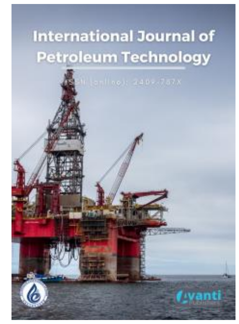
International Journal of Petroleum Technology, 2022, 91-113

Published by Avanti Publishers

International Journal of Petroleum Technology

ISSN (online): 2409-787X



Review of the Leak-off Tests with a Focus on Automation and Digitalization

Elham Bakhshi[1,2], Behzad Elahifar[3], Abbas Shahrabadi[1,*], Naser Golsanami[2,*] and Reza Khajenaeini[4]

[1]*Research Institute of Petroleum Industry (RIPI), Tehran, Iran*

[2]*College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China*

[3]*Norwegian University of Science and Technology (NTNU), Norway*

[4]*National Iranian Oil Company (NIOC), Tehran, Iran*

ARTICLE INFO

Article Type: Research Article

Keywords:
Coding
Leak-off test
Extended leak-off test
Formation integrity test
Automated leak-off test
Drilling process & digitalization

Timeline:
Received: November 13, 2022
Accepted: December 19, 2022
Published: December 24, 2022

Citation: Bakhshi E, Elahifar B, Shahrabadi A, Golsanami N, Khajenaeini R. Review of the leak-off tests with a focus on automation and digitalization. Int J Petrol Technol. 2022; 9: 91-113.

DOI: https://doi.org/10.15377/2409-787X.2022.09.10

ABSTRACT

The drilling and research communities are leading the way toward more digitally-controlled operations to ensure that the drilling process takes place as safely and gently as possible with the lowest possible carbon footprint. Today's cutting-edge operations are run on large high-performance drilling installations where operations are largely run remotely from the driller's operating station. Digitalization of the drilling process is the goal for performing drilling operations remotely from onshore. Leak-off test (LOT) or extended leak-off test (XLOT) plays a critical role in the petroleum industry. Therefore, recognizing all affecting parameters on LOT/XLOT and Formation integrity test (FIT) performance is vital. Because, in some cases, it is not possible to fully understand what happened during the test, having a deep insight into the LOT procedure is very important. One of the current study's main objectives is to thoroughly explain all stages of these tests and assemble all the significant parameters. Thus, many scientific papers on these tests were deeply reviewed and were classified into four main groups focusing on the application of LOT/XLOT (i) in stress estimation and geomechanical studies, (ii) concerning hydraulic fracturing, (iii) concerning wellbore stability, and (iv) numerical modeling, and then, the corresponding discussions were conducted. It was found that in-situ stress estimation is the most common application of the leak-off test.

Moreover, considering the importance of LOT and the desire to digitize operations in the oil and gas industry, it was found that the automatic LOT/XLOT is a fully required approach. The primary purpose of this study, which is hence considered its main contribution, is to prepare a LOT flowchart that would set off the further code development tasks of the field. The fundamental code of the present study was written and checked using a real dataset in a Python environment. The results were satisfying and indicated a successful start, which lays a foundation for future automated LOT/XLOT tests.

*Corresponding Author
Emails: abasshahrabadi@yahoo.com
golsanami_naser@sdust.edu.cn, golsanami_naser@yahoo.com
Tel: +(98) 21-44739761

1. Introduction

Estimating reservoir parameters and reservoir characterization are vital in all stages of reservoir evaluation, from exploration to exploitation, which is done by different methods and tools and for other purposes [1-9]. One of the most common jobs done during drilling operations for decades is the Leak-off Test (LOT) [10-12]. Different types of downhole formation tests could be conducted to characterize the newly drilled wellbores, especially the geomechanical properties and the state of in-situ stresses. Some of the most important of these tests include hydraulic fracturing, mini-frac tests, LOT, and the Extended Leak-off test (XLOT) [13]. But, among these tests, LOTs are commonly used to evaluate cement integrity and Fracture Initiation Pressure (FIP) at the casing shoe. By conducting LOTs and interpreting tests' results, the most important information about the casing, cement job, drilling fluid, etc would be obtained, which is very helpful for making decisions about casing design, cement job evaluation, drilling fluid type selection, and well control methods [14].

By performing LOT, the fracture pressure is specified. LOTs are widely used to interpret the minimum stress magnitude, stress determination [15-18], and in the geomechanical studies [19, 20]. Aadnoy *et al*. [10] developed one model for interpreting LOT, including evaluating after borehole fracturing. They concluded that Leak-off Pressure (LOP) correctly displayed the in-situ stress state and the tensile rock strength.

Furthermore, it could be determined from the bottom level of the pressure curve during continuous pumping. Pressure tests are a group of the most widely used tests in the oil and gas industry. Some of these tests include formation integrity tests, leak-off tests, extended leak-off tests, etc. Although these tests vary in purpose, performance, and complexity, their basic framework is the same, and all the pressure and volume are used as main system inputs. Since most of the operation and interpretation processes of pressure integrity tests, including FIT, LOT, and XLOT, are done manually, the high dependency on manual processes often results in low consistency and poor repeatability. Therefore, automating these experiments will be very useful, practical, and well-considered. This study consists of three main parts. In the first part, a complete literature review of the LOT process is performed, and in the next part, a brief review of more than 90 scientific papers about FIT and LOT is done. The reviewed papers are divided into four main groups. Finally, a LOT coding package was prepared and tested with field data. In Fig. (**1**), the workflow of the current paper will be represented.

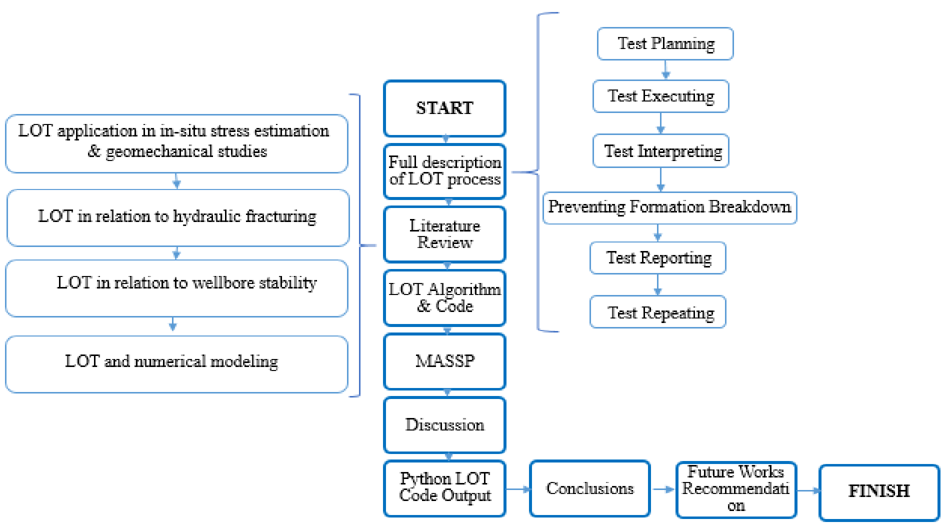


Figure 1: The workflow of the present research.

2. Materials and Methods

Because of the importance of LOT/XLOT procedure in various industries, especially in the petroleum industry, in this section, first, a complete review of them will be provided. Then, the flow chart design and the initial prepared code for the digitization of these tests will be discussed.

2.1. A Comprehensive Review of LOT/XLOT Procedure

First, the definition of these words will be explained.

2.1.1. Definition of FIT, LOT and XLOT

It is very important to increase the accuracy of recorded data in the oil and gas industry, especially in the drilling field. Thus, for determining the accurate stress data during drilling operations, the Formation Strength Tests (FST), especially the Leak-Off Test (LOT) and Extended Leak-Off Test (XLOT), were performed [21]. Based on the maximum pressure test and pressure's impact on the formation, the Formation Strength Tests can be divided into three general test types, including LOT, XLOT, and Formation Integrity Tests (FIT). The procedure of conducting these three tests is the same, and the difference is related to the number of pumping cycles and the point at which pumping is stopped. In Fig. (**2a-b**), the schematic plot of LOT vs the schematic plot of XLOT is shown. Typically, all pumping pressure tests were performed in a wellbore to determine the rock fracture strength immediately below a newly set casing, which is called the 'Leak-Off Test' [22]. In general, activities including estimating the casing setting depth, evaluating cement jobs, testing tensile failure resistance of a casing, shoe, and evaluating formation fracture gradient in the drilling operations are considered by performing the formation leak-off test [23]. The procedure of this job includes pumping drilling mud at a fixed rate into the borehole after a couple of meters of drilling down the casing shoe (fresh formation) and simultaneously checking surface pump pressures for detecting the formation breakdown pressure. The XLOT is simplest than LOT and specified by pumping beyond the leak-off point until a stable pressure is reached. The XLOT could repeat with two or more pressurization cycles, but in general, this process is divided into two cycles, and all steps of these tests are shown in Fig. (**2c**).

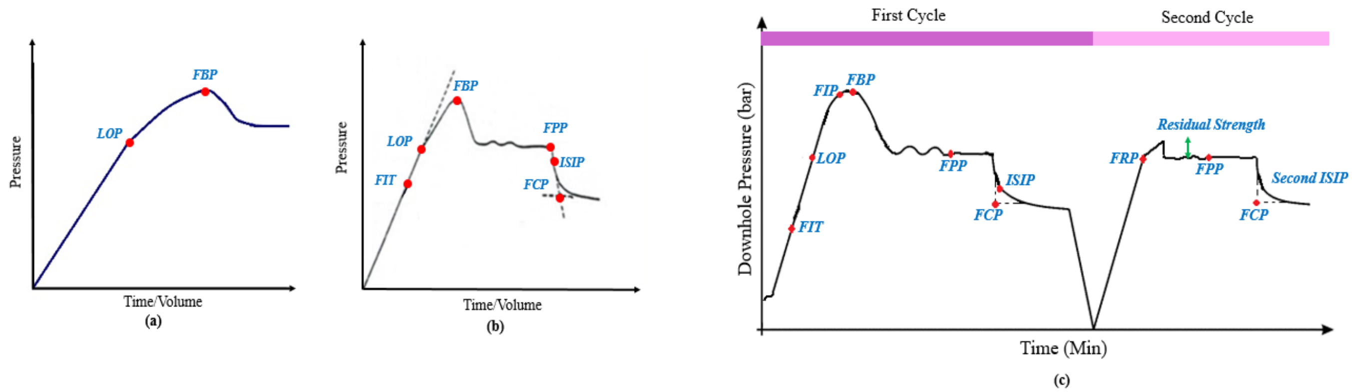


Figure 2: (**a**) Typical LOT, (**b**) Typical XLOT, (**c**) An extended leak-off test (XLOT) with two cycles.

The main purpose of performing XLOT is to obtain information about the in-situ stress magnitudes which are unaffected by near-wellbore effects. In FIT, the rock still shows Hookean behavior. At this step and after reaching the planned pressure, the pumping is ceased, so cement shoe barrier integrity and the predetermined mud weight will be checked to confirm the safe drilling without losses in the next steps. Accordingly, in most drilling operations, the FIT is done to investigate the wellbore stability and casing shoe integrity for further sections [24]. The LOT is performed immediately after FIT to determine the formation fracture gradient. The next point in the pressure-time plot is Leak-Off Pressure (LOP), which is the point where fluid penetrates the permeable parts in the wellbore, including formation, cement shoe, etc. The LOP is the first deviation from a linear part of the curve and means the rock no longer follows the Hook law [25]. In case of observing slope change in leak-off pressure or formation breakdown occurrence, the Fracture Initiation Pressure (FIP) is reported. The XLOT is a method that is used for deficiencies of LOT. This method maintains the pumping further than the Formation Breakdown Pressure (FBP) until the fracture growth is indicated in the plot [26, 27]. Eventually, the pumping is ceased when the pressure is stabilized at the constant Fracture Propagation Pressure (FPP) [25]. Instantaneous Shut-In Pressure (ISIP) happens when the initial pressure declines after pumps are turned off. If the formation stiffness and minimum stress are specified, the ISIP is used to determine the fracture geometry. The Fracture Closure Pressure (FCP) is the point that the fracture mechanically closes. This point could be identified in the shut-in or flow-back phase of the test [28]. In a way, the Fracture Reopening Pressure (FRP) is considered the beginning of the second cycle, and at this point, no tensile strength or stress perturbation components do not exist. Besides, as shown in Fig. (**3**), FRP in the second cycle is lower than FIP in the first cycle. Finally, could conclude that before conducting the XLOT at the casing shoe, both parameters, including the near-well barrier breaking down costs and the advantage of knowing the stress and FPP behind the barrier, must be considered. Fig. (**3**) shows the schematic picture of borehole configuration during LOT or XLOT.

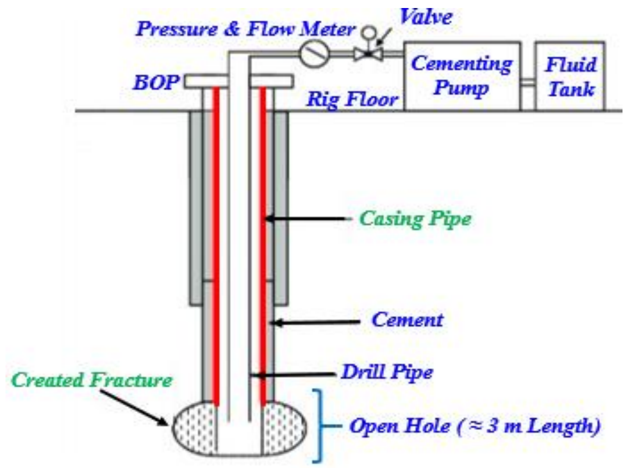


Figure 3: A schematic picture of LOT or XLOT in a borehole.

2.1.2. Factors Affecting FIT, LOT and XLOT

The pressure will increase by pumping the drilling fluid into the wellbore from the closed Blow-Out Preventer (BOP). Increasing the pressure results in an increase in induced stresses in the casing, drilling pipe, and borehole, causing them to expand until the system reaches equilibrium. This process is only acceptable if the casing does not leak and the formation does not get fractured. The Formation Strength Tests (LOT, XLOT, and FIT) can be affected by different factors, classified by different methods. As shown in Fig. (**4**), three of the most common classification methods are displayed based on controllable or uncontrollable factors, cased-hole or open-hole effects, and operational factors. Of course, it should be noted that some of these factors are common among the other classes and other factors also affect LOT operation. But in the following, the most important of them will be explained.

i. Casing Expansion

The most important item in efficiently constructing oil and gas wells is a high percentage of continuous cement bond with casing. But, because of cost reasons, the casing is not cemented up to the surface in most cases. Nevertheless, after waiting on cement, the pressure will be developed behind the casing, which conduces to the pipe expansion and contraction that negatively affects the cement bond quality. Therefore, cemented and not cemented casing should be checked in the casing expansion evaluation [29].

ii. Drilling Fluid Compressibility and Thermal Expansion

Drilling fluid is responsible for transferring pressure from the surface into the wellbore. Thus, estimating the drilling fluid density should be done according to the drilling fluid compressibility and thermal expansion. Depending on the well condition, temperature, and depth, the dominant effect might be compressibility or thermal expansion. For example, compressibility dominates deep offshore wells, while the thermal expansion role is more prominent in high-pressure and temperature wells. Moreover, it should be mentioned that fluid compressibility is a function of mud type, and in drilling deep-water wells, mud compressibility correction should be noticed. Furthermore, owing to the path drilling mud passes before reaching BOP, the mud would be cooler than at the drill floor, so its effective density at the moment of entering the BOP would be higher than the amount recorded at the surface [30, 31]. Therefore, it is concluded that in case of not considering the mud density changing during designing a LOT, the equivalent mud weight (EMW) would be underestimated at a specific casing shoe.

iii. Drilling Mud Type

Supporting the wall of the borehole with hydrostatic pressure exerted by the mud column weight, forming low permeable cake for preventing the pore pressure build-up, and maintaining the effective stress in the formation are the main roles of drilling mud in stabilizing the borehole [32]. Furthermore, the role of drilling mud type in LOT should not be neglected because different mud types have different effects on the stable fracture growth and fracture tip. In case of using Water Based Mud (WBM), the fracture tip can be isolated effectively by buildup of external filter cakes, while by using the Oil Based Mud (OBM) or Synthetic Based Mud (SBM), very low filtration loss will be caused due to the wettability contrast between the rock and the mud [10].

iv. Drilling Mud Gas Cut

During performing the LOT, the test would be affected by any gas or air in the system, especially in the early pumping phase and during bleeding off the pressure. Hence, before performing the LOT, the drilling mud should be tested to confirm mud of even density, free of solids and gas throughout the wellbore [30].

v. Wellbore Expansion

In the case of open-hole wells, the wellbore behavior is influenced by the geology and formation type. Because the different layers with various properties could be found even in small open-hole sections. Usually, the elastic deformation of the open-hole section of the wellbore will be considered, which depends on the rock properties and the formation's Young's modulus. A linear function relates the wellbore deformation and the increased pressure inside the wellbore. Thus, in case of overlooking the filtration during the LOT process, the wellbore expansion is the reason for reducing the slope of the linear area [33].

vi. Formation Properties, Including Permeability and Filtration

Permeability and filtration are two factors that affect the FST in high-permeable formations. Therefore, drilling fluids are used to prevent losing the fluid into the formation, which might lead to the wellbore controlling. In other cases, including drilling out of the casing shoe and drilling for fluid conditioning, a filter cake will reduce fluid loss to the formation.

vii. Fractures at the Wellbore

The fractures inside the wellbore might be natural fractures or caused by drilling operations because of the variable drilling rates or something else. Regardless of the reason of existing different kinds of fractures, including microfractures, cracks, vugs, or faults in the wellbore, they affect the results LOT [34]. Because the pressure required to initiate a fracture in these formations varies, and the fracture formations need lower pressure than intact rocks [23]. In the case of running liner or casing in these formations, the pressure build-up may end early during LOT. The fracture length influences initiation and breakdown pressure during hydraulic fracturing tests. The existing flaw size would affect the leak-off behavior and the magnitude of breakdown pressure relative to the wellbore radius [35].

viii. Cement Channels

During performing FST, the cement channels might be the source of unusual curve shapes. The cement channels create connections around or through the cement at the casing shoe. On the other hand, the cement channels are fluid paths that let the testing fluid pass through or around the cement to shallower zones with a lower fracture gradient. The cement channels are the most eventual reasons for low leak-off results. Poor cementing jobs or inadequate centralization at the casing shoe are some of the reasons that may result in the creation of cement channels. Detecting indications of bad cementing during a single LOT may not be feasible. Thus, by interpreting one LOT, results cannot conclude that the cement channel exists or not, and just by repeating the test, the possibility of its existence becomes stronger. Hence, the second test might be observed if the reason for the low leak-off results is related to the formation effects or cement channels. [23] concluded that the cement channels are classified into three groups, including large open cement channels, small open cement channels, and plugged channels which are explained as follows (Fig. **5**).

Factors Affecting LOT Behavior

Uncontrollable/Controllable Factors	Uncontrollable	Rock Properties Formation Characteristics Fractures at the Wellbore Temperature Variation in Time Far-Field Stresses
	Controllable	Pumping Rate Cement Channels
Cased Hole/Open Hole	Cased Hole	Casing Expansion Drilling Fluid Compressibility & Thermal Expansion Drilling Mud Type Drilling Mud Gas Cut
	Open Hole	Wellbore Expansion Permeability & Filtration Fractures at the Wellbore Cement Channels
Operational Factors	Fluid Viscosity	
	Pumping Rate	
	Injection Path & Drilling Fluid Effects	
	Using PWD Tools for Downhole Pressure Measurement	
	Mud Cuttings	

Figure 4: Different common classifications of factors affecting LOT behavior.

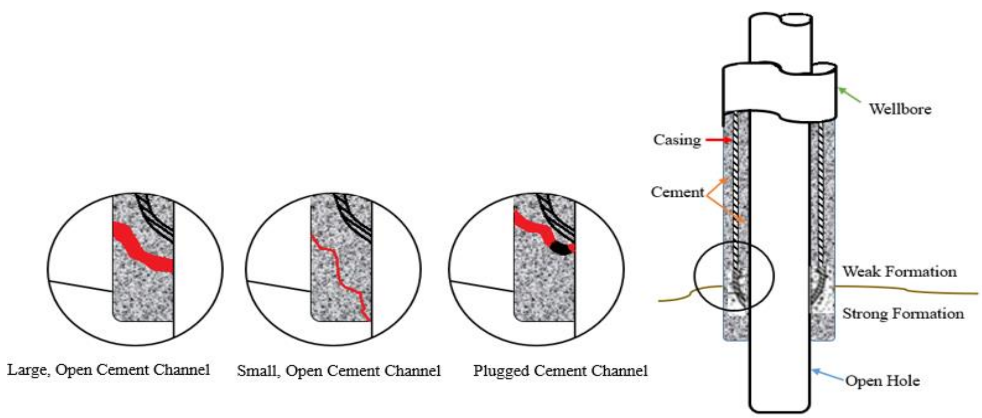


Figure 5: Three groups of cement channels.

- **Large Open Cement Channel**

A large, open cement channel does not have adequate isolated zonation at the casing, which leads to an immediate connection to the weaker zone and may cause fewer leak-off results than predicted values. Thus, observing the considerable difference between the tested and predicted leak-off values might indicate an existing large, open cement channel [23]. As shown in Fig. **(6a)**, the LOT plot does not change because of existing large, open cement channels, and just the LOP would be considerably lower than the predicted LOP. Observing the significant difference between predicted and tested LOP might be due to a large open cement channel.

- **Small Open Cement Channel**

A small and open cement channel causes to limiting the flow and does not let it have direct communication, and just a part of the flow will lead to the weaker zone and cause initiate the fracture there. But, since just one part of the flow diverts to the weaker zone, the pressure could build up in the wellbore and act on the stronger formation at a lower rate until reaching the leak-off pressure [23]. According to Fig. (**6b**), deviation in the pressure plot is observed twice during the pressurizing up period. A normal slope happens because of the low fracture gradient of shallower zones (LOP1) than a lower slope which causes due to the fracture gradient of formation at the casing shoe (LOP2). The test plot shows two slopes: a normal slope from the original until the breakdown of the weak zone (LOP1), then a lower slope until fracture opens in the zone at the shoe (LOP2).

- **<u>Plugged Cement Channel</u>**

Plugged cement channel is the third category of this group. Sometimes, the plugging materials like gelled mud caused to blocking the cement channel and plugging it off. Thus, during the LOT, plugging and unplugging might have happened. After observing the drop pressure and stopping the pumps, the shut-in pressure will happen because of the weaker zone's final pumping pressure and the breakdown pressure. In the case of reducing the shut-in pressure to zero, could conclude that the minimum stress within the weaker formation is lower than the hydrostatic pressure of the drilling fluid used during the test [23]. As explained above, sometimes the cement channels are plugged owing to the plugging materials, and this process continues until the built pressure removes it and unplugs the channel. After unplugging the channel, in the weaker zones and because of their low fracture gradient, the LOT pressure would affect the zone and causes a pressure drop. After the pressure drop and stopping of the pumps, the shut-in pressure will drop considerably, showing the major difference between the final pumping pressure and the weaker zone's breakdown pressure (Fig. **6c**).

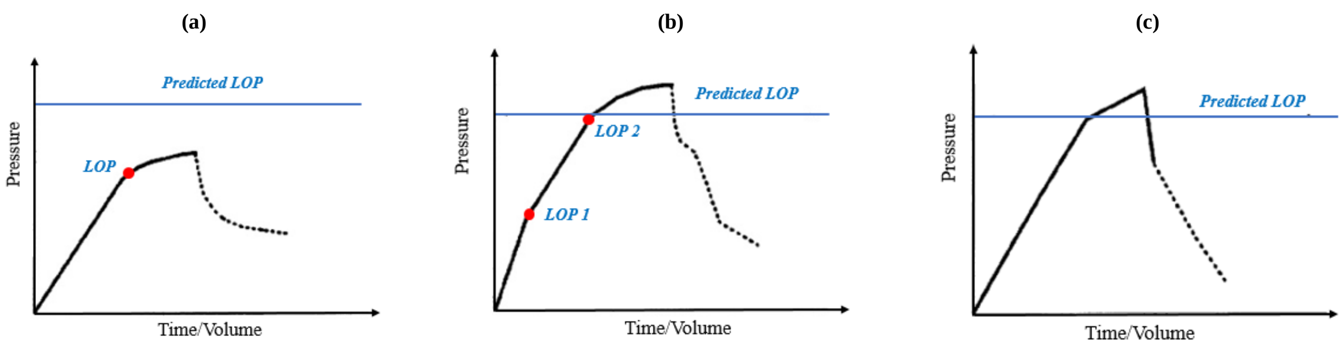


Figure 6: Schematic image of (**a**) large open cement channel effect, (**b**) small open cement channel effect, (**c**) plugged cement channel effect.

<u>ix. Fluid Viscosity</u>

The viscosity of the testing fluid has a compelling impact on crack stability and growth. Postler [23] pointed out that pressure drop in the fracture increases as the fluid viscosity increases. He also added that the pressure at the crack tip could be less than the breakdown pressure even though the breakdown pressure is being applied at the crack entrance. This infers that the full hydraulic force of the mud hasn't caused any impact on the crack tip resulting in a stable or no crack growth. In order to trigger the crack and make it unstable, more pressure must be applied. Hence, for a LOT, the breakdown is proportional to the fluid viscosity irrespective of the fracture opening pressure. Using viscous mud causes a delay between fracture initiation and fracture propagation (breakdown). In contrast, this delay is insignificant when a fluid with low viscosity is being utilized, such as water. In conclusion, the panic of "breaking down the formation" during a LOT isn't utterly pragmatic. This breakdown can be controlled and avoided by simply adjusting the fluid viscosity and other pumping properties.

<u>x. Pumping Rate</u>

The target of the LOT is to determine at what pressure the formation breaks down, and this test is basically conducted by pressurizing the formation by means of a fluid pumped down into the well. Thus, the pumping rate greatly impacts the leak-off point, and knowing the theory behind it is a must. The effects of the pumping rate on fracture initiation have been presented in many studies drawings in the same conclusion as Postler, who assured that a faster pumping rate derives a higher fracture initiation and breakdown pressure (LOP). In Fig. **(7a)**, Postler clearly conveyed the effect of the pumping rate on the leak-off point; at higher pumping rates (1 ¼ BPM), the leak-off point was at approximately 1350 psi. Whereas at low pumping rates (¾ BPM), the leak-off pressure decreased to approximately 700 psi. This difference in the recorded leak-off pressures can't be simply neglected, and thus it's vital to decide which leak-off pressure one must rely on. The leak-off pressure obtained at a high pumping rate doesn't certainly reflect the actual strength of the rock formation. Whereas the leak-off pressure obtained at slower pumping rates is capable of concluding a conservative and secure formation leak-off pressure to bank on, and that is due to the fact that lower pressure was applied over a longer duration and in slower circulations similar to how well control operations or routine circulations are conducted [23].

xi. Injection Path and Drilling Fluid Effects

Generally, during a LOT, the wellbore can be pressurized by simultaneously pumping drilling fluid through the drill string and annulus. But it should be noted that because of frictional pressure losses and the effect of gelation, the possibility of recording artifacts is maintained. Also, if there is no fluid circulation into the wellbore before the test, the gel strength of the drilling fluid will be developed. Thus, a certain pressure may be needed to restart the circulation and break the gel strength. To overcome this problem, the fluid properties could be modified to lower gel strength. After establishing the circulation, the pressure again will drop to the stable frictional pressure losses [30]. Anyway, the most suitable option will be chosen for different cases and based on the types of available equipment, the wellbore situation, and the pump properties.

xii. Using PWD Tools for Downhole Pressure Measurement

Because of the importance of wellbore pressure management during drilling operations, managing downhole pressure is an important issue in most drilling jobs. One of its applications could be measuring accurate pressure during LOT. Some of the other advantages of using PWD tools include the following:

- Eliminating the effects of mud compressibility, mud gas cut, and casing expansion.
- No need to correct the pressure from the surface to downhole pressure may not always be straightforward.
- Reducing the measurement artifacts because of providing a smoother curve than the surface curve.

Thus, by using PWD tools, recognizing the leak-off pressure could be easier, while the results of surface pressure measurement alone might be unreliable and uncertain [13].

xiii. Effect of Wellbore Distortion and Elastic/Plastic Zones on LOT

During drilling operations, the near-wellbore stresses are changed and become distorted. Usually, the behavior of most rocks up to the failure point is elastic. Hence, it can be concluded that the behavior of the rocks varies according to the distance to the wellbore, and also, two different stress zones could be formed, which included a near wellbore plastic zone and a far-field elastic zone [36]. Based on the field results [23, 36], the plastic and elastic zones have different effects on LOT (Fig. **7b**). As shown in Fig. (**7b**), the different initiation and propagation pressures during the LOT and based on the elastic/plastic zones were reported [23]. At the first part of the pressure-volume plot and in the plastic zone, the fracture initiation is approximately 850 psi, and fracture propagation increases from 850 to 900 psi and stops at 900 psi, while at the second part of the plot and in the elastic zone, the fracture initiation is around 1100 psi. Because the fracture could develop only into the near-wellbore zones and could not dominate the far-field stresses and develop into the elastic zones.

xiv. Temperature

Temperature and its changes affect parameters such as the gel strength of the mud, mud compressibility, and thermal effect, causing the leak-off behavior to change. The reason of changing leak-off behavior is discussed below. Increasing temperature and heating up the formation around the wellbore would be cause the thermal stress increasing which resulted in higher FIP and FPP. The opposite of this process is true, which ultimately leads to a change in the leak-off behavior [31].

xv. Effect of Variation in Time According to the Mud Type

Depending on the mud type used during the LOT, the shoe strength of a specific casing might be changed over time. In other words, in the case of using water-based mud (WBM) during LOT, the water is absorbed by clay particles and expands so that the fracture healing effect might happen. While owing to the use of oil-based mud (OBM), this effect cannot happen in the same way [37].

xvi. Mud Penetration and Permeability

The leak-off value is highly influenced by the drilling fluid's rheological properties and some characteristics of the formation being drilled, including permeability.

Starting with the drilling fluid penetration, several LOTs are conducted 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

The moment a higher-pressure fluid is introduced into the pores of a rock, a temporary rise in the pore pressure of the penetrated area will be witnessed; this in turn will cause a reduction in the formation strength thus explaining the fact behind why penetrating fluids exhibit lower fracture initiation pressures (lower leak-off value will be reached) when compared to non-penetrating fluids [23]. According to the International Association of Drilling Contractors (IADC), Deepwater guidelines report that leak-off pressure difference can be as high as 0.5- 0.7 ppg in favor to water-based mud (as cited in Rezmer-Cooper *et al*., 2000). In addition to the penetrating effect of different types of mud, comes the size of the interconnected pore sizes, better known as the permeability of the rock. Postler considered applying the same logic in this case where permeable rocks must have a lower breakdown pressure than impermeable rocks. This means that in a permeable rock, the highly pressurized fluid can penetrate much deeper in the formation causing the pore pressure to be equivalent to the fluid pressure. Hence, a lower leak-off value will be anticipated. On the other hand, in an impermeable formation, the highly pressurized fluid can only penetrate certain regions close to the wellbore or along the length of the fracture, causing the fluid pressure to build up and reach higher leak-off values. Postler adds that a highly permeable formation may induce some non-linearities during the pressure build-up phase, and that is mainly due to the fluid losses that will eventually occur [23].

xvii. Pre-Existing Cracks

Typically, when a formation is cracked, its strength is expected to be reduced. Cracked formation might exist prior to drilling activities or even when drilling is taking place; these induced or pre-existing cracks could be worrisome when it comes to leak-off test application and interpretation.

Newly induced or pre-existing cracks are normally closed due to the naturally occurring compressive stresses of the formation. Consequently, the tensile strength of the rock could be assumed to be zero. Hence, the pressure required to open an existing fracture in most rocks downhole would be less than the pressure needed to trigger a fracture [23]. In a LOT, this means that if a pre-existing crack occurs to be available in the drilled formation, then it's most probable to witness an early breakdown or a lower leak-off value when compared to an intact formation. In addition to that, it was confirmed that the size of a preexisting crack can have an impact on the fracture opening pressure and can easily alter the magnitude of the breakdown pressures. In 1983, Ishijima conducted a detailed study by numerically modelling a hydraulic fracture test. The test ranged from less than 0.05 times the wellbore radius, R, to more than 2.5 R. The test outcomes are conveyed in Fig. (**8**) and the impact of the crack size is crystal clear.

xviii. Mud Cuttings Effects

Poor cutting removal during drilling operation will affect the mud density. Thus, the hydrostatic pressure applied to the wellbore would be affected by the mud weight variation which finally leads to creating some fractures or cracks into the wellbore that behave like weak formations during the LOT. Therefore, for obtaining reliable LOT results, drilling fluid must be pure enough without existing cuttings. In case of insufficient cuttings transport or poor borehole cleaning, different problems include low rate of penetration, reducing drilling rate, increasing filter cake thickness, mud cake formation, borehole enlargement/pack-off, high torque and drag, high annular circulating pressure, pipe sticking, the cuttings accumulation on the low side of the hole, lost circulation, etc. will happen [38-40]. Therefore, if not enough attention is paid to the borehole cleaning, such problems can finally be a root cause of losing the well [41]. Furthermore, existing cuttings in the drilling mud and improper borehole cleaning may cause difficulties in other operations such as casing running, cementing, wireline logging, and also LOT operations.

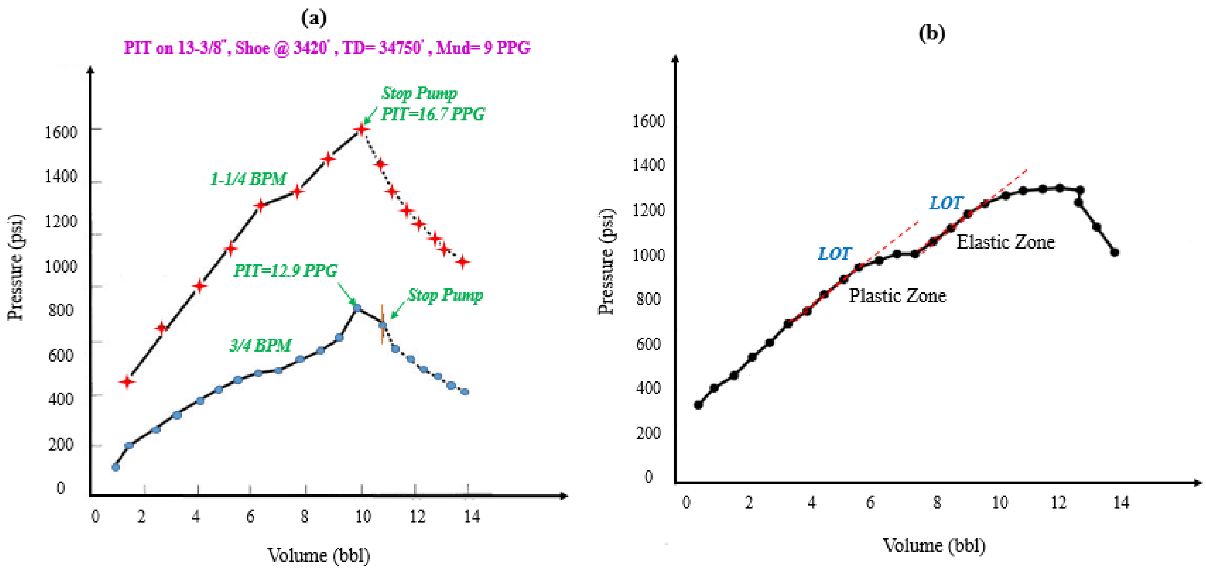


Figure 7: (**a**) Effect of pump-rate on LOT, (**b**) LOT for plastic and elastic zones after [23].

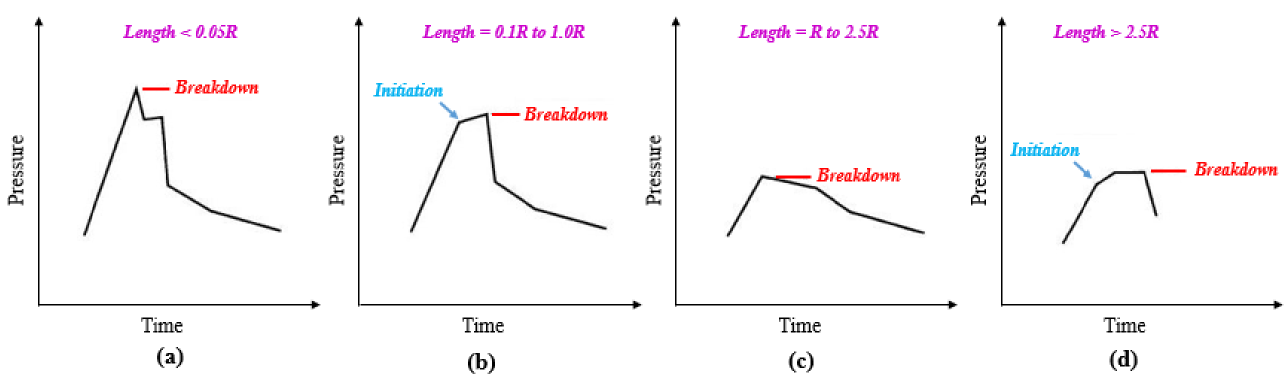


Figure 8: Impact of pre-existing crack length on breakdown pressures after [23].

2.1.3. Executive LOT/XLOT Procedure

Executing LOT is an important job in drilling operations and casing-design programs. One of the main advantages of executing LOT is verifying the fracture-gradient prediction. But sometimes, the LOT results must be more precise for demonstrating the fracture gradient or the far-field stresses. Therefore, to ensure that the fracture is extended into the area controlled by the far-field stresses, running XLOT is suggested. By performing this method, more acceptable results about the far-field stresses at the casing point would be obtained [26, 37]. In the case of executing the XLOT systematically and interpreting the results carefully, very significant data about the rock strength mechanical properties will be obtained which the most important of them are including FBP, FPP, ISIP, FCP, FRP, and RTS. The XLOT's accurate and reliable results effectively build Mechanical Earth Models (MEM) and geomechanical studies [13]. The main steps of performing LOT are explained in the following [23]:

i. Designing LOT Operation Based on the Detailed Studies

Having enough information about the possible fracture gradient before executing the LOT and knowing the expected results, will help the drilling engineers to explain the past cementing operation quality or test result's sensitivity easier.

ii. Having Rigged Up Equipment

A well-designed testing system is the most important point in performing a satisfactory LOT operation. For this purpose, the following equipment must be provided:

- Preparing a cement pump (The common cement pump rate should be 1/4 or 1/2 bpm).
- Sealing all rig lines to delete any possible leaks in the system.
- Preparing a proper pressure gauge for estimating the realistic LOT results.

iii. Using the Proper, Pure, and Uniform Fluid for Performing the Test

The purity and cleanliness of the testing fluid are very effective in the accurate and successful execution of the LOT operation. Cutting existence, in particular, the presence of cement in the testing fluid would affect the testing fluid's rheological properties and change its compressibility or other characteristics. Hence, before running the LOT, the testing fluid should be checked to be sure it is pure enough.

iv. Following Main Key Points in the Pumping Period

The following steps must be considered for obtaining significant and reliable LOT results.

- Checking the stability of the pump rate during pumping.
- Checking the pumping rate continues to be sure it is not so high -to prevent masking the real leak-off value.

v. Plotting the LOT Results Continuously

One of the main steps during LOT is plotting the pressure versus pumped volume. It is very important to record these parameters during the LOT procedure for recognizing the possible mistakes during the graph plotting because these mistakes might affect the whole wellbore's upcoming operations. Besides, the graph is plotted uniquely based on each company's LOT pumping policy.

vi. Determining the Exact Time to Stop Pumping

Estimating the exact time of stopping pumping test fluid is critical. Because the formation will be fractured uncontrollably if it continues the pumping longer than it should. Thus, the pumping must be stopped immediately after the pumping pressure decreases.

vii. Monitoring the Shut-in Period

According to the LOT operator company policy, the shut-in period might be changeable between 5–15 minutes. But normally, 10 minutes waiting period is enough to observe the quality of LOT results and cement bond at the previous casing shoe.

2.1.4. Performing LOT

During drilling operations, LOTs are usually performed for various purposes, including testing the strength or pressure containment of the shoe after a cement job, determining cement integrity, determining mud weight limit for the next borehole section, and for geomechanical studies. The LOT also is used to calibrate the least principal stress (in the vertical wells, the least principal stress is minimum horizontal stress). LOT is a verification method to evaluate the fracture pressure of exposed formations and commonly runs immediately after cementing and drilling out of the casing shoe. Moreover, the LOT results are used for determining the next casing setting depths.

LOT could be performed in both vertical [21] and horizontal wells [42]. Significant efforts have been made to model LOT or XLOT [13, 43, 44], and the non-linear LOT behavior was studied [45, 46]. But in the last decade, most efforts have been focused on the application of the LOT method in horizontal wells [47]. Sun *et al*. [42], developed an extended mathematical LOT model, which was originally proposed by Altun [34, 48] for inclined and horizontal wells. They improved Altun's model by extending the casing expansion during LOT to the directional wells concerning pressure change and developed a new leak volume model for analyzing the different flow behavior of fluid before and after FIP. They verified their model by using the field data and showed their model is accurate enough for estimating LOT values in horizontal wells.

2.1.5. LOT Interpretation

Contrary to what the LOT is simply performed, but its interpretation is sometimes difficult, especially in the formations in which the relationship between the pumped volume and the observed pump pressure is nonlinear. The nonlinear LOT behavior seems to be caused by conditions including existing gas in the system, borehole failure, or leaking of the drilling fluid into the cemented casing or borehole. The main steps of conventional LOT interpretation are described as follows [23]:

i. Leak-off Estimating

The first idea about the leak-off value will be obtained by plotting the LOT graph. The best line should be drawn over the data starting from the second data point and continuing until a change in the slope of the pressure vs mud volume line. At the end of this line, the minimum value of leak-off is determined.

ii. Leak-off Pressure Evaluating

If the LOT results are higher than the predicted values, they could be acceptable and if it is less than the predicted values, it may be due to the presence of cement channels. To confirm the results, a repeat test is recommended.

iii. Shut-in Evaluating

For checking the shut-in LOT chart, the following points should be considered. The first curvature in the chart shows σ_h. Accordingly, the measured leak-off value should be higher than σ_h. In case of observing any other values, they are not acceptable. Moreover, the following conditions should be considered:

If gauge pressure @ $h_e \geq$ gauge pressure @ leak-off → Acceptable results

$$\left.\begin{cases}\text{If gauge pressure } @\sigma_h < \text{ gauge pressure } @ \text{ leak}-\text{off}\\ \text{OR}\\ \text{If shut}-\text{in pressure does not level off above zero}\end{cases}\right\}\rightarrow \text{Possibility of existing cement channel}$$

iv. Checking the Cement Channels

Seeing the following conditions can be a reason for existing the cement channels:

Leak-off EMW > 1/2 ppg < predicted value

Gauge pressure @ σ_h < 1/2 gauge pressure @ leak-off

OR

Shut-in pressure does not level-off

v. Test Repeating

In case of being in doubt, repeating the test is suggested. If the original pump rate is acceptable, the same pump rate can be used and continued this process until the changes are visible in the chart.

2.1.6. Non-Linear LOT Interpretation

A linear trend between the pump pressure and the pumped volume is presented in most LOTs. While non-linear LOT behaviors can be seen in shallow marine sediments. LOT interpretation, especially in formations that show the non-linear relationships between the pumped volume and the observed pump pressure, is commonly complicated. Only now, a mathematical model has been developed that fully and accurately explains the non-linear LOT behavior. But, Altun *et al.* [34] developed a mathematical model to help to analyze non-linear LOT behavior and their model was used to predict the observed non-linear behavior of field examples. They concluded that the three factors impacting LOT most greatly included mud compression, casing expansion, and leak volumes. They also described the non-linearity degree increases with increasing leak volume, and borehole expansion volume was negligible. Usually, conventional LOT interpretation is done by determining the failure point where the pressure buildup curve departs from the linear trend by bending to the right. But, in case of showing non-linear behavior, the conventional LOT graph does not present a clear deflection point, so recognizing LOP would be impossible (Fig. **9a**). While by using a log-log graph, a clear deflection point could be distinguished as the slope changes from the unit slope to the half slope [46] (Fig. **9b**).

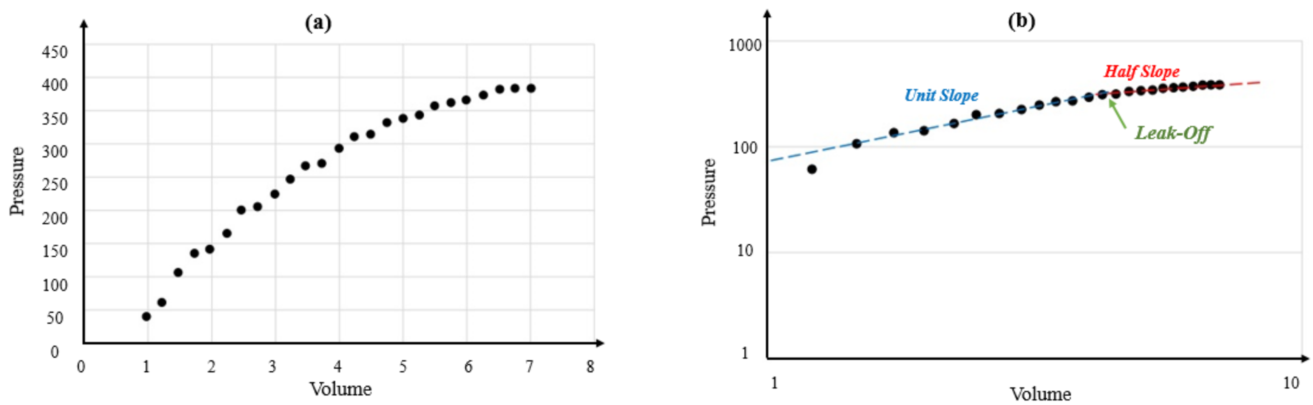


Figure 9: LOT interpretation, (**a**) conventional interpretation, (**b**) log-log plot (After Paknejad [46].

2.2. Application of LOT/XLOT in Relation to the Other Activities

The following will describe the application of these tests in the petroleum industry or other fields.

2.2.1. LOT/XLOT Application in In-Situ Stress Estimation and Geomechanical Studies

Estimating in-situ principal stresses, especially minimum horizontal stress, is critical in drilling, mining, tunneling, and petroleum engineering. Thus, the magnitude and direction of minimum horizontal stress could be determined by LOT or XLOT [11, 16, 26, 49, 50]. Determining in situ stress at depth is required in different programs, especially in hydraulic fracturing and drilling operations. In this regard, LOT and XLOT data can be used for estimating the magnitude of the in situ minimum principal stress at depth [51-53]. Addis *et al.*, for the first time, compared the LOT and XLOT results in the North West Shelf of Australia and the Norwegian North Sea and concluded that the XLOT results were more consistent than LOTs and despite consuming longer time, obtained much preferable data than LOT and recommended XLOT tests where stress data are needed [21]. In another study, the difference between LOP and ISIP by using Mid-Norway XLOT data was conducted and was explained that LOP closely matches ISIP when considering multiple cycle XLOTs. As well, it was indicated that the LOP is the fracture re-opening pressure [54]. Different scientists used LOT data in geomechanical studies [13, 55-57]. A comprehensive geomechanical model was built by integrating geophysical logs and downhole measurements. LOP, formation pressure and LOT were used to estimate formation pressure magnitudes, rock elastic properties, and minimum horizontal stress. 1D constructed geomechanical model can be used to quantify shear slippage potential [20].

2.2.2. LOT/XLOT in Relation to Hydraulic Fracturing

Investigating the rock fracture behavior under fluid pressure in hydraulic fracturing procedure is essential and is affected by in situ principal stresses. Since one of the applications of LOT/XLOT is determining minimum horizontal stress, therefore these tests results are useful in hydraulic fracturing treatments [58, 59]. By determining the formation leak-off potential, evaluating the fracture geometry, fluid flow, proppant transport, and the potential for fracking hits during hydraulic fracturing could be conducted better and more accurately [60]. Fluid leak-Off during hydraulic fracturing was modeled by Penny *et al.*, [61] under static and dynamic conditions in the low permeability matrix and highly permeable natural fractures, and the results were compared to field data. Evaluating different models showed that static and dynamic test results are very similar at shear rates of 40 sec^{-1}. Pan *et al*., by conducting an experimental study, investigated the effect of the intermediate principal stress on hydraulic fracturing in granite formations and demonstrated that hydraulic fracturing is mostly affected by rock heterogeneity. It means by increasing the intermediate principal stress, the granite formation breakdown pressure decreases, which is different from the effect of minor principal stress. Furthermore, they developed a criteria for reflecting the efficacy of intermediate principal stress on the formation breakdown pressure [62].

2.2.3. LOT/XLOT in Relation to Wellbore Stability

One of the problems that might occur during drilling operations is the phenomenon of wellbore instability [63, 64]. Thus, LOTs are performed to test the strength of the shoe after a cement job and LOT/XLOT results could be used for calibrating the minimum horizontal stress [65, 66]. Estimating horizontal stress orientation and magnitude in some operations like wellbore instability analysis, sand control, field developments, and safe drilling operations. Hence, some tests like LOT/XLOT or FIT are conducted for stress measurements [67-70]. Zhang et.al [71], reviewed the theoretical methods for evaluating in situ stresses and concluded XLOT results are acceptable in estimating horizontal principal stresses, especially in the normal or strike-slip faulting stress regime.

2.2.4. LOT/XLOT and Numerical Modeling

In general, LOT is run after cementing job in each string for determining fracture pressure of exposed formations. Despite the simplicity of running the test, its interpretation is not always easy, especially in formations with nonlinear relationships between pumped volume and injection pressure. Thus, various numerical studies have been conducted to investigate the LOT/XLOT procedure or for checking the test results [72-76]. During performing hydraulic fracturing operations in naturally fractured reservoirs, the XLOTs results are affected by hydraulic and natural fractures [77]. Zhang *et al.* [53], performed a two-dimensional discrete element model for simulating XLOT analysis. The 2D/DEM was used to analyze the formation deformation system, fracture conductivity, and their correlation in the fractured reservoirs. Furthermore, a hybrid artificial neural network–genetic algorithm (ANN/GA) method was tested for the identification of the principal in situ stresses and joint parameters. Murgas [78], numerically simulated LOT in oil wells by using a finite element program to calculate the LOP and conducting a real analysis of a LOT in permeable and impermeable rock. For this reason, the pumping rate is used as input data and pressure at the borehole wall as the answer. The possible effects of permeability change and the influence of pressurized fluid in the calculation of LOP in the permeable rock were studied. Coupled XLOT numerical simulation was performed by Lavrov *et al*., [44] to study the pressure behavior during the flow back phase and the effect of a pre-existing fracture on the test results in a low-permeability formation. During simulation, the fracture initiation pressure and the formation breakdown pressure increased steadily with decreasing angles between the fracture and the minimum in situ stress. Their results showed using the fracture initiation pressure, and the formation breakdown pressure for stress measurements or rock strength estimation was discredited. In another research, the XLOTs behavior in low-permeability formations was numerically simulated by a modified discrete-element model and the effect of pre-existing natural fractures on them was studied. They demonstrated that in case of not existing natural fractures during running the XLOT test, the created hydraulic fractures developed perpendicular to the minimum horizontal stress. While in the case of an intersecting wellbore and natural fractures, the fracture twisting was detected, and the XLOT pressure curves were noticeably different from the pressure curves recorded in the absence of a natural fracture [43].

2.3. Automated FIT, LOT & XLOT

Formation Integrity Tests, Leak-off Tests, and Extended Leak-off Tests are the most common procedures performed during drilling operations. Commonly, in these methods, activities like operating the pumps and chokes and interpreting and reporting the results are done manually. But the high dependency on manual procedures will lead to poor consistency and repeatability for the tests. Therefore, automation and digitalization of the tests will provide the ability to have a standardized and sustainable robust workflow system to meet the challenges of data gathering, data storage, test interpreting, and reporting, which are highly important to the oil and gas industry. Islam *et al*. [79] developed a new automated supervisory system that automatically provided real-time test analysis and interpretation of pressure integrity tests, including FITs, LOTs, and XLOTs. This method is further beyond the manual methods and provides the possibility of reaction to real-time trends and feedback on the tests which is impossible with manual monitoring. Generally, their method performance includes the following:

i. Automatically monitoring and supervising the fluid pressure which is supplied to/or returned from the underground formation in real-time.

ii. Automatically monitoring and supervising the fluid volume which is supplied to/or returned from the underground formation in real-time.

iii. Automatically monitoring and supervising the system to specify the relationship(s) for monitored pressure and volume while they have been changed relative to each other or (and) with time during the real-time.

iv. Automatically monitoring and supervising the system to analyze the monitored pressure and volume data by using their relationship(s) either in real-time or after completion of the pressure integrity test to provide information and(or) warnings regard to one or more of the following options:

- Parameters relating to the underground formation.
- Performance of the test during the testing procedure.
- The outcome of the test.
- Quality of the monitored data.
- Test metrics include leakage rate, trapped air, unstable pump rate, plugged choke, system compliance, surface pressure, and surface volume.

Islam *et al*. [80], in another study, described the challenges of the current pressure integrity tests and proposed a new method called "Automated Pressure Testing System". The automated pressure testing system (APIT) is a computational software-based system covering the test analysis in real-time, reporting and interpreting the test results of FITs, LOTs, and XLOTs automatically. The main specifications of this method are described in the following. Automatic interpretation of the test-related items, including:

- Leak-off pressure.
- Formation breakdown pressure.
- Instantaneous shut-in pressure.
- Fracture reopening pressure.
- Fracture propagation pressure.
- Fracture closure pressure.
- Automated data validation of test results.
- Automated test quality rating based on a pre-defined matrix.
- Automated generation of draft test reports, including test interpretations and results.

2.3.1. LOT Algorithm Prepared for This Study

The LOT algorithm and flowchart prepared for this study will be described in the following (considering 13 3/8" casing set at the desired depth) (Fig. **10** and **11a**). It's worth mentioning that Equations 1 to 5 are shown in Fig. (**10**). In addition, in Fig. (**A1**), a schematic view of the six main steps of a LOT.

2.3.2. LOT Flowchart Prepared for This Study

After preparing the LOT algorithm, the LOT flowchart also was drawn, which is considered in Fig. (**A2**).

2.4. Estimating Maximum Allowable Annular Surface Pressure (MAASP)

One of the parameters that need to be calculated when performing LOT is the Maximum allowable annular surface pressure (MAASP). The MAASP or pressure differential at the choke is defined as a safety margin used when designing the mud program. It also allows maintaining the annular pressure at a value that will not cause the formation to fracture. At the static condition, MAASP is calculated by Equations 6 or 7.

MAASP= (LOT Pressure– Current Mud Weight) × 0.052 × Casing shoe @TVD (6)

$$MAASP = \frac{(GradLOT - \rho_{mud}) \times TVD_{shoe}}{10} \quad (7)$$

Where MASSP is in (psi), LOT Pressure in (ppg), Mud Weight in (ppg), and Casing shoe in (ft).

3. Results and Discussion

The brief definition of LOT is closing the BOP, pressuring up the well slowly, using drilling mud, stopping the pumping at the first sign of fluid leak-off into the formation, and carrying out LOTs until observing the leak-off. To perform a successful LOT operation and maintain well safety, the LOT procedure should cover all steps, including proper planning, executing, interpreting, and reporting. To perform suitable mud displacement, the downhole forces inflicted by the circulating fluids in the borehole should be adequate to dominate the yield stress of any drilling fluids in the borehole [81]. The LOT interpretation in different formations, including unconsolidated, consolidated permeable, and consolidated impermeable formations, is not the same. The fluid might be lost at very low pressures in unconsolidated or highly permeable formations.

In this case, by stopping the pump, the pressure will fall (Fig. **11a**). While in consolidated permeable and consolidated impermeable formations, the situation is different. Typical plots for these formations are described in Fig. (**11b-c**) respectively. Recognizing the wellbore's actual pressure integrity is very important in different fields, especially in the drilling industry. Commonly, three main methods, including LOT, XLOT, and FIT, are categorized as the Formation Strength Tests. The most common methods for determining pressure containment values are FITs and LOTs. But most of the time these two methods are confused or used instead of each other. Hence, understanding the difference between them is very important. For this reason, the most important differences between these two methods are shown in Table **1**. By performing FITs, not expected to occur damage to the future pressure containment capability of the wellbore. During reforming the FIT, the test results are determined and recorded, and if no leak-off is observed, it means that the mud in the wellbore at the time is suitable for the anticipated fracture gradient. Besides, based on the information obtained from the FIT, the casing running speeds could be optimized, and a cementing program that will not induce a fracture would be planned. By performing LOTs, leak-off, rupture, or permanent deformation in the formation would be determined. Moreover, valuable information to specify the maximum wellhead pressure that could be stood in case of kick occurring and circulating out would be provided. Performing FITs leads to access to some wellbore information which is described as follows:

i. Estimating suitable mud weights (optimum and equivalent) for next section drilling.

ii. Minimizing the risk of lost circulation during drilling the inconvenience areas.

iii. Estimating if the planned casing running rate will destabilize the wellbore.

iv. Obtaining real information which will be used as inputs of cementing simulation models.

v. Fracturing risk reduction during cementing operations.

Using the automatic and real-time checking pressure and volume method has many advantages more than the manual method, some of the most important of which are displayed below [79]:

- Obtaining the necessary information is needed for determining the fracture closure pressure in real time.
- Determining the fracture closure pressure as soon as there is sufficient data to fit two straight lines to the plot(s) with the degree of certainty required.
- Determining the fracture closure pressure much faster than the manual method, even in some cases before completing the pressure integrity tests.
- Using plots of pressure against volume and the (or) square root of pressure against time to find values of fracture closure pressure and then compare two values.

Table 1: The most important differences between LOT and FIT.

LOT	FIT
Conducting shoe and formation pressure tests until formation breaks down.	Conducting shoe and formation strength tests by increasing BHP for pressure designing.
Performing LOT for determining the fracture pressure of formation and shoe.	Performing FIT for ensuring the ability of drilling the target depth.
During LOT procedure: • Pumping drilling fluid until observing the formation fracture trend. • At the moment of breaking the formation, LOP is the first pressure that differed from the trend.	During FIT producer: • Increasing surface pressure until catching the essential pressure (no need to formation break by FIT).
Using LOP for estimating LOT.	The ability of well controlling (In case of needing to well control) without underground blowout.

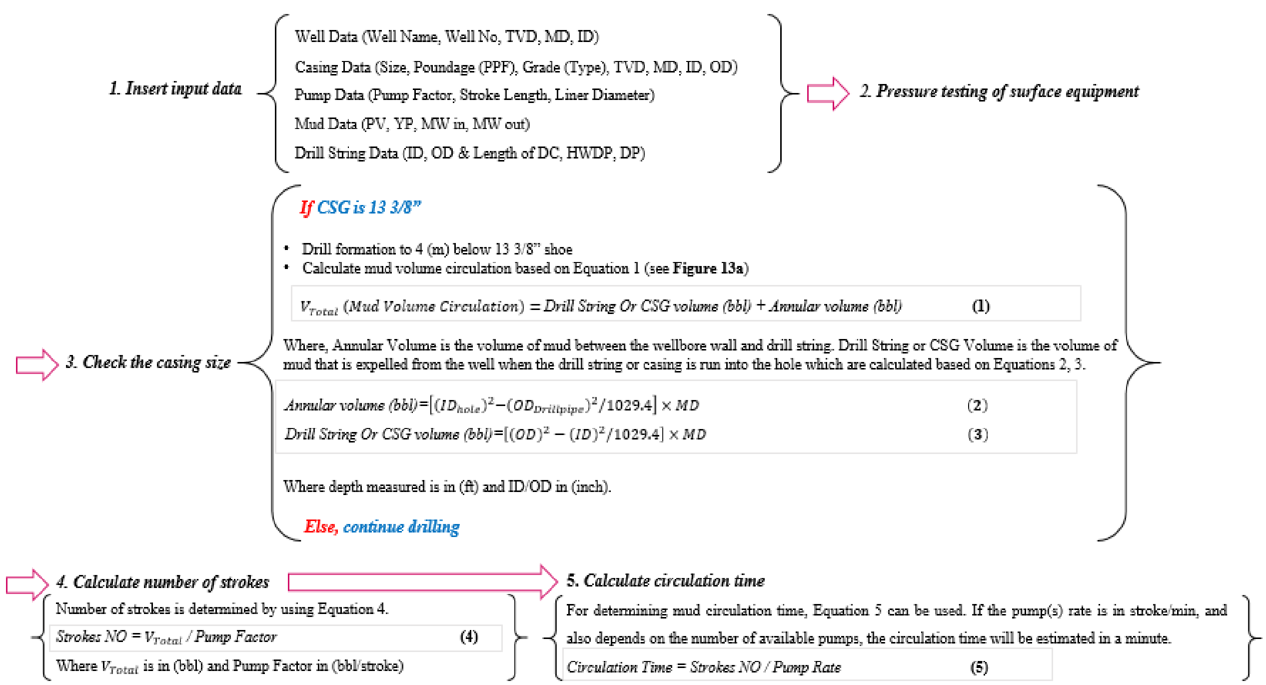


Figure 10 contd....

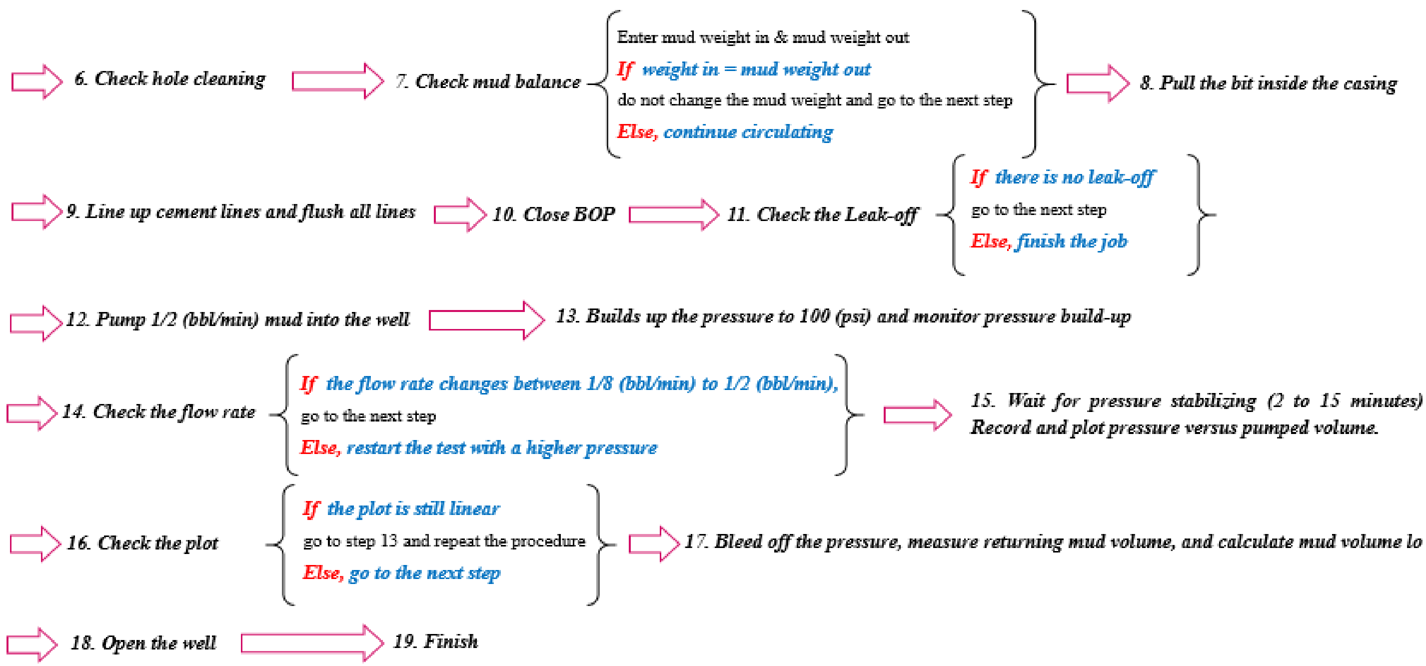


Figure 10: LOT algorithm.

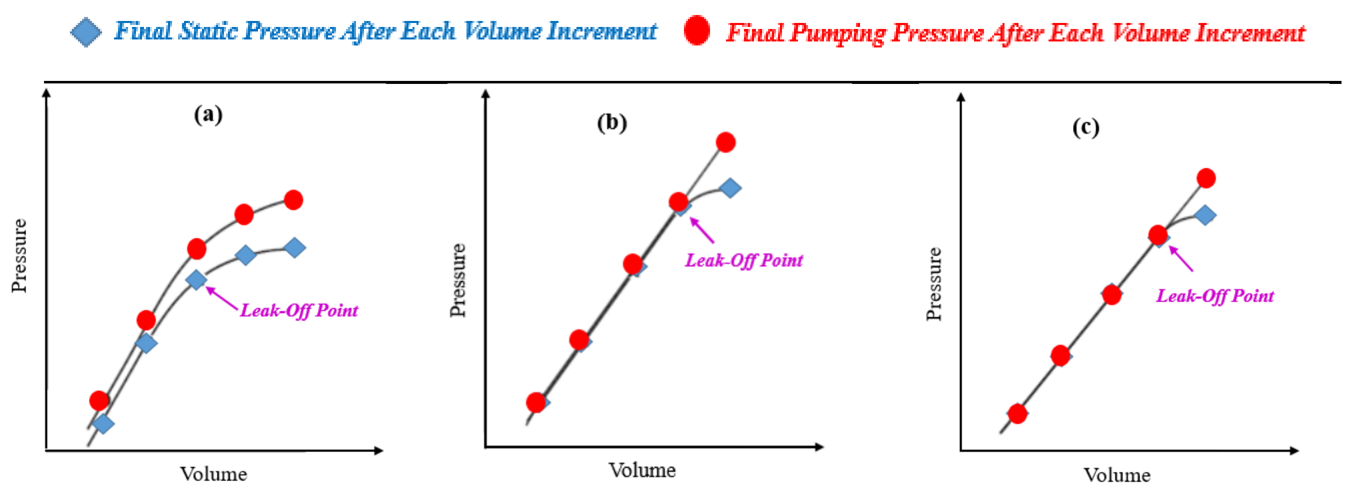
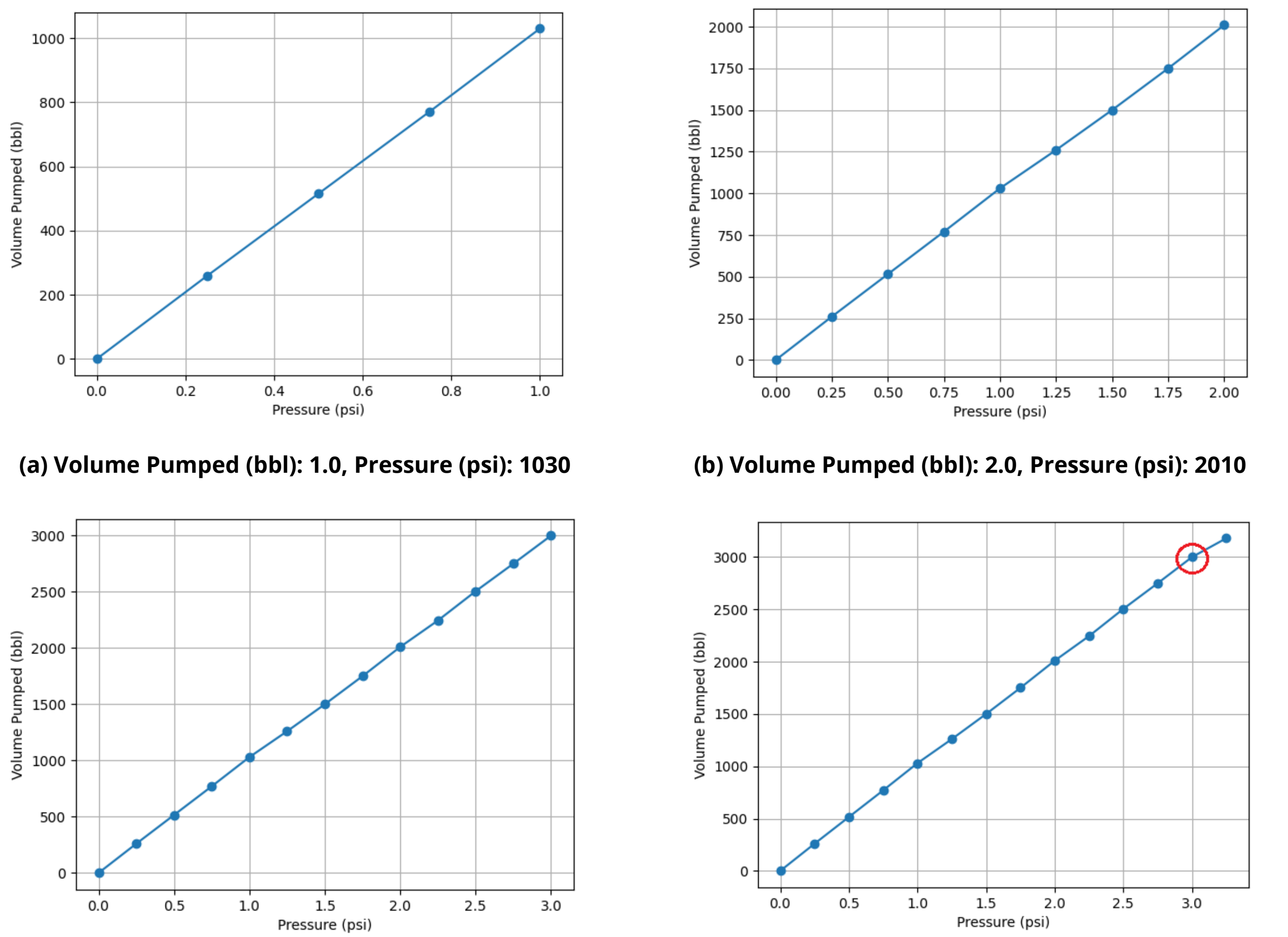


Figure 11: Idealized LOT plots for (**a**) unconsolidated formations, (**b**) consolidated permeable.

As mentioned in previous sections, owing to the lack of LOT code and the necessity of automation in this process, a simple LOT code was prepared, and the results of running the code in Python environment are shown in Figs. (**A3-a**) and (**A3-b**). A brief discussion about the written code could be as follows:

1. Calling required libraries from Python.
2. Introducing the minimum and maximum volume pumped values, which in this case study are 0 and 3.25, respectively, and in each step, 0.25 is added to the previous volume.
3. Recall the equivalent pressure value for each volume in psi.
4. Drawing a graph of volume pumped (barrel) versus pressure (psi).

Based on the code, one graph is plotted for each pair of volume and pressure, from pressure 0 to 3180 (psi). It means 14 graphs for this data set. In Fig. (**A3-b**), just the last graph (volume: 3.25 bbl and pressure 3180 psi) is shown, and on its left side, the volume and pressure values given by the user to the code are shown. Fig. (12) shows just four graphs related to the pumped volumes 1.00, 2.00, 3.00, and 3.25 (bbl), respectively. Based on the input data (Table **A1**), the maximum pressure is 3000 (psi) and is shown in Fig. (**12-c**), but at pressure 3180 (psi) deviation is seen in the graph (Fig. **12-d**). Thus, based on the graph, the LOT point could be estimated.



(a) Volume Pumped (bbl): 1.0, Pressure (psi): 1030

(b) Volume Pumped (bbl): 2.0, Pressure (psi): 2010

(c) Volume Pumped (bbl): 3.0, Pressure (psi): 3000

(d) Volume Pumped (bbl): 3.25, Pressure (psi): 3180

Figure 12: Volume vs pressure graphs for four steps of running the code.

4. Conclusion and Future Works Recommendation

The present study summarized and categorized the existing knowledge on the LOT/XLOT and FIT tests by reviewing numerous published works and introduced a fundamental code for automating these tests with the purpose of future digitization of the tests. What is more, it was found that the Leak-Off Test is usually used as a general term for all Formation Strength Tests. Therefore, to realize the general meaning of these terms and avoid confusion, in this work, each of the terms was explained separately and in detail. After all, the following conclusions were drawn.

- Despite precise tastings and adequate monitoring, in some cases of performing LOT, it is not possible to fully understand what happened during the test. Such an issue needs discussion and further investigation.
- Because of creating considerable fractures during LOTs and not expecting permanent weakening in well pressure control, performing XLOTs in some cases is preferred. Moreover, XLOTs are repeatable in several cycles without a noticeable decrement in maximum pressure attained.

- Numerous studies have been published on these three tests. Several cases, such as the comparison of LOT and XLOT, the role of these methods in estimating on-site stresses and etc., were investigated.
- A comprehensive explanation of these three methods' procedures is presented.
- An algorithm and a tangible flowchart were introduced for the Leak-Off Test, which would be considered the basis of switching to automated LOT.
- A fundamental code was developed in Python, and for its verification, the real LOT data were used, for which the results were acceptable.
- MASSP flowchart was prepared.

Finally, and at the end of this work, the MASSP flowchart was prepared which is shown in Fig. (**A4**).

5. Acknowledgements

This work was supported by the “Iran National Science Foundation (INSF) (No. 98011044)” and also “Research Institute of Petroleum Industry (RIPI)”.

6. Authors' Contribution

Behzad Elahifar and Elham Bakhshi developed the research idea. Elham Bakhshi performed the literature search, wrote the original draft text and prepared the LOT code. Behzad Elahifar guided and supervised the application of the methodology. Technical review and methodology modification were carried out by Naser Golsanami, Behzad Elahifar, and Abbas Shahrabadi. Technical guidance was provided by Reza Khajenaeini.

7. Conflict of Interest

The corresponding authors state that there is no conflict of interest on behalf of all authors.

References

[1] Golsanami N, Jayasuriya MN, Yan W, Fernando SG, Liu X, Cui L, *et al. Cha*racterizing clay textures and their impact on the reservoir using deep learning and Lattice-Boltzmann simulation applied to SEM images. Energy. 2021; 240: 122599. https://doi.org/10.1016/j.energy.2021.122599

[2] Golsanami N, Bakhshi E, Yan W, Dong H, Barzgar E, Zhang G, *et al. Rel*ationships between the geomechanical parameters and Archie’s coefficients of fractured carbonate reservoirs: a new insight. Energy Source Part A. 2020; 2020: 1-25. https://doi.org/10.1080/15567036.2020.1849463

[3] Bakhshi E, Golsanami N, Chen L. Numerical modeling and lattice method for characterizing hydraulic fracture propagation: a review of the numerical, experimental, and field studies. Arch Comput Methods Eng. 2020; 28: 1-32. https://doi.org/10.1007/s11831-020-09501-6

[4] Bakhshi E, Rasouli V, Ghorbani A, Marji MF. Lattice numerical simulations of hydraulic fractures interacting with natural oblique interfaces. Int J Min Geo-Eng. 2019; 53: 83-9. https://doi.org/10.22059/IJMGE.2019.270665.594767

[5] Golsanami N, Zhang X, Yan W, Yu L, Dong H, Dong X, *et al. NMR*-based study of the pore types’ contribution to the elastic response of the reservoir rock. Energies (Basel). 2021; 14(5): 1513. https://doi.org/10.3390/en14051513

[6] Golsanami N, Fernando SG, Jayasuriya MN, Yan W, Dong H, Cui L, *et al. Fra*ctal properties of various clay minerals obtained from SEM images. Geofluids. 2021; 2021: 1-18. https://doi.org/10.1155/2021/5516444

[7] Bosch M, Mukerji T, Gonzalez EF. Seismic inversion for reservoir properties combining statistical rock physics and geostatistics: A review. Geophysics 2010; 75: 75A165-76. https://doi.org/10.1190/1.3478209

[8] Lim J-S. Reservoir properties determination using fuzzy logic and neural networks from well data in offshore Korea. J Pet Sci Eng. 2005; 49:182-92. https://doi.org/10.1016/j.petrol.2005.05.005

[9] Grana D, della Rossa E. Probabilistic petrophysical-properties estimation integrating statistical rock physics with seismic inversion. Geophysics. 2010; 75: 21-37. https://doi.org/10.1190/1.3386676

[10] Aadnoy BS, Mostafavi V, Hareland G. Fracture mechanics interpretation of leak-off tests. Kuwait International Petroleum Conference and Exhibition, December 14-16, 2009, Kuwait: SPE; 2009. https://doi.org/10.2118/126452-MS

[11] Gjønnes M, Cruz AMGL, Horsrud P, Holt RM. Leak-off tests for horizontal stress determination? J Pet Sci Eng. 1998; 20: 63-71. https://doi.org/10.1016/S0920-4105(97)00053-3

[12] Shaghaghi T, Ghadrdan M, Tolooiyan A. Effect of rock mass permeability and rock fracture leak-off coefficient on the pore water pressure distribution in a fractured slope. Simul Model Pract Theory. 2020; 105: 102167. https://doi.org/10.1016/j.simpat.2020.102167

[13] Lee D, Birchwood R, Bratton T. Leak-off test interpretation and modeling with application to geomechanics. Gulf Rocks 2004 - 6th North America Rock Mechanics Symposium, Houston, Texas, USA, 5-9 June, NARMS 2004, OnePetro; 2004, ARMA-04-547.

[14] Allerstorfer C. Investigation of the" plastic-behavior" region in leak-off tests (Master Thesis). University of Leoben; Austria: 2011. Available from https://pure.unileoben.ac.at/portal/files/2457780/AC08882729n01vt.pdf

[15] Couzens-Schultz BA, Chan AW. Stress determination in active thrust belts: An alternative leak-off pressure interpretation. J Struct Geol. 2010; 32:1061-9. https://doi.org/10.1016/j.jsg.2010.06.013

[16] Zoback MD, Barton CA, Brudy M, Castillo DA, Finkbeiner T, Grollimund BR, *et al. Det*ermination of stress orientation and magnitude in deep wells. Int J Rock Mech Min Sci. 2003; 40:1049-76. https://doi.org/10.1016/j.ijrmms.2003.07.001

[17] de Bree P, Walters JV. Micro/minifrac test procedures and interpretation for in situ stress determination. Int J Rock Mech Min Sci Geomech Abstr. 1989; 26: 515-21. https://doi.org/10.1016/0148-9062(89)91429-0

[18] Yamamoto K. Implementation of the extended leak-off test in deep wells in Japan. In: Sugawara K, Obara Y, Sato A, Eds., Rock Stress. London: CRC Press; 2020, p. 579-84. https://doi.org/10.1201/9781003078890-90

[19] Pallikathekathil ZJ, Yang XW, Hafezy S, Puspitasari R, Harris RI, Sutton JT. Inversion of advanced full waveform sonic data provides magnitudes of minimum and maximum horizontal stress for calibrating the geomechanics model in a gas storage reservoir. SPE Asia Pacific Oil & Gas Conference and Exhibition, November 17-19, Virtual: OnePetro; 2020. https://doi.org/10.2118/202260-MS

[20] Baouche R, Sen S, Boutaleb K. Present day In-situ stress magnitude and orientation of horizontal stress components in the eastern Illizi basin, Algeria: A geomechanical modeling. J Struct Geol. 2020; 132: 103975. https://doi.org/10.1016/j.jsg.2019.103975

[21] Addis MA, Hanssen TH, Yassir N, Willoughby DR, Enever J. A comparison of leak-off test and extended leak-off test data for stress estimation. SPE/ISRM Rock Mechanics in Petroleum Engineering, Trondheim: Society of Petroleum Engineers; 1998. https://doi.org/10.2118/47235-MS

[22] Bell JS. Investigating stress regimes in sedimentary basins using information from oil industry wireline logs and drilling records. Geol Soc. 1990; 48: 305-25. https://doi.org/10.1144/GSL.SP.1990.048.01.26

[23] Postler DP. Pressure integrity test interpretation. SPE/IADC drilling conference, Amsterdam: Society of Petroleum Engineers; 1997. https://doi.org/10.2118/37589-MS

[24] Raaen MA. The pump-in/flowback test improves routine minimum horizontal stress magnitude determination in deep wells. In: Lu M, Ed., In-Situ Rock Stress: Measurement, Interpretation and Application, Trondheim: Taylor & Francis; 2006, p. 73-8. https://doi.org/10.1201/9781439833650.ch10

[25] Jing L, Hudson JA. Numerical methods in rock mechanics. Int J Rock Mech Min Sci. 2002; 39: 409-27. https://doi.org/10.1016/S1365-1609(02)00065-5

[26] Kunze KR, Steiger RP. Accurate in-situ stress measurements during drilling operations. SPE Annual Technical Conference and Exhibition, SPE; 1992. https://doi.org/10.2118/24593-MS

[27] Raaen AM, Skomedal E, Kjørholt H, Markestad P, Økland D. Stress determination from hydraulic fracturing tests: the system stiffness approach. Int J Rock Mech Min Sci. 2001; 38: 529-41. https://doi.org/10.1016/S1365-1609(01)00020-X

[28] Raaen AM, Brudy M. Pump-in/flowback tests reduce the estimate of horizontal in-situ stress significantly. SPE Annual Technical Conference and Exhibition, New Orleans: SPE; 2001. https://doi.org/10.2118/71367-MS

[29] Vavilov MB, Sekacheva YV, Chernov VI, Lyutikov KV, Perebatov AS. Impact of casing pressure test after waiting on cement on cement bond quality (Russian). SPE Russian Petroleum Technology Conference, One Petro; 2020. https://doi.org/10.2118/201861-RU

[30] van Oort E, Vargo R. Improving formation strength tests and their interpretation. SPE/IADC Drilling Conference, Amsterdam: SPE; 2007. https://doi.org/10.2118/105193-MS

[31] Rezmer-Cooper IM, Rambow FHK, Arasteh M, Hashem MN, Swanson B, Gzara K. Real-time formation integrity tests using downhole data. in SPE/IADC Drilling Conference, New Orleans: SPE; 2000. https://doi.org/10.2118/59123-MS

[32] Morita N, Black AD, Guh G-F. Theory of lost circulation pressure. in SPE annual technical conference and exhibition, New Orleans: SPE; 1990. https://doi.org/10.2118/20409-MS

[33] Almeida MA. Computer-aided analysis of formation pressure integrity tests used in oil well drilling. Louisiana State University and Agricultural & Mechanical College, 1986.

[34] Altun G, Langlinais J, Bourgoyne AT. Application of a new model to analyze leak-off tests. SPE Drilling & Completion 2001; 16: 108-16. https://doi.org/10.2118/72061-PA

[35] Ishijima Y, J. Roegiers. Fracturei nitiation and breakdowpnr essure--are they similar? The 24th US Symposium on Rock Mechanics (USRMS), American Rock Mechanics Association; 1983.

[36] Horsrud P, Risnes R, Bratli RK. Fracture initiation pressures in permeable poorly consolidated sands. Int J Rock Mech Min Sci Geomech Abstr. 1982; 19:2 55-66. https://doi.org/10.1016/0148-9062(82)91362-6

[37] Okland D, Gabrielsen GK, Gjerde J, Koen S, Williams EL. The importance of extended leak-off test data for combatting lost circulation. SPE/ISRM Rock Mechanics Conference, OnePetro; 2002. https://doi.org/10.2118/78219-MS

[38] Tomren PH, Iyoho AW, Azar JJ. Experimental study of cuttings transport in directional wells. SPE Drill Eng. 1986; 1:43-56. https://doi.org/10.2118/12123-PA

[39] Bilgesu HI, Mishra N, Ameri S. Understanding the effects of drilling parameters on hole cleaning in horizontal and deviated wellbores using computational fluid dynamics. Eastern Regional Meeting, Lexington: OnePetro; 2007. https://doi.org/10.2118/111208-MS

[40] Bizhani M., Rodriguez Corredor FE, Kuru E. Quantitative evaluation of critical conditions required for effective Hole Cleaning in Coiled-Tubing Drilling of Horizontal Wells. SPE Drill Complet. 2016; 31:188-99. https://doi.org/10.2118/174404-PA

[41] al Rubaii MM. A new robust approach for hole cleaning to improve rate of penetration. SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam: SPE; 2018. https://doi.org/10.2118/192223-MS

[42] Sun K, Wu L, Bui N, Samuel R. Leak off test LOT modeling for inclined and horizontal wells. SPE Annual Technical Conference and Exhibition, San Antonio: OnePetro; 2017. https://doi.org/10.2118/187326-MS

[43] Bauer A, Larsen I, Lavrov A. Numerical model of extended leak-off test (XLOT). 49th US Rock Mechanics / Geomechanics Symposium, OnePetro; 2015, vol. 1, p. 1359-68.

[44] Lavrov A, Larsen I, Bauer A. Numerical modelling of extended leak-off test with a pre-existing fracture. Rock Mech Rock Eng. 2016; 49: 1359-68. https://doi.org/10.1007/s00603-015-0807-x

[45] Altun G, Langlinais J, Bourgoyne AT. Application of a new model to analyze leak-off tests. SPE Drill & Complet. 2001; 16: 108-16. https://doi.org/10.2118/72061-PA

[46] Paknejad A, Schubert J, Amani M. A New method to evaluate leak-off tests in shallow marine aediments (SMS). SPE Saudi Arabia Section Technical Symposium, Dhahran: OnePetro; 2007. https://doi.org/10.2118/110953-MS

[47] Ju Y, Wang Y, Chen J, Gao F, Wang J. Adaptive finite element-discrete element method for numerical analysis of the multistage hydrofracturing of horizontal wells in tight reservoirs considering pre-existing fractures, hydromechanical coupling, and leak-off effects. J Nat Gas Sci Eng. 2018; 54: 266-82. https://doi.org/10.1016/j.jngse.2018.04.015

[48] Altun G. Analysis of non-linear formation fracture resistance tests obtained during oil well drilling operations (Thesis). Louisiana State University and Agricultural & Mechanical College; 1999.

[49] Sanaee R, Reza Shadizadeh S, Ali Riahi M. Determination of the stress profile in a deep borehole in a naturally fractured reservoir. Int J Rock Mech Min Sci. 2010; 47: 599-605. https://doi.org/10.1016/j.ijrmms.2010.03.014

[50] Haimson B, Lin W, Oku H, Hung J-H, Song S-R. Integrating borehole-breakout dimensions, strength criteria, and leak-off test results, to constrain the state of stress across the Chelungpu Fault, Taiwan. Tectonophysics 2010; 482: 65-72. https://doi.org/10.1016/j.tecto.2009.05.016

[51] 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 2008; 6: 43-7. https://doi.org/10.5194/sd-6-43-2008

[52] Li G, Lorwongngam A, Roegiers JC. Critical review of leak-off test as a practice for determination of in-situ stresses. 43rd U.S. Rock Mechanics Symposium and 4th U.S.-Canada Rock Mechanics Symposium, OnePetro; 2009.

[53] Zhang S, Yin S, Wang F, Zhao H. Characterization of in situ stress state and joint properties from extended leak-off tests in fractured reservoirs. Int J Geomech. 2017; 17(3): 1-12. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000757

[54] White AJ, Traugott MO, Swarbrick RE. The use of leak-off tests as means of predicting minimum in-situ stress. Pet Geosci. 2002; 8: 189-93. https://doi.org/10.1144/petgeo.8.2.189

[55] van-der-Zee W, Ozan C, Brudy M, Holland M. 3D geomechanical modeling of complex salt structures. SIMULIA Customer Conference, 2011, p. 1-17.

[56] Seyedsajadi S, Aghighi MA. Construction and analysis of a geomechanical model for bangestan reservoir in koopal field. Iran J Min Eng. 2015; 10: 21-34.

[57] Pandey RA, Singh TN. A critical assessment of Geomechanics of leak off test. Int J Earth Sci Eng. 2016; 9: 1393-6.

[58] Cottrell MG, Hartley LJ, Libby S. Advances in hydromechanical coupling for complex hydraulically fractured unconventional reservoirs. 53rd U.S. Rock Mechanics/Geomechanics Symposium, OnePetro; 2019.

[59] Sarmadivaleh M, Rasouli V. Simulation of hydraulic fracturing in tight formations. APPEA J. 2010; 50: 581-92. https://doi.org/10.1071/AJ09035

[60] Abell BC, Xing P, Bunger A, Dontsov E, Suarez-Rivera R. Laboratory investigation of leak-off during hydraulic fracturing into bedding interfaces. SPE/AAPG/SEG Unconventional Resources Technology Conference, Tulsa, OK, USA: OnePetro; 2019. https://doi.org/10.15530/urtec-2019-900

[61] Penny GS, Conway MW, Lee W. Control and modeling of fluid leakoff during hydraulic fracturing. J Pet Technol. 1985; 37: 1071-81. https://doi.org/10.2118/12486-PA

[62] Pan P-Z, Wu Z-H, Yan F, Ji W-W, Miao S-T, Wang Z. Effect of the intermediate principal stress on hydraulic fracturing in granite: an experimental study. Environ Earth Sci. 2020; 79: 1-18. https://doi.org/10.1007/s12665-019-8760-8

[63] Gholami R, Rabiei M, Rasouli V, Aadnoy B, Fakhari N. Application of quantitative risk assessment in wellbore stability analysis. J Pet Sci Eng. 2015; 135: 185-200. https://doi.org/10.1016/j.petrol.2015.09.013

[64] Zhang L, Cao P, Radha KC. Evaluation of rock strength criteria for wellbore stability analysis. Int J Rock Mech Min Sci. 2010; 47: 1304-16. https://doi.org/10.1016/j.ijrmms.2010.09.001

[65] Wang H, Soliman MY, Shan Z, Meng F, Towler BF. Understanding the effects of leakoff tests on wellbore strength. SPE Drill Compet. 2011; 26: 531-9. https://doi.org/10.2118/132981-PA

[66] Asadi MSS, Khaksar A, White A, Yao Z. Wellbore stability analysis in depleted deep-water reservoirs: a case study from Australia. SPE Middle East Oil & Gas Show and Conference, 8-11th of March, Manama: OnePetro; 2015. https://doi.org/10.2118/172685-MS

[67] Dutta DJ, Farouk M. Wellbore stability and trajectory sensitivity analyses help safe drilling of the first horizontal well in asl formation, gulf of suez, Egypt. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 25-27th of August, Jakarta: OnePetro; 2008. https://doi.org/10.2118/114670-MS

[68] van Steene M, Povstyanova M, Al-Attar H, el Gheit DA, Abutaleb M, Lantz J, *et al. Usi*ng wellbore stability analysis to improve drilling performance: case study from the western desert, Egypt. North Africa Technical Conference and Exhibition, 14-17th of February, Cairo: OnePetro; 2010. https://doi.org/10.2118/128112-MS

[69] Desroches J, Woods TE. Stress measurements for sand control. SPE/ISRM Rock Mechanics in Petroleum Engineering, 8-10th of July, Trondheim: OnePetro; 1998. https://doi.org/10.2118/47247-MS

[70] Dawood JK. Investigation of wellbore stability in a horizontal well drilled in interbedded sandstone reservoir of Zubair field (Thesis). Politecnico di Torino University; 2020.

[71] Zhang Y, Yin S, Zhang J. In situ stress prediction in subsurface rocks: an overview and a new method. Geofluids 2021; 2021: 1-11. https://doi.org/10.1155/2021/6639793

[72] Altun G, Langlinais J, Bourgoyne AT. New model to analyze non-linear leak-off test behavior. SPE Annual Technical Conference and Exhibition, 3-6th of October, Houston, Texas: OnePetro; 1999. https://doi.org/10.2118/56761-MS

[73] Zhou D, Wojtanowicz AK. Analysis of leak-off tests in shallow marine sediments. J Energy Resour Technol. 2002; 124: 231-8. https://doi.org/10.1115/1.1506322

[74] Gandomkar A, Fu J, Gray KE. Leak-off test model combining wellbore and near-wellbore mechanical behavior. SPE Annual Technical Conference and Exhibition, Houston: OnePetro; 2015. https://doi.org/10.2118/174876-MS

[75] Feng Y, Gray KE. A comparison study of extended leak-off tests in permeable and impermeable formations. 50th US Rock Mechanics / Geomechanics Symposium 2016, vol. 2, OnePetro; 2016.

[76] Eide VV. Numerical simulation of extended leak-off tests. Master Thesis. Norwegian University of Science and Technology; June 2014.

[77] Phusing D, Suzuki K, Zaman M. Mechanical behavior of granular materials under continuously varying b values using DEM. Int J Geomech. 2016; 16: 1-12. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000506

[78] Murgas JFC. Numerical modelling of leak off test in oil wells 2012 (Thesis). University of Rio de Janeiro, 2012.

[79] Islam MA, Helstrup OA, Skadsem HJ. Method and apparatus for automated pressure integrity testing (APIT). Google Patents NO20181062A1, 2021.

[80] Islam MA, Helstrup OA, Moi S, Carlsen LA. Automated pressure integrity testing APIT-A step change approach. Abu Dhabi International Petroleum Exhibition & Conference, 7-10th of November, Abu Dhabi: OnePetro; 2016. https://doi.org/10.2118/183273-MS

[81] Ravi K, Weber L. Drill-cutting removal in a horizontal wellbore for cementing. IADC/SPE drilling conference, New Orleans: SPE; 1996. https://doi.org/10.2118/35081-MS

Appendix

Nomenclature

bbl: Barrel

BOP: Blow out preventer

CSG: Casing

DC: Drill collar

DP: Drill pipe

DEM: Discrete element model

ECD: Equivalent circulation density

EMW: Equivalent mud weight

FBP: Formation breakdown pressure

FCP: Fracture closure pressure

FIP: Fracture initiation pressure

FIT: Formation integrity test

FPP: Fracture propagation pressure

FRP: Fracture reopening pressure

FST: Formation strength tests

HWDP: Heavyweight drill pipe

ID: Internal diameter

ISIP: Instantaneous shut-in pressure

LOP: Leak-off pressure

LOT: Leak-off test

MAASP: Maximum allowable annular surface pressure

MD: Measured depth

MW: Mud Weight

OBM: Oil-based mud

OD: Outside diameter

PPF: Poundage (pound/ft)

PV: Plastic viscosity

PWD: Pressure while drilling

RTS: Residual tensile strength

SBM: Synthetic based mud

SPM (Pump rate): Strokes per minute

TVD: True vertical depth

WBM: Water-based mud

XLOT: Extended Leak-off test

YP: Yield point

σ_h: Minimum horizontal stress

Table A1: Real LOT field data

Volume (bbl)	Pressure (psi)	Volume (bbl)	Pressure (psi)
0.00	0	1.75	1750
0.25	260	2.00	2010
0.50	515	2.25	2245
0.75	770	2.50	2505
1.00	1030	2.75	2750
1.25	1260	3.00	3000
1.50	1500	3.25	3180

1. Planning the Test

- Estimating the surface leak-off pressure.
- Limiting the test pressures to a maximum of the overburden gradient or to another realistic limit.
- Confirming the accuracy of the pressure gauges.
- Be sure the pressure exerts during the test never exceeds the maximum burst pressure of the casing.
- Estimating the mud pumped volume and determining the increased volume.
- Completing the pre-test report.

2. Executing the Test

- Drilling out the cement 20 (ft) of new formation.
- Circulating and conditioning the mud.
- Pulling the bit back into the casing shoe.
- Making sure the hole is filled up and close the BOP around the drill pipe.
- Using a high-pressure, low-volume pump.
- Lining up calibrated pressure gauges, covering various pressure ranges and preferably mounted on a special manifold.
- Pumping the mud slowly until the pressure builds up.
- Pumping a small increment of mud, and waiting for the required time for stabilizing the pressure.
- Recording the cumulative volume pumped, the initial static pressure, and the final static pressure after the waiting period.
- Repeating items 8 and 9, plotting both pressure values against cumulative mud volume for each increment until observing leak-off or until reaching the predetermined limit pressure.
- Keeping the well closed-in to verify obtaining a constant pressure. Recording and plotting the closed-in pressure every minute (in case of not stabilizing the pressure, might be a system leaking indication or bad cement bonding).
- Bleeding off the pressure and establishing the mud volume lost to the formation.
- Topping up and closing the annulus between the casing and the previous casing string.

3. Interpreting the Test

- Plotting the results and interpreting them on the large-scale volume versus pressure plot during the test.
- Interpolating the value of the initial static pressure at the first indication of leak-off and showing it as the surface leak-off pressure.
- For hard impermeable formations (like shales) the pressure increases linearly with volume and identifying the leak-off is simple.
- For a permeable formation with an ineffective mud-cake, the mud leaking away slowly, the graph is slightly curving, and the final static pressure curving away from the initial static pressure.
- For a permeable formation with an ineffective mud-cake, the leak-off identifies either by changing in curvature or from the increasing difference between initial static and final static pressures.
- For non-consolidated, plastic, loose, or highly permeable formations where even low test pressures cause loss of mud, the exact determination of the leak-off point is difficult.

4. Preventing Formation Breakdown

- In case of occurring the breakdown, treating that as an opportunity to derive real formation strength parameters.
- Indicating the formation breakdown by a sharp pressure drop on the surface. Choosing the highest pressure recording immediately before the pressure drop as the surface breakdown pressure.
- In case of occurring the formation breakdown, stopping the pumping, but keeping the well closed-in and recording the pressure decay curve.
- Indicating the fracture closure pressure by stabilizing the pressure decay curve to a constant pressure value.
- In case of observing previous options and for confirming them, continuing the test with a fracture re-opening cycle.
- In case of not consistently the first and second FCP and the FRP, considering another cycle.

5. Reporting the Test

- Reporting the formation strength tests in a consistent manner.
- Reporting actual pressure measurements, volumes, and an interpretation of the results.
- Reporting an accurate graph on a large scale of volume pumped versus surface pressure.
- Indicating whether leak-off or formation breakdown was observed.

6. Repeating the Test

- Repeating the test some distance below the previous measurement for confirming that the strength of a new formation still satisfies the requirements. for safe drilling, or to gain some additional formation strength data.
- Do not exceed the previous downhole test pressures unless there are reasons to assume that the formation strength has increased (for example after a change in mud system).

Figure A1: Six main steps of LOT procedure.

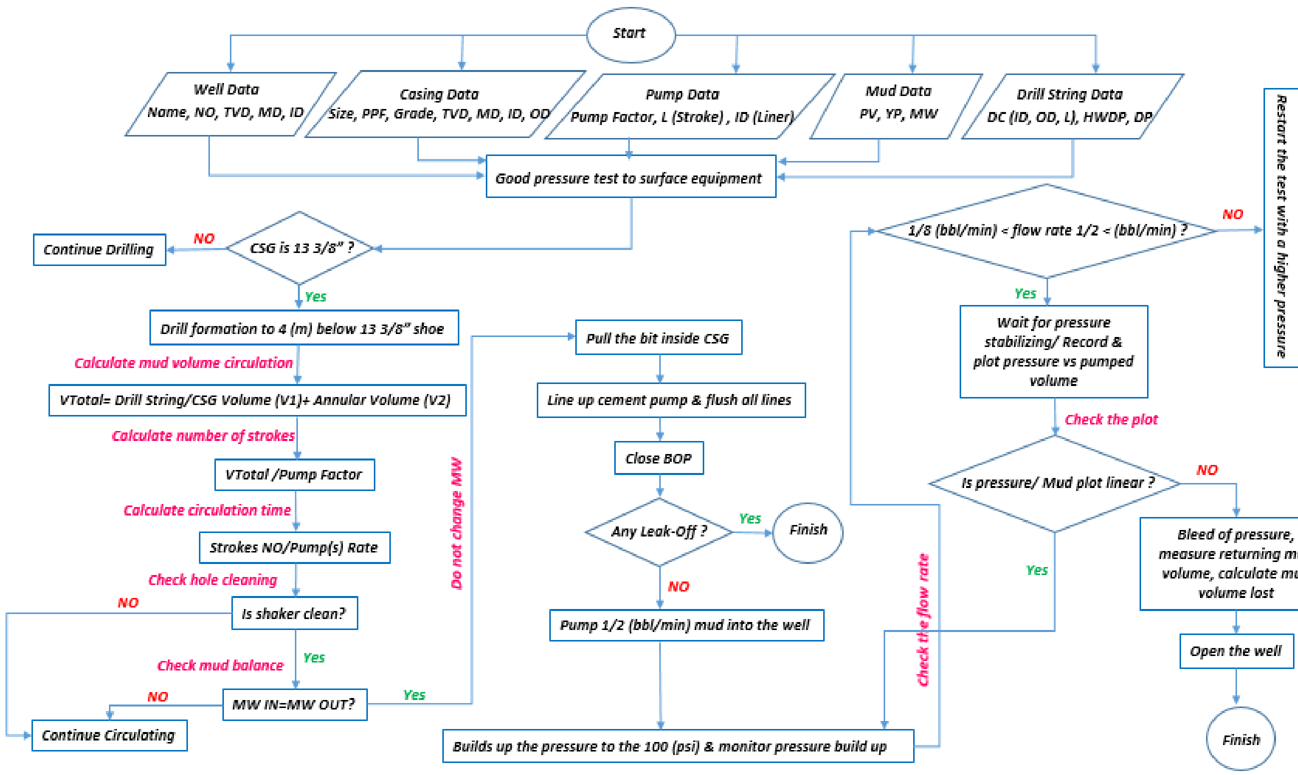
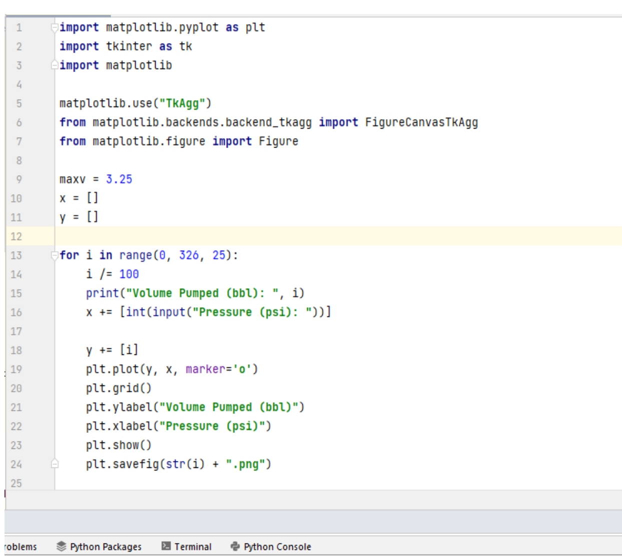
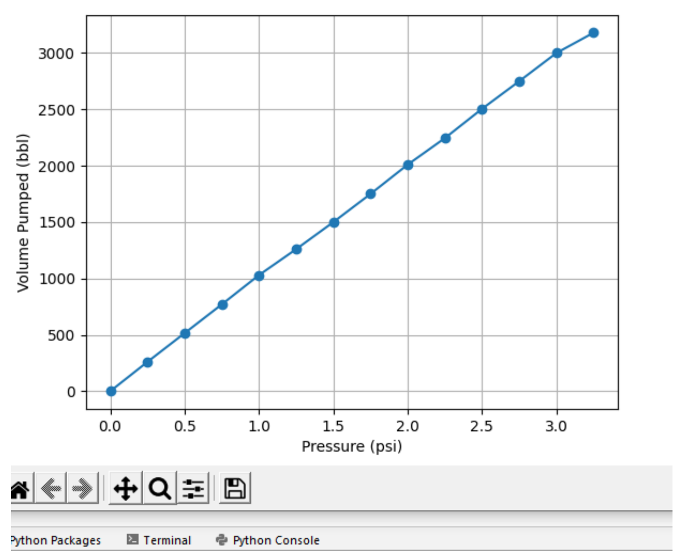


Figure A2: LOT flowchart.



(a)



(b)

Figure A3: (**a**) LOT Python code for plotting volume and pressure results, (**b**) Volume vs pressure plot after running LOT code (LOT code output).

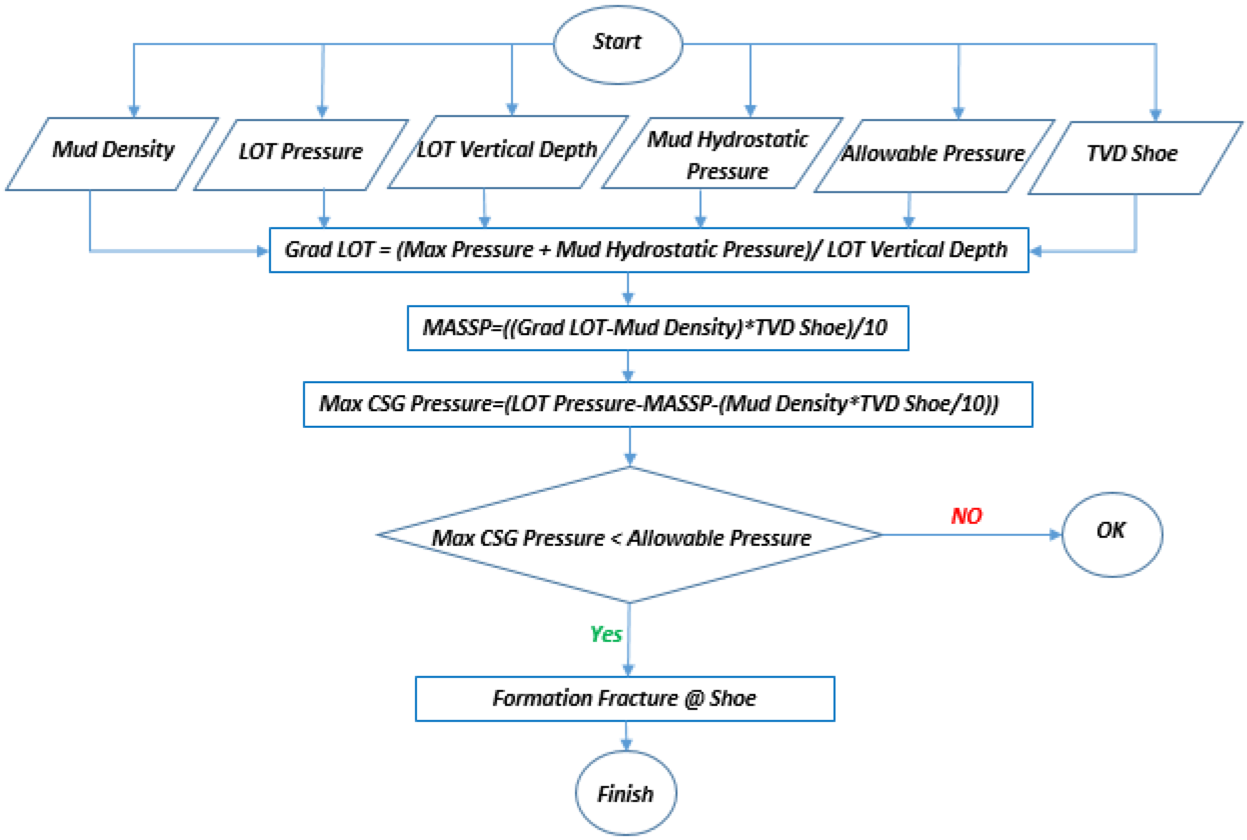


Figure A4: MASSP flowchart.