POLITECNICO DI TORINO

MSc Degree in Petroleum and Mining Engineering

Master of Science Thesis

Automation of Leak off Test and Formation Integrity Test

Politecnico di Torino 1859

NTNU Norwegian University of Science and Technology

Thesis Supervisors:

Assoc. Professor Giovanni Andrea Blengini

Assoc. Professor Behzad Elahifar (NTNU)

Candidate:

Kamal Mammadov

A.Y. 2022/2023

Abstarct

A leak-off test is one of the most common procedures to test the fracture pressure of the exposed formations. After cementing and drilling out of the casing shoe, the LOT is run to verify that the casing, cement, and formation can withstand the pressure needed to safely drill the next section of the well. The equivalent mud weight obtained from the test is recorded and reported to government agencies as the strength of the casing shoe. Drilling engineers also rely on the reading from the LOT and use it as the maximum pressure that may be imposed on the formation to avoid fracturing. Exceeding the maximum pressure may result in serious consequences such as lost circulation, one of the most costly events in drilling operations. Therefore, accurate determination of formation fracture gradient is critical and can avoid a variety of well control problems.

Considerable efforts to model LOT and leak-off behaviors have been done in the past. Altun (2001) and Paknejad (2007) each presented a unique method to estimate leakoff volume by dividing the pressurized system into four sub-systems: mud compression, casing expansion, fluid leakage, and borehole expansion. The volume response from each sub-system is then combined to represent the total volume pumped during a LOT.

However, neither model included the expansion volumes of cement sheath and formation rock outside of the casing; these volumes are not trivial and should not be neglected. In addition, both models use only pump pressure to calculate volumes generated during a LOT. The actual downhole pressure and the pressure acting from the outside are ignored.

This report will be mainly focusing on the LOT which is considered to be the most common diagnostic test conducted routinely by the drilling industry. The importance of the LOT lies in the fact that it provides so much valuable information which in turn make the test look

inexpensive and worth the cost. This report will be tackling the procedure of conducting a LOT, what are the factors that affect it and how to correctly interpret its results; thus providing a conclusive overview on what is a LOT, which in turn will serve as a base for its automation later on.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

LOT = Leak off Test

FIT = Formation Integrity Test

PIT = Pressure Integrity Test

XLOT, ELOT = Extended Leak off Test

LOP = Leak off Point

PPFG = Pore Pressure – Fracture Gradient

PP = Pore Pressure, psi

BHA = Bottom hole assembly

BPM = Barrels per minute

D = Depth (below rotary table), m

ECD = Equivalent circulating density, ppg,

EMW = Equivalent mud weight, ppg

ESD = Equivalent static density, ppg

FV = Funnel viscosity

LWD = Logging while drilling

MW = Mud weight, ppg

MW_{in} = Mud weight getting into well, ppg

MW_{out} = Mud weight getting out of well, ppg

OBG = Overburden gradient

P_h = Hydrostatic pressure, psi

P_{lo} = Leak-off pressure, psi

PV = Plastic viscosity

SPP = Standpipe pressure, psi

TD = Total depth, m

TVD = True Vertival Depth, m

MD = Measured Depth, m

WBM = Water Based Mud

OBM = Oil Based Mud

SBM = Synthetic Based Mud

BOP = Blow Out Preventor

YP = Yield point

ISIP = Instantaneous Shut In Pressure, psi

FCP = Fracture Closure Pressure, psi

1.INTRODUCTION

Wellbore pressure must be maintained throughout conventional drilling operations within the mud weight window. The naturally existing formation pore pressure describes the lowest limit of the window. A "kick" can occur when formation fluids enter the wellbore, producing issues with well control. This can happen if the wellbore pressure drops below the formation pore pressure. The greatest pressure that the formation can bear without losing integrity, also known as the formation fracture pressure, defines the top limit of the window. If the wellbore pressure is high enough to surpass the formation fracture pressure, cracks can occur at the open hole to create flow routes for drilling fluid to penetrate the formation. One of the most expensive occurrences in drilling operations and one of the significant effects of fractured rock is lost circulation. Particularly in offshore operations, the margin for safety in drilling operations is often quite small. To maintain safe drilling techniques, it is essential to comprehend and recognize both the formation pore pressure and the formation fracture pressure. [2]

The direct method and the indirect method are the two major techniques used by the drilling industry to calculate the formation fracture pressure. After drilling out of the preceding casing shoe, the direct method comprises pressure testing the open hole formation. These tests include the leak-off test (LOT), formation integrity test (FIT), extended leak-off test (XLOT), and pump-in and flow-back test. The indirect method, on the other hand, frequently makes use of empirical correlations, like the Eaton correlation, the Hubbert and Willis equations, and others. In mature fields where the fracture pressure gradients are well described by examining previous LOTs and XLOTs, drilling planning engineers also rely on basin-wide fracture pressure correlations. Many studies, including "A comparison of leak-off test and extended leak-off test data for stress estimation" by Addis et al. in 1998 and "An investigation of leak-off test data for estimating in-situ stress magnitudes: application to a Basinwide study in the North Sea" by Edwards et al. in 1998, have been published. [2, 14]

The world has been going through a shift for the past few years—a transition that started as a dream, developed into a concept, and then slammed the globe with reality. Everything that man ever utilized has been automated or digitalized, making life simpler and more effective. The oil and gas industry, like many others, had the opportunity to participate in this transition, despite the fact that it is currently one of the industries that is lagging behind because it has consistently turned to antiquated conventional methods rather than thinking creatively and creating effective techniques to address ongoing issues.[2]

This research is being undertaken to learn more about the Leak-off test, including why and how it is carried out, what factors affect it, and much more. This knowledge will eventually be used to automate the test, making it more effective and less expensive.

2.THEORY

The leak-off test, which is performed immediately after the casing is run, measures the strength or fracture pressure of an open formation under the casing shoe. In order to perform the test, the well is shut in, and fluid is pumped into the wellbore until it either fractures the formation or penetrates it through permeable pathways. Leak-off test results indicate the maximum mud weight or pressure that may be employed during drilling operations at that well segment.

2.1 What is Leak-Off Test (LOT)?

The uncertainty of drilling parameter limitations in wildcat and exploratory drilling is one of the biggest problems for well design and drilling engineering. All extra data that may be acquired during drilling operations are essential for a successful ongoing operation because there is little available data for the field (seismic results, preliminary pressure, and geological studies). Welbore's Pore Pressure - Fracture Gradient (PPFG) actions are one of the most important indicators that need to be constantly monitored. A kick or an eventual increase in mud weight (MW) may result from an abrupt rise in pore pressure (PP). A kick will cause the operator company to do a well-controll operation, which will be waste time and additional costs. Mud weight needs to be raised whether or not a kick happens to maintain a safety margin above pore pressure. The wellbore's hydrostatic pressure naturally rises as mud weight does. Every point of the wellbore is impacted by this rise, including the open hole, liners, and casings. The fracture gradient is impacted proportionally by the change since a well's overburden gradient rises with depth. By installing a casing and cementing it, wellbore is enforced. As a result, under typical circumstances, the formation immediately below the previous casing's shoe is the weakest part of a wellbore. Normal conditions define the case where no permeable/productive zone is drilled where drilling fluid can be lost. At this moment, the hydrostatic pressure shouldn't be more than the fracture gradient. If it does, there will be losses,partial or complete,which again can result in a kick. [17]

The fracture gradient at the final casing's shoe should be well known, and pore pressure should be regularly monitored, to prevent the risks mentioned above. There are a variety of methods to track pore pressure during drilling. Chasing formation cavings on shale shakers is one of the most popular approaches to observe pore pressure growth. Since hydrostatic pressure in an open hole is smaller than pore pressure, the existence of cavings in disposed cuttings indicates a rise in pore pressure. Trip Gas or Connection Gas readings are another method for monitoring the pore pressure. Gas measurements at the surface that rise as a result of tripping out of the hole should be interpreted as Trip Gas, which indicates that the hydrostatic pressure in the open hole is above pore pressure but too close to it. Swab Effect causes the hydrostatic pressure to drop as tripping out of the hole, allowing any gas that may be present to enter. Additionally, if the Equivalent Static Density (ESD) is insufficient to maintain the pore pressure but the Equivalent Circulating Density (ECD), Equation 2.1, can maintain it with additional pressures, any gas present in the wellbore will appear as connection gas (when circulation stops) and gas readings at the surface will rise significantly..

$$ECD = ESD + \frac{SPP}{0{,}052 * D * 3{,}281} \quad (2.1)$$

The most recent technique for predicting pore pressure is LWD reading interpretation. Any change in pore pressure may be predicted using sonic and resistivity readings. Despite pore pressure prediction, only a few mechanical tests can predict fracture gradient.[17]

Generic names for these tests are pump-in/flow-back tests or Pressure Integrity Tests (PIT) (Soliman and Daneshy, 1991). There are three different types of pressure integrity tests: Formation Integrity Test (FIT), Leak-Off Test (LOT), and Extended Leak-off Test (ELOT or XLOT). These tests mostly differ in terms of their durations and end point pressures (Raaen and Brudy, 2001). [17, 23]

In the FIT procedure, freshly drilled formation is pressurized to a specific pressure and maintained there for a determined amount of time. This predetermined pressure is calculated by the mud weight that must be maintained in order to drill the hole segment. For instance, if 10 ppg MW is thought to be sufficient for drilling a hole section, the formation under the previous casing shoe (at a depth of 2500 m) might be tested to 4,265 psi (about 4300 psi). The specifics of the hydrostatic pressure calculation are shown in Equation 2.2. The pressure will be held at 4,270 psi for 1-2 minutes to make sure the exposed formation can withstand it. [24]

$$P_h = 0{,}052 * MW * D * 3{,}281 \tag{2.2}$$

LOT is often used when there are uncertainties over a field's fracture gradient or the effectiveness of a preceding casing's cementing procedure. Newly drilled formation will be pressurized up to the point where the formation breaks down. Once the pump is shut down, the pressure vs. pumped volume graph is observed for predetermined amount of time. An example LOT graph is shown in Figure 1. The test fluid is pumped at a constant rate until the point where a major breakdown occurs at the open hole and pressure decreases.[16]

Interval between the C and D points demonstrates the loss of friction and pressure fall-off due to filtration (Wojtanowicz and Zhou, 2001). [25]

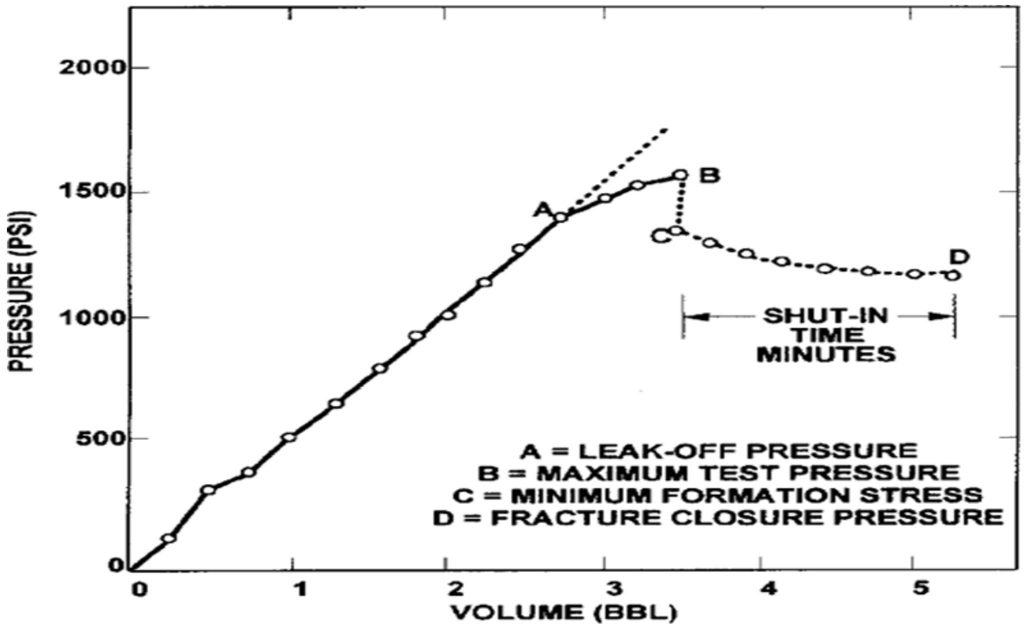


Figure 1: A sample graph for leak-off test (LOT) (Postler, 1997) [16]

ELOT is a new type of PIT that has been used in recent years. The number of repeating cycles is the main difference between LOT and ELOT. In ELOT, at least two more pressurization cycles occur after a conventional LOT. This test provides a more definite fracture gradient result, although it is still not often used in the oil business. Figure 2 below shows an example ELOT graph.[2]

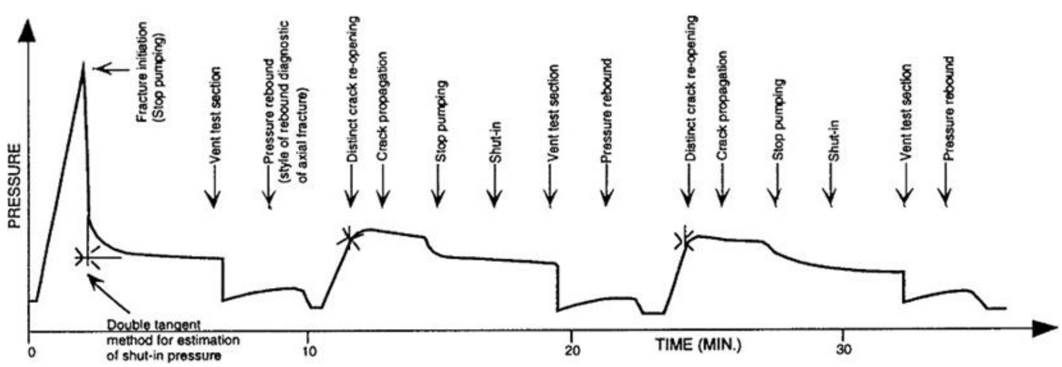


Figure 2: A sample graph for extended leak-off test (ELOT) (Addis, et al., 1998) [2]

The results from all PITs, including LOT, are expressed in units of pressure. This pressure is the maximum value which the previous casing shoe can handle. This pressure value is used to determine the maximum mud weight that may be utilized in that hole segment. This maximum pressure value is calculated using EMW formula. The relationship between EMW and leak-off pressure (Plo) is shown in Equation 2.3.

$$\mathrm{EMW} = \mathrm{MW} + \frac{P_{lo}}{0{,}052 * D * 3{,}281} \tag{2.3}$$

If the required leak-off value cannot be attained, more cement squeeze operations will need to be performed, making this EMW value extremely important for drilling operations. Each LOT run is affected by a variety of things as its nature. Examples include the type of test fluid, quality of the shoe cement, and the formation to be tested. Detailed information will be provided in the section of "Factors That Affect LOT".

LOTs are also used to estimate stress levels at certain depths. According to Breckels and van Eekelen (1982), formation stress is directly dependent on depth. This stress estimation can be utilized for exploration and drilling planning, including the formation of fractured reservoirs, mud weight design, estimation of fracture gradient, wellbore stability, and well array planning. Additionally, the sand production, reduction of production rate, compaction of reservoir, and subsidence can all be considered signs of stress (Addis, 1998). [2]

Although LOT datas can be used to estimate stress, there are several weak points for being an ideal source for it. First, the primary disadvantage facing the oil industry is the lack of a defined technique for carrying out LOT. Second, the primary method for carrying out LOT in shales completely rules out the possibility of employing LOT as a tool for stress assessment in other formations like sandstones or limestones. Last but not least, a LOT's mechanics and interpretation techniques appear inappropriate for this sort of evaluation because it is not intended to be a precise approach for estimating formation stresses (Addis, 1998) [2]

2.2 LOT modeling for inclined and horizontal wells.

In order to explore the non-linear LOT behavior, Altun provided a unique approach to estimate leak-off volume in 2001. The material balance ideas were used to analyze the LOT behavior in Altun's model. Four sub-systems were identified for the compressible system under pressure: drilling fluid compression, casing string expansion, open-hole expansion, and fluid leakage. The total volume pumped during the LOT was then predicted using the volume responses from each subsystem. The resulting material balance equation is shown below.

$$\Delta V = \Delta V_m + \Delta V_c + \Delta V_b + \Delta V_l \qquad (2.4)$$

Each sub-volume system's change calculation equation was also generated separately.

Volume to Mud:

$$\Delta V_m = cV_o \Delta P \qquad (2.5)$$

Volume to Casing:

$$\Delta V_c = 2\pi L \frac{R_i^2 \Delta P}{E}\left[\frac{R_o^2 + R_i^2}{R_o^2 - R_i^2}(1-\nu^2) + (\nu + \nu^2)\right] \qquad (2.6)$$

Volume to Borehole:

$$\Delta V_b = 2\pi L r_o^2 \frac{\Delta P}{E}\left(1 + \frac{\Delta P}{E}\right) \qquad (2.7)$$

Volume to Leak:

$$\Delta V_l = cV_o\left(\frac{D}{q}\right)\Delta P^2 + cV_o\left(\frac{D}{q}\right)^2\Delta P^3 + \cdots \tag{2.8}$$

The wellbore's open-hole segment and the inner volume of the casing are both covered by the initial system volume. Calculating the volume change brought on by the mud compression in the LOT is crucial. The following integral is used to determine the corrected initial volume.

$$V_o = \pi R_i^2 L - \frac{2\pi R_i^2}{E(R_o^2 - R_i^2)}\int_0^L\left[\left(1-\nu-\nu^2\right)R_i^2+(1+\nu)R_o^2\right]P_i - 2\left(1-\nu^2\right)R_o^2 P_o\,dL - 2\pi R_i^2\int_0^L \alpha_T \Delta T\,dL \tag{2.9}$$

Utilizing the pressure and temperature gradients shown below, we can determine the inside and outside pressure as well as the temperature.

$$P_i = \frac{dP_i}{dD}D,\ P_o = \frac{dP_o}{dD}D,\ \Delta T = \frac{dT}{dD}D \tag{2.10}$$

Since the D true vertical depth (TVD) is indicated here, the geometry of the well path must be taken into account for various scenarios.

Consider a well section that starts from the measured depth (MD) of L1 to the measured depth of L2. MD is equal to TVD for Vertical Well.

$$V_o = \pi R_i^2\left(L_2 - L_1\right) - \frac{\pi R_i^2\left(L_2^2 - L_1^2\right)}{E(R_o^2 - R_i^2)}\left\{\left[\left(1-\nu-\nu^2\right)R_i^2+(1+\nu)R_o^2\right]\frac{dP_i}{dD} - 2\left(1-\nu^2\right)R_o^2\frac{dP_o}{dD}\right\} - \pi R_i^2\left(L_2^2 - L_1^2\right)\alpha_T\frac{dT}{dD} \tag{2.11}$$

The inclination angle is taken into consideration for deviated wells.

$$V_o = \pi R_i^2(L_2 - L_1) - \left\{\frac{2\pi R_i^2}{E\left(R_o^2 - R_i^2\right)}\left\{\left[(1-\nu-\nu^2)R_i^2+(1+\nu)R_o^2\right]\frac{dP_i}{dD} - 2(1-\nu^2)R_o^2\frac{dP_o}{dD}\right\} + 2\pi R_i^2\alpha_T\frac{dT}{dD}\right\}$$

$$\left[L_1\left(1-\cos\alpha\right)\left(L_2 - L_1\right) + \frac{1}{2}\cos\alpha\left(L_2^2 - L_1^2\right)\right] \tag{2.12}$$

The relation between TVD and MD is shown below.

$$D = D_1 + (L - L_1)\cos\alpha \qquad (2.13)$$

Here, D1 is the TVD that corresponds to MD of L1. D1 = L1, if we assume that everything is vertical before the analyzed part of the well. [3]

2.3.What is Pore Pressure – Fracture Gradient (PPFG)?

It is important to study PPFG topic carefully while discussing the LOT issue. The primary goal of running a LOT is to accurately comprehend the relationship between pore pressure and fracture gradient. If LOT is well implemented and can be commented on carefully, it will provide many important hints for upcoming drilling operations.

According to the Schlumberger Oilfield Glossary, these two terms are defined as following: Pore pressure is the pressure produced by fluids within a reservoir's pores, often hydrostatic pressure or the pressure created by column of water from a formation's depth to the sea level. (Schlumberger, 2011a). Fracture Gradient is the amount of pressure needed to create fractures in the rock at a specific depth (Schlumberger, 2011b). [20,21]

Before beginning to drill, considerable study has to be done to determine the relationship between pore pressure and fracture gradient of a potential hydrocarbon bearing field. First, 2D or 3D seismic provides a basic understanding of the PPFG curves in a field. Second, any nearby offset wells that are accessible should be checked for any historical data on similar formations or dangers. Any mud weight, kick, or loss data provide information for the field. If the field is completely wildcat, then the seismic data is the only source of guidance for PPFG research. After monitoring few years on raw seismic data ,seismic velocity results can be collected which provide information regarding potential formations. In Figure 3, a sample PPFG graph is shown.

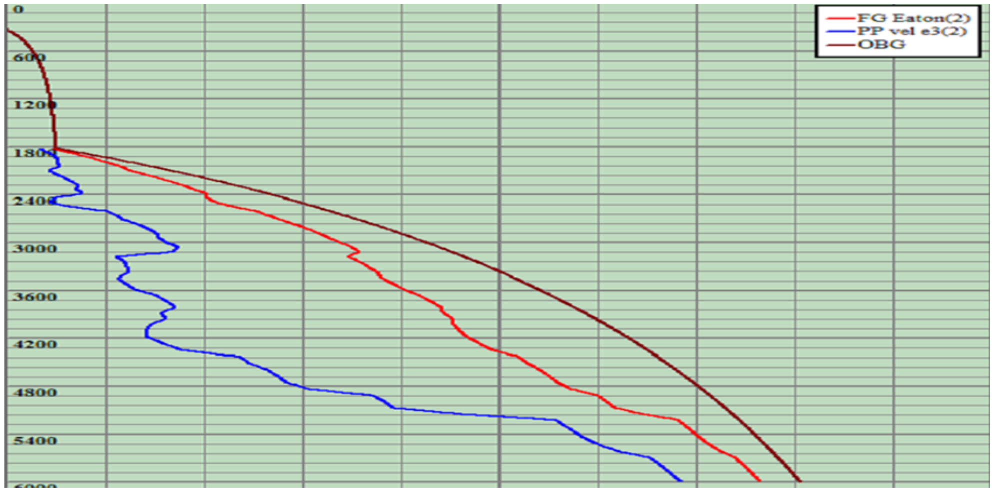


Figure 3: A sample PPFG graph that shows pore pressure, fracture gradient and overburden gradient (TPAO, 2011a) [24]

After obtaining a PPFG graph, planning the depths for casing or liner placement is the next stage in drilling. Drawing some "stairs like lines" between pore pressure and fracture gradient curves is the most basic method for determining casing setting depths. Vertical lines indicate the lengths of the hole section, while horizontal lines indicate the casing setting depths. Such a basic study will undoubtedly be independent of all formation characteristics and technical limits. Any formation feature, such as high permeability, forces the drilling team to set the casing earlier than anticipated depth. Casing setting depths may also be limited by technical factors like landing string spesifications or surge pressures. As this thesis is not specifically concerned with casing design, those limitaations will not be covered in detailed. [24]

The number of casings and liners increases when the fracture gradient curves and pore pressure curves get closer, like in deep water environments (Simmons and Rau, 1988). Each well casing installed reduces the diameter of the wellbore due to the nature of drilling. Therefore, this diameter reduction will provide some hydraulic challenges and might result in some operational issues. The number of critical operations increases as a result of more casings being set, which is a drawback that leads to longer operational days and higher costs. [22]

The casing design will be impacted by a LOT result because it will enforce horizontal and vertical lines on a graph of the casing design. Each LOT performed following the casing running operation will decide how much further each hole section can go, with each open hole can go up to a pore pressure equal to the previous casing shoe's fracture gradient. The maximum mud weight that can be used in the next hole section will depend on the outcome of the LOT. Rezmer-Cooper, et al. (2000) recommends a 0.3 ppg margin between mud weight and fracture gradient. If the LOT result is less than anticipated a shorter open hole section might be drilled before setting a new casing. This will force the operator company to install extra casings, which can cause not reaching the planned TD. This can lead to the drilling operation to end before testing any predetermined targets in the well. Even though the operation cost millions of dollars, none of the project's goals would be reached. [18]

3. HOW IS THE LOT EXECUTED (PROCEDURE)?

The LOT's field implementation remains one of the most important jobs, even after comprehending the theory behind it. The LOT must thus be carried out properly, with a suitable rig setup and definite guidelines. In his article "Pressure Integrity Test Interpretation," Postler (1997) provided a precise method for carrying out the LOT on the rig along with a list of guidelines that must be complied with. These guidelines are written below.[16]

3.1. Proper Rig-Up:

Obtaining the appropriate rigged-up equipment is one of the most crucial aspects in the execution of a LOT. In other words make sure the testing system is properly maintained.

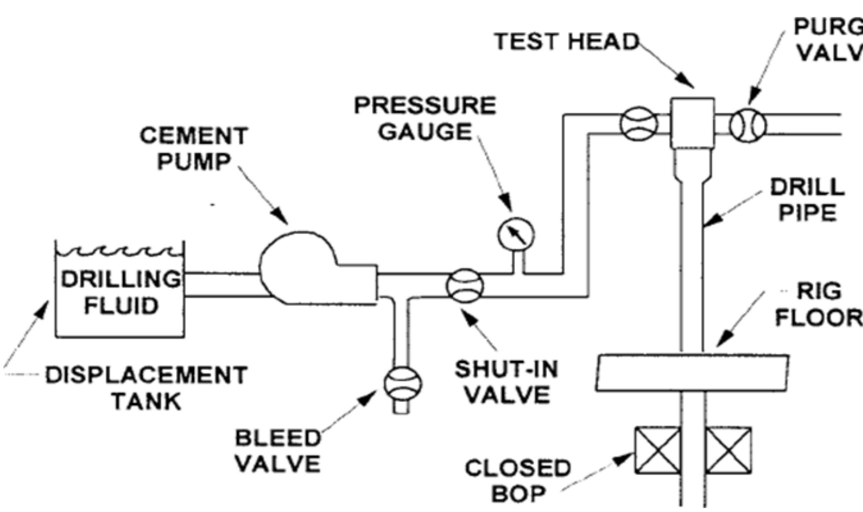


Figure 4:LOT Rig-Up(Postler,1997) [16]

The most essential equipment needed for a good LOT run is shown in Figure 4. First, a cement pump is required; however, because of their huge capacity and inability to handle low pump rates, regular rig pumps should not be used. When it comes to pressure integrity testing, slow pump rates are typically the most effective. If the pump has been calibrated, the pump's strokes can also serve as a reliable volume indicator.. If the number of pump strokes could not be counted, the displacement tanks had to be marked in 1/4-bbl increments so that the volume could be monitored from there. Second,the shut-in valve, bleed valve, and purge valve must all be completely sealed and checked for leaks because if a leak is discovered, the pressure will drop before the formation breaks down, causing incorrect test results that could hasten the occurrence of expensive issues that we could have easily avoided. Finally, a decent pressure gauge is essential for a LOT since a pressure gauge that is unreliable or difficult to read is pointless. It is crucial that the pressure gauge is readable and has a proper scale since, in low pressure testing, a variation of 50 psi might completely alter the equation and affect the decision whether the test results should be accepted or not.

3.2. Realistic LOT Scenario Set-Up.

It is crucial to conduct a thorough study about the pore pressure- fracture gradient (PPFG) of the formation being drilled, before performing a LOT. Typically, geological and geophysical experts, as well as well planning engineers, undertake such studies. Prior to conducting a leak-off test, this study gives the drilling engineer reliable knowledge about the results that should be anticipated, enabling the engineer to comment on the sensitivity of the LOT result and the quality of the cement placed.[16]

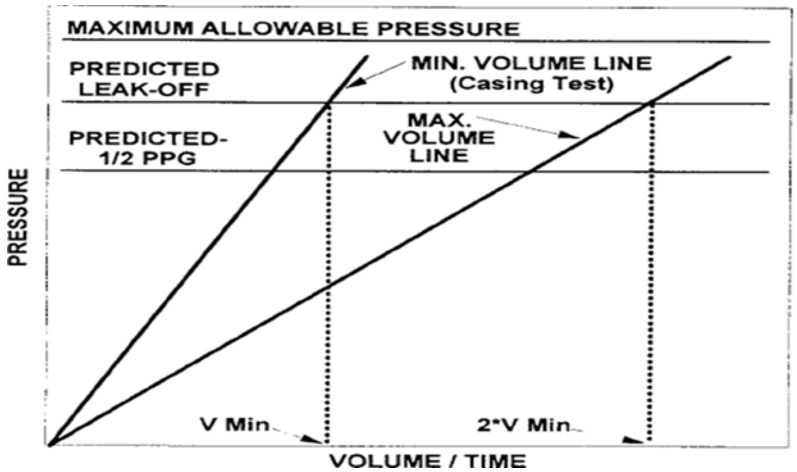


Figure 5: Reference Guidelines for LOT (Postler,1997) [16]

The horizontal line below the predicted leak-off pressure line is called the minimum leak off pressure. This line is essentially derived from the predicted leak-off equivalent mud weight (EMW) minus ½ ppg and is utilized in the same way as the predicted leak-off pressure line. According to Postler (1997), this ½ ppg difference represents the biggest "error" seen in leak-off measurements. As a result, this difference allows for inaccuracies caused by mud gelation effects, inaccurate measurements of volume, pressure, and mud weight, as well as errors in the predicted leak-off pressure [16]

The horizontal line above the predicted leak-off pressure line demonstrates the maximum allowable pressure and this is generally set depending on equipment limitations or lost circulation experiences.[16]

The diagonal line from the origin to the maximum pressure/volume data point of the casing test is the minimum volume line. This line illustrates the minimal volume of drilling fluid compensation required to reach any pressure using the available mud system. The maximum volume line, on the other hand, is a diagonal line that is drawn from the origin to a pressure/maximum volume data point. Any results displayed below this line during a leak-off test are taken into consideration as evidence that the formation has a high permeability and the pumping rate is too low. As a result, higher pumping rate must be exerted to overcome the permeability. It is also crucial to note that the maximum volume must be double the minimum volume. For example, if the minimum volume is 2 bbl at 1000 psi, the maximum volume data point should be 4 bbl at 1000 psi. [16]

3.3. Usage of Clean, Uniform Drilling Fluid.

Before performing the leak-off test, the casing shoe will be drilled out along with a few meters of the new formation, increasing the probability that the drilling mud will be contaminated with cement and cuttings, which might change the rheological characteristics of the used mud. Therefore, it is crucial to circulate and condition the mud to stabilize properties and guarantee that the hole is clean from cuttings. It's easy to make sure the hole is clean; just keep the mud circulating until the shale shakers are clean from cuttings. The mud engineer may also monitor the mud weight entering and leaving; if Mwin = Mwout, the mud is free of any cuttings and cement traces and is ready to be utilized as a testing fluid. The major goals of conditioning the mud before to testing are to acquire a column of drilling fluid with a uniform density, create a filter cake on the formation, breakdown gels, and circulate out any air bubbles that may be present. [16]

3.4. Pumping Guidelines.

In order to get reliable LOT results, it is crucial to watch over the pumping process and determine the best pumping rate for each type of formation. As a general rule, the pump rate should be slower and steadier; there is high probability of the leak-off point to be masked if the faster pumping rate is used. Additionally, it's critical to keep the pumping rate steady since unsteady pumping rates can make it more difficult to understand the test results by causing the slope of the plot to change before leak-off. Postler (1997) said that a rate of 1/4 bpm should be used for impermeable formations. The rate increases to 1/2 bpm reaching 1 bpm in permeable formations. [16]

Returning to the reference guidelines shown in figure 5, it is possible to utilize the maximum volume line to decide whether or not a greater pump rate is required. After the minimum expected volume has been pumped, it is necessary to compare the plotted data with the maximum volume line. If the results are not above the line, the pump must be turned off, the pressure must be bled to zero, and the test must be repeated at a pump rate 1/4 bpm higher than the prior test. In Figure 6, it is well illustrated that how this procedure is decided. [16]

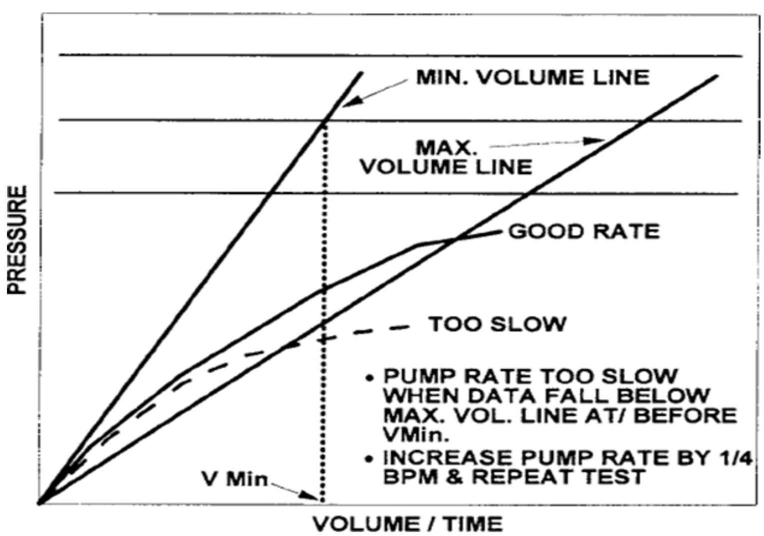


Figure 6: Pumping Guidelines (Postler,1997) [16]

3.5. Plotting data while test is running.

The data acquired from a LOT must be reported in a consistent manner. During the test, this data must be shown on a sizable graph showing the volume pumped versus the pressure. Compatible software that can concurrently record the volume pumped vs. pressure as the test is being run can be used to record this data. Such software is used in offshore operations. Otherwise, same data may be manually entered and displayed using software like Microsoft Excel and this is usually done in onshore operations. Regardless of where the test is being run, the data must be carefully plotted in order to precisely identify the leak-off point, identify any losses, and decide if the pump rate is enough or needs to be changed. Regardless of the pump rate, it is preferred to record and plot the data every 1/4 bbl pumped. [16]

3.6. When to stop pumping.

Pumping must be quickly stopped if the pressure drops, therefore knowing when to stop pumping is considered to be highly crucial decision. If pumping was continued after the pressure drop was observed, the drilling fluid will start filling the cracks, and after a period of pressure stability, the pressure will increase again, causing the formation to plastically deform. This is illustrated in figure 7 according to Mitchell (1995). The plastic rock deformation will exacerbate the cracks and therefore reduce the leak-off point, necessitating additional casing runs in the end and adding unnecessary extra cost. [9]

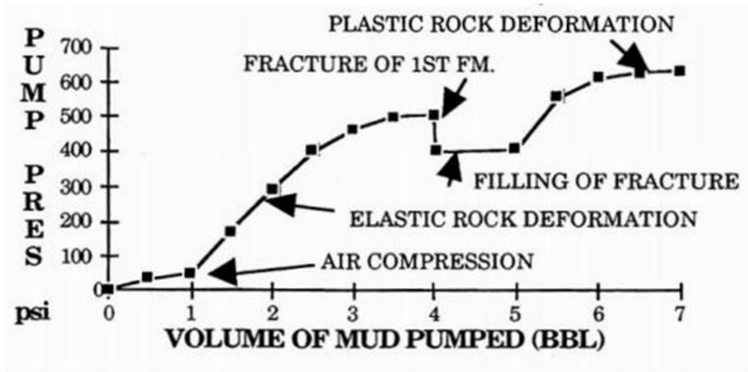


Figure 7: Excess mud pumping effect on LOT (Mitchell, 1995) [9]

In order to further support the aforementioned assertion, Aadnoy (2009) wrote in his paper "Fracture Mechanics Interpretation of a Leak-off test" that the borehole cracks at the LOT point. Aadnoy (2009) added that if pumping is continued some mud enters the fracture. However, a stress bridge builds up close to the fracture entrance, prevents further fluid flow into the crack, which in turn causes the pressure to rise once again. [1]

Postler (1997) asserts that sometimes it might be challenging to identify the leak-off point. As a result, he suggested some general guidelines for deciding when pumping must be stopped.

- *Plot Bend Below Minimum Leak off:* To determine if the pressure will rise or not, additional barrels must be pumped. If the pressure keeps increasing, pumping must be continued until it reaches the expected leak-off value or a point roughly close to it. It is crucial to understand that the pressure will not increase if the low leak-off is due to cement channel but both ways further pumping will not cause any damage.

- *Curving Plot:* If the pressure build up doesn't follow the normal linear trend, pumping must be continued until the pressure remains constant for three successive readings. This curving plot may be a result of high permeability or plastic formation.

  Finally, the choice to cease pumping is always subjective and heavily depends on the knowledge and experience of the person conducting the test. Analysis of current and offset well data can be an important factor in determining the expected leak-off pressure which will help in deciding when pumping must be stopped. [16]

3.7. Shut in Guidelines.

It is important that the shut-in is performed precisely in order to carry on a successfully and accurately interpret the results acquired. To begin with, it is crucial not to solely rely on stopping the pump when it’s about time to shut the well, the shut-in valve must be used instead in order to prevent fluid leaking past the pump during the shut-in valve. The shut-in valve has to be checked using the bleed valve and other leak detection tools in order to further confirm that there is no leakage happening. The second thing that has to be done is to monitor pressure drop. It normally takes 10 to 15 minutes of shut-in time to evaluate the LOT results' quality and the cement bond at the prior casing shoe. Various pressure drops are tolerable in certain situations. However, a significant pressure drop that occurred shortly after the pumps were turned off indicates the presence of a cement channel. Existing cement channels need to be dealt with seriously because cement channels can cause the leak-off value to be detected at a shallower depth rather than at the casing shoe. As a result, it's important to detect any cement channels and plug them using cement squeeze operations. Further discussion of cement channels and their consequences may be found in section 4.11. [16]

4. FACTORS THAT AFFECT LEAK-OFF BEHAVIOR.

Understanding the variables that influence the leak-off pressure is essential for a better interpretation of LOT data. It is well known that the LOT trend might occasionally appear irregular or unfamiliar when the leak-off point is higher or lower than anticipated. Therefore, it's crucial to figure out what changed this pattern and why our PIT/LOT plot deviated from what is considered to be "normal." Numerous factors that affect the leak-off behavior, some of them are controllable and others are not.

4.1. Rock Properties.

Postler (1997) asserts that most rock formations exhibit elastic behavior up to the point at which they crack. This result suggests that there is a linear connection between stress and strain, which in turn accounts for the linearity of the pressure build-up plot of the test before leak-off. However, it was discovered that drilling in an unconsolidated clay or sand formation, or even in salts, can produce a plastic strained zone near the wellbore, meaning that a rock can be permanently deformed without losing strength. According to Horsrud et al. (1982), depending on the characteristics of the rock, the plastic zone may increase or decrease when the injection pressure is increased. He also mentioned that the beakdown of intergranular cementation bond might result in a loss in the strength of a rock formation. As a result, there may be two distinct stress regions: a near-wellbore plastic region and a far field elastic region. The pressure build-up phase will become non-linear as a result of the near wellbore plastic region, making it more difficult to interpret the LOT. In conclusion, the rock properties can have a significant impact on the trend of the LOT results and make the LOP uncertain, however this factor cannot be controlled. [6,16]

4.2. Fluid Viscosity.

The stability and expansion of cracks are strongly affected by the testing fluid's viscosity (Postler,1997). Postler (1997) made note of the fact that when fluid viscosity increases, pressure drop in the fracture also increases. Additionally, he stated that the pressure at the crack tip may be lower than the breakdown pressure even if the breakdown pressure is being applied at the crack entrance. This implies that the fracture tip hasn't been impacted by the whole hydraulic force of the mud, resulting in a stable or no crack propagation. In order to trigger the fracture and make it unstable, more pressure must be applied. Therefore, regardless of the fracture opening pressure, for a LOT, the breakdown is proportional to the fluid viscosity. When a viscous mud is used, there is a delay between fracture initiation and fracture propagation(breakdown). When a fluid with low viscosity, like water, is being used, this delay is negligible. As a conclusion, the panic of "breaking down the formation" during a LOT is not utterly pragmatic, as this breakdown may be easily managed and prevented by altering the fluid's viscosity and other pumping characteristics. [16]

4.3. Pumping Rate.

The LOT's goal is to ascertain the pressure at which the formation breaks down, and this test is essentially carried out by pressurizing the formation using a fluid that is injected into the well. Therefore, understanding the theory underlying the pumping rate's effect on the leak-off point is essential. [16]

The pumping rate effects on fracture initiation has been presented in many researches and reached the same conclusion as Postler's (1997) where he assured the fact that a faster pumping rates derive a greater fracture initiation and breakdown pressure (LOP). [16]

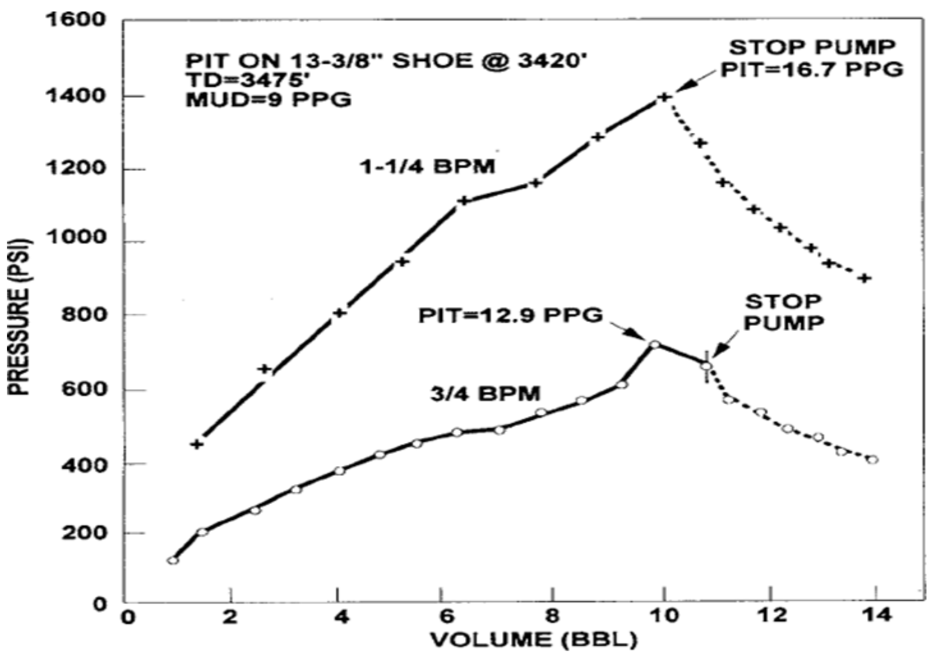


Figure 8: Effect of Pump-Rate on LOT (Postler,1997) [16]

Figure 8 by Postler (1997) illustrates how the pumping rate affects the leak-off point, where at higher pumping rates (1 ¼ BPM) the leak-off point is at around 1350 psi. In contrast, at low pumping rates (¾ BPM), the leak-off pressure dropped till approximately 700 psi. Since this variation in the recorded leak-off pressures cannot be ignore it is crucial to choose which leak-off pressure we must rely on. The leak-off pressure acquired at a high pumping rate does not accurately reflect the actual strength of the rock formation. As opposed to this, the leak-off pressure obtained at slower pumping rates can be used to determine a conservative and secure formation leak-off pressure to rely on because lower pressure was applied for a longer period of time and in slower circulations, much like how well control operations or routine circulations are carried out (Postler,1997). [16]

4.4. Mud Type.

The type of mud used during a LOT has a significant impact on the stability of fracture growth and thus affects how accurately the LOT interpretation is made.

According to Rezmer-Cooper et. al (2000), the operation becomes critical when the oil-based mud (OBM) or synthetic based mud (SBM) is used during a leak-off test. They claim that if the formation was fractured during the test with an OBM/SBM, it would then be difficult for it to recover and regain the strength it had before the test. Thus, using a water-based mud would be recommended. In addition to that, the leak-off pressures are reported to be higher when utilizing a WBM rather than OBM or SBM. In section 4.5, this fact will be covered in more detail. [18]

In his study "Fracture Mechanics Interpretation of Leak-off Tests,"(2009) Aadnoy noted another effect that mud type may have. He described how mud behaves differently when the LOP is reached and pumping is continued. [1]

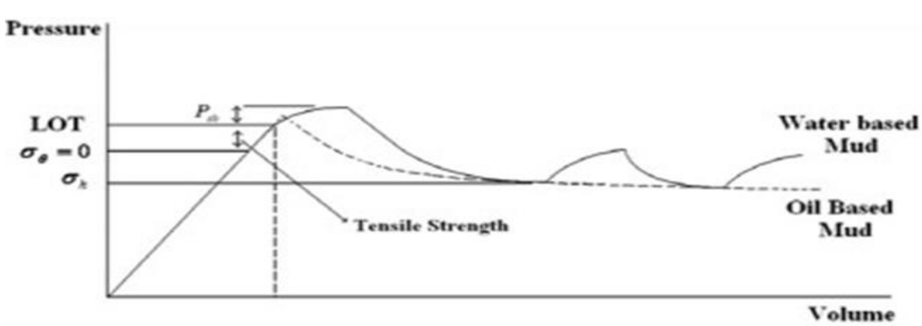


Figure 9: Behavior of WBM versus OBM (Aadnoy, 2009) [1]

According to Aadnoy (2009), after the pressure drops to a minimum normal stress (σh), the particles in a water- based mud continuously attempt to create a bridge in order to effectively isolate the fracture tip, but at a certain pressure this bridge collapses. Aadnoy (2009) called that to be the “self-healing” effect of WBM. On the other hand, it was evident that the OBM reacted completely different where a more sudden breakdown was seen, and a constant pressure propagation was maintained with continuous pumping. In the drilling industry this impact is well-known, where OBM is commonly used, it might be challenging to eliminate circulation losses. This phenomenon was later attributed to the difference in wettability between the rock and the mud, which lead to a minimal filtration loss. In conclusion, it is clear that OBM results in a lower and constant propagation pressure than a LOT carried out with a WBM. [1]

4.5. Mud Penetration and Permeability.

The leak-off value is highly affected by drilling fluid’s rheological characteristics and some properties of the formation being drilled one of which is permeability.

Starting with the drilling fluid penetration, various LOTs are carried out using:

- Water-based mud (WBM): classified as a non-penetrating fluid.
- Oil-based mud (OBM) or Synthetic based mud (SBM): considered to be penetrating fluids

Penetrating fluids display lower fracture initiation pressures (lower leak-off value will be reached) than non-penetrating fluids due to the temporary rise in pore pressure that occurs when a higher pressure fluid is introduced into a rock's pores. This, in turn, will result in a reduction in the formation strength (Postler,1997). The International Association of Drilling Contractors (IADC) reports that the leak-off pressure difference might be as high as 0.5- 0.7 ppg in favor of water-based mud (as cited in Rezmer-Cooper et al., 2000). In addition to the penetrating effect of various types of mud, comes the size of the interconnected pore sizes, well known as the permeability of the rock. Postler (1997), considered the same logic to be applied in this scenario where permeable rocks must have a lower breakdown pressure than impermeable rocks. This means that, in a permeable rock the highly pressurized fluid has the ability to penetrate considerably deeper into the formation causing the pore pressure to be equivalent to the fluid pressure. Therefore, a lower leak-off value will be expected. [16,18]

On the other hand, in an impermeable formation, the highly pressurized fluid is only able to penetrate certain regions close to the wellbore or along the length of the fracture which causes the fluid pressure to build-up and reach larger leak-off values.

A highly permeable formation, according to Postler (1997), may cause certain non-linearities during the pressure buildup phase, mostly as a result of the fluid losses that will eventually occur. [16]

4.6. Pre-Existing Cracks.

A formation's strength is often predicted to decrease as it cracks. Cracked formation may already exist prior to drilling activities or even while drilling is underway; this might be problematic for the application and interpretation of leak-off tests.

Newly induced or pre-existing fractures are normally closed because of the naturally occurring compressive stresses of the formation. As a result, the tensile strength of the rock can be assumed to be zero. Hence, less pressure would be needed to induce a fracture in most rocks downhole than to open an existing fracture (Postler,1997). In a LOT, this implies that if a pre-existing fracture is present in the drilled formation, an early breakdown or a lower leak-off value will more likely occur as opposed to an intact formation. [16]

Additionally, it was established that a preexisting crack's size may easily change the magnitude of the breakdown pressures and may have an impact on the fracture opening pressure. Ishijima carried out a detailed study by numerically modelling a hydraulic fracture test in 1983. The test's range was between less than 0.05 and more than 2.5 times the wellbore radius, R. Figure 10 illustrates the test results and makes it very evident how the fracture size affected the results. [7]

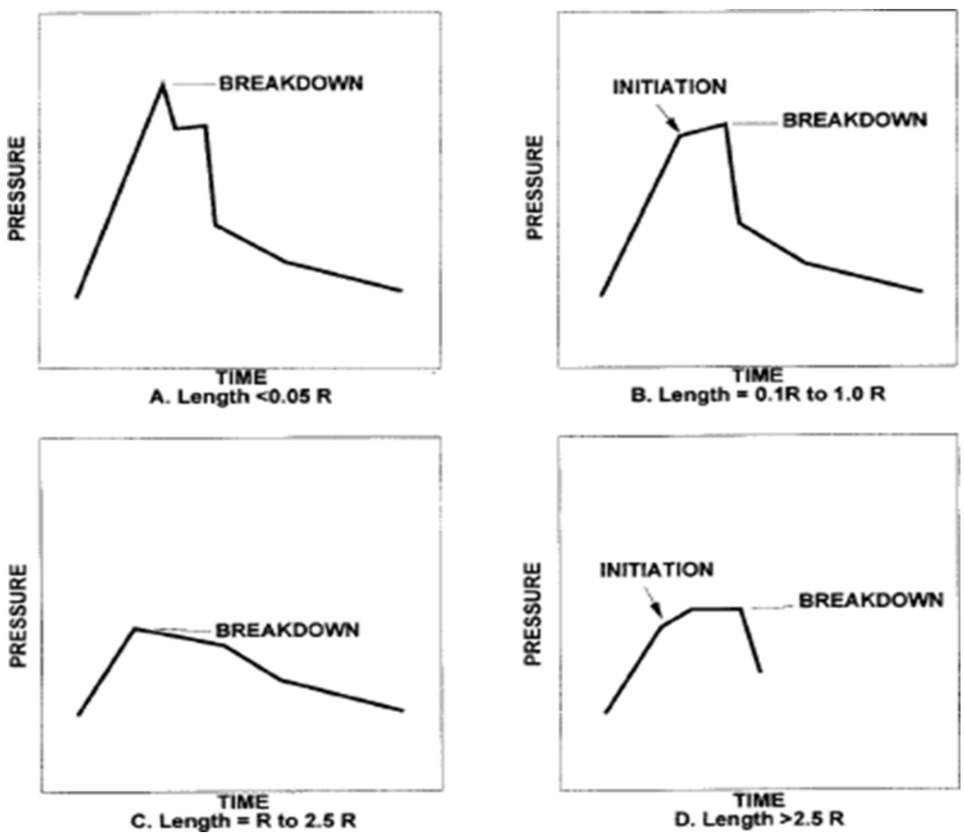


Figure 10: Impact of Pre-existing Crack Length on Breakdown Pressures (As cited in Postler, 1997) [16]

4.7. Wellbore Stress-Distortion Effect.

The natural subsurface stress field will be distorted as a result of the numerous cracks that will be created during the well-drilling process. Typically, near the wellbore, it is most common to detect extremely stressed and compressed layer of rock and that is because it must hold the load that was previously detained by the formation drilled.

The LOT essentially measures the pressure needed to re-open a crack in the formation. But the structure that we're dealing with can have different types of stress distribution. The stress in a well-consolidated rock formation is often higher than the natural minimum compressive strength of the formation because the wellbore grablesstress field in the rock. However, this stress distortion lessens when one moves further away from the wellbore. This means that a larger pressure is required to start or reopen a crack in the formation since the stress near the wellbore is higher than the surrounding rock. Typically, this pressure must be higher than the natural minimum stress (Postler, 1997). Horsrud et. al (1982), on the other hand, claimed that the fracture initiation pressure decreases slightly with increasing compressive strength before increasing rapidly again as shown in Figure 11. However, there was no physical explanation for this phenomenon, and it was unclear whether or not this behavior was actually observed. However, what has been shown so far is that the connection between compressive stress and initiation pressure is mostly one that is relatively escalating. [6,16]

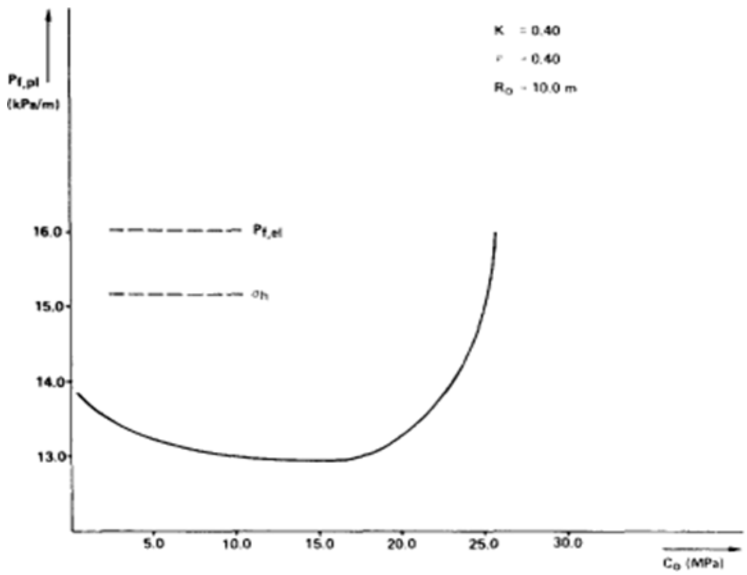


Figure 11: Fracture Initiation Pressure as a function of Compressive Strength (Horsrud et al. , 1982) [6]

A zone of plastically stressed material will be present around the wellbore in a poorly consolidated formation (Horsrud et al., 1982). Also Postler confirmed this in his paper (1997) where he said that: "in certain formations there may be two distinctly different stress regions: a weaker plastic region near the well, and a stronger elastic region farther away". He also noted that when these two regions present the fracture will not grow throughout the formation at a fixed pressure. [6]

In figure 12 , Postler (1997) displayed one field example, that better illustrates how these two regions behave when it comes to the amount of pressure required for a fracture to propagate. Within the plastic zone, it was observed that a fracture originated at about 850 psi and propagated for approximately 50 psi until reaching 900 psi. The fact that the fracture opening pressure is less than the far field stress helped to explain this little extension. The growth stopped when the fracture tip reached the boundary between the elastic and plastic regions. As a result, more pressure was applied to initiate and propagate the fracture into the elastic zone and a greater leak-off value was obtained which is the one normally adapted with.[16]

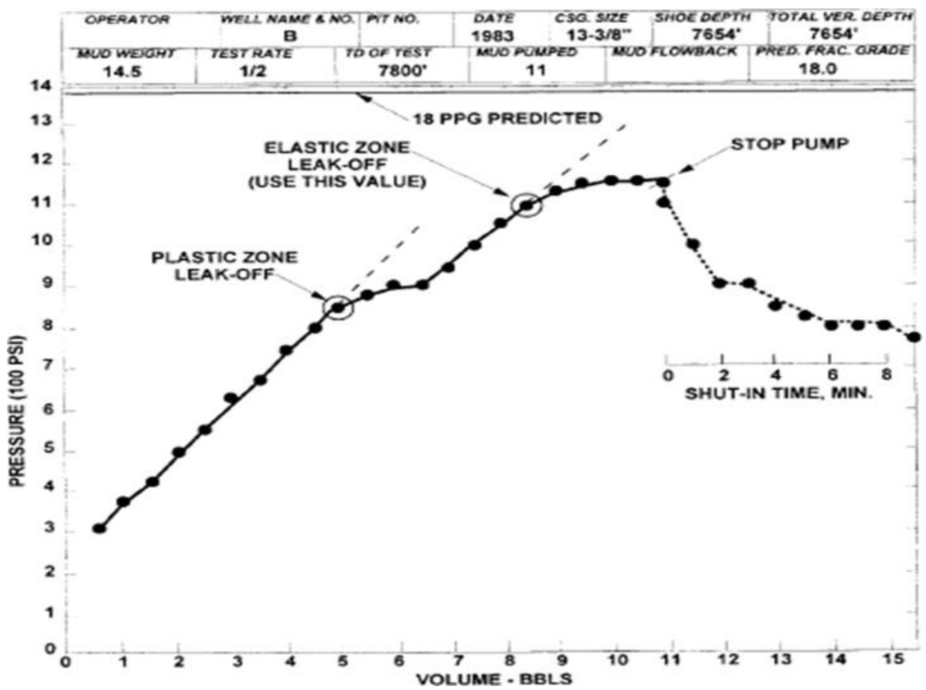


Figure 12: Plastic vs. Elastic Formation Behavior (Postler,1997) [16]

4.8. Mud Compressibility & Temperature.

When it comes to discussing how the mud compressibility affect the LOT, equivalent mud weight (EMW) is the first thing that must be taken into account , where it's still a common practice to calculate the EMW and fracture gradients based on surface readings. If the influence of mud compressibility is not taken into account, this method might cause the drilling operation to have narrow drilling margins, which would result in higher costs. The concept of mud compressibility often receives more attention in deep-water drilling since the external temperature profile typically drops from the surface to the seafloor. This situation is anticipated since the riser is encircled by cold sea water, which will cause the mud to lose part of its temperature as it travels through it until it reaches the BOP. What is unexpected, however, is how the mud's physical characteristics will respond to this shifting temperature profile. Rezmer-Cooper et al. (2000) claim that the reduced external profile has a significant influence on the whole well's circulating temperature and will eventually affect both the mud's viscosity and density. Additionally, he said that the effective density of the cooled mud entering might be much greater and more viscous than what was noted on the surface. In other words, when the temperature drops, the mud's density and viscosity rise, and vice versa. In the end, when interpreting a LOT, this will result in an incorrect assessment of EMW at a certain casing shoe. In order to compensate for the cooling effect on the mud's rheological characteristics, drillers typically warm the mud as it enters the formation or before circulation. As a result, mud compressibility must be taken into account while running a LOT and the required mud density corrections must be done. [18]

4.9. Variation in Time.

A typical misunderstanding is that the formation strength will remain intact over time after performing a leak-off test or any formation integrity test. Van Oort (2007) highlighted in his study, "Improving Formation Strength Tests and Their Interpretation." the reasons why the hypotesis that the formation strength doesn't change over time, isn't always valid.

- After the leak-off test is carried out, the casing shoe often loses its original strength and that is because of the formation breakdown induced. On the other hand, subsequent shoe remediations are later carried on.
- When water-based mud is utilized, it has been seen that the shoe gradually regains some of its strength over time; this occurrence is referred to as "Fracture Healing". However,

this healing is not detected when using OBM or SBM which in turn indicates that the loss of shoe strength will be permanent.

- The deeper the well is drilled, the higher the temperature gets rendering the mud to become warm. According to Van Oort's prediction from 2007, "circulating warm mud off-bottom through the casing shoe may raise near-wellbore thermal stresses, which may elevate the shoe strength/fracture gradient." As a result, this enables drilling at ECDs that are higher than the maximum pressures acquired during formation integrity testing without experiencing any losses.[10]

4.10. Location of Cementing Unit.

The cementing unit, which is typically situated on a deck lower than the point of reference of the well (i.e. rig floor or top of the mud column), is where the majority of the leak-off test pressure data are recorded. The elevation difference seen in Figure 13 might cause theoverestimation of the leak-off value. Calculating the hydrostatic pressure caused by the difference between the reference point selected and the location of the gauge at the cementing unit is therefore crucial (van Oort, 2007). [10]

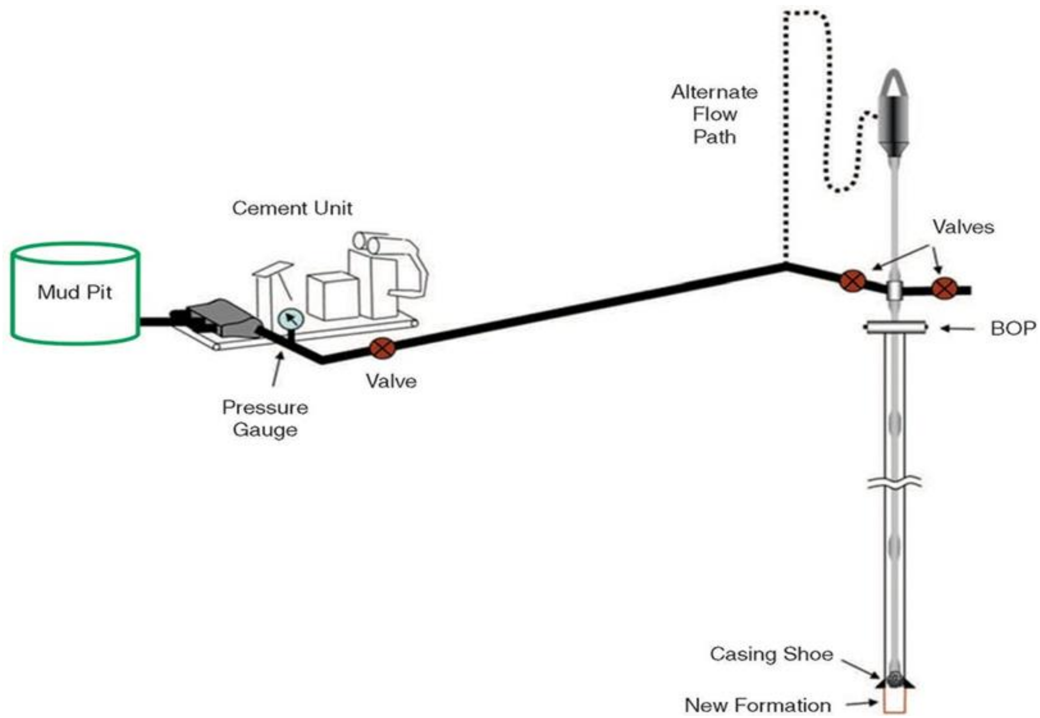


Figure 13: LOT Rig up (Retrieved from American Oil & Gas Reporter)

4.11. Cement Channels.

Commonly, the presence of cement channels results in unusual leak-off characteristics. A cement channel is described as a path that enables the drilling fluid to go through or around the cement at the casing shoe in order to reach shallower zones which in turn possess lower fracture gradient (Postler, 1997). In other words, a cement channel is a means of communication between the different layers of a formation. [16]

In most of the cases a cement channel is the result of a poor cementing job or poor cement quality. It may, however, occasionally be the result of the casing's insufficient centralization, which favors the unbalanced distribution of the cement slurry around the casing. It's crucial to repeat the PIT and not only rely on the initial plot in order to verify whether a cement channel actually does exist. The first plot typically indicates the presence of a cement channel but does not guarantee it. However, a second test can determine whether there is a cement channel or it is just formation-related effects (Postler, 1997). [16]

Not every leak-off pressure result has to match the predicted/expected values. A margin error of ± ½ ppg equivalent mud weight is typically acceptable, according to Postler (1997). Additionally, he states that an open cement channel may only be considered if the leak-off is more than 1/2 ppg EMW below the expected leak-off value. [16]

Postler (1997) distinguished three types of cement channels:

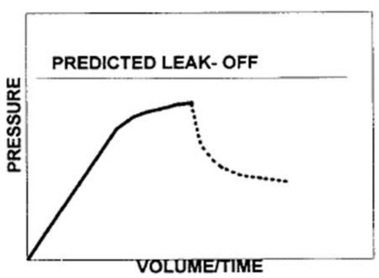
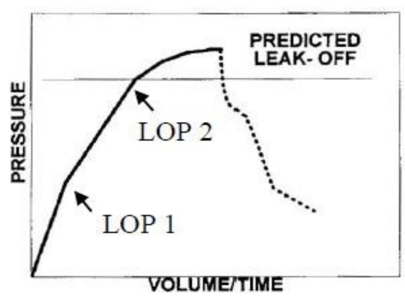
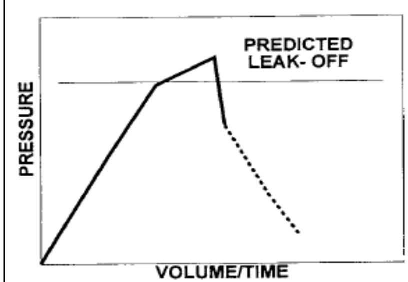
Large Open Channel	***Small Open Channel***	***Plugged Channel***
The shape of the plot is not affected but the only thing that can be clearly noticed is that leak-off pressure is significantly lower than the predicted leak-off line. It is only verified when the LOP is more than ½ ppg EMW below the predicted leak-off value	The test plot shows two slopes: a normal slope from origin until breakdown of weak zone (*LOP 1)* then a lower slope until fracture opens in the zone at shoe (*LOP 2*).	The pressure builds at a normal rate until the plugging material is forced out of the channel which can occur suddenly. When channel is unplugged the weaker zone breaks down and pressure drops. The shut-in pressure drops significantly and might approach zero.
		
Comments: • Allows immediate communication to weaker zones. • The validity of the predicted leak-off should be reevaluated before it is decided that a PIT has spotted a cement channel	**Comments:** • Acts as a choke and allows only a portion of the pumped fluid to pass through it. • Shut in behavior can also detect a small open channel. It usually drops to a value between the leak- off pressure and half that value if a fracture has been opened in the formation below the casing shoe.	**Comments:** • The plugging material is usually the gelled mud. • Pressure communication is often not immediate. • Once a channel becomes unplugged, a repeat PIT would indicate whether it is a large or small cement channel.

Table1: The three types of Cement Channels and their effect. (Modified Postler, 1997) [16]

5.INTERPRETATION OF LOT DATA.

Postler (1997) covered linear leak-off test interpretation guidelines in his work, which was based on experience and didn't include any numerical or analytical models to back up the guidelines he made. He provided the following set of guidelines:

- ***Estimate the leak-off :*** Since the first data point is frequently affected by air in the mud or irregular pump speed, one must draw a "best fit" straight line beginning from the second point on the leak-off plot. When a change in slope is noticed (a decrease), the leak-off point is typically marked. The first point that permanently decreases in slope refers to the “minimum leak-off”. It's crucial to remember that the actual leak-off could be higher.
- ***Evaluate leak-off pressure:*** Only if the leak-off pressure is greater than the minimum (within a range of 1/2 ppg of the projected value) the test result must be accepted. Otherwise, if this wasn't the case, then there is a chance that a cement channel exists and that should be verified by repeat testing. On the other hand, Postler (1997) warned that the expected leak-off might occasionally be incorrect and suggested reevaluating the prediction before going further.
- ***Evaluate shut in:*** It’s crucial to watch carefully the shut in because the first slope drop has a major significance. It indicates the “Minimum Horizontal Stress”. The evaluated leak-off value acquired in step 2 must be larger than or equal to the MHS. If this weren't the case, the leak-off value would have to be disregarded. Additionally, if the gauge pressure at MHS is greater than or equal to 50% of the gauge pressure at leak-off, the result is acceptable. However, if the result shows less than half of the gauge pressure at leak-off or if shut-in pressure doesn't level off, then it is likely that a cement channel exists, and the test must be repeated to validate the result. [16]

- ***Check for cement channels:***

As discussed before, there are numerous ways to recognize cement channels:

— Leak-off equivalent mud weight is more than half ppg below the expected value.

— Shut in pressure doesn't level off.

— Gauge pressure at the minimum horizontal stress is less than a half of gauge pressure at leak-off.

Once the test was performed and the aforementioned indicators remained unchanged, the cement channel is confirmed.

However, it's important to remember that non-linear leak-off tests are not uncommon, particularly in shallow marine sediments. And Postler (1997) didn't take this into account when he established his series of guidelines for interpreting leak-off tests. Altun (1999) asserts that interpreting a LOT can be challenging, particularly in environments like shallow marine sediments where it might be challenging to identify the end of the straight line due to nonlinear LOT behavior thus the leak-off point would be masked.[3,16]

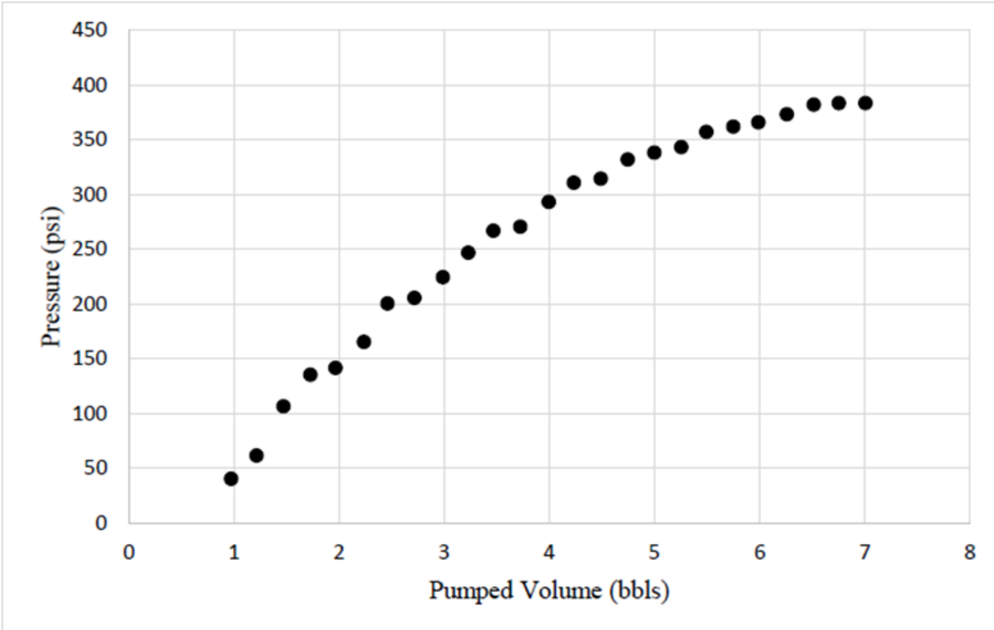


Figure 14: Non-linear LOT with regular interpretation (as cited in Fu,2014) [5]

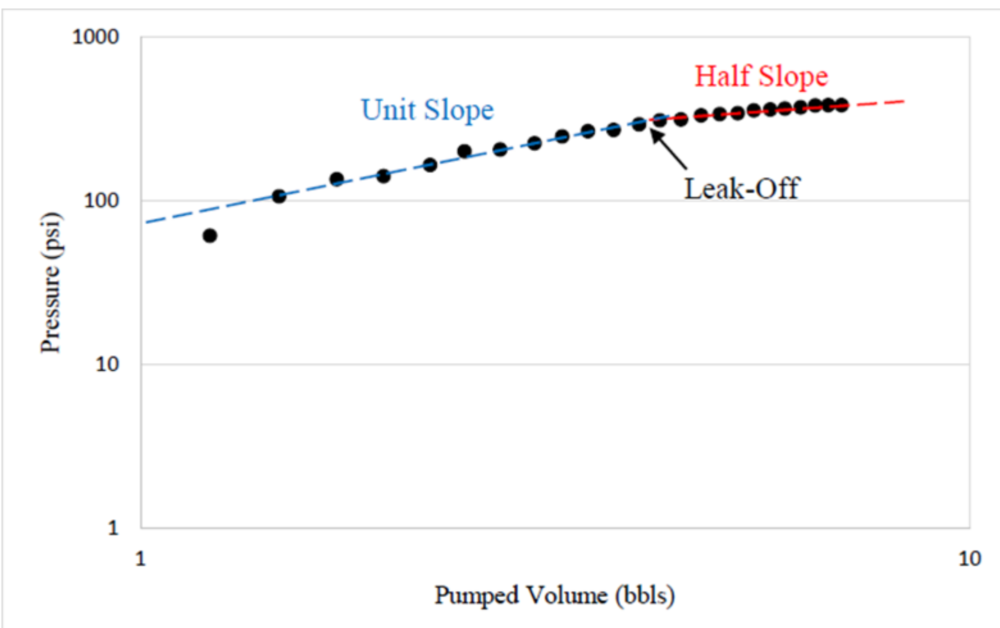


Figure 15: Identification of leak-off pressure using log-log plot (as cited in Fu, 2014) [5]

6. AUTOMATION ON PYTHON.

This project involved the use of Python programming language as a tool for simulating a leak off test and obtaining the necessary data. The objective of the project was to analyze the data from the first cycle test of a real well, which was conducted using water based mud, and to use Python to create an algorithm that could effectively read and process the data.

The use of Python in this project proved to be highly beneficial, as it allowed efficient data analysis and visualization. The algorithm created using Python was able to read the data from an Excel file and generate a graph that accurately depicted the behavior of the well during the leak off test.

One key aspect of the algorithm was its ability to detect the LOP(leak off point) on the graph. This point was identified the point where the graph begins to deviate from a straight line. The algorithm was able to accurately determine the LOP for the well in question, which was found to be 3000 psi.

The results of the analysis were presented in Figure 16, which clearly shows the behavior of the well during the leak off test.

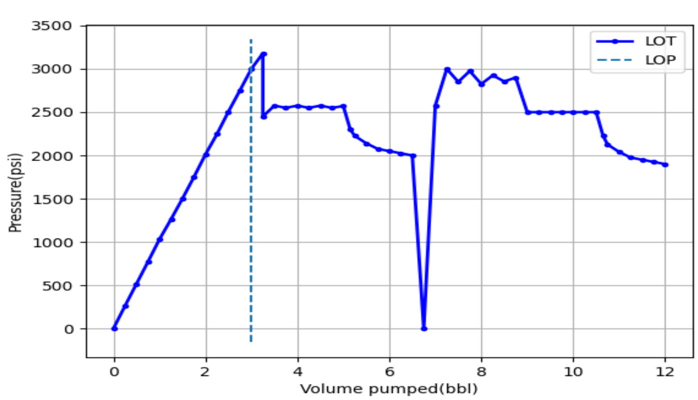


Figure 16: LOT result while using water based mud.

The algorithm developed for this project encompasses a range of important aspects of a leak off test (LOT), including key parameters that affect the LOT. In order to further explore the effectiveness of the algorithm, the next stage involved performing the LOT using oil based mud, and comparing the results to the LOT conducted using water based mud.

It is widely recognized that the compressibility of the fluid used in the LOT can have a significant impact on the results obtained. Given that oil is more compressible than water, it was expected that the pressure results obtained using oil based mud would be lower than those obtained using water based mud.

During the test using oil based mud, a leak off pressure of 2984.3 psi was observed. This result was lower than the leak off pressure of 3000 psi obferved during the water based mud test, which was consistent with expectations based on the compressibility of the two fluids. The results of the LOT conducted using oil based mud are presented in Figures 17 and 18 below.

These figures clearly depict the behavior of the well during the LOT, and provide valuable insights into the performance of the well using oil based mud. The results obtained using the algorithm developed in Python are consistent with established industry knowledge regarding the compressibility of different fluids used in the LOT.

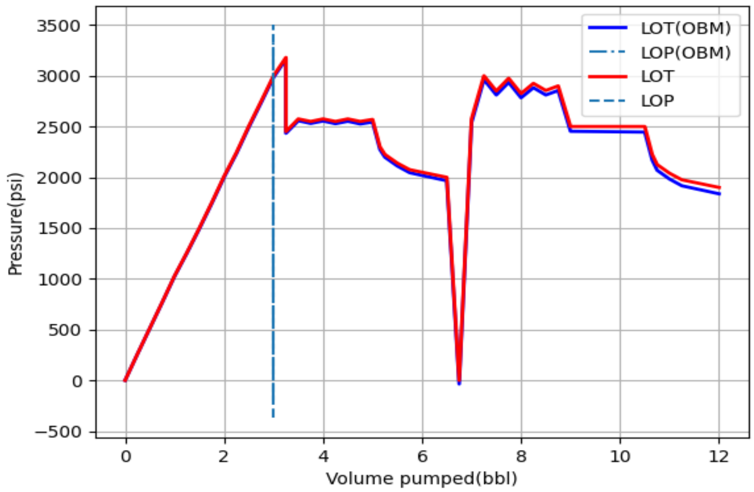


Figure 17: LOT results comparioson of WBM and OBM.

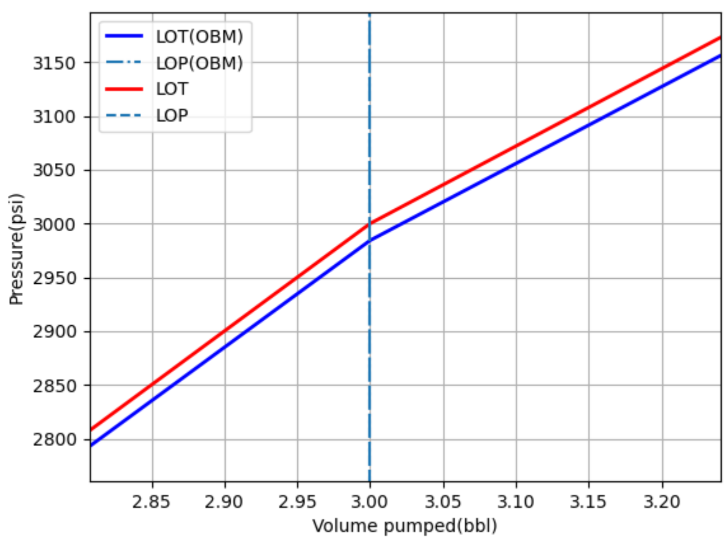


Figure 18: LOT results comparison of WBM and OBM.

In order to further test the effectiveness of the algorithm developed using Python, the next stage of the project involved simulating extended leak off test data based on existing real well data. The same algorithm that was applied to the real well data was used to analyze this simulated data.

During the analysis of the simulated data, the algorithm was able to detect the instantaneous shut in pressure (ISIP) of 2300 psi. The ISIP is an important parameter in leak off testing, as it represents the pressure at which the wellbore is completely sealed off due to the closure of the induced fractures.

Using the ISIP and the bleed off pressure, the algorithm was able to draw two tangential lines, and determine the intersection point of these lines. This intersection point corresponds to the fracture closure pressure (FCP), which is a key parameter in understanding the fracture mechanics of the well.

Based on the analysis of the simulated data, the FCP was determined to be 2125.16 psi. This result was obtained using the algorithm developed in Python, which demonstrated its effectiveness in accurately processing and analyzing extended leak off test data.

The results of this process are illustrated in Figure 19, which clearly depicts the behavior of the well during the extended leak off test. The ability to accurately determine the FCP using the algorithm developed in Python provides valuable insights into the fracture mechanics of the well, and can help inform decisions regarding future operations and maintenance.

Overall, the algorithm developed in Python was able to effectively process and analyze both real well data and simulated data, and provided accurate insights into the behavior of the well during the test.

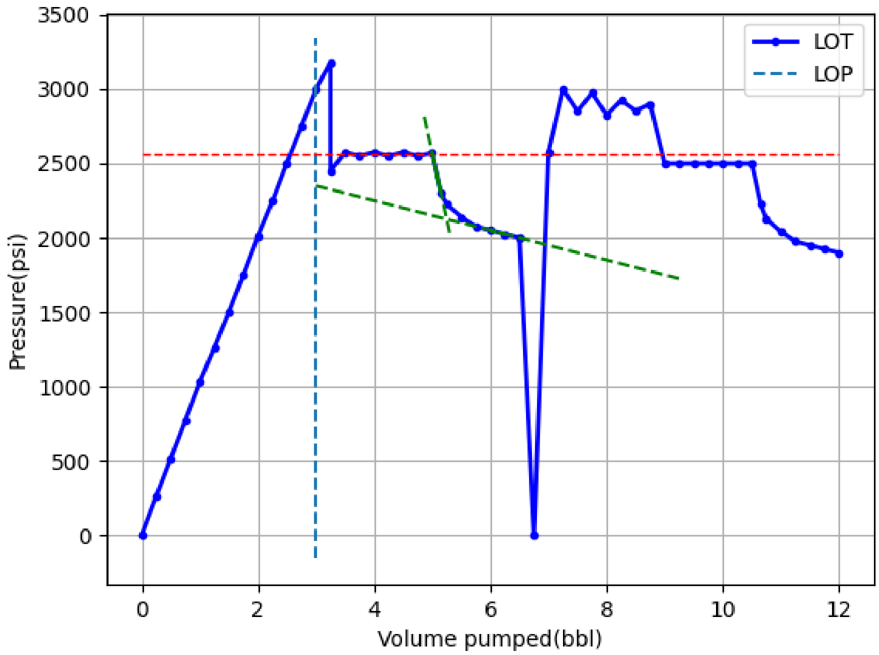


Figure 19: Fracture Closure Pressure detection.

7. CONCLUSION

After a thorough evaluation of the leak-off test, which covered everything from what it is to how to interpret the results, it became clear how crucial this test is and what advantages it has. This, in turn, explains why it is the most diagnostic inexpensive test that is routinely carried out during drilling operations. Application-wise, the leak-off test might appear simple, but its interpretation can be challenging, particularly in formations where there is a nonlinear relationship between injection pressure and pumped volume. In these situations, choosing the right mud weight, casing setting depths, and other crucial parameters is therefore extremely important. The leak-off test is identified as a priority in the world of automation and digitalization due to the significant importance of its results and the enormous amount of data a driller may obtain from one run. As can be seen, the petroleum industry has now developed the courage to step into the automation world, where the current primary focus is on how to carry out drilling operations remotely with greater efficiency, higher safety, and lower costs. The drilling sector will greatly benefit from the inclusion of the leak-off test application in this digital transition since it will save time, money, and effort while, most importantly, ensuring the safety of the drilling personnel located on the rig. As a result, the second section of this project will focus on automating the leak-off test, starting with a standard vertical well and moving on to the automation of more complicated scenarios if time allows.

REFERENCES

[1] Aadnoy, B. S., Mostafavi, V., & Hareland, G. (2009, January 1). Fracture Mechanics Interpretation of Leak-Off Tests. Society of Petroleum Engineers. doi:10.2118/126452-MS

[2] Addis, M. A., Hanssen, T. H., Yassir, N., Willoughby, D. R., & Enever, J. (1998, January 1). A Comparison of Leak-Off Test and Extended Leak-Off Test Data For Stress Estimation. Society of Petroleum Engineers. doi:10.2118/47235-MS

[3] Altun, G., Shirman, E., Langlinais, J. P., and Bourgoyne, A. T., Jr. (June 1, 1999). "New Model to Analyze Nonlinear Leak-Off Test Behavior." ASME. J. Energy Resour. Technol. June 1999; 121(2): 102–109. https://doi.org/10.1115/1.2795064

[4] Aviles, M. (2015, July 14). Technology Innovation and Adoption in Oil & Gas Industry -- Why Did It Slow? Retrieved October 01, 2020, from https://www.forbes.com/sites/drillinginfo/2015/07/14/technology-innovation-and-adoption-in-oil-gas-industry-why-did-it-slow/

[5] Fu, Y., 2014, Leak-Off Test (LOT) Models, Master's Thesis at the University of Texas at Austin.

[6] Horsrud, P., Risnes, R., & Bratli, R. K. (1982, December). Fracture initiation pressures in permeable poorly consolidated sands. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 19, No. 6, pp. 255-266). Pergamon.

[7] Ishijima, Y., & Roegiers, J. C. (1983, January). Fracture Initiation And Breakdown Pressure--Are They Similar?. In The 24th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.

[8] Kunze, K. R., & Steiger, R. P. (1992, January 1). Accurate In-Situ Stress Measurements During Drilling Operations. Society of Petroleum Engineers. doi:10.2118/24593-MS

[9] Mitchell, B. (1995). Advanced oilwell drilling engineering handbook. Lakewood: Mitchell Engineering

[10] Van Oort, E., & Vargo, R. F. (2008, September 1). Improving Formation-Strength Tests and Their Interpretation. Society of Petroleum Engineers. doi:10.2118/105193-PA

[11] Barker, J. W., Meeks, W. R., "Estimating Fracture Gradient in Gulf of Mexico Deepwater, Shallow, Massive Salt Sections", paper SPE 84552, presented at SPE Annual Technical Conference And Exhibition, Denver,Colorado, October 5-8, 2003

[12] Breckels, I. M., van Eekelen, H. A. M., "Relationship Between Horizontal Stress and Depth in Sedimentary Basins", Journal of Petroleum Technology, (September 1982): 2191-2199

[13] Detournay, E., Carbonel , R., "Fracture Mechanics Analysis Of The Breakdown Process In Minifrac Or Leak-Off Tests", paper SPE 28076, presented at SPE/ISRM Rock Mechanics In Petroleum Engineering Conference, Delft, The Netherlands, August 29-31, 1994

[14] Edwards, S. T., Meredith, P. G., Murrel , S. A. F., "An Investigation of Leak- Off Test Data for Estimating In-Situ Stress Magnitudes: Application to a Basinwide Study in the North Sea", Paper SPE/ISRM 47272, presented at SPE/ISRM Eurock "98, Trondheim, Norway, July 8-10, 1998

[15] Lin, W., Yamamoto, K., Ito, H., Masago, H., Kawamura, Y., "Estimation of Minimum Principal Stress from an Extended Leak-Off Test Onboard The Chikyu Drilling

Vessel And Suggestions for Future Test Procedures", Scientific Drilling, no. 6 (July 2008): 43-47

[16] Postler, D. P., "Pressure Integrity Test Interpretation", paper SPE/IADC 37589, presented at 1997 SPE/AIDC Drilling Conference, Amsterdam, The Netherlands, March 4-6, 1997

[17] Raaen, A. M., Brudy, M., "Pump-In/Flowback Tests Reduce The Estimate Of Horizontal In-Situ Stress Significantly", paper SPE 71367, presented at 2001 SPE Annual Technical Conference And Exhibition, New Orleans, Louisiana, September 30 – October 3, 2001

[18] Rezmer-Cooper, I.M., Rambow, F. H. K., Arasteh, M., Hashem, M. N., Swanson, B., Gzara, K., "Real-Time Formation Integrity Test Using Downhole Data", paper IADC/SPE 59123, presented at 2000 IADC/SPE Drilling Conference, New Orleans, Louisiana, February 23-25, 2000

[19] Rocha, L. A. S., Falcão, J. L., Gonçalves, C. J. C., Toledo, C., Lobato, K., Leal, S., Lobato, H., "Fracture Pressure Gradient in Deepwater", paper IADCSPE 88011, presented at IADC/SPE Asia Pacific Drilling Technology Conference, Kuala Lumpur, Malaysia, September 13-15, 2004

[20] Schlumberger (2011a), Oilfield Glossary, http://www.glossary.oilfield.slb.com/Display.cfm?Term=pore%20pressure,

[21] Schlumberger (2011b), Oilfield Glossary, http://www.glossary.oilfield.slb.com/Display.cfm?Term=fracture%20gradient

[22] Simmons, E. L., Rau, W. E., “Predicting Deepwater Fracture Pressures: A Proposal”, paper SPE 18025, presented at 63rd Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Houston, Texas,October 2-5, 1988

[23] Soliman, M. Y., Daneshy, A. A., “Determination Of Fracture Volume And Closure Pressure From Pump-In/Flow Back Tests”, paper SPE 21400, presented at SPE Middle East Oil Show, Bahrain, November 16-19, 1991

[24] TPAO (2011a) Exploration Department Thrace – Marmara District Office, 2011

[25] Wojtanowicz, A. K., Zhou, D., “Shal ow Casing Shoe Integrity Interpretation Technique”, paper SPE/IADC 67777, presented at SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February 27 – March 1, 2001

APPENDIX A

```
import pandas as pd
import matplotlib.pyplot as plt
from kneed import KneeLocator

while True:
    Rockproperties = input("Is the stress region far field elastic or near
wellbore plastic?:")
    if Rockproperties == "far field elastic":
        print("Pressure build-up phase is linear.")
        break
    elif Rockproperties == "near wellbore plastic":
        print("Pressure build-up phase nonlinear and hence the LOT will be
harder to interpret.")
        break

while True:
    Fluidviscosity = input("Have you used the mud with high viscosity or with
low viscosity?:")
    if Fluidviscosity == "low viscosity" or Fluidviscosity == "low viscous
mud":
        print("Delay between fracture initiation and fracture propagation
(breakdown) is insignificant.")
        break
    elif Fluidviscosity == "high viscosity" or Fluidviscosity == "high viscous
mud":
        print("Using a viscous mud causes a delay between fracture initiation
and fracture propagation (breakdown).")
        break
print("As viscosity increases, the pressure drop in the fracture increases.")

while True:
    Circulation = input("Have you circulated one bottoms-up or more than one
bottoms-up?:")
    if Circulation == "one bottoms-up":
        break
    elif Circulation == "more than one bottoms-up":
        break

while True:
    Welltype = input("Well type:")
    if Welltype == "vertical":
        with open("LOT Description.txt") as f:
            contents = f.read()
            print(contents)
        break
    elif Welltype == "directional":
        break
    elif Welltype == "horizontal":
        print("No information")
        exit()

while True:
    Permeability = input("Is formation permeable or impermeable?:")
```

```
    if Permeability == "permeable":
        print("Recommended pumping rate = 1/2 bpm")
        break
    elif Permeability == "impermeable":
        print("Recommended pumping rate = 1/4 bpm")
        break

Pumpingrate = input("Pumping rate:")
print("Faster pumping rate derives a higher fracture initiation and breakdown
pressure (LOP).")
print("The leak-off pressure obtained at slower pumping rates is capable of
concluding a conservative and secure formation leak-off pressure.")

Temperature = input("Temperature:")



while True:
    Mudtype = input("Have you used Water based mud,Oil based mud or Synthetic
based mud?:")
    if Mudtype == "water based mud" or Mudtype == "WBM":
        print("The leak-off pressures are reported to be higher when using a
WBM instead of an OBM or SBM.")
        break
    elif Mudtype == "oil based mud" or Mudtype == "OBM":
        print("Compressibility of the OBM should be same as oil(Co=0,5 ÷ 4 *
10^-5 psi^-1).")
        print("If the formation was fractured during the test with an OBM, it
would then be hard for it to heal and recoup the strength it possessed before
the test.")
        print("OBM leads to a lower and constant propagation pressure")

        Cmud = float(input("What is the compressibility of the mud?:"))
        print(Cmud)

        # well initial volume calculation

        casing = input("Which casing is set?:")

        while True:
            liner = input("Is there any liner hanged from the casing?: ")
            if liner == "yes" or liner == "Yes":
                #casing volume calculation
                pr = float(input("What is the poissons ratio value of the
casing?:"))
                Ri = float(input("What is the inner-casing radius
value?(in):"))
                Ro = float(input("What is the outer-casing radius
value?(in):"))
                E = float(input("What is the Young modulus value of the
casing?(psi):"))
                # dPi = float(input("What is the inner-casing pressure
value?(psi):"))
                # dPo = float(input("What is the outer-casing pressure
value?(psi):"))
                # dD = float(input("What is the true vertical depth of the
well?(in):"))
```

```
                aT = float(input("What is the thermal expansion coefficient
value of the casing?(1/F):"))
                # dT = float(input("How much is the temperature inside
well?(F):"))
                L1 = float(input("What is the starting depth of the
casing?(ft):"))
                l1 = float(input("What is the hanging depth of the
liner?(ft):"))
                ##L2 = float(input("What is the final depth of the well
section?(ft):"))
                GT = float(input("How much is the temperature gradient in the
well?(F/100ft):"))
                GPo = float(input("How much is the pressure gradient outside
of casing?(psi/ft):"))
                GPi = float(input("How much is the pressure gradient inside of
casing?(psi/ft):"))
                pi = 3.14

                Vc = (pi * (Ri ** 2) * (l1 - L1)) - ((pi * (Ri ** 2) * ((l1 **
2) - (L1 ** 2))) / (E * ((Ro ** 2) - (Ri ** 2)))) * (((1 - pr - (pr ** 2)) *
(Ri ** 2) + (1 + pr) * (Ro ** 2) * (GPi) - 2 * (1 - (pr ** 2)) * (Ro ** 2) *
(GPo))) - (pi * (Ri ** 2) * ((l1 ** 2) - (L1 ** 2)) * aT * (GT))

                Vc0 = Vc * 12 * 0.00013742869236584

                print("Vc0(bbl):", Vc0)



                #liner volume calculation
                pr = float(input("What is the poissons ratio value of the
liner?:"))
                Ri = float(input("What is the inner-liner radius
value?(in):"))
                Ro = float(input("What is the outer-liner radius
value?(in):"))
                E = float(input("What is the Young modulus value of the
liner?(psi):"))
                # dPi = float(input("What is the inner-casing pressure
value?(psi):"))
                # dPo = float(input("What is the outer-casing pressure
value?(psi):"))
                # dD = float(input("What is the true vertical depth of the
well?(in):"))
                aT = float(input("What is the thermal expansion coefficient
value of the liner?(1/F):"))
                # dT = float(input("How much is the temperature inside
well?(F):"))

                l2 = float(input("What is the final depth of the
liner?(ft):"))
                GT = float(input("How much is the temperature gradient in the
well?(F/100ft):"))
                GPo = float(input("How much is the pressure gradient outside
of liner?(psi/ft):"))
                GPi = float(input("How much is the pressure gradient inside of
liner?(psi/ft):"))
```

```
                pi = 3.14

                Vl = (pi*(Ri**2)*(l2-l1))-((pi*(Ri**2)*((l2**2)-
(l1**2)))/(E*((Ro**2)-(Ri**2))))*(((1-pr-
(pr**2))*(Ri**2)+(1+pr)*(Ro**2)*(GPi)-2*(1-(pr**2))*(Ro**2)*(GPo)))-
(pi*(Ri**2)*((l2**2)-(l1**2))*aT*(GT))

                Vl0 = Vl * 12 * 0.00013742869236584

                print("Vl0(bbl):", Vl0)

                V0 = Vc0 + Vl0

                print("V0(bbl):", V0)

                break
            elif liner == "no" or liner == "No":
                pr = float(input("What is the poissons ratio value of the
casing?:"))
                Ri = float(input("What is the inner-casing radius
value?(in):"))
                Ro = float(input("What is the outer-casing radius
value?(in):"))
                E = float(input("What is the Young modulus value of the
casing?(psi):"))
                # dPi = float(input("What is the inner-casing pressure
value?(psi):"))
                # dPo = float(input("What is the outer-casing pressure
value?(psi):"))
                # dD = float(input("What is the true vertical depth of the
well?(in):"))
                aT = float(input("What is the thermal expansion coefficient
value of the casing?(1/F):"))
                # dT = float(input("How much is the temperature inside
well?(F):"))
                L1 = float(input("What is the starting depth of the well
section?(ft):"))
                L2 = float(input("What is the final depth of the well
section?(ft):"))
                GT = float(input("How much is the temperature gradient in the
well?(F/100ft):"))
                GPo = float(input("How much is the pressure gradient outside
of casing?(psi/ft):"))
                GPi = float(input("How much is the pressure gradient inside of
casing?(psi/ft):"))
                pi = 3.14



                V1 = (pi * (Ri ** 2) * (L2 - L1)) - ((pi * (Ri ** 2) * ((L2 **
2) - (L1 ** 2))) / (E * ((Ro ** 2) - (Ri ** 2)))) * (((1 - pr - (pr ** 2)) *
(Ri ** 2) + (1 + pr) * (Ro ** 2) * (GPi) - 2 * (1 - (pr ** 2)) * (Ro ** 2) *
(GPo))) - (pi * (Ri ** 2) * ((L2 ** 2) - (L1 ** 2)) * aT * (GT))

                V0 = V1 * 12 * 0.00013742869236584

                print("V0(bbl):", V0)
```

```
                break




        pr = float(input("What is the poissons ratio value of the casing?:"))
        Ri = float(input("What is the inner-casing radius value?(in):"))
        Ro = float(input("What is the outer-casing radius value?(in):"))
        E = float(input("What is the Young modulus value of the
casing?(psi):"))
        # dPi = float(input("What is the inner-casing pressure value?(psi):"))
        # dPo = float(input("What is the outer-casing pressure value?(psi):"))
        # dD = float(input("What is the true vertical depth of the
well?(in):"))
        aT = float(input("What is the thermal expansion coefficient value of
the casing?(1/F):"))
        # dT = float(input("How much is the temperature inside well?(F):"))
        L2 = float(input("What is the final depth of the well section?(ft):"))
        L1 = float(input("What is the starting depth of the well
section?(ft):"))
        pi = 3.14

        GT = float(input("How much is the temperature gradient in the
well?(F/100ft):"))
        GPo = float(input("How much is the pressure gradient outside of
casing?(psi/ft):"))
        GPi = float(input("How much is the pressure gradient inside of
casing?(psi/ft):"))

        V1 = (pi*(Ri**2)*(L2-L1))-((pi*(Ri**2)*((L2**2)-(L1**2)))/(E*((Ro**2)-
(Ri**2))))*(((1-pr-(pr**2))*(Ri**2)+(1+pr)*(Ro**2)*(GPi)-2*(1-
(pr**2))*(Ro**2)*(GPo)))-(pi*(Ri**2)*((L2**2)-(L1**2))*aT*(GT))

        V0 = V1*12*0.00013742869236584

        print("V0(bbl):", V0)

        # read excel file
        excel_file = "LOT Data.xlsx"
        df = pd.read_excel(excel_file, "LOT1")
        Vmud = (df["Volume -bbl"])
        print("Vmud:", Vmud)
        P = (df["Pressure psi"])
        print("P:", P)

        # calculate dP
        dP = []
        count = 0
        while count <= (len(Vmud) - 1):
            dP.append((Vmud[count]) / (Cmud * V0))
            count += 1
        print("dP(psi)=", dP)

        # calculate pressure applied by compressible mud
        P1 = []
```

```
        count = 0
        while count <= (len(P) - 1):
            P1.append((P[count]) - (dP[count]))
            count += 1
        print("P1(psi)", P1)
        break
    elif Mudtype == "synthetic based mud" or Mudtype == "SBM":
        print("if the formation was fractured during the test with an SBM, it
would then be hard for it to heal and recoup the strength it possessed before
the test.")
        break

while True:
    Formationtype = input("Is the formation intact or cracked?:")
    if Formationtype == "Intact" or Formationtype == "intact" or Formationtype
== "intact formation":
        print("Higher leak-off value")
        break
    elif Formationtype == "Cracked" or Formationtype == "cracked" or
Formationtype == "cracked formation":
        while True:
            Cracks = input("Are the cracks open or closed?:")
            if Cracks == "open" or Cracks == "Open":
                print("It's most probable to witness an early breakdown or a
lower leak-off value.")
                break
            elif Cracks == "closed" or Cracks == "Closed":
                print(
                    "The pressure required to open an existing fracture in
most rocks downhole would be less than the pressure needed to trigger a
fracture.")
                break
        break


while True:
    WSDE = input("Do you have information about Wellbore Stress - Distortion
Effect?:")
    if WSDE == "yes":
        input("Are the stresses perpendicular or paralel to your wellbore?:")
        break
    elif WSDE == "no":
        break


MW = float(input("Mudweight(ppg):"))
TVD = float(input("TVD(ft):"))

# read excel file
excel_file = "LOT Data.xlsx"
df = pd.read_excel(excel_file, "LOT1")

print(df)

# find LOP(knee point)
if Mudtype == "oil based mud" or Mudtype == "OBM":
    kn = KneeLocator(df["Volume -bbl"], P1, S=0.2, curve='concave',
```

```
direction='increasing')
    print(kn.knee)
    print(kn.knee_y)
    print("LOP(OBM):", kn.knee_y)

    LOP = float(kn.knee_y)
    LOT = ((LOP / 0.052) / TVD) + (MW)
    print("LOT in equivalent mud weight(ppg):", LOT)

    """
    kn = KneeLocator(df["Volume -bbl"], df["Pressure psi"],
S=0.2,curve='concave', direction='increasing')
    print(kn.knee)
    print(kn.knee_y)
    print("LOP:", kn.knee_y)
    """

    # plot graph from excel file
    plt.plot(df["Volume -bbl"], P1, color="blue", linewidth=2,
label="LOT(OBM)")
    plt.vlines(kn.knee, plt.ylim()[0], plt.ylim()[1], linestyles='dashdot',
label="LOP(OBM)")

    plt.plot(df["Volume -bbl"], df["Pressure psi"], color="red", linewidth=2,
label="LOT")
    plt.vlines(kn.knee, plt.ylim()[0], plt.ylim()[1], linestyles='dashed',
label="LOP")

    plt.xlabel("Volume pumped(bbl)")
    plt.ylabel("Pressure(psi)")
    plt.grid()

    plt.legend()


else:
    kn = KneeLocator(df["Volume -bbl"], df["Pressure psi"], S=0.2,
curve='concave', direction='increasing')
    print(round(kn.knee))
    print(round(kn.knee_y))
    print("LOP:", kn.knee_y)

    LOP = float(kn.knee_y)
    LOT = ((LOP / 0.052) / TVD) + (MW)
    print("LOT in equivalent mud weight(ppg):", LOT)

    # plot graph from excel file
    plt.plot(df["Volume -bbl"], df["Pressure psi"], "b.-", linewidth=2,
label="LOT")
    plt.vlines(kn.knee, plt.ylim()[0], plt.ylim()[1], linestyles='dashed',
label="LOP")

    plt.xlabel("Volume pumped(bbl)")
    plt.ylabel("Pressure(psi)")
    plt.grid()

    plt.legend()
```

```
#Fracture Propagation Pressure
PP1 = float(input("How much is the first fracture propagation 
pressure?(psi):"))  #2575
VolPP = float(input("How much is the pumped volume corresponding to the first 
fracture propagation pressure?(bbl):"))  #3.50
PP2 = float(input("How much is the second fracture propagation 
pressure?(psi):"))  #2550
PP3 = float(input("How much is the third fracture propagation 
pressure?(psi):"))   #2575

#BleedOff Pressure and Volume
BleedOff = float(input("How much is the Bleed Off pressure?(psi):"))  #2000
Vol = float(input("How much is the pumped volume corresponding to the Bleed 
Off pressure?(bbl):"))  #6.5
BleedOff1 = float(input("How much is the first pressure before Bleed 
Off?(psi):"))    #2025
Vol1 = float(input("How much is the pumped volume corresponding to the first 
pressure before Bleed Off?(bbl):"))  #6.25
BleedOff2 = float(input("How much is the second pressure before Bleed 
Off?(psi):"))    #2050
Vol2 = float(input("How much is the pumped volume corresponding to the second 
pressure before Bleed Off?(bbl):"))  #6



#horizontal line Y value
PropP = ((PP1 + PP2 + PP3)/3)
print(PropP)

plt.hlines(y=PropP, xmin=VolPP, xmax=Vol, linewidth=1, color='r', 
linestyles='dashed') #to draw horizontal line

# draw line through 2 points on graph
def draw_line(x, y, length):
    delta_x = x[0] - x[1]
    delta_y = y[0] - y[1]
    max_x = max([x[0], x[1]]) + length
    max_y = max([y[0], y[1]]) + length
    min_x = min([x[0], x[1]]) - length
    min_y = min([y[0], y[1]]) - length
    new_xs = [x[0], x[1]]
    new_ys = [y[0], y[1]]
    for i in range(1000):
        new_x = new_xs[-1] + delta_x
        new_y = new_ys[-1] + delta_y
        if new_x >= min_x and new_x <= max_x and new_y >= min_y and new_y <= 
max_y:
            new_xs.append(new_x)
            new_ys.append(new_y)
        else:
            break
    for i in range(1000):
        new_x = new_xs[0] - delta_x
        new_y = new_ys[0] - delta_y
        if new_x >= min_x and new_x <= max_x and new_y >= min_y and new_y <=
```

```
max_y:
            new_xs.insert(0, new_x)
            new_ys.insert(0, new_y)
        else:
            break

    plt.plot(new_xs, new_ys, "--", color='green')
    return new_xs, new_ys
new_xs, new_ys=draw_line([Vol1,Vol2],[BleedOff1,BleedOff2], 300)
#plt.plot(new_xs, new_ys, "--", "g")


new_xs, new_ys=draw_line([5,5.15],[PropP,2300], 300) #write a code to find
isip coordinates automatically
#plt.plot(new_xs, new_ys, "--", "g")

# Define the coordinates of the two points
x1, y1 = Vol1, BleedOff1
x2, y2 = Vol2, BleedOff2

# Define the coordinates of the two points for the second line
x3, y3 = 5, PropP
x4, y4 = 5.15, 2300

# Calculate the slopes and y-intercepts of the two lines
slope1 = (y2 - y1) / (x2 - x1)
intercept1 = y1 - slope1 * x1
slope2 = (y4 - y3) / (x4 - x3)
intercept2 = y3 - slope2 * x3

# Calculate the x-coordinate of the intersection point
x_intersect = (intercept2 - intercept1) / (slope1 - slope2)

# Calculate the y-coordinate of the intersection point
y_intersect = slope1 * x_intersect + intercept1

# Print the coordinates of the intersection point
print("Intersection Point: ({}, {})".format(x_intersect, y_intersect))

#Fracture Closure Pressure
print("Fracture Closure Pressure:", y_intersect)

plt.show()
```