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HOW TO PLAN A SAFE AND SUCCESSFUL PERMEABILITY TEST PROGRAM IN COAL SEAMS

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ABSTRACT: While discussing coal permeability testing, it is often asked what constitutes a successful test and why. An understanding of these concepts will assist the development of an optimum test program that uses appropriate test equipment and procedures. This approach will provide reliable results, which in turn will improve the design, exploitation and economic recovery of gas and coal resources.

The main purpose of this paper is to explain what to do and how to do it safely to complete a successful and cost effective testing program. In this paper, test guidelines are provided which are based on more than 60 years combined experience and over 3,000 tests. Topics discussed are:

1. Understanding and discussing the test objectives between the operator, testing provider, gas drainage and ventilation design engineers to ensure all requirements are known, considered and met.
2. Selection and use of the appropriate testing procedures – Drill Stem Test (DST), Injection Falloff Test (IFT), Step Rate Test (SRT) and vertical temperature measurements.
3. Selection of testing equipment and related information including packer type, testing strings, pressure recorders, packer spacing based on available coal seam data, borehole logs, reference level, wellbore location maps and testing results in nearby boreholes - including gas content and regional pressures if known.
4. Well conditioning practices to clean out debris and mud cake to ensure that the test results reflect the in-situ coal properties.
5. Appropriate relaxation time after the completion of drilling operations to ensure the coal is properly relaxed to reflect as close as possible the in-situ conditions.
6. Full integration of test results to define the coal characteristics and in-situ stress, presenting the results ready for analysis. Pressure, temperature and permeability should be reported with reference to the sea level depth to evaluate the structural effects.

Setting Test Objectives

The proximity of a mining operation affects the coal characteristics in a variety of ways. Typically, a reduction in seam reservoir pressure could affect the DST, IFT and SRT procedures. Therefore, it is important that all parties be engaged in the planning of any program at an early stage. This includes the operator, testing provider, and gas drainage and ventilation design engineers. Experience shows that detailed planning based on analysis of the available data results in less costly delays and program modifications due to site specific conditions. Successful testing is about informed planning from the outset and by having an onsite multi-procedural testing capability. Well Testing is all about getting out there, testing the wellbore and "seeing" a representative amount of coal without exceeding the individual test parameters.

Test Procedure Selection

Each test procedure: DST, IFT and SRT provide permeability and pressure; however some procedures are suited to produce more reliable results for particular coal conditions. For example, a

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DST should not be undertaken in near or fully gas saturated seams as the simultaneous production of gas and water (two phase flow) will not provide the absolute permeability we are trying to measure. In this case the IFT procedure is most useful since only water is injected into the coal. The IFT test can be compromised in low coal stress environments where even moderate injection pressures “jack the cleats open" or fracture the coal seam. This will falsely indicate high permeability. In this case the DST or the SRT should provide more reliable results. The combined SRT and fall off procedure provides the fracture opening and closure pressures as well as the coal minimum stress. Permeability is derived from the Diagnostic Fracture Injection Test analysis (DFIT). The coal stress data is presented with the permeability results derived from DST, IFT and DFIT to help correlate the relationship between stress and permeability.

Note that the coal seam pressure is usually unknown in exploration areas. For this reason, the test operator should have flexibility in the field to decide the best test to run based on the conditions encountered. If the three procedures are run in a seam and the results coincide, this indicates “high confidence”. However, this is not usually the case because each procedure is affected differently by the stress and the direction of the flow. For example, in a DST as the fluid flows from the coal to the wellbore the coal relaxes because of the reduced pressure. In comparison, in the IFT the flow is from the wellbore to the formation and the coal is stressed by the injection.

When the test results produce two out of three permeability readings in close proximity these are selected as the most representative data. It is considered that the comparatively slight increase in time on site required to run the three procedures is readily justified as it assists mine ventilation and gas drainage engineers to produce designs that are more accurate.

Establishing the reservoir pressure: This parameter is vital to confirm that the seam is stable and ready for testing. It is well worth the time spent and particularly applies to coals near mining operations. For consistency, all tests need to start and finish as closely as possible to the seam reservoir pressure. To help achieve the testing objectives the operator should also have capability to assess testing on site so they can respond whilst still there.

DST cushion size: There have been repeated attempts to estimate DST cushion size rules of thumb, which are a very important part of the testing strategy. Since it is necessary to induce a controlled flow from a coal seam, it is important to size a water cushion that is small enough to allow water to flow but not the gas! Three parameters are required to calculate the cushion accurately:

a. Reservoir pressure
b. Langmuir isotherm coefficients
c. Gas content in the coal seam

Assuming the size of the water cushion is risky, and may result in the test failing. Why? Because before conducting the test it is important to be reasonably sure about the value of the reservoir pressure. This is not hard. By simply setting the straddle packer across the target formation this pressure can be measured and the cushion size to achieve a successful DST can be determined.

If a short cut is taken and a reservoir pressure from the normal hydrostatic is assumed water cushion that is too large may be used. Therefore the DST cushion may be injected into a low pressure coal seam, completing an IFT to the surprise of the Tester and the Company man. This is shown graphically in Figure 1. Both the pre flow and main flow have negative slopes indicating water is not produced from the coal. In this case the water cushion is being injected into the coal. At the end of each flow, the pressure falls very rapidly instead of building up. This is another consequence of starting a test not knowing the basic pressure conditions, and using the incorrect water cushion.

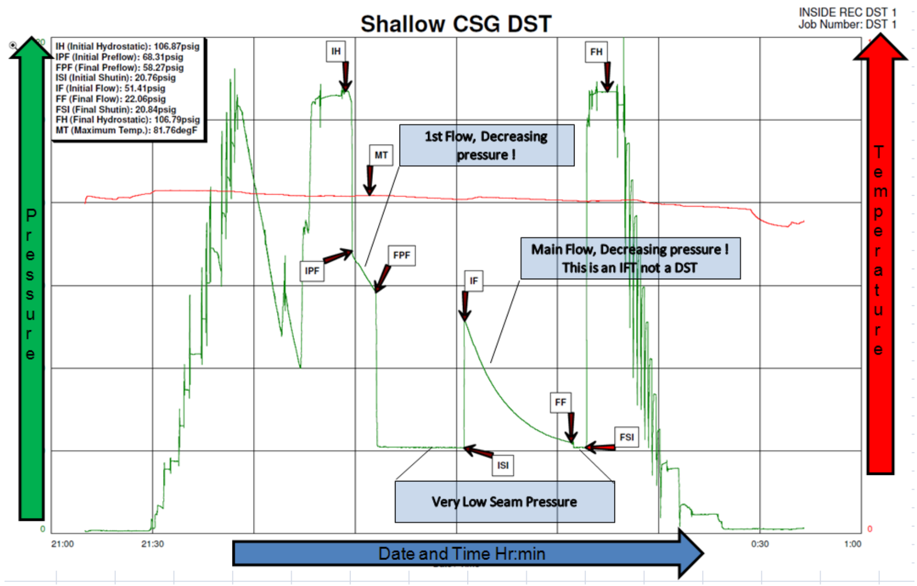

Figure 1: Results of a planned shallow CSG DST that is actually an IFT

Maximum injection pressure: To produce a reliable permeability estimate, the injection pressure must not exceed the coal stress or fracture will result. Exceeding the coal stress generates high injection rates which result in erroneously high permeability. The injection rate must be set to ensure a minimal pressure increase over the duration of the injection period without exceeding the coal stress. In some low stress environments, simply applying the full hydrostatic head pressure to the coal will exceed the coal stress. An obvious sign of this is unusually high injection rates. A good indicator is assessing the permeability derived from the DST test. If this shows a good history match, then there is a reasonable probability that the IFT permeability is correct. If the IFT permeability is too high compared to the DST results, then there is a probability that the stress was exceeded and the IFT test is invalid.

A SRT consists of multiple injection rate increases of equal time durations. It is undertaken at the end of the test sequence. The DST should always be run first since the minor drawdown used will not damage the wellbore. The IFT is run as the second test without moving the packers so the same test interval is used. The well is tested using this rationale on the way down. The SRT is run on the way up. Even when there is some minor fracturing close to the wellbore this does not create problems when moving the tool upwards after each seam is tested. The SRT will induce pressure increases into the formation by increasing the injection rates as shown in Figure 2, taking the formation to breaking point, defining the Fracture Extension Pressure. Even though the SRT is completed in 40 minutes or so, it provides very useful information to avoid exceeding the fracture pressures during the subsequent IFT.

A regression analysis using the Nolte Smith G function applied to the pressure fall off data provides the Closing Pressure as shown in Figure 3. This then provides the Effective Stress which is defined as follows:

Effective Stress = Fracture Closing Pressure – Reservoir Pressure

For this reason, the Effective Stress represents the net pressure (stress) confining the coal seam, which is also called the coal confining stress.

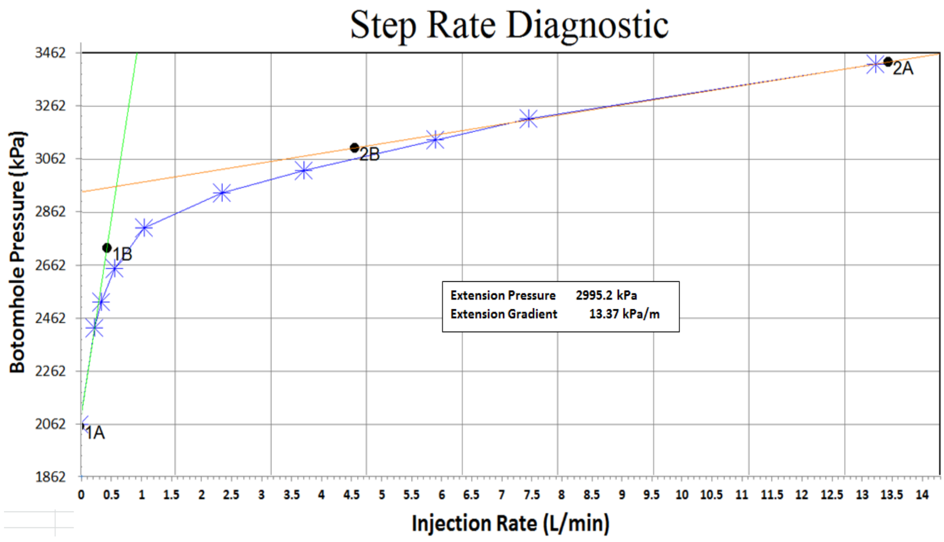

Figure 2: Step rate test of coal seam, with estimation of Fracture Extension Pressure

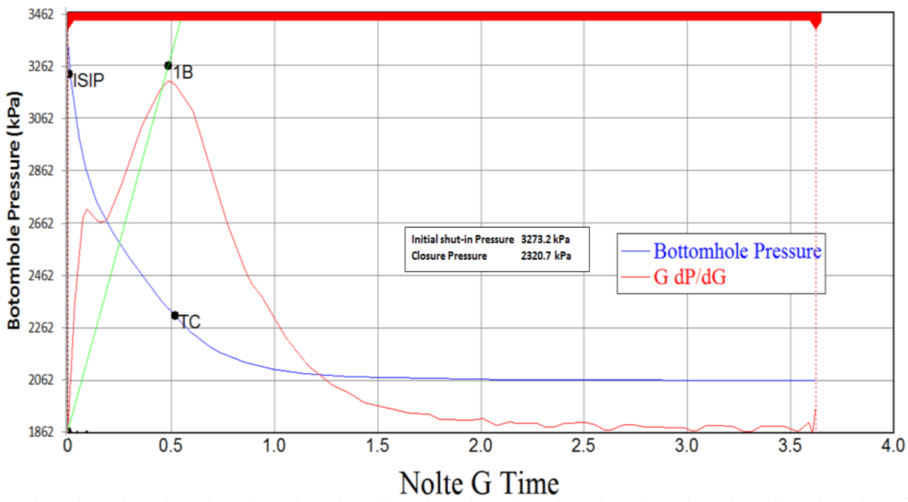

Figure 3: Coal closing pressure determination

Test equipment selection

The packers: For a long time DST and IFT tests were conducted with mechanical packers which were set with string weight. In open hole testing sometimes this weight on the string caused the packer to slide down when the formation was not competent or was fragile, causing not only an invalid test but also borehole instability that could generate tool trapping. If the conditions are favorable, the mechanical packers work. Since the introduction of inflatable packers, which are more reliable and easy to operate, test operators prefer their use.

Straddle inflatable packers are now very reliable particularly those using water as the inflation fluid. Experience operators do not recommend packer inflation using high pressure gas since this increases the risk of well site accidents. It may also create wellbore control issues if the gas is released down hole due to packer failure.

Test tool design*:* Most test holes intersect multiple coal seams at various depths and pressures. When the straddle packer inflates to isolate a specific coal seam it also isolates the section below the test tool from that above. If a seam below the tool has low pressure (a pressure sink zone), any gas generated in the hole would migrate to this sink zone during the test duration, which is typically 12 – 36 hrs. The formation of a gas pocket below the tool, when the packers deflate can cause a well "kick" as this free gas now rises to the surface pushing water out of the hole as it comes up. Typically, the current pressure of all the seams intersected by the well is unknown at test time, therefore, it is difficult to prevent this problem. To mitigate this effect, the tool design incorporates a fluid connection path to equalize the pressure above and below the tool. This is an important safety feature that has proved successful for many years.

Testing strings: Typically, permeability service providers utilize two types of strings: - Wireline Drill Rods and dedicated Test Strings.

Wireline drill rods: When used for testing purposes, these can leak at the tool joints - even new rods tend to exhibit some leakage and old rods are prone to more severe leakage due to fatigue. Permeability estimates from the DST and IFT are directly related to the accuracy of flow rate measurements. Hence, a leaking string will increase the apparent permeability of the coal. The water pumped from surface is assumed to be totally injected into the target coal when in reality a fraction of that is leakage. Furthermore, due to the small wall thickness of the drill rods, the threads do not have a perfect metal-to-metal seal. The use of liquid Teflon or other materials to prevent leaks is problematic as the deformation and stress induced onto the threads by these materials tends to shorten the life of the test string. Therefore, there is a high probability that a wireline drill rod, which is often used by the drillers, will have some leakage compromising the test results. In particular, when permeabilities are small, even a very small leak will create a significant error in permeability. Have you ever heard the comments “the coal permeability is low and the permeability estimates are all over the place”? When considering the methodology used, leaking strings may have contributed to that problem and this poses a question. Is the scatter real, or a result of adopting less than best practice? This is a dilemma for the end user given what is potentially at stake. Therefore, if wireline drill rods must be used for permeability testing, to confirm the validity of each result, it is recommended to test and record for rod leakage before and after each test is conducted.

Dedicated test strings: Leak proof test strings provided by test operators have a major advantage. They are designed solely for the purpose of testing and ensure that 100% of the injected or produced fluids are accounted correctly. Figure 4 provides an example of how a leakage error affects the water rate and the permeability estimate in a coal seam. This chart simulates a coal seam where the only variable is permeability. Note that a rate increase from 100 L/d to 200 L/d corresponds to a permeability increase from 2 md to 4 md. This is a slope of 50 L/d per md or about 2 L/h per md. Therefore, if the injection rate has an error of say 2 L/h the permeability will be overestimated by 1 md. Assuming the true permeability was 10 md and that because of the leakage the permeability will be computed 11 md, with 10% error. Conversely, if the true permeability was 1 md, the permeability will be calculated at 2 md with a 100% error.

Due to this effect, leaks through either a test string, surface lines or in the packer's bypass will result in an apparent increase in permeability. This problem becomes more serious as permeability decreases or the injection pressure rises. A professional test operator will always detect and solve equipment and packer leaks aiming to provide quality results.

Pressure recording: Technology changes in the last 30 years have created a revolution in well testing. Operators have moved from mechanical pressure gauges that used metallic pressure charts that were loaded into a chart reader with micrometers, so that pressure readings could be made every few minutes. This was time consuming and potentially inaccurate. Electronic memory gauges record downhole pressures and temperature. However the test string had to be brought back to surface to recover the gauge, and download the data for analysis. Currently Surface Read Out systems that provide real time pressure and temperature data at the surface as the test proceeds are used.

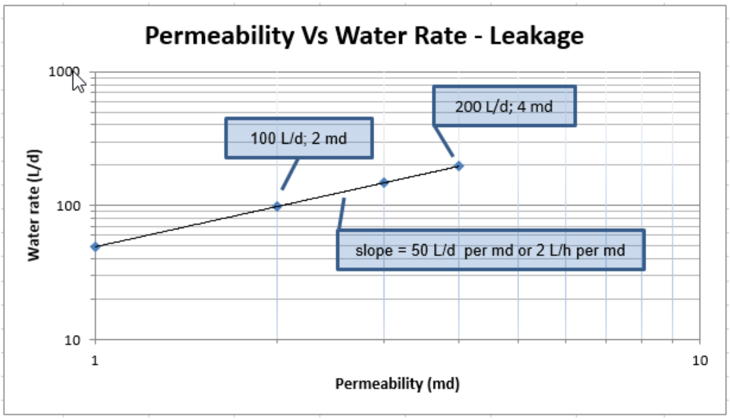

Figure 4: Possible errors due to a HQ test string leakage of 2 L/h

This allows the operator to "drive" the test through its stages ensuring "best practice test procedures" and allows optimization of test duration and results. With this approach, the data quality has improved significantly whilst also reducing costs by eliminating unproductive time.

Temperature profile from DST data: The Surface Read Out system allows the pressure and temperature data to be seen at real time as the test develops ensuring test optimization and minimum duration. However, we do not always use all the information available. Although pressure gauges record pressure and temperature, most of the time only pressure data is analysed. Traditionally, geological logs are used to record the coal seam depth and hole temperature immediately after drilling. However the recorded temperature is lower than the actual reservoir temperature due to the cooling effect of the drilling fluids. The main advantage of the DST temperature is that the test is run a few days after the well is drilled after the reservoir has had sufficient time to recover to its true temperature. These readings are far more representative than those derived from the geological logs because the DST produces water from each isolated coal seam.

Very accurate DST temperature profiles for a number of projects have been generated, confirming the reservoir temperatures at which the LANGMUIR ISOTHERMS should be prepared, Figure 5. Temperature data also helps pinpoint potential cross flows between coal layers. This is of interest to the mine design or development engineers. Adjusting the depth scale to subsea depth, allows for a meaningful correlation of temperatures across the field/mine area, identifying cross flows between seams. Underestimating the reservoir temperature implies over estimating gas contents which may considerably increase the mine development costs.

The message is: to avoid costly mistakes, use the temperature from the DST's that are run a week or two after drilling the wells.

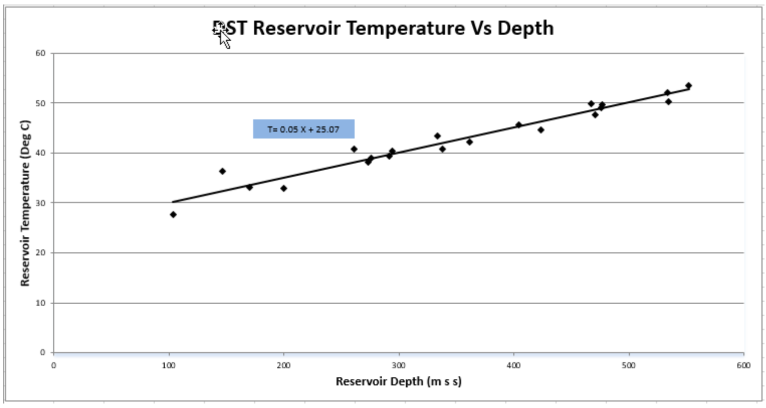

Figure 5: Field temperature gradient from DST measurements

Well control

Although Well Control is a specialized topic beyond the scope of this paper, some points need to be observed. Well Control aims to keep the well and crew safe during the test and prevent uncontrolled gas flow into the hole by keeping the hole full of fluid at all times. This is the best insurance and the basis of well control principles. The hydrostatic pressure must be greater than the seam desorption pressure to ensure no gas flows into the wellbore. To avoid a potential gas kick, it is strongly recommended not to deflate the packers until both the test rods and annulus are full of fluid, and the coal seam is essentially at reservoir pressure. This ensures that there is no potential gas kick from the seam. Once the packers are deflated control could be lost since it takes valuable time to re-inflate. Pulling the test tools out of the hole (POOH) causes swabbing and potentially induces gas flow. The operator needs to POOH slowly while keeping the hole annulus full with fluid to prevent gas kicks. This is mandatory. Moreover, remember that test tools/rods have volume and as removed from the hole, the hole water level will drop!

Be wary of holes that suddenly appear to be making water (like artesian wells). If the water is lifting and flowing from the hole, there is a reason. This could be gas release from a seam pushing the water out.

Well conditioning

During drilling operations the mud viscosity is increased with additives to help keep the hole clean by lifting the cuttings to the surface. It is always recommended to have some extra rat hole below the lower coal seam to allow for the accumulation of fill, leaving sufficient room for the test string and tool to operate properly. After reaching the total depth, the hole is circulated clean and logged in preparation for testing. Quality testing requires that the wellbore be circulated clean with water before the test, to remove viscous drill mud and cuttings. When estimating the coal permeability by measuring the water flow through the coal, contaminated fluid will affect the results. If an IFT is conducted and viscous mud is wrongly injected into the coal instead of clean water, then the estimated permeability is going to be significantly lower. As a result the coal could be dismissed by the miner or the coal seam gas operator.

For example Figure 6 shows that the injection rate in a 2 md coal is inversely proportional to the fluid viscosity. For the same injection pressure, this 2 md coal could take either water at 230 Lpd or 2.95 cp mud at 66 Lpd.

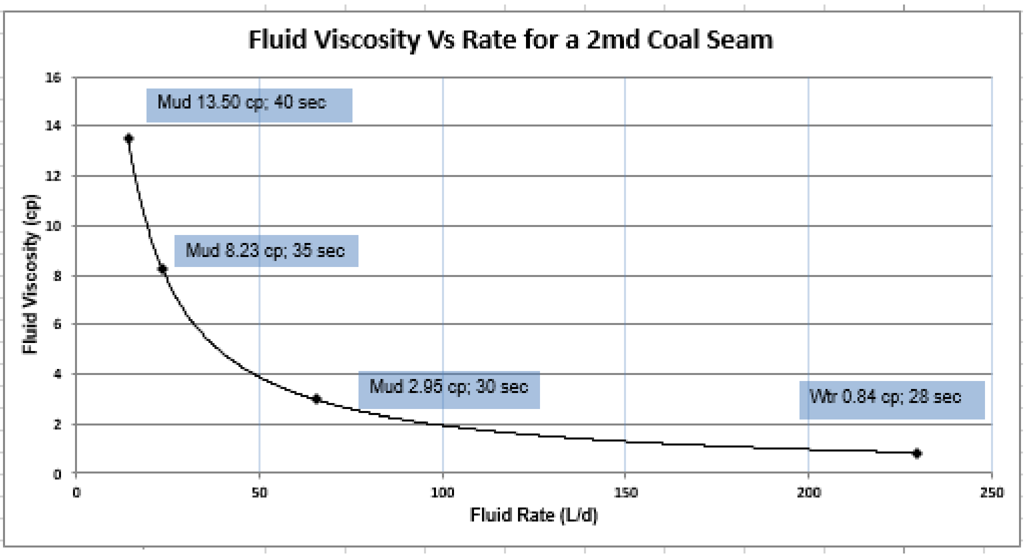

Figure 6: Relationship between viscosity and injection rates for a 2 md Coal Seam

However if the test injects mud instead of water and the viscosities are not used correctly, the estimated permeability will be wrong as shown in Table 1.

Table 1 – Example showing relationship between rates, viscosity and permeability

Injected Fluid	Rate (Lpd)	Viscosity (Cp) @ 30 Deg C	Estimated Permeability (md)	Comments
Water	230	0.84	2.00	Correct
Mud	66	2.95	2.00	Correct
Assuming Water instead of Mud	66	0.84	0.57	Incorrect Perm

If the well was not conditioned properly and the mud was not fully replaced by clean water, we could still salvage the IFT by recalculating the permeability using the drill mud viscosity records that are traditionally measured and recorded at the drill rig using the Marsh Funnel.

Post drilling seam relaxation time

In the majority of cases, the coal seam reservoir pressure is observed to be lower than the full hydrostatic head pressure. Drilling through such an environment exposes the seam to this full hydrostatic pressure, essentially resulting in an “injection test” because of the “positive” pressure increment exposure. In our view, it is important to let the water level in the hole stabilize upon drilling completion for a few days prior to testing to let the seams equilibrate to a stable condition. This needs to be coordinated with the Operator to avoid potential hole stability issues.

Integration and presentation of results

Step rate test and DFIT analysis - Data integration

The use of the DFIT allows the permeability results across a site to be placed in context, comparing the DFIT, DST and IFT permeability results against the minimum stress. This is very important since it provides an opportunity to critically review and integrate the results of various testing campaigns in a particular area where stress and faulting occur. Figure 7 presents an example.

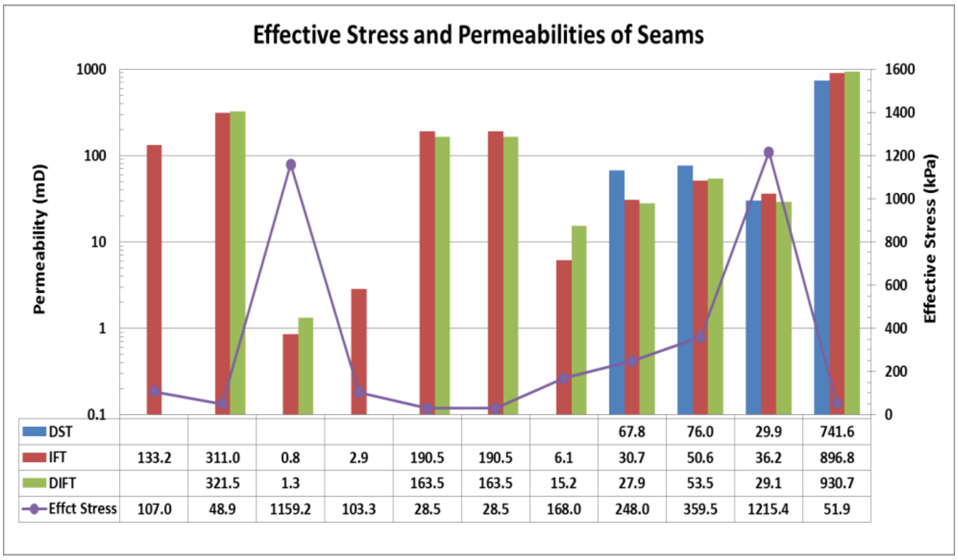

Figure 7: An example of integration of field permeability and minimum stress

In low permeability conditions both the DST and IFT may have limited radii of investigation and both can be materially influenced by near well bore damage (high skin for example). This could result in a situation where the DST and IFT potentially underestimate the coal permeability. The recent development in DFIT analyses allows permeability estimation based on fluid diffusion in the fractures within the coal. Fracturing the coal allows the test fluid "to get out there" and see clean undamaged coal.

Finally, the pressure, temperature and permeability results estimated at specific depths need to be reported at a sea level depth so as to account for the topography/changes in the area. This is computed using the wellbore elevation and the well logs depths.

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