Spring 2016

A comprehensive study of lost circulation with application in the South Rumaila field, Iraq

Abo Taleb Tuama Al-Hameedi

A COMPREHENSIVE STUDY OF LOST CIRCULATION WITH APPLICATION IN THE SOUTH RUMAILA FIELD, IRAQ

by

ABO TALEB TUAMA AL-HAMEEDI

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN PETROLEUM ENGINEERING

2016

Approved by

Shari Dunn-Norman, Advisor
Runar Nygaard
Steven Hilgedick

ABSTRACT

Drilling mud losses and problems associated with lost circulation while drilling account for a major expense in drilling oil and gas wells. By industry estimates, more than 2 billion USD is spent annually to combat and mitigate this problem (Ali et al., 2015).

The South Rumaila field in Iraq is one of the largest oilfields in the world. Wells drilled in this field are highly susceptible to lost circulation problems when drilling through the Dammam, Hartha and Shuaiba formations. Lost circulation events range from seepage losses to complete loss of the borehole and are a critical issue in field development.

This thesis describes a study of the lost circulation events in more 50 wells drilled in the Rumaila field. Lost circulation events were extracted from daily drilling reports. Key drilling parameters (e.g. RPM, RPM, bit type) and mud properties (e.g. density, yield point, gel strength) at the time of each event were recorded along with the lost circulation remedies attempted, and the outcome of those remedies. These data were analyzed to determine ranges for the key drilling parameters and mud properties that have the greatest chance of mitigating lost circulation in each of the three formations.

Practical field information from a range of sources were reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the South Rumaila Field.

Best field procedures for avoiding or minimizing lost circulation events in the South Rumaila field were identified and were provided as tabled procedures, or as additional data in the appendices of this thesis.

This study provides a unique compilation of information regarding traditional approaches and the latest approaches of lost circulation control. The thesis attempts to provide useful guidelines or references for both situations.

ACKNOWLEDGMENTS

First and foremost, I would like to express my appreciation to my country for granting me this opportunity to be one of the scholarship recipients of the ExxonMobil Iraq Training, Technology & Scholars Program, and a fully funded scholarship program. In the same vein, I would like to express my sincere gratitude to ExxonMobil Company and Institute of International Education (IIE) for supporting and a good management for my program.

Second, I really have a big desire in order to express about my deepest gratitude and my honest feelings to my advisor, Dr. Shari Dunn-Norman for accepting me and trusting me to be one of her research group as a master student even though my topic is different from her research area. Additionally, I really like to thank Dr. Shari Dunn-Norman for her immense contribution to the success of this work. She wholeheartedly helped me and supported me morally and scientifically in spite of her busy schedules. As well, I would also like to thank Dr. Runar Nygaard (Head of Department) and Dr. Steven Hilgedick for accepting to serve as members of my Graduate Advisory Committee and for their inputs to the success of this work.

Last but not least, I am very grateful to my family especially my mother and my wife for their love, encouragement and support. Strictly speaking, I cannot be able to achieve any of my objectives without them. Therefore, I do not have sufficient expressions and appropriate words to show how grateful I am to my compassionate mother and my lovely wife. Without their prayers, it is very difficult to accomplish my study.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

Symbol	Description
APL	Annular Pressure Loss
bbl/hr	barrels per hour
BPC	Basra Petroleum Company
BPC	British Petroleum Company
$CaCo_3$	Calcium Carbonate
CC	Cross Linked Cement
$C_{\circ}$	Compressive Strength for Formation
CDS	Casing Drilling Shoe
CMC-HV	Carboxymethl Cellulose (High Viscosity)
CWD	Casing While-Drilling
D	Depth
DDR	Daily Drilling Report
DITF	Drilling Induced Tensile Failure
DOB	Diesel Oil Bentonite
DOBC	Diesel Oil Bentonite Cement
DOH	Diameter of Open Hole
DVC	Deformable Viscous Cohesive
E	Young’s Modulus
ECD	Equivalent Circulation Density
ELOT	Extended Leak-off Test

F°	Degree Fahrenheit
FCL	Ferro Chrome Lignosulfonate
FCP	Fracture Closure Pressure
FG	Fracture Gradient
FIP	Fracture Initiation Pressure
FIT	Formation Integrity Test
FRP	Fracture Re-opening Pressure
FP	Fracture Pressure
FPP	Fracture Propagation Pressure
Ft/min	foot per minute
FWB	Fresh Water Bentonite
g	Gravitational Acceleration
Gm/cc	gram per cubed centimeter
GM	Ground Marble
GNS	Ground Net Shells
H	Depth
HCL	Hydrochloric Acid
HP	Hydrostatic Pressure
H.V	High Viscosity
Ib/bbl	pounds per barrel
Ib/ft^3	pounds per cubed feet
ID	Internal Diameter

in	Inch
IPC	Iraq Petroleum Company
ISIP	Initial Shut-in Pressure
Kg/m^3	Kilogram per cubed meter
L/min	Litter per minute
LCMs	Lost Circulation Materials
m	meter
m^3/hr	cubed meter per hour
MCC	Magnesia Cross-Linked Cement
mm	Millimeters
MW	Mud Weight
NAOH	Caustic soda
NPT	Non-productive Time
n	Rigidity
OBM	Oil Base Mud
O.E.D.P	Open End Drill Pressure
P_0	Pore Pressure
PAC-HV	High Viscosity Polyanionic Cellulose
PFTSC	Production Field Technical Service Contract
PIT	Pressure Integrity Test
ppg	pounds per gallon
PP	Pore Pressure

PSD	Particle Size Distribution
Psi	pounds per square inch
Pw	Wellbore Pressure
Q	Flow Rate
RGC	Resilient Graphitic Carbon
RCC	Regular Cross-Linked Cement
ROP	Rate of Penetration
RPM	Revolutions per Minute
SBM	Synthetic Base Mud
SCM	Seepage Control Material
Sh	Minimum Horizontal Stress
S_H	Maximum Horizontal Stress
SPM	Stroke per Minute
TD	Total Depth
T_o	Tensile Strength
TVD	True Vertical Depth
T_y	Yield Point Viscosity
Vp	Compressional Velocity
Vs	Shear Velocity
W	Mud Weight
WBM	Water Base Mud
WOB	Weight of Bit

WOC	Waiting of Cement
WON	Without Nozzles
WPC	Wellbore Pressure Containment
Yp	Yield Point Viscosity
Бv	Vertical Stress
Бh	Minimum Horizontal Stress
БH	Maximum Horizontal Stress
БѲѲ	Hoop Stress
Бrr	Radial Stress
ρ	Density
ρ_f	Fluid Density
ρb	Formation Bulk Density
ρma	Matrix Density
Бov	Overburden Pressure
Бovg	Overburden Gradient
V	Poisson's Ratio

1. THE LOST CIRCULATION PROBLEM

1.1. INTRODUCTION

Drilling mud accounts for a major expense in drilling oil and gas wells. The drilling mud is circulated through the drill string and drill bit, to remove cuttings from the borehole and to enable drill bit performance. Drilling mud is specifically formulated to develop a thin coating on the borehole wall, referred to as a 'mud cake' which limits fluid losses to the formations already drilled and exposed in the borehole, as drill bit proceeds deeper and deeper.

The concept of lost circulation or lost returns can be defined as **"**the partial or total loss of circulating fluid from the wellbore to the formation. It is the loss of whole fluid, not simply filtrate, to the formation. Losses can result from either natural or induced causes and can range from a couple of barrels per hour to hundreds of barrels in minutes. Lost circulation is one of drilling's biggest expenses in terms of rig time and safety. Uncontrolled lost circulation can result in a dangerous pressure control situation and loss of the well**"** (Baker Hughes, 1999)

Loss circulation is a significant problem in the oil and gas industry. By industry estimates, more than 2 billion USD is spent to combat and mitigate this problem (Ali et al., 2015). Although it may occur in any formation, some primary contributors to loss circulation are high permeability weakly consolidated formations, fracture calcium carbonate reservoirs and depleted aquifer zones. (Al Menhali et. al, 2015).

Lost circulation may also occur at any point in the drilling operation. If losses occur while drilling a long section of the well, the objective of the treatment will likely be to plug off or limit the losses to allow drilling ahead without casing and cementing. In other situations, the approach may be to limit the losses and cement the well.

Given sufficient experience in drilling a particular type of formation, it may be possible to avoid, or significantly minimize, lost circulation events by controlling mud properties, drilling rate, or other field parameters. However, this requires a high level of experience and study, which is generally not available. For this reason, industry relies heavily on using methods of mitigating lost circulation events after they occur.

There is a wide range of lost circulation treatments available applied to control or eliminate lost circulation events. These systems can be divided into conventional systems, which include granular, fibrous and flaky materials that are mixed with the drilling fluids during either the drilling phase or with the cement slurries during the drilling and primary cementing phases. The other approach to controlling lost circulation is specialized cements, dilatant slurries, soft or hard reinforcing plugs, cross-linked polymers, and silicate systems that are also used during the drilling/cementing phases.

This study provides basic information on lost circulation, including an introduction to the problem, identifies a range of factors that affect lost circulation, and reviews historical work in lost circulation materials. The study summarizes mud loss and lost circulation information extracted from drilling data from the Southern Rumalia Field in Iraq. A lost circulation screening criteria is presented for the Rumalia Field, based on the historical mud loss and lost circulation problems, materials used to mitigate the problems, and potential solutions found by this study.

1.2. RESEARCH OBJECTIVES

The purpose of this research is to provide a comprehensive overview of lost circulation, and to study a dataset of wells that have already been drilled in the Southern Rumaila Field where lost circulation is a significant problem. The work will provide an integrated analysis regarding the loss problems in terms causes, treatments, and recommendations, and present general practical guidelines for mud properties to avoid or mitigate lost circulation in the Rumalia Field.

1.3. RESEARCH METHODOLOGY

The research methodology consisted of gathering information regarding drilling and lost circulation events for 50 wells in the South Rumalia Field, Iraq. These data were summarized and analyzed to determine screening criteria for the various lost circulation treatments. The research also employed a thorough literature review to identify relevant information that could be included in developing the screening guide.

It is recognized that there is no single solution to lost circulation, and that most treatment and trial-and-error. However, the screening guide presents a high-level 'go to' document with coherent guidelines, which engineers can utilize in making decisions regarding lost circulation treatments in the South Rumalia Field, Iraq.

1.4. ORGANIZATION OF THESIS

This thesis is going to be organized into four chapters. Chapter one and two will concentrate on basic formulation of this problem, illustrate theoretical concepts and fundamental background regarding losses problem, demonstrate the factors that affect lost circulation, literature review, and evolving lost circulation approaches. Chapter three will include the detailed study of lost circulation in the Southern Rumaila Field. Finally, Chapter four provides a summary, conclusions, and recommendations of the work.

2. FUNDAMENTALS AND MITIGATION OF LOST CIRCULATION

There is an extensive body of literature related to defining lost circulation, classifying types of the lost circulation, demonstrating causes of the lost circulation, illustrating consequences of lost circulation, detecting lost circulation, identifying factors that impact lost circulation, finding methods of reducing or avoiding LC, and using materials or methods for mitigating LC. A complete literature review of all aspects related to lost circulation is beyond the scope of the work; however, some fundamental aspects are discussed in this chapter.

2.1. DEFINITION OF LOST CIRCULATION

The concept of mud losses can be defined, as "Lost circulation or lost returns is the partial or total loss of circulating fluid from the wellbore to the formation. It is the loss of whole fluid, not simply filtrate, to the formation. Losses can result from either natural or induced causes and can range from a couple of barrels per hour to hundreds of barrels in minutes. Lost circulation is one of drilling's biggest expenses in terms of rig time and safety. Uncontrolled lost circulation can result in a dangerous pressure control situation and loss of the well" (Baker Hughes, 1999).

Historically technical journals, papers, and textbooks have classified the types of formations that cause a lost circulation problem. There is agreement that subsurface conditions fall in four categories, which include natural or intrinsic fractures, induced or created fractures, cavernous formations, and unconsolidated or highly permeable formations. Figure 2.1 illustrates the types of the lost circulation zones (Howard and Scott, 1951).

This classification is considered universal and has been adopted throughout this thesis.

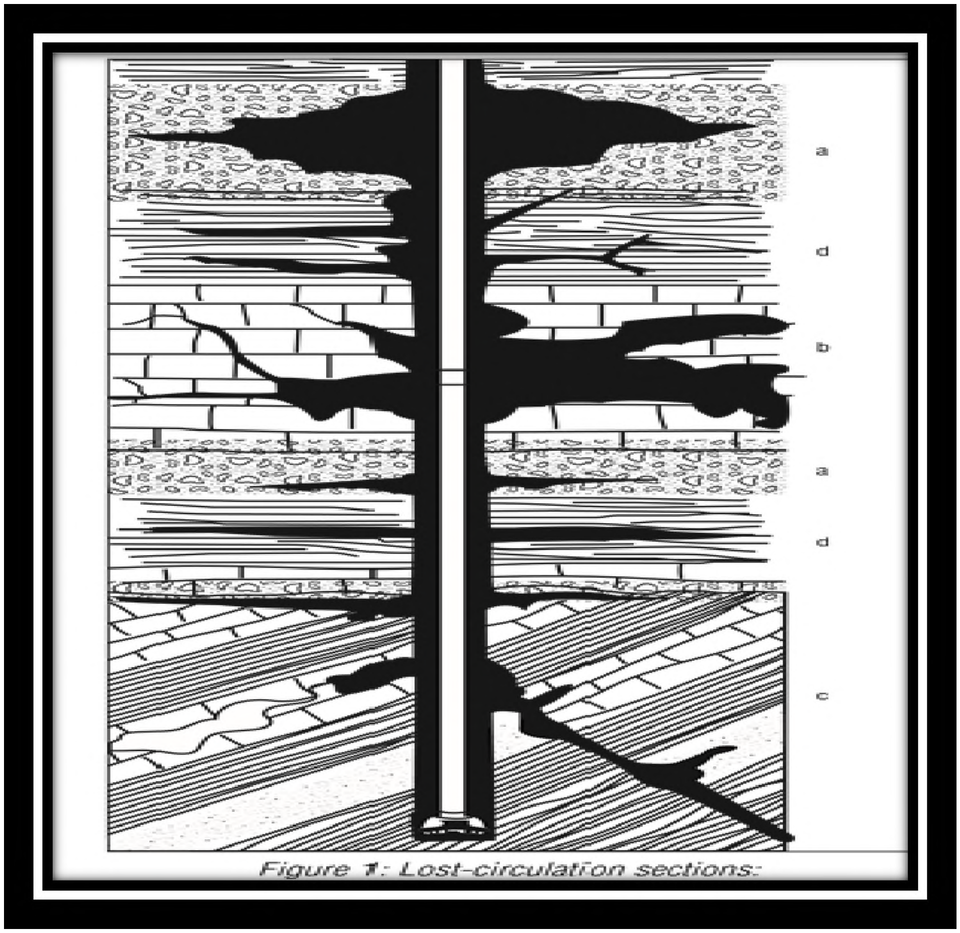


Figure 2.1. Candidate Formations for Losses Circulation (World Oil, 2003)

2.2. TYPES OF LOST CIRCULATION

Lost circulation events are categorized according to the total volume of fluid lost during the event. The volume of mud losses depends on a number of factors, including formation properties, drilling fluid properties, and formation breakdown pressure (Eni Company, 2010). The categories of losses have been described as follows, depending on the volumes of mud losses and thief zone (Nayberg & Petty, 1986).

1. Seepage loss: These losses could occur in type of formation due to differential pressure (over-balanced drilling). The other name for this type is filtration. The fluid loss rate is 0.5–1 m^3/hrs (3-6 bbls/hrs).

2. Partial loss: This kind of losses usually happen in gravel beds, small natural horizontal fractures and barely opened induced vertical fractures. The fluid loss rate is 1-10 m^3/hrs (7-70 bbls/hrs).
3. Severe loss: This kind of loss will be more than partial loss about 15 or above m^3/hrs (95 or above bbls/hrs).
4. Complete loss: In this type of losses, we will completely lose the mud cycle into formation. This type of losses happens to long open sections of gravel, large natural horizontal fractures, caverns, interconnected vugs and to widely opened induced fractures.

This categorization of losses is widely accepted and has been used in this study.

2.3. CAUSES OF LOST CIRCULATION

There are several drilling activities that may lead to lost circulation (World Oil, 2003). These include,

- ❖ Running drill strings pipes in hole very quickly resulting in an increase surge pressure, especially with high strength gel (High Viscosity).
- ❖ Insufficient and inefficient cleaning of the wellbore hole that leads to accumulating cuttings in the annulus and around the bit which in, produces extra pressure on the weak formations.
- ❖ Mud cover will surround bit which cause that bit will work as compressor on the zones, this phenomenon is called balling
- ❖ During dynamic drilling operation, the mud weight is higher than during static operations that increases equivalent circulation density (ECD). The elevated equivalent circulation density will increase significantly if there is high mud viscosity (high Yp). Figure 2.2 shows the relationship between ECD and time.

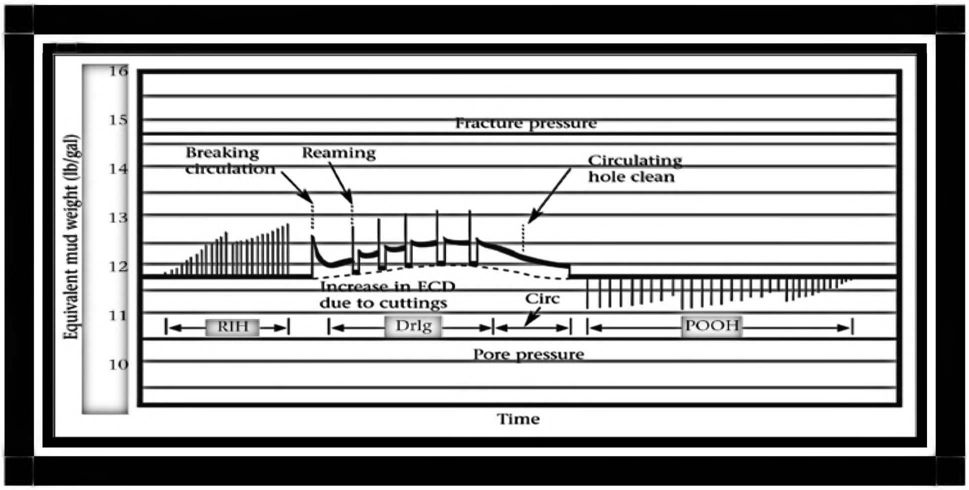


Figure 2.2. Bottom-hole Pressure for Normal Drilling Cycle (World Oil, 2003)

- After shutting down the rig, subsequent pumping of drilling fluid in high flow rate will lead to extra pressure on the formations, especially if mud has high viscosity (high yield point).
- If the drilling mud has high viscosity (high yield point and gel strength), the mud pumps will be operated at higher pressures, with potential pressure surges, that can negatively affect thief zones. Figure 2.3 shows a relationship between gel strength and surge pressure.

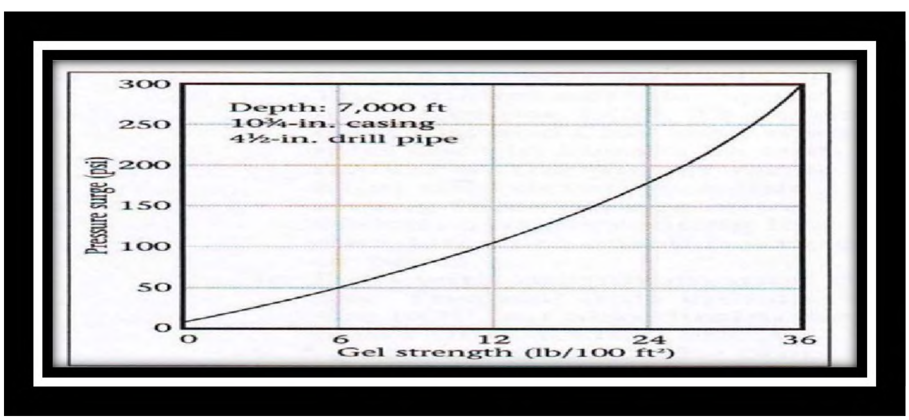


Figure 2.3. Effect of Gel Strength on Pressure Surge (World Oil, 2003)

Howard and Scott in 1951 describe three main factors that affect lost circulation: types of formations causing lost circulation, hole conditions, and drilling fluid pressure.

- Types of Formation Causing Lost Circulation: Subsurface formation and conditions susceptible to lost circulation can be classified in the following four categories:

  1. Natural or Intrinsic Fractures.
  2. Induced or Created Fractures.
  3. Cavernous Formations (crevices and channels).
  4. Unconsolidated or Highly Permeable Formations (loose gravels).

There is the possibility that induced fracture may be horizontal, vertical, or at various angles to a bore by depending on coring of wells. Created fractures can occur by using sufficient pressure to overcome and break formations. On the other hand, intrinsic fractures typically require less pressure to open. Lost circulation mud in cavernous formations differs from lost circulation to induced fracture and natural fractures. Cavernous losses can result from solution phenomena, and mud losses occur when hydrostatic pressure is higher than the formation pressure of the caverns. Figures 2.4 and 2.5 are examples of natural and induced fractures, respectively.

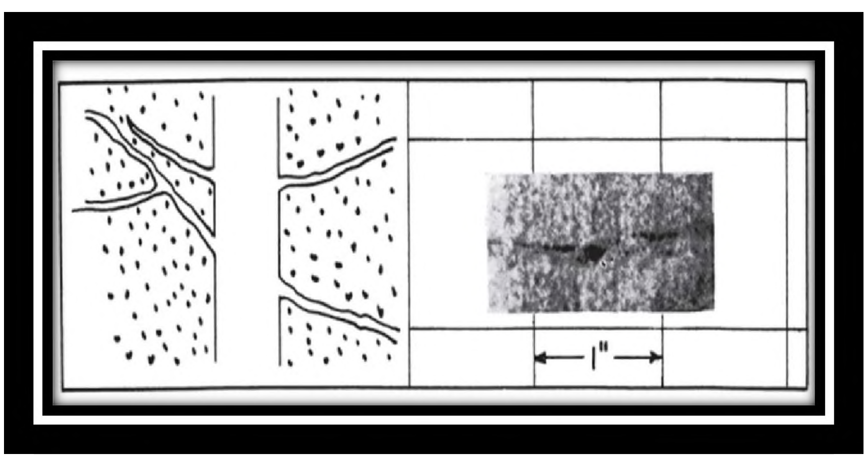


Figure 2.4. Natural or Intrinsic Fractures (Howard and Scott, 1951)

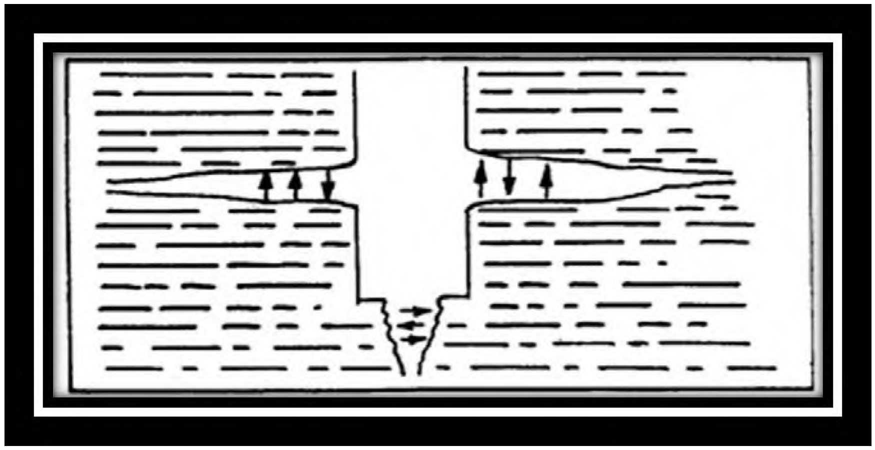


Figure 2.5. Induced Fractures (Howard and Scott, 1951)

Lost circulation in cavernous formations occurs when hydrostatic pressure is higher than the formation pressure of the caverns. Loose gravel formations usually exhibit high permeability and weak structure, and this kind of formation has enough pore size to permit mud entry. Lost circulation in unconsolidated or highly permeable formations only requires drilling mud pressure higher the formation pressure (and absence of a filter cake). Figures 2.6 and 2.7 are examples of cavernous and highly permeable formations, respectively.

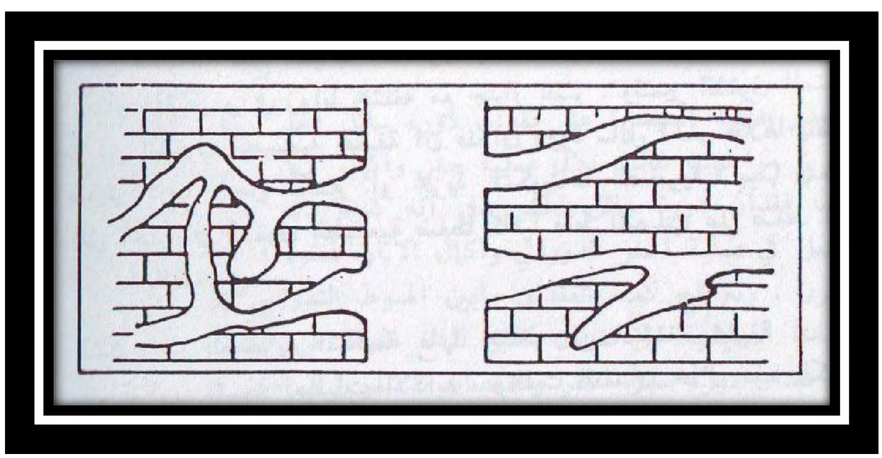


Figure 2.6. Cavernous Formations (Howard and Scott, 1951)

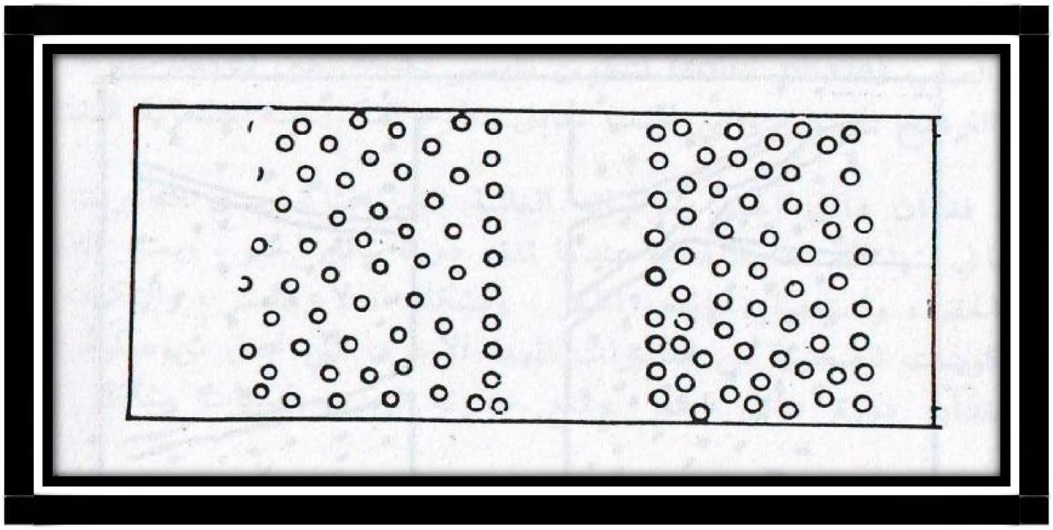


Figure 2.7. Highly Permeable Formations (Loose Gravels) (Howard and Scott, 1951)

Understanding the lost circulation problem requires a thorough understanding of the type of formations drilled, their formation characteristics (porosity, permeability, strength) and how the formations may respond to drilling fluids and pressures. Understanding the formation is a crucial aspect of designing lost circulation control and mitigation.

Howard and Scott (1951) made field observations to identify the types of lost circulation zones based on their drilling responses, so that precautions may be taken before mud losses occur. Tables 2.1 and 2.2 summarize their observations. It should be noted that it requires drilling experience in a particular formation or area, to apply these guidelines as they are based on an understanding of normal drilling responses.

Table 2.1. Identify Features of Fractures

Induced Fractures	**Natural Fractures**
This kind of fractures may occur in type of formation, but these fractures are expected in formations that have shale.	May occur in any type of formation.
Mud losses will be sudden with complete loss for mud cycle. Conditions are conducive to the forming of induced fractures when mud weight exceeds 10.5 ppg.	Mud losses will be gradual in mud tanks system, but if drilling operation will continue without preventive measures, fractures will increase which in turn lead to complete loss for mud cycle.
May happen after any sudden increasing in hydrostatic mud pressure	
These induced fractures in specific well have adverse effect on adjacent wells. In other words, lost circulation mud may occur for close wells.	

Table 2.2. Identifying Features of Cavernous Formations and Unconsolidated or Highly Permeable Formations (Loose Gravels)

Cavernous Formations	**Unconsolidated or Highly Permeable Formations (loose gravels)**
This kind of cavernous are usually available in carbonates rocks.	Mud losses will be gradual in mud tanks system.
Mud losses will be sudden with complete loss for mud cycle.	If drilling operation will continue without preventive measures, mud losses may be complete.
Drilling operations will be irregular.	The main reasons for losses in these types of formations are high permeability and excessive drilling mud weight.

In addition to the type of formation, the condition of the hole may promote or encourage the formation of fractures, leading to mud loss. Hole rugosity may depend on a combination of formation strength, bit type, WOB and penetration rate. The resulting shape of the borehole may be smooth and in caliper, while other wells may have irregular shaped and notched boreholes. Howard and Scott (1951) note five wellbore wall conditions that affect the creation of fractures.

1. Homogeneous, Impermeable Walls: By application of the thick wall cylinder theory, when the internal (fluid) pressure exceeds the tensile strength of the rock, plus the unknown external pressure acting to prevent the rock from breaking in tension, in this case vertical fracture will create. Figures 2.8 is to illustration of this case.

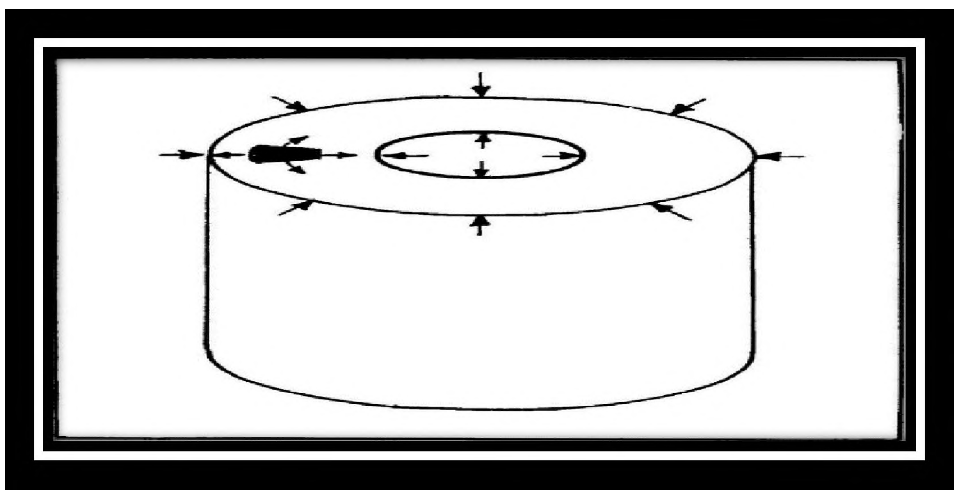


Figure 2.8. Homogeneous, Impermeable Walls for Fracturing According to Thick Wall Cylinder Theory (Howard and Scott, 1951)

2. Well Irregularities: Sometimes, notches and elliptically shaped enlargements cause fractures due to well irregularities. Pressure works to separate formations at these enlargements. Mostly, pressure has to be higher than the sum of the rock strength, plus the effective overburden pressure. Figures 2.9 illustrates this case.

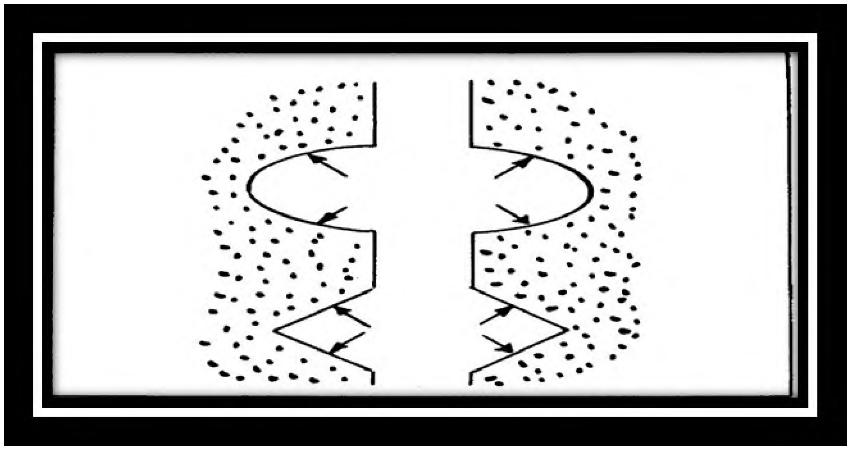


Figure 2.9. Well Irregularities Such as Notches and Elliptically Shaped Enlargements Cause Fractures (Howard and Scott, 1951)

3. Intrinsic Fractures: Formations that have natural fractures, which permit drilling mud to invade these fractures, lead to an enlarged volume of fractures. The mud pressure will act in directions perpendicular to fracture planes. This case can occur when the mud pressure is higher than the effective overburden pressure, plus the pressure required to extend the fractures. Figures 2.10 illustrates this case.

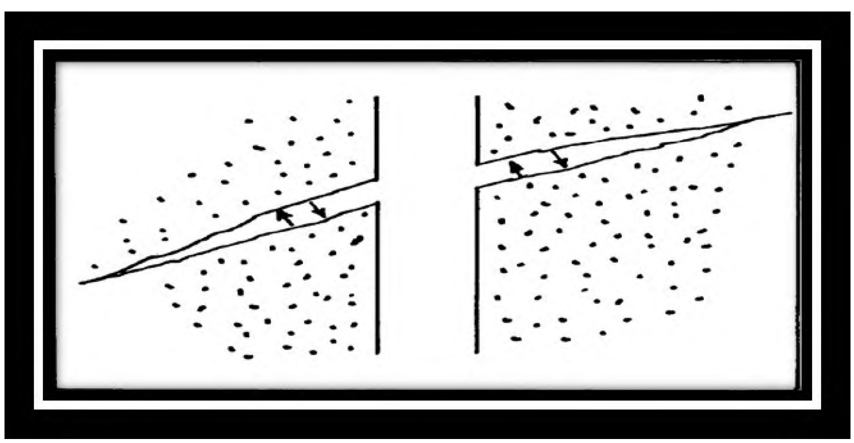


Figure 2.10. Intrinsic Fractures as the Cause of Fracturing (Howard and Scott, 1951)

4. Permeable Zones: Permeable zones have ability to receive drilling mud. That exerts pressure in the porous media. The permeable zone will fracture when the hydrostatic pressure has to be higher than the sum of effective overburden pressure plus

the pressure required to overcome the strength of the rock in the permeable zone along the unconsolidated plane. Figures 2.11 illustrates this situation.

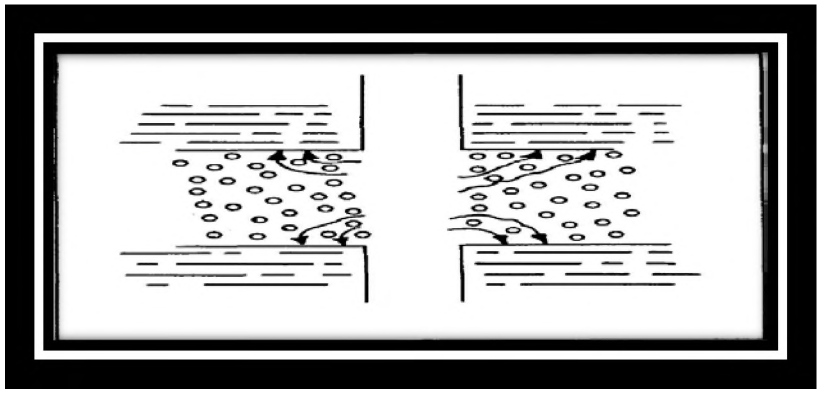


Figure 2.11. Permeable Zones as the Cause of Fracturing (Howard and Scott, 1951)

5. Closed Hydraulic System: When well is under closed-in situation, bottom hole pressure will increase, and portion of a formation may be in tension by exerting an upward force on the pipe equal to the surface pressure times the inside cross-sectional area of the pipe. This condition is probably significant in shallow wells only. This case will occur due to surface pressure during a well closed-in. Figures 2.12 shows this case.

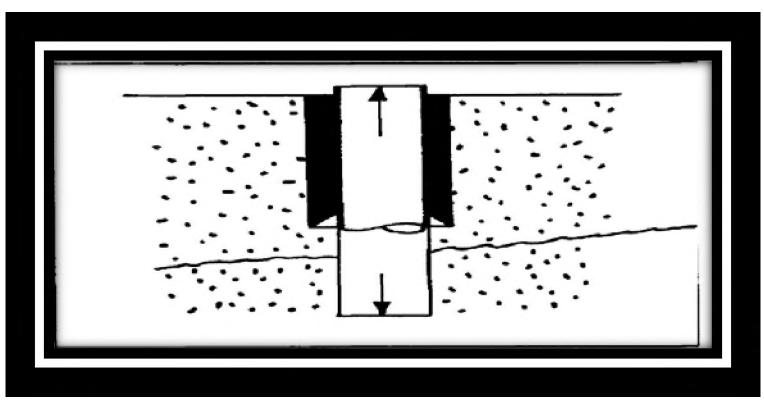


Figure 2.12. Closed Hydraulic System Causing of Fracturing (Howard and Scott, 1951)

Mud pressure is one of the most important factors in both causing and mitigating lost circulation. The following discussion details aspects of mud pressure important in the process.

1. Pressure to Fracture: Fracturing pressure has historically been obtained from a number of field operations; including leak off tests after casing has been run, breakdown pressure in squeeze cementing operations, or acid fracturing treatments. In today's shale plays, formation breakdown pressures are recorded from either the hydraulic fracturing process or pre-treatment pump-in tests. In many cases, the reported breakdown pressure gradient is similar to the mud weights used to drill. Howard and Scott (1951) reports 276 wells in the Mid-Continent and Gulf Coast areas that the require bottom hole pressure gradients to intentionally create fractures varied 0.65 psi to 1.14 psi per ft of depth, and other Values showed as low as 0.55 to 0.60 psi per ft of depth have also been reported It is possible to exceed these pressure gradients from mud weight between 10.5 Ib/gal to 22 lb/gal (1.26 – 2.63 gm/cc) which are routinely used mud weights. Figure 2.13 illustrates pressure required to fracture the formations. Actually, the required pressure required to displace or invade fluids into formations is less than the required pressure to induce fractures. It is very crucial to design the lowest possible pressure against formations in order to inhibit mud losses. Figures 2.13 and 2.14 are going to illustrate the importance of the lowest possible pressure.

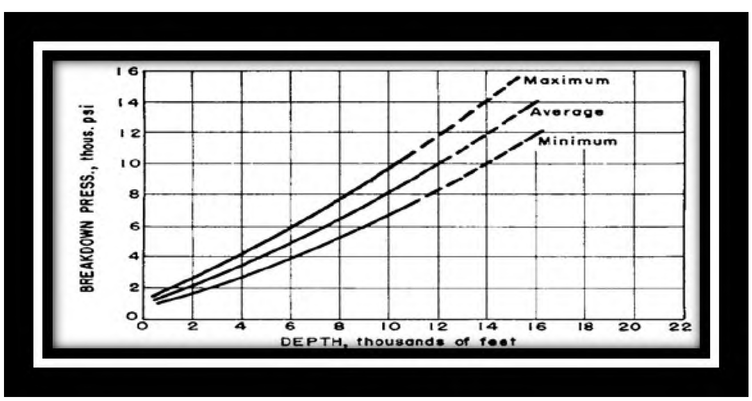


Figure 2.13. Formation Breakdown Pressures Observed During Treatment of 276 Wells in the Mid-Continent and Gulf Coast Areas (Howard and Scott, 1951)

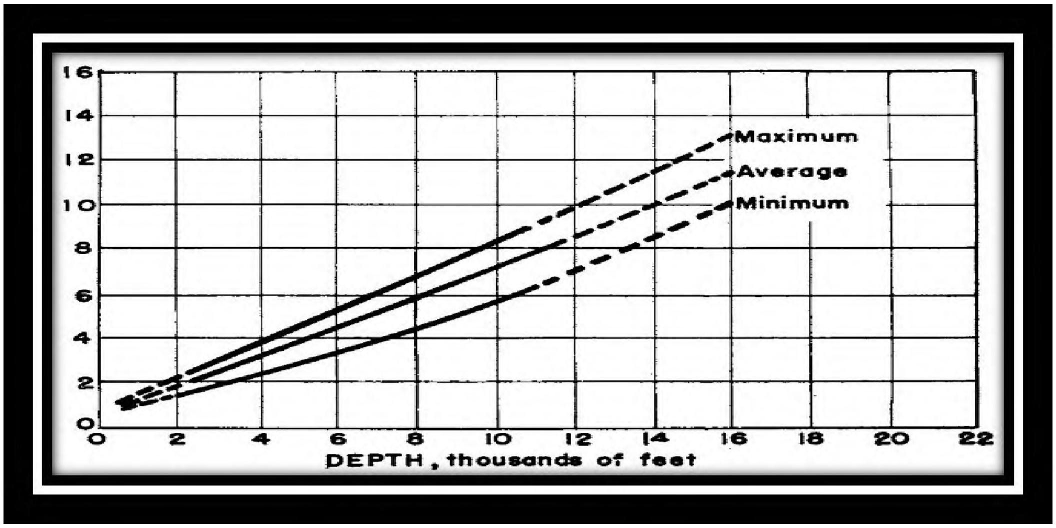


Figure 2.14. Pressures to Inject Fluids into Fractures during the Treatment of 276 Wells in the Mid-Continent and Gulf Coast Areas (Howard and Scott, 1951)

2. Causes of Excessive Pressure: Sometimes, drilling mud weight has potential to beak formations. Hydrostatic pressure has individually ability to create fractures in the zones individually. In other words, even without surging pressure, the mud pressure may be inducing fracturing. There are several drilling fluid properties and cases, which are responsible to excessive pressure (Howard and Scott, 1951).

- Drilling Mud Weight: By increasing drilling fluid density, the hydrostatic pressure will increase. Also by other investigations, it showed that mud weight reduction would decrease pumping pressure for a constant circulation rate.
- Flow Properties: Laboratory tests have been performed which demonstrate that drilling muds behave as plastic fluids. In laminar flow pattern, by decreasing yield point (Yp), the pump pressure will decrease. On other hand, by increasing yield point (t_y), the circulation mud pressure will increase which in turn cause extra pressure on the formation. Figure 2.15 illustrates the yield value t_y and rigidity n.

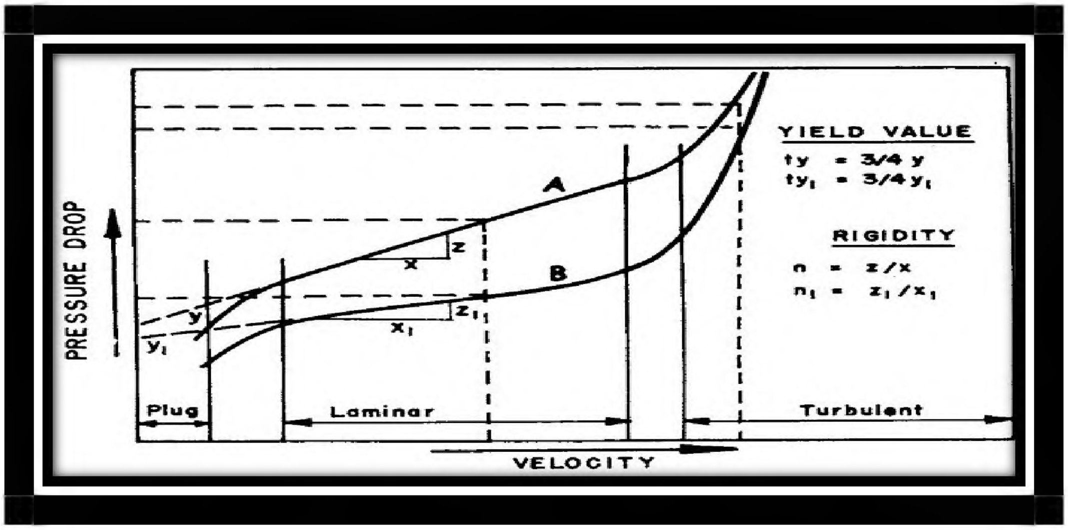


Figure 2.15. Effects of Changing Mud Flow Properties (Howard and Scott, 1951)

- Filtrate Rate: Either directly or indirectly, high filtration in drilling mud can increase pressure on the drilled formations by forming thick and not homogenous mud cake. Drilling mudflow in the annulus will be impeded due to thick mud cake. In addition, high filtration will cause bridging in the annulus that in turn will narrow and seal annulus.
- Inertia of Mud Column: During stopping for mud circulation cycle into wellbore, the gel strength of the drilling mud will increase. Therefore, any sudden pumping to drilling fluid will face high resistance due to high viscosity that will increase pressure on the drilled formations.
- High Circulating Rate: By using high pump pressure just to increase the hole cleaning efficiency has a side impact regarding increasing pressure on the formations. There is alternative technique to obtain high effective hole cleaning by altering the mud properties in order to avoid bad consequences due to high circulating rates.
- Hole Enlargements: This case will minimize drilling mud velocity in the annulus which strongly impact on the cleaning efficiency. Therefore, cutting will accumulate in which that will form bridges and seals in the wellbore, and all these factors in turn will increase pressure on the formation.

- Surging of Pumps: This factor has already been indicated in West Texas regarding increasing pressure greater than 250 psi due to pump surges. Such a surge in a well 5,000 ft deep would be equivalent to increasing the mud weight over 1 Ib / gal. The above-mentioned indicator has been deduced by depending on the results of an investigation in West Texas.
- Swelling of Casing Protectors: There is possibility that swelling of casing protectors has a role to increase pump pressure because it will cause restrictions for the drilling mud in the annulus. For the purpose overcoming swelling of casing protectors and obtaining high cleaning efficiency, the mud pressure should be increased.
- Lowering of Drill Pipe: By lowering drill strings pipes in the hole very quickly that will result to increase surge pressure especially with high strength gel (High Viscosity). In other words, bit will push drilling fluid in high rate in which cause extra pressure on the formations.

2.4. BAD CONSEQUENCES DUE TO LOST CIRCULATION

Either directly or indirectly, mud loss has an enormous negative impact on drilling operations. The concept of lost circulation can be described as "mud losses is one of the most troublesome and costly problems encountered while drilling a well. It can be characterized by a reduction in the rate of mud returns from the well compared to the rate at which it is pumped down hole during a lost circulation an appreciable part or entire volume of drilling fluid can be lost into the formation" (Pilehvari and Nyshadham, 2002). There are several negative effects due to lost circulation mud (South Oil Company, 2008).

- ❖ Loss a big amounts of the drilling mud, and therefore this has remarkable financial impact on the drilling operations cost.
- ❖ It has unwanted consequences on the productive zones because mud losses will damage formation after invasion them.
- ❖ Non-productive time (NPT).

- There is possibility to occur kick or blowout due to mud level reduction in the wellbore especially in front of abnormally high formations pressures.
- It is possible to enter a big amount of water from formations into wellbore.
- Borehole enlargement.
- Stick pipes problems.
- Damaging in the bit and drilling equipment.
- Wellbore instability.

2.5. SOME MECHANISMS TO DETECT LOST CIRCULATION

One of the most important steps is to recognize when mud losses are occurring during the drilling operation. The most common way to recognize mud loss is to monitoring mud tank level at the surface, during the drilling operation. If mud is being lost to uncased, subsurface formations, the mud levels in the surface tanks will drop. This is a technique used on nearly every drilling rig.

Survey methods, such as spinner, thermal or radiation surveys can be used to identify loss zones. Although survey methods have great utility, these techniques have some limitations (Baker Hughes, 1999). It is not easy to get accurate interpretations from Survey methods.

1- Survey methods is required much time to run and detect losses zone.
2- These methods lead to waste a considerable amount of drilling mud during the survey.
3- It is not easy to get accurate interpretations from Survey methods.
4- There is possibility to lose tool in the wellbore.
5- Sometimes, survey methods are not easily to be available in the site.

2.6. FACTORS WHICH IMPACT LOST CIRCULATION

Several factors have a pivotal role on lost circulation. The following concepts are the most significant factors related to lost circulation:

2.6.1. Definitions for the Wellbore Pressures. All formations penetrated during the drilling of a well contain pressure that may vary in magnitude depending on depth, location and proximity to other structures. In order to understand the nature, extent and origin of formation pressures, it is necessary to define and explain basic wellbore pressure concepts" (Rabia, 2002).

1. Hydrostatic Pressure: The concept of hydrostatic pressure can be defined as "is defined as the pressure exerted by a column of fluid. The pressure is a function of the average fluid density and the vertical height or depth of the fluid column" (Rabia, 2002).

Mathematically, hydrostatic pressure is expressed as:

$$HP = g \times \rho f \times D \tag{1}$$

Where,

HP = hydrostatic pressure.

g = gravitational acceleration.

ρf = average fluid density.

D = true vertical depth or height of the column.

In the Imperial system of units, when fluid density is expressed in ppg (pounds/gallon) and depth in feet, the hydrostatic pressure is expressed in psi (lb/in2):

$$HP(PSI) = 0.052 \times \rho f \times D \tag{2}$$

2. Overburden Pressure: The concept of overburden pressure can be defined as "is defined as the pressure exerted by the total weight of overlying formations above the point of interest. The total weight is the combined weight of both the formation solids (rock matrix) and formation fluids in the pore space. The density of the combined weight is referred to as the bulk density (ρb). The overburden pressure can therefore be

expressed as the hydrostatic pressure exerted by all materials overlying the depth of interest" (Rabia, 2002).

$$\sigma ov = 0.052 \times \rho b \times D \tag{3}$$

Where,

σov = overburden pressure (psi).

ρb = formation bulk density (ppg).

D = true vertical depth (ft).

Because of different densities for formation, the overburden pressure will not be constant. In addition, the overburden gradient will change due to variations in lithology, pore fluid densities, and compaction. Hence, the practical equation to calculate the overburden gradient under field conditions of varying lithological and pore fluid density is given by:

$$\sigma ovg = 0.433[(1 - \Phi)\rho ma + (\Phi \times \rho f)] \tag{4}$$

Where,

σovg = overburden gradient, psi/ft.

Φ = porosity expressed as a fraction.

ρf = formation fluid density, gm/cc.

ρma = matrix density, gm/cc.

3. Pore Pressure: The concept of pore pressure can be defined as "is defined as the pressure acting on the fluids in the pore spaces of the rock. This is the scientific meaning of what is generally referred to as formation (pore) pressure. Depending on the magnitude of pore pressure, it can be described as being either normal, abnormal or subnormal" (Rabia, 2002).

4. Fracture Pressure: The concept of fracture pressure can be defined as "is the pressure required to induce fractures in the rock formation at a given depth. Fracturing of wellbore is initiated when the rock stress changes from compression to tension. By increasing the wellbore pressure, the circumferential hoop stress reduces. Therefore, fracturing occurs at high wellbore pressures" (Aadnoy & Looyeh, 2011). Equation below will illustrate this issue.

$$\sigma\theta = \frac{1}{2}(\sigma x + \sigma y)(1 - \frac{a2}{r2}) - \frac{1}{2}(\sigma x - \sigma y)\left(1 + 3\frac{a4}{r4}\right)cos2\theta - \tau xy\left(1 + 3\frac{a4}{r4} - 4\frac{a2}{r2}\right)sin2\theta - \frac{a2}{r2}Pw \quad (5)$$

Where,

σθ = Hoop Stress.

Pw = Borehole pressure (Drilling Mud Pressure).

5. Collapse Pressure: The concept of collapse pressure can be defined as "is a phenomenon associated with low borehole pressure. Under these conditions, the hoop stress become large, but the radial stress reduces at the Sam rate as the pressure. Due to a considerable difference between the radial and hoop stress, a large shear stress will arise" (Aadnoy and Looyeh, 2011). Equation below will illustrate this point.

$$\sigma r = \frac{1}{2}(\sigma x + \sigma y)(1 - \frac{a2}{r2}) + \frac{1}{2}(\sigma x - \sigma y)(1 + 3\frac{a4}{r4} - 4\frac{a2}{r2})cos2\theta + \tau xy(1 + 3\frac{a4}{r4} - 4\frac{a2}{r2})sin2\theta + \frac{a2}{r2}Pw \quad (6)$$

Where,

σr = Radial stress.

Pw = Borehole pressure (Drilling Mud Pressure).

6. Mud Weight Window: The concept of mud weight window can be defined as "The boundary between Collapse pressure/ Pore pressure and Fracture pressure is called the mud weight window. It should be in excess of former and lesser than the latter. Collapse pressure/Pore pressure constitute low bound side of mud weight window whereas Fracture pressure constitutes upper bound side of mud weight window. There

may be a temptation to keep mud weight as low as possible in order to maximize penetration rate and reduce cost" (Sharma et al, 2012).

2.6.2. Stresses around Borehole during Drilling Operations. "Oil and gas production is moving to harsher geological condition, such as deep waters and high-pressure high-temperature reservoirs, so better and more accurate knowledge of wellbore stability becomes crucial. This is especially the case for highly deviated or horizontal wells, underbalanced drilling and penetration into deeper and unknown rock formations with naturally fractures layers and other geological complexities. The main causes of instabilities are high pore pressure in the formation, drilling-induced disturbance of a stable formation and the possible chemical reactions between the reservoirs formation and the drilling and completion fluids. Figure 2.16 illustrate a schematic showing in-situ stresses around a wellbore. Identifying this stress state is the first step to avoid wellbore instability issues. Prior to any excavation, rock formation is usually in balance (Static Stresses) with a little or no movement, by assuming no nearby seismic activities" (Aadnoy and Looyeh, 2011).

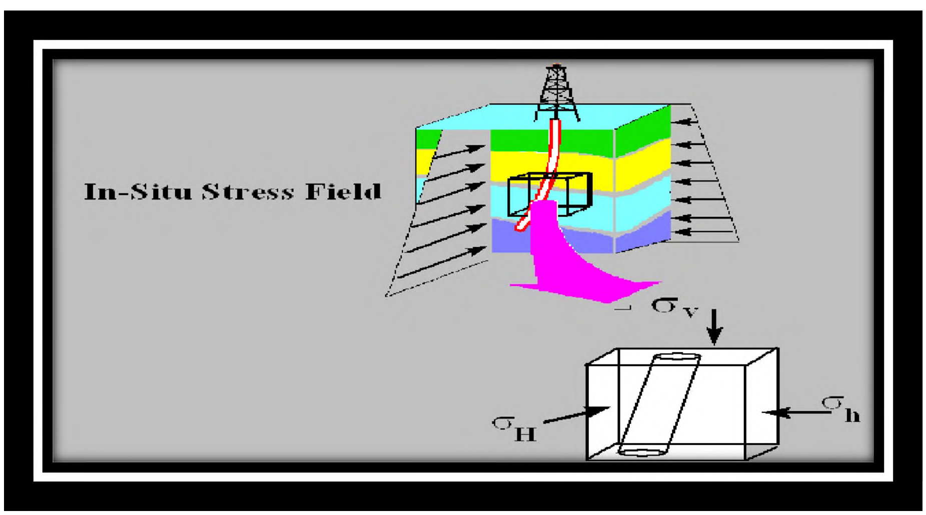


Figure 2.16. A Schematic Showing in-Situ Stresses around a Wellbore (Aadnoy and Looyeh, 2011)

Drilling a well means, that rock is removed from its original position. In other words, stresses have to readjust to match conditions at the borehole wall. I mean there is stresses that will generate due to drilling operation around a borehole. The most Important stresses will initiate are (Aadnoy and Looyeh, 2011):

1. Hoop Stress ($\sigma_{\theta\theta}$): This stress will be tangential to the borehole.
2. Radial Stress (σ_{rr}): This stress will be perpendicular to the borehole.

Before we start in the drilling operations there is no hoop stress or radial stress. The relationship between hoop stress and mud weight are not linear. Hence, in the field, if we increase mud density that means the hoop stress will decrease. On the other hand, mud weight has linear relationship with radial stress. Figure 2.17 will show Stress Distribution in a Wellbore.

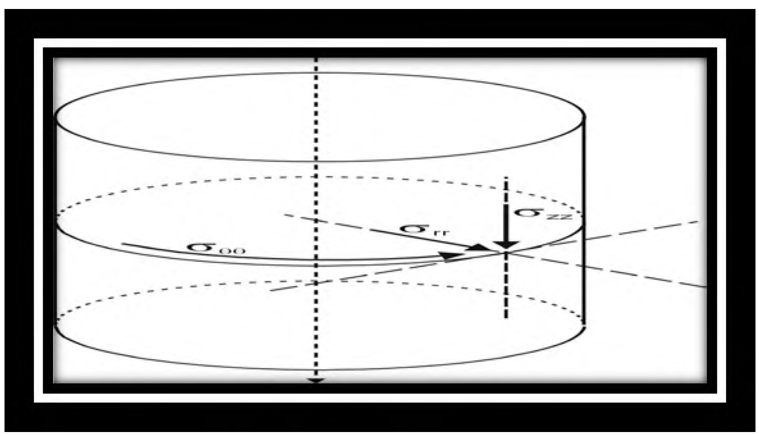


Figure 2.17. Stress Distribution in a Wellbore (Aadnoy and Looyeh, 2011)

Borehole Failure: We commonly observe two-borehole failure (Aadnoy and looyeh, 2011):

1. Shear Failure (Breakouts): In this case, the mud weight is not sufficient to resistance the pressure and stresses of formation (Underbalance or balance situation).

$\sigma_{\theta\theta} > C_o$ the hoop stress will be greater than uniaxial compressive strength of formation due to low mud weight.

Where,

$\sigma\theta\theta$ = Hoop Stress.

C_o= Compressive Strength for Formation.

2. Tensile Failure (Drilling Induced Tensile Failure): In this case, the mud weight is larger than the pressure and stresses of formation (Overbalance situation). Figure 2.18 illustrates both shear failure and tensile failure.

$\sigma\theta\theta \leq - T_o$ the hoop stress will be lesser than tensile strength.

Where,

$\sigma\theta\theta$ = Hoop Stress.

T_o = Tensile Strength

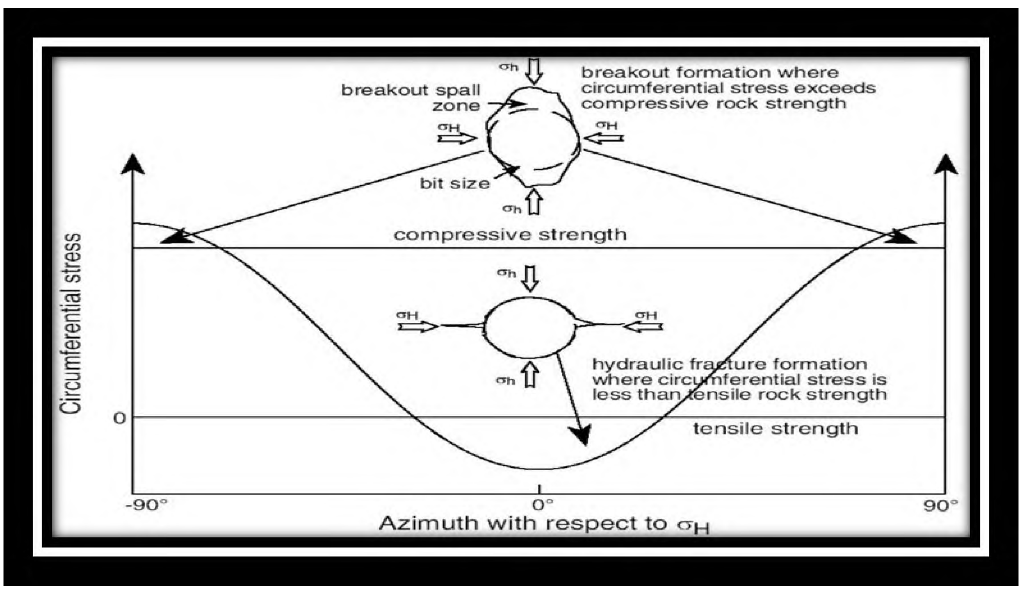


Figure 2.18. Schematic Cross-sections of Borehole Breakout and Drilling-Induced Fracture (Tingay et al., 2008)

- Identification of the Borehole Failure: Borehole failure can be detected by using Image logs or Caliper loge individually or together, breakouts will appear as two dark patches 180° apart on Image logs while DITF will appears two vertical lines (black) 180° apart on Image logs. Below figures will demonstrate image log to identify borehole failure. Figure 2.19 and 2.20 will demonstrate examples for both borehole breakouts and tensile failure.

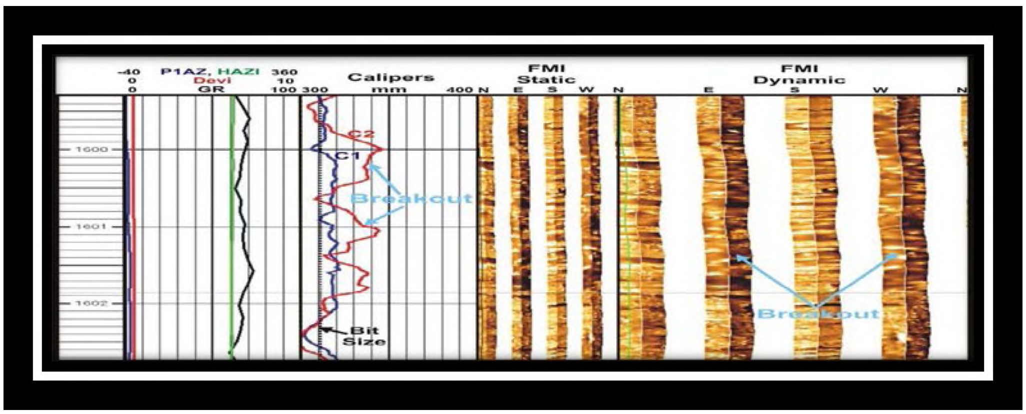


Figure 2.19. Example of Borehole Breakout Interpreted on a Formation Micro Imager (FMI) Log (Tingay et al., 2008)

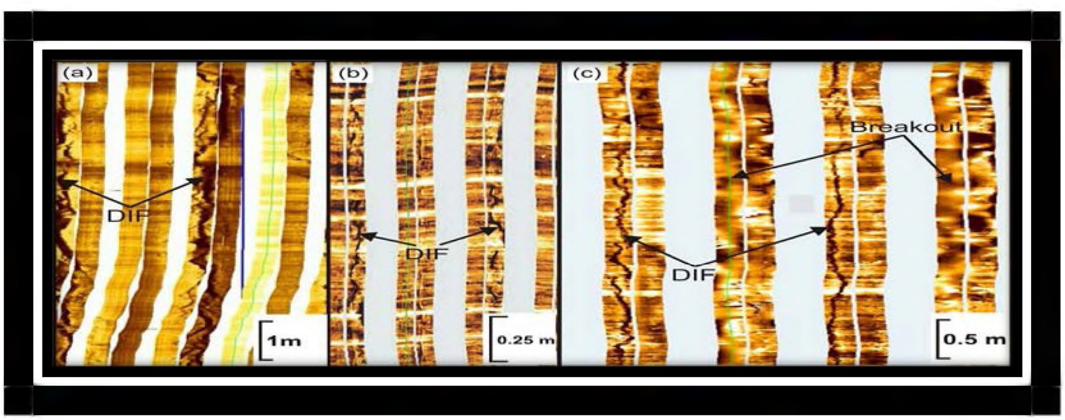


Figure 2.20. Example of Drilling-Induced Fractures (DIFs) Interpreted on Formation Micro Imager (FMI) logs (Tingay et al., 2008)

2.6.3. Flow Patterns of Drilling Mud. Patterns of flow for drilling fluids are very important because they have explicit impact on the efficiency of the hole cleaning and wellbore stability. There are three types of flow (Bourgoyne et al., 1986), (Moore, 1986) and (Amoco Production Company).

1. Laminar Flow:

- Flow pattern is linear (no radial flow).
- Velocity at wall is almost ZERO.
- Produces minimal hole erosion.
- Preferred flow type for annulus (in vertical wells).
- Laminar flow is sometimes referred to as sheet flow, or layered flow.
- Mud properties strongly affect pressure losses.
- As the flow velocity increases, the flow type changes from laminar to turbulent.
- Results in low-pressure losses (takes less energy).

2. Turbulent Flow:

- Flow pattern is random (flow in all directions).
- Tends to produce hole erosion.
- Results in higher-pressure losses (takes more energy).
- Provides excellent hole cleaning.
- Mud properties have little effect on pressure losses.
- The usual flow type inside the drill pipe and collars.
- Thin laminar boundary layer at the wall.

3. Transition Flow: Due to the increased momentum forces and velocity increases, in this case the laminar flow will change to transition flow. In other words, this type of flow occurs because of unstable turbulence. Below, figure 2.21 will clarify flow patterns of drilling mud.

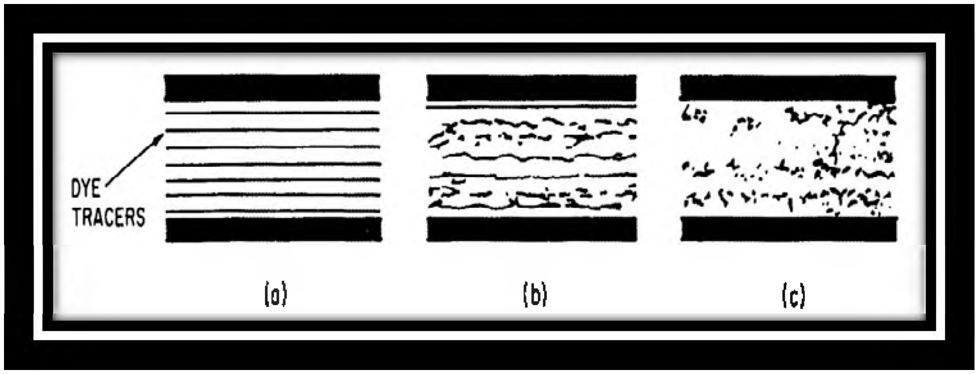


Figure 2.21. Laminar and Turbulent Flow Patterns in a Circular Pipe: (a) Laminar Flow, (b) Transition between Laminar and Turbulent Flow and (c) Turbulent Flow (Bourgoyne et al., 1986)

Turbulent flow is most desirable for efficient removal of cutting. On the other hand, the potential for whole erosion may be significant, especially with abrasive fluid. Also. It results in higher-pressure losses, so it need higher pump pressure. Moreover, turbulent flow is harmful and hazardous for unconsolidated formation (Weak Formation) because turbulent flow has equal speed in the center and sides in annulus. Therefore, this high speed will affect negatively on the wellbore wall stability. In laminar flow, fluid layers' flow paralleled to each other in an orderly fashions. This flow occurs at low or moderate shear rates when friction between the fluid and the channel walls is at its lowest. This results in lower pressure losses. On the contrary, turbulent flow happens at high shear rates where the fluid particle in a disorderly and chaotic manner and particles are pushed forward by current eddies. Friction between the fluid and the channel walls are highest for this type of flow, therefore; it results in higher pressure losses, whereas laminar flow results in less pressure losses. Due to the above-mentioned reasons, laminar flow is preferred flow type for annulus in vertical wells. Laminar flow is very appropriate for weak formation because the flow speed in sides is lesser than center. Hence, laminar flow will contribute in more wellbore stability (Bourgoyne et al., 1986), (Moore, 1986) and (Amoco Production Company).

2.6.4. Management of the Equivalent Circulation Density. One of the most important functions for drilling mud is to control of downhole pressures and support wellbore wall. During drilling operations for well, abnormal pressure (high gradient pressure zones) as well as subnormal pressure (depletion zones) may be encountered. Hence, drilling mud has to be design properly to avoid many problems. In Some cases, it is required to divide a well to three or four holes, and it will be necessary to set for each hole separate casing strings to isolate high or low-pressure zones.

Hydrostatic pressure from the drilling fluid column plus the total of the annular pressure losses (APL) above that point is called downhole pressure. The equivalent meaning for this downhole pressure is effective fluid density or commonly called equivalent circulating density (ECD). The concept of equivalent circulating density (ECD) can be defined, as "ECD is the sum of the static fluid weight plus the total of the Annular Pressure Losses (APL) above any point in the hole" (Baker Hughes, 1999).

$$ECD\ (lbs/gal) = \frac{\text{Annular Pressure Loss (APL)}}{0.052 \times \text{True Vertical Depth}} + Fluid\ Density \quad (7)$$

Where,

APL is in pounds per square inch (psi).

TVD is in feet (ft).

Fluid Density is in pounds per gallon (lbs/gal).

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

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

Drilling fluid properties affect and help regulate the equivalent circulation density. (Yield point) has a linear relationship with ECD because high viscosity for drilling fluid is going to increase friction pressure in the annulus. In turn, the pressure loss in the annulus increases. High equivalent circulation density may initiate a fracture in a formation or propagate existing fractures. The following factors affect ECD, either directly or indirectly. (Baker Hughes, 1999):

1. Minimizing solids loading in the annulus by:

- Regulating on RPM parameter.
- Provide Sufficient and efficient circulation rate.
- High cleaning efficiency for hole.
- Circulating bottoms up before trips.
- Circulating successive thin turbulent and viscous sweeps when drilling holes with angles $\leq 35°$.
- Decreasing pump pressure and velocity during pumping out of hole.

2. Providing moderate circulation rate by controlling on mud pumps to reduce APL, as well decreasing the penetration rate.

3. Maintaining good drilling fluid properties by:

- Providing effective solids control by using good surface equipment.
- Preparing allowable minimum limit for drilling mud density.
- The same thing with viscosity, maintaining gel strengths, yield point, and viscosity at allowable minimum limit that will provide efficient hloe cleaning.
- Using appropriate dilution rates.

4. Reducing restrictions in the annulus, particularly through:

- Reduction filtration property and providing thin, homogenous, and impermeable mud cake.
- Avoiding balling problem for bit.
- Excellent selection for downhole drilling equipment.

5. Minimizing swab and surge pressures by:

- Running drill strings pipes in hole slowly that will result to decrease surge pressure especially with low strength gel (low Viscosity).
- It is the best to make rotation for drill string into hole to break gel strength between 5-10 minutes before drilling fluid circulation into the hole.
- Bringing the pump up to speed slowly after connections and trips.

2.6.5. Effect of Cuttings Concentration from Excessive ROP. Excessive cutting and high rate penetration will lead to increase downhole pressure. In addition, rate of penetration, flow rate, and drilling fluid density have a linear relationship to maximize equivalent circulation density. The increase in ECD due to the effect of cutting concentration can be calculated by the following equation (Baker Hughes, 1999).

$$\text{ECD (lbs/gal)} = \frac{0.00068 \times \text{ROP} \times \text{D2} \times (21.7 - \text{MW})}{\text{Q} + 0.00068 \times \text{ROP} \times \text{D2}} \quad (8)$$

Where,

ROP is in ft/hr.

D is in inches

MW is in lbs/gal.

Q is in gal/min.

An example of this relationship is shown below in Figure 2.22.

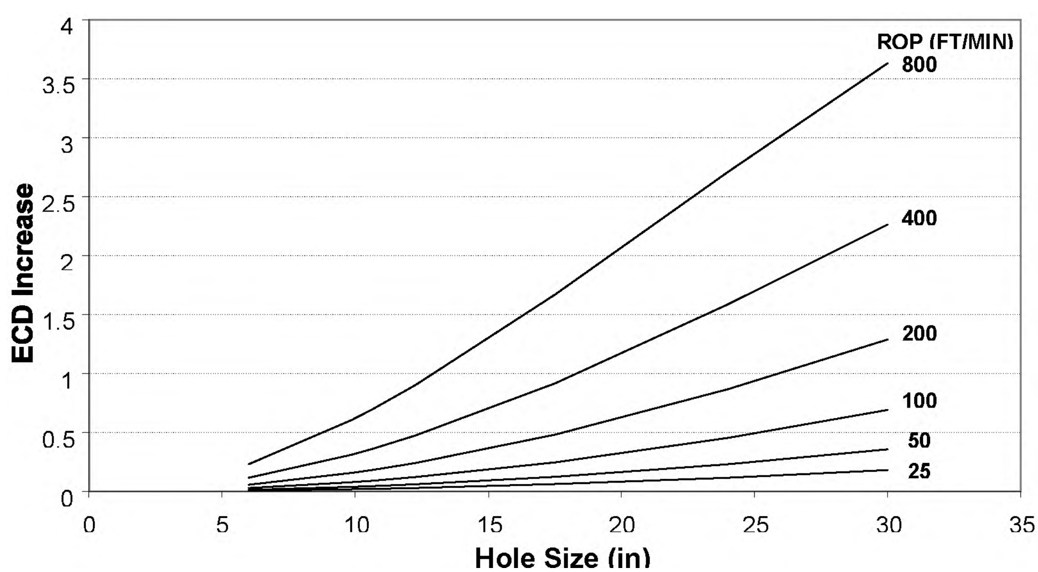


Figure 2.22. Effect of Cuttings on ECD (Baker Hughes, 1999)

2.6.6. Casing Point Selection. Selection points for casing are very crucial to success drilling operations. Well program design should decrease the amount of open hole occurring between the casing shoe and any known or anticipated thief zone. It is the best to run casing strings to cover any transition zone or potentially productive horizon.

In addition, it is necessary to prepare for emergencies by setting casing in order to isolate productive intervals or a loss zone. Another crucial point regarding casing point selection is the hole size and length of this hole. It is important to study and analyze the hole size issue to avoid or mitigate lost circulation problem. Equivalent circulation density will maximize if too small size. As well as, plugging problem for small diameter drill pipe is going to face during LCM remedies due to hole size. On other hand, the magnitude of loss and reduce the efficiency of the LCM treatment will face with too large hole. During designing the casing program, it is prudent to take into account water sensitive or heaving shales (Baker Hughes, 1999).

"Optimized well construction is the compromise between running too many costly casing strings and enduring expensive lost circulation and well control events. Setting protective casing too high leaves a weaker formation exposed to the higher fluid weights required to drill the deeper, high-pressure zones. Optimized casing point selection is dependent upon pressure transition zone identification. A detectable transition interval usually precedes the high-pressure zone. There are a number of indicators that signal when a transition zone is being drilled. They include" (Baker Hughes, 1999):

Cuttings becoming larger and possibly increasing in quantity.

- An increase in connection or trip gas.
- An increase in penetration rate from a reduction in the overbalance pressure.
- The hole becoming tight on connections.

By observing one of the indicators, drilling operation have to cease. Several actions should be taken like running well logs, recalculating pore pressure and fracture gradient pressure, and wellbore stability analysis to select casing point to avoid or mitigate tensile failure issues and shear failure problems.

2.6.7. Effect of Hole Angle. In deviated wells, the most important issue is maintaining downhole pressure. Lack of downhole pressure control will cause tensile failure and shear failure. Deviated wells are less tolerant to high or low mud weights. Hole angle for deviated wells has an inverse relationship with mud weight window. In other words, with deviated wells, mud weight window will be narrow, and it is difficult to have wellbore stability. For these reasons, both ECD and surge/swab pressures should be carefully analyzed and controlled in highly deviated wells (Baker Hughes, 1999). Figures 2.23 illustrates mud losses occur at pressures above the tensile failure line, and shear failure occurs at pressures below the compressive failure line.

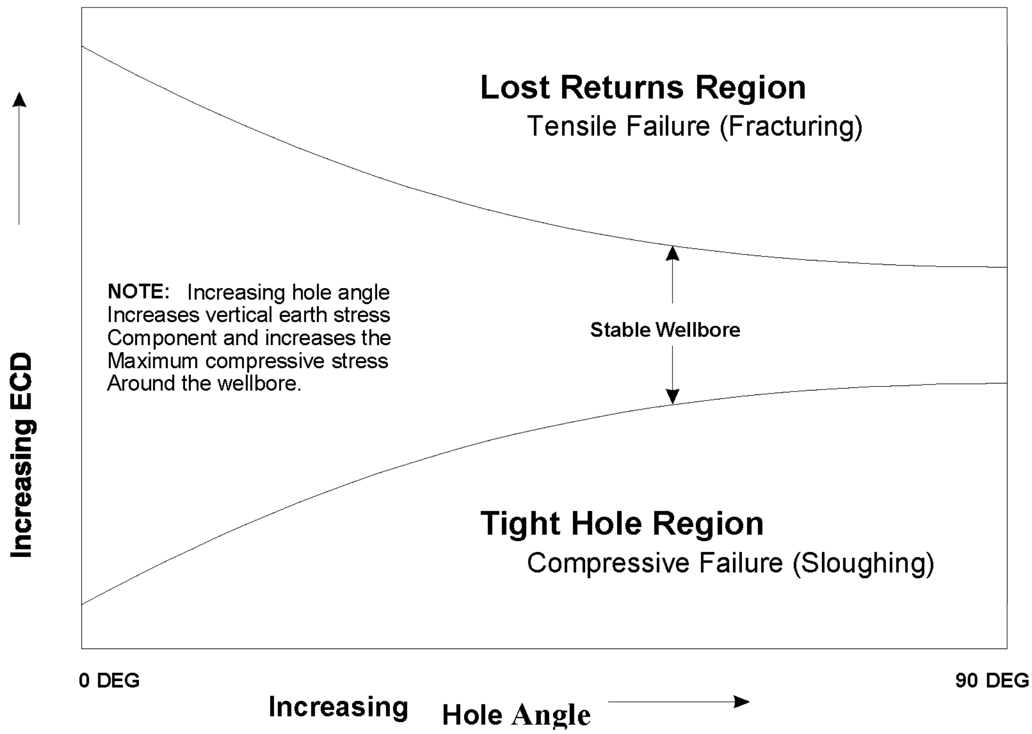


Figure 2.23. Wellbore Stability vs. Hole Angle (Baker Hughes, 1999)

2.6.8. Drilling Fluid Selection and Conditioning. One of the most important factors that contribute wellbore stability is optimal drilling program. The selection of the drilling fluid properties often relies on the lithology of the formation. There are various base fluids like water-base mud, oil-base mud, and synthetic mud, each one of them usually uses for specific formation lithology and minerology. Equivalent circulation density has a direct relationship with drilling mud characteristics. The two greatest drilling mud properties, which influence on equivalent circulation density, are yield point (τy) and drilling density. By increasing yield point, gel strength, mud weight that will lead to maximize ECD, which in turn may cause lost circulation mud. Hence, it is essential to prepare good drilling program that properly perform their functions like good hole cleaning, support wellbore wall, maintaining solids suspension, and good control for equivalent circulation density to avoid several bad consequences. It is prudent to maintain and monitor solids content in the drilling fluid continuously because that will reflect positively on the wellbore stability. If solids content increased above (5%) that will lead to increase pressure losses into annulus and maximize equivalent circulation mud that in turn cause to initiate fracture and lost circulation mud, therefore; it is crucial to maintain solids content into drilling fluid less or equal to (5%). Good drilling properties will help maintain uniform hole size, or keep the well in gauge. One of the most significant factor which contribute to success remedies of the lost circulation materials is knowing the exact hole volume. A caliper log may be run to detect the hole volume otherwise the hole is generally assumed to be in-gauge. This assumption will affect negatively on the placement of lost circulation pills and LCM material

"Oil or synthetic fluids (OBM or SBM) are usually much more expensive than water base fluids. Nevertheless, the OBM /SBM fluids generally provide the best overall drilling results for a number of reasons, including" (Baker Hughes, 1999):

- Shale control.
- Lubricity.
- Resistance to contaminants.

The kind of base fluid has a pivotal role on the lost circulation mud. Oil or synthetic based fluids (OBM or SBM) tend to aggravate mud losses and these results have already been concluded in oil industry. In addition, numerous reports that have been demonstrated lost circulation mud occurs more easily with OBM / SBM and that the size of the mud losses are significantly larger. As well as, mud losses remedies for OBM/SBM systems are more complicated and more difficult than WBM. There are theoretical studies and practical observations which have already been proved that lost circulation mud in OBM / SBM systems is seemed to be exacerbated and complicated more than WBM system in terms the size of the losses and corrective remedies (Baker Hughes, 1999).

2.7. METHODS OF AVOIDING LOST CIRCULATION

Controlled field methods may be used to inhibit or recover from lost circulation. These methods are fundamental techniques and simplistic mechanisms to avoid or combat mud losses (South Oil Company, 2007). These approaches include:

- Waiting Method:

1- Pull out drilling strings to casing shoe.
2- Waiting period between (4-8) hours.
3- Drilling strings will gradually run in hole.
4- Circulation drilling mud and rotation drilling string slowly.
5- Check mud levels in mud tanks system to make sure there is no mud losses.
6- Starting drilling operation at moderate speeds in order to seal formation apertures by engraved cutting.

- Reduction of the Pump Pressure: This technique usually uses when mud losses is partial losses. By reduction the pump pressure that lead to decrease extra pressure due to mud circulation.
- Reduction of the drilling mud density: By decreasing mud weight within allowable limits in order to reduce hydrostatic pressure on the weak formations. Drilling fluid density is usually minimized by adding water or diesel oil.
- Increasing of the drilling fluid viscosity: This mechanism often uses during drilling shallow, unconsolidated, and high permeability formation like (loose sand and gravel). It better to magnify viscosity (yield point and gel strength) to prevent mud losses by sealing high permeability. Drilling fluid viscosity is usually maximized by adding bentonite, lime, salt clay, or gypsum.
- By Using Bit without Nozzles: The benefit from this issue to just reduce jet velocity due to nozzles.
- If drilling operations are under shutdown situation, it is the best to rotate drilling strings about 15 minutes without mud circulation when drilling operations resume in order to break gel strength.

- Stabilizers should not be used during drilling depleted or weak formations.

  Lowering drill strings into wellbore slowly in front of unconsolidated zones.

  Some of these methods are shown in Figure 2.24 along with the formations where they are best applied.

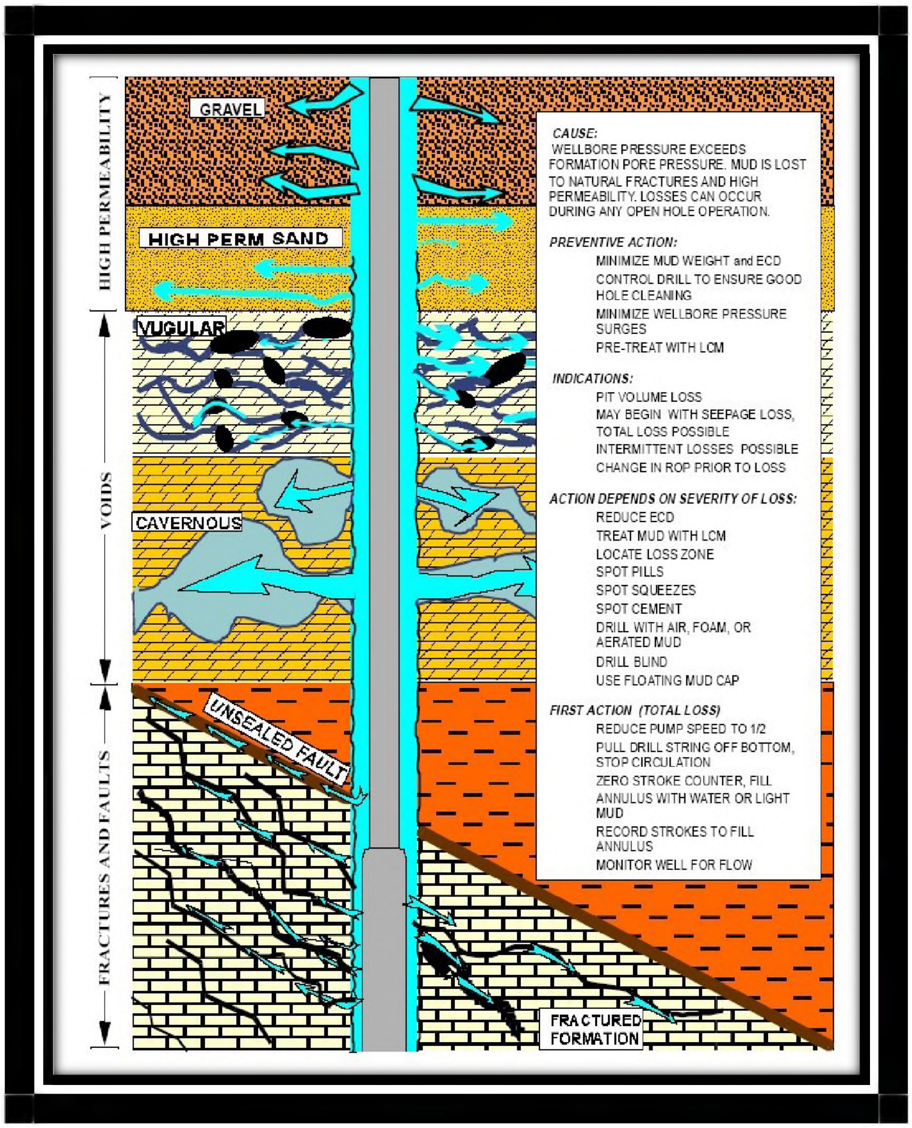


Figure 2.24. Lost Circulation Mud Cases and Appropriate Treatment (Baker Hughes, 1999)

2.8. METHODS OF MITIGATING LOST CIRCULATION

This section will involve empirical studies and laboratory tests found in the literature that address remedies of the lost circulation in the various oil and gas fields around the world. Many authors and researchers used analytical and practical data from real historical cases in the different oil and gas fields in order to evaluate fluids losses to get coherent insights and integrated analysis about this problem. This section reviews experimental works and mathematical models that have already experienced in pilot tests and drilling operations sites.

In 1986, Moore pointed out that the most common treatment used to combat shallow and unconsolidated formations is high viscosity pills. This remediation can be prepared by using fresh water muds by adding high viscosity materials like bentonite, cement, and lime. In addition, He mentioned regarding zones like below surface casing in normal- pressure formations that have intrinsic fractures, the best normal method to mitigate mud losses is to drill formation without drilling fluid returns to the system mud tanks. In this case, from time to time, it is supposed to use high viscosity patches in order to remove and lift the excavated cutting from the hole and deposit them at mud losses zone. In order to use this practice in the above mentioned cases, it is required to provide sufficient amount of water, high viscosity materials and accurate surveillance to avoid encountering high drill-string torque and drag (Moore. 1986).

A study from Nayberg and Petty in 1986 shows the performance of lost circulation materials with oil-base muds. They mentioned that several conventional LCM’s work efficiently in water-base drilling muds. However, very few lost circulation materials perform properly in oil-base muds. Laboratory studies have been performed regarding the effectiveness of conventional lost circulation materials with a new material that consisted of thermoset rubber in different oil-base drilling muds. In this work, the authors used mica, modified hydrocarbons, cellulose fibers, ground walnut shells, a blend of fibers, flakes and granules, and thermoset rubber to analyze the performance of these materials with oil-base drilling fluids in combating lost returns to simulated medium-size fractured formations.

This study demonstrated that thermoset rubber-medium with ground walnut shells-coarse and a blend of fibers, flakes and granules (coarse grade) were outstanding in controlling mud loss in five oil-base drilling muds. However, all other traditional LCM's were not successful in regulating mud losses for five oil-base drilling muds. These laboratory tests also demonstrated that the extreme amount of ground walnut shells-coarse and thermoset rubber-medium should be 20 lb/bbl in certain oil-base drilling muds. In other words, it is better not to exceed this concentration in order to get an effective treatment. The authors also demonstrated that granular lost circulation materials, such as ground walnut shells-coarse and thermoset rubber-medium, occasionally exhibit a phenomenon referred to as a channeling effect. They showed that this situation usually happens due to high differential pressure, and when drilling fluids have insufficient solids concentration. This channeling effect has bad consequences producing many channels whereby mud or gas migration may move through the channels, leading to test failure. Moreover, the authors deduced that the application 2: 1 blend of thermoset rubber-medium: thermoset rubber-fine outperformed a 2:1 blend of ground walnut shells-coarse: ground walnut shells-medium were superior in the tested oil-base drilling muds (Nayberg and Petty, 1986).

In 1987, Nayberg extended his laboratory studies to identify the effectiveness of conventional lost circulation materials (granules, flakes and fibers) with thermoset rubber in regulating mud loss in simulated fractured formations by using both water-based and oil-based muds. His work demonstrated there is elegant performance by using the medium thermoset rubber and a blend of medium and fine grades of this material to regulate on lost returns whether in the fresh water-based or salt water-based drilling muds in laboratory-simulated medium-size fractures. However, various size and types of conventional LCM's (granules, flakes and fibers) failed to control mud loss for the same muds at comparable conditions. His work showed that the application of thermoset rubber and a blend of medium and fine grades of this material were superior to coarse ground walnut shells, a blend of coarse and medium grades of walnut shells, and a blend of fibers, flakes, and granules (coarse grade) in controlling mud loss in five oil-based drilling muds tested in simulated medium-size fractures. Naybger's work (1987) demonstrates the importance of the maximum concentration granular LCM's, coarse ground walnut shells and medium thermoset rubber-should not exceed 20 Ibm/bbl [57 kg/m3] in certain oil-based drilling muds. From field applications and case histories, he deduced that the use of thermoset rubber was very vigorous in mitigating and regulating severe mud losses in fractured formations (Nayberg, 1987).

Ali et al. (1994) performed laboratory tests to show and analyze the sealing efficiency of the LCM blend. This study also indicated the application and validity of this treatment in the field after it was successfully tested in the laboratory. This blend of lost-circulation materials (LCM's) used with water-based drilling fluid to drill through multiple severely depleted, unconsolidated sandstone reservoirs. The authors utilized blend of the lost circulation materials that are commercially available. The blend which used in laboratory tests and field application was composed of the following: (a) 15 Ibm/bbl [43 kg/mg3] of a fine grind of vegetable fibers/granules mixed with medium-sized polymer flakes, (b) 15 Ibm/bbl [43 kg/mg3] of a medium grind of vegetable fibers/granules mixed with medium-sized polymer flakes, and (c) 10 Ibm/bbl [28.5 kg/m3] of uniquely processed microcrystalline cellulosic fibers with particle sizes ranging from 2 to 120 mm. Their specially formulated LCM was designated 15115/10 LCM blend.

Ali (1994) notes that this blend was examined in laboratory under conditions of 1,500 psi [10 MPa], and the same mixture was used in field with as high as 1,600 psi [11 MPa] overbalanced differential pressure. In this work, they pointed out that this application used as proactive remediation before entering potential loss formations. This blend has excellent advantage in terms cost-effective by reducing the number of casing strings above expected loss zones. In addition, laboratory tests illustrated there is no damage in productive zone due to this blend, and the seal created by the cellulosic fibers of the LCM blend is partially removed with 7.5 vol% HCl or 3 vol % NaCIO solution. The authors note that this blend is effective in providing a positive, impermeable seal across severely depleted sands, if used as complete LCM blend, but it will not be efficient used as a component of the 15/15/10 LCM blend alone. Another feature for this blend of LCM is to form a good and seal barrier in the vicinity of the wellbore. In other words, this blend can be enhanced with other drilling fluids properties to achieve wellbore instability. Even though the 15/15/10 LCM blend is more expensive than drilling mud materials, this blend contributes to cost reductions such as reduced rig time, reduced mud loss, and decreasing the number of the casing strings (Ali et al., 1994).

In 2002, Pilehvari and Nyshadham showed importance of the lost circulation material (LCM) and seepage control material (SCM) to mitigate drilling mud to acceptable levels. In this study, they conducted laboratory tests by using a permeability plugging apparatus (PPA) at a differential pressure of 2500 psi and 250 F°, using ceramic disks to determine the performance of various LCM/SCM including. the impact type particle size distribution on their performance. The authors used twenty-four different LCM/SCM and blends of materials with three different types of mud (water base mud, regular oil base mud, and environmentally safe oil base mud). Their work also showed detailed explanations about experimental work, used materials, and results discussion.

Pilehvari and Nyshadham (2002) indicate that regular oil base mud has the lowest seepage losses whether with LCM/SCM or not, followed by synvert oil base mud and then water base mud. They noted addition 5 Ibs/bbl from any type of the LCM/SCM will mitigate and enhance filtration characteristics of each of the three muds. They deduced that mud type, material type, and particle size distribution have a big impact on the filtration property improvements. Their tests reported increasing LCM/SCM additives concentration from 5 Ibs/bbl to 10 Ibs/bbl effected negatively on the amount of total filtrate volume. From various experimental tests, the ideal concentration of LCM/SCM was notes as almost 8 Ibs/bbl. Fine size distribution for corncob and inner shell were more efficient than the medium and the coarse size distribution. Medium and the coarse size distribution for almond was more effective than fine size distribution. There was no impact regarding particle size distribution. Finally, they concluded from these tests that inner shell fine and almond shell coarse samples are the best performing additives in twenty-for different LCM/SCM samples (Pilehvari and Nyshadham, 2002).

Babadali and Kuru (2004) evaluated cements as lost circulation material. They note that cement is one of the most common LCMs, and different types of cement have already been used as loss circulation material. The authors indicate there some factors that determine the type of cement, e.g. l fluid type and properties, wellbore conditions, and the size and type of the thief zone. Their work noted specific types of cement applications, like thixotropic and ultra-thixotropic cement slurries; slurries containing cello flakes, mica, and CaCO3 for mechanical bridging; unique spacers and surfactant packages; and foamed cement for controlling loss. Laboratory tests and field cases are presented regarding using the cement as lost circulation remediation.

Babadali and Kuru (2004) note that various kinds of drilling mud are required to use primary cementing applications where there is a problem regarding cementing a casing string at desired depths. The case study demonstrated if using loss-control drilling mud has ability to reduce losses lesser than 3-4 m3/hour before using primary cementing, so this treatment will be accomplished effectively by using reactive flushes to control seepage into formations and lead foamed cement by lightening up the hydrostatic head of the cement. Moreover, the foam cement will assist to decrease excessive equivalent circulation density while placing the cement slurries because of its internal inherent energy. The authors note if conventional drilling mud additives will not reduce losses to less 3-4 m3/hour, cement plugs treatment should be executed before running the casing strings. If this treated zone is productive, acid-soluble cement plugs must be considered. The authors also present practical observations that spacer package pumped before cement plugs will effect placement negatively, especially with oil-base mud. This study indicated it is practical to pump effective water-based spacers before to guarantee that the zone of interest is water-wetted to allow the cement to bond (Babadali and Kuru, 2004).

Mata and Veiga in 2004 conducted a new approach to solve lost circulation problems that included cross-linked cements (CC). The main composition for CC is a combination of cement and frac products mixed as regular cement slurry in a gelled fluid. There are two kinds of this treatment, the first is a Magnesia cross-linked cement (MCC), the second is regular cross-linked cement (RCC), and each of them has specific additives to stop or mitigate fluid losses. Cross-linked cement remediation has capability to seal tentatively or permanently where there are restrictions to continue in the drilling and cementing operations because of lost circulation. Their work illustrated that MCC is especially useful in productive zones due to its high solubility (up to 98% soluble). MCC has a minor or negligible effect on the pay zones in terms permeability or plugging. RCC has less solubility than MCC which is 73% soluble. On other hand, RCC is economically effective than MCC. Moreover, MCC can be dissolved up to 98% by using HCL acid, and RCC dissolved up to 73% with HCL acid. The strong points for MCC and RCC have shown through application of traditional lost circulation materials (LCM) where each of them has disadvantage in terms inefficiency or side effect.

Based on two historical field cases in Southeast Lake Maracaibo, Venezuela and in the Neuquén basin in Argentina, the authors concluded that the application of MCC and RCC are the best to cure severe lost circulation problems in situation where there are naturally or induced fractures. The study also demonstrated that the application of this system has many excellent features. For instance, both types of cross linked cement have higher compressive strength, lesser thickening time, rigid interconnected gelled fluid, and strong plugging of fractures and lost circulation zones (Mata and Veiga. 2004).

2.9. EVOLVING LOST CIRCULATION APPROACHES

Strictly speaking, several empirical studies, Laboratory tests, and field cases have been found in the literature that address different treatments and various approaches of lost circulation in the various oil and gas fields around the world. Many of authors and researchers used analytical and practical data from real historical cases in the different oil and gas fields in order to evaluate fluids losses to get coherent insights and integrated analysis about this problem. This section will have a broad work to review experimental works and mathematical models that have already experienced in the Pilot tests and drilling operations sites. Because the mud losses is an extensive and crucial topic, so there are several theoretical studies, numerical models, laboratory researches, and field cases have been addressed in this subject to combat or mitigate it. In the same vein, lost circulation solutions may be applied before or after the occurrence of the problem. The solutions are therefore grouped into preventive and remedial respectively. This chapter highlights some of the lost circulation control methods/techniques that are used in the petroleum industry.

2.9.1. Lost Circulation Material (Remedial Measures). This section demonstrates the various lost circulation treatment materials and their application. The treatments are categorized into general groups to assist in describing the way they work and to differentiate their applications. A wide range of bridging or plugging materials is available for reducing lost circulation or restoring circulation while drilling or cementing a well (Nayberg and Petty, 1986). Each one of lost circulation material is selected by depending on type of losses, cost, and type of formation (Pilehvari and Nyshadham, 2002). Lost circulation material are used to achieve two goals (Jiao and Sharma, 1995):

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

1. High viscosity muds: Detailed description of this treatment has been covered in chapter 3 of this thesis**.**

2. Conventional lost circulation materials (LCM): These materials are used to stop or mitigate mud losses by using sufficient large particles (Granular) to form bridge in front of the largest openings of the pores or in the fracture. The second stage, by using deformable fibrous and flaked LCM material to seal loss zone. Sometimes, conventional lost circulation materials are not effective to cure vugs or induced fractured because particle size distribution, concentration, and type are not appropriate to seal vugs and created fractures, so alternative treatments should be used. Lost circulation materials can be broadly classified into the following groups (Baker Hughes, 1999).

- Fibers: It is easy for fibrous materials to be deformable because these materials are long and slender particles. These materials has ability to form" brush heap" like mat in pore openings. These materials are usually not effective treatment if they use individually. On other hand, they work best in combination with other granular and flake materials. They can be classified to short and rather weak fibers such as ground paper, wood, cane, rice hulls, peanut hulls, leather, and tree bark, or longer and strong fibers such as flax, hemp, animal hair, cotton linters, nylon, and other fibers. Finely ground cellulose fibers are often used for seepage loss control and as a pretreatment in high permeability zones. These materials are effectively cost, and it is much recommended to use these materials in pills or patches in order to cure partial to severe losses. Most fibrous materials absorb large amounts of water and increase viscosity.

- Flakes: These types of materials have large planar surfaces and are very thin, and they have possibility to form a "shingle-like" layer against pore openings. It is possible to use individually as effective treatment to combat seepage losses or partial losses, but in the same time, it is preferred to use flakes materials with fibrous and granular materials to produce blends. There are various types of materials like ground mica, plastic laminate, cellophane, and polyethylene plastic chips. Mica material has advantage as effective material for seepage losses and partial losses, and advantage of mica is that it does not absorb large amounts of free water or oil like cellophane material.
- Granules: Granules are roundish shaped particles and rigid. They have ability to form "bridging" agent that use to combat mud losses. These materials can be categorized to ground walnut shells, pecan shells, almond hells, plastic, and calcium carbonate. These materials are better than cellulose fibers regarding water absorption. In other words, they absorb less water than cellulose fibers. Other granular LCM materials frequently used in cement slurries are Gilsonite, ground coal, and calcinated shale. These materials can be used individually or with flakes, and fibers as blend. Granules materials will be more effective if they use with flakes and fibers as blend, and it is much recommended to use these materials in pills or patches in order to cure partial to severe losses.
- Lamellated: Additives with the appearance of thin layers, scales, flakes, or sheets, which may or may not have any degree of rigidity. The action of such an additive is to mat as shingles over a formation face or bridge in restrictions in a fracture.
- Dehydratable: These types of materials have ability to separate from fluids that are carrier for them, and they form rigid seal in front of formation to combat mud losses.

- Mixtures: These are combinations of granular, flaky and fibrous materials that will penetrate fractures, vugs, or extremely permeable formations and seal them off effectively. Table 2.3 will show conventional lost circulation materials (LCM).

Table 2.3. Conventional Lost Circulation Materials (LCM) (White, 1956) and (Baker Hughes, 1999)

Type	Material
Fibrous	Ground paper, Wood fiber, Cane, Rice hulls, Peanut hulls, Leather, Tree bark, Flax, Hemp, Animal hair, Cotton linters, Nylon, Cellulose fibers, Raw cotton, Bagasse, Flax shive, Bark fiber, Textile fiber, Mineral fiber, Glass fiber, Peat moss, feathers, Beet pulp.
Granular	Ground walnut shells, Pecan shells, Almond shells, Plastic, Calcium carbonate, Perlite, Coarse bentonite, Ground plastic, Nut shells, Nut hulls, Ground tires, Asphalt, Wood, Coke.
Flake	Ground mica, Plastic laminate, Cellophane, Polyethylene plastic chips, Cork, Mica, Corn cobs, Cottonseed, hulls, Vermiculite.
Mixtures	Film, fiber and sawdust; Textile fiber and sawdust; Cellulose fiber and sawdust; Perlite and coarse bentonite.

Figure 2.25 illustrates a summary of the evaluation tests for various sizes and types of the lost circulation mud in order to determine the effectiveness of these LCMs regarding seals forming. This compilation indicates that the most effective materials for plugging fractures and withstanding high pressure differentials are the granular type (Howard and Scott, 1951).

Material	Type	Description	Concentration (lb/bbl)	Largest Fracture Sealed (in.)
				0 .04 .08 .12 .16 .20
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	3/4-in. flakes	8	
Sawdust	Fibrous	1/4-in. particles	10	
Prairie hay	Fibrous	1/2-in. fibers	10	
Bark	Fibrous	3/8-in. fibers	10	
Cotton seed hulls	Granular	Fine	10	
Prairie hay	Fibrous	3/8-in. particles	12	
Cellophane	Lamellated	1/2-in. flakes	8	
Shredded wood	Fibrous	1/4-in. fibers	8	
Sawdust	Fibrous	1/16-in. particles	20	

Figure 2.25. Summary of Lost-Circulation Material Tests (Howard and Scott, 1951)

3. Super stop material: Detailed description of this treatment will be covered in chapter 3 of this thesis.

4. High filtration spot pills: High filtration drilling mud is used in order to seal loss zone. The principle of work for this treatment is by passing water into formation, and solids content will form seal in front of thief zone. Figure 2.26 illustrates this treatment. There are three types of this method (Eni Company, 2010):

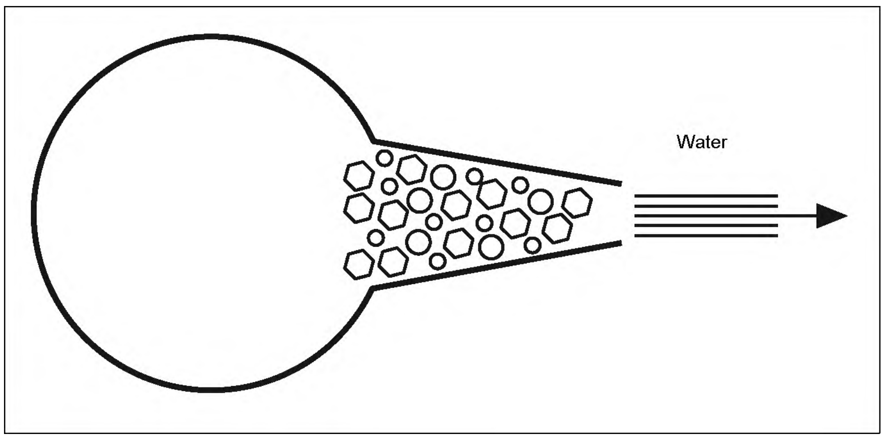


Figure 2.26. High-fluid-loss-squeeze Technique for Lost Circulation (Eni Company, 2010)

- High filtration mixtures (200-400 cc API)

Procedure formula for 1 m3 (final) of high filtration mixtures

Attapulgite	3 - 6 %
Bentonite	1.5 - 6 %
Lime	0.15 %
Diatomite	15 %
Mica	1 – 1.5 %
Granular LCM	1.5 – 2.5 %
Fibrous LCM	0.3 – 1 %

This treatment will be pumped in front of loss zone, and it is preferred to do squeezing during displacement under pressure (50-150 Psi). Waiting period should be around (± 4-6 hours).

- Very high filtration mixtures (> 600cc API)

Procedure formula for 1 m3 (final) of very high filtration mixtures

Diatomite	30 %
Lime	15%
Attapulgite	0-4 %
Granular LCM	1 – 2.5 %
Fibrous LCM	1 %
Lamellar LCM	1 %

This treatment will be pumped in front of loss zone, and it is preferred to do squeezing during displacement under pressure (50-150 Psi). Waiting period should be around (± 4-6 hours).

- Diaseal M (> 1000 cc API)

Procedure

Formula for 1 m3 (final) of Diaseal M

Density gm/cc	Diaseal Sack	Barite Ton	Water m3
1.08	6	0	0.9
1.45	5	0.2	0.8
1.80	4	1	0.7
2.15	3	1.5	0.6

This treatment will be pumped in front of loss zone, and it is preferred to do squeezing during displacement under pressure (50-150 Psi). Waiting period should be around (± 4-6 hours).

5. Gel – cement: This plug is used to reduce time of the cement hardness and to create high viscosity of cement dough by adding bentonite material to cement which strongly contribute to seal loss zone and it also increase resistance of the cement (Eni Company, 2010).

Procedure

Slurry Composition
(Class G Cement)

Bentonite %	water weight%	Y.Slurry L/100 kg	Density gm/cc
0	44	75.7	1.90
2	84	116.5	1.60
3	104	136.9	1.51

This blend is prepared in special tank, and it should be mixed effectively in order to be more homogenous. After that, it should be displaced in front of thief zone. This plug is executed in the same way for cement plug. Waiting period is (8 hours).

6. Gilsonite cement. The principle of work for Gilsonite cement is exactly the same in Gel-Cement plug. There is just on difference by using Gilsonite material instead of bentonite material. Gilsonite material is more effective than bentonite material, and this plug is often used in cavernous formations (Eni Company, 2010).

Procedure

Slurry Composition
(Class G Cement)

Gilsonite %	water weight%	Y.Slurry L/100 kg	Density gm/cc
0	44	75.7	1.90
50	61	139.5	1.51
100	78	203.2	1.37

It has exactly the same execution procedure for cement plug. Waiting period is (8 hours).

7. DOB squeeze (diesel oil + bentonite): Detailed description of this treatment will be covered in chapter 3 of this thesis.

8. DOBC squeeze (diesel oil + bentonite + cement): Detailed description of this treatment will be covered in chapter 3 of this thesis.

9. Cement plug: Detailed description of this treatment will be covered in chapter 3 of this thesis.

10. Barite plug: Detailed description of this treatment has been covered in chapter 3 of this thesis.

11. InstandSeal: This treatment is one of the most important and more successful treatment that use to combat lost circulation material. It is emulsion that has a big ability to form high viscosity and high gel strength after arriving in front of formation. This emulsion has already proved its success in high temperature. The most important feature in this emulsion is controlling on the hardness time. In other words, it is possible to be time of the hardness from few minutes to many hours. We can regulate on the hardness time for this treatment by increasing or decreasing concentration of this emulsion and by controlling on pumping rate. It is possible to pump this emulsion by drill strings (Bit and other Accessories), and this will contribute to reduce non-productive time (NPT) and minimizing cost of drilling. After pumping this emulsion to wellbore, the hardness and gel strength will stay for many weeks under well conditions. It is much recommended to make prior preparation for this treatment before expected occurrence for mud losses (Eni Company, 2010).

Advantages for this treatment:

- Low solid content.
- It is possible to pump this material by drill strings.
- Controlling on the hardness time from few minutes to many hours.
- It is possible to prepare this treatment before weeks.

- It is compatible with all types of the drilling mud.
- There is no need to use lost circulation materials.
- It is easy to break high gel strength by using weak acid.
- It contributes to reduce non-productive time (NPT) and minimizing cost of drilling.
- Very high efficiency to cure lost circulation mud.

Application of this treatment:

- It is used to stop severe and complete losses.
- It is possible to work in high temperature 190 F° (89 C°).
- Higher density that is allowable to use with this emulsion is 1.44 gm/cc.

This emulsion has two phases:

1. Aqueous phase: It has high concentration of polymer.
2. Oil phase: It has particles with a hyperlink.

When this emulsion goes out from bit and it lowers in front of loss zone, its particles interrelate with aqueous phase that in turn lead to form high gel strength in high speed. The hardness time can be regulated in surface, but after this emulsion enter formation, we cannot control on the hardness time. Figure 2.27 will illustrate this treatment.

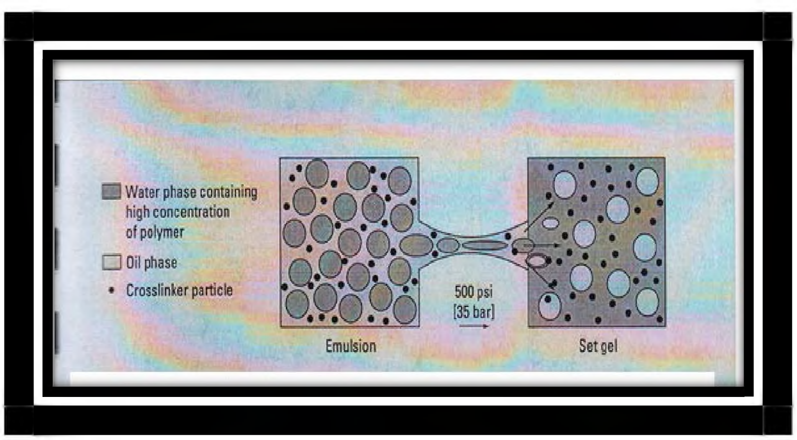


Figure 2.27. Composition of the Emulsion and How It Harden (Eni Company, 2010)

This emulsion has already been used in the Middle East in Shuaiba formation. This zone is very critical. Shuaiba formation in one of the fields in the Middle East had mud losses around (400 bbl/hr), after pumping (75 bbl) of emulsion (InstanSeal) in front of loss zone, the losses were reduced and drilling operation is resumed. Figure 2.28 will clarify the hardness time of the remedy.

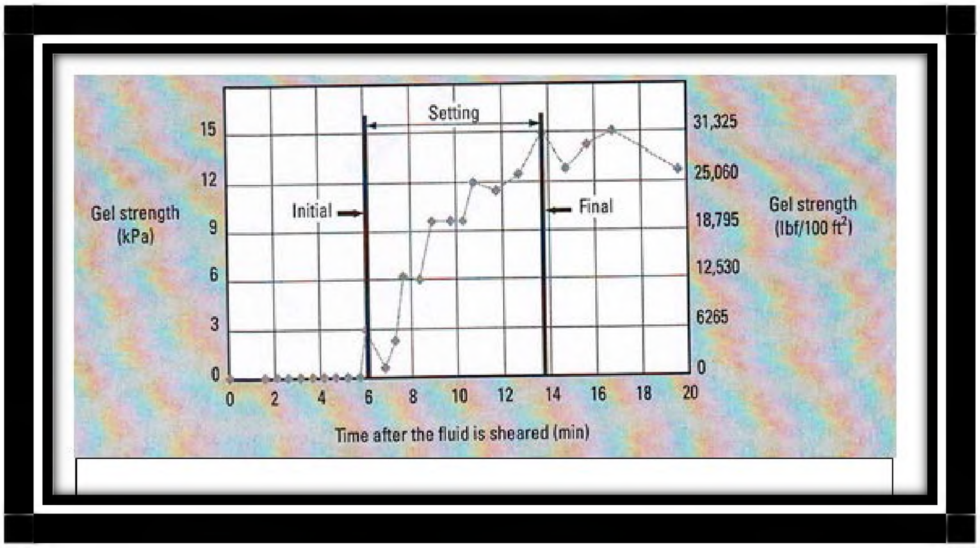


Figure 2.28. Illustrates the Hardness Time of Emulsion during Its Lowering from Drill Strings (Eni Company, 2010)

12. Fibers in cement: This plug is prepared by mixing lost circulation material (Fiber) with cement in specific and homogenous proportions in order to restore and combat lost circulation mud. These plugs have already been implemented by Shulmberger Company in Indonesia (Duri Field), and it was very successful. The principle of work for this plug is by forming synaptic situation for cement with fiber in front of thief loss. In different words, it is very difficult to enter cement into formation, and it guarantee to stay cement in front of loss zone. This plug works under any temperature, and the required lost circulation material which need to mix with cement is (30 Ib/bbl), figure 2.29 will show synaptic situation for cement with fiber in front of thief loss (Shulmberger, 1999).

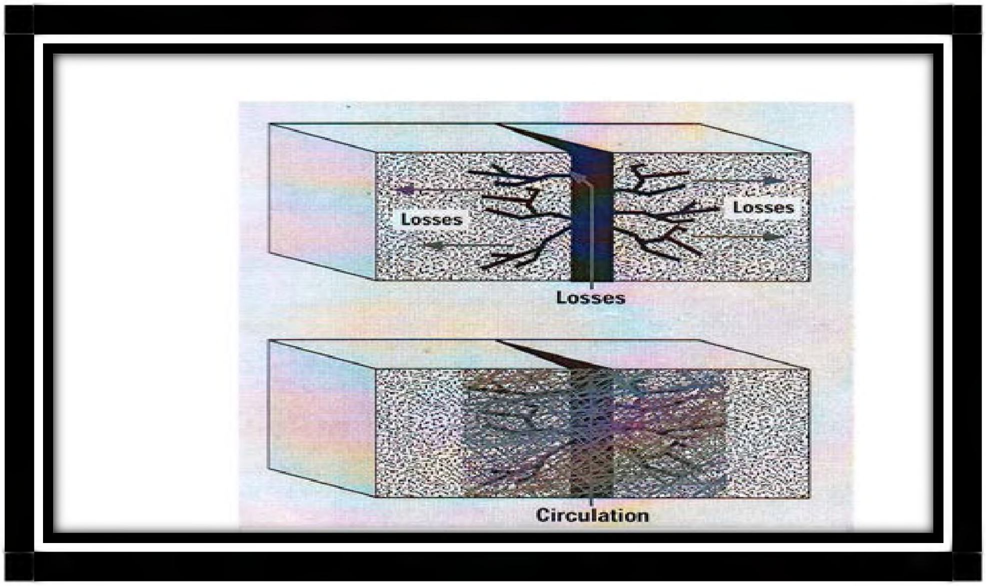


Figure 2.29. Shows Synaptic Situation for Cement with Fiber in front of Thief Loss (Shulmberger, 1999)

13. Plugging materials: There are specific lost circulation materials which use as plugging material while Circulation. LCMs that can be used are (Eni Company, 2010):

- MICA: is a silica-base lamellar material. It is used to prepare pills with oil-base, synthetic-base and water-base muds. This material is common and effective because it has some positive points like:
- It is readily available and can easily be added to LCM pills, or in circulation as a preventer.
- Granulometry varies from fine- coarse, with particle sizes from 2-3 mm for fine up to 4-6 mm for coarse.
- Mainly used to control seepage and partial losses especially in highly permeable sandstone.
- Nut plug: Is a granular material with vegetable base (nutshells). It is used to prepare pills with oil-base, synthetic-base and water-base muds.
    - It is readily available and can easily be added to LCM pills.
    - Classified into three categories: Fine – Medium – Coarse with particle size from 0.15 to 0.5 mm for the fine type; from 0.5 to 1.6 mm for medium; from 1.5 to 6 mm for coarse.

  - Used to control partial or total losses in fracture formation and/or in micro fractures. This material can also be used in combination with other plugging materials.
- $CaCO_3$: Is one of the most valid and adaptable lost circulation materials. It is a granular occurring, ground rock. It is used to prepare pills with oil-base, synthetic-base and water-base muds.
  - It is readily available and can easily be added to LCM spot pills in high concentrations. It can be added in circulation as prevention.
  - Granulometry is divided in Fine – Medium – Coarse categories, with particle sizes of 0.05 mm for the fine type, 0.1 mm for the medium, 3 mm for coarse and super coarse > 3 mm.
  - The fine and medium types are used to control seepage and partial losses. The medium, coarse and super coarse types are used for partial and total losses in fracture formation and/or in micro fractures (Carbonates). This material can also be used in combination with other plugging materials.
- Magma fiber: Is a material acidizable with hydrogen chloride and could be in reservoirs. It is fibrous and very adaptable. It can be used as an additive for oil-base, synthetic-base and water-base muds.
  - It is non-damaging inert material that forms a good filter cake panel.
  - In concentration of 30 Ib/bbl, it is used to control total losses; it also can be used to spot pills or as mud additive for prevention. In concentration between 5 and 15 Ib/bbl it is used for seepage and partial losses.
  - It is used to plug highly permeable unconsolidated formation and all kinds of fractures.

2.9.2. Wellbore Strengthening (Proactive Approaches). Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al., 2005). All those remedies/techniques that are applied prior entering lost circulation zones in order to prevent the occurrence of losses can be defined as proactive methods. The overall objective of this method is to strengthen the wellbore (Withfill, 2008). The concept of wellbore strengthening can be defined as "a set of techniques used to efficiently plug and seal induced fractures while drilling to deliberately enhance the fracture gradient and widen the operational window" (Salehi and Nygaard, 2012). This approach depends on propping or sealing the fractures using LCM's (Salehi and Nygaard, 2012). The main advantage of using wellbore strengthening is to increase the fracture gradient of the formation and the hoop stress. This provides an opportunity to use higher mud weight windows for drilling, especially, weaker and depleted formations. In different words, by using wellbore strengthening approach, the range of the mud weight window will increase. Wellbore strengthening methods generally use in order to get the following targets (van Oort et al., 2009):

- Enhance the near-wellbore stress by increasing hoop stress, thus raising the threshold for fracture re-opening and growth.
- In order to increase the design range of the mud weight window.
- Increase the formation's resistance to fracture propagation.

In this section. We are going to mention proactive approaches that have already been used to increase wellbore strengthening and some case histories.

1. Plug forming assurance technology: In 2011, Wang conducted a detailed study regarding plug forming assurance technology. One of the most important factor that largely contribute to combat lost circulation mud whether in natural fractures or induced fractures is determination the size and dimensions of the fracture. Most conventional LCMs are failed due to unknown geometries that in turn, lead to waste money and non-productive time. In this paper, unique method will be introduced which has been successfully applied in the field. This technology is applied using two components:

highly compressible and permeable foam rubber-like polymer chunks or foam wedges with a high fluid loss particle formula. Foam wedges material has excellent advantage due to the unique deformation properties that allows the foam wedges to be compressed and forced into openings of different sizes and shapes. As result, by using this material, there is no need to know the shape and size for fractures. In addition, foam wedges will form permeable bridge in order to carry fluid of the fine particle-laden high fluid loss pill. The second component consists of high fluid loss fine particles will form a plug within the filtration bridge. Hence, by using these two components, fracture and vugs will be treated without unknown geometries. It is very important to provide high pump rates regarding the displacement of this method in order to be more successful. By appropriate selecting for foam wedges, this technology can be applied many kinds of mud losses. It is very easy to select suitable foam wedge since one size of this material will be appropriate for many various sizes and shapes of openings. PFA technology that will describe in the subsequent paragraphs is used to prevent lost circulation problems (Wang, 2011).

1. Using new plug forming assuring technology for wellbore strengthening: This technique has already been proved in the field regarding wellbore strengthening approach (as preventive method). Actually, two components are required to success this technology. The first one is many small pieces of specially designed, open cell, foam rubber-like chunks, or foam wedges. Figure 2.30 shows some of these foam wedges. The second component consists of many micron-sized particles that can enter very small openings and promote a high fluid loss.

Figure 2.30. Wedge Foam (Wang, 2011)

- Foam wedges – “One size fits many”: Strictly speaking, foam wedges has a prominent role in the plug forming assuring technology regarding guarantee the sealing of unknown geometries of the fractures and vugs. The features of this material such as highly compressible and very rubbery or resilient have pivotal role regarding foam wedges success. Foam wedges material has excellent advantage due to the unique deformation properties that allows the foam wedges to be compressed and forced into openings of different sizes and shapes. Furthermore, foam wedges have ability to conform to the shape of the opening and supply a good fit although the opening may have a very various shape or size. Due to this “one size fits many” property of the foam wedges, unknown geometries for fractures and vugs will not be obstacle in order to prevent lost circulation mud. There are various sizes of foam wedges like less than 3 mm, 10 mm, and 25 mm, and these various kinds of sizes will provide a big possibility to seal a large range of fracture openings.
- Foam wedges – form an internal filtration bridge: Foam wedges has very high compressibility that readily contribute to be placed inside a smaller fractures or vugs. Experimental works have already been performed on slurry with the foam

- wedges for sealing up to 3 mm against a disc with slots of 1 mm, 2 mm, and 3 mm in width (Figure 2.31). The lab tests point out that at a high flow rate, the foam wedges can easily pass through. On other hand, foam wedges has potential to block all slots and enable a filter plug to form on the foam at a low rate.

Figure 2.31. Filter Disc with Different Slots (Wang, 2011)

In the field applications, it is recommended to use appropriate pump rate for foam wedges in order to get a good result. Each phase requires specific pump rate. For instance, a high pump rate can be used to drive them into smaller subterranean openings to overcome the resistance or dragging force from the wall. On other hand, the high permeability of the foam wedges enables the majority of the carrying fluid to flow through the foam wedges by using low pump rate. Plainly, it cannot rely on the first component (Foam Wedges) to form a seal directly because foam wedges just contribute to build a filtration bridge due to their high permeability. This material has ability to have permeability equal or higher than 10 Darcy. Hence, this high filtration bridge will supply provides a plug forming assurance for the second component of the technology.

- High fluid loss slurry–plug forming inside openings: This second component will be integral with the work of the first component. It is possible to mix high fluid loss fine particles with water or base oil. This component is originally designed to have an enormously high fluid loss. Figure 2.32 illustrates forming a plug with an API fluid loss cell at a 100 psi pressure differential requires approximately 30 seconds.

Figure 2.32. High Quality Plugs Formed by Filtration (Wang, 2011)

After the second component is pumped into the openings that have already treated with foam wedges, the particle slurry then will rapidly begin to create a filter plug on the foam wedge filtration bridges, even under a small pressure differential. These particles can be so fine that they can enter large or small openings rather than block the entrance. Figure 2.33 shows results from a lab test; a varied size of a gap was formed by a tube inside a fluid loss cell (left), and the gap is uniformly sealed by a filter plug by the fine particles regardless of the width of the gap (right).

Figure 2.33. Lab Apparatus Showing a Particulate Plug Seal Forming in a Gap that has a varied Size (Wang, 2011)

- Squeeze to gain enough strength: Experimental results show that squeeze is very necessary to high fluid loss pill. In other words, high pressure for this technology is fundamentals in order to achieve strength after forming a plug by squeeze. There is no strength without formed plug. Figure 2.34 indicates that the plug is stronger when additional squeeze pressure is applied to pack the filter plug tighter. From this figure, we can demonstrate the importance of pressure squeeze on the success of this technology.

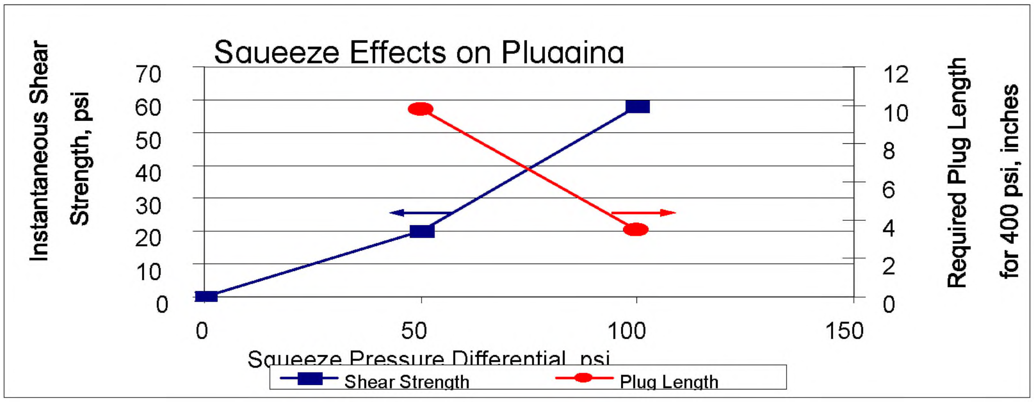


Figure 2.34. Lab Test Results for Plug Strengths under Various Pressure Differentials and Related Plug Lengths for 400 psi Parallel Fracture Extrusion Resistance (Wang, 2011)

- Squeeze to monitor progress and customize the plug for the required wellbore strength: In order to guarantee the plug forming assurance from the foam wedges, squeeze mechanisms should be applied. The so-called hesitation squeeze method is an ideal squeeze technique. This method can supply a good control to form the plug and monitor the squeeze progress. In short, Figure 2.35 illustrates the main steps and the work principle of the plug forming assuring technology. Foam wedges are pumped into the openings to form a filtration bridge on which the high fluid loss slurry will deposit its fine particles to form a filter plug that is impermeable to mud. An additional increase in squeeze pressure will either move the plug a little further for growing it longer or pack the plug tighter.

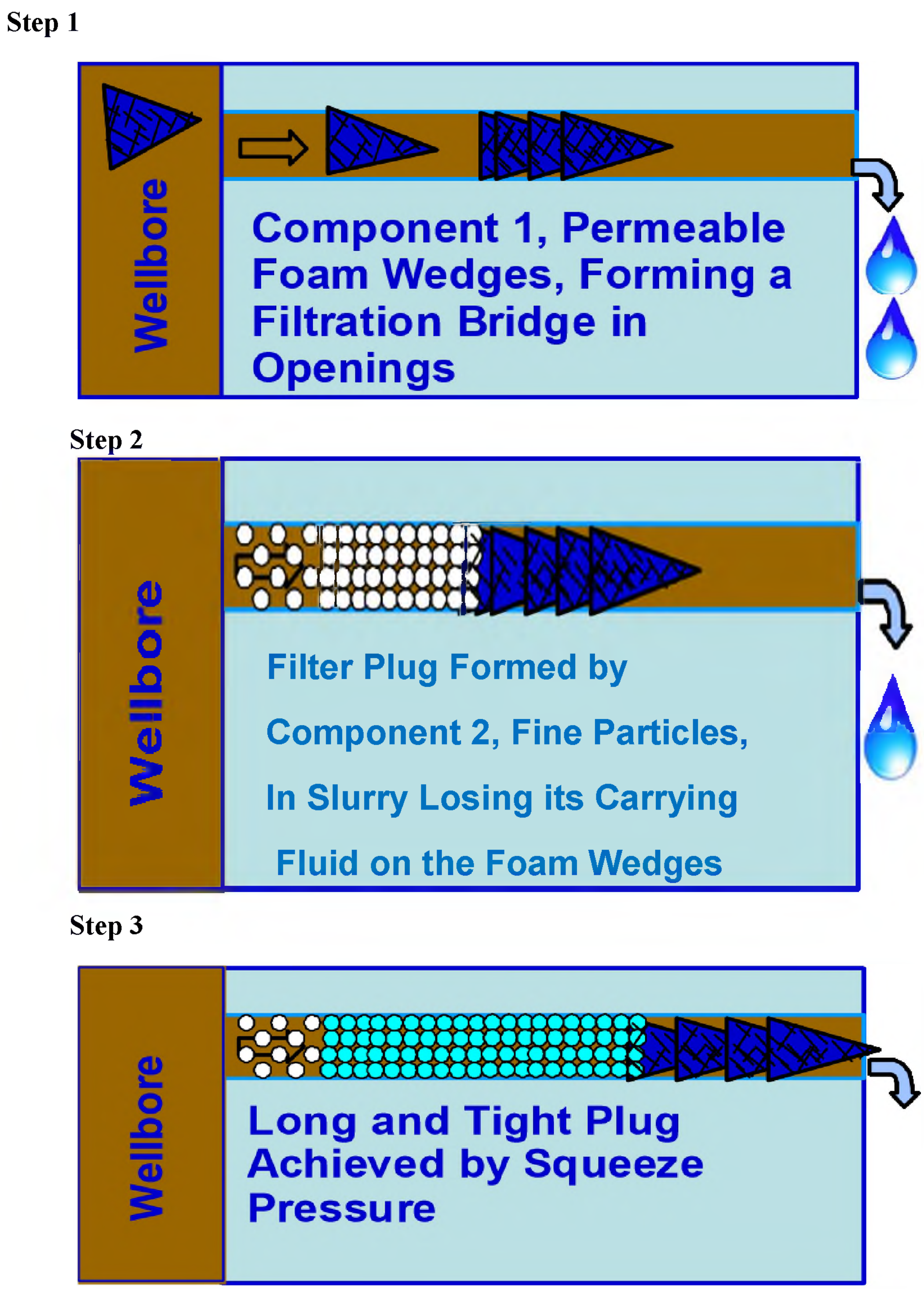


Figure 2.35. Designed Working Mechanism for the PFA Technology (Wang, 2011)

- Versatile PFA technology: Plug forming assurance technology has a wide application regarding the type of openings. In different words, PFA technology can use with various kinds of the fractures and vugs. The excellent features for this method contribute to make it highly eligible to seal the following flow paths:
  1. Natural fractures.
  2. Highly permeable zones.
  3. Rubble zones.
  4. Vugular zones.
  5. Open faults.
  6. Reef zones.
  7. Cement channels (shoe squeezes).
  8. Large perforations.
  9. Induced fractures.
  10. Breathing fractures.
  11. Multiple loss zones and multiple loss types.
  12. Cross-flows.

- Field application: It is much recommended to use two components (Foam Wedges + High Fluid Loss Particle Slurry) together. However, the two components can be used separately for simplicity in operation. A typical field application procedure consists of the following:

1. Mix foam wedges and the high fluid loss particles together with water or base oil.
2. Pump the pill downhole to cover the entire loss zone or above the zone.
3. Apply the hesitation squeeze technique to form a filtration bridge and filter plug.
4. Squeeze to the desired wellbore strength plus a safety factor of approximately 50 to100 Psi.
5. Wash through and clean out possible leftovers inside the wellbore.
6. Perform a pressure test to verify the wellbore strength, if needed.

- Field cases: In China, plug forming assuring technology has already been applied effectively in order to combat lost circulation mud in highly fractured formations. Successful applications include those deep and high pressure gas wells in northwest China. Roughly, 5000 m, gas wells have a highly fractured zone with narrow mud weight window. Drill density that is required around 2.3 to 2.4 sg. In other words, it is difficult to cure lost circulation mud. The wellbore must also be strengthened to ensure cementing quality for later gas production. In addition, Resistivity image logs from the wells in this area have shown many natural fractures penetrating the wellbore. Figure 2.36 shows a section of the logs. In this case, two components (Foam Wedges + High Fluid Loss Particle Slurry) are mixed together in saturated salt water and weighted to 2.3 to 2.4 sg to be placed in the zone, followed by a hesitation squeeze.

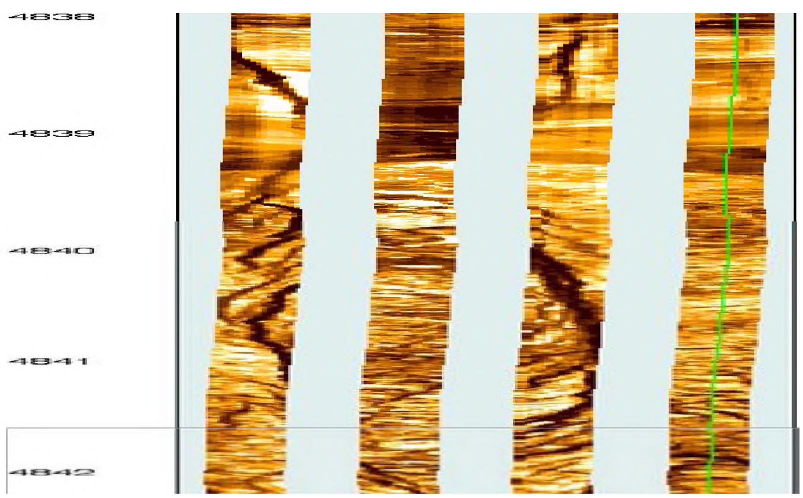


Figure 2.36. Resistivity Image Log Shows Natural Fractures Penetrated by a Wellbore. (Wang, 2011)

- Conclusions

1. It is essential to find new technology in order to cure lost circulation mud in subterranean openings, such as large pores, open fractures, and vugs.
2. In unknown geometries like size, shape, and location of multiple openings, it is difficult to use conventional particulate technologies.
3. The two major-component plug forming assuring technology, in concept, uses highly compressible and permeable sized foam wedges and high fluid loss particle slurry. It promotes the formation of filtration bridges inside those openings, then deposits long and tight filter plugs on the bridges to seal off the openings.
4. Because Foam wedges material has excellent advantage due to the unique deformation properties that allows the foam wedges to be compressed and forced into openings of different sizes and shapes, foam wedges can be "one size fits many."
5. Foam wedges has high permeability which contributes to form filtration bridges, and this can ensure long filter plugs formed by the high fluid loss fine particulate slurry.
6. It is crucial to apply hesitation squeeze with this technology in order to get a good result. Foam wedges can be placed into smaller openings by using high pump rates. On the other hand, low pump rates are used to ensure that the foam wedges engage the wall to form filtration bridges and to deposit filter plugs.
7. PFA technology can use with various kinds of the fractures and vugs. The excellent features for this method contribute to make it highly eligible to seal different types of the openings.
8. By mixing foam wedges directly with cement, this blend can be used to plug much larger subterranean openings.
9. The PFA technology has been successfully applied in the field for curing mud losses in naturally fractured formations.

2. Using wellbore strengthening approach (Stress Cage) as a cost-effective option for drilling with narrow mud weight windows (Case Histories): It is very difficult to preclude unwanted consequences for drilling operations during encountering a narrow mud weight window. Both of tensile failure and shear failure are expected to occur when a narrow mud weight window is encountered. Hence, a lot of efforts have been exerted to avoid risky problems like lost circulation, hole collapse, well kicks and stuck pipe. However, the most appropriate methods to widen the mud weight window in some cases is wellbore strengthening techniques. The main target of this approach is to increase in pressure containment for a wellbore and hoop stress by designing a particulate LCM formulation. Both numerical studies and field cases have been shown that this application is reliable and effective, and it has a pivotal role to solve the problem of narrow mud weight windows. On other hand, there are some weak points in this method that still need further improvement. This wellbore strengthening method is sometimes referred to as building a "stress cage". Experimental works and field applications have proved that high wellbore pressure can be resisted in the unconsolidated formations by using wellbore strengthening. This approach can be implemented by customizing particulate-treated drilling fluids based on formation mechanical properties as well as the stress field. The authors review the latest results on the mechanism study and general design procedures. In this paper, case histories selected from several stress cage jobs to illustrate how the technology has been effectively applied in the field (Wang et al., 2008).

- General application procedure

The application of a stress cage treatment generally falls into the following procedure:

1. Data collection.

2. Fracture modeling.

3. Mud formulation.

4. Field implementation.

It is crucial to collect sufficient data in order to build coherent engineering design. The amount of the information will rely on the complexity of the wellbore and stress field. Vertical well that is drilled in a uniform horizontal stress is the simplest case. The data required are the following:

- Young's Modulus (E).
- Poisson's Ratio (v).
- Hole size.
- Minimum Horizontal Stress (Sh).
- Needed Wellbore Pressure Containment (WPC).

By knowing basic rock mechanical properties like Young's Modulus and Poisson's Ratio, rock elastic deformation under stresses and pressure can be determined. Two ways to get these data, first method is from lab tests, and second one is derived from log interpretation with the following equations:

$$E = \frac{\rho vs2 \times [3 \times \left(\frac{vp2}{vs2}\right) - 4]}{\left(\frac{vp2}{vs2}\right) - 1} \quad (9)$$

$$v = \frac{\left(\frac{vp2}{vs2}\right) - 2}{2[\left(\frac{vp2}{vs2}\right) - 1]} \quad (10)$$

Where,

V_P = compressional velocity.

V_s = shear velocity.

ρ = Density.

By calculating vertical stress integrating bulk density log data and Poisson's ratio, the minimum horizontal stress can be calculated. In addition, the accurate value for Sh can be obtained from analyzing leak-off tests. Pressure containment values can be obtained by drilling fluid and cementing computer simulations that are routinely done in the drilling industry. After collecting these data, it is very important to make sure that these data are reasonable values. The fracture size is modeled by input the data. A fracture width will be estimated by using the computer program that builds based on the linear elastic theory and within the constraints of the model. After determining the fracture width, the program can also be used to design the particulate formulations that provide an efficient particle size distribution to seal and prop the fracture.

- Case histories: The big challenge for the drilling operations is narrow mud weight window scenarios. The most complicated situation to well designers when a narrow mud weight window is encountered in the same interval of the high collapse pressure. Actually, this case is often seen in drilling depleted formations. Hence, the best technique to face these scenarios is stress cage applications.
- General considerations**:** If the depleted zone is at the top of the hole, it is important to reduce mud density that in turn lead to reduce equivalent circulation density. In addition, it should make sure that this formation is weak. If zone is not depleted, wellbore strengthening is not needed. There are specific techniques to determine the fracture gradient of the formations like Formation Integrity Test (FIT) or Leak-Off Test (LOT). Sometimes, because of instability concerns, indirect method will be used as the pressure test. This indirect method may use a formation tester while drilling to determine the real formation pressure of the depleted formation right after it has been penetrated. After that, the decision will be made, if there is need to do the wellbore strengthening method or not. After the weak zone has been drilled, the mud system may be treated with designed particulate formulation for increasing the mud weight necessary for drilling the higher pressure deeper zones.

If it is essential to apply wellbore strengthening during drilling the weak zone which is on the top of the hole. The designed pill can be spotted and the stress cage can be "set" by pressurizing the wellbore to a designed pressure level. The patch can be swapped out with normal mud. In order to make sure that the strengthening effect has been accomplished, pressure test can be performed. After that, high drilling density can be used for the lower interval drilling. Stress cage has been done effectively in the field even though there are risks associated with this technique.

There is no question, the well strengthening method will be required if the weak zone is below a high pore/collapse pressure zone. The drilling density must be higher the low fracture strength when penetrating this weak formation in order to avoid shear failure in the above zones. Hence, the drilling fluid has to be treated with the designed particulates for strengthening while drilling. On other hand, after drilling the specific weak zone, there will be possibility to swap out the particulate treated mud with particulate free mud to continue drilling, in case there are not additional weak zones are anticipated.

It is possible to restore coarse particulate LCM by controlling on the selection of the shale shakers and circulation rates. The addition of the coarse particulate LCM can be designed also based on these data. In addition, there are new developed mechanisms that use for recovering the particulate LCM. It is necessary to take in account that a high concentration of abrasive particles in the active mud system may cause erosion for surface equipment and subsurface like downhole mud motors, mud pump liners, etc.

- Case 1. Narrow mud weight window formed by high collapse pressure and low fracture pressure in the same drilling interval: In this case, a higher pore pressure shale formation lies above a weak reservoir formation. Hence, it is required to use high mud pressure as much as possible to drill depleted zone in order to avoid wellbore instability in shale formation. Sometimes, in order to stabilize shale formation, the weak reservoir zones below shale zone will fracture. In this situation, after lost circulation mud is occurred, unwanted consequence will be associated with this case like collapse, stuck pipe and further loss of the bottom hole assembly due to the sudden drop of wellbore pressure with the decrease of the fluid level may take place. In this case, it is very complicated to cure mud losses, and there is probability to loss the hole and a sidetrack may have to be implemented. Therefore, it is prudent to find an appropriate approach to preclude these negative consequences. A drilling engineer may consider the following solutions:

- Drilling and setting the casing as close to the depleted formation as possible, then using lower mud weights to drill the reservoir section.
- Using expandable casing to isolate the high pressure shale;
- Setting a liner to isolate the shale formation.
- Using casing drilling to cope with the losses and potential hole collapse.

Above solutions also have a high risk in terms hole collapse or mud losses. As well as, high cost will be associated with these methods, and non-productive time is possible to be encountered with these approaches. In contrary, the situation will completely be different by using stress cage, or wellbore strengthening. Because it is possible to use these techniques while drilling, and it provides a means to help prevent lost circulation while drilling. However, it is necessary to be properly implemented.

Well A in the North Sea area was facing exactly the problem described above. The reservoir pressure gradient was predicted to be 8.8 ppg due to depletion. The depleted reservoir formation had a predicted fracture gradient of 14.8 ppg, however, the required wellbore pressure for stabilizing the cap rock shale was over 20 ppg. Engineering modeling based on the parameters shown in Table 2.4 resulted in an estimated fracture width of about 1500 microns due to the large pressure overbalance. Particulate formulations were designed and selected by depending on the modeling. One of the selected formulations is shown in Table 2.5. The particulate formulation comprised resilient graphitic carbon (RGC) and ground marble calcium carbonate particulates. The particulate concentrations and D50 are shown in Table 2.5, the particulate size distribution (PSD) is shown in Figure 2.37

In this well, the depleted zone was drilled by using high drilling density in order to stabilize the cap rock in the shale reservoir. In spite of the huge overbalance, the well was drilled successfully without lost circulation mud.

Table 2.4. Input Parameters for Drilling Well A (Wang et al., 2008)

Depth, ft			Stress				E		PR
			bar	g/cc	psi	ppg	bar	psi	
17095	Cap Rock - Shale	S_h	1237	2.42	17937	20.2	120	1,740,000	0.3
		S_H	1427	2.79	20692	23.3			
		S_v	1295	2.54	18778	21.1			
		P_o							
17135	Depleted Reservoir - Sandstone	S_h	907	1.77	13152	14.8	120	1,740,000	0.2
		S_H	1107	2.16	16052	18.0			
		S_v	1218	2.38	17661	19.8			
		P_o			7803	8.8			

Table 2.5. Designed Particulate Formulation for Well A (Wang et al., 2008)

Materials	Amount	D50, microns
Base mud (17.1 ppg), bbl	1.0	(Barite + clay)
RGC-1, lb	40	1180
Ground Marble 1, lb	8	600
RGC-2, lb	8	425
Ground Marble 2, lb	8	325
RGC-3, lb	8	150
RGC-4, lb	8	80

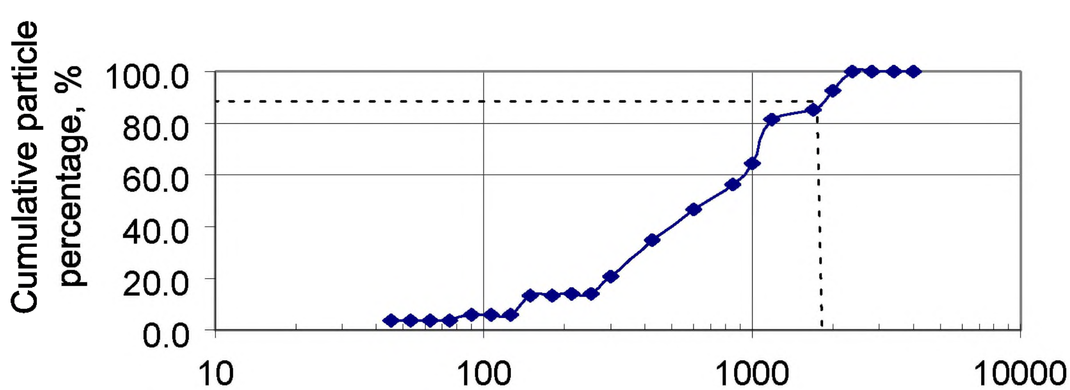


Figure 2.37. Particulate Size Distribution of the Designed Formulation (Wang et al., 2008)

- Case 2. Narrow mud weight window formed by high and low formation pressures in different layers of the same drilling interval: Well B is going to be another example that drilled in Europe by a different operator. In this well, there was zone with a highly depleted high permeability sand layer in the reservoir section due to production from a nearby well, so fracture gradient was low in this zone. In the same time, high drilling density was required for balancing the formation pressure from other less permeable layers. For this reason, it was necessary to apply wellbore strengthening application.

By using geophysicists and simulations of drilling and cementing operations, the zone characteristics and equivalent density circulation values were obtained. In addition, appropriate particulate formulation was determined by relying on the inputs with a specially coded computer software program for wellbore strengthening. The formulation is shown in Figure 2.38, which also shows the PSD for each particulate component. The d10, d50 and d90 of the composite mixture are also shown. By depending on particle size distribution, additions of new materials used to achieve wellbore stability. After this stress cage approach, the drilling operation continued without obstacles except one occurrence of mud losses. By using patch, a 2.5 m3 LCM pill with a higher concentration of the coarse materials, mud losses were cured. No further losses were observed even during cementing.

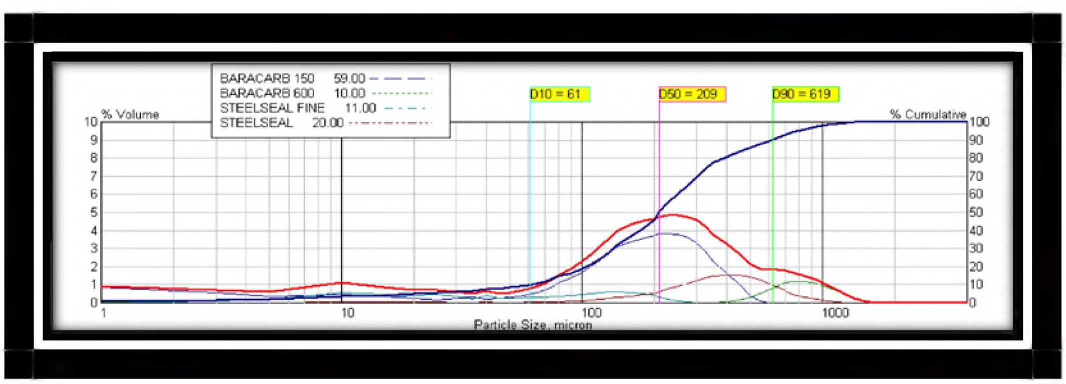


Figure 2.38. Particulate Formulation for Well B (Wang et al., 2008)

- Case 3. Engineering design process enables better engineering decisions: Another case is Well C with depleted formations. The reservoir has depleted over the years from over 17.5 ppg to about 6.5 ppg as shown in Figure 2.39 Collapse pressure for shale zone is 17.0 ppg. On other hand, the sand fracture pressure was predicted to be between 13.2 and 14.5 ppg. Therefore, wellbore strengthening approach was required for this situation. Collection and modeling for rock mechanical properties were implemented with the computer program. By using conservative parameters, the estimation of the fracture width was about 4000~5000 microns while fracture width was still about 2500 microns with a less conservative approach. At that time, wellbore strengthening approach did not execute due to the lack of appropriate particulate materials and the potential complication of the operation. Hence, other remedy was applied to drill well and prevent unwanted consequences.

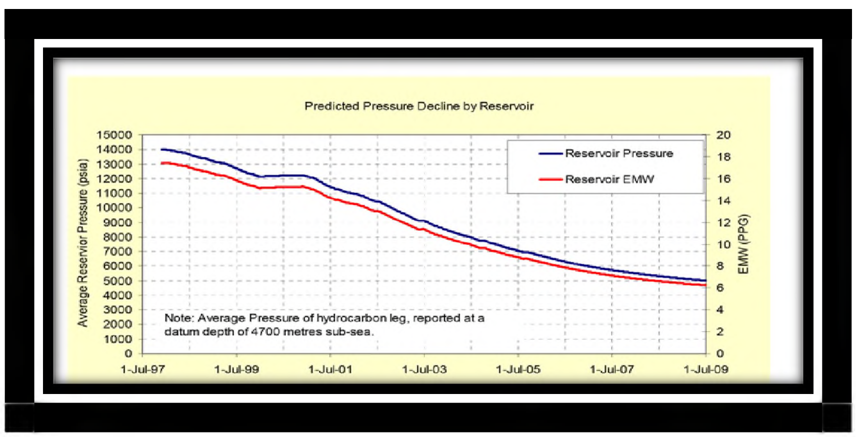


Figure 2.39. Predicted Reservoir Pressure Decline Well C (Wang et al., 2008)

- Conclusions**:** Wellbore strengthening (stress cage) has been proved that is a successful approach and cost-effective remedy. This conclusion has been drawn through both numerical studies and field applications. Stress cage is not complicated technique in terms field application, but it needs specialized engineering planning tools and materials. Numerical studies on wellbores with stable fractures show that the wellbore strengthening may be achieved by sealing the fractures. There are four required steps for the application of wellbore strengthening approach in which are collection data, fracture modeling, mud formulation, and field implementation. Case histories show that wellbore strengthening treatments has ability to solve effectively narrow range of the mud weight problems by using the wellbore strengthening techniques (Stress Cage).

3. Resilient graphitic carbon (RGC): High performance material as proactive treatment and wellbore strengthening: Resilient graphitic carbon (RGC) is one of the most successful materials in preventing lost circulation mud. Because this material has several advantage which contribute to regulate on mud losses. In different words, resilient graphitic carbon (RGG) has many unique characteristics that can be exploited in controlling on lost circulation mud. RGC contribute to impart its excellent properties like resiliency and crush resistance to other LCM combinations. In addition, this material is appropriate to use in reservoir sections because it is completely inert; therefore, RGC does not cause damage for productive zone. This paper is going to demonstrate the unique properties for RGC like resiliency, lubricity, resistance to attrition, and compatibility with downhole tools. As well, this paper includes field and laboratory data that illustrate that RGC is versatile material regarding lost circulation control and wellbore strengthening applications. The main objective of this study to exhibit the importance of LCM type, more importantly about the compressive and resilient LCM (Resilient Graphitic Carbon, RGC) and its significance in effective wellbore strengthening applications. The content of this paper can be classified into three points (Savari et al., 2012):

- Resiliency results of RGC and other LCM-RGC combinations.
- RGC for effective wellbore strengthening.
- RGC, non-magnetic and non-interactive with any downhole tools.
- Important characteristics for resilient graphitic carbon (RGC)

- Resilient, dual composition carbon- based material.
- This material has minor impact on rheological properties of drilling fluids.

- Minimum effect on down hole drilling equipment.
- RGC does not cause damage for productive zone.

- Application of resilient graphitic carbon (RGC)

- It can be used effectively in synthetic, oil-base and water-base drilling mud.
- It can be used as remedial treatment.
- For lubricity in water-base fluids.
- It is broadly applied as proactive approach.
- Wellbore strengthening applications.

- Resiliency test results for RGC

Strictly speaking, it is necessary for LCM combinations to have sufficient resiliency in order to supply good crush resistance for controlling mud losses as well as providing wellbore strengthening. RGC has excellent resilience property that in turn contribute in bearing the stresses without a big change in particle size. Figure 2.40 illustrates comparison between various materials, and it shows that RGC is the only product that exhibit higher resiliency that can be used for wellbore strengthening.

Many tests have been made to present which material has high resiliency. Various materials have been used for these tests like resilient graphite, ground marble (GM), and ground nut shells (GNS) at 500 psi and 1000 psi. Table 2.6 shows all results for these tests, and it shows that RGC was the only material that has high resiliency even at 10000 psi of loading pressure. From these tests, results can be deduced that ground marble (GM) and ground nutshells (GNS) will not be effective to achieve wellbore strengthening if they use separately. In other words, GM and GNS should be used in conjunction with RGC because resilient graphitic carbon will not just contribute by reducing the crushing but also imparts resiliency to the combination in order to provide efficient wellbore strengthening.

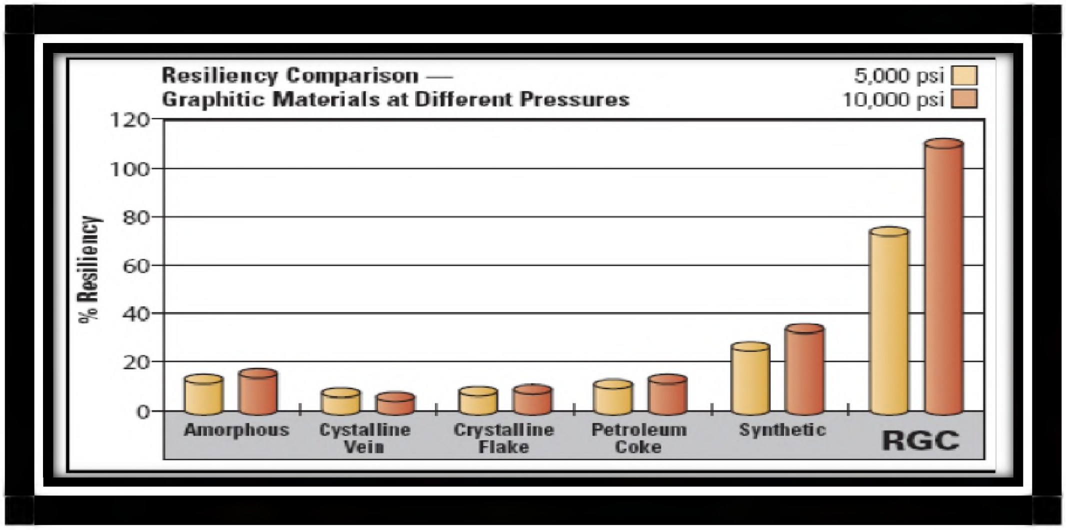


Figure 2.40. Comparison of Resiliency for Different Materials (Savari et al., 2012)

Table 2.6. Resiliency Results for Different LCM (Savari et al. 2012)

Material	Combination	Pressure	
		5000 psi	10000 psi
GM 600	100	0.0%	---
GM 1200	100	0.0%	---
RGC 100	100	48.4%	61.4%
RGC 400	100	69.4%	114.0%
RGC 1000	100	69.4%	114.0%
WALNUT - M	100	16.1%	---
CPC 100 (China)	100	12.2%	12.2%
CPC 400 (China)	100	12.2%	12.2%
CPC 1000 (China)	100	12.2%	13.0%
5018-S	100	41.7%	48.4%
5020-L	100	41.7%	52.2%
RGC 400 Exp - High Resilient	100	97.0%	153.8%
RGC Powder	100	11.5%	12.2%

- RGC: A cornerstone in effective wellbore strengthening: Joint industry project in 2000 (GPRI 2000) have been made many tests in which demonstrate that RGC has a high efficiency to seal fracture. As well, these repeated testes showed that RGC was more effective when it used with in conjunction with other materials that were ineffective on their own. The unique properties for RGC LCM is resiliency, a compressive property allowing it to "mold" itself into the fracture tip, promoting screen-out. As well, this material has advantage to be "rebounds" after pressure is released in order to plug the fracture. Due to these above mentioned properties, resilient graphitic carbon is one of the most effective lost circulation materials for both pre-treatments to aid in preventing mud losses and to treat lost circulation mud after occurrence.
- Case history 1. Depleted limestone reservoir (H06116): Drilling the 8 ½" hole that has high pressure Thamama III formation required a largely high drilling density. In the same time, there is depleted limestone reservoir below high pressure formation, so to avoid collapse and tensile failure, the drilling mud is treated with 10 ppb RGC lost circulation material, 3 ppb oil coated fiber lost circulation material and 5 ppb both medium and fine sized calcium carbonate before drilling the depleted zone in order to provide wellbore strengthening and increase the range of the mud weight window. Therefore, the hole was penetrated with up to 2200 psi overbalance without any mud losses.
- Case history 2. South Louisiana well, drill and slide: The problem was an inability to slide while drilling horizontally in South Louisiana. Hence, the decision was made to utilize RGC 40 Ib/bbl sweep. A 50 bbl pill allowed drilling to continue without adverse on MWD tools or mud motor.
- Case history 3. Depleted sand (H06116): During drilling in a highly depleted sand formation, seepage losses were occurred. After using a 40 bbl pill containing 40 ppb of RGC 100 lost circulation material was spotted, the mud losses completely ceased. As well, there was a reduction in torque due to RGC material. A second patch of RGC lost circulation material was pumped on bottom after the hole was drilled; therefore, there were no mud losses associated with casing running.

- Case history 4. North Sea depleted reservoir: In this case, high drilling density was required to drill the cap rock shale over 20 ppg. In the same time, the reservoir pressure gradient was predicted to be 8.8 ppg with fracture gradient of 14.8 ppg. For this reason, particulate formulations containing RGC and ground marble were formulated and used. As result, the depleted zone was drilled with the required high mud weight without mud losses.
- Case history 5. Narrow mud weight window in Europe: Because of production from an adjacent well, there is a well that had a highly depleted high permeability sand layer in the reservoir. As result, this depletion resulted to reduce formation fracture gradient below equivalent circulation density (ECD). After doing modeling to estimate the width of the fracture, the formulation was consisted of two grades of RGC and two grades of ground, size marble with a composite d50 of 209 and a d90 of 619 microns; therefore, the interval was drilled without mud losses.
- RGC: Inert, non-interactive with downhole tools: As mentioned earlier, RGC is manufactured by proprietary furnace process where the base material is subjected to temperature around 2200 C° - 3000 C° in order to remove all the impurities and impart graphitic properties. After that, RGC will completely be inert. In different words, RGC will not affect on the drilling fluid properties or with any magnetic-sensitive downhole tools. In related development, test has been made on the sample the drilling fluid that divided into three parts. The first part is without RGC, and the second one is treated with 4 Ib/bbl of RGC. The third part was containing 8 Ib/bbl. The average neutron count on all three sample, and it was almost the same. Table 2.7 that resulted from the test was proved that RGC is really an inert and non-interacting material.

Table 2.7 Sigma Chamber Test Results on Neutron Count (Savari et al., 2012)

summary	Avg counts per 10 seconds	std err	% change
12.5 ppg Barite w/ No RGC	8766	4	-
12.5 ppg Barite w/ 4 lb/bbl RGC	8765	6	0.0%
12.5 ppg Barite w/ 8 lb/bbl RGC	8687	10	-0.9%

- RGC: A non-magnetic material: Due to the high temperature manufacturing and graphitization process, RGC is inert and non-magnetic material. As well, RGC will not interact with downhole magnetic-sensitive tools. Figure 2.41 illustrate that RGC is indeed non-magnetic.

Figure 2.41. RGC with a Strong Magnet, Showing the Non-Magnetic Nature of RGC (Savari et al., 2012)

- Conclusion

- It is much recommended to use material that has compressive and resilient properties in LCM combinations for wellbore strengthening applications in order to provide effective approach.
- RGC has ability to impart its properties to combinations of RGC and non-resilient materials.
- Some case studies and experimental results have been proved that RGC is successful and effective materials in terms proactive approaches and remedial treatments.
- RGC has a big role to widen the range of the mud weight window and wellbore strengthening techniques.
- Laboratory tests have been shown that RGC is inert material, and it has a minor impact on drilling mug rheology and equivalent circulation density (ECD).
- It is possible to use RGC material in order to decrease downhole torque and drag.

4. Nanoparticles technology: This treatment is a blend of organic and inorganic component with particle range of 1 to 200 nm. By mixing nanoparticles with drilling fluid, bridge will be built among the grains and bond them together. Hence, zone will be consolidated with passed time. This remedy will be displaced by using low viscosity fluid (Soroush and Sampaio, 2006). This approach has ability to form a tough, dense filter cake and sealing micro cracks in zones resulting in a significant impact on wellbore stability in which turn reduces lost circulation mud. Silica nanoparticles has pivotal role to achieve wellbore stability during drilling shale formation (Friedheim et al., 2012). As well, Iron hydroxide and calcium carbonate nanoparticles at low concentrations have also been used for wellbore strengthening purposes (Nwaoji et al., 2013). Generally speaking, there are pros and cons regarding using this technology (Soroush and Sampaio, 2006):

- Advantages
  - It is easy to prepare and efficient.
  - Providing sand control.
  - There is no damage on permeability or porosity.
  - It is required short time for application.
  - Reducing shale swelling.
  - Wellbore strengthening approach.
- Disadvantages

- Not effective for long intervals with vastly different pore pressure.
- It will not be effective with low permeability formation.
- It is still not common and widely used in field application.
- It is not having a significant possibility to increase rock strength.

5. Chemical grout: This treatment is chemical consolidation mechanism that has been proved as effective way in underground openings for many years. This method is usually used inhibit water influx into well and to increase rock strength as wellbore strengthening approach. In different words, this technology has prominent role on wellbore stability in fractured and unstable formations. Experimental works have already been proved that this remedy provide a good stability for wellbore wall. Obviously, there are pros and cons regarding using this technology (Soroush and Sampaio, 2006):

- Advantages
- Appropriate for fractured zones.
- It strongly contributes to increase range of the mud weight window.
- Providing wellbore strengthening approach.
- Prevent or deduce lost circulation mud.
- Disadvantages
- It needs more laboratory tests and field applications
- Stepped methods that interrupts drilling operations.

6. Deformable, viscous, and cohesive systems (DVC): This method is usually used for strengthening the zone. DVC sealant may deform under pressure or stress. Deformation of this seal has ability to maintain the seal and isolate the fracture tip from the wellbore pressure. It is recommended to provide differential pressure in order to dislodge the seal body and keep it immobile. As usually, each method has strongpoint and weak points. Figure 2.42 will illustrate the DVC system reacts with a water-based mud (Soroush and Sampaio, 2006):

- Advantages
- It does not rely appropriate permeability zones.
- It is not required to know permeability.
- Disadvantages
- It is required to use large amount of sealant has to travel along distance along wellbore to cover the unconsolidated zone.
- Limited squeeze pressure by other weak formations.

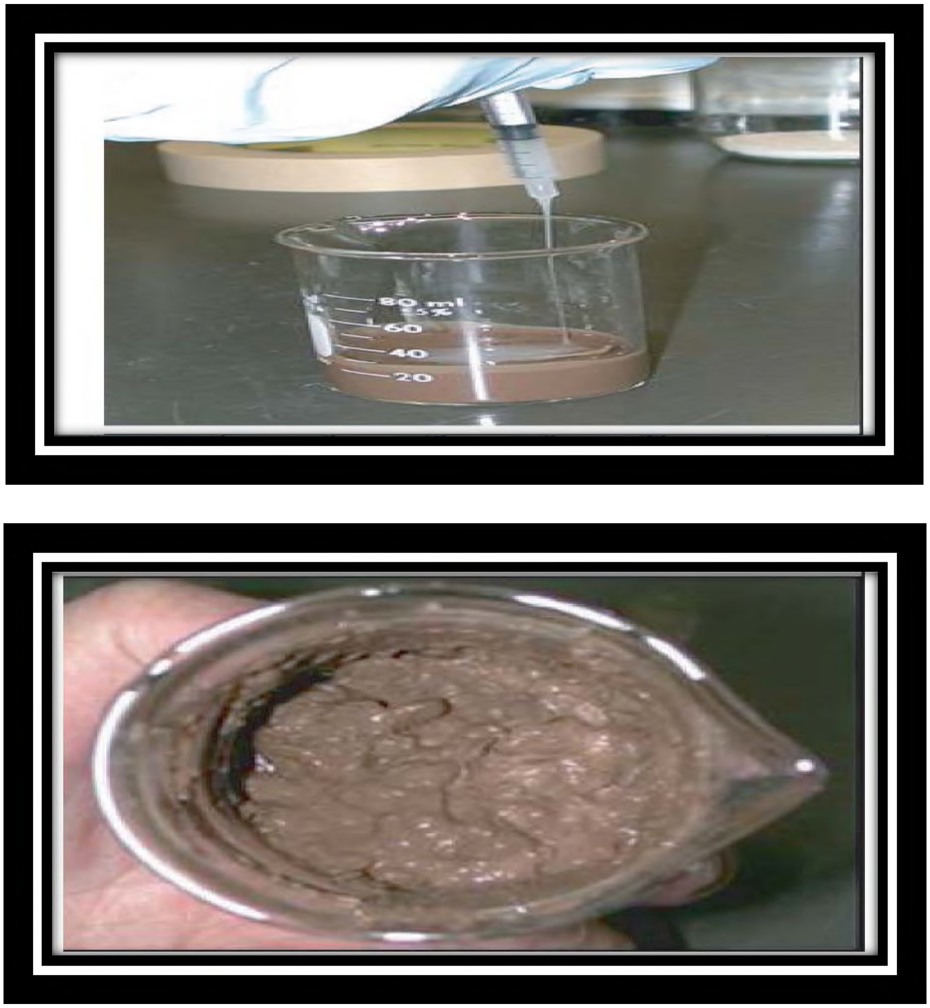


Figure 2.42. The DVC System Reacts with a Water-Based Mud to Form a DVC Sealant. (Wang et al., 2008)

7. Resin treatment (Formation consolidation and chemical casing method): In this method, water dispersible resins is used in order to increase rock strength and support weak zones. There are various kinds of resins that have already used like epoxies, phenolic, and furans to control for wellbore stability. It is recommended to use drilling mud with pH between 6 and 10 with this method. As usually, each method has strongpoint and weak points (Soroush and Sampaio, 2006):

- Advantages
- Wellbore strengthening approach and drilling operations can be done simultaneously.
- It is efficient technique for both shales and sandstones.
- It does not have a big effect on drilling fluid properties.
- This method has possibility to increase fracture gradient to 1200 psi.
- Disadvantages
- It is difficult to remove damage.
- It is not cost-effective.
- The leftovers cannot be reused or recycled.

8. High fluid-loss and high solid-content squeeze pills: This remedy mainly consists of a blend of different fibers where some of these fibers might be treated or coated to enhance their performance. It is necessary for fluids that carry these treatments to leak off into permeable formations in order to form a good seal. An ideal HFHS treatment should apply for different losses scenarios, and this remedy is easy to pump through bottom hole assemblies. However, this method is not effective in low permeability formations such as shale and might not perform as expected when using a non-aqueous drilling fluid. There are pros and cons regarding using this technology (Soroush and Sampaio, 2006):

- Advantages
- Simple application which contribute to reduce both cost and time
- This treatment is appropriate to work in depleted, highly permeable formations with water-based drilling fluid.
- This method has been successfully applied in the field.
- Disadvantages
- It is complicated to apply for low permeability formation.
- Formation damage.
- It is not effective treatment with non-aqueous drilling fluid.

2.9.3. Using Drilling Techniques/Procedures. In some situations, it is very difficult to regulate on mud losses by using conventional lost circulation materials (LCMs). As well as, the cost of these materials is expensive, so it is important to find techniques and mechanism to live with losses. In different words, the driller must "live with the losses". In this section, we are going to demonstrate methods that have been used to ameliorate lost circulation without the use of lost circulation materials. However, it is much recommended to be very cautious when these techniques are applied because utilizing these methods involve risk to the drilling operation. Hence, it must be carefully and thoroughly planned to ensure the safest possible outcome. The drilling techniques/procedures that will describe in the subsequent paragraphs may be used to prevent or remedy lost circulation problems (Baker Hughes, 1999).

2.9.3.1. Blend drilling. This method means that drilling operation is continuous but without any returns. In other words, there is drilling with lost circulation mud. This situation is very hazardous because we will not know anything about lithology of formation. In addition, cutting will be accumulated around bit, which in turn, that lead to occur stick pipe problem. In this method, water will be used instead of drilling mud, so it is important to prepare sufficient quantities of clean water before use this technique, and it is necessary to prepare enough amounts of high viscosity mud and normal drilling fluid. Formation will be drilled by using water, and high viscosity mud must be pumped after drilling one drill pipe in order to lift cutting above bit. These cutting will enter to the thief zone. Sometimes, one drill pipe is drilled by using just water, and another drill pipe will be drilled by using drilling mud. But in this case, cost will be high due to drilling mud losses. Blind drilling will continue with pumping high viscosity after drilling each one drill pipe. In this method, it is prudent to monitor surface parameters for bit, and after completing formation drilling, it is necessary to circulate drilling mud into hole to clean well from cutting.

The reasons for using the blind drilling technique:

- If loss zone is the last zone of hole, and there is no ability to plug it. In this case, blind drilling is used to drill all formation and running casing after that.

- In order to reach competent formations, the blind drilling approach is recommended to use to exactly determine the depth of the thief zone. Hence, after implementing cement plug after blind drilling, the competent zone will fill with hard cement, so that will give indication on the bottom of the loss zone.
- Sometimes, thief zone is the first in the hole, so there is no complications and implications if blind drilling technique is used

2.9.3.2. Aerated mud. There are two-phase flow in this kind of method, and two-phase flow are air and mud. The principle of work for aerated mud to decrease equivalent circulation mud (ECM) to the 4 to 8 lb/gal range. In subnormally pressured intervals, this method is usually used in order to reduce massive mud losses that cannot be easily resolved. Equivalent circulation mud in this type of mud will slightly be higher than the pore pressure in order to avoid breakout failure and tensile failure. In this technique, there is equipment on the surface to separate the air and mud so that the mud can be processed through the surface system and recirculated. It is very important to use air drilling compressor and other equipment with this method like a rotating head and mist and air/mud separator. Some issues are associated with aerated mud such as severe corrosion rates, unsteady flow in large diameter holes, and erosion from turbulent flow.

There are several different methods used for achieve aerated mud:

- "Down the drill pipe" aeration – injecting both air and mud into the standpipe.
- Using a parasite tubing string run outside the last casing string to inject the air and pumping mud as normal. The mud and air mix at the casing shoe and aerated mud flows up the annulus.
- "Dual casing micro-annulus" aeration – where a temporary casing is hung inside the last cemented casing so that air is injected down the two casings annulus and flows into the mud at the inner casing shoe then back up the drill pipe to inner casing annulus as aerated mud.

The most common method that uses to achieve aerated mud is by injection of both air and mud into the standpipe. For parasite aeration, it is easy to regulate on air and mud flows, the air pressure requirement is usually lower. On other hand, extra cost and more time are required for parasite injection in terms tubing plus extra equipment for pressure control. As well as, in parasite aeration, equivalent circulation mud will not be low as can be obtained with standard aeration due to the restricted air volume capacity of the tubing and the depth of injection being higher. While dual casing micro-annulus aeration, the last the last cemented casing must be large sufficient to allow the temporary inner casing to be run. This may require a larger casing size and previous hole size.

2.9.3.3. Foam. In this method, air (or gas) with water and foaming surfactant slurry are used to form foam drilling. This method will lead to reduce equivalent circulation density to the 2 to 4 lb/gal range that in turn will affect positively on wellbore stability. This kind of method is applied in very low pressure zones where massive lost circulation occurs and is difficult to cure. When drilling, the air and foamer slurry foam must be metered within a narrow range of ratios and requires a rotating head and extra mechanical equipment. There are two types of this mud. The first one is stable foam drilling, and other is stiff foam drilling. Stable foam uses mainly water and a surfactant (commonly called soap) to form a stable air-in-water foam mixture with the air while stiff foam drilling uses a mud-like formulation as the foamer slurry with bentonite and polymers to form a longer lasting foam. Stiff foam drilling is preferred to drill large holes more than stable foam drilling. Stiff foam drilling has sufficient air volumes to do proper cleaning for large holes while stable foam drilling does not have enough air volumes to do good cleaning for large holes. In general, foam has excellent hole cleaning features and uses less air volume as compared to air or mist drilling. On other hand, high cost is associated with water and foamer chemical because the foamer slurry cannot be recovered and reused.

2.9.3.4. Air or mist. Equivalent circulation mud in this kind of mud will be the lowest from 0 to 2 lb/gal. The most application for this method is in dry formations where the well produces little liquid and massive lost circulation and networks of vugs or caverns are encountered. The requirements of this method is large capacity high pressure air compressors, a rotating head, and other mechanical equipment. Air drilling is commonly referred to as “dust” drilling as the discharge from the well is dust. Mist drilling uses water and a small amount of 1% foamer solution injected to help remove small amounts of produced fluids from the well.

2.9.3.5. Floating mud cap drilling.

- Theory

Usually, this technique is used during total mud loss and the intrusion of reservoir fluids into the wellbore. By using weighted drilling mud that is continuously pumped into the annulus, the well will be under control. Water is used instead of drilling fluid, and the water and drill cuttings are lost to the zone. Mud column pressure in the annulus will regulate on formation fluids. It is very necessary to design appropriate mud weight which is preferred to be (~250 psi) higher than the formation pressure. In addition, it is important to maintain drilling density from time to time by using the addition of fresh mud to the annulus in order to avoid mud losses. Theoretically, in some levels, mud pressure will be equivalent to the formation pressure that in turn cause the mud to “float” against the formation pressure, just above the lost circulation zone. It is much recommended to maintain hydrostatic pressure to slightly be higher than the formation pressure in order to preclude unwanted consequences due to shear failure or tensile failure. Figure 2.43 will show floating mud cap drilling method

- Operation

Mud cap drilling cannot take place without a large dedicated water supply. It is essential that pump rates that will clean the bit and annular velocities that will convey the cuttings into the loss zone be maintained. Slip velocity calculations for the cuttings can be performed. Generally, annular velocities above 120 ft/min will be required. The drilling circumstances have a big role on the procedures for executing the floating mud cap. In the deep waters wells, the implementation of this method will slightly be different from an onshore operation. In the same time, the same basic principles will apply in all cases. When the kick has been identified the steps listed below should be followed.

1. Pull the bit off bottom and close the BOP.
2. Pump 100 to 150 barrels of mud (at the density calculated to be slightly above that needed to balance the formation pressure) down the annulus and note the annular pressure.
3. If pressure is still noted, pump another 50 to 100 barrels of mud into the annulus.
4. Repeat step 3 until no annular pressure is observed.
5. When no pressure registers on the annulus, open the choke line and check for flow.
6. If there is no flow, open the BOP, run to bottom and drill, circulating water down the drill pipe at the calculated rate and adding mud continuously to the annulus.
7. If the well flows, close the BOP and pump a small quantity of mud into the annulus.
8. Repeat steps 5 and 6.

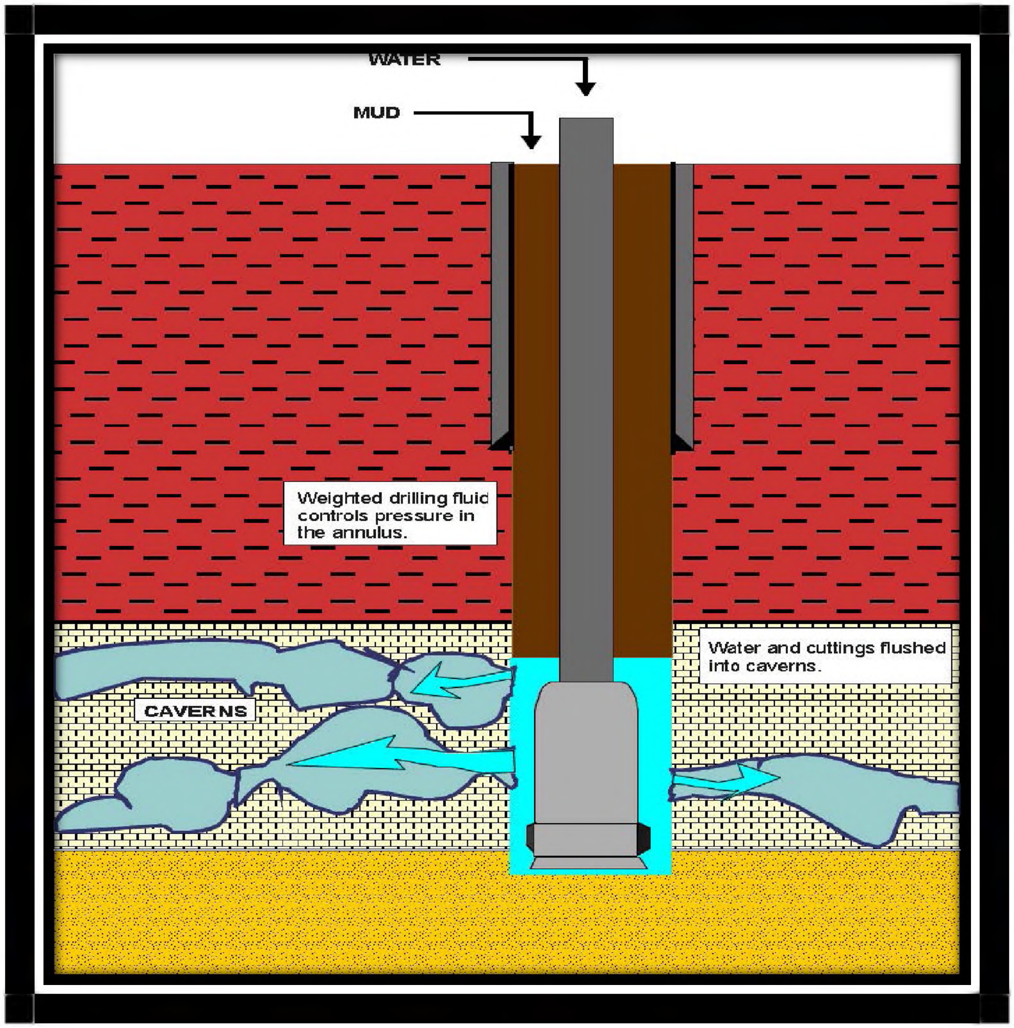


Figure 2.43. Shows Floating Mud Cap Drilling Method (Baker Hughes, 1999)

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

In conclusion, "all alternatives for drilling conventionally should be exhausted before committing to floating mud cap drilling, as it is a very high risk technique. The well is on the verge of being uncontrolled at any time during the drilling operation. When mud cap drilling is anticipated, specific well control procedures should be in place prior to penetrating the loss zone. It should be matched with the characteristics of the zone. Successful use of a floating mud cap can result in the penetration of the loss zone without setting an extra string of casing" (Baker Hughes, 1999).

2.9.3.6. Using advances in drilling technology. Sometimes, lost circulation mud will not be cured by using remedial methods and preventive measures are not; therefore, it is important to find techniques or mechanisms in order to ceases mud losses. There is specific advanced technology that use for this purpose like expandable tubulars and casing-while-drilling (CWD), and these methods can serve as long term methods that will reduce the costly effects of lost circulation while drilling (Davison et al., 2004). There is a positive advantage for expandable tubulars which contribute to use a number of mud weights for different sections without losing hole size due to the telescoping effect of casing. Casing-while-drilling employs downhole and surface components to provide the ability to use normal oilfield casing as the drill string so that the well is simultaneously drilled and cased (Tessari et al., 1999). The casing is rotated from the surface with a top drive. Drilling fluid is circulated down the casing internal diameter (ID) and up the annulus between the casing the wellbore. The main target of this method is to reduce the non-productive time (NPT), cost, and the casing running times where partial and total fluid losses make conventional drilling practices difficult and expensive. Casing while drilling (CWD) technology has already been used for six wells in the Cashiriari field (Peruvian Jungle). Lost circulation mud stopped after using this technique in this field. Casing while drilling (CWD) technology demonstrated to be an effective technical-economical solution to drill and cement surface casing string (20 in, 18 5/8 in, 9 5/8 in) in the Cashiriari field. There are two kinds of casing while drilling (CWD) technology: retrievable and non-retrievable systems. The retrieval system uses a drill pipe or wireline to retrieve the bottom hole assembly (BHA) assembly attached to the casing or liner. The non-retrievable system is designed to leave the casing drill shoe (CDS) on bottom if the last section of the well is being drilled to total depth (TD) or is to be drilled afterwards to continue with the following hole sections. Figures 2.44 and 2.45 are pictures of part of the CwD assembly. There are some visions and ideas that has already deduced after applying casing while drilling (CWD) technology in the Cashiriari field (Gallardo et al., 2010):

- Unwanted consequences of the lost circulation mud like drilling and operation cost, tripping time to land conventional casing to bottom, and rig floor safety in comparison with traditional mechanisms will be reduce by using casing while drilling (CWD) technology.
- High efficiency cleaning due to high annular velocity which in turn lead to avoid bit balling issue, drag problem, and stick pipe dilemma.
- No collision was observed between the wells drilled from the same cluster.
- Lost circulation zones have been clearly identified, even drilling without returns.
- Casing while drilling (CWD) technology helps to restore mud circulation to surface.

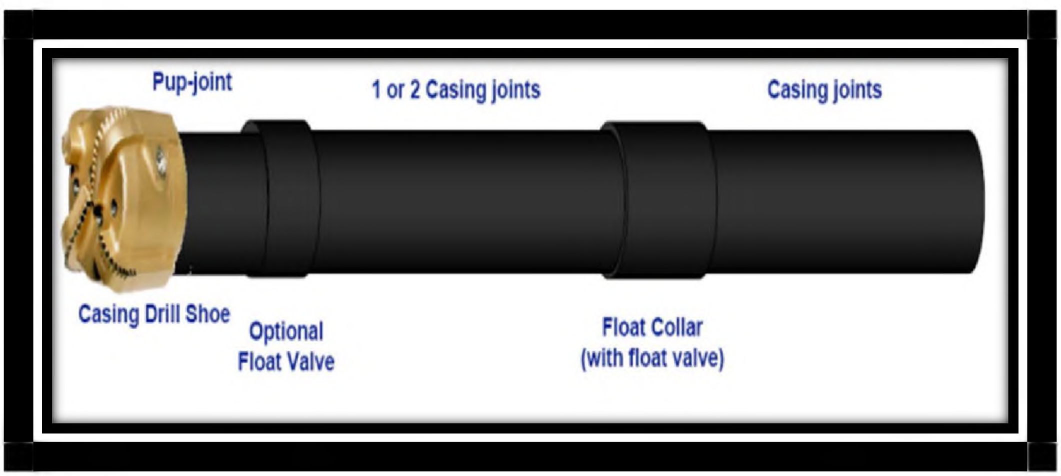


Figure 2.44. BHA Components of CwD Assembly (Gallardo et al., 2010)

Figure 2.45. Top Drive and Internal Casing Drive (Tessari et al., 2006)

3. PROBLEM OF THE MUD LOSSES IN THE SOUTH RUMAILA FIELD

3.1. INTRODUCTION ABOUT THE SOUTHERN RUMAILA FIELD

The Rumaila oil field is a super-giant oil field located in southern Iraq, Basra city approximately 20 mi (32 km) from the Kuwaiti border. The Basra Petroleum Company (BPC), an associate company of the Iraq Petroleum Company (IPC), discovered this field in 1953. Since then, this massive oil field has remained under Iraqi control. Rumaila field is considered the third largest field in the world. The field is owned by Iraq and subcontracted to BP and CNPC under Iraq Producing Field Technical Service Contract (PFTSC). BP is an operator of the project with 47.6% while CNPC and SOMO hold 46.4% and 6%, respectively. As of October 2016, the field produces 1,000,000 barrels per day. Currently around 200 production wells are operating at Rumaila. Until 2010, this field was under South Oil Company, and the target zone was Zubair zone. After 2010, the operator for this field is British Petroleum Company, and the target becomes Mishrf. Figure 3.1 shows the field location. (South Oil Company, 2016).

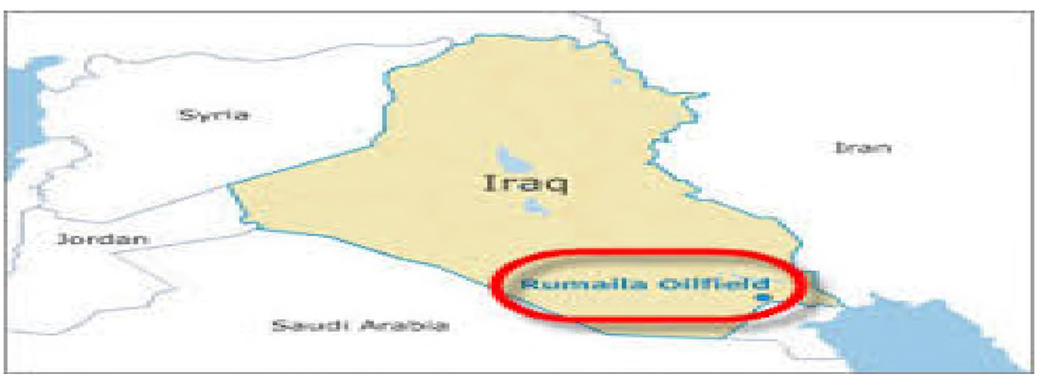


Figure 3.1. Southern Rumaila Field (South Oil Company, 2008)

This field is estimated to have about 17 billion barrels, which is equivalent to 12% of Iraq's oil reserves. One of the greatest challenges in drilling wells in the Southern Rumaila Field is the amount of non-productive time (NPT) caused by lost circulation.

Lost circulation represents more than 66% of the total non-productive time. More than 90% of wells that have already been drilled, have suffered from mud loss problems. Figure 3.2 shows a typical wellbore schematic with all the drilled hole sections and casings in place (South Oil Company, 2016) and (Ali et al., 2015).

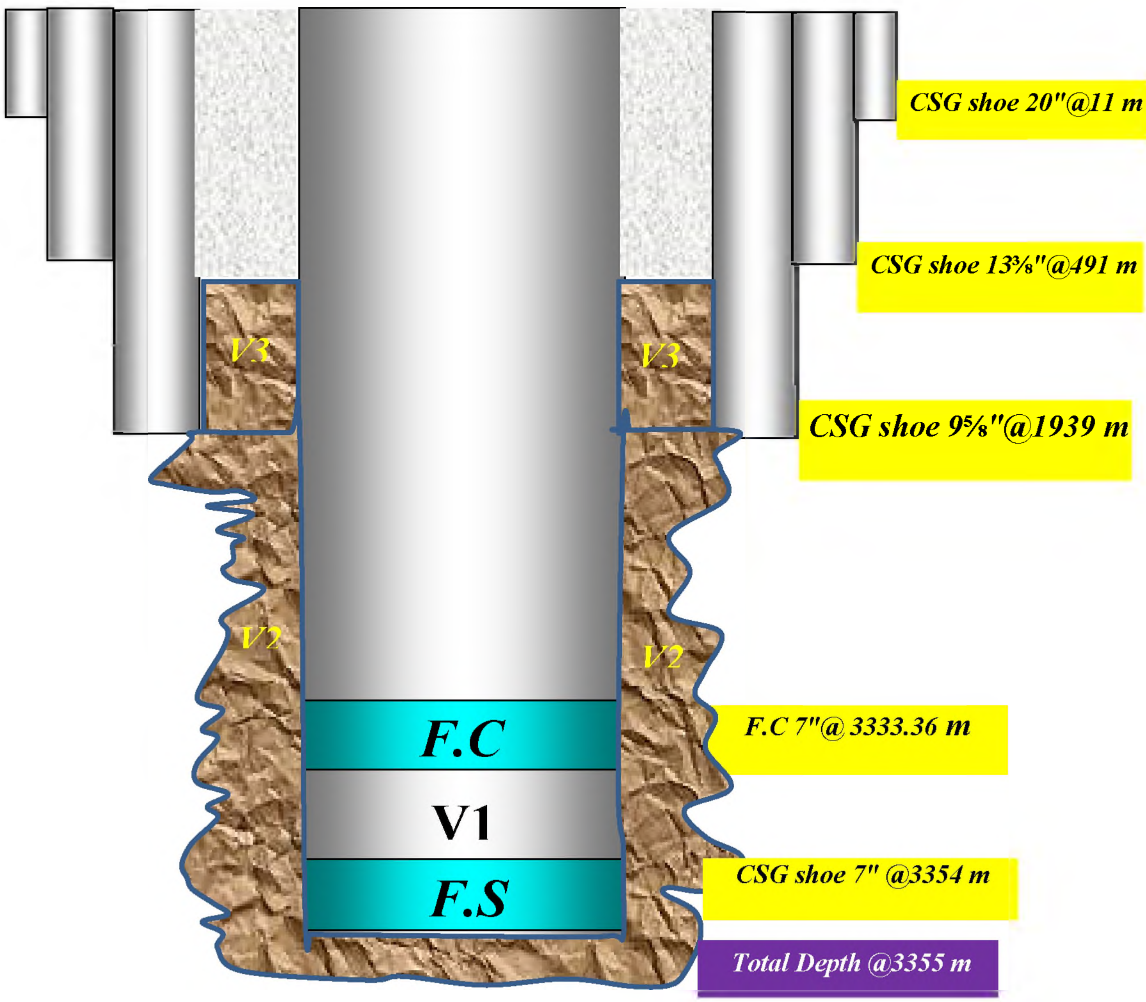


Figure 3.2. Wellbore Schematics with all the Open Hole Sections and Casings in Place

3.2. LITHOLOGY OF SOUTH RUMAILA FIELD

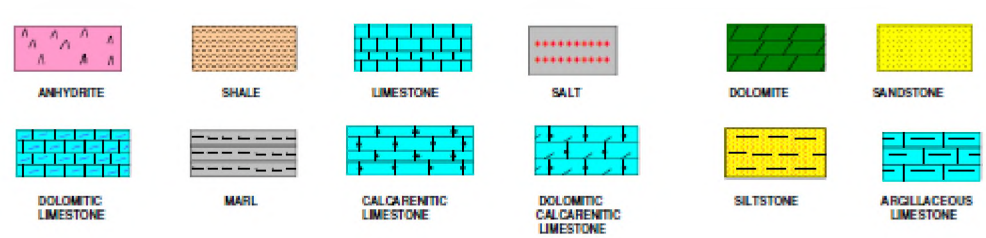
Table 3.1 provides a summary of the primary geological formations and lithology in the South Rumaila Field. Formations where loss circulation has occurred include the Dammam, Hartha and Shuaiba formations. These formations are outlined in red in Table.

Table 3.1. Geological Information (South Oil Company, 2010)

Formation	Lithology	Description	Formation Intervals	Problems
DIBDIBA		**SAND&PEBBLE:** Vary color, red, translucent to transparent, medium to coarse grain, occasionally fine granular to pebble, sub angular, sub rounded, sub spherical, good inferred porosity, no oil show.	200 m or less	High gel strength, high sand content, and high filtration.
L. FARS		**Argillaceous Limestone:** Mudstone, dark gray, soft, amorphous, plastic, sticky, non-calcareous cement, nil porosity.	200 - 315 m	High viscosity and balling.
GHAR		**SAND&PEBBLE:** Translucent to transparent, friable, unconsolidated, fine to coarse grain, sub rounded, sub angular, sub spherical.	315 - 440 m	Wash pipe and equipment corrosion due to high sand content.
DAMMAM		**Dolomite: Yellowish gray, firm, moderately hard in place, fine to moderately crystalline, fine to moderately sorted, micro scurosic in place, vuggy in place, good visible porosity, good inferred permeability.**	**440 -700 m**	**Lost circulation mud due to Vugs and caves.**
RUS		**ANHYDRITE:** White, firm, moderately hard, no porosity, massive, occasionally soft, no oil show.	690 – 860 m	Drilling mud clotting, very high viscosity, and high filtration due to high contamination of Ca^{++}.
UMM ER-RADHUMA		**DOLOMITE:** Light gray to gray, firm, occasionally moderately hard, fine crystalline, occasionally medium crystalline, occasionally sub blocky, argillaceous, occasionally sucrosic, good visible porosity, occasionally vuggy, no oil show.	860 – 1310 m	H_2S flow.
TAYARAT		**SHALE:** Black, occasionally, dusky yellowish brown, slightly hard, occasionally firm, non-fissile, blocky, commonly bituminous, rare trace of coal.	1300 – 1550 m	H2S flow.
SHIRANISH		**ARGILLACEOUS LIMESTONE:** Mudstone, medium light gray, very light gray, soft to firm, crypto to micro crystalline, sub blocky to blocky, amorphous, semi plastic, marly, no visible porosity, no oil show.	1550 – 1660 m	Stuck pipe, high viscosity, balling, and low penetration rate.
HARTHA		**LIMESTONE:** Mudstone, occasionally wackestone to grain stone, white, light gray to gray, occasionally pinkish gray, fine crystalline, no visible porosity, argillaceous, occasionally glauconitic, chalky in place no oil show.	1660 – 1850 m	Lost circulation mud due to naturally fractures.

Table 3.1. Geological Information (Cont'd) (South Oil Company, 2010).

MISHRIF		**LIMESTONE:** Mudstone to wackstone, white, pale yellowish orange, slightly hard, occasionally moderately hard, blocky to sub blocky, limonitic, chalky, in places, occasionally compact, no visible porosity, no oil show.	2240 – 2390 m	Gas cut due to abnormal pressure.
RUMAILA		**LIMESTONE**: Mudstone, light gray to gray, soft, fine crystalline, sub blocky, earthy luster, well sorted, semiplastic, marly, occasionally argillaceous, no visible porosity, no oil show.	2400 – 2490 m	Low penetration rate.
AHMADI		**SHALE:** Greenish gray, gray, slightly hard, sub fissile, occasionally sub blocky, splintery in places, slightly calcareous cement, no oil show.	2490 – 2635 m	Low penetration rate due to shale sloughing and collapse.
MAUDDUD		**LIMESTONE:** Mudstone, Packstone, dark gray, slightly hard, dark gray, occasionally moderately hard, fine crystalline, blocky, earthy luster, argillaceous, occasionally compact, no visible porosity, no oil show.	2630 – 2723 m	Sometimes, partial mud losses.
NAHR UMR		**SHALE:** Greenish gray, black, sub blocky, occasionally fissile, slightly calcareous cement, no oil show.	2720 – 2990 m	Low penetration rate, shale sloughing and collapse, bit corrosion, and kick.
SHUAIBA		**LIMESTONE:** Mudstone to wackstone, very pale orange to moderate greenish yellow, moderately hard, fine crystalline, blocky, earthy, luster, compact, commonly pyritic, no visible porosity, no oil show.	2990 – 3090 m	Lost circulation mud due to induced fractures and low penetration rate.
U. SHALE ZUBAIR		**SHALE:** Dark gray, greenish black, firm, sub fissile, sub blocky, slightly calcareous cement, splintery, occasionally thinly banded with dark gray claystone, no oil show.	3090 – 3205 m	Shale collapse and stuck pipe.
M. SHALE ZUBAIR		**SHALE:** Dark gray, black, firm, sub fissile to sub blocky, blocky in place, splintery, non-calcareous cement, no oil show.	3390 – 3445 m	Shale collapse and stuck pipe.
L. SANDSTONE ZUBAIR		**SANDSTONE:** Quartzes, transparent to translucent, firm, friable in places very fine to fine grain, sub rounded, sub spherical, well sorted, glassy, luster, good visible porosity, good inferred porosity, good inferred permeability, no oil show.	3445 – 3515 m	Low penetration rate.



3.3. LOST CIRCULATION TREATMENTS USED IN THE RUMALIA FIELD

Proactive actions which usually take like Reduction of the Pump Pressure, Reduction of the drilling mud density, waiting method, increasing of the drilling fluid Viscosity, and using bit without nozzles are not sufficient to avoid lost circulation material. Narrow mud weight window between pore pressure and fracture pressure lead to mud losses. Several remedies that have already been used in southern Rumaila field in order to prevent or mitigate mud losses. Strictly speaking, each type of the mud losses is required specific treatment to stop it or mitigate. Therefore, it is necessary to detect which kind of losses that we have in order to prepare optimal remedy for it. By selecting appropriate treatment for the mud losses, that, in turn will reflect positively on the drilling operations in terms combating the problem, saving time, and reducing expenses. In this section, remedies will be classified depend on type of treatment (South Oil Company, 2010).

3.3.1. Partial Losses Remedies. In this kind of loss, part of drilling fluid will be lost into formation about (1-10 m3/hr). This type of loss is the simplest one, and it is easy to control on it. However, by ignoring this kind of the losses, it will aggravate to severe loss or complete loss. Therefore, it is very crucial to do required actions to stop this loss to avoid unwanted consequences. Actually, several treatment use to control and mitigate this type of loss. Table 3.2 will illustrate remedies that use to regulate this type of the loss.

Table 3.2. Partial Losses Treatments

Type of Losses	Type of the Treatment	Approach of the Treatment	Waiting
Partial Loss	Waiting Method	• Pull out drilling strings to casing shoe. • Waiting period between (2-4) hours. • Drilling strings will gradually run in hole. • Circulation drilling mud and rotation drilling string slowly. • Check mud levels in mud tanks system to make sure there is no mud losses. • Starting drilling operation at moderate speeds in order to seal formation apertures by engraved cutting.	(2-4) hours
	Reduction of the Pump Pressure	By reduction the pump pressure that lead to decrease extra pressure due to mud circulation.	No Waiting
	Reduction of the drilling mud density (ρmud)	By decreasing mud weight within allowable limits in order to reduce hydrostatic pressure on the weak formations. Drilling fluid density is usually minimized by adding water or diesel oil.	No Waiting
	By Using Bit Without Nozzles	The benefit from this issue to just reduce jet velocity due to nozzles.	No Waiting
	By Reduction Yield Point (Yp)	To Reduce Equivalent Circulation Density (ECD) that lead to reduce friction between drilling fluid and well wall.	No Waiting
	High Viscosity Patch	High viscosity drilling mud (Patch) with low mud weight. By using Bentonite, lime, or salt clay to increase viscosity.	(2-3) hours

- High Viscosity Muds: This treatment is high viscosity drilling mud (Patch) with low mud weight. Usually, Bentonite, lime, or salt clay are used to increase viscosity. This pill is pumped in front of the thief zone in calculated and sufficient quantities to plug losses zone especially in partial losses. It is recommended after displacing this patch to interesting zone to wait around (±2-3 hours). Sometimes, the above remediation is used before lost circulation material or cement plug to guarantee zone plugging. The viscosity for this pill will be roughly 100 to 120 sec (Marsh funnel measurement).

3.3.2. Severe Losses Remedies. This kind of loss will be more than partial loss about (15 or above m3/hr). This type of loss is risky, and it is not easy to control on it. In addition, by ignoring this kind of the losses, it will aggravate to complete loss. Therefore, it is very necessary to do required actions to combat this kind of the losses to avoid bad consequences. Actually, many treatments use to control and mitigate this type of loss. Table 3.3 will illustrate remedies that use to regulate this type of the loss.

Table 3.3. Severe Losses Treatments

Type of Losses	Type of the Treatment	Approach of the Treatment	Waiting
Severe Loss	Drilling Mud (Low Density) + LCMs (Fibrous Materials)	These materials have ability to form" brush heap" like mat in pore openings, then creating plug to seal thief zone.	(3-4) hours
	Drilling Mud (Low Density) + LCMs (Granular Materials) like $CaCo_3$ and graphite	They have ability to form "bridging" agent, then creating plug to seal thief zone.	(3-4) hours
	Drilling Mud (Low Density) + LCMs (Flake Materials)	These types of materials have large planar surfaces and are very thin, and they have possibility to form a "shingle-like" layer against pore openings, then creating plug to seal thief zone.	(3-4) hours
	Drilling Mud (Low Density) + Blend of the LCMs	By creating effective plug to seal thief zone.	(4-6) hours
	High Viscosity Drilling Mud (Low Density) + Blend of the LCMs	By creating plug to seal thief zone.	(4-6) hours
	Super Stop Material	• Mixing (4-5) bags (Weight of Bag 25 kg) of super stop material for each 1 m3 water. • This treatment should be mixed in separate and clean tank. • It is very crucial to mix quickly in order to avoid treatment bulge in surface tank. • Displacing the remediation in front of the loss zone. • Pulling out drill pipe strings above loss zone, and making mud circulation about (10 minutes) to enforce treatment to enter formation.	(1 -2) hours
	Cement Plug	By pumping cement slurry with specific density in front of thief zone, by using O.E.D.P to plug zone.	(18-20) hours

Each of the treatment will be explained in details below in order to get integrated image about how can apply them.

- $CaCo_3$ and Graphite with low mud weight: By depending on broad research, Graphitic carbon and sized calcium carbonate are effective LCMs, and it is advisable to add to the drilling mud before drilling depleted and weak zone as wellbore strengthening approach. These materials will be mixed with low mud weight, and it is pumped in front of the loss zone, and it has to wait around (± 3-4 hours) before resuming drilling processes.
- Plugging Material While Circulation (LCM): High filtration and high viscosity drilling mud (Low Mud Weight) is mixed with lost circulation material. LCMs should be added in accurate proportions and calculated quantities in order to get effective treatment. (2-4%) from mica and (2-3%) from granular are added to high filtration and high viscosity drilling mud (Low Mud Weight). This remediation is pumped in front of the thief zone, and it should wait around (±3-4 hours) after displacing this patch to interesting. It is advisable to use low mud weight with blend of LCMs to avoid excessive equivalent circulation density (ECD).
- Lost Circulation Materials Blend (LCM Blend): This remediation is often used for induced fractures in severe losses especially if there is not exact information regarding the width of fracture. That is why; this blend is used in various size distribution. Mixture of LCMs (Fibrous, Granular, Flakes) are used to form this treatment. Lost circulation materials should be used in various volumes (Coarse, Medium, and Fine) in order to get on effective remedies. Two ways are common to mix LCMs with high viscosity mud. First one, it mixed a blend of commercially available LCMs including the following: by adding 5 kg/m3of coarse volume and 5 kg/m3 of medium and fine volume to total mud cycle. Second one, by mixing specific pill individually, by adding 15 kg/m3 of coarse volume and 15 kg/m3 of medium and fine volume to the patch of high viscosity mud. This blend should be pumped in front of the losses zone, and it has to wait around (± 4-6 hours) before resuming drilling processes. It is better to use squeeze pressure technique with this kind of remedies. It is very important to use low mud

weight with blend of LCMs to avoid excessive equivalent circulation density (ECD).

- High Viscosity Drilling Mud (Low Density) + Blend of the LCMs: First of all, pill of the high viscosity mud will be pumped in front of the thief zone. Blend of LCMs mix with low density mud will be directly pumped after high viscosity patch to create effective plug. It is very important to use low mud weight with blend of LCMs to avoid excessive equivalent circulation density (ECD). This blend should be pumped in front of the losses zone, and it has to wait around (± 4-6 hours) before resuming drilling processes.

3.3.3. Complete Losses Remedies. In this kind of loss, mud cycle will completely be lost into formation. This type of loss is the worst one, and it is difficult to control on it. In addition, this kind of the problem will lead to maximize the expenses of the drilling operations and non-productive time (NPT). Therefore, it is very necessary to do required actions to combat or mitigate this kind of the losses to avoid unwanted consequences. Actually, many treatments use to control and mitigate this type of loss. Table 3.4 will illustrate remedies that use to regulate complete losses treatments

Table 3.4. Complete Losses Treatments

Type of Losses	Type of the Treatment	Approach of the Treatment	Waiting
Complete Loss	Cement Plug	By pumping, cement slurry with specific density in front of thief zone, by using O.E.D.P to plug zone.	(18-20) hours
	High Viscosity Mud (Low Density) + Cement Plug	First, pumping high viscosity mud (low density), then pumping cement plug directly to create efficient seal, by using O.E.D.P.	(18-20) hours
	Drilling Mud (Low Density) + Blend of the LCMs + Cement Plug	First, pumping drilling mud (low density) plus blend of the LCMs, then pumping cement plug directly to create efficient seal, by using O.E.D.P.	(18-20) hours
	DOB Squeeze (Diesel Oil Bentonite)	By mixing oil base + bentonite to create plug, by using O.E.D.P to seal zone with squeeze technique.	(8-10) hours
	DOBC Squeeze (Diesel Oil Bentonite Cement)	By mixing oil base + bentonite + cement to create plug, by using O.E.D.P to seal zone with squeeze technique.	(8-10) hours
	Barite Plug	This barite plug is used to pump in front of zone of interest by using barite material and other materials.	(3) hours

Table 3.5 will demonstrate the description and the executive steps for each of the remedial plug in order to get integrated image regarding procedures of the application.

Table 3.5. The Executive Procedures for the remedial Plugs

Name of the Treatment	Description	Procedures
Cement plug	This plug is very prominent and very prevalent in oil industry field. This treatment is used to combat complete losses, and it is rarely used in partial or severe losses. It is very necessary to do very accurate calculations regarding the weight of cement.	1. Calculate the density of the cement. 2. Using open end drill pipe (O.E.D.P). 3. Pumping the required cement volume. 4. Displacing the plug in front of losses zone by using normal drilling mud. 5. Avoidance contamination between plug and drilling fluid. 6. Pumping normal drilling fluid in order to clean open end drill pipe (O.E.D.P). 7. Pulling out drill pipes strings to casing shoe. 8. Waiting period around (± 18-20 hours) in order to harden cement plug.
DOB Squeeze (Diesel Oil Bentonite)	This remediation is very important and common. However, it is not easy to apply in the field. Some conditions are required for this treatment. Water has to be removed from mixing tank and pumping pipes lines. In addition, it is much recommended to content loss zone on water in order to be effective treatment. Otherwise, this method is difficult to be successful.	Formula for 1 m^3 (Final) Oil base 0.70 m3 Bentonite 800 kg 1. Using open end drill pipe (O.E.D.P). 2. Cleaning all mixing tanks and pumping pipes. 3. Two Pumps are required. 4. Initially, pumping clean water in front of the loss zone to guarantee bentonite hydration. 5. Squeezing process is required. 6. Displacing the plug in front of losses zone by using normal drilling mud. 7. Avoidance contamination between plug and drilling fluid. 8. Pulling out drill pipes strings to casing shoe. 9. Waiting period around (± 8-10 hours) in order to harden cement plug.

Table 3.5. The Executive Procedures for the remedial Plugs (Cont'd)

Name of the Treatment	Description	Procedures
DOBC Squeeze (Diesel Oil Bentonite Cement)	It is also very important and common. However, it is not easy to apply in the field. Some conditions are required for this treatment. Water has to be removed from mixing tank and pumping pipes lines. In addition, it is much recommended to content loss zone on water in order to be effective treatment. Otherwise, this method is difficult to be successful.	Formula for 1 m3 (Final) Oil base 0.72 m3 Bentonite 450 kg Cement 450 kg The implementation principle of this treatment is exactly the same technique for diesel oil bentonite plug.
Barite Plug	This kind of the plug is used to regulate on the abnormal zone pressure. Sometimes, some wells suffer from kick or blowout problem, and in the same time, it is not possible to increase mud weight to dodge lost circulation in upper zones in the same hole. Hence, this barite plug is used to pump in front of the zone of interest	Composition of this plug • Water. • SAPP. • NaoH. • FCL. • Barite Implementation Method of the Barite Plug: 1. Identification of the height of zone 2. Selecting the appropriate density of this plug. 3. Using bit with nozzles to avoid nozzles plugging. 4. Displacing this barite plug by using normal drilling mud. 5. Avoidance contamination between plug and drilling fluid. 6. Pulling out drilling pipes strings above blowout zone and continue in rotation only to deposit barite plug into formation. 7. Waiting period about (3 hours).

3.4. SOUTH RUMALIA WELL DATA

This section presents samples of the wells data, including number of wells analyzed for each thief formation. Around more than 50 wells have been analyzed in order to collect and study parameters which directly or indirectly affect lost circulation in the South Rumailia. Actually, all these real data precisely collected from various daily drilling report (DDR), final reports, and technical reports. A broad research has been made in international oil companies courses, journal papers, textbooks, international oil fields, and real field data to South Rumaila in order to determine which drilling mud properties and operational drilling parameters that have a pivotal influence on lost circulation. These extensive study shows that all mud weight, equivalent circulation density (ECD), yield point (Yp) have direct impact on lost circulation whereas SPM, RPM, and bit nozzles directly indirectly affect on this problem. Real data were minutely collected to find out the minimum and maximum range of the related parameters to avoid or mitigate lost circulation. Tables 3.6, 3.7, and 3.8 are samples of daily drilling report (DDR) for each thief zones to get coherent image about how all these real data were collected.

Table 3.6. Well 192, Daily Drilling Report, Dammam zone (South Oil Company, 2009)

Rig No	**O.W-21**	***Field***	**S.RU**	***Location***	**P-338**	***Well No***	**RU-192**	***Report No***	**23+11**
Date	12/22/2009	CSG Size	13⅜	WT(#)	54.5	Grade	K-55	Shoe @ (m)	433
1) 10 PM Depth (m)			632	Position	P.O.O.H to depth 160 m				
2) 6 AM Depth(m)			632	Position	R.I.H O.E.D.P to depth 590 m				
3)Meterage(m)			120	HRS	14	ROP m/h	8.57	Mud Type	FWB
4) Totco Degree			1	@	434	Fm.Name:	Damam	Top (m)	419
5) Mud Properties:						*1*			
SP Gr	1.07	Visc(mf)	55	Filt.(W.L)		PH	10	P.vis	
Y.P	16	A.V	/	0.Gel	/	10.GEL	/	Oil %	
Water %	/	ECD	1.085	Solid%	/	Cake(mm)	/	NaCl	11550
								Ca^{++}	400
6) Bit Record					*Gas Oil (m^3)*			43	
Bit/ Cor No	2				*7) Drg .Ass.Above :*				
Mfr.	Hughes				Bit			Length(m	0.4
Size	12¼				Bit Sub			Length(m	0.1
Ser. No	193yk				X.O.S			Length(m	1.08
Type	X3								
Jet(1/32)	WON				*8) D.C (ODXID)in*		8" + 6¾"	WT(*kg/m)*	218.8
Depth In	434				T.J :	D.C No.	21 +3	Length(m)	213.17
Depth Out									
RPM	75				*9) D.P (ODXID)in*		(5*4.276)"	WT *(#)*	19.5
W.O.B(ton	5 , 10				CRAD:	T. jnt. OD:	6⅝"	Thread	4½IF
Meterage(m	(12 m)Cem + (198m) For.								
Hours	(13 cem) + (25 For).				*10) Pumps Type:*		A 1700 PT		
					ST.Length(in)		12"	L.size(in)	6½"
					FlowRate		1997	SPM	120
					Press. Psi		300		
11) The Operations									

From	*To*	*Hrs*	*Operations*
22:00	8:30	10.50	Cont drilling formation from depth 512 m to depth 562 m at depth 562
			Complete mud losses
8:30	9:00	0.50	pumping 10 m^3 patch & displace it by 5 m^3 of mud
9:00	9:30	0.50	P.O.H from depth 560 m to depth 433 m
9:30	12:30	3.00	Wait for patch
12:30	13:00	0.50	Cir to check mud losses - No Return
13:00	13:30	0.50	R.I.H from depth 433m to depth 562 m
13:30	19:30	6.00	blind drilling from depth 562m to depth 632m & pumping 4m^3 patch for all single
19:30	20:00	0.50	pumping 15 m^3 patch & displace it by 5 m^3 of mud

Table 3.7. Well 192, Daily Drilling Report, Hartha Zone (South Oil Company, 2009)

Rig No	**O.W-21**	***Field***	**S.RU**	***Location***	**P-338**	***Well No***	**RU-192**	***Report No***	**23+32**
Date	1/11/2010	CSG Size	13⅜	WT(#)	54.5	Grade	K-55	Shoe @ (m)	433
1) 10 PM Depth (m)			1790	Position	**Drilling Formation**				
2) 6 AM Depth(m)			1802	Position	**Drilling Formation**				
3)Meterage(m)			56	HRS	24	ROP m/h	2.33	Mud Type	FCL
4) Totco Degree			¾	@	1686	Fm.Name:	Hartha	Top (m)	1674
5) Mud Properties:									
SP Gr	1.12	Visc(mf)	52	Filt.(W.L)	8	PH	10	P.vis	17
Y.P	15	A.V	25	0.Gel	6	10.GEL	13	Oil %	6
Water %	89	ECD	1.14	Solid%	5	Cake(mm)	½	NaCl	13900
								Ca^{++}	700
6) Bit Record					*Gas Oil (m^3)*			50	
Bit/ Cor No	5				*7) Drg .Ass.Above :*				
Mfr.	SEC				Bit			Length(m	0.4
Size	12¼				Bit Sub			Length(m	0.62
Ser. No	30751				X.O.S			Length(m	1.08
Type	S44								
Jet(1/32)	WON				*8) D.C (ODXID)in*		8" + 6¾"	WT(*kg/m)*	218.8
Depth In	1686				T.J :	D.C No.	21 +3	Length(m)	213.17
Depth Out	......								
RPM	60				*9) D.P (ODXID)in*		(5*4.276)"	WT *(#)*	19.5
W.O.B(ton)	10				CRAD:	T. jnt. OD:	6⅜"	Thread	4½IF
Meterage(m	103								
Hours	37.5				*10) Pumps Type:*		A 1700 PT		
					ST.Length(in)		12"	L.size(in)	**6½"**
					FlowRate		1600	SPM	100
					Press. Psi		1400		
11) The Operations									
From	*To*	*Hrs*	*Operations*						
22:00	22:00	24.00	**Cont. Drilling formation from depth1734m to depth1797m.**						

Table 3.8. Well 192 Daily Drilling Report, Shuaiba Zone (South Oil Company, 2009)

Rig No	O.W-21	Field	S.RU	Location	P-338	Well No	RU-192	Report No	23+66
Date	2/15/2010	CSG Size	9 ⅝	WT(#)	36,47	Grade	K-55,P-110	Shoe @ (m)	1843
1) 10 PM Depth (m)			3109	Position	Drilling formation.				
2) 6 AM Depth(m)			3125	Position	Drilling formation.				
3)Meterage(m)			76	HRS	22	ROP m/h	3.45	Mud Type	FCL-CL
4) Totco Degree			1°	@	2860	Fm.Name:	Shuaiba	Top	3050
5) Mud properties									
SP Gr	1.15	Visc(mf)	48	Filt.(W.L)	5	PH	10	P.vis	15
Y.P	13	A.V	21	0.Gel	4	10.GEL	12	Oil %	6
Water %	89	ECD	1.17		5	Cake(mm)	½	NaCl	13600
								Ca^{++}	520
6) Bit Record					Gas Oil (m^3)			27	
Bit/ Cor No	11				7) Drg .Ass.Above :				
Mfr.	REED				Bit		8½	Length(m)	0.24
Size	8½				Bit Sub		...	Length(m)	0.59
Ser. No	AC1317				Reamer		...	Length(m)	...
Type	S53A								
Jet(1/32)	WON				8) D.C (ODXID)in		6¾ * 213/16	WT(kg/m)	149.4
Depth In	2861				T.J :	D.C No.	21	Length(m)	210
Depth Out	...					H.W	3	WT(kg/m)	73.4
RPM	60				9) D.P (ODXID)in		5	WT (#)	31.83
W.O.B(ton)	15				CRAD: E-G	T. jnt. OD:	6⅜	Thread	4½IF
Meterage(m	248								
Hours	116				10) Pumps Type:		A 1700 PT		
					ST. Length(in)		12"	L.size(in)	6½"
					FlowRate		1487	SPM	85
					Press. Psi		2200		
11) The Operations									
From	To	Hrs	Operations						
22:00	22:00	24.00	Cont. drilling formation from depth (3033)m to depth (3109)m.						

3.5. LOST CIRCULATION IN THE DAMMAM, HARTHA, AND SHUAIBA FORMATIONS

Lost circulation events were identified for more than 50 wells discussed in section 3.4, according to the formation and depth. Drilling parameters known to have the greatest impact on lost circulation (Chapter 2), and readily adjusted during the drilling operation were tabled for analyses. The following discussion provides examples of the tabled data. Appendix A includes a complete summary of the lost circulation events table and used in the study.

3.5.1. Dammam Formation. The Dammam formation is the first formation in the Southern Rumaila field that is prone to mud losses. The top of this zone is found between 435 to 490 m, and all of the wells in the field must be drilled through this zone. The interval is composed of interbedded limestone and dolomite, which is generally 200 to 260 m thick. The top of the Dammam was eroded after burial and is karstified at depth. The karst features are believed to lead to the mud losses seen while drilling through this interval (Arshad, 2015).

Figure 3.3. Shows borehole and well construction typical of a well drilled in the South Rumaila Field at the time the well passes through the Dammam formation. 13-3/8” casing has been set, and most commonly a 12 ¼” bit is used to drill through the formation. A lost circulation event is shown near the bottom of the openhole in Figure 3.3, but may occur anywhere in the openhole section through the Dammam.

Lost circulation may occur in Dammam formation during drilling the zone or completing the zone. Common field practices in drilling the Dammam include reducing drilling parameters like WOB, RPM, and SPM, and altering drilling mud properties while drilling this formation. In addition, a bit without nozzles is often used to avoid jet velocity against the borehole walls. It is also recommended to run in and pull out drill strings slowly to reduce pressure on the formation. It is also very important to break gel strength for drilling mud into hole by using rotation before circulating drilling fluid into hole. (South Oil Company, 2008).

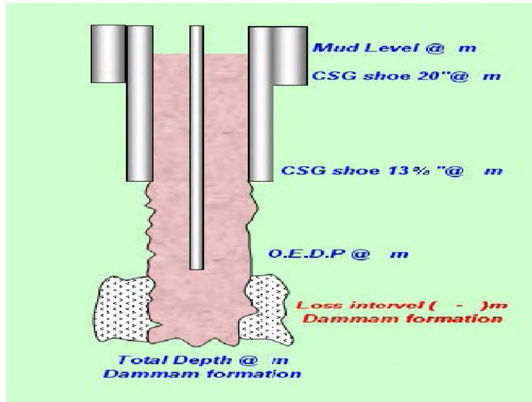


Figure 3.3. Lost Circulation Mud in Dammam Formation

Table 3.9 shows loss circulation events data collected while drilling the Dammam Formation in Well 1. Table 3.9 shows four events that occurred while drilling from 512 m to 668 m. The mud density, yield point, pump strokes per minute, bit rotation rate, bit type/nozzle type, fluid treatment and description of the losses are included for each event. A result of the treatment is also noted. Some events may be missing one or more pieces of data. A '/' mark indicates the data that could not be found in the daily drilling report for a particular event.

Table 3.9.Well 1 Data, Dammam Formation

, (m)	ρmud, (gm/cc)	Yb	Spm	RPM	Nozzles	Type of losses	Type of Treatment	Result
438 - 512	1.06	12	110	60	WON	No Loss	/	/
512 - 562	1.07	20	130	70	WON	Complete Loss	H.V Mud	Fail
562 - 632	/	/	140	75	WON	Complete Loss	Blind Drilling	Success
632	/	/	140	75	No Bit	Complete Loss	Cement Plug	Fail
632	/	/	180	75	No Bit	Complete Loss	H.V Mud + Cement Plug	Success
632 - 668	1.05	14	100	55	WON	No Loss	/	Success
668 - 704	1.05	14	105	55	WON	No Loss	/	Success

For Well 1, there was complete loss of mud while drilling 512 m to 668 m. Treatments attempted included H.V. mud, blind drilling, and placing cement plugs. In this case, cement plug combined with H. V. mud and blind drilling successfully mitigated losses in two sections of the zone, but treatments in two other zones failed.

Appendix A provides a complete summary of the lost circulation events for the Dammam formation in all 50 wells used in the study.

3.5.2. Hartha Formation. The Hartha formation is the second zone that is usually prone to lost circulation problems. Mud losses in Hartha formation are more complicated than Dammam formation. This zone is deeper (formation top 1530 to 1640 m), and it is located below transitional zones like the Tayarat and Ummer-Radhuma zones which have abnormal pressures and H_2S flow.

Figure 3.4. shows the borehole and well construction typical of a well drilled in the South Rumaila Field at the time the well passes through the Hartha formation. 13-3/8" casing has been set, and most commonly a 12 ¼" bit is used to drill through the formation. The Dammam formation has been drilled and is exposed openhole while the Hartha is drilled. A lost circulation event is shown near the bottom of the openhole in Figure 3.4, but it is possible to have losses simultaneously the Dammam and the Hartha formations, or only losses in the Hartha as it is drilled.

Field methods used to drill the Hartha are similar to those noted for the Damman, i.e. reduced WOB, RPM, SPM; adjusting mud properties; slow are careful removal or insertion of drill pipe to avoid surging, and breaking gel strength with rotation. (South Oil Company, 2008).

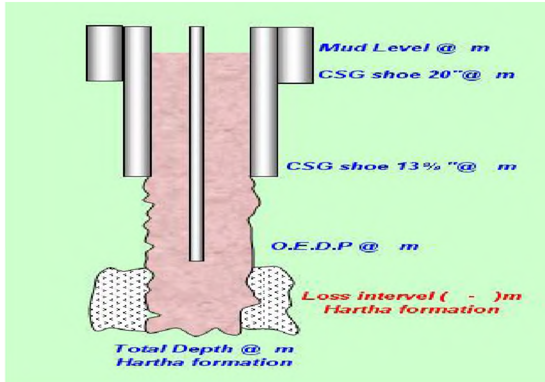


Figure 3.4. Lost Circulation mud in Hartha Formation

For Well 1, there were no lost circulation events while drilling the Hartha (Table 3.10) but in Well 2 (table 3.11), partial losses occurred from 1670-1740 m, and severe losses at 1795 m. In these cases, H.V. mud and blended LCM were able to resolve the lost circulation event. Appendix A provides a complete summary of the lost circulation events for the Hartha formation in all 50 wells used in the study.

Table 3.10. Well 1 Data, Hartha Formation

D, (m)	ρmud, (gm/cc)	Yb	Spm	RPM	Nozzles	Type of losses	Type of Treatment	Result
1674 - 1734	1.12	14	120	60	3*14/32	No Loss	/	Success
1734 - 1790	1.12	15	110	60	3*14/32	No Loss	/	Success
1790 - 1821	1.12	14	120	60	3*14/32	No Loss	/	Success

Table 3.11. Well 2 Data, Hartha Formation

D, (m)	ρmud, (gm/cc)	Yb	Spm	RPM	Nozzles	Type of losses	Type of Treatment	Result
1670 - 1740	1.13	16	120	60	3*14/32	Partial Losses	H.V Mud	Success
1740 - 1790	1.13	16	140	60	3*14/32	No Loss	/	Success
1795	1.14	17	150	70	WON	Severe Loss	Blend LCM	Success

It is possible to have losses in both the Hartha and Dammam formations at the same time due to the density difference required to drill the Hartha compared to the Dammam. But simultaneous losses are actually rare. Since both zones are exposed openhole, it is often difficult to diagnose which one of two zones has lost circulation because most clues will indicate mud losses in Hartha formation. In the case of complete mud loss, drill pipe pressure goes to zero. Remedial measures are executed first for the Hartha formation. If pressure still drops this indicates mud losses are actually occurring in Dammam formation, for these situations, the same techniques and mechanisms are used to mitigate lost circulation mud.

Some methods of lost circulation control cannot be readily applied in the Hartha formation. Two zones, Umm ER Radhuma and Tayarat, located above the Hartha, contain H_2S. If mud density is reduced to control loss into the Hartha, then a kick may occur in these shallower zones. Table 3.12 summarizes the close tolerances of mud density for these formations.

Table 3.12. Various Drilling Densities

Formation	Required Density, gm/cc
UMMER-RADHUMA	1.14 to 1.15
TAYARAT	1.14 to 1.15
HARTHA	1.12 to 1.13

In addition, if mud losses in the Hartha lower the mud level in the well, there will be a kick or blowout in Umm ER.Radhuma and Tayarat zones.

3.5.3. Shuaiba Formation. The Shuaiba formation occurs at approximately 2900 m and is a limestone with little to no visible porosity. However, the zone is highly susceptible to fracturing and lost circulation, which is more troublesome and even more complicated than lost circulation in the Dammam or the Hartha formations. Sometimes, mud losses in the Shuaiba formation lead to abandonment of the drilling operation due to unsustainable non-productive time (NPT) and drilling cost. Mud losses in Shuaiba also cause severe wellbore stability problems.

Therefore, it is very necessary to do some prior preparations and making to work meeting that consists of supervisor, mud engineer, log engineer, and geologist before drilling this formation in order to take all the necessary measures. Precise monitoring before and during drilling operations for Shuaiba formation.

Field methods used to drill the Hartha are similar to those noted for the Damman, i.e. reduced WOB, RPM, SPM; adjusting mud properties; slow are careful removal or insertion of drill pipe to avoid surging, and breaking gel strength with rotation. (South Oil Company, 2008). However, the level of planning and attention is far higher for this zone because it is the most problematic lost circulation zone amoung all fields. All rig and field personnel conduct extensive planning prior to drilling the Shuaiba. Increased supplies of lost circulation materials are ensured, and there is precise monitoring of all surface gauges (e.t. bit torque), the shale shaker, desilter, degasser and mud-cleaners.

Figure 3.5. shows the borehole and well construction typical of a well drilled in the South Rumaila Field at the time the well passes through the Shuaiba formation. Both the 13-3/8" and 9-5/8" casing strings have been set. Commonly an 8 $^{1/2}$" bit is used to drill through the formation.

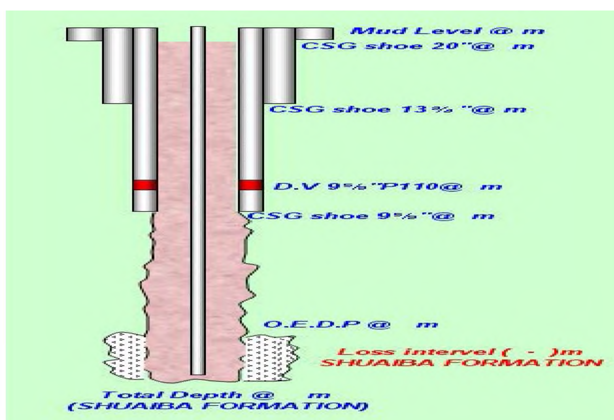


Figure 3.5. Lost Circulation mud in Shuaiba Formation

Tables 3.13 and 3.14 illustrate contrasting lost circulation events in the Shuaiba formation for Wells 1 and 2. Well 1 encountered two lost circulation events between 2993-3088m. The lost circulation was successfully controlled with H. V. Mud. Well 2 encountered a succession of lost circulation throughout the Shuaiba which could not be controlled until the lower portion of the zone, when diesel, bentonite and cement plugs were combined. Appendix A provides a complete summary of the lost circulation events tabled for the Shuaiba formation in all 50 wells used in the study.

Table 3.13. Well 1 Data, Shuaiba Formation

D, (m)	ρmud, (gm/cc)	Yb	Spm	RPM	Nozzles	Type of losses	Type of Treatment	Result
2993 - 3042	1.15	12	85	70	3*12/32	No Loss	/	Success
3042 - 3088	1.16	13	85	70	3*12/32	Partial Loss	H.V Mud	Success

Table 3.14. Well 2 Data, Shuaiba Formation

D, (m)	ρmud, (gm/cc)	Yb	Spm	RPM	Nozzles	Type of losses	Type of Treatment	Result
3024	1.17	14	80	65	3*12/32	Complete Loss	H.V Mud	Fail
3024 3038	/	/	80	65	3*12/32	Complete Loss	Blind Drilling	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3020 - 3038	/	/	80	65	No Bit	Complete Loss	H.V Mud + Cement Plug	Fail
3021 - 3038	/	/	80	65	No Bit	Complete Loss	H.V Mud + Cement Plug	Fail
3022 - 3038	/	/	80	65	No Bit	Complete Loss	Blend LCM + Cement Plug	Fail
3023 - 3038	/	/	80	65	No Bit	Complete Loss	Blend LCM + Cement Plug	Fail

It is also very crucial to take into account that Shuaiba formation is located below transitional zones like Mishrif, Mauddud, and Nahr Umr zones. These formations have abnormal pressures, so it is very prudent to consider this case in order to avoid collapse issues in formations like the Mishrif, Mauddud, and Nahr Umr.. Table 3.15 illustrates various required drilling densities for these formations. These zones will also be susceptible to a kick, should mud levels in the borehole fall due to lost circulation in the Shuaiba formation.

Table 3.15. Different Drilling Densities

Formation	Required Density, gm/cc
Mishrif	1.17 to 1.18
Nahr Umr	1.17 to 1.18
Shuaiba	1.15 to 1.16

3.6. DATA ANALYSIS AND RECOMMENDATIONS

This section provides an analysis of the lost circulation events tabled for more than 50 wells drilled in the Rumaila Field. The data is analyzed by formation to deduce drilling mud properties, operational drilling parameters, treatments Classifications, reason of the remedies failure, and practical guidelines that minimize lost circulation while drilling each formation.

3.6.1. Recommended Parameters to Drill the Thief Zones. By doing data review and integrated analysis for plenty of the wells (More than 50 wells) in order to find out optimal drilling mud parameters and proper operational drilling parameters to avoid or mitigate lost circulation mud in these formations as much as possible. In this study, several wells data have been examined to detect the typical range of the required parameters. Each of the property will be analyzed separately in order to figure out the influence of this property on the lost circulation.

1. Mud weight: This parameter has a pivotal role on lost circulation. By increasing drilling density, hydrostatic pressure will be increased. In the same vein, equivalent circulation density will be maximized. Therefore, excessive mud weight will

initiate or aggravate lost circulation problem. Hence, this property should be designed between pore pressure and fracture gradient to avoid unwanted consequences, and it is advisable to do strict surveillance during drilling operations. It is completely normal to change mud weight during drilling by depending on well conditions. In other words, we should not adhere in drilling program completely because it is possible to change drilling density by relying on drilling situation. Table 3.16, 3.17, and 3.18 will show pore pressure and fracture gradient for Dammam, Hartha, and Shiaba zones respectively (British Petroleum Company, 2013 and South Oil Company, 2010).

Table 3.16. Pore and Fracture Gradient for Dammam (British Petroleum, 2013)

Formation	Depth, m	PP, (gm/cc)	FP, (gm/cc)	PP, (gm/cc) + Swap Margin	FP, (gm/cc) - Surge Margin
Dammam	500	1.045	1.08	1.065	1.07

Table 3.17. Pore and Fracture Gradient for Hartha (British Petroleum Company, 2013)

Formation	Depth, m	PP, (gm/cc)	FP, (gm/cc)	PP, (gm/cc) + Swap Margin	FP, (gm/cc) - Surge Margin
Hartha	1660	1.1	1.14	1.12	1.13

Table 3.18. Pore and Fracture Gradient for Shuaiba (South Oil Company, 2010)

Formation	Depth, m	PP, (gm/cc)	FP, (gm/cc)	PP, (gm/cc)+ Swap Margin	FP, (gm/cc) - Surge Margin
Shuaiba	2990	1.13	1.18	1.15	1.16

Figure 3.6 shows a plot of lost circulation rate versus mud weight for the 50 wells drilled through the Dammam formation. The data show a noticeable increase in losses when the mud weight exceeds 1.06 gm/cc. Therefore, from this Plot, we can deduce that the optimal drilling density to drill Dammam formation is 1.05 gm/cc to 1.06 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

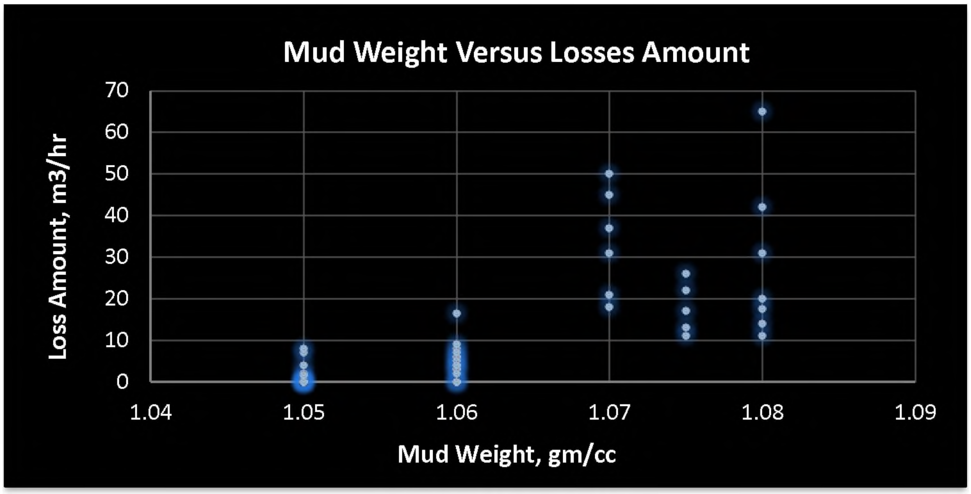


Figure 3.6. Mud Weight versus Losses Amount (Dammam Zone, 50 wells)

Figure 3.7 illustrate a plot of lost circulation rate versus mud weight for the 50 wells drilled through the Hartha formation. The data show a noticeable increase in losses when the mud weight exceeds 1.13 gm/cc. From this Plot, we can deduce that the optimal drilling density to drill Hartha formation is 1.12 gm/cc to 1.13 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

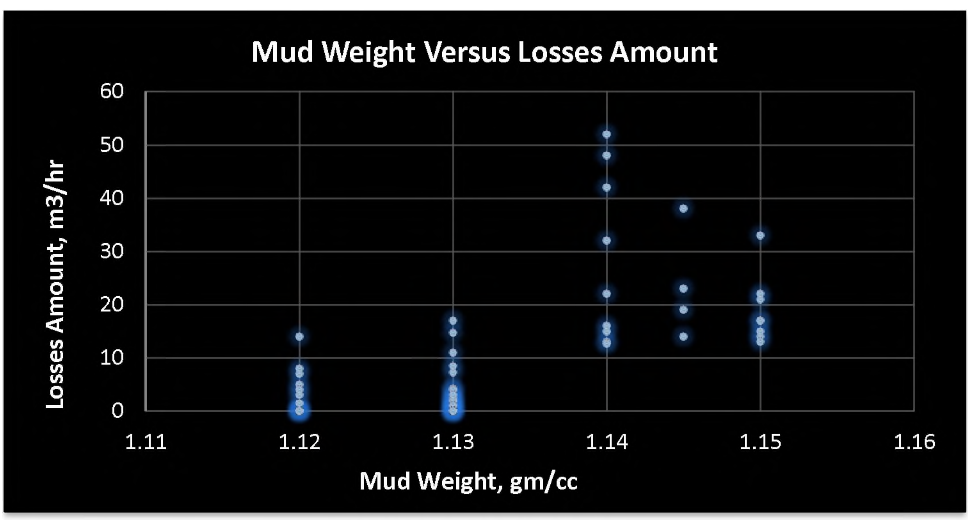


Figure 3.7. Mud Weight versus Losses Amount (Hartha Zone, 50 wells)

Figure 3.8 shows a plot of lost circulation rate versus mud weight for the 50 wells drilled through the Shuaiba formation. The data show a noticeable increase in losses when the mud weight exceeds 1.16 gm/cc. From this Plot, we can diagnose that the optimal drilling density to drill Shuaiba formation is 1.15 gm/cc to 1.16 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

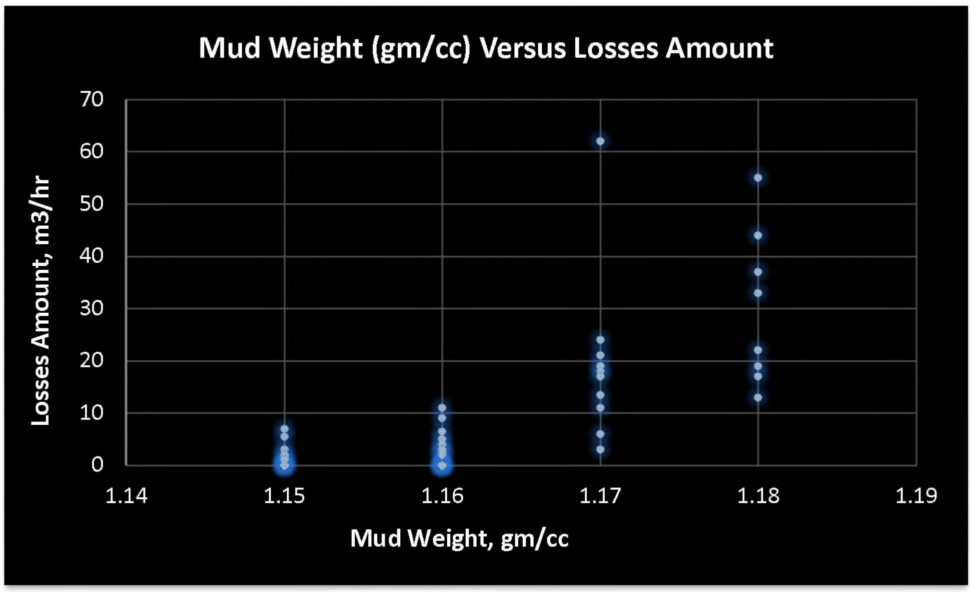


Figure 3.8. Mud Weight versus Losses Amount (Shuaiba Zone, 50 wells)

2. Equivalent circulation density (ECD): This property is related with real downhole pressure (Friction Pressure) into annulus. Therefore, it is much recommended to monitor this parameter during drilling operations. This property has linear relationship with yield point, mud weight, flow rate, rate of penetration. By doing gathering data for various wells that have been drilled to determine the optimal equivalent circulation density (ECD) which contribute to avoid or mitigate lost circulation issue in the thief zones.

Figure 3.9 shows a plot of lost circulation rate versus equivalent circulation density (ECD) for the 50 wells drilled through the Dammam formation. The data show a noticeable increase in losses when the ECD exceeds 1.075 gm/cc. Therefore, from this Plot, we can see that proper equivalent circulation density to drill Dammam formation is 1.06 gm/cc to 1.075 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

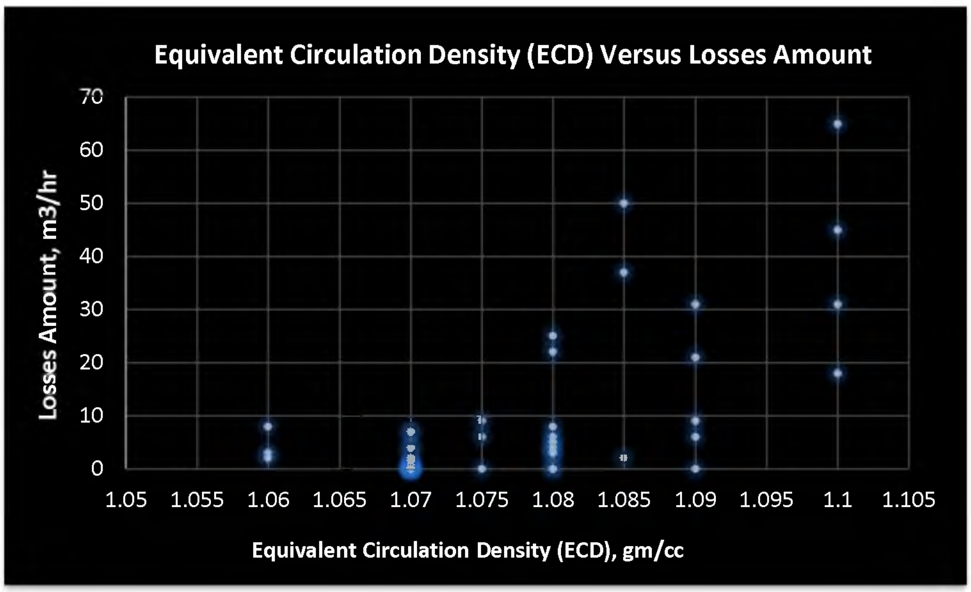


Figure 3.9. Equivalent Circulation Density (ECD) versus Losses Amount (Dammam Zone, 50 wells)

Figure 3.10 shows a plot of lost circulation rate versus equivalent circulation density (ECD) for the 50 wells drilled through the Hartha formation. The data show a noticeable increase in losses when the ECD exceeds 1.15 gm/cc. From this Plot, we can note that proper equivalent circulation density to drill Hartha formation is 1.13 gm/cc to 1.15 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

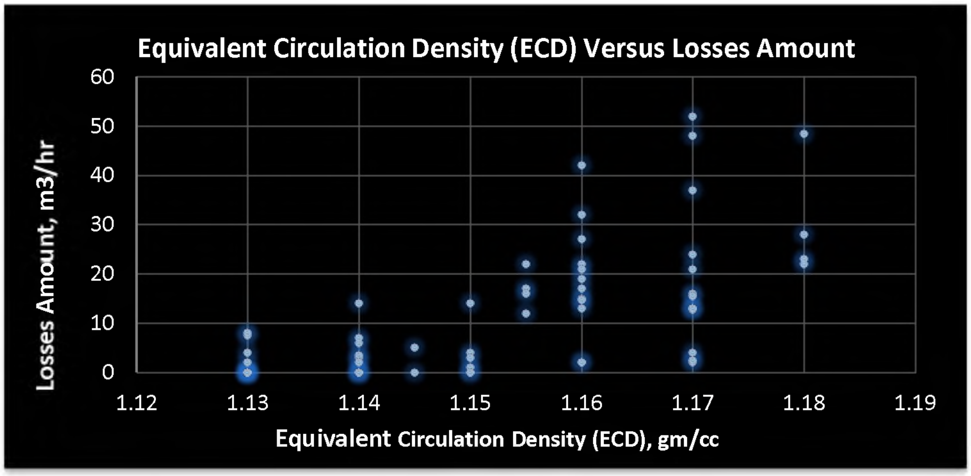


Figure 3.10. Equivalent Circulation Density (ECD) versus Losses Amount (Hartha Zone, 50 wells)

Figure 3.11 shows a plot of lost circulation rate versus equivalent circulation density (ECD) for the 50 wells drilled through the Shuaiba formation. The data show a noticeable increase in losses when the ECD exceeds 1.18 gm/cc. From this Plot, we can see that proper equivalent circulation density to drill Shuaiba formation is 1.16 gm/cc to 1.18 gm/cc. By using these values, we can avoid or mitigate lost circulation as much as possible.

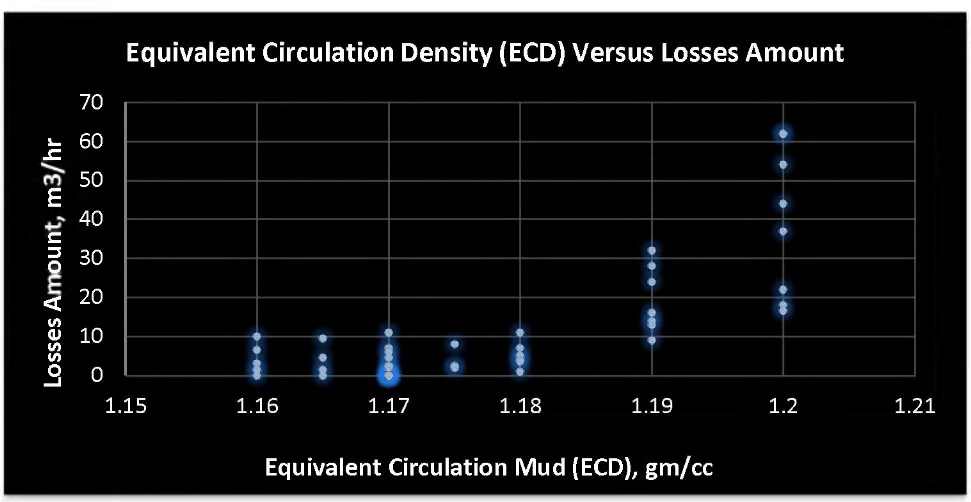


Figure 3.11. Equivalent Circulation Density (ECD) versus Losses Amount (Shuaiba Zone, 50 wells)

3. Yield point (Yp): Efficient hole cleaning is largely relying on yield point. In other words, this property is responsible to suspend and lift cutting to the surface. During drilling operations, this property calls yield point, and during static drilling operations calls gel strength. Bentonite is one of the most important materials that provides a good yield point, and in the same time, there are other materials like salt clay, PAC-HV, CMC-HV, and lime. There are some chemical materials, which use to control and decrease this property. By increasing this property, equivalent circulation density (ECD) will also maximize. Therefore, it is advisable to maintain this property within upper and lower bound limits. In addition, this parameter is completely depending on the type of drilling mud.

Figure 3.12 demonstrates a plot of lost circulation rate versus yield point (Yp) for the 50 wells drilled through the Dammam formation. The data show a noticeable increase in losses when the yield point exceeds 25 Ibf/ft^2. Polymer mud was used for these wells. From this figure, we can diagnose that proper yield point (Yp) that should be used to drill Dammam zone is from 20 Ibf/ft^2 to 25 Ibf/ft^2. By using these values, we can provide efficient hole cleaning and decrease equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

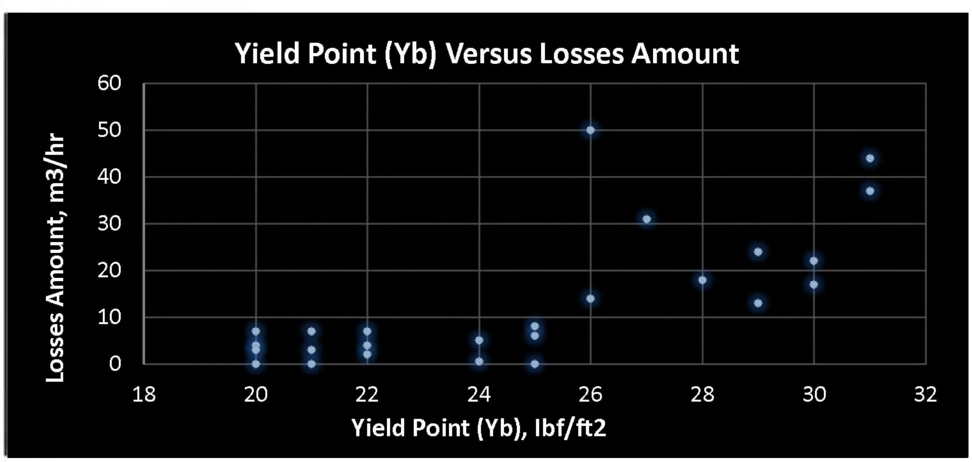


Figure 3.12. Yield Point (Yp) versus Losses Amount (Dammam, Polymer Mud, 30 Wells)

Figure 3.13 deonstrates a plot of lost circulation rate versus yield point (Yp) for the 50 wells drilled through the Hartha formation. The data show a noticeable increase in losses when the yield point exceeds 24 Ibf/ft^2. Polymer mud was used for these wells. From this plot, we can diagnose that proper yield point (Yp) that should be used to drill Hartha zone is from 20 Ibf/ft^2 to 24 Ibf/ft^2. By using these values, we can provide efficient hole cleaning and decrease equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

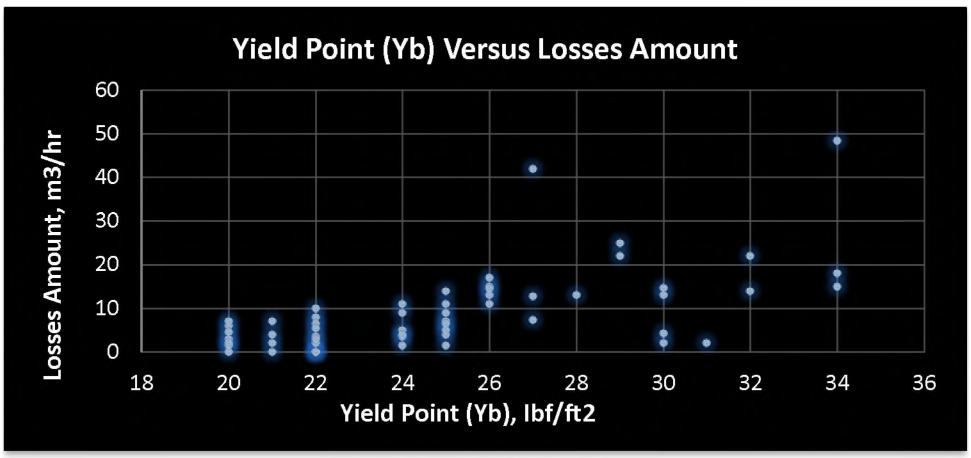


Figure 3.13. Yield Point (Yp) versus Loss Amount (Hartha Zone, Polymer Mud, 30 Wells)

By using fresh water-bentonite mud (FWB-Mud) for Dammam and Ferro Chrome Lignosulfonate mud (FCL-Mud) for Hartha and shiaba zones, values of the yield point (Yp) will be different. In this type of the mud, we will largely depend on bentonite material to increase this property. Figure 3.14, 3.15, and 3.16 will illustrate the different range of the yield point (Yp) due to different type of the mud for Dammam, Hartha, Shiaba zones respectively.

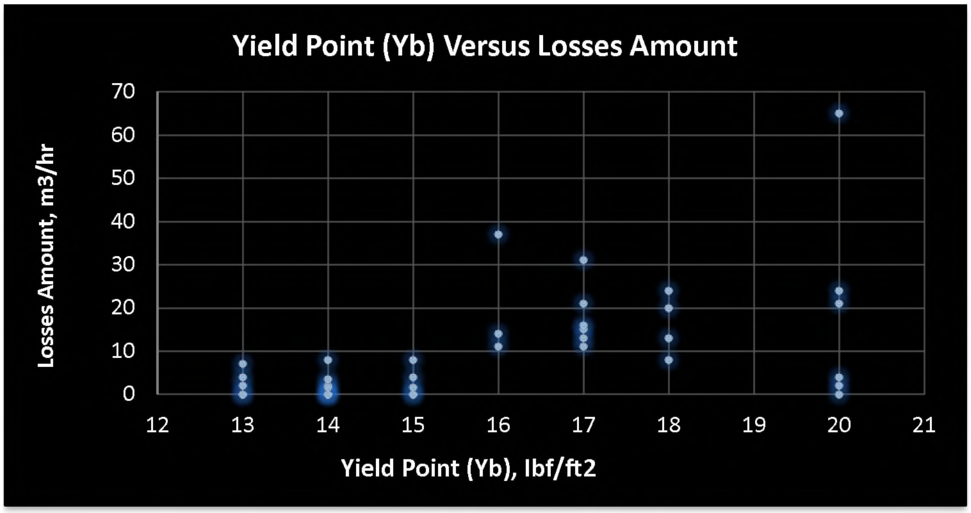


Figure 3.14. Yield Point (Yp) versus Loss Amount (Dammam Zone, FWB Mud, 30 Wells)

From above figure 3.14, we can conclude that proper yield point (Yp) that should be used to drill Dammam zone is from 13 Ibf/ft^2 to 15 Ibf/ft^2. By using these values, we can provide efficient hole cleaning and decrease equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

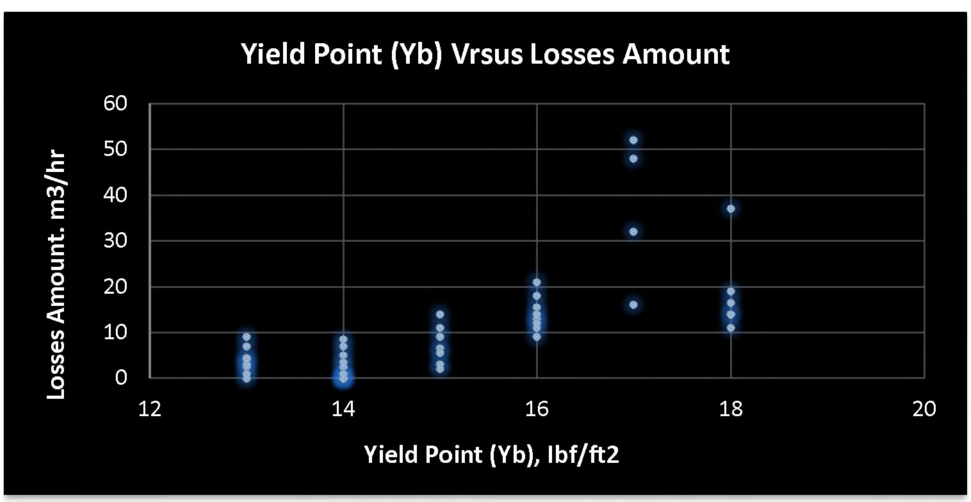


Figure 3.15. Yield Point (Yp) versus Losses Amount (Hartha Zone, FCL Mud, 30 Wells)

From above figure 3.15, we can conclude that proper yield point (Yp) that should be used to drill Hartha zone is from 13 Ibf/ft^2 to 15 Ibf/ft^2. By using these values, we can provide efficient hole cleaning and decrease equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

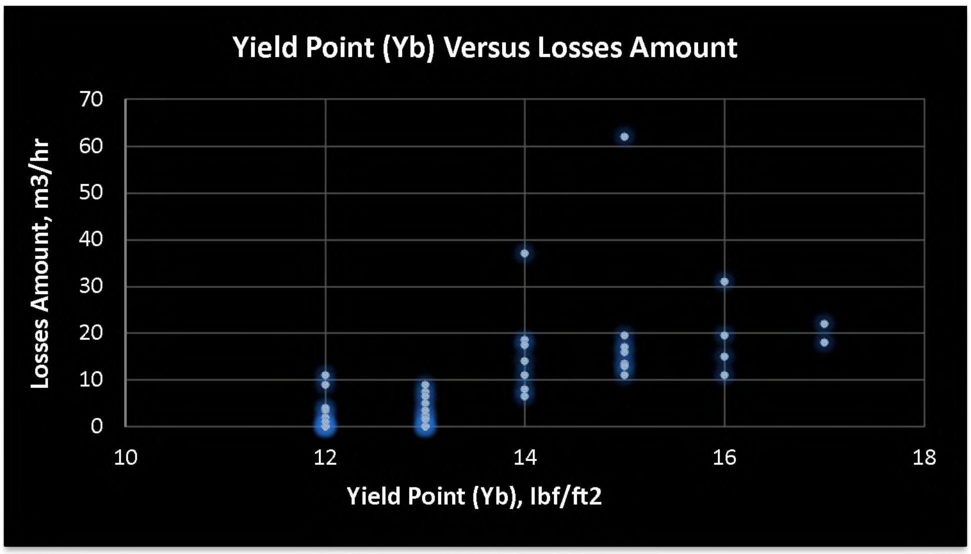


Figure 3.16. Yield Point (Yp) versus Losses Amount (Shiaba Zone, FCL Mud, 50 Wells)

From above figure 3.16, we can conclude that proper yield point (Yp) that should be used to drill Shuaiba zone is from 12 Ibf/ft^2 to 13 Ibf/ft^2. By using these values, we can provide efficient hole cleaning and decrease equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

4. Strokes per minute (SPM): This parameter is related to flow rate. It is responsible about drilling mud cycle from mud system to wellbore by using mud pumps. In addition, this property is associated with effective wellbore cleaning into annulus. This parameter has either directly or indirectly role on lost circulation issue. In other words, by using high mud pump pressure, extra annulus pressure will be on the thief zone. Hence, it is recommended to use proper range of this parameter.

Figure 3.17 shows a plot of lost circulation rate versus strokes per minute (SPM) for the 50 wells drilled through the Dammam formation. The data show a noticeable increase in losses when the SPM exceeds 110. From this figure, we can conclude that proper strokes per minute (SPM) that should be used to drill Dammam zone is from 100 SPM to 110 SPM. By using these ranges, we can provide efficient hole cleaning, decrease downhole pressure, equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

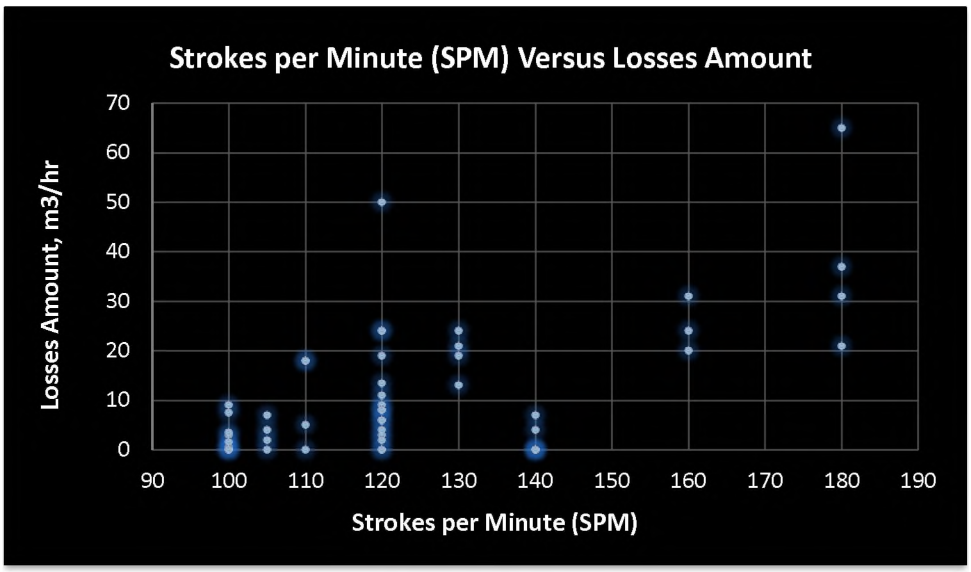


Figure 3.17. Strokes per Minute (SPM) versus Losses Amount (Dammam Zone, 50 wells)

Figure 3.18 shows a plot of lost circulation rate versus strokes per minute (SPM) for the 50 wells drilled through the Hartha formation. The data show a remarkable increase in losses when the SPM exceeds 120. From this figure, we can diagnose that proper strokes per minute (SPM) that should be used to drill Hartha zone is from 100 SPM to 120 SPM. By using these ranges, we can provide efficient hole cleaning, decrease downhole pressure, equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

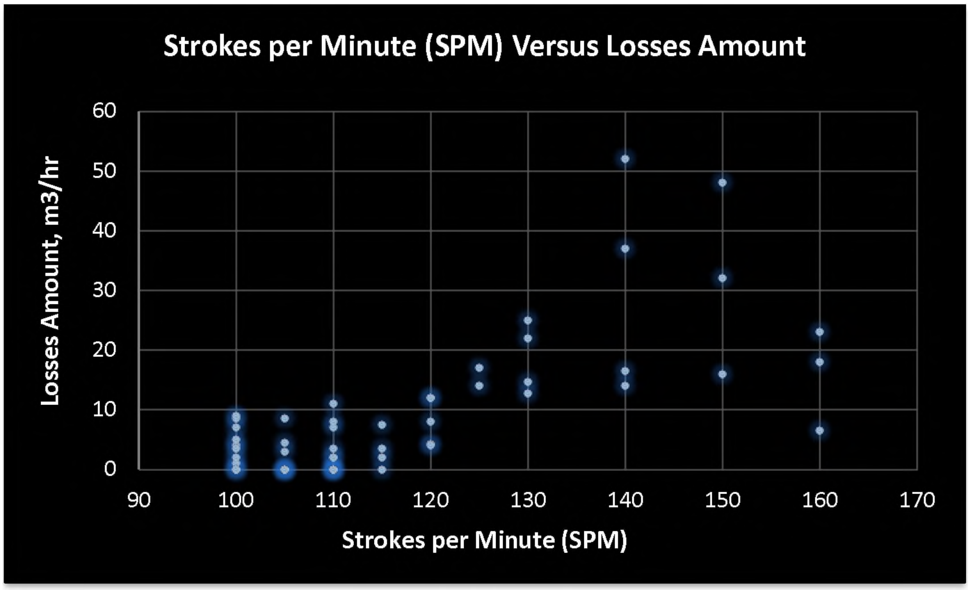


Figure 3.18. Strokes per Minute (SPM) versus Losses Amount (Hartha Zone, 50 wells).

Figure 3.19 shows a plot of lost circulation rate versus strokes per minute (SPM) for the 50 wells drilled through the Shuaiba formation. The data show a remarkable increase in losses when the SPM exceeds 90. From this figure, we can diagnose that proper strokes per minute (SPM) that should be used to drill Shuaiba zone is from 80 SPM to 90 SPM. By using these ranges, we can provide efficient hole cleaning, decrease downhole pressure, equivalent circulation density (ECD) and losses pressure (Friction Pressure) into annulus.

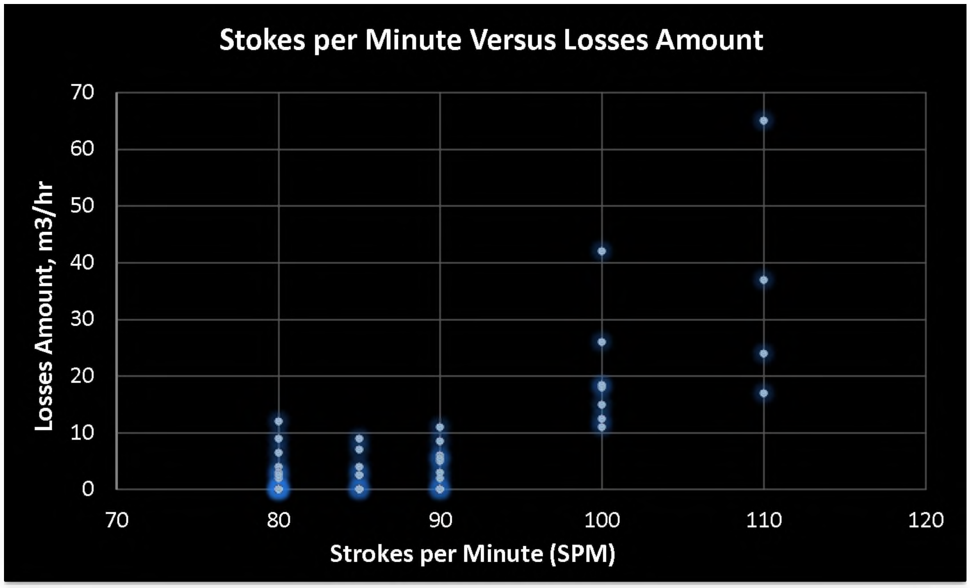


Figure 3.19. Strokes per Minute (SPM) versus Losses Amount (Shuaiba Zone, 50 wells)

5. Revolutions per minute (RPM): This property is related to rotate drill string, bit, and penetration rate. That means by using high RPM that will lead to have excessive cutting into annulus, which in turn, it will increase downhole pressure and narrow annulus. Therefore, it is crucial to use RPM parameter within upper and lower bound limits to avoid unwanted consequences. Figure 3.20, 3.21, and 3.22 will clarify the relationship between revolutions per minute (RPM) and the loss amount for Dammam, Hartha, Shiaba zones respectively.

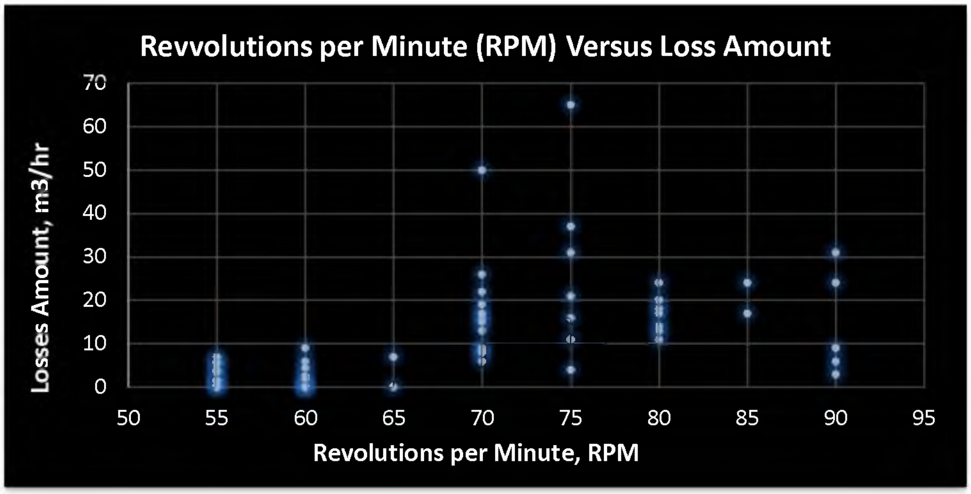


Figure 3.20. Revolutions per Minute versus Losses Amount (Dammam Zone, 50 wells)

From above figure 3.20, we can deduce that appropriate revolutions per minute (RPM) that is advisable to us to drill Dammam zone is from 55 RPM to 65 RPM. By using these ranges, we can provide a good penetration rate, decrease cutting amounts, and minimize friction pressure into annulus.

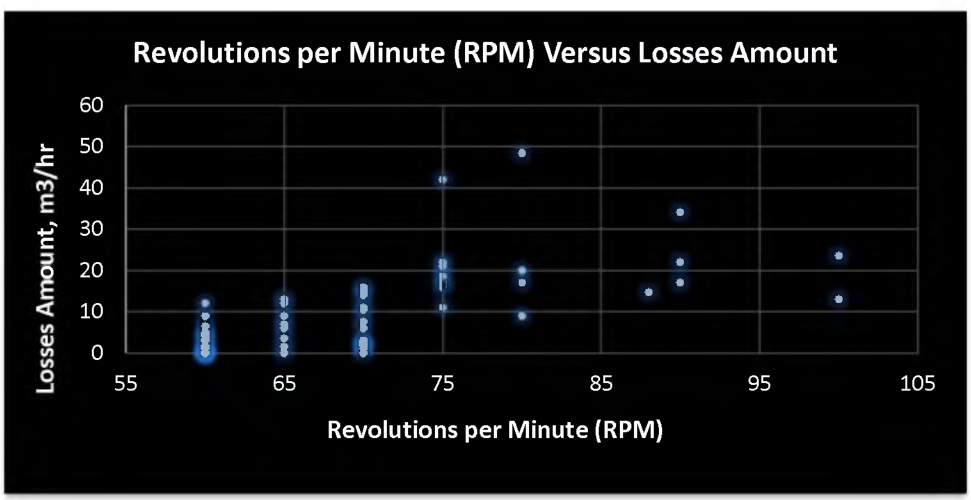


Figure 3.21. Revolutions per Minute (RPM) versus Loss Amount (Hartha Zone, 50 wells)

From above figure 3.21, we can deduce that appropriate revolutions per minute (RPM) that is advisable to us to drill Hartha zone is from 60 RPM to 70 RPM. By using these ranges, we can provide a good penetration rate, decrease cutting amounts, and minimize friction pressure into annulus.

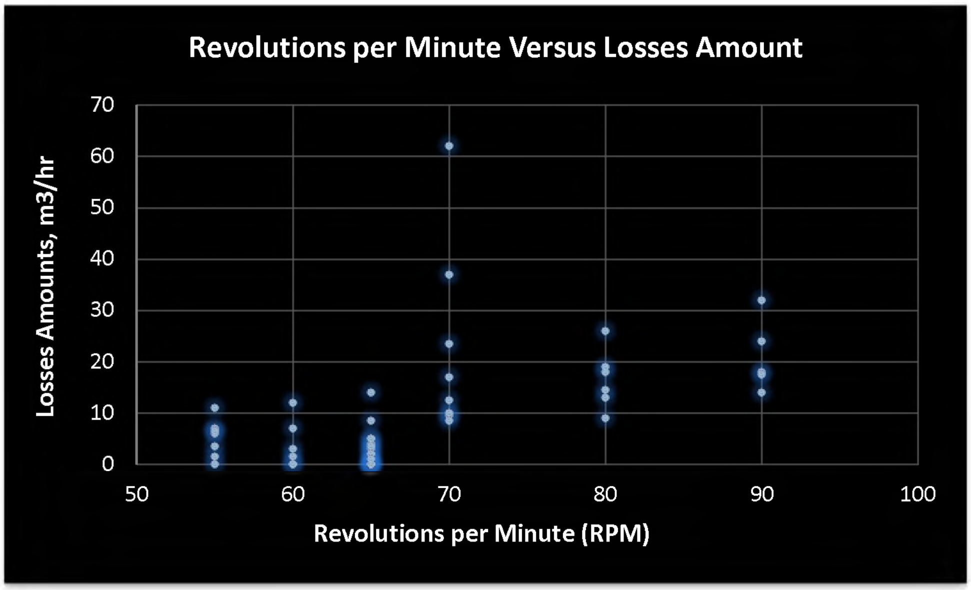


Figure 3.22. Revolutions per Minute (RPM) versus Loss Amount (Shuaiba Zone, 50 wells)

From above figure 3.22, we can deduce that appropriate revolutions per minute (RPM) that is advisable to us to drill Shuaiba zone is from 55 RPM to 65 RPM. By using these ranges, we can provide a good penetration rate, decrease cutting amounts, and minimize friction pressure into annulus.

6. Bit without nozzles (WON): It is advisable to use bit without nozzles during drilling Dammam formation for several reasons like to reduce jet velocity on the formation, minimize non-productive time (NPT), to use any type of lost circulation mud (LCMs), and to avoid nozzles plugging. In the same time, by doing a broad research for various drilled wells, it showed there is no side effect due to bit without nozzles during drilling weak zones. Therefore, it is practically interest to use bit without nozzles (WON).

Hence, after doing analysis for various drilled wells in south Rumaila field, it is recommended to use the following values to drilling mud properties and operational drilling parameters to avoid or mitigate lost circulation issue during drilling operations. Table 3.19, 3.20, and 3.21 will show recommend parameters to drill Dammam, Hartha, Shuaiba zones respectively.

Table 3.19. Recommended Drilling Mud Properties and Operational Drilling Parameters for Dammam Formation

Property	**Minimum Value**	**Maximum Value**
Mud Weight (ρmud),	1.05	1.06
Equivalent Circulation Density (ECD),(gm/cc)	1.06	1.075
Yield Point (Yp), (Ibf/ft3) (Polymer Mud)	20	25
Yield Point (Yp), (Ibf/ft3) (FWB Mud)	13	15
Strokes per Minute (SPM)	100	110
Revolutions per Minute (RPM)	55	65
Bit Nozzles	Without Nozzles	Without Nozzles

Table 3.20. Recommended Drilling Mud Properties and Operational Drilling Parameters for Hartha Formation

Property	**Minimum Value**	**Maximum Value**
Mud Weight (ρmud),	1.12	1.13
Equivalent Circulation Density (ECD),(gm/cc)	1.13	1.15
Yield Point (Yp), (Ibf/ft3) (Polymer Mud)	20	24
Yield Point (Yp), (Ibf/ft3) (FCL Mud)	13	15
Strokes per Minute (SPM)	100	120
Revolutions per Minute (RPM)	60	70
Bit Nozzles	Without Nozzles	Without Nozzles

Table 3.21. Recommended Drilling Mud Properties and Operational Drilling Parameters for Shuaiba Formation

Property	Minimum Value	Maximum Value
Mud Weight (ρmud),	1.15	1.16
Equivalent Circulation Density, (gm/cc)	1.16	1.18
Yield Point (Yp), (Ibf/ft3) (FCL Mud)	12	13
Strokes per Minute (SPM)	80	90
Revolutions per Minute (RPM)	55	65
Bit Nozzles	Without Nozzles	Without Nozzles

In some cases, under the same above parameters, Thief zone will suffer from sever losses circulation problem or even complete losses. In these cases, the major reason to have these types losses is using high range of the drilling properties and operational drilling parameters. In different words, the lost circulation will initiate due to high ranges of the above parameters. After problem occurred even if low ranges of the parameters are used, the problem will continue and we need to do the required treatments to mitigate or stop mud losses.

3.6.2. Preparations before Starting to Drill These Formations. Many steps must to take and prepare for them before drilling the formations, which are prone to lost circulation mud (South Oil Company, 2008).

- Prior preparation for work meeting which consists of supervisor, mud engineer, log engineer, and geologist before drilling formations which are prone for mud losses in order to take all the necessary measures.
- Providing a sufficient amount of drilling mud for emergencies especially bentonite material.
- By supplying required precautions of various lost circulation materials.
- Determination accurate depth of the mud losses in these formations by strict monitoring and by depending on previous geological information and old documents.
- It is necessary to change drilling mud properties before entering these formations to avoid or mitigate sudden losses.

- Prior preparation for drilling fluid with low mud weight in anticipation for any increasing in the drilling mud density during drilling operations.
- Prior planning by mixing sufficient amount of the high viscosity mud (Pill) to provide quick remedy for partial losses.
- In case severe or complete losses are occurred, it is better to continue in drilling operations as much as possible. After that, pulling out drilling strings from hole to case shoe and using required remedies.
- It is recommended in some cases to use the wellbore strengthening technique especially during drilling Hartha and Shuaiba zones to avoid lost circulation mud due to narrow mud weight window. Because Hartha zone is located below high pressure formation like Rus, Umm ER-Radhuma, and Tayarat; therefore, it is important to use the wellbore strengthening technique. In addition, Shuaiba formation is also located below high pressure formation like Nahr Umr and Mishrif zones, so it is practically interest to use the wellbore strengthening methods. The main advantage of using this approach is to increase the fracture gradient of the formation and the hoop stress. This provides an opportunity to use higher mud weight windows for drilling, especially, weaker and depleted formations. In different words, by using wellbore strengthening approach, the range of the mud weight window will increase.

3.6.3. Occurrence Indicators to Lost Circulation. The results of an investigation conducted in order to diagnose occurrence indicators of lost circulation in the Southern Remaila field (South Oil Company, 2008).

1. Gradual decline in mud level in the drilling fluid tanks system. Sometimes, this gradual decline will aggravate to high drop which lead to lose returns from wellbore in case complete lose.
2. Remarkable decline in the mud pumps pressure. Sometimes, this decline may be reach to zero in the complete losses situation.
3. Penetration rate for bit will be high.

3.6.4. Importance of the Location for Open End Drill Pipe (O.E.D.P). The location of the open end drill pipe (O.E.D.P) is one of the most important factors that assist to prevent or mitigate lost circulation mud. Therefore, it is very necessary to place open end drill pipe (O.E.D.P) in appropriate depth to avoid unwanted consequences. Hence, there are three locations for open end drill pipe (O.E.D.P) (South Oil Company, 2008):

1. Bottom of the loss zone: This location usually selects to determine accurate depth for thief zone and try to seal loss zone in the same time. If the loss zone is small, and it is easy to control on it, it is prudent to be careful and use relatively low flow rate during displacement in order to avoid pressure increasing on the loss zone. This location of open end drill pipe (O.E.D.P) is usually used for high viscosity drilling mud and LCMs remedies

2. Above of the loss zone: This location is effective and successful. It is very common, and it is used in the most remedies and plugs. This location of open end drill pipe (O.E.D.P) is often used in balanced plugs that depends on hydrostatic pressure calculations. It is much recommended to determine required height above the loss zone.

3. Middle of the loss zone: This location is not common, and it rarely select to implement remedies and plugs. This location is hazardous, and it often lead to aggravate lost circulation mud in the loss zone by increasing pressure on the zone that in turn lead to break formation. This location is usually used for high viscosity drilling mud and LCMs remedies. It is not preferred to do cement plugs in this kind of location.

3.6.5. Lost Circulation Strategy to South Rumaila Field. This section will be summarized the required treatments for each type of the lost circulation. Figure 3.23 is concluded by depending on data analysis for treatments that were used for thief zones (Dammam, Hartha, and Shuaiba). More than 50 wells have been studies to figure out successful remedies for each type of the losses, and these treatments are classified by relying on the losses classifications in order to get effective remedies, minimize cost, reduce non-productive time, avoid unwanted consequences due to inappropriate actions.

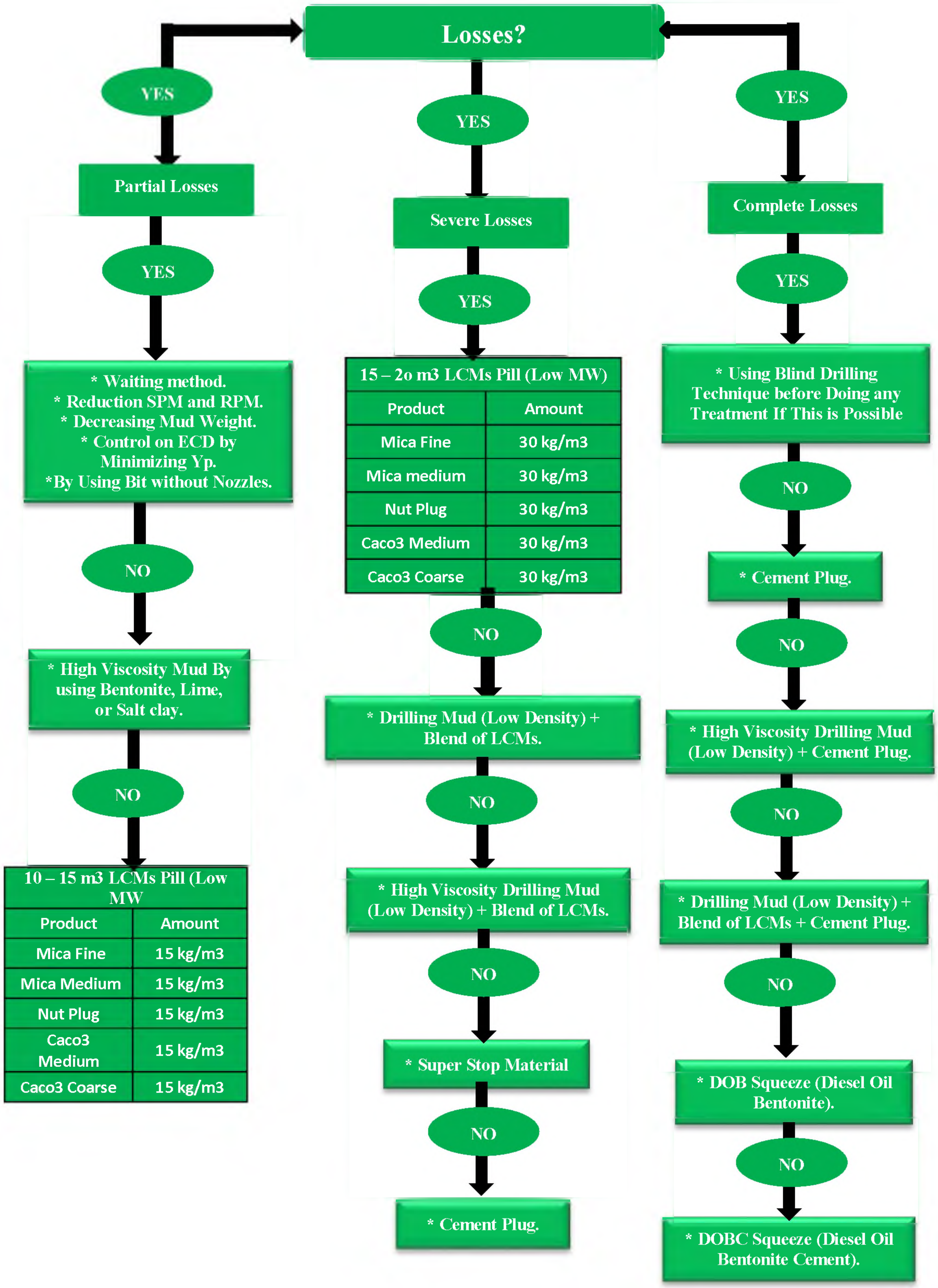


Figure 3.23. Lost Circulation Strategy to South Rumaila Field

3.6.6. Reasons for Failure to Cure Lost Circulation. The reasons for failure to cure lost circulation are:

1. The first step to combat lost circulation mud is accurate identification to the loss zone. Sometimes, there is not exact information about the location of the thief zone that will lead to fail remediation. To avoid non-productive time and money wasting by repeating ineffective treatment, it is very necessary to run one of the survey methods to know the precise location of the loss zone.
2. There is no sufficient study and integrated analysis for loss zone before treatment. In different words, remediation and techniques are not appropriate to the type and riskiness of the thief zone
3. Failure to take the necessary measures quickly.
4. Old documents like daily reports and detailed applications are not kept for the same field. It is very crucial to save all techniques and mechanisms that have already been used for several wells as reference for next methods.
5. Contamination the pill or plug with drilling mud which lead to reduce or prevent proper settings for treatment. So, some techniques and methods are affected negatively due to this contamination. Hence, it is necessary to apply balanced column methods to avoid this dilemma.
6. Bad application for the squeeze pressure method. In other words, by using high squeeze pressure for the treatment that will lead to create fractures and aggravate the problem. Hence, drilling mud pressure plus surface pressure should be lesser than fracture gradient pressure.
7. Gunk ratios to drilling mud are not appropriate. It is very important to apply ratio of mud-to-gunk accurately in order to have sufficient viscosity and good strength for plug to stop losses.
8. The lack of a crucial decision or hesitation to take appropriate remedies. Sometimes, application of the unsuccessful remedies lead to aggravate mud losses problem.
9. No information regarding geometry of the fractures, vugs, and caves.

10. Calculations will not be accurate regarding the fluid displacement, the volume of the plug, pressure of the loss zone, and the required density of the treatment. Therefore, that will strongly reflect negatively on the effectiveness of the remedies.
11. No appropriate selection to type of the treatment. Selected remedies should be used by depending on the type of the loss mud in order to reduce expense and non-productive time.
12. The absence of the engineering approaches in the executive solutions.
13. Insufficient thickening time for plugs to harden.

3.6.7. Practical Guidelines to Stop or Mitigate the Lost Circulation. It is important to do prior preparation for any contingency plans like sufficient materials of the drilling mud especially bentonite material, enough amounts LCMs, and adequate water source in order to control on the drilling operations.

- It is much recommended to do the following actions before do the required remedies:
  1. Determine the top and the bottom of the loss zone.
  2. Detect the type of the lithology.
  3. Diagnose the type of the losses.
  4. Estimate the pressure in the loss zone.
  5. Do precise calculations for the required treatments.
- It is practically interest to drill the thief zone as much as possible by using blind drilling method, and then do the required remedy.
- A quick economic evaluation is desirable before do any action.
- It is necessary to reduce human error as much as possible by preparing optimal drilling program, monitoring to apply this program during drilling operations, and avoiding mechanical issues. The following drilling practices have already been identified, which have a prominent role on the problem of the lost circulation mud:

1. High pump pressure (High SPM) will lead to generation of excessive equivalent circulation density (ECD). Therefore, it is preferable to use the lowest circulation rate that will clean the hole adequately.
2. High rotation (High RPM) and high circulation rates directly after shutdown, it will cause more pressure on the loss zone. Hence, if drilling operations are under shutdown situation, it is the best to rotate drilling strings with low RPM about 15 minutes without mud circulation when drilling operations resume in order to break gel strength.
3. Running drill string into wellbore quickly will affect negatively on the weak formations. Therefore, it is a desirable to lowering drill strings into wellbore slowly in front of unconsolidated zones.
4. Do strict surveillance to downhole annular pressure and make sure that the equivalent circulation density (ECD) within allowable limits.

- Formations which are prone to the mu losses, it is preferable to add sized LCM in the drilling mud before drilling these formation, because that will improve the strength of the weak formation, widen the fracture gradient, and prevent or mitigate induced fractures from propagating beyond their initiation stages.
- By depending on broad research, Graphitic carbon and sized calcium carbonate are effective LCMs, and it is advisable to add to the drilling mud before drilling depleted and weak zone as wellbore strengthening approach.
- It is important to avoid high concentration of the coarse LCMs in order to avoid excessive equivalent circulation mud (ECD).
- Lost circulation materials (LCMs) have many various forms, and each of them has specific properties and cost. The performance of the lost circulation materials (LCMs) is basically relied on its particle size distribution (PSD), shape, size, and concentration.
- It is practically interest to reduce yield point (Yp) and the solids content of the drilling mud within allowable limits in order to reduce gel strength and equivalent circulation density (ECD) rather than using lost circulation materials (LCMs).

- Economic aspect has a pivotal role whether to use wellbore strengthening approaches as proactive remedies or deal with the problem when/if the problem occurs.
- During handling losses, it is much recommended to get ready for well control issues.
- Proper selection for the type of the remedies in order to avoid non-productive time and reduce expenses.
- It is very advisable to get integrated image about the geometry of the formations that are prone to mud losses by using image log or caliper log in order to do proper actions.
- It is very essential to provide sufficient time to harden plugs into wellbore especially cement and barite plugs to enhance compressive strength for treatment and get good results.

4. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1. SUMMARY

This thesis has provided a detailed study of lost circulation, including a brief review of fundamentals of lost circulation, a discussion of methods of mitigating losses and an introduction to newer methods of loss control used in industry.

The central focus of the work has been to review the daily drilling reports for 50 wells drilled in the South Rumaila field, where the Dammam, Hartha and Shuaiba formations are prone to lost circulation problems. Lost circulation events extracted from the drilling reports, and key drilling parameters and mud properties at the time of each event, were recorded along with the lost circulation remedies attempted, and the outcome of those remedies. The data were analyzed to determine ranges for the key drilling parameters and mud properties that have the greatest chance of mitigating lost circulation in each of the three formations.

In addition, practical information from journals, papers, textbooks, and confidential company manuals were carefully reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the South Rumaila Field.

Best field procedures for avoiding or minimizing lost circulation events in the South Rumailia field were identified and were provided as tabled procedures, or as additional data in the appendices of this thesis.

Finally, it should be noted that this thesis provides a unique compilation of information regarding traditional approaches and the latest approaches of lost circulation control. Traditional approaches of lost circulation are used widely in the Rumailia field and other, newer methods are evolving in their use. This thesis attempts to provide useful guidelines of references for both situations.

4.2. CONCLUSIONS

In short, this problem is very common, and most fields in the world suffer from lost circulation mud in the drilling engineering. So it is very essential to research, study, and prepare some studies and researches to avoid or mitigate this problem because that will reflect positively on the oil industry especially the drilling operations in terms time and cost.

Based on this study, the following conclusions are made:

- Based on reviewing drilling reports, it is possible to extract lost circulation event data and determine operational parameters and drilling mud paramaeters that can mitigate mud losses while drilling through the Dammam, Hartha and Shuaiba formations.
- The optimal parameters summarized in this work (Tables 3.19, 3.20 and 3.21) are all within the range of parameters currently used to drill wells for thief zones in Rumaila field and it should be feasible to restrict the properties to these values and still successfully drill to TD.
- One challenge in drilling wells in the Rumaila field is the inconsistency of approaches to the lost circulation problem. Hence, a formalized methodology for responding to losses in the Rumaila field is developed and provided as means of assisting drilling personnel to work through the lost circulation problem in a systematic way.
- Sometimes, it is of a practical interest to do preventive measures and wellbore strengthening approaches before occurrence lost circulation mud.
- A plenty of the factors which contributes to provide successful control or treatment on mud losses like borehole temperature, pressure, depth, geometry of the fractures, type of the lithology, and size of the thief zone.
- It is not easy to find guaranteed methods which entirely control or solve lost circulation problems. However, there are some techniques and approaches can be used to prevent its occurrence
- Practical guidelines have been developed that will contribute to give clear image regarding this complicated problem.

4.3. RECOMMENDATIONS

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

- It is crucial to do experimental works for many materials and blend of the materials in order to find optimum mixture to control or mitigate mud losses and apply all these laboratory treatments in the field to determine their effectiveness.
- It is practically interest to apply laboratory works in the field in order to figure out the validity of these treatments in terms wellbore conditions.
- It is very beneficial to classify the remediation by depending on the lithology of the thief zone.
- It is very complicated to exactly determine the geometry of the fractures, so it is of a practical interest to find material or blend of the LCMs which is fixable and appropriate for each kinds of the fractures.
- It is very important to study the side effect of the LCMs especially for the productive zone.
- Since the subject of lost circulation control is very broad and very complex, so it is better to establish work team of the various disciplines that are related to drilling engineering in order to get creative solutions and integrated methods to control or mitigate lost circulation.

APPENDIX A

DATA FOR MORE THAN 50 WELLS FOR DAMMMAM, HARTHA AND SHUAIBA IN THE SOUTH REMAILA FIELD

Table A.1. Collected Real Data for Dammam Zone,
(More than 50 wells, FWB Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2,	SPM	RPM	Type of Losses	Treatment	Result
1.05	1.08	13	110	60	No Loss	No Treatment	Success
1.05	1.085	20	120	70	Partial Loss	H.V Mud	Fail
1.05	1.07	14	100	55	No Loss	No Treatment	Success
1.05	1.08	14	120	70	Partial Loss	H.V Mud	Success
1.05	1.08	13	120	70	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.05	1.07	13	105	70	No Loss	No Treatment	Success
1.05	1.1	17	110	80	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.05	1.09	20	120	90	Complete Loss	Plug Cement	Fail
1.05	1.06	14	100	60	No Loss	No Treatment	Success
1.05	1.07	16	105	65	Partial Loss	H.V Mud	Success
1.05	1.07	15	105	65	Partial Loss	H.V Mud	Fail
1.05	1.08	17	120	90	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.05	1.07	13	120	65	No Loss	No Treatment	Success
1.05	1.08	14	110	70	Partial Loss	H.V Mud	Success
1.06	1.1	19	110	90	Severe Loss	Super Stop Material	Success
1.06	1.08	15	120	75	Partial Loss	H.V Mud	Fail
1.06	1.08	16	180	75	Partial Loss	H.V Mud	Fail
1.06	1.07	15	140	55	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.07	18	120	55	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.07	14	110	65	No Loss	No Treatment	Success
1.06	1.09	20	140	70	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.06	1.09	20	140	70	Severe Loss	Cement Plug	Success
1.06	1.075	15	100	65	No Loss	No Treatment	Success
1.06	1.07	15	100	60	No Loss	No Treatment	Success
1.06	1.08	15	100	70	Partial Loss	H.V Mud	Success
1.06	1.075	14	140	60	Partial Loss	H.V Mud	Success
1.06	1.09	14	180	75	Severe Loss	Cement Plug	Success
1.06	1.07	14	105	60	No Loss	No Treatment	Success
1.06	1.07	14	100	60	No Loss	No Treatment	Success
1.06	1.07	17	100	60	No Loss	No Treatment	Success
1.07	1.08	17	100	70	Complete Loss	Cement Plug	Fail

Table A.1. Collected Real Data for Dammam Zone (Cont'd),
(More than 50 wells, FWB Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2,	SPM	RPM	Type of Losses	Treatment	Result
1.07	1.085	17	140	60	Complete Loss	DOB Plug	Success
1.07	1.085	17	180	75	Severe Loss	Cement Plug	Success
1.07	1.09	17	120	80	Complete Loss	Cement Plug	Fail
1.07	1.08	18	130	70	Complete Loss	Cement Plug + HV Mud	Success
1.07	1.08	18	120	90	Severe Loss	Super stop	Fail
1.08	1.085	18	120	75	Complete Loss	Cement Plug + HV Mud	Success
1.08	1.09	15	130	75	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.08	1.1	17	130	55	Complete Loss	Blend of LCM + Cement Plug	Success
1.075	1.08	13	100	55	Partial Loss	H.V Mud	Success
1.075	1.08	14	160	55	Severe Loss	Cement Plug	Fail
1.075	1.09	16	160	75	Complete Loss	Cement Plug	Fail
1.075	1.09	16	160	55	Complete Loss	DOCB Plug	Success
1.075	1.085	14	100	55	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.08	1.1	13	100	55	Complete Loss	Cement Plug + HV Mud	Fail
1.08	1.1	15	100	60	Complete Loss	Cement Plug	Fail
1.08	1.095	14	120	60	Severe Loss	Super stop	Success
1.08	1.085	13	100	60	Partial Loss	H.V Mud	Success

Table A.2. Collected Real Data for Dammam Zone,
(Around 50 wells, Polymer Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2,	SPM	RPM	Type of Losses	Treatment	Result
1.05	1.06	21	100	60	No Loss	No Treatment	Success
1.05	1.085	29	120	70	Partial Loss	H.V Mud	Fail
1.05	1.07	24	100	55	No Loss	No Treatment	Success
1.05	1.08	31	120	70	Severe Loss	Super stop Material	Success
1.05	1.08	25	120	70	Partial Loss	H.V Mud	Success
1.05	1.07	22	105	70	Partial Loss	H.V Mud	Success
1.05	1.1	30	130	80	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.05	1.09	29	120	90	Complete Loss	Cement Plug	Fail
1.05	1.06	22	100	60	No Loss	No Treatment	Success
1.05	1.07	20	105	65	Partial Loss	H.V Mud	Success
1.05	1.07	20	105	65	No Loss	No Treatment	Success
1.05	1.08	23	110	90	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.05	1.07	25	100	65	No Loss	No Treatment	Success
1.05	1.08	24	110	70	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.1	28	120	90	Severe Loss	Super stop	Fail
1.06	1.09	30	120	70	Severe Loss	Cement Plug	Success
1.06	1.08	26	160	75	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.07	21	110	55	No Loss	No Treatment	Success
1.06	1.09	31	120	55	Severe Loss	Super stop Material	Success
1.06	1.07	21	110	65	No Loss	No Treatment	Success
1.06	1.09	31	140	70	Severe Loss	Cement Plug	Success
1.06	1.07	21	120	70	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.075	22	100	65	No Loss	No Treatment	Success
1.06	1.07	20	100	60	No Loss	No Treatment	Success
1.06	1.08	22	100	70	Partial Loss	H.V Mud	Fail
1.06	1.075	24	140	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.06	1.09	27	180	75	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.06	1.07	21	105	60	No Loss	No Treatment	Success
1.06	1.07	21	100	60	No Loss	No Treatment	Success
1.06	1.07	20	100	60	No Loss	No Treatment	Success

Table A.2. Collected Real Data for Dammam Zone (Cont'd),
(Around 50 wells, Polymer Mud), (South Oil Company & Britch Petroleum) Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2,	SPM	RPM	Type of Losses	Treatment	Result
1.07	1.08	22	130	70	Complete Loss	Cement Plug	Success
1.07	1.085	23	140	60	Complete Loss	Cement Plug + HV Mud	Success
1.07	1.085	20	180	75	Severe Loss	Cement Plug	Fail
1.07	1.09	22	140	80	Complete Loss	DOBC Plug	Success
1.07	1.08	20	100	70	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.07	1.085	26	120	90	Severe Loss	Blend of LCMs	Success
1.08	1.085	20	120	75	Complete Loss	Cement Plug	Fail
1.08	1.085	22	100	75	Severe Loss	HV Mud + Blend of LCMs	Success
1.08	1.1	27	120	55	Complete Loss	DOBC Plug	Success

Table A.3. Collected Real Data for Hartha Zone, (More than 50 wells, FCL Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.12	1.145	14	110	60	No Loss	No Treatment	Success
1.12	1.145	17	110	75	Partial Loss	H.V Mud	Success
1.12	1.13	14	120	60	No Loss	No Treatment	Success
1.12	1.14	16	100	60	Partial Loss	H.V Mud	Success
1.12	1.16	18	100	60	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.12	1.14	17	110	65	Partial Loss	H.V Mud	Fail
1.12	1.16	18	110	65	Complete Loss	Cement Plug	Success
1.12	1.16	20	110	65	Severe Loss	HV Mud + Blend of LCMs	Success
1.13	1.16	21	110	65	Severe Loss	HV Mud + Blend of LCMs	Success
1.12	1.13	15	160	80	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.12	1.14	14	150	70	Partial Loss	H.V Mud	Fail
1.12	1.13	15	140	60	Partial Loss	H.V Mud	Fail
1.12	1.13	15	105	60	No Loss	No Treatment	Success
1.12	1.16	19	110	65	Severe Loss	Cement Plug	Success
1.13	1.155	17	100	70	Partial Loss	H.V Mud	Success
1.13	1.15	16	100	80	Partial Loss	H.V Mud	Success
1.13	1.16	18	120	90	Severe Loss	HV Mud + Blend of LCMs	Success
1.13	1.14	14	100	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.15	15	120	80	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.155	16	105	90	Partial Loss	H.V Mud	Fail
1.13	1.15	16	130	80	Partial Loss	H.V Mud	Success
1.13	1.17	20	100	70	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.14	13	105	60	No Loss	No Treatment	Success
1.13	1.15	13	125	100	Partial Loss	H.V Mud	Success
1.13	1.18	22	130	90	Complete Loss	Cement Plug + HV Mud	Success
1.13	1.17	18	140	60	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.13	1.155	14	110	60	Partial Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.13	1.14	14	150	70	Partial Loss	H.V Mud	Success
1.13	1.155	14	140	65	Partial Loss	H.V Mud	Success

Table A.3. Collected Real Data for Hartha Zone (Cont'd), (More than 50 wells, FCL Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.13	1.14	13	100	60	No Loss	No Treatment	Success
1.13	1.15	14	140	60	Partial Loss	H.V Mud	Success
1.13	1.155	14	110	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.14	14	110	70	No Loss	No Treatment	Success
1.13	1.155	14	140	65	Partial Loss	H.V Mud	Fail
1.13	1.14	15	110	60	No Loss	No Treatment	Success
1.13	1.16	15	140	60	Partial Loss	H.V Mud	Success
1.13	1.14	13	100	60	No Loss	No Treatment	Success
1.13	1.14	15	105	60	No Loss	No Treatment	Success
1.14	1.16	16	150	70	Severe Loss	HV Mud + Blend of LCMs	Success
1.14	1.17	18	100	65	Complete Loss	Cement Plug	Fail
1.14	1.17	15	130	60	Complete Loss	Cement Plug + HV Mud	Success
1.14	1.16	15	105	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.14	1.17	16	115	60	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.14	1.15	13	100	60	Partial Loss	H.V Mud	Fail
1.145	1.17	15	115	70	Severe Loss	Cement Plug	Success
1.145	1.18	17	115	70	Severe Loss	Super stop Material	Success
1.145	1.165	18	115	70	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.15	1.17	14	160	75	Complete Loss	Cement Plug	Fail
1.15	1.16	13	105	65	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.15	1.17	14	105	70	Complete Loss	DOBC Plug	Fail
1.15	1.17	15	120	70	Complete Loss	DOBC Plug	Success
1.15	1.18	17	125	70	Complete Loss	Cement Plug + HV Mud	Success

Table A.4. Collected Real Data for Hartha Zone, (More than 50 wells, Polymer Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.12	1.145	22	110	60	No Loss	No Treatment	Success
1.12	1.145	27	100	65	Partial Loss	H.V Mud	Success
1.12	1.13	20	120	60	No Loss	No Treatment	Success
1.12	1.14	25	100	70	Partial Loss	H.V Mud	Success
1.12	1.16	23	100	60	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.12	1.14	22	110	65	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.12	1.16	22	110	65	Complete Loss	Cement Plug	Success
1.12	1.16	29	120	65	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.12	1.16	30	110	70	Severe Loss	HV Mud + Blend of LCMs	Success
1.12	1.13	21	160	80	Partial Loss	H.V Mud	Fail
1.12	1.14	20	140	70	Partial Loss	H.V Mud	Fail
1.12	1.13	22	140	60	Partial Loss	H.V Mud	Success
1.12	1.16	30	110	65	Severe Loss	H.V Mud	Success
1.13	1.155	26	100	70	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.15	25	100	80	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.13	1.16	32	120	90	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.13	1.15	22	120	80	Partial Loss	H.V Mud	Success
1.13	1.17	34	105	90	Severe Loss	Super stop Material	Success
1.13	1.15	24	130	80	Partial Loss	H.V Mud	Fail
1.13	1.17	30	100	70	Severe Loss	15 – 20 m3 LCMs Pill (L. MW)	Success
1.13	1.14	21	105	60	No Loss	No Treatment	Success
1.13	1.16	27	125	100	Partial Loss	H.V Mud	Fail
1.13	1.18	30	130	90	Complete Loss	DOB Plug	Success
1.13	1.17	28	140	80	Severe Loss	Cement Plug	Success
1.13	1.155	25	110	60	Partial Loss	H.V Mud	Fail
1.13	1.14	20	120	70	No Loss	No Treatment	Success
1.13	1.14	20	100	60	No Loss	No Treatment	Success
1.13	1.15	24	130	70	Partial Loss	H.V Mud	Success
1.13	1.15	22	110	60	Partial Loss	H.V Mud	Success
1.13	1.14	22	100	60	No Loss	No Treatment	Success

Table A.4. Collected Real Data for Hartha Zone (Cont'd), (More than 50 wells, Polymer Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.13	1.14	22	110	60	No Loss	No Treatment	Success
1.13	1.14	22	120	75	Partial Loss	H.V Mud	Success
1.13	1.14	22	100	60	No Loss	No Treatment	Success
1.13	1.14	22	105	60	No Loss	No Treatment	Success
1.14	1.16	24	150	70	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.14	1.17	25	100	65	Complete Loss	HV Mud + Blend of LCMs	Fail
1.14	1.17	23	130	80	Complete Loss	Cement Plug + HV Mud	Success
1.14	1.16	25	105	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.14	1.17	25	115	60	Severe Loss	Super stop Material	Success
1.14	1.15	25	100	60	Partial Loss	H.V Mud	Success
1.145	1.17	24	130	75	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.145	1.18	28	115	70	Severe Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.15	1.17	21	160	75	Complete Loss	Cement Plug	Fail
1.15	1.16	21	105	65	Severe Loss	Cement Plug	Success
1.15	1.17	24	110	75	Complete Loss	Cement Plug	Success
1.15	1.17	23	120	80	Complete Loss	Cement Plug + HV Mud	Success
1.15	1.18	29	125	70	Complete Loss	Cement Plug + HV Mud	Success

Table A.5. Collected Real Data for Shuaiba Zone, (More than 50 wells, FCL Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.15	1.17	12	85	70	No Loss	No Treatment	Success
1.15	1.17	12	80	60	No Loss	No Treatment	Success
1.15	1.18	15	80	65	Partial Loss	H.V Mud	Success
1.15	1.2	18	100	70	Sever Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.15	1.165	12	80	65	No Loss	No Treatment	Success
1.15	1.17	12	90	65	No Loss	No Treatment	Success
1.15	1.16	12	100	75	Partial Loss	H.V Mud	Success
1.15	1.16	13	85	70	Partial Loss	H.V Mud	Fail
1.15	1.16	12	110	70	Partial Loss	H.V Mud	Fail
1.15	1.16	12	80	55	No Loss	No Treatment	Success
1.15	1.17	12	80	55	No Loss	No Treatment	Success
1.15	1.17	12	80	55	No Loss	No Treatment	Success
1.15	1.17	12	110	75	Partial Loss	H.V Mud	Success
1.15	1.17	12	110	55	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.16	1.18	13	100	90	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.16	1.17	13	90	60	No Loss	No Treatment	Success
1.16	1.19	13	90	80	Complete Loss	Cement Plug	Success
1.16	1.19	14	90	55	Complete Loss	Cement Plug	Success
1.16	1.17	14	90	55	Partial Loss	H.V Mud	Success
1.16	1.17	14	80	65	Partial Loss	H.V Mud	Success
1.16	1.2	19	85	70	Complete Loss	Cement Plug + HV Mud	Fail
1.16	1.17	13	90	60	No Loss	No Treatment	Success
1.16	1.17	13	100	60	No Loss	No Treatment	Success
1.16	1.165	13	100	60	No Loss	No Treatment	Success
1.16	1.165	14	100	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.16	1.17	13	90	65	No Loss	No Treatment	Success
1.17	1.18	13	100	65	Complete Loss	DOB Plug	Fail
1.17	1.19	15	100	65	Complete Loss	DOBC Plug	Fail

Table A.5. Collected Real Data for Shuaiba Zone (Cont'd), (More than 50 wells, FCL Mud), (South Oil Company & Britch Petroleum Company)

MW, gm/cc	ECD, gm/cc	Yp, Ibf/ft2	SPM	RPM	Type of Losses	Treatment	Result
1.17	1.19	15	85	65	Complete Loss	DOBC Plug	Fail
1.17	1.19	15	85	65	Complete Loss	Blend of LCMs + Cement Plug	Fail
1.17	1.19	15	85	65	Complete Loss	DOBC Plug	Success
1.18	1.2	17	90	90	Complete Loss	DOBC Plug	Success
1.18	1.2	16	100	80	Sever Loss	Cement Plug	Fail
1.18	1.185	12	80	80	Sever Loss	Cement Plug	Success
1.18	1.19	13	90	65	Sever Loss	10 – 15 m3 LCMs Pill (L. MW)	Fail
1.18	1.2	14	80	70	Complete Loss	Cement Plug	Fail
1.18	1.19	12	80	65	Complete Loss	Cement Plug	Fail
1.18	1.19	12	90	65	Complete Loss	Cement Plug	Fail
1.17	1.19	15	85	65	Complete Loss	DOBC Plug	Success
1.17	1.18	12	80	60	Partial Loss	10 – 15 m3 LCMs Pill (L. MW)	Success
1.18	1.2	16	80	60	Complete Loss	Cement Plug + HV Mud	Fail
1.18	1.2	16	90	90	Complete Loss	Cement Plug + HV Mud	Fail
1.18	1.2	16	90	90	Complete Loss	DOB Plug	Fail
1.18	1.2	16	90	90	Complete Loss	DOBC Plug	Success

APPENDIX B

CALCULATIONS THAT ARE ASSOCIATED WITH TREATMENTS

- The success of the mud losses remedies is associated with necessary steps. Accurate calculations for the used treatment is one of the most important step that contribute to combat or mitigate lost circulation mud effectively. In other words, it is practically interest to do precise calculations in order to guarantee efficient treatment. Therefore, this section will be involved some important calculations, which are related with the remedies of the thief zone. The following information is required about the loss zone before an effective treatment could be achieved:

1. The volume of the displacement fluid. Plainly, it is necessary to do accurate calculations for the required volume of the placement fluid because that will positively reflect on the treatment success. Placement fluid is used to displace various remedies in front of thief zone to seal it. This kind of the fluid will be used with partial, severe, and complete treatment. Normal drilling mud is usually used as placement fluid. Hence, it is prudent to detect the required volume of it. Equation is below, which use to calculate the replacement fluid.

$$Displacement\ Volume = (IDdrill\ pipe)2 \times 0.785 \times h \tag{1}$$

Where,

Displacement volume = Required volume of the drilling mud (m^3), which is needed to displace treatment in front of thief zone.

$ID_{Drill\ Pipe}$ = inside diameter of drill pipe (m).

h = Depth to the top of plug or treatment in front of the thief zone (m).

2. The volume of the required plug. Several plugs that use to stop or mitigate lost circulation mud. So, it is required to calculate the required volume of these plugs in front of the thief zone to get positive result. Usually, more than actual volume of the required plug which pump as safety factor roughly (1-2 m^3). Equation is below, which use to calculate the required plugs or treatments.

$$Volume\ of\ Required\ Plug = (DOH)2 \times 0.785 \times h \tag{2}$$

Where,

Plug Volume: is the required volume of the plug to cover the entire thief zone (m^3).

DOH = Diameter of open hole (m).

h = height of interval of the thief zone (m).

3. Estimating the density of the required plug. It is necessary to do precise calculations in order to get appropriate density for the required plug to avoid unwanted consequences. Some steps should take to obtain on the density of the required plug.

- By detecting the static level column of the drilling mud above the loss zone.
- Subtracting the static level column of the drilling mud above the loss zone from total drilled depth to get level of the mud.
- By using below equation, we can get hydrostatic pressure

$$HP = \frac{\rho mud \times h}{10} \quad (3)$$

Where,

HP = Hydrostatic pressure that thief zone can resist it without unwanted consequences (Kg/cm^2).

ρmud = Mud Weight (gm/cc)

h = the static level column of the drilling mud above the loss zone (m).

- By using hydrostatic pressure, we can get the required density of the plug that does not affect negatively on the thief zone. By using below equation:

$$\rho plug = \frac{HP \times 10}{h} \quad (4)$$

Where,

ρmud = Density of the required plug (gm/cc).

HP = Hydrostatic pressure that thief zone can resist it without unwanted consequences (Kg/cm^2).

h = the height of the thief zone (m).

4. Estimating pressure in the loss zone. It is of a practical interest to determine the pressure of the loss zone. That pressure can be found from the following procedure by measuring the static fluid column above the loss zone (Baker Hughes, 1999).

- First, pull out the drill string to the top of the suspected thief zone.
- Attaching Length of wood is approximately (4 feet) to the rig's survey line.
- By running this Length of wood down the drill pipe in order to detect the static fluid level. (A sonic echo measuring device can also be used to locate the fluid level).
- Finally, Calculate the loss zone pressure from the following equation:

$$Ploss\ zone = \text{Dstatic fluid column } \times (MW) \times (0.052) \quad (5)$$

Where,

P_{loss} zone = Loss zone pressure (psi).

Dstatic fluid column = is the static fluid column above the loss zone (feet)

MW = is the mud weight (lb/gal).

5. Estimating mud weight in the loss zone during the drilling operations. During drilling operation, it is recommended to estimate the density of the drilling fluid. This estimation will mitigate lost circulation mud. We can calculate the mud weight that should use it in the loss zone to reinforce formation by using a simple formula:

$$MW = \frac{Ploss\ zone}{D \times (0.052)} \quad (6)$$

Where,

MW = is mud weight (lb/gal).

P_{loss} zone = Loss zone pressure (psi).

D = True vertical depth (TVD) till the loss zone (feet).

APPENDIX C
UNIT CONVERSION FACTORS

Table C.1. Units Conversion Factors

Multiply	***by***	***To Obtain***
Length		
m	3.2808	ft
ft	0.3048	m
in	0.0254	m
m	39.37	in
ft	12	in
in	0.0833	ft
in	2.54	cm
cm	0.393	in
in	25.4	mm
Volume		
bbl	0.159	m^3
m^3	6.289	bbl
m^3	1000	liter
gal	3.785	liter
bbl	42	gal
bbl	5.615	ft^3
m^3	35.34	ft^3
ft^3	7.48	gal

Pressure		
Psi	6.8948	KPa
KPa	0.145	Psi
Psi	0.068948	bar
Psi	0.0703	kg/cm^2
bar	100	KPa
kg/cm^2	98.1	KPa

Density		
gm/cc	8.345	Ib/gal
Ib/gal	0.11983	gm/cc
Ib/gal	119.8	kg/m3
Ib/ft^3	16.02	kg/m3

Mass		
Ib	453.6	gm
Ib	0.4536	kg
kg	2.204	Ib
Ib	4.4	Newton

Concentration		
Ib/bbl	2.85	kg/m^3
Ib/ft	1.49	kg/m

BIBLIOGRAPHY

Aadnoy, S. and Looyeh, R. 2011. Petroleum Rock Mechanics: Drilling Operations and Well Design, 2nd Edition. Gulf Professional Publishing Is an Imprint of Elsevier.

Alberty, M. W. and McLean, M. R. 2004. A Physical Model for Stress Cages. SPE-90493-MS, SPE Annual Technical Conference and Exhibition, Houston, USA, 26-29 September.

Al Menhali, S., Kashwani, G., Sajwani, A. 2015. Saftey Engineering Controls of Lost Circulation during Cementing in Onshore Oil Construction Projects. This paper Published Online at http://Journal.sapub.orh/ijme.

Amoco Production Company. 2000. MI-Drilling fluids, Drilling fluids manual.

Arshad, U., Jain, B., Ramzan, M., Alward, W., Diaz, L., Hasan, I., Aliyev, A., and Riji, C. 2015. Engineered Solutions to Reduce the Impact of Lost Circulation during Drilling and Cementing in Rumaila Field, Iraq. This Paper was prepared for Presentation at the International Petroleum Technology Conference Held in Doha, Qatar, 6 – 9 December.

Azlz, A., Kalloo, C.L. and Singh, U.B. 1994. Preventing Lost Circulation in Severely Depleted Unconsolidated Sandstone Reservoirs. SPE presented at the Drilling & Completion, March. (LR. S).

BAKER HUGHES Company. 1999. Prevention and Control of Lost Circulation Best Practices.

British Petroleum Company. Various Daily Reports, Final Reports, and Tests for 2013, 2014 and 2015. Several Drilled Wells, Southern Ramiala Field, Basra, Iraq.

Bourgoyne, A., Chenevert, M. and Young, FS. 1986. Applied Drilling Engineering. Second Edition, SPE Text Book.

Canson, B. E. 1985. Lost Circulation Treatment for Naturally Fractured, Vugular, or Cavernous Formations. SPE/IADC 13440, SPE/IADC Drilling Conference, New Orleans, USA, 5-8 March.

Carlton, L.A. and Chenevert, M.E. 1974. A New Approach to Preventing Lost Returns.SPE 4972 Presented at the 49th Annual Fall Meeting of the Society of Petroleum of AIME Held in Houston, Texas, 6-9 October.

Davison, J.M., Leaper, R., Cauley, M.B., Bennett, B., Mackenzie, A., Higgins, C.J., huttleworth, N., and Wilkinson, D. 2004. Extending the Drilling Operating Window in Brent: Solutions for Infill Drilling in Depleting Reservoirs. IADC/SPE 87174 presented at the IADC/SPE Drilling Conference Held in Dallas, Texas, U.S.A, 2-4 March.

E.Kurru. T.Babadagli University of Alberta. 2004. Use of Cement as Lost-Circulation Material: Best Practices. Paper SPE Presented at the Petroleum Society's 5th Canadian International Petroleum Conference (55th Annual Technical Meeting), Calgary, Alberta, Canada, 8 – 10 June.

Eni Company, Exploration &Production division. 2010. Lost Circulation.

Fidan, E., Babadagli, T. and Kuru, E. 2004. Use of Cement as Lost Circulation Material – Field Case Studies. Paper IADC/SPE 88005 presented at the IADC/SPE Asia. Pacific Drilling Technology Conference and Exhibition held in Kuala Lumpur, Malaysia, 13-15 September.

Friedheim, J. E., Young, S., De Stefano, G. Lee, J., and Guo, Q. 2012. Nanotechnology for Oilfield Applications – Hype or Reality? SPE-157032-MS, SPE International Oilfield Nanotechnology Conference and Exhibition, Noordwijk, Netherlands, 12-14 June.

Gallardo, H., Cassanelli, J.P., Barret, S., Romero, P., and Mufarech, A. 2010. Casing Drilling Technology (CwD) Mitigates Fluid Losses in Peruvian Jungle. Paper SPE 139065 Presented at the SPE Latin American & Caribbean Petroleum Engineering Conference Held in Lima, Peru, 1-3 December.

Howard, G.C., and Scott, P.P. 1951. An Analysis and the Control of Lost Circulation. Paper SPE 951171 presented at the Annual Meeting of the AIME held in St. Louis, Mo., 19-21 February.

Jiao, D., and Sharma, M.M. 1995. Mud-Induced Formation Damage in Fractured Reservoirs. SPE 30107 Presented at the European Formation Damage Control Conference Held in The Hague, the Netherlands, 15-16 May.

Kumar, A., Sharath, S., Whitfill, D.L., and Jamison, D.E. 2010. Wellbore Strengthening: The Less-Studied Properties of Lost-Circulation Materials. Paper SPE 133484 presented at the SPE Annual Technical Conference and Exhibition held in Florence, Italy, 19-22 September.

Mata, F., and Veiga, M. 2004. Crosslinked Cements Solve Lost Circulation Problems. SPE- 90496-MS, SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 26-29 September.

Moore, P.L. 1986. Drilling Practices Manual. Second Edition. Penn Well Publishing Company. Tulsa, Oklahoma.

Nayberg, T.M. 1987. Laboratory Study of Lost Circulation Materials for Use in Both Oil-Based and Water-Based Drilling Muds. Paper SPE 14723 presented at the SPE Drilling Engineering, September.

Nayberg, T.M., and Petty, B.R. 1986. Laboratory Study of Lost Circulation Materials for Use in Oil-Base Drilling Muds. Paper SPE 14995 presented at the Deep Drilling and Production Symposium of the Society of Petroleum Engineers Held in Amarillo, TX, 6-8 April.

Nwaoji, C.O., Hareland, G., Husein, M., Nygaard, R., Zakaria, M.F. 2013.Wellbore Strengthening-Nano-Particle Drilling Fluid Experimental Design Using Hydraulic Fracture Apparatus. SPE-163434-MS, SPE/IADC Drilling Conference and Exhibition, Amsterdam, the Netherlands, 5 – 7 March.

Pilehvari, A., Nyshadham, R.V.2002. Effect of Material Type and Size Distribution on Performance of Loss/Seepage Control Material. Paper SPE 73791 presented at the SPE International Symposium and Exhibition on Formation Damage Control Held in Lafayette, Louisiana, 20-21 February

Rabia, H. 2005.Well Engineering & Construction. Entrance Consulting. Second Edition.

Ramirez, M., Diaz, A., Luna, E., Figueroa, Y., and Per-Bjarte, T. 2005. Successful Application of Synthetic Graphite to Overcome Severe Lost Circulation Problem in the Troublesome Foothills of Colombia. Paper AADE-05-NTCE-30 presented at the AADE National Technical Conference and Exhibition Held at the Wyndam Greenspoint in Houston, Texas, 5-7 April.

Redden, J., Carpenter, B., Polnaszek, S., Bloys, B., and Headley, J. 2011. Lost Circulation Manual. MI-SWACO.

Salehi, S. and Nygaard, R. 2012. Numerical Modeling of Induced Fracture Propagation: A Novel Approach for Lost Circulation Materials (LCM) Design in Borehole Strengthening Applications of Deep Offshore Drilling. SPE-135155-MS, SPE Annual Technical Conference and Exhibition, San Antonio, USA, 8-10 October.

Salehi, S. and Nygaard, R. 2011. Evaluation of New Drilling Approach for Widening Operational Window: Implications for Wellbore Strengthening. SPE-140753-MS, SPE Production and Operations Symposium, Oklahoma City, USA, 27-29 March.

Savari, S., Whitfill, D. l., and Kumar, A. 2012. Resilient Lost Circulation (LCM): A Significant Factor in Effective Wellbore Strengthening. SPE-153154-MS, SPE Deepwater Drilling and Completions Conference, Galveston, Texas, USA, 20-21 June.

Sharma, Vinod., Kumar, Ajay., and Dutt, S. 2012. Importance of Collapse Gradient of Formation for Stable Well. Biennial International Conference & Exposition on Petroleum Geophysics.

Soroush, H., and Sampaio, J.H.B. 2006. Investigation into Strengthening Methods for Stabilizing Wellbores in Fractured Formations. Paper SPE 101802 presented at the SPE Annual Technical Conference and Exhibition Held in San Antonio, Texas, USA, 24-27 September.

South oil Company. Various Daily Reports, Final Reports, and Tests for 2007, 2008, 2009 and 2010. Several Drilled Wells, Southern Ramiala Field, Basra, Iraq.

Schlumberger Company. 2003. Using a Novel Fiber Cement System to Control Lost Circulation: Case Histories from the Middle East and the Far East.

Tessari, R., Madell, G., and Warren, T. 1999. Drilling with casing promises major benefits. Oil and Gas Journal.

Tessari, R.M., Warren, T.M., and Jo, J.Y. 2006. Drilling with Casing Reduces Cost and Risk Paper SPE 101819 Presented at the SPE Russian Oil and Gas Technical Conference and Exhibition Held in Moscow, Russia, 3-6 October.

Tingay, M., Reinecker, J., Müller, B. 2008. Borehole Breakout and Drilling-induced Fracture Analysis from Image Logs. World Stress Map Project.

Uday, A.T., Whitfill, L., and Fersheed, K.M., SPE. Halliburton Energy Services, Inc. 2001. Drilling Fluid Losses and Gains: Case Histories and Practical Solutions. SPE 71368 Presented at SPE Annual Technical Conference and Exhibition Held in New Orleans, Louisiana, 30 September–3 October.

Van Oort, E., Friedheim, J., Pierce, T., and Lee, J. 2009. Avoiding Losses in Depleted and Weak Zones by Constantly Strengthening Wellbores. Paper SPE 125093 presented at the SPE Annual Technical Conference and Exhibition Held in New Orleans, Louisiana, USA, 4-7 October.

Wang, H. 2011. Is It Really Possible to Efficiently Form a Strong Seal inside Subterranean Openings without Knowing Their Shape and Size?. AADE-11-NTCE-25, AADE National Technical Conference and Exhibition, Houston, USA, 8-9 April.

Wang, H., Soliman, M. Y., Whitfill., and Towler, B. F. 2008. Case Histories Show Wellbore Strengthening as a Cost-Effective Option for Drilling with Narrow Mud Weight Windows. Paper AADE presented at the AADE Fluids Conference and Exhibition Held at the Wyndham Hotel, Houston, Texas, USA, 8-9 April.

Wang, H., Soliman, M.Y., Towler, B.F., and Shan, Z. 2009. Strengthening a Wellbore with Multiple Fractures: Further Investigation of Factors for Strengthening a Wellbore. Paper ARMA 09-67 presented at the 43rd US Rock Mechanics Symposium and 4th US-Canada Rock Mechanics Symposium Held in Asheville, NC, 28 June – 1 July.

Wang H, Sweatman R, Engelman B, Deeg W, Whitfill D, Soliman M, Towler BF. 2008. Best Practice in Understanding and Managing Lost Circulation Challenges. SPE Drilling & Completion, Vol. 23 (2), pp. 168-175.

Wang, H., Sweatman, R., Engelman, B., Deeg, W., Whitfill, D., Soliman, M., and Towler, B. 2005. Best Practice in Understanding and Managing Lost Circulation Challenges. Paper SPE 95895 presented at the 2005 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 9-12 October.

Whitfill, D. 2008. Lost Circulation Material Selection, Particle Size Distribution and Fracture Modeling with Fracture Simulation Software. SPE-115039-MS, IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Jakarta, Indonesia, 25- 27 August.

World Oil. 2003. Drilling &Completion Technology. Second Edition. Publication, United States.

VITA

Abo Taleb Tuama Al-hameedi was born in June 1984, in Thi Qar, Iraq. He received his bachelor degree in Petroleum Engineering from Baghdad University, Baghdad, Iraq in 2006. After graduation, in October 2007, Abo Taleb joined South Oil Company as trained engineer. He worked as a mud engineer in various oil field like South Rumaila, Zubair, Nahur Umar, and Allhis. He also worked in Weatherford Company as mud engineer. In February 2013, he was a scholarship recipient of the ExxonMobil Iraq Training, Technology & Scholars Program, and a fully funded scholarship program administered by the Institute of International Education (IIE) to study Master's degree in Petroleum Engineering. He started at Missouri University of Science and Technology during the fall semester of 2014 to work under the supervision of Dr. Shari Dunn-Norman as a graduate student. His thesis topic is about lost circulation mud to study this issue with field cases. He received a Master of Science degree in Petroleum Engineering from Missouri University of Science and Technology in December 2016.

His research interests are in avoiding and mitigation of lost circulation problem, a comprehensive study for this issue with application in the South Rumaila field, IRAQ and other historical cases in international oil fields.