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A Critical Assessment of Geomechanics of Leak off Test

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Abstract: A detail Knowledge of *insitu* stress and formation pore pressure in a basin brings understandings into their configuration as well as its implications for well design and drilling safety. Leak off pressure (LOPs) recorded during leak-off tests (LOTs) accompanied down boreholes are frequently used for the evaluation of magnitude of the minimum stress (usually assumed to be horizontal – σh) in the subsurface. Though, the reliability of these tests has been questioned in the literature as well as in oil and gas industry. Newly acquired extended LOTs provide more reliable estimate of minimum stress as compared to other available methods. But standard LOTs performed in each borehole section and provide huge data set for geologist which can be further used for the estimation of minimum horizontal stress. In present study geomechanical assessment of parameter used for LOT are discussed which specify the relation between LOP and minimum horizontal stress.

Keywords: *Leak-off test, extended leak-off test, radial stress, hoop's stress, minimum horizontal stress, maximum horizontal stress, lost circulation*

1. Introduction

Proper determination of pore pressure and fracture gradient is critical to make effective, efficient and economical operation of borehole for optimum exploitation of oil and gas [1-3].In Drilling operations wellbore pressure must be kept within the mud weight window at any depth. The lower limit of window is defined as naturally occurring formation pore pressure. If the wellbore pressure falls below the formation pore pressure, a 'kick' occurs in which formation fluids enter the wellbore causing well control problems. The upper limit of the window is known as maximum pressure that formation can withstand without losing integrity, this pressure is known as formation fracture pressure. If the wellbore pressure is high enough to exceed the formation fracture pressure, cracks can generated at the open hole which offer pathways to drilling fluid to enter in formation. The severe result of this is lost circulation which is one of the expensive operations during drilling a well [4].The drilling industry relies on two main methods to estimate the formation fracture pressure: the direct method and indirect method. The direct method involves pressure testing of open hole formation after drilling out previous casing shoe such as LOT, XLOT. Indirect method often utilized empirical correlations like Eaton correlation, Hubbert and Willis equations. Apart from giving the fracture pressure which is useful for wellsite personals, LOT data has very important and common tool to determine the stress state of earth. It itself is not the direct measurement of minimum horizontal stress. However, it often refers as the approximation of σh (minimum horizontal stress). Altun et al. (1999) [5] published the first ever LOT model aimed to better analyze LOT results in formations that give non-linear relationship between pumped volume of drilling fluid and the observed pump pressure. Numerous workers have published many theories on Formation Strength tests, particularly on Leak off test (LOTs) and extended leak-off tests (XLOTs). These tests have been performed throughout the industry for decades. Even though Formation Strength Test are widely considered as, well established and routine operation, with its straight forward execution and interpretation, it provide a series of challenges, which are rarely accounted for in daily operation [6]

2. Difference between Standard LOT and Extended LOT

Standard Leak-Off Test (LOT)

For borehole integrity and its modelling, LOT is an important parameter. The detail can be obtained from the previous borehole details. Leak off test is performed to check that the casing, cement and rock formation can hold out the pressure needed to safely drill the next section of the well. So, fresh formation is drilled which is very near to casing shoe and wellbore is pressurized until a hydraulic fracture is created and the magnitude of minimum horizontal stress can be determined from this value [7].

Extended Leak-Off Test (XLOT)

The LOT is not performed to measure minimum horizontal stress (σh) so, using the LOT data for the measurement sometimes gives misleading results. Procedure to conduct XLOT and LOT are similar. XLOT add repeated pressurization cycles in order to reduce shortcoming of standard LOT. Figure 01 represent idealistic picture of pressure vs time record from an XLOT. Figure 02 represent the actual recorded XLOT from a well drilled by ONGC. The

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test starts by pumping fluid (preferably low viscosity fluid), same as leak off test, until a leak off point is established, and then pump is shut down to monitor pressure decay. Then again pump is start and again leak off point is established and pump is shut down to check pressure decay. At this point XLOT procedure has been complete. To observe good result a third cycle is advised but practically only two cycles are performed in field. First cycle shut in pressure gives the estimation of minimum horizontal stress magnitude. Fracture pressure is recorded in second and third cycle.

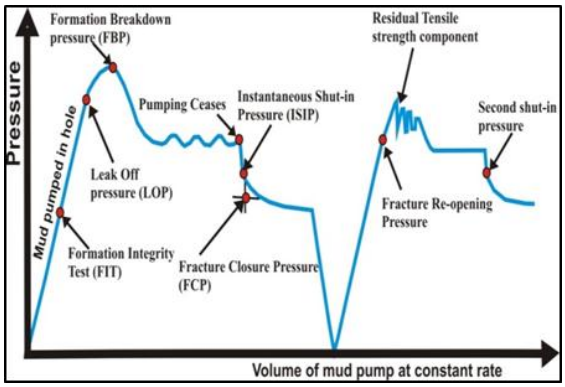

Figure 01 *Idealized extended leak off test (after white et.al. in Year 2001) [8]*

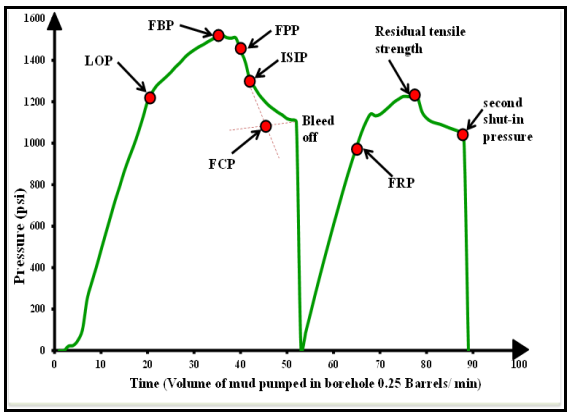

Figure 02 *Actual XLOT carried out in a well drilled by ONGC in 2014 (Source – Well completion report, Western Offshore Basin, ONGC, Mumbai)*

Other than conventional leak-off test nomenclature above, some important points on extended leak-off tests plots are described below:

Leak-Off Pressure (LOP)

This is the pressure where the pressure/time or pressure/volume curve starts to deviate. This can be interpreted as the pressure where fluid starts to flow into the formation. LOP point depends on the type of formation, permeability, and the presence of pre-existing fractures.

Fracture Initiation Pressure (FIP)

This is the point where it is believed that first fracture is formed. This point displays diverse forms such as normal slope change or formation breakdown event. In the breakdown occurrence, pressure falls rapidly which indicate that volume of induced fractures increasing faster than the pumping rate.

Formation Breakdown Pressure (FBP)

Maximum pressure recorded during LOT is indicating formation breakdown pressure.

Instantaneous Shut-In Pressure (ISIP)

The pressure recorded just after pumping of mud stops is instantaneous shut in pressure. This point indicates that formation stresses trying to close the fracture.

Fracture Closure Pressure (FCP)

This is the pressure when fractures are believed to be closed, after pump has stopped. This point is identified in the shut-in or flow-back phase.

Fracture Reopening Pressure (FRP)

In the second phase of test this pressure will yield. It is lower than formation breakdown pressure or fracture initiating pressure in the first cycle.

Theory of Stress Determination by LOT

Calculation of stress around wellbore is done by Kirsch's (1898) equation-[9]

$$\sigma_r = \frac{1}{2}(\sigma_H + \sigma h)\left(1-\frac{a^2}{r^2}\right)+\frac{1}{2}(\sigma_H - \sigma_h)\left(1+\frac{3a^4}{r^4}-\frac{4a^2}{r^2}\right).\cos 2\theta + \frac{a^2}{r^2}\,pm.....(1)$$

$$\sigma_\theta = \frac{1}{2}(\sigma_H + \sigma_h)\left(1+\frac{a^2}{r^2}\right)-\frac{1}{2}(\sigma_H - \sigma_h)\left(1+\frac{3a^4}{r^4}\right).\cos 2\theta - \frac{a^2}{r^2}\,pm.....(2)$$

$$\sigma_{r\theta} = -(\sigma_H - \sigma_h)\left(1-\frac{3a^4}{r^4}+\frac{2a^2}{r^2}\right).\sin 2\theta.....(3)$$

Where, σ_r =Radial Stress, σ_θ =Tangential or Hoop's stress, $\sigma_{r\theta}$ =shear stress, σ_H =Maximum Horizontal stress, σ_h=Minimum horizontal stress, a= Distance from the center of well, r= radius of well, pm=wellbore pressure.

For a passive margin field, or area which is far from the active fault region or for unconsolidated /plastic sediments where low overburden occurs, value of both horizontal stresses can be taken as equal ($\sigma_H = \sigma_h$).So, from the above mentioned Kirsch's equations, the Hoop's stress at the borehole wall (where a=r) can be written as

$$\sigma_\theta = 2\sigma_h - Pm.....(4)$$

So, during leak off test, when pumping of mud starts at borehole wall, fracture opening pressure, Hoop's stress has to be zero.

$$\sigma_{\theta e} = 0$$
$$\sigma_\theta - Pp = 0$$

Where, $\sigma_{\theta e}$ = Effective Hoop's stress, Pp=Pore pressure

Putting the value of Hoop's stress in equation 4, gives

$$Pm = 2\sigma_h - Pp$$

However, once fracture is opened (or preexisting fracture open) mud enters in the fracture, then at that time.

$$Pm = \sigma h.$$

So, during a LOT operation, when mud is pumped and susiquently Pm rises and opening of existing fracture or initiation of a fresh fracture without flow happens at that time, Pm=2σh-Pp. Once the fracture open compressed mud found additional volume, thereby releasing potential energy into kinetic energy and increase in volume creates pressure drop and at this time Pm=σh. So, during LOT pressure slope change occur when the mud enters the fracture and fracture start propagating in the weak zone. So, it can be written as

$$Pm^{LOT} = \sigma h$$
$$\sigma_{he} = Pm^{LOT} - Pp \ldots\ldots\ldots\ldots\ldots(5)$$

Equation 5 gives the value of σh at LOT point.

Leak of pressure gives a good approximation of minimum horizontal stress but this pressure not gives actual reading of σh as mud has certain viscosity losses due to movement of mud in induced/open fracture. In XLOT ISIP (instantons shut in pressure) is good estimate of σ_h as at that time the fluid movement into or out of induced/opened fractures is not there. Although, there are some more pressure readings which are good approximation of σ_{he} like FCP and LOP.

3. Relation between standard LOT and minimum horizontal stress (σh)

Although the standard LOT data are not the best quality measure of σh but in oil and gas industry this test is performed at each casing shoe (before drilling the new borehole section).So it offer a huge data set for any reservoir. During the leak off test as the pumping rate is constant so the pressurization is constant, the factors which can impact the result of LOT is the nature of borehole wall. The nature of borehole wall can be taken as three cases, described in figure 03:

Case1-Borehole is surrounded by an intact impermeable rock.
Case 2-Borehole is surrounded by a rock containing preexisting, long, cracks which is oriented perpendicular to σh and permeable in nature.
Case 3-This is actually an intermediate of above two cases where micro fractures created along the borehole, during drilling the borehole.

In case 1, pressure vs volume plot shows sudden drop which indicate that LOP will be theoretically equal to the breakdown pressure. This pressure is function of both horizontal stresses and tensile strength, as the value of LOP will depend on relative magnitude of these two parameter. LOP of this plot can be significantly higher than the minimum horizontal stress (σh).

In Case 2, as rock containing cracks fluid can enter in the cracks. During pressurization mud enters on the sides of the cracks. In this situation LOP gives approximate value of minimum horizontal stress (σh).

Case 3, its evident the most common slope of LOT. Figure 04 shows LOT plot of the well drilled by ONGC. Above two cases represent the two end member of behavior of fluid but in reality, LOPs probably falls between these two. Although long permeable fractures are possible but intact impermeable rock are rare. It is clear from the plots that the pressure vs volume/time plot shows gradual growth as the pressure increase continuous. After pumps were shut down pressure decline shows gradual path. This can be interpreted in the way that, fluid can penetrate in micro fracture and create fluid pressure on the wall of the cracks. Thus the leak off pressure represents the approximation of σh but more influenced by fluid viscosity, tensile strength or fracture toughness and other near wellbore effects like pressure at the tip of crack, solid content etc.

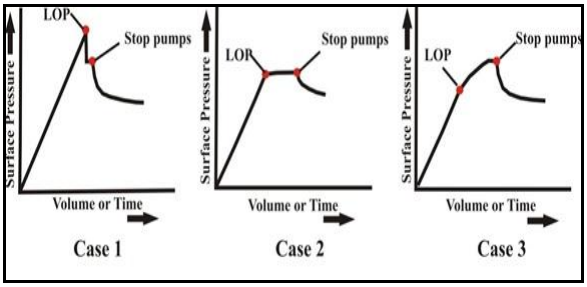

Figure 03 *Different types of LOT, representing different downhole processes (modified after Bernt,S.,2009)[10]*

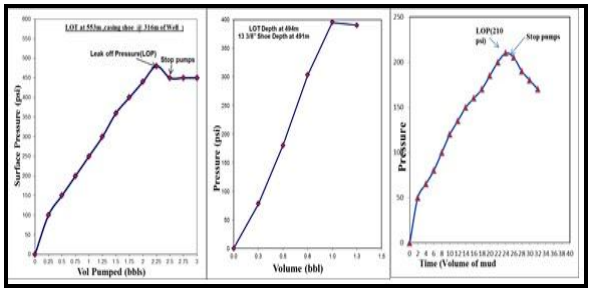

Figure 04 *Actual recorded LOT in different wells drilled by ONGC (Source-Well completion reports of wells)*

4. Conclusion

Determination of near wellbore stresses can be done by many methods which include direct and indirect

methods. LOT is most common method, done in wellsite. The prime objective of LOT is to determine formation fracture strength before drilling next borehole section. Data available from LOT can be used for the determination of minimum horizontal stress, as it provides the good approximation of minimum horizontal stress. Decent calculation of minimum horizontal stress from leak of point is depended on the *insitu* stresses, nature of cracks around wellbore and fluid properties. So, caution should be taken when using LOT data for determination of minimum horizontal stress.

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