PaperID **AU472**
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Mitigation of risk and uncertainty in oil and gas Exploration wells using Geoscience approach for Extended Leak off Tests (XLOT) & its Interpretation

1. Abstract

Many challenges lie today in the oil and gas Industry for the correct execution and interpretation of Pressure Integrity Tests (PIT), which are conducted during drilling of oil and gas wells to ensure integrity of casing, cement and rathole below the shoe. There are various pressure tests like Jug test, Formation-Integrity Test, Hermitical Test, Casing-Integrity Test, Shoe-Integrity Test, but the Leak Off Test (LOT) and Extended Leak off Test (XLOT) are the most prerequisite tests. Among the two, XLOT offers more accuracy since it takes account of geomechanics of far-field stresses. However, despite correct execution, if Geomechanical data (Overburden Pressure, Effective-stress etc.), Geological data (lithology, stratigraphy etc.), Geophysical data (like fault) and simple procedural data (pump-rate) aren't combined together to interpret XLOT, then misinterpretation of test result is possible, which could lead to (1) inaccurate estimation of fracture pressure, which in turn might lead to Lost Circulation, (2) unnecessary squeeze jobs, (3) premature setting of casing and consequently (4) sabotaging the progress of well, resulting in huge Non-Productive Time (NPT). This paper analyzes XLOTs that were due to absence of a symbiotic/geosciences approach and emphasizes the lessons learned which will serve as a guideline for correct execution-Interpretation of future XLOTs.

2. Introduction

During drilling of an oil and gas well, especially as an exploration well, accurate measurement of the pressure integrity of the casing and formation is extremely important. These measurements would indicate the maximum limit of Mud Weight to be used while drilling subsequent formations [Addis et al, 1998] and also serves as a guideline for drilling future developmental wells. As per the Government regulations, it is also mandatory to perform minimum number of pressure integrity tests at different depths in the well during drilling. If the measured results of pressure integrity tests are found good, only then further drilling for the higher depths will be permitted. Compared to Leak Off Test (LOT), Extended Leak Off Test (XLOT) would be most reliable, because it takes (i) casing and cement sheath expansion, (ii) anisotropic lithology, (iii) wellbore ballooning, (iv) formation compressibility, (v) formation tortuosity, (vi) mud properties into account [Zoback et al, 2003]. Thus, XLOT gives true information of downhole fracture events. XLOT data is versatile as well, as the information it provides can help determine and calibrate (i) direct measurement of minimum in-situ compressive stress or strength of formation(S_3), (ii) correct mud weight during drilling (helps to prevent Lost Circulation (LC), (iii)maximum strength of the casing shoe and cement acting against it, (iv) In-situ stress S_3 profile (if multiple XLOTs are taken) and (v) Setting depth of the Casing shoe [Okland et al, 2002]).

To carry out LOT or XLOT, after setting casing and cementing, a short length (several meters) of extra open hole (2-5m) is drilled below the casing shoe **(**Fig 1a). The casing shoe along with the rathole are then pressurized by drilling fluid delivered through drill pipe from a cementing pump set on the rig floor of the drilling vessel. XLOT requires mud, fluid tank, cement pump *(because of its ability to produce low flow rates)*, shut in valve, accurate pressure gauge, flow meter, blowout preventer (specifically pipe ram, closed throughout the test) or a packer, and a conduit such as a riser or a drill pipe (*or drill rod)* to convey mud (Fig. 1a). The pressure data is noted w.r.t time and can be simply plotted on Excel as Scatter plot (Fig. 1b.)

3 Extended Leak Off Test (XLOT)

3.1 Textbook Field example of XLOT

If XLOT is conducted taking standard (geology, geomechanics etc.) and procedural data (especially pump rate) then an XLOT would look like Fig. 2 which in turn is very reminiscent of Fib 1.b. Analysis of Fig. 2 done below:

Zero to LOP: Pressure built linearly and continuously straight. This indicates that the rathole is being properly pressurized and that fluid is exerting pressure uniformly to the rathole. Following which, a small but distinct departure to the right can be observed which is indicative of fracture-initiation [Postler, 1997].
LOP to FBP: Following fracture-initiation, pressure seems to build towards FBP also in linear and continuous manner. This indicates that the rate of injection is faster than the rate of fluid flow through fractures.
FBP to FPP: Following formation-breakdown, pressure abruptly but briefly falls for a minute. This indicates that the rate of pumping is slower than the rate of fluid flow through fractures [Zoback, 2003]. After the abrupt but brief fall, pressure build in linear and continuous manner, this is the fracture propagation pressure where the rate of pumping is equal to rate of mud flowing through the fractures.
Generally FPP is characterized by the 'Saw-tooth' shape which occurs primarily because of: (i) the pressure inside the fracture is still above minimum horizontal stress, therefore, propagation would occur in a mini-breakdown fashion, causing the fracture to grow in steps, (ii) due to formation tortuosity, (iii) fluid expansion and (iv) fast pressure diffusion [Jihoon, 2015] as shown in Fig. 1b. In Fig. 2's case, it cannot be seen due to low resolution of gauge (1 pressure point per minute).
FPP to ISIP: Following fracture-propagation, pumping was stopped (see secondary y- axis of Fig.2) which results in pressure to abruptly fall in one instant, this is Initial Shut-in pressure (ISIP). This clearly indicates that shut-in has taken place where pump has been shut-off (stopped, shut-in valve) [Postler, 1997].

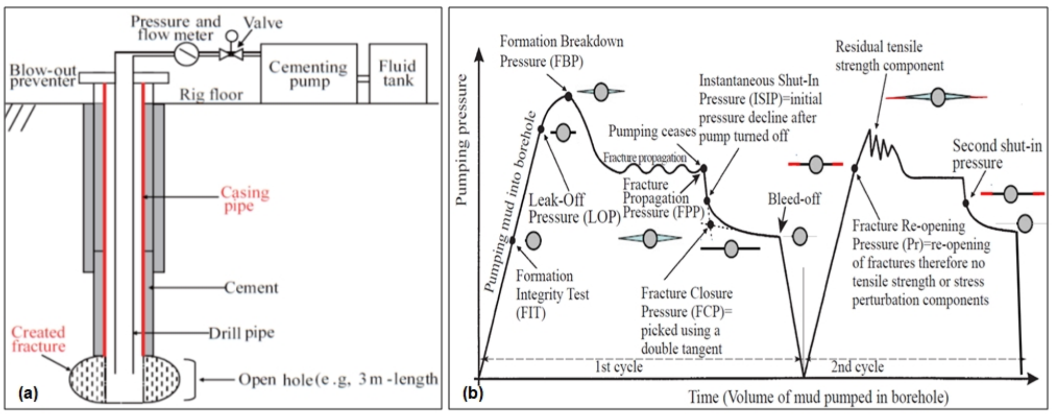
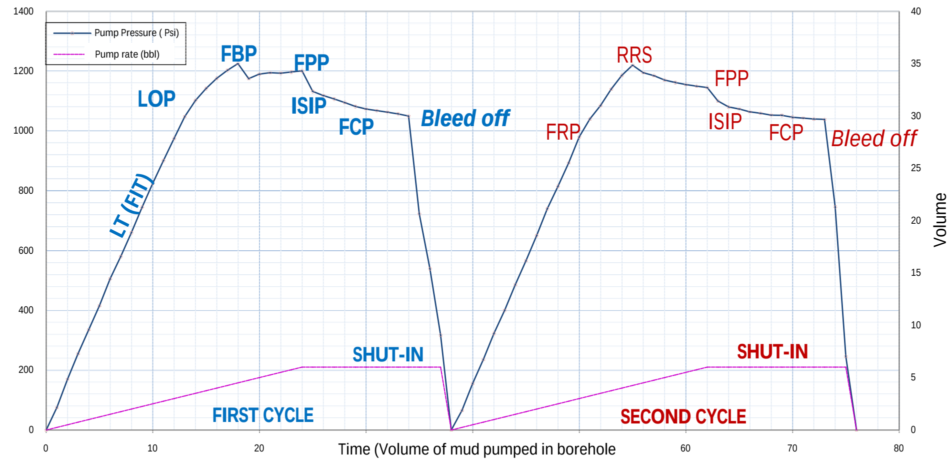


Fig 1: (**a**) Borehole Configuration during XLOT [Lin et al, 2008]and (**b**) Idealized relationship between pumping pressure and time or volume of injected fluid during an XLOT [modified after White et al, 2002].

ISIP to Bleed-off: Following ISIP (pumping stopped), and with the annulus sealed throughout the test, this phase is the most important phase as this is when **true** fracture closure pressure (which is the minimum compressive stress S_3) is seen in action, closing the fractures from the recent-most initiated tip. FCP can be obtained by i) simply plotting data as received during the test and by ii) plotting $\mathrm{S_h utinTime}$ vs Pressure from both cycles, later using double-tangent method picking FCP. XLOT is commonly recognized as the best estimation of far-field minimum stress compared to ISIP or FPP [Zoback, 2007].
Second Cycle: The second cycle is conducted to validate the fracture events observed in first cycle since the mechanical design of the well, equipment and other factors etc. are a concern, especially offshore. In Fig. 2, the shape of second cycle very much mirrors the first cycle, almost, as if a mirror is placed after first cycle.
RRS: The maximum pressure obtained in the extended cycle is called as Residual Rock Strength (RRS). Its significance lies in indicating the compressibility of the formation and the in-situ stresses acting.
This test was executed taking every factor with standard recommended procedure into account, and this resulted in a field example of a perfect textbook looking XLOT.



LT = Limit Test, LOP = Leak off Point, FBP = Formation Breakdown Pressure, FPP = Fracture Propagation Pressure, ISIP = Initia l Shut in Pressure, FCP = Fracture Closure Pressure, RRS = Residual Rock Strength, FRP = Fracture reopening pressure

Fig 2: Extended Leak off Test carried out at 1942m depth for Well KS-2 located in Kutch-Saurashtra Basin.

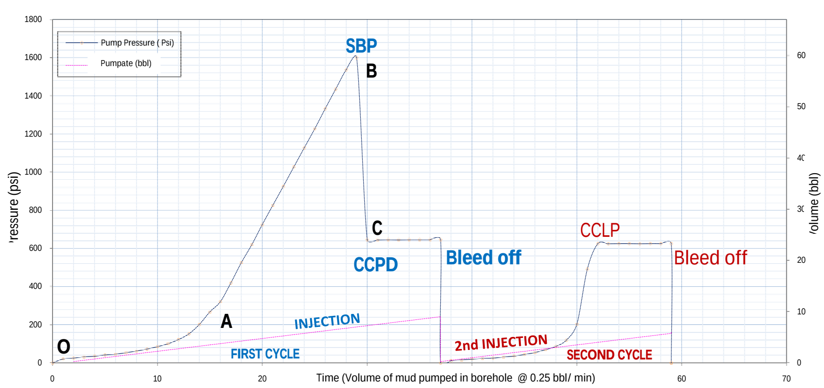
3.2 Importance XLOT in Geomechanics: Huge Pressure Drop Plots - A Field Example

During XLOT, after pressurizing to a certain time, depending upon formation's resistance to fracture & in-situ stresses acting over it, a distinct change in slope must be observed (as was demonstrated in Fig 1b & Fig. 2). The change in slope essentially represents the initiation/propagation of a fracture beyond wellbore. Graphically, these types of plots represent a brittle behavior – A Steep buildup *(from A-B)* in beginning (with a constant slope from 15 till 29 minute) but once brittleness ends, a huge pressure drop is observed, second pressure cycle doesn't increase beyond the drop. Possibilities along with best fit situations along with its remedies are discussed below.

Symptoms for Sudden Pressure Drop (Huge)

(i) Sudden & Huge drop in pressure without distinct LOP (1600 psi to 646 psi in a minute)
(ii) Repeat test shows no rise of pressure beyond 630 psi and pressure remains constant throughout the test, regardless the number of cycles.

Well and Lithology data		Test data		Surface Pressure			
				1st Cycle		2nd Cycle	
Well	MOB-3	**Mud System**	KCL-PHPA	**SBP** (psi)	1600	**Highest pressure** (psi)	625
Area	Mumbai High	**Mud Weight** (ppg)	13	**CCPD** (psi)	646	**CCLP** (psi)	625
Drilled Depth (m)	1606	**Hydrostatic EMW** (ppg) &	18.85	**Time taken** (min)	37	**Time taken** (min)	23
Shoe Depth (m)	1602	**Equivalent Gradient** (psi/ft)	0.98	**ISIP** (psi) & **FCP** (psi)	No shut in	**ISIP** (psi) & **Avg. Shut in time** (min)	No shut in
Casing size (")	13.375						
Rathole (m)	4	**Total Vol. pumped** (bbl)	14.75	**Vol. pumped** (bbl)	8.75	**Vol. pumped** (bbl)	6
Lithology	Claystone	**T. Vol. flowed back** (bbl)	4	**Flowback** (bbl)	3.5	**Flowback** (bbl)	0.5



SBP = Shoe Breakdown Pressure, CCPD = Cement Channel Pressure Drop, CCLP = Confirmed Cement Leaking pressure, ABC = Anomaly feature

Fig. 3: Extended Leak off Test (XLOT) carried out 1602m depth for Well MOB-3 located in Mumbai Offshore Basin.

Analysis

O to A*:* Before interpreting this anomaly notice the slow buildup till 15 minutes which is unusual and repeats in second cycle as well. This 'slow buildup' or 'delayed buildup' which is independent of 'continuous' build up later

(A to B), due to tensile fractures in wellbore vicinity.
***A to B**:* From the plot, taking equivalent mud weight at point B, the operating gradient was 0.98 psi/ft, which is very high. Generally, Overburden Gradient averages around 1 psi/ft, approaching or pressurizing very near that value is risky and unnecessary because the objective of XLOT is to estimate minimum compressive stress not vertical stress (the pressure of all the beds above).
B to C: A huge pressure drop has taken place, probably representing creation of huge volume / void where the flow rate of mud through the void is much faster than the rate at which mud is being pumped at surface.
C to bleed off: After the Huge drop, comes another characteristic, the 'linear Pressure' slope, it might represent a conduit or a voidage (with constant permeability) which is already pre-existing**.** Conduit theory is more plausible since Cement shrinks to attain a good bond, thus leaving a conduit [Kundan et al, 2017]
From 2nd cycle: It can be observed that i) pressure is at same level as that of first cycle (*C to bleed off)* and ii) no build up beyond 650 psi.
Therefore, after taking first cycle's 'huge pressure drop', 'linear breakdown pressure' *(overall, a pressure spike of first cycle)* and second cycle's 'linear pressure with no build' observations, into account, as well as 0.98 psi/ft as an operating gradient, the Entity (shoe) wasn't *(fully)* cemented & that the test was run when cement shrinked. Thus, indicating a fragile (like Glass or Ceramic) and brittle characteristic of an entity (shoe) that was pressurized. Dry cement can produce this result [Paulo, 2014]. This 'Spike' cannot be seen again, since cement is not self-closing unlike rock grains. Fig 4 is a possible scene reconstruction made from Fig. 3 & Fig. 3's analysis from Geoscience approach.
Role of Geomechanics: As a rule of thumb, every integrity test or Injection pressure for every Water or Tertiary flood must be around 0.75 psi/ft since one must stay under the limits of Overburden Pressure to avoid loss of fluid. Another peculiar characteristic of this result is that, before even attaining such a high gradient, the lithology appears to have been very tolerant (since there's no indication of FIP, FBP, FPP etc); this could be an attribute of High Pore Pressure resulting in an abnormally high fracture pressure. Rest assured, this behavior was not exhibited by the formation, since second cycle would've ascertained distinct rock fracture events and the plot also suggests that the test was conducted in either a Strike Slip fault or a Reverse Fault environment since Vertical (Overburden) stress is near Minimum compressive stress. Thus, it is conclusive to say that, the entity (shoe) has indeed been damaged. Consequently, it is more appropriate to term point B as Shoe Breakdown Pressure (SBP), point C as Cement Channel pressure drop (CCPD) and Second cycle constant pressure as Confirmed Cement Leak Pressure (CCLP).

Consequences of Cement shoe rupture: The importance of maintaining a good cement job extends for Gas Reserve estimation and Water coning as well. If there is gas leakage to another zone due to bad cement jobs *(like this one)*, the computed value of Initial Gas In place would decrease with time. [Tarek, 2001], and many water production problems attributed to coning are due to faulty cement jobs or casing leaks [Gatlin, 1989].

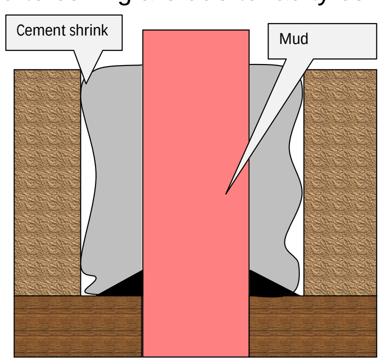


Fig. 4: Scene reconstruction from an extended leak off test plot (Red denotes Mud and Grey denotes Cement above shoe which has shrinked to bond to casing)

3.3 Importance of Constant Pump Rate in Geomechanics: 2 Stage slope– A Field Example

In this anomaly (Fig. 5) during build-up section, compared to ideal XLOT curve, there are two build up's. For the first one, it is observed that there is a departure of curve quite early (even if LOT was predicted or lower than other values near that vicinity) and after 7 minutes, there is again a departure to the right.

Symptom for 2 Stage Slope curve - 2 apparent Leak offs

Interpretation (observations and reasoning)

Trapped Pressure - A to B & G to H: One of the most frustrating/confusing feature of this plot is from A to B or G to H. Graphically, it means just by injection of 0.25 bbl/min, pressure suddenly built to ~500 psi in a minute. Operational data is misleading in this case. It is hypothesized that trapped pressure (result of improper circulation before test) is contributing to this rapid built, but contrary to above sentence, it shouldn't have repeated in second cycle. It is more believable that the gauge was not properly zeroed, if so, it shouldn't have repeated in second cycle.

Importance of constant pump-rate, B to C & C to D: From B to C, there is a steady built but after crossing C, slope changes and then builds-up again till D. So far, slope has changed twice, as in, two leak-offs. Postler, [1997] has explained that this is due to the drilling process, which can create a lower strength plastic zone near the wellbore (responsible for initial leak off), and the formation retains its strength away from the wellbore (responsible for final leak off – True Leak off).Anisotropic lithology (formation heterogeneity might exist in the form of presence of shale streaks through limestone, observe the cuttings data from the test result (table above graph. Because of altered permeability and mechanical strength, two leaks off are possible in this scenario or due to unconsolidated lithology, where insufficient compressive stresses might give rise to two buildups or could give 3 buildups, but since unconsolidated lithology's are dependent upon depth (this depth is 1942m) so this reason can be ruled out. Heterogeneity may or may not be true in this case as the data has been compromised due to a change in pump-rate (i.e. increasing pump-rate from 0.25 bbl/min to 0.5 bbl/min results in increased turbulence which results in increased circulating pressure) which is also sufficient to give another pressure build.

Well and Lithology data		Test data		Surface Pressure: 1st Cycle		Surface Pressure: 2nd Cycle	
Well	MOB-6	Mud System	KCL-PHPA	LOP (psi/ppg)	1610 / 14.26	FRP (psi/ppg)	1060 / 12.6
Area	Mumbai High	Mud Weight (ppg)	9.4	FBP (psi/ppg)	1632 / 14.32	RRS (psi/ppg)	1485 / 13.88
Drilled Depth (m)	1960	Mud Hydrostatic LOP (psi)	1610	FPP (psi/ppg)	1530 / 14.01	FPP (psi/ppg)	1480 / 13.86
Shoe Depth (m)	1942	LOP EMW (ppg)	14.26	ISIP (psi/ppg)	1284 / 13.27	ISIP (psi/ppg)	1358 / 13.5
Casing size (")	13.375	LOP Eq. Grad (psi/ft)	0.75	FCP|S_3* (psi/mPa/ppg)	960/6.62/12.3	Avg. Shut in time (min)	20
Rathole (m)	18	Total Vol. pumped (bbl)	28	Vol. pumped (bbl)	15.5	Vol. pumped (bbl)	12.5
Lithology	Limestone 55% / Shale 45%	T. Vol. flowed back (bbl)	1.75*	Flowback (bbl)	1*	Flowback (bbl)	0.75

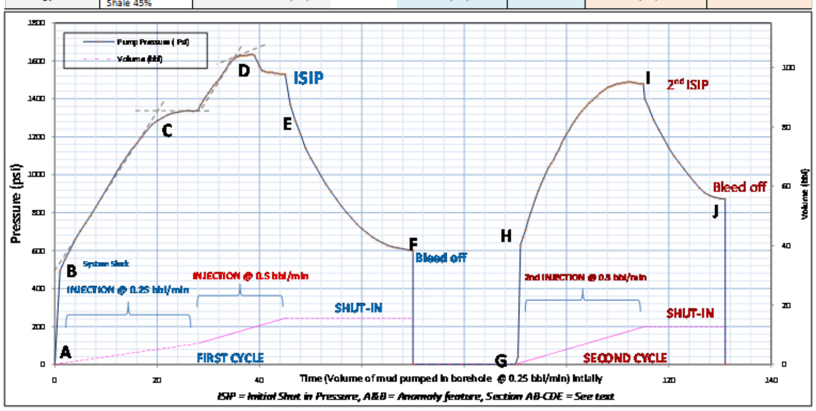


Fig 5: Extended Leak off Test carried out at 1942m depth for Well MOB-6 located in Mumbai Offshore Basin.

Beyond Wellbore region? D to ISIP: Formation Breakdown pressure is visible and has been propagated for a good few minutes. Therefore, it **appears** fractures have extended beyond wellbore region, but analysis of subsequent features of this figure will prove otherwise.

ISIP to E*:* A clear pressure drop can be observed which can be termed as ISIP. This feature is again cross-referenced with operational data i.e. pump-rate. Therefore, it is recommended that all Pressure Integrity Tests be conducted at same Flowrate from start to finish.

Wellbore breathing or Formation kicking, E to F & H to I: Another key feature of this test result can also be drawn from the superimposed image of Fig. 5 i.e Fig. 6a. Observing 1st cycle's shut in behavior and 2nd cycle's non-linear buildup, one can assume that the area upon which pressure is being exerted is dynamic in nature unlike other formation. This can be indication of formation with small cracks or with permeability where drilling fluid is stored during pressurization [Fig. 6b] as a result it gives curved build up when pumping. When pumps are shut off, the formation returns mud like a balloon [Zoback, 2007]. Thus this is a Ballooning event, as Ballooning causes delayed stabilization and exponential drop off when pumps are shut off [Yuan et al, 2016]. This causes many at site to confuse ballooning event with a kick as both return mud to surface when circulation is stopped. Consequently, one should not pick Fracture Closure Pressure (FCP) using double tangent method during 'shut in', as 'shut in' behavior may have been compromised due to ballooning (see Fig. 6a as well as Fig. 6b). Cause of ballooning is due to 1) Equivalent circulating density is more than Equivalent static density 2) Tensile fractures. Another possibility for the shut-in behavior may have to do with the integrity of shut-in valve.

Importance of drilled depth vs. Casing depth (rathole): An 18m (1960m minus 1942m) rathole could be one of the reason why multiple anomalous events are observed in this XLOT (Fig. 6a). The casing couldn't reach near drilled depth due to excessive friction being generated by possible cave-ins. Therefore, after analyzing each part of this test, it is conclusive to say that fracture **has not** gone beyond wellbore region. Therefore, any stress estimation will be wrong.

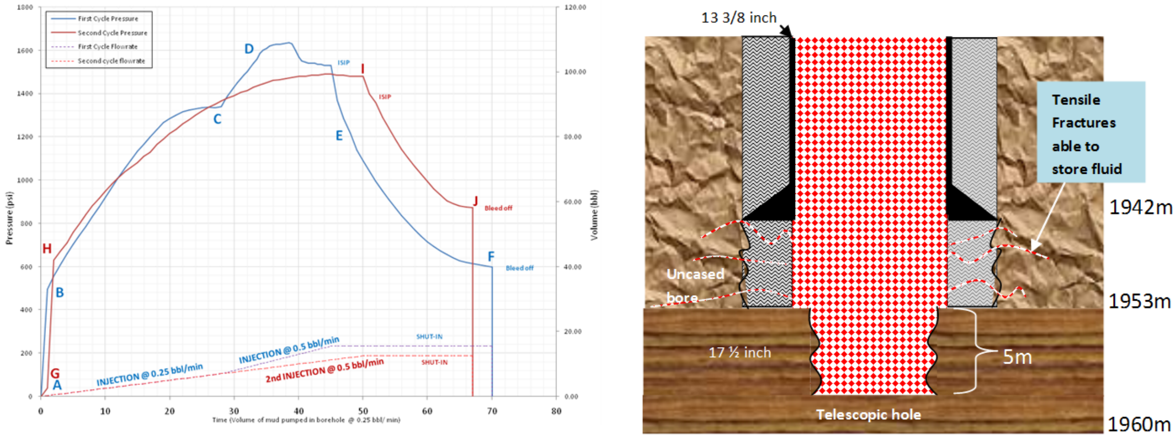


Fig. 6 (a) Super imposed Graph of XLOT carried out at well MOB-6 at 1942m. Note the impact of Ballooning; it causes slow decay during Shut-in period of first cycle and non linear build up during second **(b)**. Possible depiction of a ballooning event showing tensile fractures (which are able to store drilling fluids during XLOT i.e. during pressurization)

4. Conclusions

1. Pressurizing near 1 psi/ft (0.98 psi/ft) will probably damage casing shoe, and hence must never be reached regardless even if test zone, still shows elastic behavior. Once exceeding 0.8 psi/ft operating gradient, the test must be stopped, and an FIT value should be reported. If damaged, Shoe strengthening procedures can be run (cement squeeze/sand plug/mica plug etc.) which would cause a lot of NPT.All of it would've been avoided, if only geomechanics was considered by the operator.
2. One can ponder upon the fact that despite pressurizing beyond 0.8 psi/ft, casing-shoe was damaged, but lithology didn't. It's because a) the operator didn't consider fault stress regime before executing the test and b) Lithology had higher formation pressure. Thus, Caution must be exercised while executing Pressure Integrity Test in Strike slip and Reverse fault environment.
3. Two Stage slope curves have many reasons to exist- but predominantly because of lower stress field (resulting in permeable streaks of another lithology). Other reasons are unconsolidated lithology, Change in Pump rate etc. The one explained in this paper had 2 stage slope due to dynamic pump-rate.
4. Shut in data will always be compromised if XLOT is conducted in a ballooning wellbore
5. XLOT can also provide an idea of the stress regime of the area which will be useful for Hydraulic fracturing of Reservoir rocks.
6. A symbiotic/geosciences approach is a must to execute and interpret an XLOT by combining elementary data from Geology, Geophysics, Geomechanics and cross verifying these with operational data (pump rate, first gauge reading, proper flushing etc). Doing so will not only help in identifying a good test / bad test (GTBT) but also to extrapolate further information from XLOT related to Geosciences (i.e. Maximum Horizontal Stress, Wellbore stability analysis etc.). Thus, this paper's approach towards XLOT's execution & its interpretation in Oil and Gas exploration wells will/should mitigate any risk and uncertainty for drilling subsequent depths and serve as a guideline for future XLOT.

5. Acknowledgement

The authors are very grateful to Oil and Natural Gas Corporation (ONGC), Human Resource for providing the infrastructure and data. Also, further gratitude is expressed to Mr. Agniwesh Kumar, Mr. Vikas Gupta, Mr. Shiv Singh and Mr. Sanjoy Chanda.

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