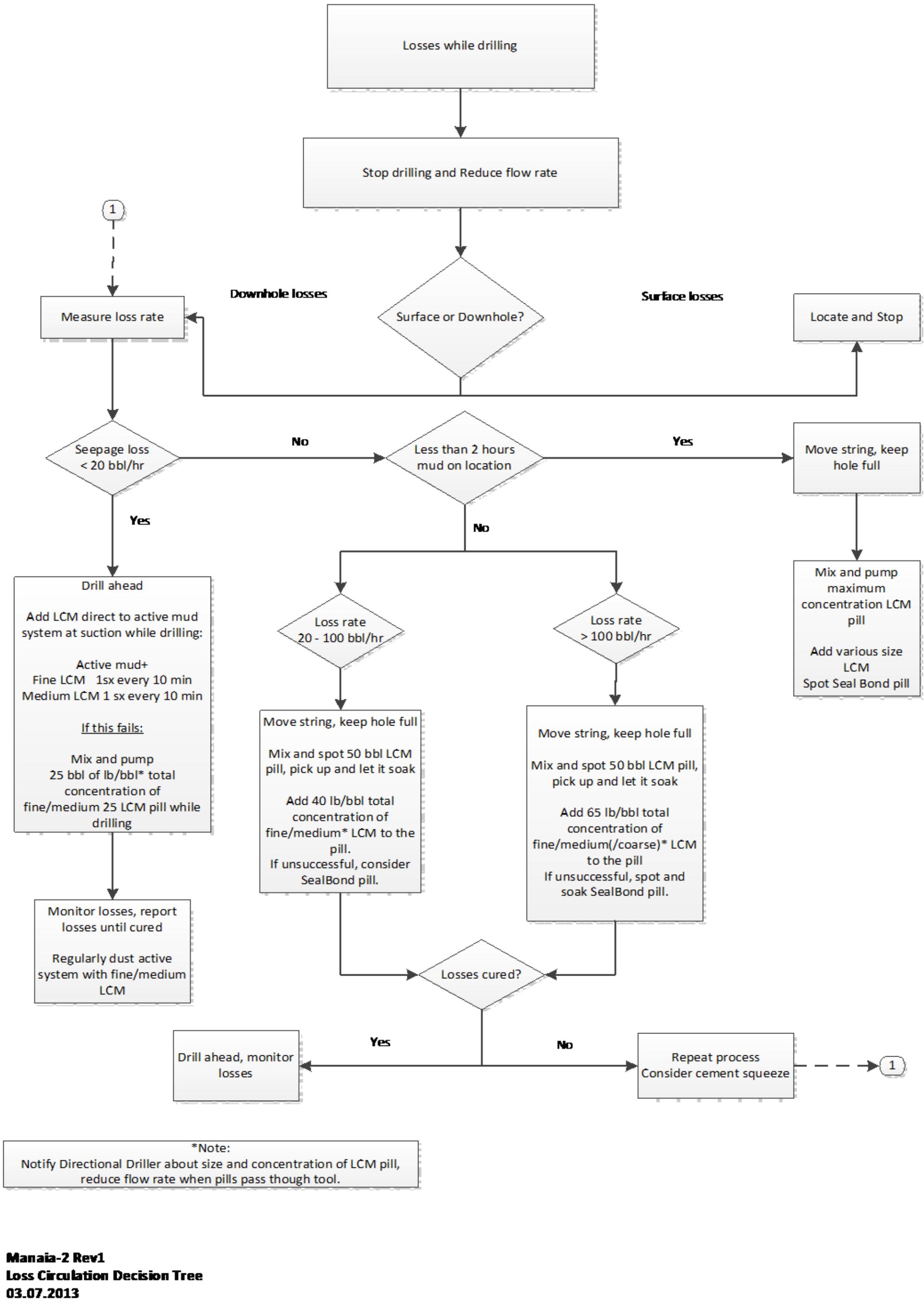
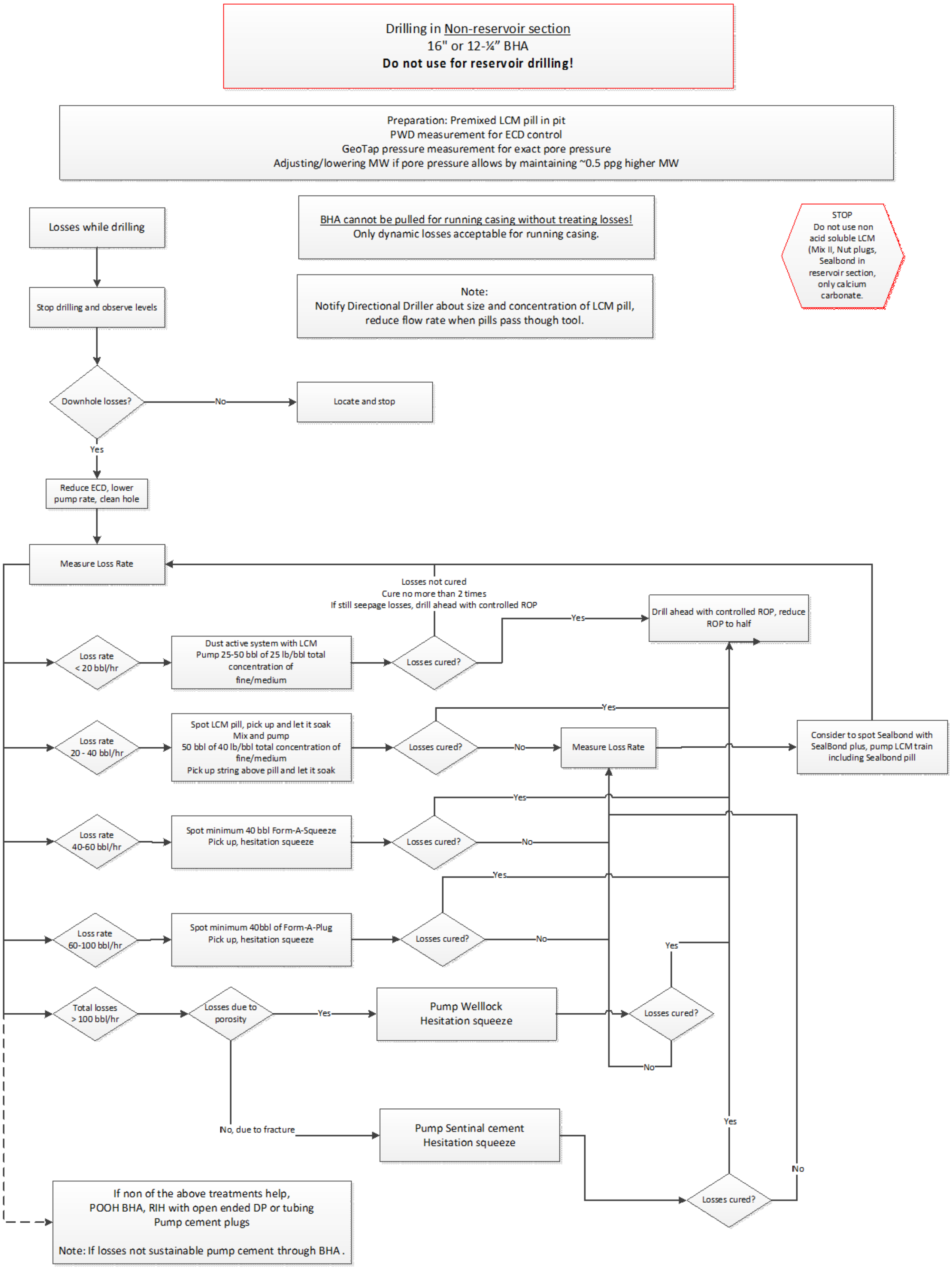


Figure 68: Lost Circulation Decision Tree Manaia-2 (OMV 2013)



Maari Growth
Losses During Drilling NON Reservoir Section
Decision Tree – Rev A
11.12.2013

Figure 69: Lost Circulation Decision Tree Maari Field (OMV 2013)

Figure 69 shows the decision tree for the Maari field and is just valid for the non-reservoir section. All treatment options shown cannot be applied in the reservoir zone without the risk of jeopardising the later production. The decision tree itself is well designed and gives options for every loss rate and loss type. But since this tree is tailored to the Maari field, its usability in other fields is limited.

Figure 70 below displays the lost circulation decision tree from another Austrian company – RAG. It just distinguishes between two different loss rates and is very unprecise in how to mitigate those losses. Moreover, it does not even consider many of the settable materials, including cement, and does not differentiate between reservoir and non-reservoir section. On the other hand, the decision tree is well organised and reminds the engineer of the potential unsustainability when experiencing losses for longer periods. In this case, WBM shall be used.

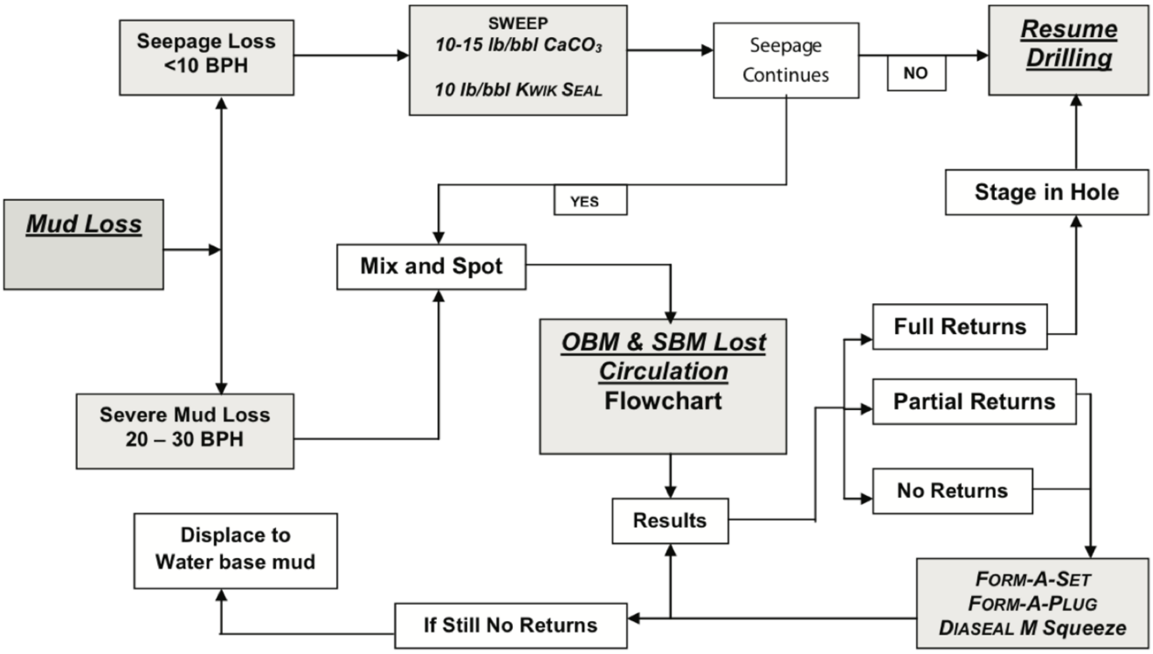


Figure 70: Lost Circulation Decision Tree RAG Austria (RAG 2011)

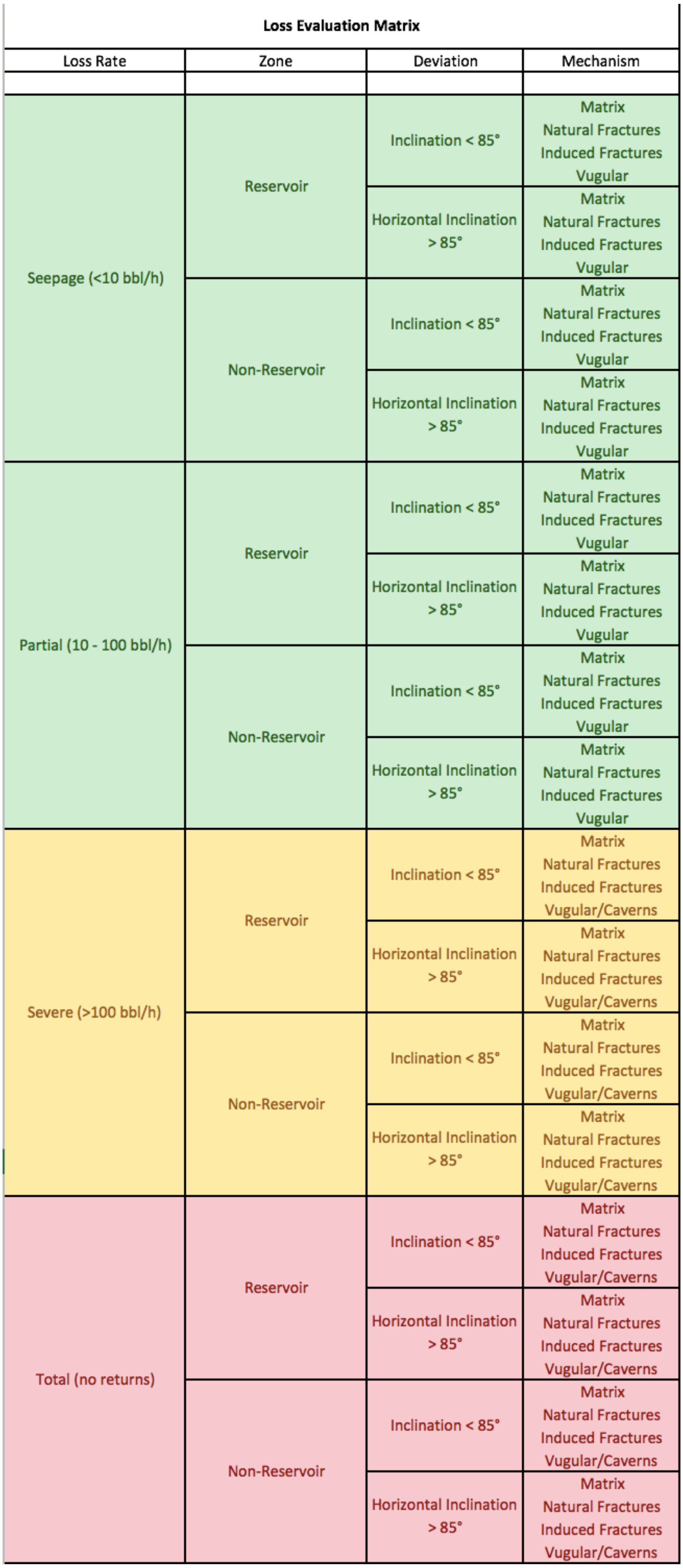
All lost circulation decision trees shown in this paragraph accomplish the aim they were created for. None of them is generally applicable or gives a complete overview of what product categories are available to combat losses effectively.

6.2. Lost Circulation Evaluation Matrix

To find the best match to a lost circulation situation, independent advice can matter a lot. A company with the desire of selling their own product might not recommend the best cure, but the best fitting product they have in stock. Many perspectives might not be disclosed on the way to find the best match. The lost circulation evaluation matrix created in this paragraph shows all treatment categories and matches them step-by-step to the existing loss situation. Within a minimal timeframe, an overview of treatment options is provided. Decisions of what should be done can be made based on sustainability and availability. The lost circulation evaluation matrix tries to get as close as possible to the best match without any actual input data from site.

Table 14 gives an overview of the left side of the matrix. Its use it the characterisation of the existing loss scenario. Loss rate, zone, deviation and mechanism need to be known to identify the kind of loss situation. As discussed in chapter two of this thesis, the loss rate is divided into seepage, partial, severe and total losses. The zone refers to the place, where the losses happen. This can either be in the reservoir or non-reservoir zone. If a well has an inclination of more than 85°, some treatment options are no longer recommended. Therefore, deviation is an important classification. As stated and discussed in chapter two, the loss mechanism should be known for a good match. Those are matrix, natural fractures, induced fractures and vugular/caverns.

Table 14: Loss Circulation Evaluation Matrix - Loss Description



Loss Evaluation Matrix

Loss Rate	Zone	Deviation	Mechanism
Seepage (<10 bbl/h)	Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular
	Non-Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular
Partial (10 - 100 bbl/h)	Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular
	Non-Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular
Severe (>100 bbl/h)	Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
	Non-Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
Total (no returns)	Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
	Non-Reservoir	Inclination < 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns
		Horizontal Inclination > 85°	Matrix Natural Fractures Induced Fractures Vugular/Caverns

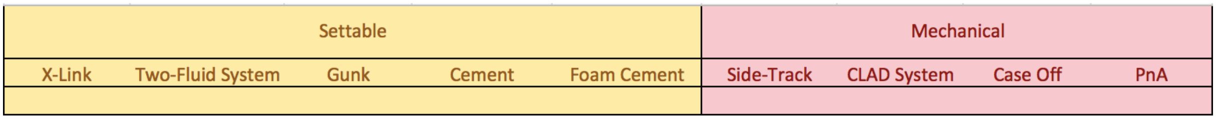
With the nature of the problem properly described, treatment options can be matched. There are four groups of treatment options presented in the matrix: actions, LCM, settable and mechanical. The first two groups, actions and LCM, are shown in table 15. Actions split into drill ahead, drill “blind” and mud-cap drilling. Drill ahead and drill “blind” are mutually exclusive, because drilling ahead happens with returns and drilling “blind” without returns. Mud-cap drilling is a managed pressure drilling technique, which especially helps minimising losses and NPT in natural fractured formations, depleted formations and vugs/caverns. LCM is divided into dusting, spot & squeeze and circulating, which are techniques to apply LCM. For well control reasons, the drill ahead options should not be considered, if dynamic losses happen.

Table 15: Lost Circulation Evaluation Matrix - Actions and LCM

Actions			LCM		
Drill Ahead	Drill "Blind"	Mud-Cap Drilling	Dusting	Spot & Squeeze	Circulate
Drill ahead options are only possible if no static losses					

Settable and mechanical options are shown in table 16. Settable treatments are categorised in cross-link, two-fluid system, gunk, cement and foam cement, which are all discussed in chapter three of this thesis. Mechanical options are side-track, CLAD system, case off and plug & abandon (PnA). Side-tracks can be carried out to bypass to loss the lost circulation zone. A side-track is a secondary well drilled with a different well trajectory. Side-tracks can be drilled for different reasons, one of them is drilling fluid losses. CLAD systems are like drilling liners for contingency, which can isolate lost circulation zones without losing the hole size - unlike case off, which means losing the hole size. PnA is the last of all options and even eliminates the ability to produce at a subsequent date. The well is then cemented and the well head is removed.

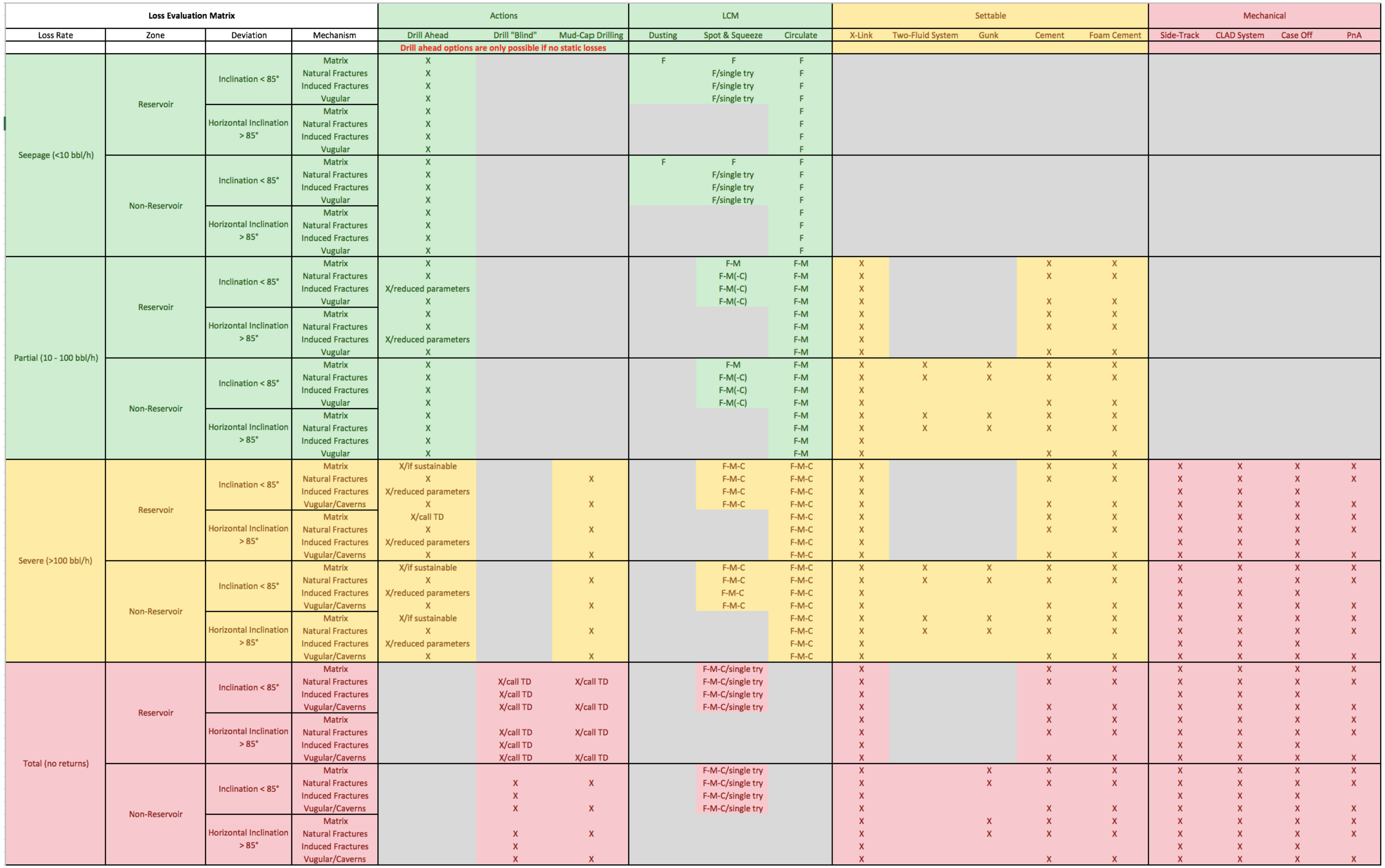
Table 16: Lost Circulation Evaluation Matrix - Settable and Mechanical



Settable					Mechanical			
X-Link	Two-Fluid System	Gunk	Cement	Foam Cement	Side-Track	CLAD System	Case Off	PnA

The entire matrix is shown in table 17. Greyed out fields are either not applicable or would not be a good option at all. Unfilled boxes are possible, but not recommended treatments. From green to red, treatments are getting more time consuming (NPT), risky and have wider-ranging economic consequences.

Table 17: Lost Circulation Evaluation Matrix



Loss Evaluation Matrix				Actions			LCM			Settable					Mechanical			
Loss Rate	Zone	Deviation	Mechanism	Drill Ahead	Drill "Blind"	Mud-Cap Drilling	Dusting	Spot & Squeeze	Circulate	X-Link	Two-Fluid System	Gunk	Cement	Foam Cement	Side-Track	CLAD System	Case Off	PnA
				Drill ahead options are only possible if no static losses														
Seepage (<10 bbl/h)	Reservoir	Inclination < 85°	Matrix	X			F	F	F									
			Natural Fractures	X				F/single try	F									
			Induced Fractures	X				F/single try	F									
			Vugular	X				F/single try	F									
		Horizontal Inclination > 85°	Matrix	X					F									
			Natural Fractures	X					F									
			Induced Fractures	X					F									
			Vugular	X					F									
	Non-Reservoir	Inclination < 85°	Matrix	X			F	F	F									
			Natural Fractures	X				F/single try	F									
			Induced Fractures	X				F/single try	F									
			Vugular	X				F/single try	F									
		Horizontal Inclination > 85°	Matrix	X					F									
			Natural Fractures	X					F									
			Induced Fractures	X					F									
			Vugular	X					F									
Partial (10 - 100 bbl/h)	Reservoir	Inclination < 85°	Matrix	X				F-M	F-M	X			X	X				
			Natural Fractures	X				F-M(-C)	F-M	X			X	X				
			Induced Fractures	X/reduced parameters				F-M(-C)	F-M	X								
			Vugular	X				F-M(-C)	F-M	X			X	X				
		Horizontal Inclination > 85°	Matrix	X					F-M	X			X	X				
			Natural Fractures	X					F-M	X			X	X				
			Induced Fractures	X/reduced parameters					F-M	X								
			Vugular	X					F-M	X			X	X				
	Non-Reservoir	Inclination < 85°	Matrix	X				F-M	F-M	X	X	X	X	X				
			Natural Fractures	X				F-M(-C)	F-M	X	X	X	X	X				
			Induced Fractures	X				F-M(-C)	F-M	X								
			Vugular	X				F-M(-C)	F-M	X			X	X				
		Horizontal Inclination > 85°	Matrix	X					F-M	X	X	X	X	X				
			Natural Fractures	X					F-M	X	X	X	X	X				
			Induced Fractures	X					F-M	X								
			Vugular	X					F-M	X			X	X				
Severe (>100 bbl/h)	Reservoir	Inclination < 85°	Matrix	X/if sustainable				F-M-C	F-M-C	X			X	X	X	X	X	X
			Natural Fractures	X		X		F-M-C	F-M-C	X			X	X	X	X	X	X
			Induced Fractures	X/reduced parameters				F-M-C	F-M-C	X					X	X	X	
			Vugular/Caverns	X		X		F-M-C	F-M-C	X			X	X	X	X	X	X
		Horizontal Inclination > 85°	Matrix	X/call TD					F-M-C	X			X	X	X	X	X	X
			Natural Fractures	X		X			F-M-C	X			X	X	X	X	X	X
			Induced Fractures	X/reduced parameters					F-M-C	X					X	X	X	
			Vugular/Caverns	X		X			F-M-C	X			X	X	X	X	X	X
	Non-Reservoir	Inclination < 85°	Matrix	X/if sustainable				F-M-C	F-M-C	X	X	X	X	X	X	X	X	X
			Natural Fractures	X		X		F-M-C	F-M-C	X	X	X	X	X	X	X	X	X
			Induced Fractures	X/reduced parameters				F-M-C	F-M-C	X					X	X	X	
			Vugular/Caverns	X		X		F-M-C	F-M-C	X			X	X	X	X	X	X
		Horizontal Inclination > 85°	Matrix	X/if sustainable					F-M-C	X	X	X	X	X	X	X	X	X
			Natural Fractures	X		X			F-M-C	X	X	X	X	X	X	X	X	X
			Induced Fractures	X/reduced parameters					F-M-C	X					X	X	X	
			Vugular/Caverns	X		X			F-M-C	X			X	X	X	X	X	X
Total (no returns)	Reservoir	Inclination < 85°	Matrix					F-M-C/single try		X			X	X	X	X	X	X
			Natural Fractures		X/call TD	X/call TD		F-M-C/single try		X			X	X	X	X	X	X
			Induced Fractures		X/call TD			F-M-C/single try		X					X	X	X	
			Vugular/Caverns		X/call TD	X/call TD		F-M-C/single try		X			X	X	X	X	X	X
		Horizontal Inclination > 85°	Matrix							X			X	X	X	X	X	X
			Natural Fractures		X/call TD	X/call TD				X			X	X	X	X	X	X
			Induced Fractures		X/call TD					X					X	X	X	
			Vugular/Caverns		X/call TD	X/call TD				X			X	X	X	X	X	X
	Non-Reservoir	Inclination < 85°	Matrix					F-M-C/single try		X		X	X	X	X	X	X	X
			Natural Fractures		X	X		F-M-C/single try		X		X	X	X	X	X	X	X
			Induced Fractures		X			F-M-C/single try		X					X	X	X	
			Vugular/Caverns		X	X		F-M-C/single try		X			X	X	X	X	X	X
		Horizontal Inclination > 85°	Matrix							X		X	X	X	X	X	X	X
			Natural Fractures		X	X				X		X	X	X	X	X	X	X
			Induced Fractures		X					X					X	X	X	
			Vugular/Caverns		X	X				X			X	X	X	X	X	X

F – Fine

C – Coarse

M – Medium

Call TD – Call Target Depth

6.3. Summary

This matrix shows a good first-action-tool to combat lost circulation. But more work needs to be done. The dynamic test stand illustrated in chapter four could scientifically prove the ability to cure losses in different scenarios and could contribute a performance rating or success rate for each treatment tested. More detailed case studies as started in chapter five could lead into a lost circulation database and support this success rate or even add a risk to implement to certain cure options. The evaluation matrix has a high potential to consult and advice engineers in lost circulation situations. A potential, which needs to be unlocked.

7. Conclusion

Significant headway was achieved in combatting losses over the last thirty years. However, the clearer lost circulation seems to get, the more questions raise and knowledge gaps appear.

The best option to mitigate or cure losses is to prevent them before they even take place. This can be done by not exceeding the pressure when lost-circulation happens (lost-circulation pressure). This lost-circulation pressure is normally predicted prior to drilling, if possible. It can depend on all principal in situ stresses, the mechanism, orientation and apertures of the fracture. All this data is difficult to obtain before the bit touches the formation and even then, e.g. the fracture aperture is measured in no sense. Better formation characterisation could therefore improve lost-circulation treatments and deliver a better outcome.

Moreover, laboratory tests are irreplaceable to create more theoretical input, which helps to understand the mechanisms behind and prove individual materials to be effective in certain conditions.

Better well planning is a possibility to prevent lost circulation more effectively. Especially a differentiation between harmless and potentially troublesome geological structures can be cost-effective.

The moment losses occur, diagnosis and interpretation of the mechanism are defining for choosing a treatment. High-frequency flow metres are one important point to improve this process by providing a typical diagram of the flow rate over time. This interpretation gives a good indication of the mechanism behind the losses. Other data, e.g. WOB and ROP substantiate this diagnosis.

Severe or even total losses are very challenging to treat. There are effective treatments (e.g. polymer pills, gunk squeeze, cement squeeze) but no universal remedy was found yet. The applicable treatments on the market are hardly useable close to the reservoir, because they all damage the formation irreversibly. Therefore, depleted and naturally fractured reservoirs are still a big issue because of their narrow margins. Another challenge when designing LCM are fracture apertures exceeding 5 mm in width.

Despite that, the research done in lost circulation mainly contributes to the development of new and more effective methods to treat. In consequence, more difficult and deeper wells can be drilled year by year. Solutions to the problems we currently have are likely coming in the near future.

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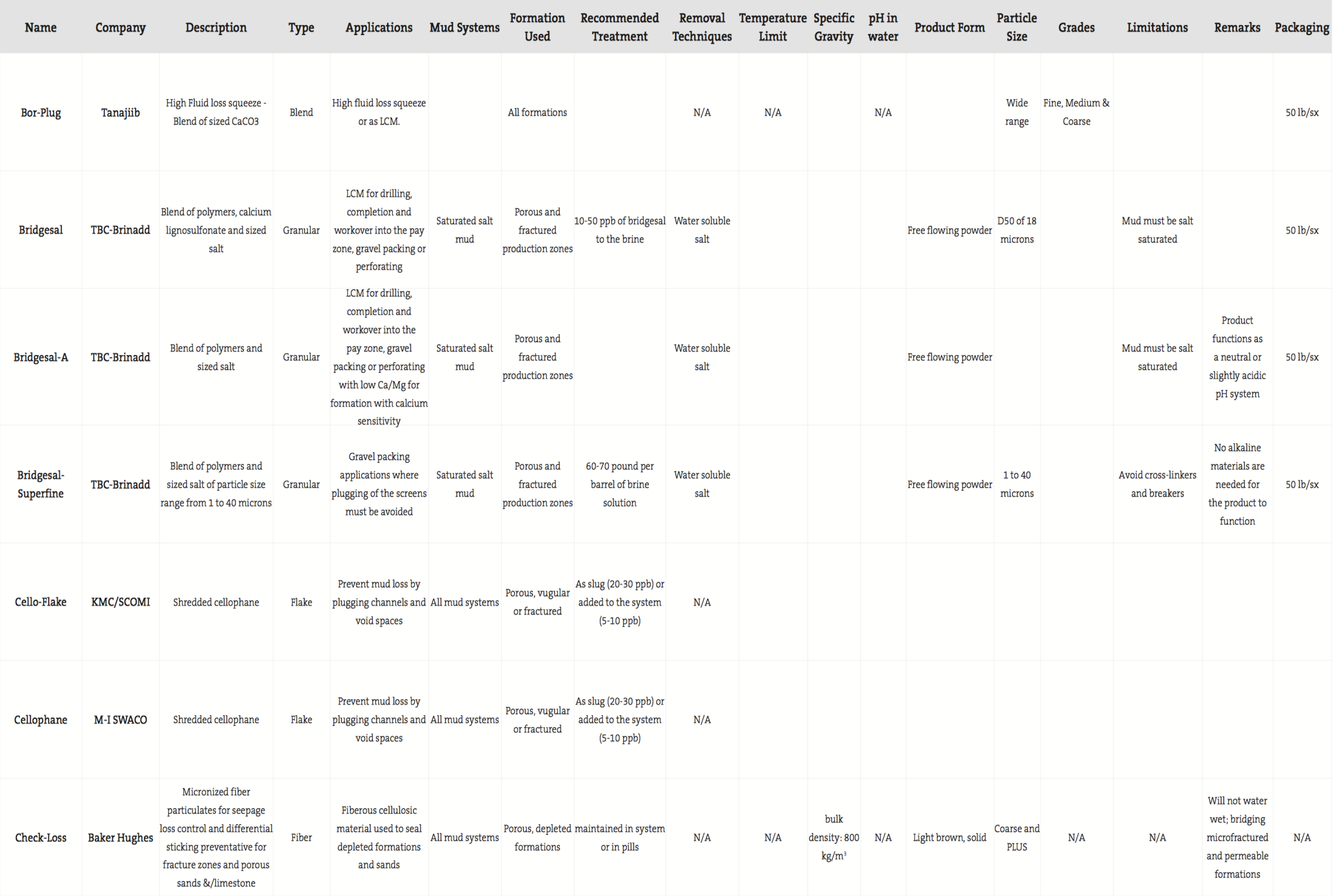
9. Appendix

Table 18: Lost Circulation Material Index (M-I SWACO 2010)

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Baracarb	**Baroid**	Sized CaCO3; Acid Soluble	Granular	As a weighting agent up to 14.0 ppg. Bridging agent. Temporarily seal lost circulation zones	All mud systems	Porous and fractured production zones	5-10 ppb for brigding	Acid soluble		2.8		White powder or granules	D50's = #5 - 9.5; #25 - 25; #50 - 46; #150 - 170.	Ultra fine, Fine, Medium, Coarse			50 lb/sx
Barofiber	**Baroid**	Micronised Fiber particulates for seepage loss control & diff. pressure sticking preventive for fracture zones and porous sands & limestone	Fiber	Fiberous cellulosic material used to seal fractured formations and sands	All mud systems	Sands and fractured zones	Preventative treatment @ 2-10 ppb; Slug treatment @ 30-50 ppb		N/A	bulk density: 31 lb/ft4	5 - 7	Regular- brown- powdered material; Coarse - granulated material		Regular and Coarse	WBM- need to treat with Algaecide/ biocide to prevent bacterrial contaminaion; OBM-		Regular 25 lb/ sx; Coarse 40 lb/sx
Barolift	**Baroid**	Filamentous fibers for sweeps or seepabe loss control	Fiber	Synthetic fiber sweeping agent; does not increase viscosity	All mud systems		(1) 15 pound box/ 50 bbls	removed at shakers	Insoluble		N/A	white fiber	N/A	N/A	removed by shakers	N/A	15 lb box
Baroseal	**Baroid**	Blend of particles which contains high strength granules, flakes & fibers with a definite PSD	Blend	All types of lost circulation	Most WBM's	All formations	Preventative - 5-20 ppb; Pill - 30-50 ppb	Can be removed by shakers and mud cleaner.	N/A	1.1		Blend of different materials; brown white and gray particles and fibers		Fine, Medium & Coarse	May water-wet solids in Invert emulsion mud.	Do not use in OBM due to water wetting of solids; can plug downhole tools with small tolerances.	40 lb/sx
Blen-Fyber OM	**Boysenblue/ Celtec International Inc.**	Preferentially oil wettable, surface modified micronized cellulose fiber	Fiber	Seepage loss control	mainly Oil base muds	Under-pressured, depleted sands	As slug (15-35 ppb) or added to the system (4-10 ppb)			1.1 - 1.3	6.5 - 7.5	Light tan, finely divided cellulose fiber				Environmentally safe, Bio-degradable, effective secondary emulsifier due to oleophyllic properties	40 lb/sx
Blen-Plug OM	**Boysenblue/ Celtec International Inc.**	Mixed, selected cellulose fibers, surface modified to preferentially oil-wet in the presence of oil & water	Fiber	Pre-treatment & cure for Lost Circulation for oil base muds - Can be used alone or with Blen-Fyber OM, Blen-Seal WB, CaCO3,...	Oil base muds	Highly vugular, dolomite or limestone formations	As slug (20-40 ppb) or added to the system (4-12 ppb)			1.3 - 1.5	6.5 - 7.5	Dark brown to tan mixed of sized cellulose fibers	Coarse			By-pass shakers when used	25 lb/sx
Blen-Seal WB	**Boysenblue/ Celtec International Inc.**	Micronized cellulose fibers, pre-absorbed with a low-aormatic / low-toxicity lubricant	Fiber	- Prevent, cure seepage losses, differential sticking, high torque & drag	All mud systems	Under-pressured, depleted sands	As slug (20-40 ppb) or added to the system (4-8 ppb)			1.3 - 1.5	6.5 - 7.5	Tan to light brown Micronized cellulose fibers				Bio-degradable & non-polluting, environmentally safe	50 lb/sx



Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Bor-Plug	**Tanajiib**	High Fluid loss squeeze - Blend of sized CaCO3	Blend	High fluid loss squeeze or as LCM.		All formations		N/A	N/A		N/A		Wide range	Fine, Medium & Coarse			50 lb/sx
Bridgesal	**TBC-Brinadd**	Blend of polymers, calcium lignosulfonate and sized salt	Granular	LCM for drilling, completion and workover into the pay zone, gravel packing or perforating	Saturated salt mud	Porous and fractured production zones	10-50 ppb of bridgesal to the brine	Water soluble salt				Free flowing powder	D50 of 18 microns		Mud must be salt saturated		50 lb/sx
Bridgesal-A	**TBC-Brinadd**	Blend of polymers and sized salt	Granular	LCM for drilling, completion and workover into the pay zone, gravel packing or perforating with low Ca/Mg for formation with calcium sensitivity	Saturated salt mud	Porous and fractured production zones		Water soluble salt				Free flowing powder			Mud must be salt saturated	Product functions as a neutral or slightly acidic pH system	50 lb/sx
Bridgesal-Superfine	**TBC-Brinadd**	Blend of polymers and sized salt of particle size range from 1 to 40 microns	Granular	Gravel packing applications where plugging of the screens must be avoided	Saturated salt mud	Porous and fractured production zones	60-70 pound per barrel of brine solution	Water soluble salt				Free flowing powder	1 to 40 microns		Avoid cross-linkers and breakers	No alkaline materials are needed for the product to function	50 lb/sx
Cello-Flake	**KMC/SCOMI**	Shredded cellophane	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A									
Cellophane	**M-I SWACO**	Shredded cellophane	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A									
Check-Loss	**Baker Hughes**	Micronized fiber particulates for seepage loss control and differential sticking preventative for fracture zones and porous sands &/limestone	Fiber	Fiberous cellulosic material used to seal depleted formations and sands	All mud systems	Porous, depleted formations	maintained in system or in pills	N/A	N/A	bulk density: 800 kg/m^3	N/A	Light brown, solid	Coarse and PLUS	N/A	N/A	Will not water wet; bridging microfractured and permeable formations	N/A

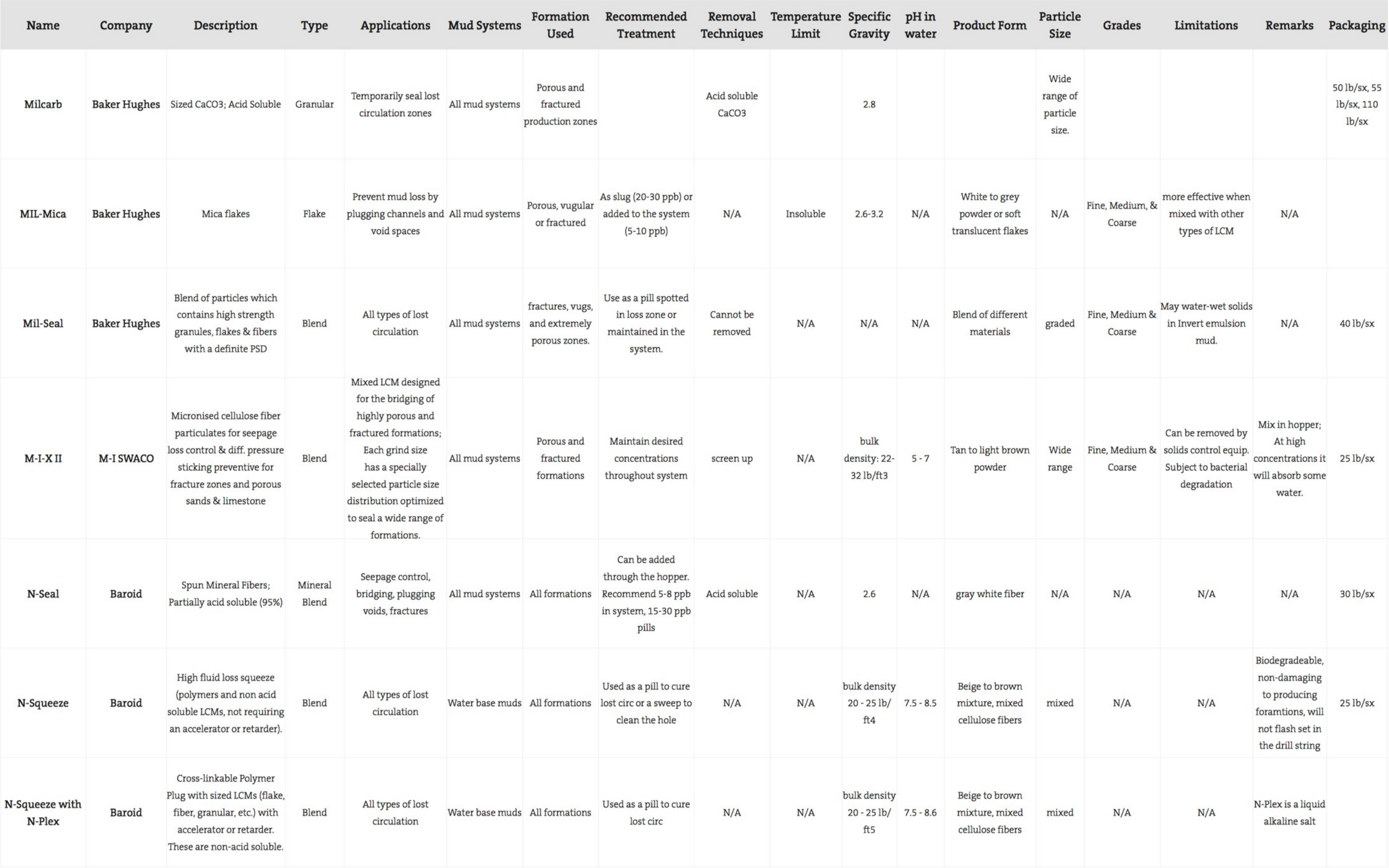
Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Chip Seal		Coarsely shredded wood	Fiber	For porous, fractures and vugular formations, where large particles bridging materials are needed	All mud systems	Porous and fractured formations	0.5 to 1.0 ppb for seepage, and higher concentration for complete losses	Not removed							Will be screened at shakers	Better succes in sealing loss zones when combined with smaller fibers	40 lb/sx
Cruseal	**Boysenblue/ Celtec International Inc.**	Graded & sized crustacean flakes	Flake	- Cure losses in depleted sands - Reduce torque & drag, differential sticking, bit balling - Plug perforations in workovers	All mud systems	Depleted, porous sands	As slug (20-40 ppb) or added to the system (5-10 ppb)	Acid soluble	Stable at high temp.	1.73		White to orange flakes		Fine & Medium		Optimum performance is obtained when fine & medium blend is used	50 lb/sx
Delta "P"	**Venture Chemicals, Inc.**	Polysacharide complex	Fiber	Bridge depleted porous formations	Water mud systems	Porous, depleted formations	2 to 8 ppb for whole mud and 10 to 50 ppb as pills	50% soluble in 15% HCl, biodegradable and low temp. stability			6	Light tan to brown fibrous powder	85% passes 60 mesh, dry basis		Low temp. stability - will be removed at shakers	Increase rheology at high concentration - Pilot test if used in OBM	25 lb/sx
Diaseal M	**Many Companies**	High fluid loss squeeze (polymers and non acid soluble LCMs, not requiring and accelerator or retarder).	Blend	High fluid loss squeeze for WBM or as LCM in WBM and NAF.	All mud systems	All formations	Mix per tech bulletin, then pump into annulus to the loss zone depth; then pull pipe above plug and "squeeze" the plug into the loss zone.	N/A	N/A	0.8	N/A	mix of white/gray particles and black and tan granules and fibers		N/A		0.5 ppb oil wetting agent	40 lb/sx
Duo-Squeeze H	**Baroid**	High Fluid loss squeeze - Blend of sized CaCO3	Blend	High fluid loss squeeze for WBM or as LCM in WBM and NAF.	All mud systems	All formations	Mix per tech bulletin, then pump into annulus to the loss zone depth; then pull pipe above plug and "squeeze" the plug into the loss zone.	N/A	N/A	1.8	N/A	mix of white/gray particles and black and tan granules and fibers	Wide range	Fine, Medium & Coarse		Bimodal particle size distribution shows efficient sealing of 190 micron pores to 1000 micron slots; Can be weighted.	50 lb/sx
Dynamite Red Fiber	**Drilling Specialties Co**	Proprietary Solid Mixture	Fiber	Seepage to complete loss of circulation	All mud systems	Depleted, porous zones	As slug (25-35 ppb) or added to the system (3-8 ppb)	28.3% soluble in 15% HCl	Stable at high temp.			Brownish red powder	Fine: 91.6% thru 200 mesh - Medium: 37% - Coarse: 32.4%	Fine, Medium & Coarse		Works at any pH, resistant to attack by bioorganisms, compatible with other LCM	25 lb/sx
EZ-Squeeze	**KMC/SCOMI**	High fluid loss squeeze (polymers and non acid soluble LCMs, not requiring and accelerator or retarder).	Blend	High fluid loss squeeze for WBM or as LCM in WBM and NAF.	All mud systems	All formations	Mix per tech bulletin, then pump into annulus to the loss zone depth; then pull pipe above plug and "squeeze" the plug into the loss zone.	N/A	N/A	2.8	12.4	mix of white/gray particles					25 lb/sx

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Fibro-Seal	**KMC/SCOMI**	Micronized fiber particulates for seepage loss control and differential sticking preventative for fracture zones and porous sands & limestone	Fiber	Porous and fractured formations, depleted sands	All mud systems	Depleted, porous zones	As slug (25-35 ppb) or added to the system (3-8 ppb)							Medium and coarse			
FlexPlug	**Baroid**	Chemical Sealant plug; Polymer blend	Blend	Blend of LCM to provice a stress cage for the borehole and improve frac gradients	All mud systems	All formations	Preventative or Pills	N/A	N/A	mixed	mixed	mixture	Wide range	Fine, Medium & Coarse		Similar to I-BOSS	Mixture
Form-A-Plug II	**M-I SWACO**	High Fluid loss squeeze - Blend of sized CaCO3	Blend	Pumpable lost Circulation plug is a blend of minerals and polymers to create suspension, fluid-loss control and cross-linking to plug the loss zone.	All mud systems	All formations	Mix, then pump into annulus to the loss zone depth; then pull pipe above plug and "squeeze" the plug into the loss zone.	95% Acid soluble in 15% HCl		2	7 - 8	White to beige powder	Fine		Do not stop pumping while plug is in pipe.	Can be adjusted for density.	55 lb/sx
Form-A-SET (AK)	**M-I SWACO**	Cross-linkable Polymer Plug with sized LCMs (flake, fiber, granular, etc.) with accelerator or retarder. These are non-acid soluble.	Blend	All types of lost circulation	All mud systems	Fractures, faults and vugular formations	As a pill spotted in loss zone	N/A		0.96	Bulk density 34.5 lb/ft3	Light tan powder	Fine		Pilot test for temperatures above 250 F	Follow instuctions from FAS software.	47 lb/sx
Form-A-SQUEEZE	**M-I SWACO**	High fluid loss squeeze (polymers and non acid soluble LCMs, not requiring and accelerator or retarder).	Blend	All types of lost circulation	All mud systems	Fractures, faults and vugular formations	As a pill spotted in loss zone	somewhat acid soluble	450 F	1.7		Gray powder			Not 100 % Acid soluble	Cures without time or temperature	50 lb/sx
Fracseal Fine	**Summit**	Micronized fiber particulates for seepage loss control and differential sticking preventative for fracture zones and porous sands & limestone	Fiber	Porous and fractured formations, depleted sands	All mud systems	Depleted, porous zones	As slug (25-35 ppb) or added to the system (3-8 ppb)							Fine, Medium & Coarse			
Gel Fib	**Gumpro**	Blend of particles which contains high strength granules, flakes & fibers with a definite PSD	Blend	All types of lost circulation	All mud systems	All formations	As a pill spotted in loss zone	Cannot be removed				Blend of different materials		Fine, Medium & Coarse	May water-wet solids in Invert emulsion mud.		40 lb/sx

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Gel Seal M	**Gumpro**	High fluid loss squeeze (polymers and non acid soluble LCMs, not requiring and accelerator or retarder).	Blend	All types of lost circulation			As a pill spotted in loss zone										
G-SEAL/G-SEAL PLUS/G-SEAL PLUS C	**M-I SWACO**	Synthetic Graphite; non acid soluble	Granular	LCM for bridging and plugging formations. Also increases lubricity in fluids.	All mud systems		Can be run in active system or in pill form.	Can be removed at shakers	500oF	2.19-2.26		Black powder or granules	Avg. size 250 microns		Can be removed by shakers. Not acid soluble.	Insoluble in water	50 lb/sx
Hydro-Plug	**Baroid**	Hydrating Polymer Blend; Hydrating Gel Plug	Blend	All types of lost circulation	All mud systems	Cavernous and vugular formations	45 bbls of freshwater + 80 50 lb bags of Hydroplug, No Caustic and ime. Spot pill across zone, and squeeze	Cannot be removed	N/A	2	N/A	dark gray to black granules and flakes	N/A	N/A	90-120 minute window is required to mix and pump	Must be mixed in freshwater if used with NAF.	50 lb/sx
Hysal-II	**TBC-Brinadd**	Blend of sized salt, complexed lignisulfonates and selected polymers	Granular	Added to high density CaCl2, CaBr2 and ZnBr2 brines to provide bridging and filtration control	Saturated salt brines	Porous and fractured production zones	100 ppb of base fluid, and 150 ppb for densities above 17 ppg	Water soluble salt	250oF			Free flowing powder			Mud must be salt saturated	Can be used in brines ranging from 12.5 to 19.2 ppg	50 lb/sx
Hysal-Superfine	**TBC-Brinadd**	Blend of polymers and sized salt of particle size range from 1 to 40 microns	Granular	Added to high density CaCl2, CaBr2 and ZnBr2 brines to provide bridging for gravel packing where plugging the screens must be avoided	Saturated salt brines	Porous and fractured production zones	100 ppb of base fluid, and 150 ppb for densities above 17 ppg	Water soluble salt				Free flowing powder			Avoid cross-linkers and breakers	Can be used in brines ranging from 12.5 to 18.5 ppg	50 lb/sx
Jel Flakes	**Baroid**	Shredded cellophane	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A									
K-Max	**Baroid**	Solids free cross-linkable HEC polymer gel for completions	Blend	All types of lost circulation	All mud systems	Cavernous and vugular formations	as a pill spotted in loss zone	Cannot be removed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
KMC-Mica	**KMC/SCOMI**	Mica flakes	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A	Insoluble	2.6-3.2	N/A	White to grey powder or soft translucent flakes	N/A	Fine, Medium, & Coarse	more effective when mixed with other types of LCM	N/A	25 lb/sx
Kwik-Seal	**Kelco-Rotary**	Blend of particles which contains high strength granules, flakes & fibers with a definite PSD	Blend	All types of lost circulation	All mud systems	All formations		Cannot be removed				Blend of different materials		Fine, Medium & Coarse	May water-wet solids in Invert emulsion mud.		40 lb/sx
LC Lube	**Baker Hughes**	Synthetic Graphite; non acid soluble	Granular	LCM for bridging and plugging formations.	All mud systems		Can be run in active system or in pill form.	Can be removed at shakers	500oF	2.19-2.26		Black powder or granules	Avg. size 250 microns		Can be removed by shakers. Not acid soluble.	Insoluble in water	50 lb/sx
LCP-2000	**EDTI or Impact Solutions**	Shear thickening slurry with graded LCMs; Special Polymer + fiber, granules & flakes	Blend	All types of lost circulation													
Liquid Casing	**Gabriel International, Inc.**	Blend of fibrous particles integrated with their distinctive size distribution	Fiber	Porous and fractured formations, depleted sands	All mud systems	Depleted, porous and fractured formations	As slug (25-65 ppb) or added to the system (2-8 ppb)	35% soluble in 15% HCl, & the remainder is biodegradable	> 400oF	< 2.0	7		< 234 microns upper limit and 44microns lower limit			Requires small addition of NaOH, Non-Toxic & environmentally safe	50 lb/sx
Liteplug	**TBC-Brinadd**	Specially sized borate salt	Granular	Sized to temporarily seal lost circulation zones in porous and fractured formations, depleted sands	Used in Litesal brine systems	Porous and fractured production zones	5 to 65 ppb of varying sizes	Soluble in acid, fresh and brine waters		2.0		Free flowing crystals	D50 of 19 for liteplug fine, 300 for liteplug and 640 microns for liteplug-X	Fine, liteplug, liteplug-X		Liteplug will seal fractures up to one-third inch	50 lb/sx
Litesal	**TBC-Brinadd**	Blend of polymer and specially sized borate salts (Ulexite) hydrated calcium sodium borate salt	Granular	Bridging materials to minimize losses in low density brine (Na or K) application : 8.7-10 ppg	Sodium or Potassium chloride solutions	Porous and fractured production zones	20 - 30 ppb	Water soluble salt				Free flowing powder	D50 of 20 microns			Can be used as circulating fluid, lost circulation pill, perforating or gravel packing fluid	50 lb/sx

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Litesal-XCP	**TBC-Brinadd**	Blend of XC-Polymer, derivatized polymer and sized borate salt	Granular	Thixotropic system designed for application where max. suspension is required.	Sodium or Potassium chloride solutions	Porous and fractured production zones	18 - 35 ppb	Water soluble salt				Free flowing powder				pH-6, a supplemental additive is necessary to stabilize the system and avoid cross-linking of the XC-Polymer	50 lb/sx
Lubra-Seal	**SUN Drilling Products Corp.**	Micronized cellulose fibers, chemically modidied by a reaction with surface modifiers. Hydrophobic nature.	Fiber	Seals depleted sands and micro-fractures	All mud systems	Depleted, porous and micro-fractured formations	As slug (20-150 ppb) or added to the system (4-10 ppb)		450oF	0.4		Light brown powder				Need to pre-disperse in diesel oil prior addition to WBM. Effective secondary emulsifier in OBM	30 lb/sx
Magma Fiber	**Lost Circulation Specialists, Inc**	Extrusion spun mineral flexible long fiber, coated with a mono nuclear film of surfactant	Fiber	Losses in fractures, permeable formations	All mud systems	All types of formations	As slug (30-40 ppb) or added to the system (5-15 ppb).	98.4% in HCl, or 60/40 HCl & Acetic Acid	1800oF	2.6	< 8	Powder	Wide range, Coarse	Fine & Regular		No asbestos, inert, non-fermenting, non-corrosive, environmentally safe	40 lb/sx
Magne-Set	**Baker Hughes**	Acid soluble (95%) Crosslink Polymer Gel with Retarder and accelerator	Blend	All types of lost circulation				Acid soluble (95%)									
Mi Flake	**Baker Hughes**	Shredded cellophane	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A									
MI MICA	**M-I SWACO**	Mica flakes	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A	Insoluble	2.6-3.2	N/A	White to grey powder or soft translucent flakes	N/A	Fine, Medium, & Coarse	more effective when mixed with other types of LCM	N/A	40 lb/sx
MicaTex	**Baroid**	Mica flakes	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A	Insoluble	2.6-3.2	N/A	White to grey powder or soft translucent flakes	N/A	Fine, Medium, & Coarse	more effective when mixed with other types of LCM	N/A	N/A



Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Milcarb	**Baker Hughes**	Sized CaCO3; Acid Soluble	Granular	Temporarily seal lost circulation zones	All mud systems	Porous and fractured production zones		Acid soluble CaCO3		2.8			Wide range of particle size.				50 lb/sx, 55 lb/sx, 110 lb/sx
MIL-Mica	**Baker Hughes**	Mica flakes	Flake	Prevent mud loss by plugging channels and void spaces	All mud systems	Porous, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	N/A	Insoluble	2.6-3.2	N/A	White to grey powder or soft translucent flakes	N/A	Fine, Medium, & Coarse	more effective when mixed with other types of LCM	N/A	
Mil-Seal	**Baker Hughes**	Blend of particles which contains high strength granules, flakes & fibers with a definite PSD	Blend	All types of lost circulation	All mud systems	fractures, vugs, and extremely porous zones.	Use as a pill spotted in loss zone or maintained in the system.	Cannot be removed	N/A	N/A	N/A	Blend of different materials	graded	Fine, Medium & Coarse	May water-wet solids in Invert emulsion mud.	N/A	40 lb/sx
M-I-X II	**M-I SWACO**	Micronised cellulose fiber particulates for seepage loss control & diff. pressure sticking preventive for fracture zones and porous sands & limestone	Blend	Mixed LCM designed for the bridging of highly porous and fractured formations; Each grind size has a specially selected particle size distribution optimized to seal a wide range of formations.	All mud systems	Porous and fractured formations	Maintain desired concentrations throughout system	screen up	N/A	bulk density: 22-32 lb/ft3	5 - 7	Tan to light brown powder	Wide range	Fine, Medium & Coarse	Can be removed by solids control equip. Subject to bacterial degradation	Mix in hopper; At high concentrations it will absorb some water.	25 lb/sx
N-Seal	**Baroid**	Spun Mineral Fibers; Partially acid soluble (95%)	Mineral Blend	Seepage control, bridging, plugging voids, fractures	All mud systems	All formations	Can be added through the hopper. Recommend 5-8 ppb in system, 15-30 ppb pills	Acid soluble	N/A	2.6	N/A	gray white fiber	N/A	N/A	N/A	N/A	30 lb/sx
N-Squeeze	**Baroid**	High fluid loss squeeze (polymers and non acid soluble LCMs, not requiring an accelerator or retarder).	Blend	All types of lost circulation	Water base muds	All formations	Used as a pill to cure lost circ or a sweep to clean the hole	N/A	N/A	bulk density 20 - 25 lb/ft4	7.5 - 8.5	Beige to brown mixture, mixed cellulose fibers	mixed	N/A	N/A	Biodegradeable, non-damaging to producing foramtions, will not flash set in the drill string	25 lb/sx
N-Squeeze with N-Plex	**Baroid**	Cross-linkable Polymer Plug with sized LCMs (flake, fiber, granular, etc.) with accelerator or retarder. These are non-acid soluble.	Blend	All types of lost circulation	Water base muds	All formations	Used as a pill to cure lost circ	N/A	N/A	bulk density 20 - 25 lb/ft5	7.5 - 8.6	Beige to brown mixture, mixed cellulose fibers	mixed	N/A	N/A	N-Plex is a liquid alkaline salt	

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Nut Plug	**SCOMI**	Nut Shell Particles	Nut shells	All types of lost circulation, and high filtration squeezes	All mud systems	All formation types	preventative in the active, pills across loss zones, sweeps to help clean bit and hole.	screen up	N/a		N/a	Granular material	N/a	Fine, medium, coarse	Coarser grades can be screened out	N/A	50 lb/sx
NUT PLUG	**M-I SWACO**	Nut Shell Particles	Nut shells	All types of lost circulation, and high filtration squeezes	All mud systems	All formation types	preventative in the active, pills across loss zones, sweeps to help clean bit and hole.	screen up	N/a		N/a	Granular material	N/a	Fine, medium, coarse	Coarser grades can be screened out	N/A	50 lb/sx
Nutshells	**Gumpro**	Nut Shell Particles	Nut shells	All types of lost circulation, and high filtration squeezes	All mud systems	All formation types	preventative in the active, pills across loss zones, sweeps to help clean bit and hole.	screen up	N/a		N/a	Granular material	N/a	Fine, medium, coarse	Coarser grades can be screened out	N/A	50 lb/sx
OM-Seal	**Gabriel International, Inc.**	Blend of fibrous particles integrated with their distinctive size distribution	Fiber	Porous and fractured formations, depleted sands	All mud systems	Depleted, porous and fractured formations	As slug (15-100 ppb) or added to the system (2-8 ppb)	Partly acid soluble, & the remainder is biodegradable	> 400oF	< 2.0	7		< 2000 microns upper limit and 74microns lower limit			Requires small addition of NaOH, Non-Toxic & environmentally safe	25 & 40 lb/sx
Opta-Carb	**KMC/SCOMI**	Sized CaCO3; Acid Soluble	Granular	Temporarily seal lost circulation zones	All mud systems	Porous and fractured production zones		Acid soluble CaCO3		2.8			Wide range of particle size.				50 lb/sx, 55 lb/sx, 110 lb/sx
Perfect Seal	**International Drilling Products, Inc.**	Chemically inert, inorganic granular material	Granular	Forms a seal and prevent lost circulation	All mud systems	Porous and fractured formations	2 ppb for seepage and 10-15 ppb for partial to complete losses	Not removed	1000oF	1.5			Wide range from #6 mesh to #120 mesh screens		Check Environmental regulations	Has extrememly high compressive stength & cannot be squeezed into the formation	40 lb/sx
Perfsal	**TBC-Brinadd**	Blend of polymer and sized salt	Granular	In gravel packing where perforations need to be temporarily sealed.	Used in Bridgesal systems	Porous and fractured production zones	3 sx / barrel of fresh water or brine.	Gelled brine wash is circulated to clean & open the perforation				Free flowing powder				Perfsal is spotted ahead of Bridgesal to fill perfs. The volume should be limited to minimize the coarse salt.	50 lb/sx

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Plug-git	**Baroid**	Shredded hardwood fiber	Fiber	Prevent or overcome lost circulation in porous formation	All mud systems	Porous formations	3 to 30 ppb to be added to the whole mud	Not removed	N/A	1.1	N/A	wood shavings	N/A	Fine, Med, and Coarse	Can be screened at the shakers		40 lb/sx
Plugsal	**TBC-Brinadd**	Sized and treated salt. It has a wide distribution of finely divided particles	Granular	Temporarily seal lost circulation zones	Saturated salt mud	Porous and fractured production zones	25-50 ppb tobe added to a bridgesal system	Water soluble salt		2.18		Free flowing crystals	D50 for : Plugsal of 75, Plugsal-X of 450 and plugsal-X-C of 3100 microns	Plugsal, X, X-C	Mud must be salt saturated		50 lb/sx
Polymesh	**KMC/SCOMI**	Cross-linkable Polymer Plug with sized LCMs (flake, fiber, granular, etc.) with accelerator or retarder. These are non-acid soluble.	Blend														
Ruf-Plug	**Kelco-Rotary**	Angular material produced by grinding, sizing and blending the hard woody ring portion of corn cobs	Blend	All types of lost circulation	All mud systems	Effective in fractured and unconsolidated formations.		50% soluble in 15% HCl				Blend of different materials	-20 > Fine > 60 mesh 14 > Medium > 40mesh 4 > Coarse > 40 mesh	Fine, Medium & Coarse	May water-wet solids in Invert emulsion mud.	Resists physical breakdown upon impact.	50 lb/sx
SAFE-CARB	**M-I SWACO**	Sized CaCO3; Acid Soluble	Granular	Temporarily seal lost circulation zones	All mud systems	Porous and fractured production zones		Acid soluble CaCO3		2.8			Wide range of particle size.				50 lb/sx, 55 lb/sx, 110 lb/sx
SAFE-LINK	**M-I SWACO**	Solids free cross-linkable polymer gel for completions	Blend														
Silvanite	**Weyerhaeuser**	100% red alder wood fiber, chemically treated to produce an oleophilic, hydrophobic product for use in OBM	Fiber	To cure seepage losses in porous formation	Oil mud systems	Porous formations	2 to 4 ppb to be added to the whole mud	Not removed	350oF	0.4 - 0.8		Compressed form	Fine : D90 of 200 mesh Medium: D90 of 150	Fine and Medium	Will be screened at the shakers	Small shredder/ feeder is recommended for mixing	40 lb/sx

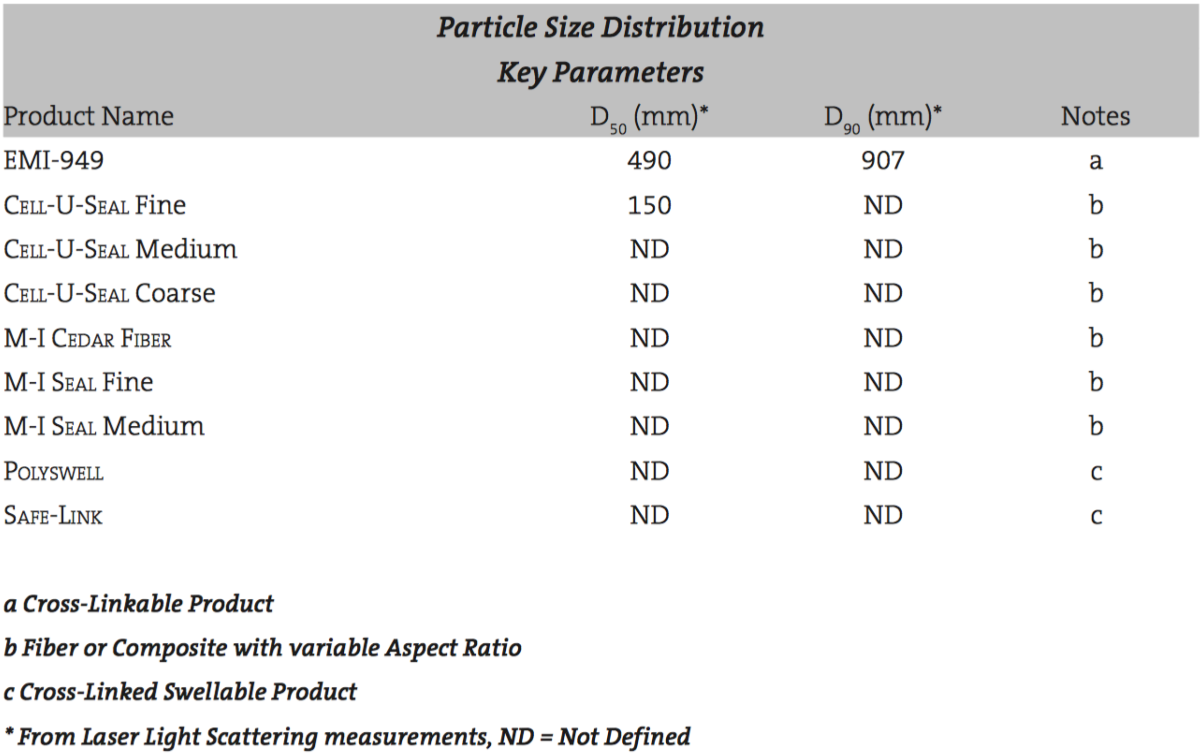
Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Slicke-n-Side	**KMC/SCOMI**	Synthetic Graphite; non acid soluble	Granular	LCM for bridging and plugging formations.	All mud systems		Can be run in active system or in pill form.	Can be removed at shakers	500oF	2.19-2.26		Black powder or granules	Avg. size 250 microns		Can be removed by shakers. Not acid soluble.	Insoluble in water	50 lb/sx
Solu-Flakes	**Baker Hughes**	CaCO3; Acid soluble flakes	Flake	Prevent and reduce losses from seepage to total	All mud systems	Depleted, porous sands, vugular or fractured	As slug (20-30 ppb) or added to the system (5-10 ppb)	Acid soluble	N/A	2.8	8.4 - 10.2	Solid, white, powder	varied	Super Fine, fine, medium, coarse	N/A	N/A	N/A
Solu-Squeeze	**Baker Hughes**	High Fluid loss squeeze - Blend of sized CaCO3	Blend	moderate to severe losses	All mud systems	vugular and fractured formations	squeeze across a thief zone	N/A	N/A	2.5 - 2.8	N/A	granular white material	mixed	mixed	N/A	N/A	N/A
Steel Seal	**Baroid**	Resilient, angular, dual-composition carbon & graphite material	Angular	Loss circulation prevention in porous and fractured zones. Also for torque & drag reduction in WBM	All mud systems	Porous, depleted and fractured formations	As slug (15-100 ppb) or added to the system (2-8 ppb)	N/A	N/A	1.75	N/A	Black, angular material	100% < 40 mesh(635) 56% > 85 mesh (300) 95% > 200 mesh (127)	Fine, Medium, and Coarse	N/A	N/A	50 lb/sx
Stop-Loss	**Conoco**	Polynuclear Aromatic Hydrocarbon/ carboneceous material of both granular & fibrous shape	Blend	Porous and fractured formations, depleted sands	All mud systems	Porous and fractured formations	40-100 ppb pills			2.2		Black porous powder	D50 of 250 microns		Check Environmental regulations		50 lb/sx
StrataWool	**Rockwool Industries**	Interlocking mineral wool fiber that provides a strong framework for a durable mud cake	Fiber	Porous and fractured formations, depleted sands; General lost circulation cases, drilling and workovers	All mud systems	Porous and fractured formations	1 to 5 ppb to be added	90% soluble in 10% HCl in 80 min.	1800oF	2.6	7 - 8	Powder				Non-combustible, non-fermenting, non-polluting, non-toxic, non-corrosive, odorless inorganic.	
Super Sweep	**Gumpro and Sun**	Filamentous fibers for sweeps or seepage loss control	Fiber	Porous and fractured formations, depleted sands; General lost circulation cases, drilling and workovers	All mud systems	Porous and fractured formations	0.25 ppb	at Shakers	315oF	1		synthetic monofilament fiber				13 mm in length	15 lb boxes

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
TekPlug (BJ)	**Baker Hughes**	Solids free cross-linkable polymer gel for completions	Blend														
Thermatek	**Baroid**	Acid soluble (95%) Crosslink Polymer Gel with Retarder and accelerator	Blend	Porous and fractured formations, depleted sands	All mud systems	Porous and fractured formations	15-25 ppb treatments, mixes below the BHA	Acid soluble (95%) in 15-28% hydrochloric acid	N/A	N/A	N/A	N/A	N/A	N/A	N/A	This is a systematic approach to lost circulation.	N/A
Truseal	**Petrochem**	Micronized fiber particulates for seepage loss control and differential sticking preventative for fracture zones and porous sands & limestone	Fiber	Porous and fractured formations, depleted sands; General lost circularion cases, drilling and workovers	All mud systems	Porous and fractured formations								Fine, Medium & Coarse			
Ven-Fyber 201	**Venture Chemicals, Inc.**	Micronized, surface modified, cellulose derivative	Fiber	Prevent seepage losses	Oil mud mainly	Porous, depleted formations	6 to 10 ppb for whole mud and up to 150 ppb as pills			1.54	3 - 7	Light tan to brown finely divided powder	95% wet washes through 100 mesh			Suplement emulsifier in OBM	40 lb/sx
Ven-Pak	**Venture Chemicals, Inc.**	Blend of organic fibers of wide variety of types and sizes of particles	Fiber	Porous and fractured formations, depleted sands	Water mud systems	Porous and fractured formations	As slug (20-50 ppb) or added to the system (3-20 ppb)			0.41		Dark brown to light tan fluffy, voluminous fibrous solid	5/16" grind			Will be screened out at shakers.	25 lb/sx
Ven-Pel	**Venture Chemicals, Inc.**	Blend of both long & short cellulose base organic fibers	Fiber	Fibrous LCM designed to expand up to 5 times its volume when brought in contact with water, which will provide high water loss bridging properties in large voids spaces	Water mud systems	Severely fractured formations, except the production zones	As slug (20-50 ppb) or added to the system (5-40 ppb)	Not removed		0.74		Dark brown pellets	Diameter : 5/16 inch, Length : less than 0.5"		Not used in OBM or in production zones	- Should be fully desintegrated before pumped to prevent bit plugging - Non fermenting products included	40 lb/sx
Ven-Plug	**Venture Chemicals, Inc.**	Blend of water soluble polymers & fibrous cellulose bridging agents.	Fiber	Highly viscous, temporary plugging agent in severe cases of lost circulation	Water mud systems	Porous and fractured formations	20 - 40 ppb			0.4	5 - 7	Light brown fibrous material			Avoid mixing with Aluminum	Ven-Plex cross-link and strengthen Ven-Plug pill	25 lb/sx

Name	Company	Description	Type	Applications	Mud Systems	Formation Used	Recommended Treatment	Removal Techniques	Temperature Limit	Specific Gravity	pH in water	Product Form	Particle Size	Grades	Limitations	Remarks	Packaging
Walnut	**Baroid and Baker Hughes**	Nut Shell Particles	Nut shells	All types of lost circulation, and high filtration squeezes	All mud systems	All formation types	preventative in the active, pills across loss zones, sweeps to help clean bit and hole.	screen up	N/a		N/a	Granular material	N/a	Fine, medium, coarse	Coarser grades can be screened out	N/A	50 lb/sx
X-Link	**Baker Hughes**	Cross-linkable Polymer Plug with sized LCMs (flake, fiber, granular, etc.) with accelerator or retarder. These are non-acid soluble.	Blend														

Table 19: Particle Size Distribution (M-I SWACO 2010)

	Particle Size Distribution Key Parameters		
Product Name	D_{50} (mm)*	D_{90} (mm)*	Notes
C-Seal (EMI-738)	127	191	
C-Seal F (EMI-739)	29	114	
Form-A-Plug II	45	150	a
Form-A-Set	300	1180	a
Form-A-Set AK	180	355	a
Form-A-Set AKX	180	300	a
Form-A-Squeeze	45	480	
G-Seal	280	501	
G-Seal Plus	189	602	
G-Seal Plus C	500	1500	
Mica	613	989	
M-I-X II Fine	86	202	b
M-I-X II Medium	174	449	b
M-I-X II Coarse	447	1513	b
Safe-Carb 2 (Very Fine)	4	10	
Safe-Carb 10 (Fine)	9	22	
Safe-Carb 20	19	93	
Safe-Carb 40 (Medium)	40	111	
Safe-Carb 250 (Coarse)	240	464	
Safe-Carb 500 (Extra Coarse)	489	717	
Safe-Carb 1000 (Extra Extra Coarse)	1062	1607	
VinSeal Fine	59	246	
VinSeal Medium	305	589	
VinSeal Coarse	396	948	
	Additional Products		
EMI-1759 (Marble)	686	967	
OptiSeal #1	530	843	
OptiSeal #2	620	880	
OptiSeal #3	595	875	
OptiSeal #4	500	960	
NutPlug Fine	626	945	
NutPlug Medium	ND	1400	
NutPlug Coarse	ND	2360	



	Particle Size Distribution Key Parameters		
Product Name	D_{50} (mm)*	D_{90} (mm)*	Notes
EMI-949	490	907	a
Cell-U-Seal Fine	150	ND	b
Cell-U-Seal Medium	ND	ND	b
Cell-U-Seal Coarse	ND	ND	b
M-I Cedar Fiber	ND	ND	b
M-I Seal Fine	ND	ND	b
M-I Seal Medium	ND	ND	b
Polyswell	ND	ND	c
Safe-Link	ND	ND	c

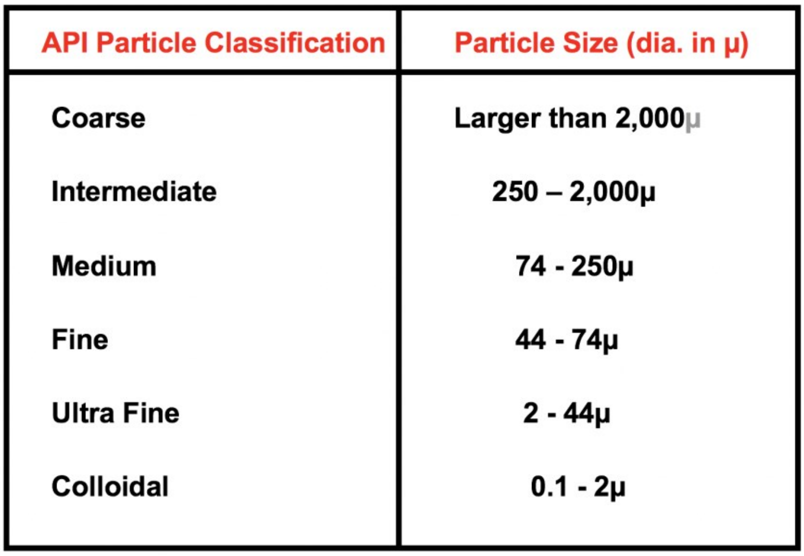
a Cross-Linkable Product

b Fiber or Composite with variable Aspect Ratio

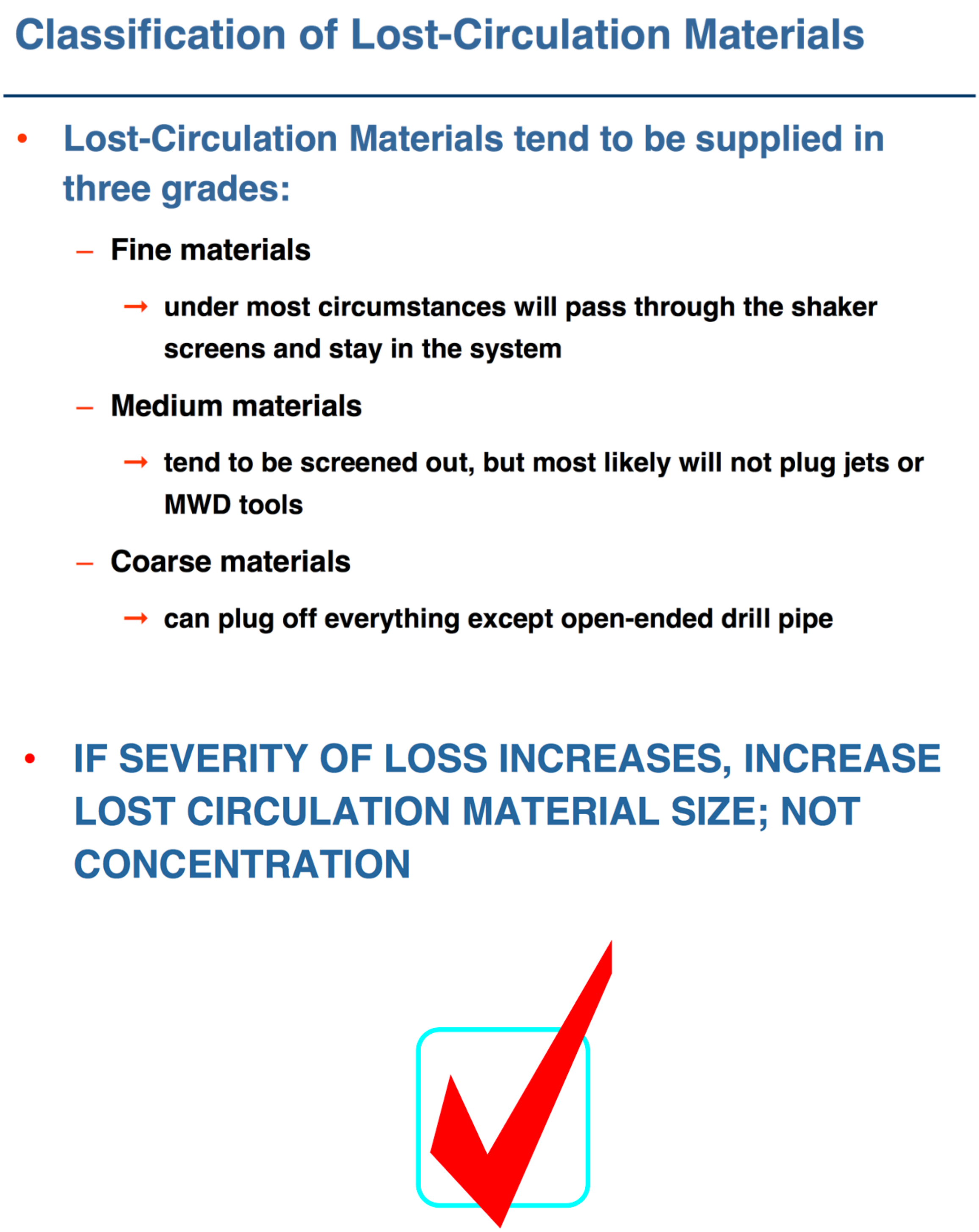
c Cross-Linked Swellable Product

**** From Laser Light Scattering measurements, ND = Not Defined***

Table 20: LCM Size Classification (Santos Mud Awareness School 2003)



API Particle Classification	Particle Size (dia. in µ)
Coarse	Larger than 2,000µ
Intermediate	250 – 2,000µ
Medium	74 - 250µ
Fine	44 - 74µ
Ultra Fine	2 - 44µ
Colloidal	0.1 - 2µ



Classification of Lost-Circulation Materials

- Lost-Circulation Materials tend to be supplied in three grades:
  - Fine materials
    - → under most circumstances will pass through the shaker screens and stay in the system
  - Medium materials
    - → tend to be screened out, but most likely will not plug jets or MWD tools
  - Coarse materials
    - → can plug off everything except open-ended drill pipe

- IF SEVERITY OF LOSS INCREASES, INCREASE LOST CIRCULATION MATERIAL SIZE; NOT CONCENTRATION

Figure 71: LCM Equipment Restrictions (M-I SWACO 2002)

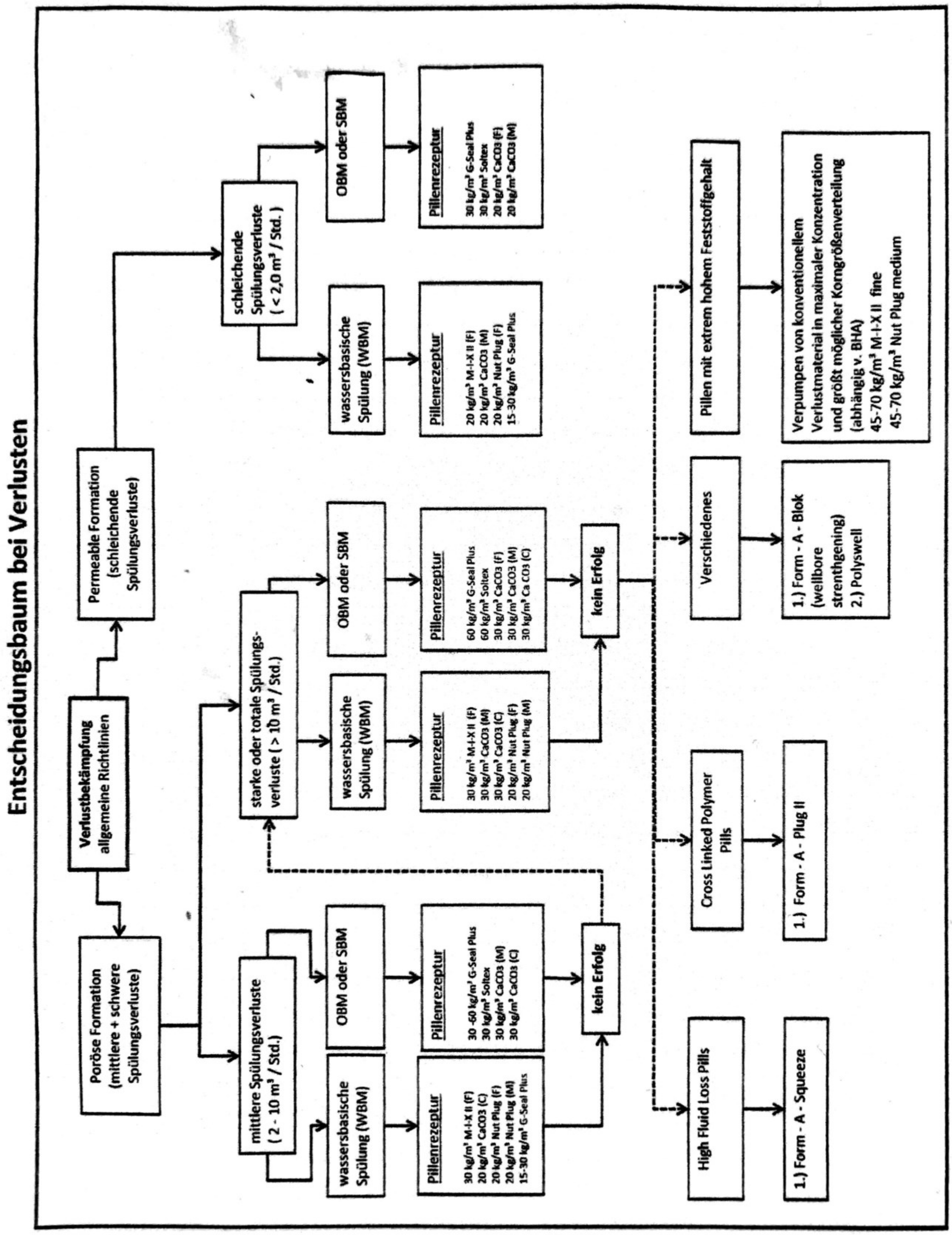


Figure 72: Lost Circulation Decision Tree RAG (RAG 2015)