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Step-Rate Formation Integrity Test Method for Geothermal Wells

William M. Rickard, Ernesto Rivas, Mary Mann and Abraham S Samuel

77530 Enfield Lane Building E, Palm Desert, CA-92211, USA

samabraham@geothermalresourcegroup.com

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ABSTRACT

Obtaining fracture gradient data is a critical objective in oil, gas, and geothermal well drilling, from the well construction perspective. Fracture gradient data is important for properly executing many drilling phases and maintaining safe practices. Applying proper well design techniques ensures that a well can be shut in safely, mitigating underground well control issues Availability of fracture gradient data also results in significant improvements to the design and reduces the cost of future wells in the same field by allowing for the determination of the minimum number of casing strings required for safe drilling and completion. Thus, measuring the fracture gradient at relevant depths in a well is critical to reducing well cost, producing a safe well design and reducing the likelihood of downhole well control incidents. The step rate formation integrity test method is a safe and practical method of measuring the fracture gradient and leak-off pressure of a well while minimizing the risk of causing lost circulation.

1.INTRODUCTION

The step-rate formation integrity test (sFIT) is a practical method of measuring the leak-off pressure of a well without the risk of inducing circulation losses. Leak-off pressure, as an indication of the fracture gradient, allows for the engineering assessment of the formation strength at the casing shoe. Otherwise, the leak-off pressure can only be estimated using empirical data. Not measuring the leak-off pressure increases the likelihood of underground blowouts, some of which become above ground blowouts. The costs associated with well control can easily exceed the well drilling cost. Well control insurance is available, but it is expensive. Ensuring that a well can be shut in safely through proper design should significantly decrease underground well control issues. In general, the shoe formations in geothermal wells are brittle. Therefore, it is necessary to find the FIP or leak-off pressure without breaking down the formation directly beneath the casing shoe.

2. BACKGROUND

Prior knowledge of how formation fracture pressure varies with depth can be just as important as prior knowledge of how the formation pore pressure varies with depth when planning and drilling a well. Techniques for determining formation fracture pressure, like those for determining pore pressure, include predictive methods and verification methods. Initial well planning must be based on formation fracture data obtained by a predictive method. However, after a casing is cemented in place, the anticipated fracture resistance of the formation just below the casing shoe should be verified by a pressure test before drilling continues to the next planned casing depth. This pressure test is called a leak-off test (LOT). The aim of such a test is to verify that the casing, cement and formation below the casing shoe can withstand the well bore pressure required to safely drill to the next casing depth.

It is common practice to use cementing pumps or rig pumps to perform a LOT. Although such pumps are capable of pumping fluid at high pressure, a low flow rate is often difficult to maintain. As a result, by the time a break of formation is noticed at surface, an undesirable amount of fluid has already entered the formation, initiating and even extending a fracture, and thus increasing the risk of lost circulation. In geothermal drilling, this induced lost circulation, most often, must be cured with costly lost circulation cement plugs.

A LOT is conducted by shutting in the well at the surface with a blowout preventer, and then pumping into the closed well at a constant rate until the well begins to take fluid, causing a departure from the linear trend of pressure versus volume. The pump then is stopped, and the pressure observed for at least 10 minutes to determine the rate of pressure decline. The casing cement and formation just below the casing shoe are tested in this manner after the cement and about 10 feet of new formation is drilled below the casing shoe. A variation of the LOT is to only increase the bottom hole pressure (BHP) by pumping until a previously designated maximum surface pressure is reached. This is called a formation integrity test (FIT). However, blindly pumping to a predetermined pressure can lead to fracturing of the formation, and in geothermal formations, loss of circulation.

By pumping fixed incremental volumes, and allowing the pressure to stabilize for a few seconds, the risk of fracturing the formation, beyond what is needed or desirable, can be limited. The goal is to initiate a fracture while limiting propagation that could lead to unnecessary problems with lost circulation. Shoe tests in recent volcanic formations almost invariably led to lost circulation in a series of wells drilled in one field. Shoe tests were required by the regulatory agency due to an underground blowout that had occurred in the field. The sFIT was developed to measure a leak-off pressure without causing damage that would require squeeze cementing prior to drilling ahead. This damage is recognized as unstable fracture growth, or breakdown pressure. In brittle formations, the difference between leak-off and breakdown pressure is often a few tens or less of pounds per square inch. A cement pump truck in low gear, at an idle, pumping at a relatively low pressure, usually pumps about 20 gpm (1.3 l/s). This rate is too high for a formation integrity test that uses a surface readout to determine the leak-off pressure without causing formation breakdown. The procedure described herein reduces the rate to 10 gpm or less (≤0.6 l/s), with waiting periods between pump rate steps allow the surface pressure to be measured without any influence from pressure drop caused by friction in the system. Evaluating the pressure versus volume trend, in real time, also simplifies selection of the fracture initiation point in the sFIT.

The sFIT procedure has become GRG's standard method, and is used in all geothermal drilling operations, whether in volcanic, sedimentary or metamorphic formations. The results are consistent with what is expected from a conventional LOT, and the test results are repeatable.

3. PREVIOUS WORK

Yao (2014) discusses unstable fracture growth or breakdown that can cause lost circulation. In brittle volcanic rock, a total loss of circulation can occur, subsequently requiring cement plugs to regain returns. As an illustration, tests done by GRG in Hawaii were performed at a constant rate of about 20 gpm (1.3 l/s) and once the pressure broke over, the only pressure showing on the gauge was from friction in the 2" steel hose to the floor, and the fluid level in the well fell below ground level. In this case, as is often the case in geothermal applications, drilling was being done on a remote location with no access to equipment that could pump at a lower rate.

When unstable fracture growth in geothermal areas of high fracture density are encountered, unstable fracture growth in the tens to thousands of feet can occur (Yu, 2014), thus increasing the probability of connecting with existing open fractures. When this occurs, the hydrostatic gradient of the drilling fluid usually exceeds the pressure in those fractures, and circulation losses occur. If, however, the fracture initiation pressure (FIP), or leak-off point (LOP), can be detected and pumping terminated before causing unstable fracture growth, the required information can be obtained without causing any loss of circulation, thus eliminating the expense incurred to cure circulation losses. Geothermal drilling is highly cost-conscious and, therefore, often relies on affordable surface pressure measurement and readily available pumping equipment. Drilling supervisors and field drilling engineers are only interested in one aspect of the LOT, the actual FIP. Their main interest is in keeping the well bore pressure below the FIP until the next string of casing has been run and cemented, so that operations can safely control any kicks that might be encountered. Pressure and temperature in geothermal production zones usually mirror the conditions found at or near the steam-water saturation curve in the Mollier diagram. The standard practice is to use the maximum temperature encountered, and the corresponding saturation pressure, to estimate the maximum pressure in a geothermal production zone and then selecting the maximum isotherm to drill to by using the FIP as the maximum allowable shut-in pressure during a well control event.

4. METHOD

4.1 Discussion

The sFIT is a low flow rate test performed with clean mud in the well bore, like the standard oil and gas FIT or LOT. The use of a low flow rate yields a conservative (lower) leak-off (Fu, 2014). If the fracture closure pressure becomes important in later operations, the minimum horizontal far field stress can be approximated when modeling unstable formations, and xLOT or extended LOT should be performed. The FIT should be short, with the purpose of establishing FIP only. A couple of data points beyond leak-off (unless in a sedimentary area where clay could be exposed) is more than sufficient to confirm the LOP (clay can act plastically in the early part of a FIT and the resulting curve can have two distinctive straight line slopes).

If the slope of the curve in a standard LOT changes due to the presence of exposed clay, it can lend to an inaccurately low value, as demonstrated by the variation in measured leak-off values at similar depths in a single geothermal field (Figure **1**).

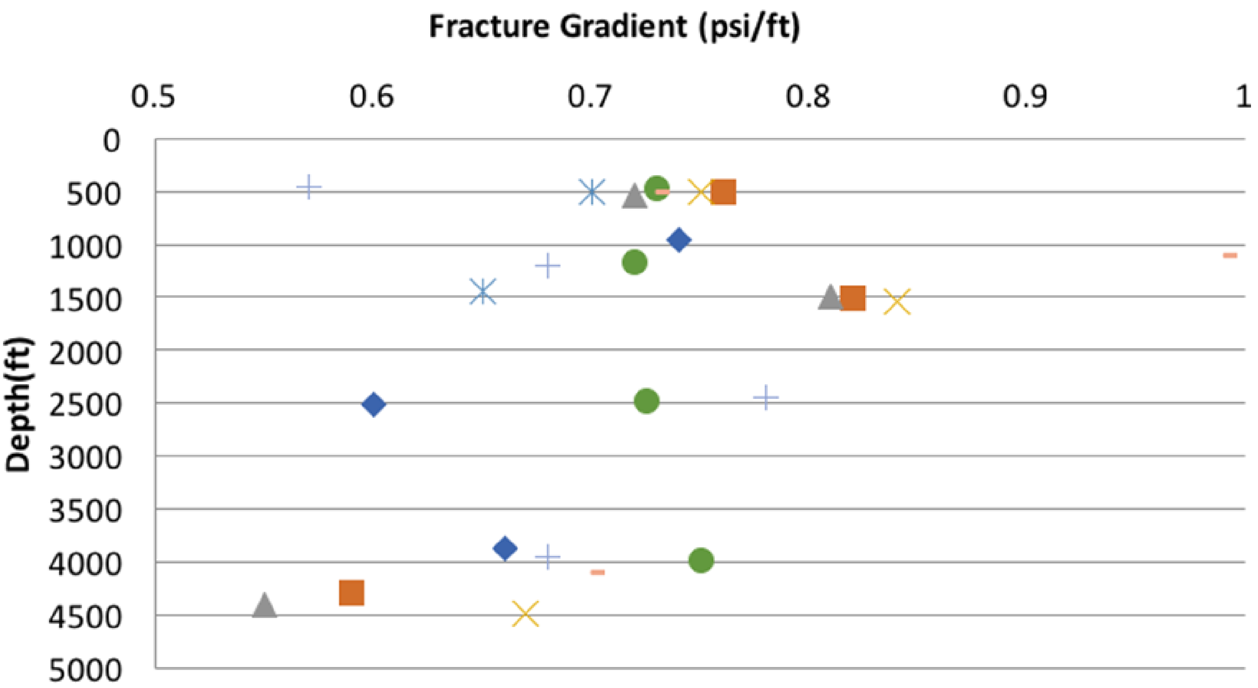


Figure 1: Fracture gradients measured in a single geothermal field, with each symbol representing a different well

The FIT procedure usually limits the maximum pressure so as not to exceed a 1.0 psi/foot gradient (23 kPa/m). Once that gradient has been met, from a control of well standpoint, it is usually safe to drill to the next casing point.

The objective is to provide a standard FIT procedure that can be used with confidence by any drilling supervisor in any field, while minimizing the risk of damaging the formation. This will minimize the time required to perform a successful FIT.

It is important that the measured test data be assessed in real time between pumping intervals. Assessing the test results in real time is essential to recognize the leak-off point and to discontinue the test immediately after the leak-off pressure is determined. This is also the key to timing the pumping intervals. It is recommended to pump 1/10th of a barrel per minute (step) increments. The time between pumping intervals should be limited to that needed for the pressure to stabilize (eliminating any impact from water hammer) and the pressure trend to be assessed to identify a significant change in slope. Pumping one or two additional intervals to confirm a change in slope or determine the formation breakdown pressure (FBP), which is the peak pressure where additional volume pumped no longer results in a pressure increase, is often beneficial.

Geothermal drilling often involves large diameter casing strings and well bores, and low drilling system pressures. As a result, the pressure usually doesn't start to increase until an appreciable volume has been pumped. In the interest of saving time, the first point on a FIT graph should be the total volume pumped when the pressure gauge on the pump truck is first observed to move. It is not unusual to pump a barrel or more before the first positive pressure measurement is obtained. This is often due to partially filled flow lines and air entrainment. Thereafter, it is important that the volumetric increments pumped remain constant in every succeeding pumping interval, with an aim to obtain a volume and pressure relationship to identify the FIP.

4.2 Prior to testing

Drill out the casing shoe. Clean out cement below the shoe. Drill 10 feet (3 m) of new hole and circulate the hole clean. Since this test is completed reading pump pressure, it is not important to ensure that the mud weight going in the well is the same as the mud weight flowing out of the well. Construct a plot of pressure versus volume of fluid pumped. Record mud weight, casing size and shoe vertical depth. Identify the 1.0 psi/ft (23 kPa/m) gradient and an estimated leak-off pressure to establish an upper test pressure limit.

4.3 Test Procedure

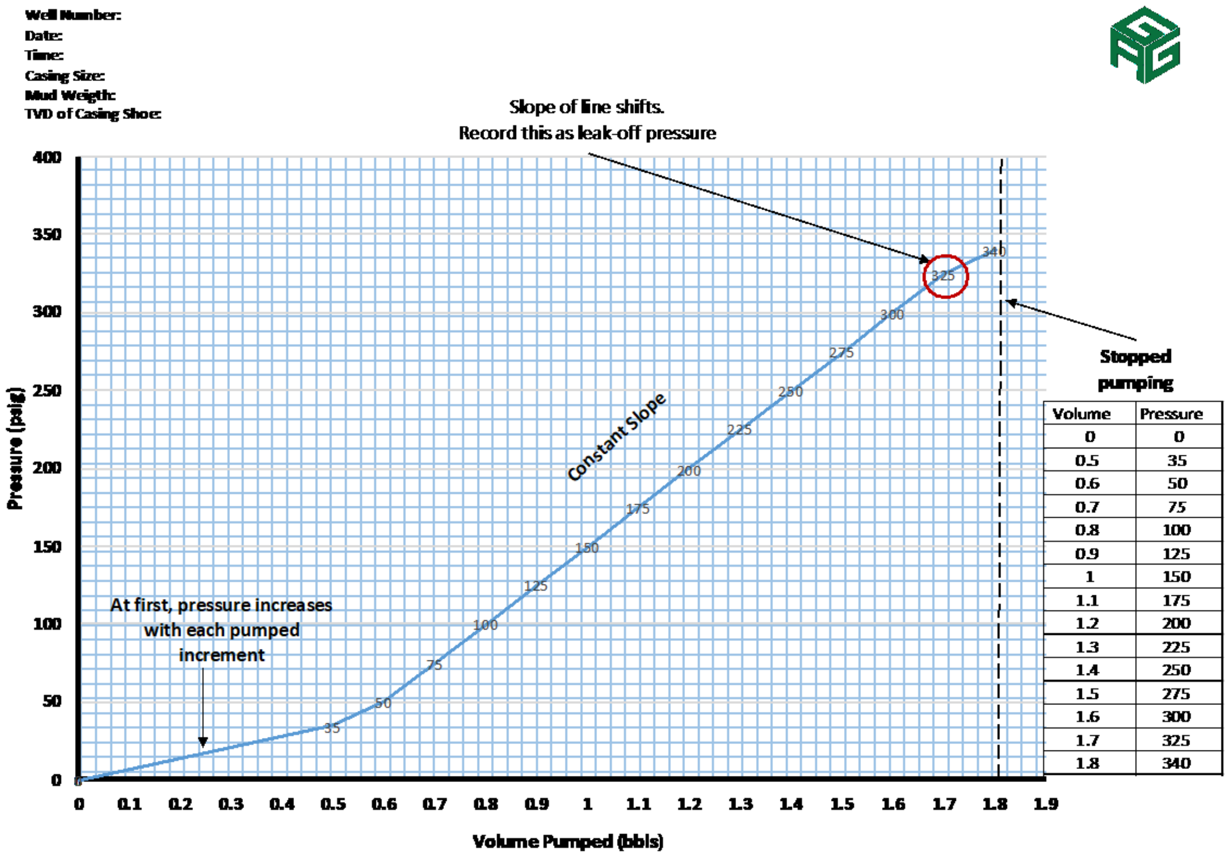
After circulating the hole clean, pull into the shoe, fill the stack and close the pipe rams. Pump until positive pressure is observed. The starting point should be 0 psig starting pressure on the y-axis and 0 barrels injected on the x-axis. Graph the start at first pressure (Figure **2**). As soon as a positive pressure is observed, stop pumping, plot the total volume pumped and the corresponding pressure. Then, begin pumping incremental volumes. All the incremental volumes should be the same size. In the following example the volume is 1/10th of a barrel (0.3 l/s). It will take some volume pumped before a pressure greater than zero is recorded, but it is more accurate to record these volumes.

At first, the pressure versus volume slope will increase with each pumped increment. This is not what it is looked for, but rather a constant increase in pressure with each pumping increment. (Note that the plotted curves appear not to reflect transient behavior of flow into the formation during each step in the step-rate integrity test, this is intentionally plotted that way, with distinct points of measurement, not actual pressures while pumping)

The most important part of the FIT data is the point that denotes a decrease in the slope of pressure versus volume. This is the leak-off pressure and the point at which pumping can be discontinued. In a standard LOT or FIT, the leak-off is at the last point on the constant slope segment of the volume versus pressure trend. Previously, in the sLOT, it is the next point. The reason for this was twofold. First, pumping was paused at each volume increment, allowing the pressure to stabilize and thus allowing the pressure recorded to initial shut in, less than the FIP. Second, this step-rate test yields a very conservative FIP or leak-off Yao (2014).

In the example shown, leak-off occurred at 1.7 barrels (2 liters) and 325 psig. The sFIT method described herein provides a conservative LOP, and the last data point recorded before the change in slope is close to the fracture reopening pressure. The only way to determine which is being measured, fracture initiation or reopening pressure is by completing an XLOT. This requires significantly more circulating time and fluid injection into the interval if interest and can easily lead to lost circulation in geothermal wells. Sometimes, the change in slope is very dramatic and easy to identify. Other times it is subtle, and more fluid must be pumped to ensure that leak-off has occurred. In such a case, the operator should pump at least two more increments after the initial indication of leak-off.

The curve does not always develop as neatly as shown in Figure **2**, and step pumping should continue until a change in slope is apparent or the pre-determined maximum pressure has been reached. The recorded leak-off is the point at which the slope of the pressure versus volume curve starts to decrease.



Volume	Pressure
0	0
0.5	35
0.6	50
0.7	75
0.8	100
0.9	125
1	150
1.1	175
1.2	200
1.3	225
1.4	250
1.5	275
1.6	300
1.7	325
1.8	340

Figure 2: Record volume pumped and start pressure before looking for leak-off

4.4 Calculation of Results

To determine the fracture gradient, the following data is required

True vertical depth of the casing shoe (ft or m)

Density of the fluid in the well bore (lb/gal or g/ml)

Leak-off pressure or fracture initiation pressure (psig or MP)

Using this information, calculate the fracture gradient using the following formulas:

$$Hydrostatic\ Pressure\ of\ the\ Fluid\ (psi) = Weight\ of\ Fluid\ in\ Wellbore\ (ppg)\ x\ True\ Vertical\ Depth\ (ft)\ x\ 0.052$$

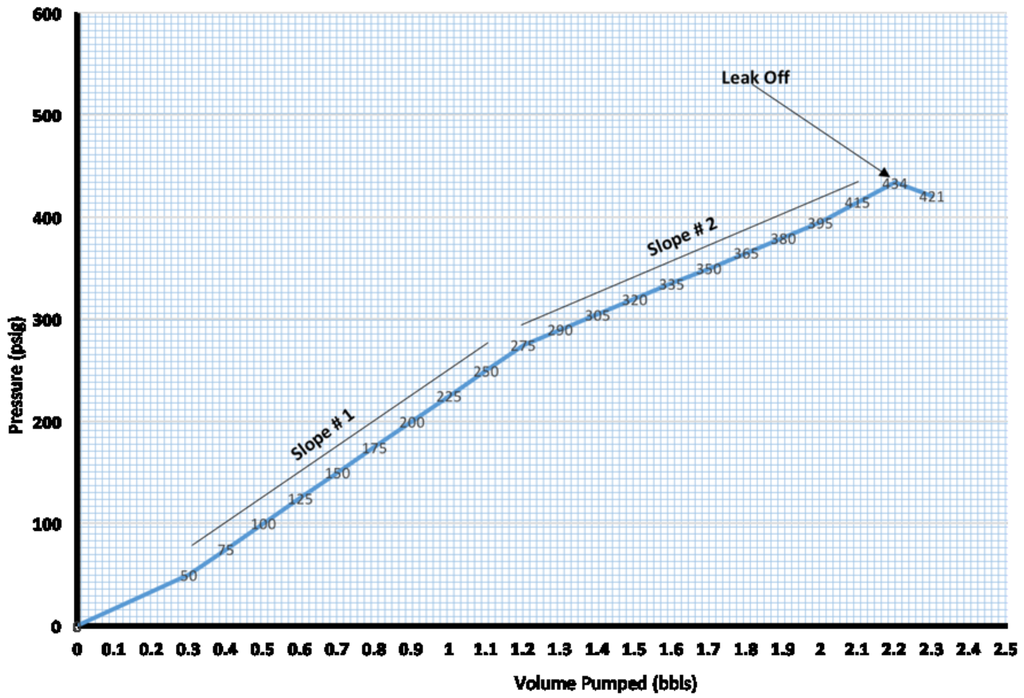
$$Fracture\ Gradient\ \left(\frac{psig}{ft}\right) = \frac{Hydrostatic\ Pressure\ of\ the\ Fluid\ (psig) + Leak-off\ Pressure\ (psig)}{True\ Vertical\ Depth\ (ft)}$$

$$Equivalent\ Mud\ Density\ (lb/gal) = \frac{Fracture\ Gradient\ (\frac{psig}{ft})}{0.433\ (\frac{psig}{ft})}\ x\ 8.33\ (lb/gal)$$

5. EXAMPLES

5.1 Case 1

For this case, consider a well drilled to a true vertical depth of 5,706 ft (1,739 m), with 13-3/8” casing set at 1,750 ft (533 m) TVD (casing point) and a mud density of 8.7 lb/gal. The equivalent 1.0 psi/ft fracture gradient is 1,750 psig (12 MPa). Therefore, the surface pressure should not exceed 958 psig (fluid hydrostatic pressure is 792 psig, hence 1,750 psig -792 psig = 958 psig). The surface reading for leak-off pressure is 434 psig (3 MPa) (Figure **3**).



Volume	Pressure
0	0
0.3	50
0.4	75
0.5	100
0.6	125
0.7	150
0.8	175
0.9	200
1	225
1.1	250
1.2	275
1.3	290
1.4	305
1.5	320
1.6	335
1.7	350
1.8	365
1.9	380
2	395
2.1	415
2.2	434
2.3	421

Figure 3: Case 1 volume pumped and recorded pressure.

The results of this calculation are:

a) Hydrostatic Pressure = 8.7 lb/gal x 0.052 lb/inch^2 x 1,750 ft = 791.7 psig

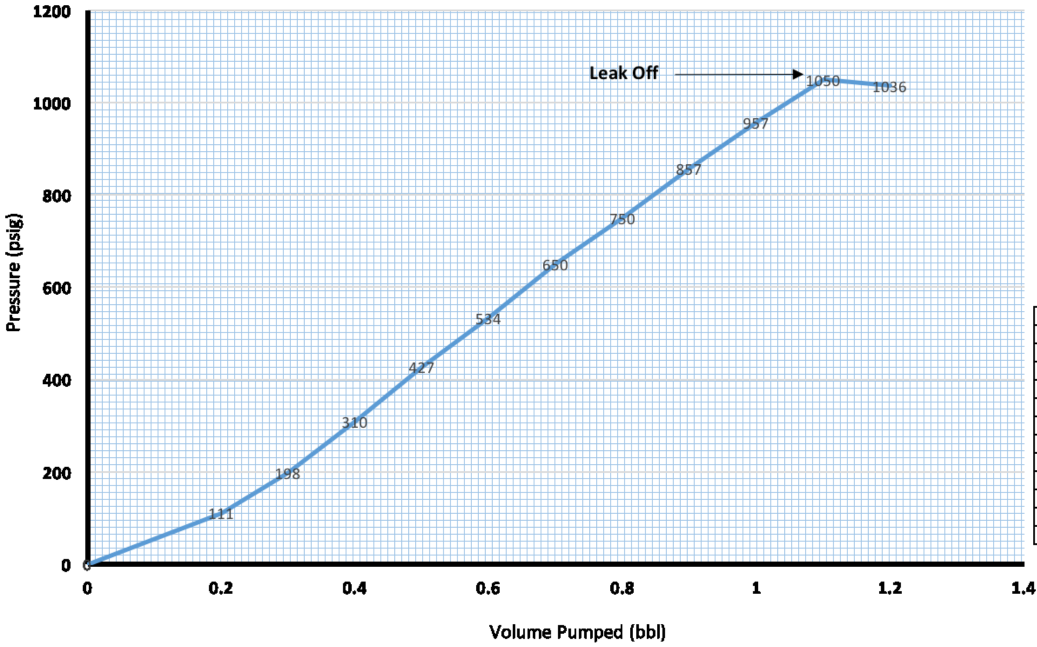
b) Fracture Gradient = (791.7 psig + 434 psig) / 1,750 ft = 0.70 psig/ft

c) Equivalent Mud Weight = (0.70 psig/ft / 0.433 psig/ft) X 8.33 ppg = 13.4 lb/gal

The resulting trend produces two slope segments. A sLOT might have mistakenly determined FIP by not allowing the pressure to stabilize, leading to an erroneous conclusion. The second constant slope provided a higher indicated leak-off pressure. The 0.70 psi/ft fracture gradient shows that the formation is of average strength and drilling can safely continue to the next casing point. By using the sFIT approach, fracture gradient data was obtained, and lost circulation issues were avoided.

5.2 Case 2

For this case, consider a well with 9-5/8" production casing set at 4,315 ft (1,315 m) TVD (casing point) and a fluid density of 8.5 lb/gal. The surface reading recorded for leak-off pressure is 1,050 psig (7.3 MPa) (Figure 4).



Volume	Pressure
0	0
0.2	111
0.3	198
0.4	310
0.5	427
0.6	534
0.7	650
0.8	750
0.9	857
1	957
1.1	1050
1.2	1036

Figure 4: Case 2 volume pumped and recorded pressure.

The results of this calculation are:

a) Hydrostatic Pressure = 8.5 lb/gal x 0.052 lb/inch^2 x 4,315 psi = 1,907 psig

b) Fracture Gradient = (1907 psig + 1050 psig) / 4,315 ft = 0.69 psig/ft

c) Equivalent Mud Weight = (0.69 psig/ft /0.433 psi/ft) X 8.33 lb/gal = 13.2 lb/gal

It can be inferred from the sFIT graph that the pressure was well on the way to creating lost circulation and it was only 2/10th barrels (32 liters) over the leak-off point. If the formation was brittle, another volume increment may have created lost circulation that would require plugging with cement. Again, by using the sFIT procedure, the proper fracture gradient data was obtained, and circulation losses were avoided.

5.3 Case 3

Consider a core hole well drilled to a vertical depth of 1,955 ft through 4-1/2" casing set at 810 ft (247 m) TVD and a circulating fluid density of 8.3 lb/gal. Following the sFIT procedure, the equivalent 1.0 psi/ft fracture gradient is 810 psig. Therefore, surface pressure should not exceed 460 psig (fluid hydrostatic pressure is 350 psig, hence 810 psig - 350 psig = 460 psig). Step pumping was terminated at 460 psig (Figure 5).

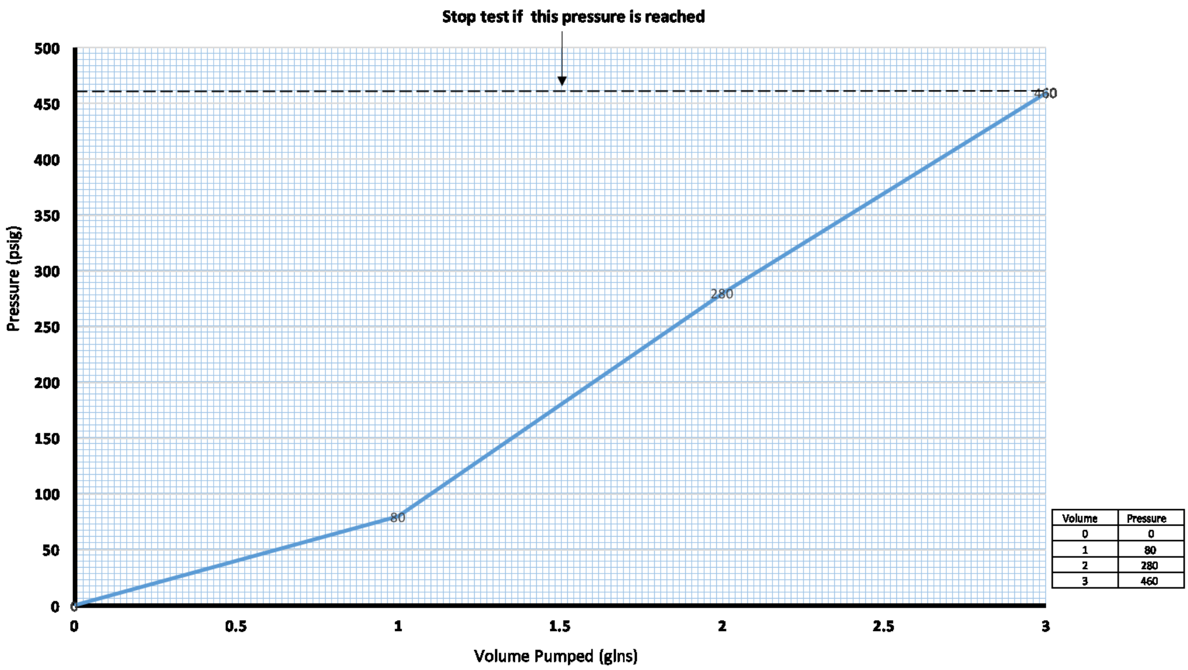


Figure 5: Case 3 Volume pumped and recorded pressure.

The results of this calculation are:

a) Hydrostatic Pressure = 8.3 lb/gal x 0.052 lb/inch^2 x 810 ft = 350 psig

b) Fracture Gradient = (460 psig + 350 psig) / 810 ft = 1.00 psig/ft

c) Equivalent Mud Weight = (1.0 psig/ft /0.433 psig/ft) X 8.33 lb/gal = 19.2 lb/gal

The results show that formation is extremely strong. Using the sFIT method, the fracture gradient data was accurately calculated and circulation losses were mitigated.

6 CONCLUSIONS

The step-rate formation integrity test method (sFIT) is a safe, quick and practical method of measuring the fracture gradient and leak-off pressure or FIP of a casing shoe in a well, minimizing the risk of circulation losses below the casing shoe. As can be seen in the examples (based on actual field data), once FIP is reached, the pressure immediately starts decreasing. This indicates that formation breakdown pressure has been reached. And very little additional volume is required to reach fracture propagation, which can quickly lead to unstable fracture growth and the ensuing lost circulation. Although the more common LOT or FIT procedures provide a method to verify that it is safe to continue drilling to the next casing depth, they don't consider the possible damage caused by pumping additional fluid into the formation, potentially creating loss of circulation issues. The sFIT provides a conservative pressure limit without causing unstable fracture growth and circulation losses, to ensuring that the next interval can be drilled safely. By using the sFIT to determine the FIP of every casing shoe in each area, conclusions can be drawn that may lead to longer open hole intervals, and fewer strings of casing required for drilling future wells.

The sFIT method is conservative and is intended primarily for the drilling engineer and drilling supervisor to be better able to manage the drilling operation and to guide in the design of future offset wells. Classic LOT and XLOT tests are still required to capture the data that is needed for geoscientists to study regional stresses, or for engineers to plan hydraulic fracturing jobs

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