Extended Leak-Off Tests (EXLOT) & Its Applications to Geomechanical Study: Field examples of Western Offshore Basin, ONGC, India

Geology Operations Group, Western Offshore Basin, ONGC, Priyadarshini, Mumbai – 400022, Maharashtra, India
kundan_a@ongc.co.in, ashani.kundan@gmail.com
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EXLOT (Extended Leak off Test), MTF (Mind the Fall), WTS (When to Stop), FIT (Formation Integrity Test), $S_{\text{hmin}}$ (Minimum Horizontal Stress) $S_{\text{hmax}}$ (Maximum Horizontal Stress)

Summary
Extended Leak -Off Test (EXLOT) had never been a part of formation strength tests or pressure integrity tests at either offshore or onland fields of Oil and Natural Gas Corporation Ltd. Indeed, Western Offshore Basin (WOFF Basin) became first to introduce extended leak off tests in ONGC and so far conducted more than 50 EXLOT across the fields.

Our study shows that, Extended Leak off Tests (EXLOT), if executed systematically and interpreted properly would certainly yield very significant data inputs pertaining rock strength mechanical properties such as Formation Breakdown Pressure (FBP), Fracture Propagation Pressure (FPP), Instantaneous Shut in Pressure (ISIP), Fracture Closure Pressure (FCP), Fracture Reopening Pressure (FRP), Residual Tensile Strength (RTS) which shall be helpful in estimating magnitude of two principal stresses, viz. Minimum Horizontal Stress ($S_{\text{hmin}}$) and constraining Maximum Horizontal stress ($S_{\text{hmax}}$). Effective stress ratio ($K_0$) and Poisson’s Ratio ($\nu$) derived from EXLOT tests shall be applicable for estimation of fracture gradient using Matthews & Kelly method, Daines method and Eaton’s method.

Our study prevails over all the related myths carried by the petroleum drillers of the ONGC and shall definitely substantiates that, Extended Leak off Tests (EXLOT), if executed systematically and interpreted properly, yield excellent contributions for building Mechanical Earth Model (MEM) or Geomechanical studies. The lessons learnt during the execution of EXLOT tests in western offshore shallow water regimes further augmented the quality tests and would benefit to reduce the procedural errors in future too. Both the wellsite geologist and driller must be at same page prior to execution of job. Incorrect procedure and interpretation of the test can lead to a variety of problems and/or unnecessary expense on a well cost. It’s extremely difficult to understand the characteristics of subsurface lithology so unusual behavior of test graph may not be the big surprise.

Introduction
As E&P companies in India are now needed to move further challenging environment, the understanding of the Geomechanics becomes progressively important for combating wellbore instability issues and further planning reservoir development. During drilling, information on the principal stresses can only be obtained by performing Pressure Integrity Tests particularly Leak-Off Test (LOT) and XLOT (Extended Leak-Off Test). The invaluable inputs obtained are excellent guiding factors to estimate the main principal stress magnitudes used to build Geomechanical model.
Extended Leak-Off Tests (EXLOT) & its Applications to Geomechanical Study

For decades, LOT tests have been performed throughout the industry but because of the common fear that EXLOT causes permanent damages to wellbore, these tests were sidestepped. As recent studies were carried out with increasing demand of valuable data, EXLOT tests were performed in different fields of Western Offshore Basin (WOB). Our study areas comprise of fields of Kutch Saurashtra (KS), Tapti Daman (TD) and Mumbai Offshore (MO) in WOFF Basin and are purposely given random numbers. In this study, more than 50 number of EXLOT datasets from more than 34 offshore wells have been plotted (Fig.1 & 2), critically analyzed and interpretations are established.

The analysis of these EXLOT plots gave us the idea of various shapes of the EXLOT plots which occurred due to different situation present therewith.

Methodology:

LOT/EXLOT tests are carried at casing shoe after drilling 3 to 5m of new formation of respective drilling phase. In Western Offshore Basin, these tests are conducted at 20”, 13 3/8” and 9 5/8” casing shoe. The basic procedure is used in all pressure integrity tests (LOT/EXLOT) is to conditioned the well thoroughly, BOP is closed and fluid is pumped into wellbore at constant pumping rate 0.25-0.5 bbl/min with cementing unit up to certain surface pressure build up. Shut in pressure is also monitored for about 10 to 15mins and then released the pressure. The second pressurization cycle is to be followed at same constant pumping rate. For unconsolidated/permeable formation pumping rate of 0.5bbl/min or more is required.

Fig. 3 explains classic textbook example of EXLOT and the methodology for the same carried out at well MO-6. Similar methodology was adopted for all other EXLOT tests performed in WOFF Basin. In this test, uniform and constant pump rate was maintained at 0.25bbl/min for both cycles. Plot begins with a linear trend denoting formation being elastically compressed till formation is leaked and indicates a homogenous lithology as well as elastic region of plot. The test where leak off pressure is not reached is called Limit Test (LT) or Formation Integrity Test (FIT).

At Leak-Off Point (LOP), fracture occurs and slope of graph deviates toward right, directing that mud has started going inside the formation through a small stable fracture (Postler, 1997). This is also called Fracture Initiation Point (FIP). After LOP, curve is still deviating towards right, indicating a stable
fracture growth, meaning the rate at which mud is flowing is slower than the rate at which it is being pumped. This is the plastic region of plot.

Further, a peak pressure is reached during the test is estimated as **Formation Breakdown Pressure (FBP)** where formation breakdown happens. Zoback et.al.(2009) suggests that at FBP, the fluid is flowing into fracture from wellbore faster than pump is supplying which results in pressure drop after FBP. It is still vital to maintain pumping at a constant rate 0.25 bbl/min. The pumping pressure drops after the FBP to a relatively constant value called the **Fracture Propagation Pressure (FPP)** where the fracture is propagating away from the wellbore into the far field stress region. When fractures propagate for some volume pumped, pump is shut off and pressure on gauge is observed, this is shut in phase where rapid drop in pressure occurred because of the loss of pump friction pressure and the loss of fluids to the fractures and called **Initial Shut In pressure (ISIP)**. Once pumping is stopped, earth’s stresses (i.e. $S_{\text{min}}$) starts to close fracture plane from its tip. This explains the change of slope after ISIP in the plot and this pressure point is called **Fracture Closure Pressure (FCP)**.

Numerous methods for the analysis of shut in pressure data for determination of the least principal stress have been proposed over the years. A discussion of various techniques was reviewed by Zoback and Haimson (1982), Baumgartner and Zoback (1989) Rummel and Hansen (1989), Hayashi Haimson(1991). However, the least principal stress magnitude from FCP can be determined more correctly by plotting pressure as a function of $\sqrt{\text{time}}$ and detecting a change in linearity of the pressure decay (Nolte and Economides,1989) which gives accurate value of magnitude of minimum horizontal stress or $S_{\text{min}}$. (Fig. 4).

To verify the values obtained from first cycle, it is imperative to re-pressurize the wellbore, to obtain correct value of **Fracture Reopening Pressure (FRP)** and **FCP** as well as to know residual tensile strength (RTS) of the rock formation left. In hydraulic fracturing terminology, the breakdown pressure of the second cycle i.e. second FBP is also referred to as **Reopening or ReFrac Pressure (RFP)**. (Zang Arno, 2010).

**Case studies:**

As discussed earlier more than 50 EXLOT tests have been attempted at various depths and different areas/structures of the basin. Unfortunately many plots do not resemble the classic plot. Some plots were severely affected by the procedural problems and in some cases Leak off Pressure observed much higher than anticipated. In few instances the shut in pressure decay was very unusual consequently became difficult to construe the true fracture closure pressure. The authors have selected some of typical EXLOT plots observed in fields of shallow water regimes of WOFF Basin.

**Field Exemple: EXLOT at shallowest level (C/shoe 207m)**

Fig. 5 shows EXLOT test conducted at shallowest level in Kutch –Saurashtra field of WOFF Basin, 20” casing shoe depth at 207m, having dominant lithology was clay.
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This test is probably one of the shallowest EXLOT test carried out in offshore basin of E&P industry. Here, non-linear curve up to LOP occurs and is attributed to the presence of unconsolidated clay at shallow level which behaves elastically. LOP occurred at surface pressure of 96psi which is 12.22ppg EMW, formation breakdown at 101psi and fracture closure at 61psi (11.23ppg EMW).

Second cycle was done and observed fracture reopens at 76psi, FBP at 91psi and FCP occurs at 56psi. The second cycle is much cleaner and also demonstrates that wellbore strength has not been significantly reduced by the fracture created in the first test and that too at shallow level. It is also certain that permanent damage not happens always if EXLOT test is carried out with proper planning and procedure even at shallow depth.

Field Example: EXLOT having RFP higher than FBP

In this plot, it is seen than RFP of second cycle observed higher than first cycle FBP or in other words, second pumping cycle is taller than first. Here, FBP occurs at 1489psi surface pressure or 13.9ppg EMW @depth of 1942m wherein the second cycle FBP/RFP occurs at 1595psi or 14.21EMW. Most possible cause for this would be the mud with its solid content, got plugged within the matrix in first cycle and hence higher pressure was required in second cycle to re-fracture the breakdown. Colloidal solids, polymers, or clay present in the mud can sometimes be lost into the formation and can cause plugging. (Economides and Nolte, 1980). This also demonstrates that tensile strength of the formation has increased significantly instead of loosing it.

Field Example: Two-stage EXLOT displaying plastic / elastic zones in same formation

This plot is an excellent example of plastic/elastic zones in the same formation. Plot shows two stage curve where there is a plastic zone followed by elastic zone before reaching FBP.

The drilling process can create a lower-strength plastic zone near the wellbore; however, the formation retains its strength away from the wellbore (Postler, 1997). Also, it could be because of the anisotropy of the formation. This plot shows two apparent leak-offs; the first at surface pressure of 214psi indicates fracture opening within plastic zone which propagates from 71psi to 214psi. At 343psi, the fracture reaches stronger elastic zone, further growth occurs up to true LOP and fracture breakdown happens at 357psi.

Existence of these zones is also supported by shut-in behavior as in the plot. FCP also occurs at 300psi signifies the Shmin in the elastic zone only. LOT analysts suggested considering higher Leak off value for drilling purpose.

Field Example: EXLOT in Basement of MO field

This is the example where extended leak off test was carried out first time in Basement rock of WOFF Basin. The basement was metamorphic rock and the test was carried out at 9 5/8” casing shoe at a depth of 2097m.

In first cycle, stable and unstable regions are evident. Leak-off occurred at surface pressure of 1850psi or 14.07ppg EMW. Pumping was continued until
breakdown at 2000psi. At shut-in, pressure dropped to 1900psi and FCP observed at 1810psi representing $S_{\text{hmin}}$ of the formation.

Second cycle was conducted to check results of first cycle and shows again a stable region and with further reapplication of pressure, the existing fracture re-opens at 1750psi, breakdown at 1915psi and fracture closure at 1805psi. The values are essentially the same as in the first test with minor differences which can be attributed to filter cake build-up and/or inaccuracies in reading data. This plot closely resembles a classic test. Test also shows absence of pre-existing fractures at test interval.

EXLOT carried out in basement is a breakthrough in history of drilling operations all around the world. Data acquired through this test was further used in the critical stress analysis of Basement wells in Mumbai Offshore field positively.

Field Example: Huge Pressure drop from FBP - Evidence of Casing shoe break (a lesson learnt also)

Fig. 9 shows the evidence of small channel in casing shoe identified during EXLOT. Here, in first cycle, linear trend is observed till FBP where sudden drop in pressure (1600 psi to 646psi in a minute). Since there was no indication of LOP till 1600psi surface pressure which is 18.89ppg EMW, the operator ignored the rules of maximum allowable pressure. Any pressure integrity tests must govern by the ethics of WTS (When to stop).

It’s imperative to understand the nature of fault system where tests are conducted accordingly the risk of maximum allowable pressure shall be decided. In normal stress regime fracture indication may occurs between 0.6-0.7psi/ft. Another significant observation in this plot is huge drop in pressure while pressurization at 1600psi surface during first cycle. Nearly 950psi of pressure fall is a clear indication of creation of cement channel near shoe during pumping.

Repeat test in 2nd cycle proved breaking of casing shoe inadvertently. Here comes MTF (Mind the Fall) if fall in pressure is sudden > 200psi then pressurization of second cycle may be skipped.

One can ascertain the fact that casing shoe has indeed been fractured and cement channel has been created. The significance effect of pre-existing formation cracks and different types of cement channel also need to be analyzed prior to decide for cement repair job.

Significance of EXLOT:

It is a common fear that extended leak off test lead to permanent damage to the wellbore and lost circulation and hence are often not performed due to the fear of permanently weakening the formation by creating a fracture away from wellbore.

As seen in above plots, as a fracture is created, the formation strength is ultimately reduced by the tensile strength, which low in most cases. However, in most EXLOT tests reviewed during this study, no evidence for a significant reduction in formation tensile strength could be found.

An example is presented in Fig. 10 where one can perceive a superimposed graph of first and second cycle of EXLOT allowed for pressurization up to almost the same maximum test pressure. No
significant evidence of reducing the ultimate tensile strength of the formation can be found in this example.

**Estimation of Poisson’s Ratio (v) and Effective stress ratio (k₀):**

Since fracturing involves the deformation of solid materials, it is necessary to examine one of the more significant mechanical properties of rocks, Poisson’s ratio. When a rock specimen is compressed in one direction, not only will it “shorten” along the loading direction, but also it will “expand” in the lateral directions. This effect is quantified by the introduction of an additional elastic constant “Poisson’s ratio”. Accurate \( k_0 \) can be calculated from EXLOT by the following equation:

\[
 k_0 = \frac{(FCP-P_p)}{(OBP-P_p)}
\]

This computed \( k_0 \) then can be used to calculate Eaton’s Poisson’s Ratio (\( v \)) by the following equation:

\[
 v = k_0 / (1+k_0)
\]

These values then can be used in Daine’s Equation, Matthew and Kelly’s Equation, Eaton’s Equation and to make Geomechanical model more superior.

**Estimation of S_{Hmax}:**

EXLOT test can also be used to estimate \( S_{Hmax} \) using the fracture initiation and/or reopening pressure (Hubber and Willis, 1957). Minimum hoop stress concentration around the wellbore is given by:

\[
 \sigma_{00min} = 3S_{hmin} - S_{Hmax} - P_w - P_p
\]

where \( P_w \) is mud pressure and \( P_p \) is pore pressure of formation.

Tensile failure will be occurred at the wellbore when concentration exceeds the tensile strength of the rock

\[
 \sigma_{00min} = 3S_{hmin} - S_{Hmax} - P_w - P_p \leq T
\]

The fracture initiation pressure at LOP (\( P_t \)) is mud pressure (\( P_w \)) at fracture initiation point. Hence,

\[
 3S_{hmin} - S_{Hmax} - P_t - P_p = T
\]

\( S_{hmin} \) can be computed from FCP (\( P_c \)). Again at FRP, (\( P_r \)) the tensile strength of the rock is overcome. So, by reaarranging the above equation, we get,

\[
 S_{Hmax} = 3P_c - P_r - P_p
\]

From above eq, it is possible to estimate \( S_{Hmax} \) from EXLOT pressure test. But, to make \( S_{Hmax} \) estimate more accurate, tensile rock strenth value from the lab testing sampels of rock from test interval are required. The magnitude of the maximum principal stress in deep wells is best practically determined through an integrated analysis of borehole breakouts and tensile fractures from image logs, rock strength and the minimum principal horizontatal stress from XLOT (Zoback et al,2003)

**Conclusions:**

Extended Leak off tests carried out at different fields of WOB in different formations having different lithology, at different depths, etc. By studying these various EXLOT, it can now be established that EXLOT should be avoided at shallow depth (up to 500m) in the Mumbai Offshore field because of unconsolidated nature of sediments and also the wells falls in normal stress regimes. Pressurization of second cycle may unnecessarily damage formation. However, in Tapti Daman and Kutch Saurashtra fields, EXLOT conducted at shallow level depth gave
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good result. Kutch - Saurashtra fields comparatively falls in high stress regimes.

XLOT tests conducted in lower Mahim and Mahuva formation witnessed classic textbook examples. Both the formations appear to be free from pre-existing fractures.

Mind the Gap: Prior to carrying out EXLOT, it is essential to study leak-off tests of offset wells to know the expected leak-off pressure and to set the lower and upper limit of surface pressure to be applied.

When to Stop: it’s imperative to issue clear guidelines to the operator to decide the maximum allowable pressure to avoid unnecessary damage of casing shoe.

Mind the Fall: If there is substantial fall in the surface pressure during test (as seen the field example fig.8), which signals cement shoe leakage, it is better not to carry out second cycle as it could further intensify wellbore problem. This can also be evaded by proper analysis of EXLOT plots of offset wells and by counselling with specialists.

Every well may not be candidate for EXLOT, therefore, wellsite geologist has to be vigilant prior to carry out the job and to decide repeat cycle. It is imperative to note that shut in period should be proper i.e. levelling of the curve after ISIP. This is important to get more accurate FCP which is our ultimate goal. Thus, there should not be a rush in bleeding off the wellbore pressure during test and suggested that minimum 15 minutes should be given for this to occur.

Kutch-Saurashtra Basin also witness some very high pressure integrity/LOT value which are in the range of 17 to 19ppg indicates wells falls in strike-slip stress regime or in reverse fault stress regime. If a LOT/EXLOT value is to be greater than magnitude of vertical stress component, then it’s certainly a reverse fault stress regime field.

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