AADE-11-NTCE-24

A Critical Review of Wellbore Strengthening: Physical Model and Field Deployment

Runar Nygaard and Saeed Salehi Missouri University of Science and Technology

Abstract

Lost circulation is one of the largest contributors to down time in drilling operations. Especially when drilling wells in complex geological settings or when drilling deepwater with a small tolerance between pore pressure and fracture pressure gradients. To prevent or mitigate wellbore losses an engineering practice referred to as "wellbore strengthening" is conducted to increase the fracture gradient. Wellbore strengthening relies on propping and/or sealing the fractures with specially designed materials. Several field cases have been reported to improve fracture gradient by either increasing the hoop stress around the wellbore or hindering fracture propagation. However there seems to be unclear which results can realistically be expected when conducting wellbore strengthening operations in a wellbore.

The purpose of this work was twofold. First objective was to identify types of environment creating losses in the wellbore. The second objective is to investigate the physical explanation of wellbore strengthening and what can be expected results when deployed in the field.

Leak off tests does not give a good indication if the leak off point represents the fracture breakdown pressure or fracture propagation pressure. Therefore to understand the wellbore condition, i.e. if the wellbore is fully intact or the wellbore has existing fractures, performing extended leak off tests is required. The simulation results indicate that fracture gradient improvement is caused by sealing of fractures which hinder further fracture propagation. However the placement of loss circulation material inside the fracture is important. To restore the theoretical maximum fracture gradient, given by the Kirsch solution, the fracture has to be sealed off close to the wellbore wall to obtain full hoop stress restoration. To conduct a successful wellbore strengthening operation fracture width at the wellbore phase has to be determined and this fracture area has to be targeted with the lost circulation material with a suitable particle size distribution.

Introduction

In planning and executing conventional drilling operations it is well established practice to keep the mud weight below formation fracturing resistance but higher than formation collapse pressure, or pore pressure for permeable formations. The fracture pressure gradient is the key factor when deciding on casing point depth and to identify the required number of casing strings. However when drilling in complex geological settings like high tectonic stress areas or close to salt structures the required number of casing strings adds significantly to the overall drilling cost. The same situation occurs when drilling in deepwater where a small tolerance between pore pressure and fracture gradients requires excessive number of casing strings. Possible lost circulation and reduced fracture gradient can create very challenging drilling conditions in infill drilling in depleted reservoirs. In general a narrow pore-fracture pressure window is repeatedly causing; lost circulation, excessive number of casings required to reach the target, kick and blow out, stuck pipe, hole stability problems, and inefficient cuttings removal in deviated and horizontal wellbores[1,2].

To stop mud losses into the formation lost circulation materials (LCM) are added to the mud system to fill the fractures which are created while drilling or fractures or vugs already naturally occurring in the formation. Although using these materials decreases the loss rate the method does not give consistent results and materials are selected by trial and error. Further, it is not clear to what extent loss rate can be decreased and how long LCM's are stable and effective for a given loss zone. Often the only remedy working when encounter losses is to set a cement plug and drill a sidetrack.

The objective of this paper is to investigate how different wellbore environments and operational conditions contribute to lost circulation and how they can be identified. The second objective of the paper is to investigate the physical explanation of wellbore strengthening and what can be expected results when deployed in the field.

Wellbore hoop stresses

In the subsurface the underground must, in most instances, carry the weight of the overlying formations. Therefore the vertical stress for any given depth (D) can be calculated based on;

$$Sv = \int_0^D 0.052\rho(z)dz \qquad (1)$$

Where Sv is vertical stress, $\rho(z)$ is bulk density of overburden formations and an eventual water column for offshore situations, dz is depth increment. Assuming the surface being flat the vertical stress will be one of the principle stress direction. In the subsurface any stress state will consist of three principal stresses which will be 90 degrees apart. Therefore any stress in the subsurface can be expressed as the function of vertical stress and two horizontal stresses.

In porous rocks pore fluids will carry some of the load and to deformations in the subsurface is caused by the effective pressure defined as total stress subtracted the pore pressure[3]. In a geological relaxed area and when assuming rock behave as a linear elastic material and undergoing 1-dimensional compression, horizontal stresses can be calculated based solely as a relationship between vertical effective stress and Poisson's ratio;

$$S'h = \frac{v}{1-v} S'v \tag{2}$$

where S'_h is effective horizontal stress, v is Poisson's ratio, and S'_v is effective vertical stress. In most geological basins tectonical compression forces, extensional faults, salt diaperism, chemical compaction, compressional creep, erosion and uplift can give very different result for horizontal stress. Also in most geological settings the two principal horizontal stresses will be different.

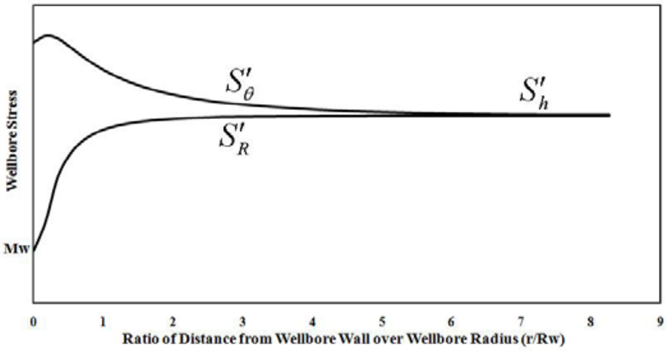


Figure 1 A vertical wellbore with the principal stresses represented in cylindrical coordinates as function of distance from borehole.

When drilling the wellbore, stressed rock is removed and the wellbore surface acts like a free surface not able to transfer shear stresses and only the mud pressure supports the wellbore walls. Therefore the far field stresses will align themselves with the wellbore walls and the principal stresses at the wellbore wall can be represented as an infinite hollow cylinder (Figure 1). Around the wellbore the principal stresses are given in cylindrical coordinates as;

$$\begin{aligned} S_r &= MW \\ S_\theta &= 3S_h - S_H - MW \\ S_z &= S_v \end{aligned} \tag{3}$$

where MW is mudweight. This expression assumes an impermeable borehole wall. If the effect of pore pressure is included the stresses around a the wellbore wall are;

$$\begin{aligned} S_r &= MW \\ S_\theta &= 3S_h - S_H - MW + \alpha\left(\frac{1-2\nu}{1-\nu}\right)(MW - PP) \\ S_z &= S_v + \alpha\left(\frac{1-2\nu}{1-\nu}\right)(MW - PP) \end{aligned} \tag{4}$$

where α is Boit's coefficient. This formulation of the wellbore stresses assumes there is no fluid pressure drop over any potential mud-cake in the hole. As seen on Figure 1 the hoop stresses are highest close to the wellbore wall and then is reduced until it reach the far field stresses just a few wellbore radius away from the wellbore. Fracture around the wellbore (P_{frac}) occur when the mudweight is higher than the sum of the effective hoop stress (hoop stress subtracted pore pressure) and the tensile strength of the rock given as;

$$P_{frac} = S_\theta - PP + T_0 \tag{5}$$

where S_θ is hoop stress, T_0 is tensile strength of the rock for the general situation. For the non-permeable situation i.e. when no pore fluid is leaking into the formation fracture criteria is given as;

$$P_{frac} = 3S_h - S_H - PP + T_0 \tag{6}$$

This model of the fracture pressure also implies that the least horizontal stress is less than the vertical stress and the fracture created is a vertical fracture oriented parallel with the largest horizontal stress. For a permeable formation with full communication between wellbore and pore fluids the fracture pressure is given as;

$$P_{frac} = \frac{3S_h - S_H - \alpha\left(\frac{1-2\nu}{1-\nu}\right)PP + T_0}{2 - \alpha\left(\frac{1-2\nu}{1-\nu}\right)} \tag{7}$$

When fracture is initiated according to equation 5, 6 or 7 the fracture propagates away from the wellbore where hoop stresses is reduced until it reach the far field least horizontal stress. The fluid pressure required to further propagate the fracture outside the elevated hoop stress is the sum of the least horizontal stress, the pressure required to overcome the fracture tip resistance and frictional pressure losses caused by fluid flow inside the fracture and leak off of fluids into the formation. Several models exist for modeling the fracture propagation pressure see for instance Valko and Economides[4] for a review.

Fracture Pressure Measurements

To identify the fracture pressure gradient in the formation leak off tests, extended leak off tests (XLOT) or mini-frac tests can be conducted. For a leak off test a volume is pumped slowly with a constant flow rate into a few feet of formation below the casing shoe. The pressure and volume readings are plotted until the linear pressure versus volume response shows a distinct break in the curve (Figure 3). If a mini-frac or XLOT (Figure 4 and Figure 5) test is conducted pumping is continued until a clear formation breakdown is seen and pumping is continued to identify fracture propagation pressure before pumping is stopped. When the pressure is stopped the frictional dynamic loss for pumping fracture is lost and pressure is bled off. The instantaneous shut in pressure and fracture closure pressure can be recorded[5,6]. For a mini-frac or extended leak off test the instantaneous fracture pressure or fracture closure pressure can be used to estimate the least horizontal stress value. See Fjaer et al.[7] for a review of the different methods to interpret minimum horizontal stress from XLOT and mini-frac tests.

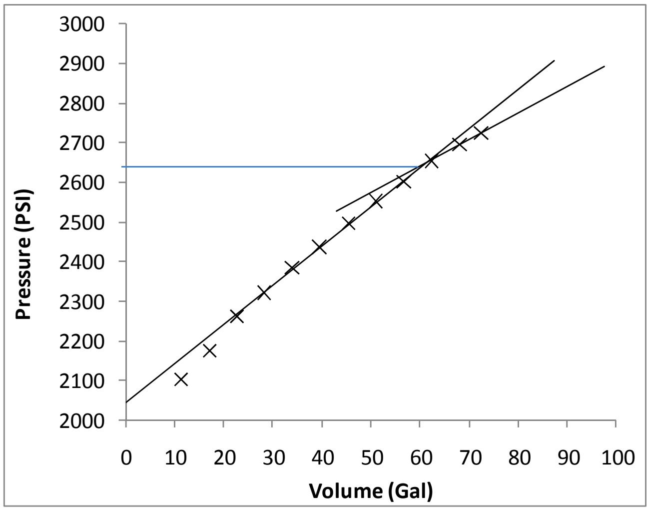


Figure 2 Leak off test from Southern North Sea.

The break in the linear trend seen in the leak off test in Figure 2 at 2653 psi is the Leak off point (LOP). The leak off point is the onset of fracture initiation and not where the ultimate fracture breakdown pressure is reached as determined by equation 5. Onset of fracture initiation can be influenced by drilling induced fractures, breakout of parts of the wellbore, chemical reactions occurring between drilling fluids and formations, fluid pressure drop in filter cake, filter cake plasticity and drilling fluid type, formation plasticity[8,9]. Actually the fracture model given in equation 5 assumes that there should not be any LOP. The model estimates a deformation to appear linear elastically until fracture point is reached. Figure 3 show an extended leak off tests where the ultimate fracture strength is reached without any leak off point can be determined. The ultimate fracture strength occurs at 1855 psi. When the fracture propagates further the fracture has overcome the hoop stresses close to the wellbore and 1285 psi is required to further propagate the fracture. The least horizontal stress can be estimated based on the ISIP or change of slope in the bleed back phase of the XLOT test.

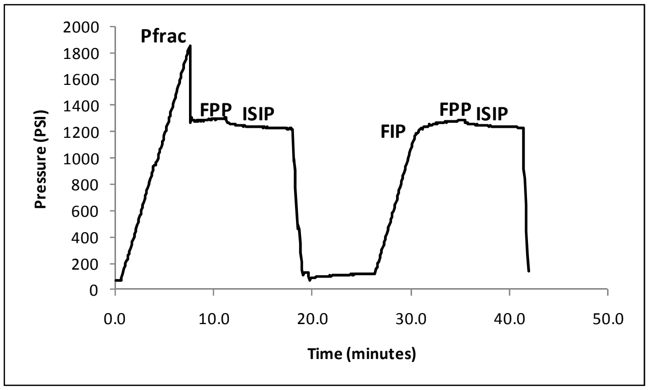


Figure 3 XLOT test in from the southern North Sea.

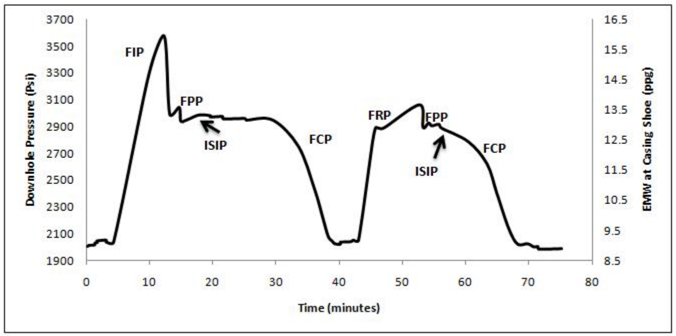


Figure 4 XLOT test well 10-7 in the Norne field[10].

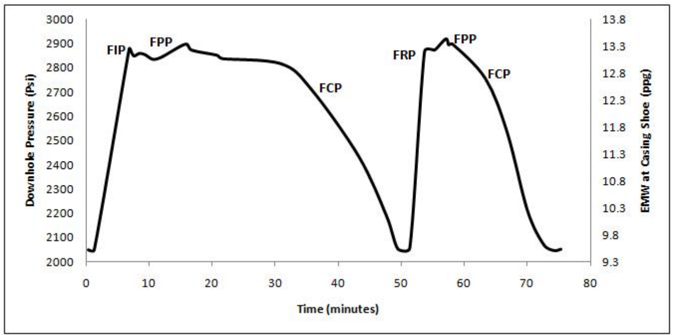


Figure 5 XLOT test well 10-8 in the Norne field[10].

Figure 4 show an extended leak off tests where the fracture initiation pressure is 3400 psi and ultimate fracture strength is 3625 psi[10]. For the second pressure test cycle is fracture initiate pressure is significantly less than the initial maximum fracture pressure. When the fracture is reopened in the second pressure cycle the tensile strength in the rock is destroyed. Further a clearer leak off point is seen in the second curve before reaching the maximum fracture pressure of 3045 psi. The difference of 580 psi will be an upper measure of the tensile strength of the rock. In addition to breaking down the tensile strength of the rock an existing fracture might be hydraulically open and to further propagate the fracture the pressure has only to be bigger than the least horizontal stress (when neglecting friction and fluid losses). Figure 5 shows the XLOT test from the next well drilled where the fracture initiation pressure is around 2975 psi which is significantly less than the fracture breakdown pressure of the first well in Figure 4. The fracture initiation pressure is approximately the same as the fracture reopening for the second fracture cycle and comparable to the fracture reopening pressure of the first well. The leak off test from well 10-8 in Figure 5 shows clearly that the leak off tests can represent a value close to the fracture propagation pressure in an already damaged formation with preexisting fractures. The fracture initiation pressure value from LOT tests can be controlled by fractures or weakness planes and give significantly lower values than expected.

For pre-existing fractures it will be important to distinguish between mechanical open or closed or hydraulically open or closed fractures. The formation can be brittle so an existing fracture can stay hydraulically open even if there are normal forces acting above the fracture plane[11]. When fractures are hydraulically open losses might occur if the mudweight is higher than the pore pressure gradient. The mud will then displace the pore fluid in the open fracture volume. A simple criteria to evaluate if there is risk for experiencing hydraulically open fractures and experience losses with mud weights above pore pressure gradient is given as;

$$OCR = \frac{80.75UCS^{.55}}{Sv - PP} \qquad (8)$$

where OCR is overconsolidation ratio and UCS is unconfined compressive strength. OCR is a concept taken from soil mechanics which tells us how brittle the rock will be under current effective stresses. Details about OCR can be found for instance in Lambe and Whitman[12]. If fractures naturally exist hydraulically open fractures are to be expected for OCR values above 2.5. UCS can be estimated from well logs and numerous correlations have been developed between well logs and UCS[13]. When experiencing losses in hydraulically open fractures losses will continue until the fracture volume is filled up. To propagate or widen these fractures the mudweight has to be above the least horizontal stress. Therefore these losses will often stop after some time, even if no lost circulation material is added or not.

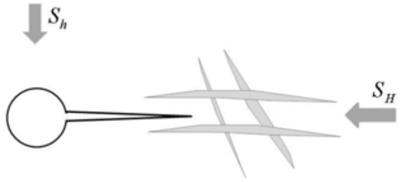
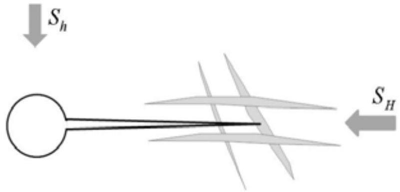
Wellbore Condition	**Leak Off Test Measurement**
Intact Borehole 	$S_\theta - PP + T_0$
Borehole with a very small fracture 	$S_\theta - PP$
Borehole with a large propagated fracture in far field zone 	S_h
Borehole where fracture has propagated to intersect with vugs and / or natural fractures 	PP

Figure 6. Effect of how different wellbore conditions change the interpretation of LOT measurements.

As seen above the wellbore condition will greatly control what a leak off tests will measure. If an extended leak off test is performed it is easier to identify the actual physical condition of the wellbore. Figure 6 summarize the different wellbore conditions and what measurement can be obtained from a LOT or XLOT. For an intact borehole the leak off test has to exceed the elevated effective hoop stress and tensile strength before fracture propagation starts. If a small fracture appears at the wellbore wall the tensile strength has been destroyed but hoop stresses still prevent fractures to propagate. However for a situation where a large fracture exists around the wellbore the hoop stress vanish into the least horizontal stress perpendicular to the fracture far away from the wellbore (Figure 1). In this situation the LOT test will break off when the fracture starts to propagate and therefore the LOT is measuring the least horizontal stress. The last wellbore condition in Figure 6 is when a fracture has propagated to intersect with vugs and / or natural fractures. In this situation LOT measures only the pore pressure gradient. The upper limit of fracture gradient for the intact wellbore where both hoop stress and tensile strength contributes to the fracture resistance which is given by equation 5.

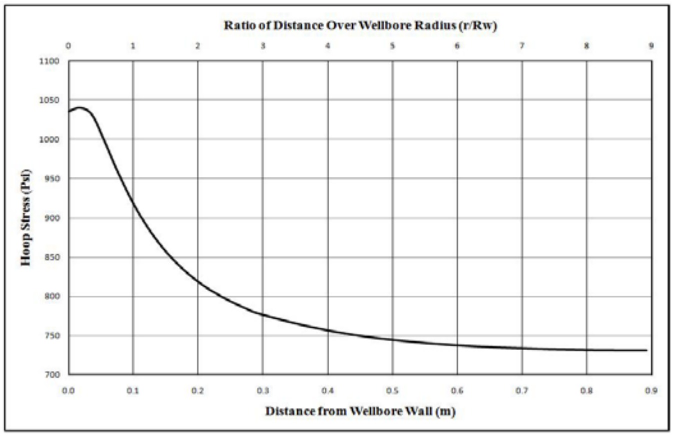


Figure 7. Wellbore hoop stress as a function of distance from the borehole wall (Poro-elastic conditions).

Naturally existing fractures intersecting the wellbore will reduce the leak off gradient as seen in Figure 6. However in most drilling operations XLOT is not performed and which of the situations in Figure 6 the LOT test represent is not easily to determine. If LOT results are available from nearby wells comparing the results can help in determine the wellbore integrity. When losses are experienced in a situation with larger fractures (the two lower situations on Figure 6) sealing off the fracture and void space with LCM material will stop losses. However if drilling commence and losses continues because of the added pressure from annular friction pressure the LCM material has to be placed so that the fracture is sealed off close to the wellbore wall. Near the wellbore wall the hoop stresses rises which can significantly increase the fracture pressure. Figure 7 show that for an 8 ½” wellbore about one feet into the formation most of the hoop stress is gone. Therefore it is required that the LCM material has a size distribution comparable to the fracture width of the fracture close to the wellbore wall.

Wellbore strengthening to increase fracture gradient

Several field cases and methodologies have been reported to increased fracture gradient or prevent losses which are referred to as hoop stress restoration or wellbore strengthening[14]. Different materials in the LCM pills or in the drilling fluid have been used. Gels including cross-linked polymers showed to increase fracture gradient in the Arkoma shale[15]. Calcium carbonates in Gulf of Mexico and California wells[16,17,18,19], deformable, viscous, and cohesive sealants (DVCS) in Gulf of Mexico and South Texas[20,21], drill and stress fluid (DSF) water based systems in Jerneh field of Malaysia and Trawick field in East Texas[14], did all successfully increase the fracture gradient. Without XLOT tests it is very difficult to verify the wellbore condition, as shown in Figure 6, before the treatment. Therefore it is only field experience which can tell us if the desired result will be obtained or not. Since XLOT tests clearly are breaking down the formation as seen in Figure 3 and 4 it is not desirable to conduct these test in wellbore where losses might be expected or with a narrow mud weight window. However the critical additional information obtained from XLOT and mini-frac test justifies the test to be run in wellbore where narrow fracture and pore pressure gradient is less of an issue. Either it can be run on an shallower casing shoe than the most problematic zones or planned as part of an appraisal well where the regional geology is known but where the data is available before deviated production wells are drilled.

Physical models of wellbore strengthening beyond the intact wellbore strength

Fracture gradient can theoretically only be increased by conducting lost circulation or wellbore strengthening treatments up to the limit provided by the Kirsch solution (equation 5). Increasing fracture propagation pressure by sealing off fractures and wedging out fractures around the wellbore and thereby increasing hoop stresses are proposed possible mechanisms that can increase the hoop stress beyond the stress estimated from equation 5[16,17,21].

Both of these possible mechanisms for wellbore strengthening are addressed below. In the first case, which is based on increasing fracture propagation pressure an analytical solution was investigated. In the second case, we have used three-dimensional finite-element analysis for the wellbore hoop stress by wedging out fractures.

Investigating the effect of fracture sealing on fracture propagation pressure

An analytical solution is derived by Abe et al.[22] for fracture propagation in a penny-shaped fracture crack in a isotropic stress field. The complete solution for this equation is solved and discussed in another reference[23]. The fracture pressure away from the near wellbore region is given by;

$$P_{frac} = (\lambda + 1)S_h - \lambda PP \qquad (9)$$

λ is defined as sealing efficiency factor which is described as a function of the non-penetrated zone close to the fracture tip. λ can be in the range from 0 to 1.5. For the case of fully penetrating fluid, this term will be zero and fracture propagation pressure will be equal to minimum far field stress. If the fracture is near the wellbore wall the horizontal stress term in equation 9 can be replaced with hoop stress. The sealing efficiency factor is a function of the length of the non-invaded zone at the tip of the fracture. This effect is verified in hydraulic fracturing experiments which showed that the fracture reopening pressure depends upon the amount of mud cake left on wellbore wall[9,24,25]. Since water based mud develops a larger mud cake, they will normally have higher reopening pressure than oil-based muds as observed in laboratory experiments.

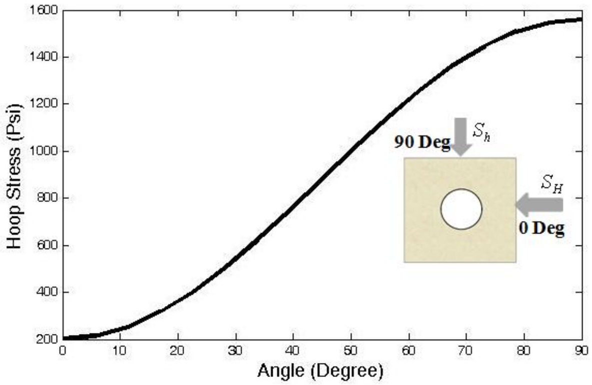
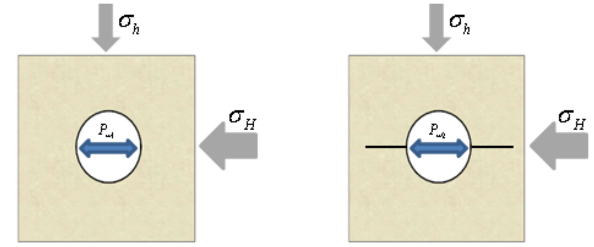


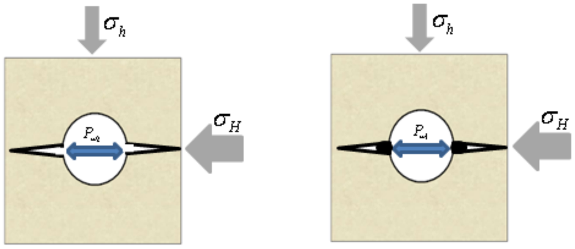
Figure 8. Wellbore hoop stress for a vertical wellbore as a function of radius around the wellbore.

With a mud system which creates a significant λ the reopening pressure for this fracture might be higher than the original fracture if the fracture is sealed off close to the wellbore wall. If the fracture is sealed off far into the formation even for a lambda of one, the hoop stress close to the wellbore will be equally large. For a drilling fluid λ equal one for a fracture close to the wellbore, the fracture pressure can be significantly higher than the fracture pressure estimated with equation 5 which is the Kirsch solution. Unfortunately there is limited data for λ for different mud systems and formations to be able to quantify this parameter for a specific case. But if the fracture is sealed off in the maximum horizontal stress direction fractures might form in a different orientation in the wellbore. For a different orientation the fracture pressure will increase since the hoop stress increase for other wellbore orientations (Figure 8). For the situation where the two principal horizontal stresses are the same the hoop stress will be equal around the wellbore and fractures can occur in any orientation. But for the general situation where the two principal horizontal stresses are different, sealing off the fracture will force the next hydraulic fracture in a different orientation. Since the hoop stresses are lowest around the existing fracture parallel to maximum horizontal stress it would be expected the next fracture to form within the same region. As shown in Figure 8 for the second fracture to be propagated for instance in the 10 degree from the first one this fracture needs to overcome 50 psi higher hoop stress than the initial fracture. However if multiple fractures are created and sealed and force the next fracture to form at around 30° from the first one this fracture needs to overcome more than 350 psi additional hoop stress compared to the initial fracture. This might be a possible method to increase fracture gradient above wellbore hoop stress at maximum horizontal stress orientation by conducting fracture hesitation squeeze in multiple stages. It is worth to note that to obtain this hoop stress increasing effect the fracture sealing has to be close to the wellbore wall where the hoop stresses are elevated.



Step 1-Intact borehole with no fracture (Pw1)

Step 2-Fracture initiated with increasing wellbore pressure (Pw2)



Step 3-Fracture propagated with pumping fluid inside fracture (Pw2)

Step 4-Fracture sealed and wellbore pressure dropped down to intact case (Pw1)

Figure 9. A schematic of steps required for a detailed wellbore strengthening study.

Investigating the effect of wedging on hoop stresses

Filling and sealing of a fracture by wedging out the fracture is also identified to be a mechanism to increase the hoop stresses around the wellbore. To address the increase of hoop stresses by wedging out fractures Finite Element Methods (FEM) simulation was used in this study to solve three-dimensional poro-elastic models. Details of geomechanical model and fracture simulations have been explained elsewhere[26]. A schematic of this approach is given in Figure 9. It is first assumed that no fractures exist around the wellbore initially. The first step will be looking at the state of stress around the borehole before fractures are formed. The second step will be to increase the wellbore pressure till the hoop stress around the borehole drops down and fractures start to initiate. Then the drilling fluid starts to gradually enter the fracture, fracture breakdown happens and the fracture starts propagating. It is very critical to precisely record stress changes around the borehole in each step. The final step will be the fracture sealing and to see whether wellbore strengthening has actually increased the wellbore hoop stress, the stress condition in the last step should be compared with the initial condition which both having the same mud weight.

Figure 10 shows the results form that wellbore hoop stress for a vertical wellbore with maximum and minimum effective horizontal stresses of 1160 psi and 725 psi respectively. Rock porosity is 20%, rock permeability is 40 mD, tensile strength is 0 psi, Poisson's ratio is 0.25, and Young's modulus is 3625 ksi. The blue line in Figure 10 represents the hoop stress around the wellbore when fractures are intact. At fracture initiation effective hoop stresses are 0 in the fracture orientation since the rock has no tensile strength. The hoop stress around the wellbore is less than the intact case since the mudweight is increased in the wellbore. During and after fracture propagation the hoop stresses at the fracture surface is tensile and hence negative (green line on Figure 10). After inserting the wedging material in the fracture which seals of the fracture the pressure is bled off in the wellbore to its original hydrostatic mudweight. Again the hoop stresses are recorded after creating and wedging the fracture (red line on Figure 10). The hoop stress around the wellbore after sealing is comparable to the intact case but the results indicates that wellbore strengthening has the capability to restore the hoop stress but it is not really able to strengthen the wellbore by increasing its stress more than its ideal state, which can also be defined by Kirsch analytical solution.

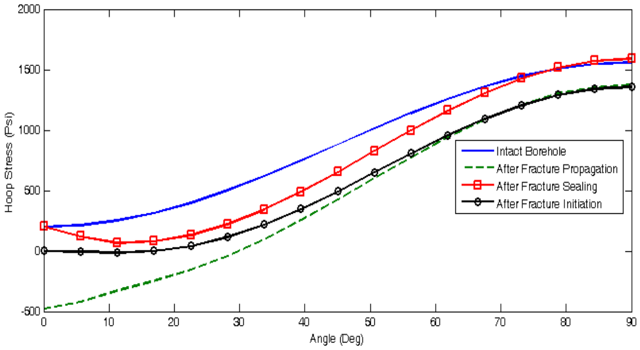


Figure 10. Wellbore hoop stress for intact borehole, after fracture initiation, propagation and sealing.

Field implications

When planning and evaluating results of lost circulation treatment or wellbore strengthening treatments it is important to understand how the limitation of data is controlling the interpretation and understanding of the results. The following list summarizes the field implication of the analysis performed above.

- Leak off tests does not give a good indication if the LOP represent the fracture breakdown pressure or fracture propagation pressure. Therefore conducting XLOT tests where more accurate reading of minimum horizontal stress and intact fracture breakdown pressure is imperative for understanding the type of losses occurring.

- Well logs can be used to estimate if large losses is likely at low mudweight by using equation 8. If the OCR is above 2.5 losses should be planned for even when drilling with mud weights at or below minimum horizontal stress.

- Simulations of anticipated fracture width should be conducted so the particle size distribution of the lost circulation or wellbore strengthening material can be designed to seal off the fracture at the wellbore wall to take full effect of the elevated wellbore hoop stresses near the wellbore.

- The actual strength or stiffness of the particulate material seems to be of a lesser importance than the size distribution of the materials since the hoop stresses is not elevated beyond the Kirsch solution regardless of material strength.

- The lost circulation or wellbore strengthening material should be selected so necessary bleed off of the pressure inside the material to prevent further propagation of the fracture.

- LCM materials which can increase the size of non-invaded zone can increase the fracture reopening pressure and hence force new fractures to form at less favorable orientations around the wellbore where the hoop stresses are higher than the maximum horizontal stress orientation.

Conclusions

Leak off tests are a deceiving measure of establishing a baseline from to establish an intact fracture gradient. Therefore to identify type of losses and the cause of wellbore strengthening approach taken XLOT is required.

To obtain maximum effect of a lost circulation treatment or wellbore strengthening procedure fractures width should be modeled to select a suitable particle size for the LCM material.

Fracture sealing can improve fracture gradient to the theoretical maximum if fracture is sealed off close to the wellbore wall. However the numerical modeling conducted of the wellbore strengthening approach did not indicate any hoop stress increase around the wellbore beyond the theoretical maximum.

Nomenclature

BHA = *Bottomhole assembly*
α = *Boit's coefficient*
D = *Depth (feet)*

FCP = *Fracture closure pressure (psi)*
FIP = *Fracture initiation pressure (psi)*
FPP = *Fracture propagation pressure (psi)*
ISIP = *Instantaneous shut in pressure (psi)*
λ = *Sealing efficiency factor.*
LOP = *Leak off point (psi)*
LOT = *Leak off test*
MW = *Mudweight (lb/gal)*
v = *Poisson's ratio*
OCR = *overconsolidation ratio*
P_{frac} = *Fracture pressure (psi)*
PP = *Pore pressure (psi)*
$\rho(z)$ = *Bulk density (lb/gal)*
S_h , σ_h = *Minimum horizontal stress (psi)*
S'_h = *effective minimum horizontal stress (psi)*
S_H , σ_H = *Maximum horizontal stress (psi)*
S_θ = *Hoop stress (psi)*
S_v = *Vertical stress (psi)*
$S'v$ = *Effective vertical stress (psi)*
T_0 = *Tensile strength (psi)*
UCS = *unconfined compressive strength (psi)*
XLOT = *Extended leak off test.*

References

1.Murchison, J., "Lost Circulation For The Man On The Rig." Murchison Drilling Schools Inc. 2006.

2. Ivan C., Bruton., J. and Bloys, B. " How can we best manage lost circulation." AADE-03-NTCE-38, AADE National Technology Conference Houston, 2008.

3. Terzaghi, K., "Erbdbaumeckanik auf bodenphysikalischer Grundlage." Leipzig: Deuticke. 1925.

4. Valko, P. and Economides, M.J.,"Hydraulic Fracture Mechanics." John Wiley & Sons,1995.

5. Raaen, A.M., Horsrud, P., Kjoerholt, H. And Oekland, D. "Improved routine estimation of the minimum horizontal stress component from extended leak-off tests." Int. J. Rock Mech. 7 min. Sci Vol. 43 37-48. 2006.

6. Warpinski, N.R., Peterson, R.E., Branagan, P.T. and Wolhart, S.L. "In situ stress and moduli: Comparison of values derived from multiple techniques. SPE 49190. SPE Annual Technical Conference & Exhibition, Louisiana September 27-30, 1998.

7. Fjaer, E., Holt, R.M, Horsrud, P., Raaen, A.M. and Risnes, R., "Petroleum related Rock mEchanics" 2^{nd} Edition, Developments in Petrolem Science, Vol, 53, Elsevier, 2008.

8. Aadnoy, B.S.; Belayneh, M. "Design of Well Barriers to Combat Circulation Loss." SPE Drilling & Completion, 295-300, 2008.

9. Morita, N.; Black, A.D. and Fuh, G.F. "Theory of Loss Circulation Pressure." SPE 20409, SPE Annual Technical Conference, New Orleans, 23-26 September 1990.

10. Okland,D., Gabrielsen, G.K., Gjerde, J., Sinke, K. and Williams E.L. "The Importance of Extended Leak-Off Test Data for Combatting Lost Circulation." SPE/ISRM Rock Mechanics Conference, Irving, Texas, 20-23 October 2002.

11. Nygaard, R., Gutierrez, M., and Bratli, R.K. "Brittle-ductile transition mudrocks and shales it's implication for hydrocarbon migration and seal." Marine and Petroleum Geology, 2006.

12. Lambe T.W. and Whitman, R.V. "Soil Mechanics S.I. version, 2nd ed." New York: J. Wiley and Sons, Inc, 1979.

13. Chang, C., Zoback, M.D. and Khaksar, A. "Empirical relations between rock strength and physical properties in sedimentary rocks." J. Pet. Sci. Eng. Vol 51, 223–237, 2006.

14. Dupriest, F.E., Smith, M.V., Zeilinger, C.S. and Shoykhet, I.N. "Method to Eliminate Lost Returns and Build Integrity Continuously with High-Filtration-Rate Fluid." SPE/IADC 112656. Orlando, 4-6 March 2008.

15. Aston, M.S., Alberty, M.W., Duncum, S., Bruton, J.R., Friedheim, J.E., and Sanders, M.W. "A New Treatment for Wellbore Strengthening in Shale. SPE 110713, SPE Annual Technical Conference, Anaheim, California. 11-14 November 2007.

16. Alberty, M.W, and McLean, M.R. "A Physical Model for Stress Cages." SPE 90493, SPE Annual Technical Conference, Houston, 26-29 September 2004.

17. Fuh, G.F., Morita, N., Byod, P.A., and McGoffin, S. J. "A New approach to preventing lost circulation while drilling." SPE 24599, SPE Annual Technical Conference and Exhibition, Washington. 4-7 October 1992.

18. Fuh, G.F., Beardmore, D., and Morita, N. "Further Development, Field Testing, and Application of the Wellbore Strengthening Technique for Drilling Operations." SPE/IADC 105809, SPE/IADC Drilling Conference, Amsterdam, 20-22 February 2007.

19. Van Oort, E., Friedheim, J., Pierce, T., and Lee, J. "Avoiding Losses in Depleted and Weak Zones by Constantly Strengthening Wellbores." SPE 125093, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana. 4-7 October 2009.

20. Traugott, D., Sweatman, R., and Vincent, R. "Increasing the Wellbore Pressure Containment in Gulf of Mexico HP/HT Wells." SPE Drilling and Completion, 16-25. 2007.

21. Wang, H., Sweatman, R., Engelman, B., Deeg, W., Whitfill, D., Soliman, M., and F.Towler, B. "Best Practices in Understanding and Managing Lost Circulation Challenges." SPE Drilling and Completion, 168-175, 2008.

22. Abe, H., Mura, T., and Keer, L.M. "Growth Rate of a Penny-Shaped Crack in Hydraulic Fracture of Rocks." J. Geophys. Res., Vol 81, No. 29, 5335-5340, 1976.

23. Salehi, S., and Nygaard, R., 2010. "Finite-Element Analysis of Deliberately Increasing the Wellbore Fracture Gradient." 44th

US Rock Mechanics Symposium, Salt Lake City, June 2010.

24. Morita, N.; Black, A.D. and Fuh, G.F. Borehole Breakdown Pressure with Drilling Fluids-I. Emperical Results. Int. J. Rock Mech. Min. Sci. & Geomech., 39-51, 1996.

25. Onyia, E.C. “Experimental Data Analysis of Lost-Circulation Problems During Drilling with Oil-Based Muds.” SPE Drilling & Completion, March, 25-31, 1994.

26. Salehi, S. and Nygaard, R. “Evaluation of New Drilling Approach for Widening Operational Window: Implications for Wellbore Strengthening, SPE 140753, SPE Productions and Operations Symposium, Oklahoma City, March 27-29, 2011.