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SOFTWARE FOR INTERPRETATION OF NON-LINEAR LEAK OFF TEST

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Abstract— To effectively manage the reservoir and its containing fluid, the fracture pressure must be determined. The two methods of determining fracture pressures are indirect method (involving correlations) and direct method which is the leak-off test. The interpretation of leak-off test is based on the linear behaviour of pump pressure at a given pump volume. There are situations caused by leak where the leak-off test (LOT) does not follow this behaviour, hence, a different method is required to analyse the non-linear leak-off test. The method employed in this research was based on the combination of fluid compressibility and material balance to formulate functions for fluid compressibility, casing expansion, well bore expansion and leak. The test result was able to predict the non-linear behaviour of LOT to at least 99% correct.

Index Terms— Casing expansion and leak, Fluid compressibility, Fracture pressure, Leak off Test, Linear and Non-Linear Behaviour, Pump Pressure and Volume.

1 INTRODUCTION

There have been cases of loss of well control which in some cases resulted in severe casualties in oil fields around the world; this has brought to fore the need for increased emphasis on the safe delivery of wells [3], [7].

It is an established fact that pore pressure and fracture pressure (the maximum wellbore pressure at the point of formation rupture) increase with increase in well depth; according to Altun *et al.*, [2] the drilling mud weight is increased to maintain the overbalance and prevent possible drilling flow of fluid from the wellbore into the formation. The mud weight (wellbore pressure) required to balance the pore pressure is increased until it approaches the fracture pressure.

Direct and indirect methods of determining formation fracture pressure have been employed [9]. It is common practice to use geologic and geophysical data together with empirical correlations such as Hubbert and Willis [5] equation, Matthew and Kelly [8] correlation, etc. to predict pore pressure and facture pressure in the indirect method.

The direct method employ actual measurement of the pressure required to fracture the formation and the pressure required to propagate the resulting fracture. The leakoff test (LOT) is a direct method which uses drilling mud to pressurize the well until formation fracture is initiated. It is a pumping pressure test carried out immediately below newly set casing in a borehole. A well is normally subjected to formation integrity test which seeks to determine the maximum stress the formation would be subjected to by the pumping mud without losing its integrity; while the casing-shoe integrity test determines the maximum stress the formation can withstand from the casing-shoe without it breaking down.

Exposed formation will rupture and accept drilling mud from the wellbore when subjected to the maximum wellbore pressure that the formation can withstand without losing integrity. Loss circulation is the consequence of fractured formation. Ajienka *et al.*, [1] remarked that, the accurate knowledge of fracture pressure is very essential for well drilling operations, well stimulation and injection operations in secondary recovery.

The leakoff test provides the basic information on fracture pressure and hence on the strength of the rock, but its interpretation is not always easy, particularly in formations that give nonlinear relationship between the pumped volume of fluid and the observed pressure. According to Altun *et al*, [2] The nonlinear behaviour of the leakoff test is occasioned by factors such as gas in the system, borehole failure, and/or leakage of drilling fluid into the cemented casing/borehole annulus.

This study seeks to address the issue of interpretation of nonlinear behaviour of leakoff test with a mathematical model coupled with reasonable assumptions.

2 MATHEMATICAL MODEL

2.1 Development of Mathematical Model

There are situation where LOT is difficult to interpret because of nonlinear behaviour. Such situations are caused mainly by leak which mask the straight line behaviour of the pump pressure and pump volumes. Figure 2.1 showed the behaviour of the normal and nonlinear LOT.

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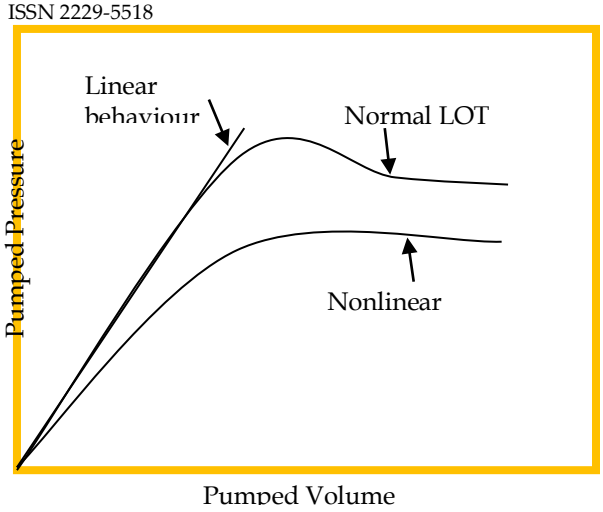

Fig. 2.1: Linear and Nonlinear behaviour of LOT

The mathematical model to analyse nonlinear LOT was based on the compressibility equation and the material balance equation. The compressibility equation was developed for three systems which include compression of the drilling fluid, expansion of casing string and fluid leakage. If the compressibility equations are integrated to volume, then the material balance is given by the following equation

$$\begin{pmatrix}\text{Volume}\\ \text{Pumped}\end{pmatrix} = \begin{pmatrix}\text{Volume}\\ \text{to Mud}\end{pmatrix} + \begin{pmatrix}\text{Volume}\\ \text{to Casing}\end{pmatrix} + \begin{pmatrix}\text{Volume}\\ \text{to Leaks}\end{pmatrix} \quad 2.1$$

The typical assumptions for the application of the model are: isotropic formation, compressible and isothermal fluid.

2.1.1 Volume contribution to drilling fluid compression

The pressure change was derived from pumping drilling fluid into the well at a steady rate this result in compression of well fluid. Fluid compressibility is given by

$$c_f = -\frac{1}{V_o}\left(\frac{\mathrm{d}V}{\mathrm{d}p}\right) \quad 2.2$$

Assuming is the borehole was totally closed ensuring that during the LOT the pressure boundary is essentially rigid and fixed; using Taylor series approximation of the exponential function i.e.

$$c\,p = \frac{V}{V_o} - \left(\frac{V}{V_o}\right)^2 + \left(\frac{V}{V_o}\right)^3 - \left(\frac{V}{V_o}\right)^4 + \cdots \quad 2.3$$

Assuming the volume pumped is far less than the initial volume in the wellbore, the powers higher than 1 are neglected, hence the approximate solution is given by

$$V = V_o c\,p \quad 2.4$$

2.1.2 Volume contribution to casing expansion

Consider the different principal stresses: radial stress, σ_r, tangential or hoop stress, σ_θ, and vertical or longitudinal stress, σ_z acting on the casing string. The combined effects of these stresses will cause strain and therefore result in volume change.

Assuming that there is no strain in the vertical direction and so there is only plain stress. The change in the vertical stress is then derived from the Hook's law which relates the principal stress and strain using linear elasticity concept. Thus, the equation predicting change in vertical stress with plain strain is given by

$$\sigma_z = v\left(\Delta\sigma_r + \Delta\sigma_\theta\right) \quad 2.5$$

where v is the Poisson ratio. The strain caused by the change of the inside pressure is given from Hook's law as

$$\varepsilon_\theta == \frac{1}{E}\left(\Delta\sigma_\theta - \Delta\sigma_z\right) \quad 2.6$$

Having found the vertical stress, Jaeger and Cook [6] expressed the radial and tangential stresses as with the sign convention that compression and contraction are positive while tension and elongation are negative.

The radial and tangential stresses vary with radial location in the casing wall. The radial and tangential stresses on the inner-casing wall can be computed from Equation 2.9 and 2.10 by replacing the inner wall radius by any radius *r*. Hence casing expansion volume is estimated using the following equation appropriately derived

$$V_c = 2\pi\, h_c\, R_i^{\,2}\, \frac{p}{E}\left[\frac{R_i^{\,2} + R_o^{\,2}}{R_i^{\,2} - R_o^{\,2}}\left(1 - v^2\right) + \left(v - v^2\right)\right] \quad 2.7$$

This equation expressed the casing expansion volume as a function of pump pressure. The volume required to compress the drilling fluid created by attributed to casing expansion is given as

$$V = V_c c\,p \quad 2.8$$

That is, the wellbore volume in Equation is replaced with casing expansion volume to obtain Equation 2.8.

2.1.3 Contribution to leak

In general, the leak volume is directly related to the pressure drop at any time of pumping. That is

$$V_L = D\,t\,\Delta p \quad 2.9$$

$$D = 8.7\times 10^9\,\frac{W^2 A}{\mu L} \quad 2.10$$

D *and* t are variously defined [4]

We assumed that the LOT allows only volume pumping to cause fluid compression and leak, so that the pumped volume following other combination becomes

$$V = V_o c\,p + D\,p\,\frac{V}{q} \quad 2.11$$

The exact solution can be gotten by using Equation 2.4 for the first term in Equation 2.11 to have

$$V = \frac{V_o\left(e^{c\,p} - 1\right)}{1 - \frac{D}{q}\,p} \quad 2.12$$

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2.1.4 Contribution to wellbore expansion

Owing to occasional but rare cases of wellbore expansion due to loading, we assumed that the well is closed but the boundary is not constant. In reality, the wellbore expands due to loading from the original volume, V_o, with increased pumping time to a new volume $V_o + V_w$. The term V_w is the volume increment of the wellbore due to expansion caused by pumping pressure. The strain relationship is given from Young's Modulus expression as

$$\mathrm{d}p = E\mathrm{d}\varepsilon \quad \text{or} \quad \int_0^p \mathrm{d}p = E\int_{r_o}^{r_o+\Delta r} \mathrm{d}\varepsilon \qquad 2.13$$

But $\mathrm{d}\varepsilon = \frac{\mathrm{d}r}{r}$ such that solving for the wellbore expansion with pump pressure gives volume increment due to expansion can be expressed by

$$V_w = \pi h_w r_o^2 \left(e^{2p/E} - 1\right) \qquad 2.14$$

The approximate solution for the expansion of the wellbore can be obtained using the first power approximation of the Taylor's series expansion of the exponential function to have

$$V_w = 2\pi h r_o^2 \left[\frac{p}{E} + \left(\frac{p}{E}\right)^2\right] \qquad 2.15$$

Finally, the volume required to compress the volume created by the borehole expansion is given by

$$V = V_w c\, p \qquad 2.16$$

2.1.5 Overall volume contribution in LOT

The overall volume contribution in LOT equivalent to the pumped volume is the summation of all the sub-volumes contributed by fluid compression, casing expansion, leak and wellbore expansion. That is, if the wellbore radius is equal to the outer radius of the casing string then

$$V = V_o c\, p + 2\pi h R_i^2 \frac{p}{E}\left[\frac{R_i^2 + R_o^2}{R_i^2 - R_o^2}\left(1 - v^2\right) + \left(v - v^2\right)\right] + \frac{V_o c\, p}{1 - \frac{D}{q}p} \qquad 2.17$$

$$+ \pi h R_o^2 \left(e^{2p/E} - 1\right)$$

3 STUDY AREA AND DATA COLLECTION

3.1 Description of the study area

The Niger Delta region is located in south-south Nigeria. The region is an oil rich region which separates the Bight of Benin and Bight of Biafra basin.

3.2 Data collection

LOT data from three different wells from three different fields in the Niger Delta were used to verify the LOT model proposed by the study.

4 APPLICATION

The basic input data for the LOT analysis that was used to develop the software are presented in Table 4.1 below.

Table 4.1: Basic Input Data for LOT Analysis

Basic Input Data for LOT			
	Well 1	Well 2	Well 3
Wellbore Volume [bbl]	666	632	371
Mud Compressibility [/psi]	2.27E-06	2.78E-06	2.89E-06
Casing Length [ft]	8773	1765	1029
Casing Outer Diameter [ft]	9 5/8	20	20
Well Length [ft]	8782	1780	1044
Formation Young Modulus [psi]	1.24E+06	8.51E+05	6.40E+05
Pump rate [bpm]	0.25	0.25	0.25

The basic data present are not enough to model LOT. So, reasonable assumptions and approximations were made when certain input data are not known. The assumed or read inputs are given in Table 4.2

Table 4.2: Data Assumed or Read

Data Assumed or Read	
Casing Young's Modulus [psi]	3.00E+07
Casing Poisson's ratio [-]	3
Mud Viscosity [cP]	30

The pressure against volume recorded during the LOT indicated that the tests were characterized by nonlinear behaviour as shown in Figure 4.1. Thus, this type of behaviour cannot be analysed by the conventional method which employs linear regression to match up to fracture gradient.

Fig. 4.1: LOT indicating Nonlinear Behaviour

One startling about the behaviour of the nonlinear LOT test is that unlike linear function that is monotonically continuous up till formation fracture, the function exhibit turning at which point the formation fractures. Thus, there will not be the need

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to run the LOT to formation fracture pressure.

3.1 Simulation results analysis

The straight-line analysis of LOT implied that the pressure-volume relationship obtained during the test is a reflection of the total well compressibility. The total well compressibility is therefore the sum of drilling fluid compressibility, casing expansion and wellbore expansion. In the case where there is leak, the fourth contributor to the total compressibility of shows up causing nonlinear behaviour.

The three wells were selected for study because there is significant leak to cause the nonlinear behaviour shown in Figure 4.1. The per cent contribution of the four factors contribution to total compressibility is shown in Figure 4.2. As it expect, the major contributor to the total compressibility is the fluid compression, followed by leak. Casing expansion is negligible and the expansion due to the wellbore is relatively small. This contributory behaviour is seen in wells 2 & 3 (see Figure 4.3 & 4.4), but the casing contribution is not totally masked in well 2 & 3 as in well 1.

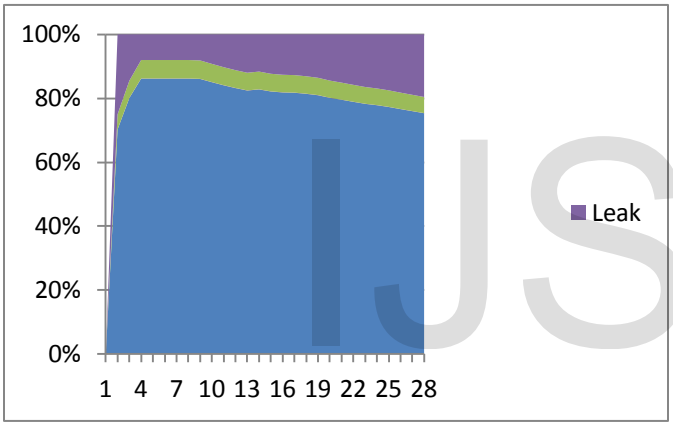

Fig. 4.2: Contributors to the Total Compressibility for Well 1

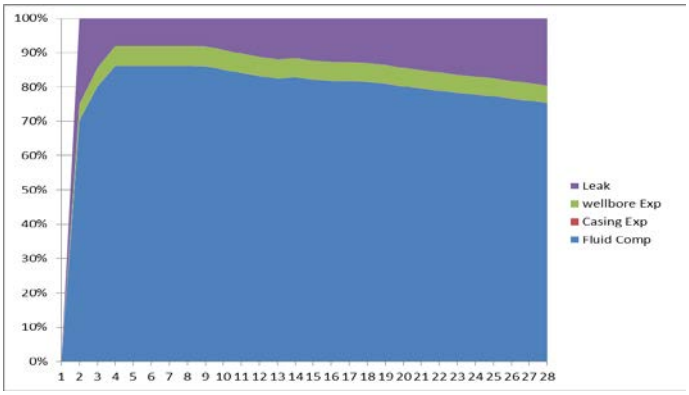

Fig. 4.3: Contributors to the Total Compressibility for Well 2

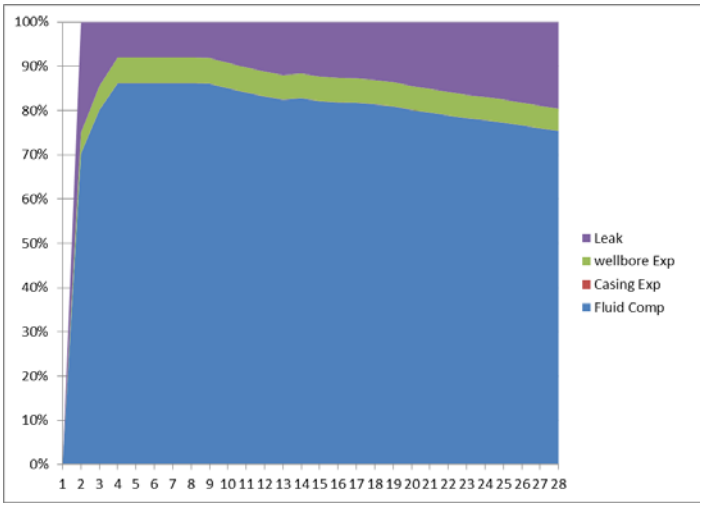

Fig. 4.4: Contributors to the Total Compressibility for Well 3

To characterize the LOT model developed by the study, the leak constant *D* and the channel width *W* were computed. The channel width is then plotted simulteneously against pumped volume and pumped pressure as shown in Figure 4.5 as well as Figures 4.6 & 4.7. The Figured showed that the channel width is larger at the early stage of LOT due to trappped air. However, at the late stage of LOT the channel width convergenced to a constant smaller value due to the expulsion air on compression.

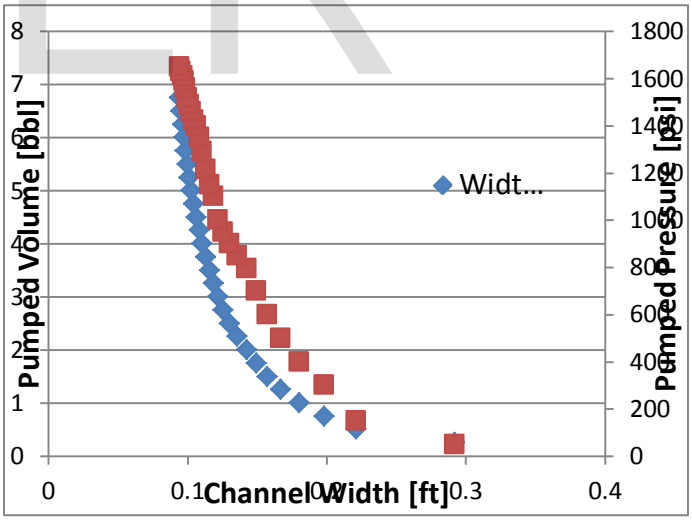

Fig. 4.5: Channel Width Variation during LOT for Well 1

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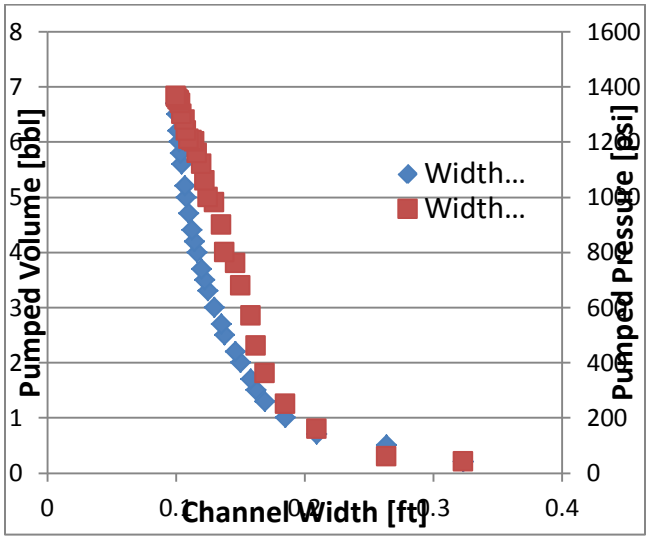

Fig. 4.6: Channel Width Variation during LOT for Well2

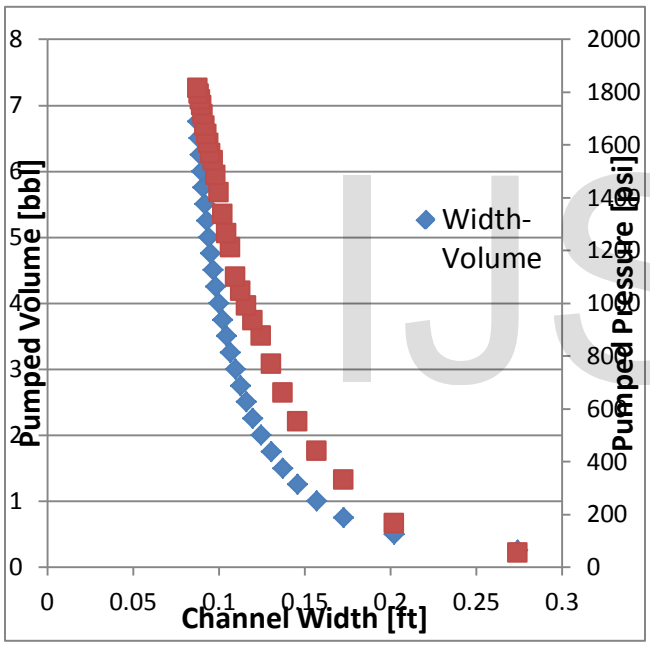

Fig. 4.7: Channel Width Variation during LOT for Well3

That is, compession generally reduces channel width. However, well 2 deviated from from behaviour and seemed to converge at the early stage (see Figure 4.6), but failed to stablize as pumped volume, and by implication pumped pressure, is increased. This bevaviour was caused by naturally occuring fractures, given that the completion cement bonds strong and the large errosion is not possible at this short period. Thus, squeeze cementing is recommended for well 2 to solve this problem of naturally occuring fractures. Well 2 finnaly converged at a stable value at the late time of the test.
The values of channel width, and the coresponding leak constant, are read-off from the plots when they converge and become stable as shown in Table 4.3.

Table 4.3: LOT Update Parameters

Update Parameters	W1	W2	W3
Leak Constant [ft4-h/lb]	0.000244	0.00029	0.000196
Channel Width [ft]	0.094419	0.100005	0.087759
Coefficient 0	-28.13	-130.65	-30.99
Coefficient 1	446.83	467.76	491.59
Coefficient 2	-29.62	-36.99	-32.6
Coefficient of Determination	0.998	0.9947	0.998

With the values of leak constant and the channel width, the relationship between pumped pressure and volume were genrated. The predicted pressures were ploted in Figure 4.8 as well as Figures 4.9 & 4.10. The plot showed that the nonlinear LOT followed a quadratic path with coefficient of dtermination r^2 greater than 0.99 as can be seen in the last row of Table 4.3. That is to say that the prediction were almost exact.

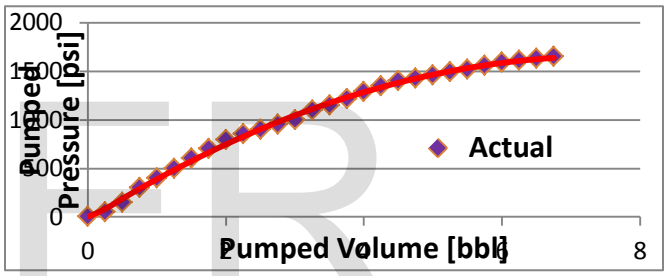

Figure 4.8: Actual and Predicted LOT for Well 1

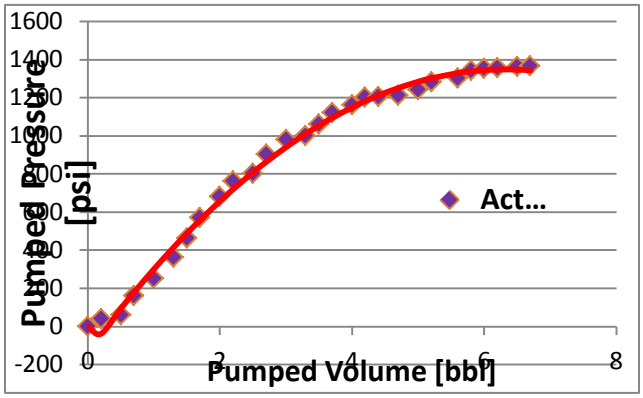

Figure 4.9: Actual and Predicted LOT for Well 2

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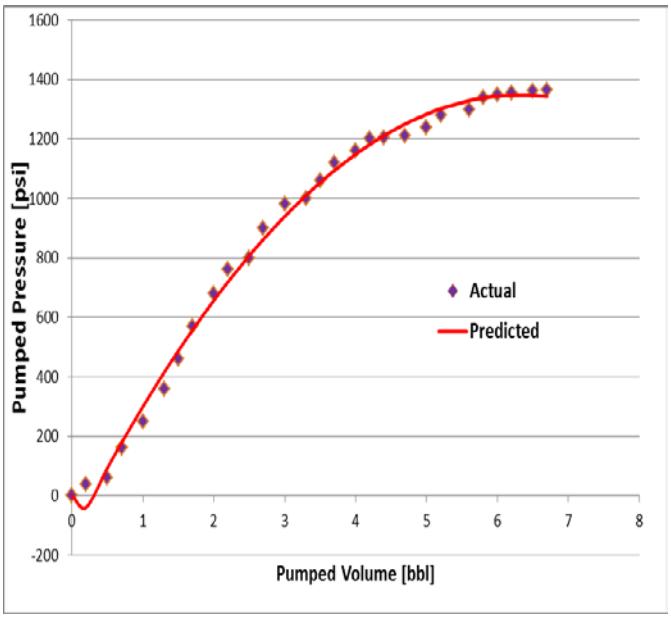

Figure 4.10 :Actual and Predicted LOT for Well 3

5 Conclusion

The developed model does not require running LOT test up till formation fracture. Once the model is accurately matched with LOT history, extrapolation to predict future is done with trust of reliability. The advantage of this is that it removes the fear of losing casing shoe integrity due to formation fracture at the late stage of LOT.

1. It was observed that the nonlinear behaviour of test is largely dependent on the amount of compression and leak.
2. The key parameters that were used to model the nonlinearity of LOT are leak constant and channel width.
3. The method employed was a combination of the definition of compressibility and material balance.
4. The errors in the developed LOT model were errors due to certain assumption to simplify mathematics.
5. The developed model made it possible to evaluate the effects of pumped volume on the pressure, and then predict the maximum pressure to cause formation fracture.
6. The existence of natural fracture as shown in well 2. So, when the LOT is analysed based on its nonlinear behaviour, it will provide information about the natural fracture of the formation. This will aid proper well and reservoir surveillance.

Acknowledgement

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References

[1] Ajienka, J.; Egbon, F. and Onwuemena, U. "Deep Offshore Fracture Pressure Prediction in the Niger Delta – A New Approach", SPE 128339. Proc of 33 *SPE International Technical Conference and Exhibition*, Abuja 2009.

[2] Altun, G.; Langlinais, J. and Bourgoyne, A. T. "Application of a New Model to Analyze Leakoff Tests", SPE 56761, *SPE Annual Technical Conference and Exhibition*, Houston, Texas 1999.

[3] Chevron. "Chevron Provides Update on Rig Incident Offshore Nigeria", http//www.chevron.com/chevron/pressrelease/article/01172012 2012.

[4] Craft, B. C.; Hawkins, M.; Terry, R. E. *Applied Petroleum Reservoir Engineering*, 2nd Edition, Prentice Hall, Englewood Cliffs, New Jersey, 1991.

[5] Hubbert, M. K. and Willis, D. G. "Mechanics of Hydraulic Fracturing", Trans, AIME, 210, pp. 153 – 166, 1957

[6] Jaeger, J. C. and Cook, N. G. W. *Fundamentals of Rock Mechanics*. John Willey & Sons, Inc., New York, 1976

[7] Jenakumo, T. D.; Itua, O. J. and Ebimobowei, W. K. 2014. "Fracture Pressure Prediction Model for Deep water Fields, Gulf of Guinea", SPE 172454-MS, *Annual SPE International Technical Conference and Exhibition*, Lagos 2014

[8] Matthew, W. R. and Kelly, J. "How to Predict Formation Pressure and Fracture Gradient", *Oil and Gas Journal*, pp. 92 – 106, 1967.

[9] Rocha, L. A. S.; Falcao, J. L. and Goncalves, C. J. C. "Fracture Pressure Gradient in Deep water", IADC/SPE 88011, *Asia Pacific Drilling Technology Conference and Exhibition*, Kuala Lumpur, Malaysia, 2004.