Wellbore Integrity – Cuadrilla Land Based Wells

1.0 Introduction

In discussions about oil and natural gas wells, we often use the term "**good wellbore integrity**" to mean that the well is constructed in a manner that will prevent any unplanned release of well fluids or gas to the atmosphere or to other shallow formations underground, either through leakage in surface wellhead equipment, or from the well casing or cement in the wellbore. One of the key concerns is the protection of groundwater from well fluids and/or natural gas.

There is often the misunderstanding that wells drilled for producing natural gas from shale reservoirs are more likely to be a threat to groundwater supplies than wells drilled into conventional oil and gas reservoirs. In reality however, the standards for wellbore design and construction are identical for all types of oil and gas reservoirs, whether the reservoir is comprised of sandstone, shale, limestone, dolomite, etc. Achieving good wellbore integrity starts with a well design that uses industry best practices, and a lot of common sense.

This document provides a down to earth discussion about the Cuadrilla well operations in the Lancashire region, and the special measures we take in our drilling operations to achieve good wellbore integrity. For this discussion we will use our first well, **Preese Hall #1**, as an example.

2.0 Well Schematic - Preese Hall #1

Figure 1 is a casing diagram of the wellbore at the Preese Hall-1, which was drilled to a depth of 9097 ft. The 3 principle hole sections shown here are the surface hole, intermediate hole, and production hole. In addition to the 3 casing strings there is also the "cellar" and "conductor pipe". To help make our points about wellbore integrity, each of these hole sections and casing strings are briefly discussed in the following pages.

2.1 Well Cellar

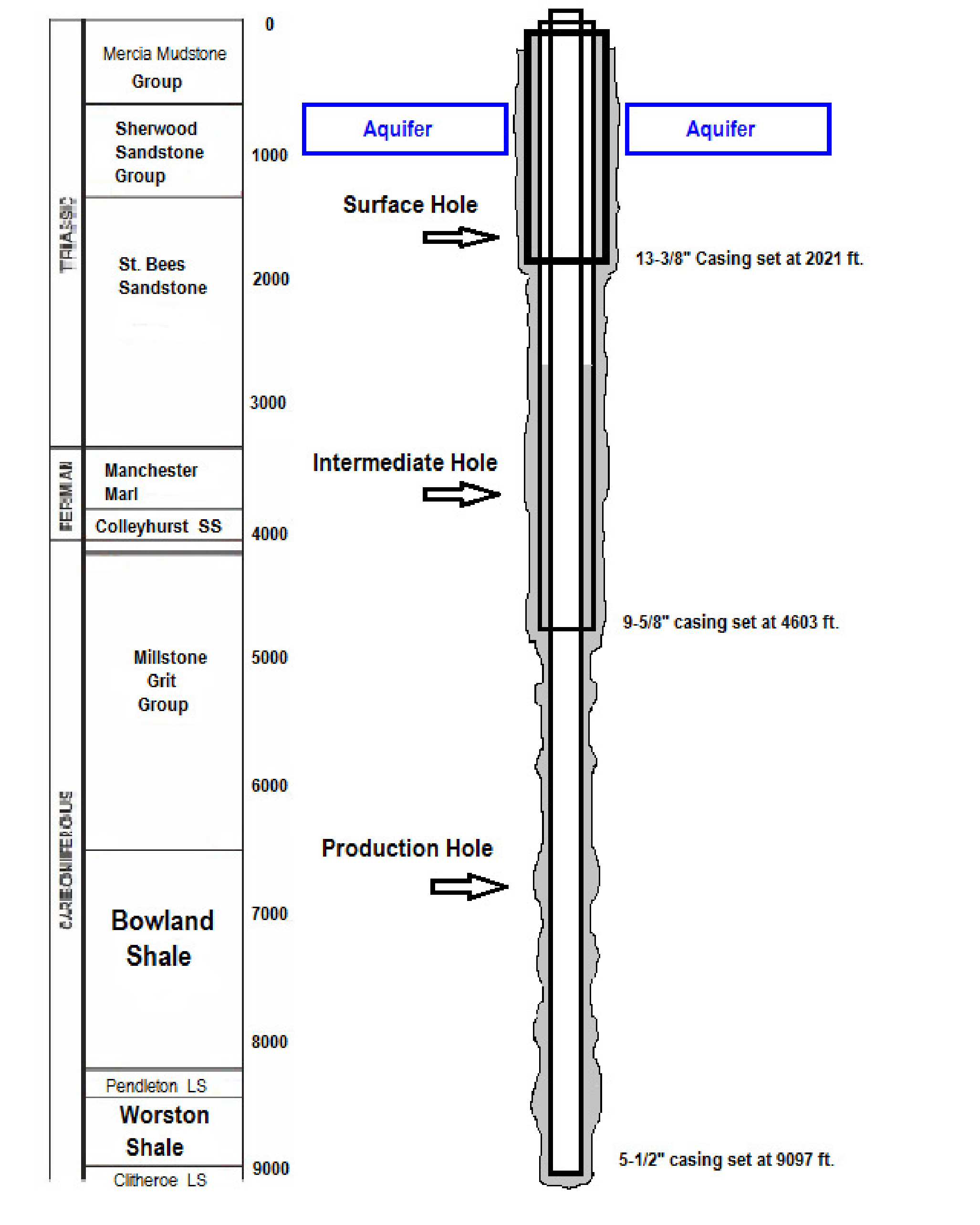
The cellar is a concrete cylindrical structure that is built into the ground, which is the starting point for the well. It is made of concrete rings that are approximately 3 meters in diameter and 3 meters from the ground level to the bottom of the cellar. The floor of the cellar is concrete, and the entire structure is sealed and leak-proof. The cellar provides ample work space below the rig floor to accommodate the installation of the BOP (blowout preventer), and it reduces the overall height of the wellhead to mitigate surface impact.

2.1 Conductor Pipe

The drilling operation starts with the installation of the conductor pipe. The purpose of the conductor pipe is to provide a steel casing through the shallow layers of soil, sand and gravel, and any shallow water seams that may be encountered close to surface. Typically the hole for the conductor pipe is drilled down to the first solid bed rock, then the casing is lowered into the hole, and cemented back to surface. Once installed, the conductor pipe isolates shallow water seams and prevents loose soil, sand and gravel from falling in on the drill bit as we start to drill our surface hole section. In our Preese Hall #1 well the conductor pipe is a 20 inch casing, set at a depth of 100 ft and cemented back to surface in a 26 inch diameter hole. It was installed using a small water well rig, so it was in place when our deep hole rig arrived on site to start the surface hole.

Figure 1

Preese Hall #1 - Well Schematic



2.2 Surface Hole Section

The purpose of the surface hole section is to drill past the deepest fresh water zones, or known aquifers, and cement a steel casing across the water zones that we are intending to protect. One of the key conditions presented in our planning permit from Lancashire County Council is that we must demonstrate that our well will be constructed in a manner that will provide complete protection of the Sherwood Aquifer. Prior to the start of drilling operations we hired a UK water consulting firm who advised us that the bottom of the Sherwood Aquifer would no deeper than 1200 ft in depth from the surface.

In many of the wells in other parts of the world, it is typically required to set the bottom of the surface casing only 50 to 75 feet below the bottom of the deepest water zone that is to be protected. However, in the interest of deploying best practice for groundwater protection, we have made it our standard policy that we will always set the surface casing at depth of between 500 ft. to 1000 ft. below the bottom of the aquifer. In that regard, for the Preese Hall -1 we have set the surface casing shoe at a depth of 2021 ft, which is about 800 ft. deeper than the bottom of the aquifer. We used a 17-1/2" bit to drill the surface hole, and we then installed 13-3/8" surface casing (K-55 grade, 61 lbs/ft) and cemented it back to surface.

2.3 Intermediate Hole Section

The purpose of the intermediate hole section is to tie the wellbore into a regional sealing formation. This is done to prevent formation water or hydrocarbon leakage (from the deep producing zones) from reaching shallow formations and groundwater. This is probably the most important string of casing in the wellbore, with regards to achieving good wellbore integrity.

In the Preese Hall #1 well we have used a 12-1/4" drill bit for the intermediate hole, and have drilled to a depth of 4630 ft MD. We then ran 9-5/8" intermediate casing to a depth of 4603 ft. MD, and cemented it back to surface.

The regional seal formation in our Bowland Shale project is the **Manchester Marl**. There are no oil or gas deposits found above it (at least in the Bowland Basin). And it is a proven cap rock to the Colleyhurst Sandstone and the hydrocarbon bearing Carboniferous shales. By ensuring that we have our intermediate casing cemented through the Manchester Marl we ensure that gas or well fluids cannot migrate uphole to any water zones.

2.4 Production Hole Section

The primary purpose of the 5-1/2" casing is to provide wellbore isolation between the various depth intervals that we may decide to hydraulically stimulate. That is, the section of 5-1/2" casing that is cemented over the Carboniferous formations is not intended to serve the purpose of groundwater protection, as it is going to have holes placed in it to connect the formation to the wellbore. Rather, our focus on cementation of this string is to ensure that we get the most value in our hydraulic stimulation program through precision placement of the stimulation fluid.

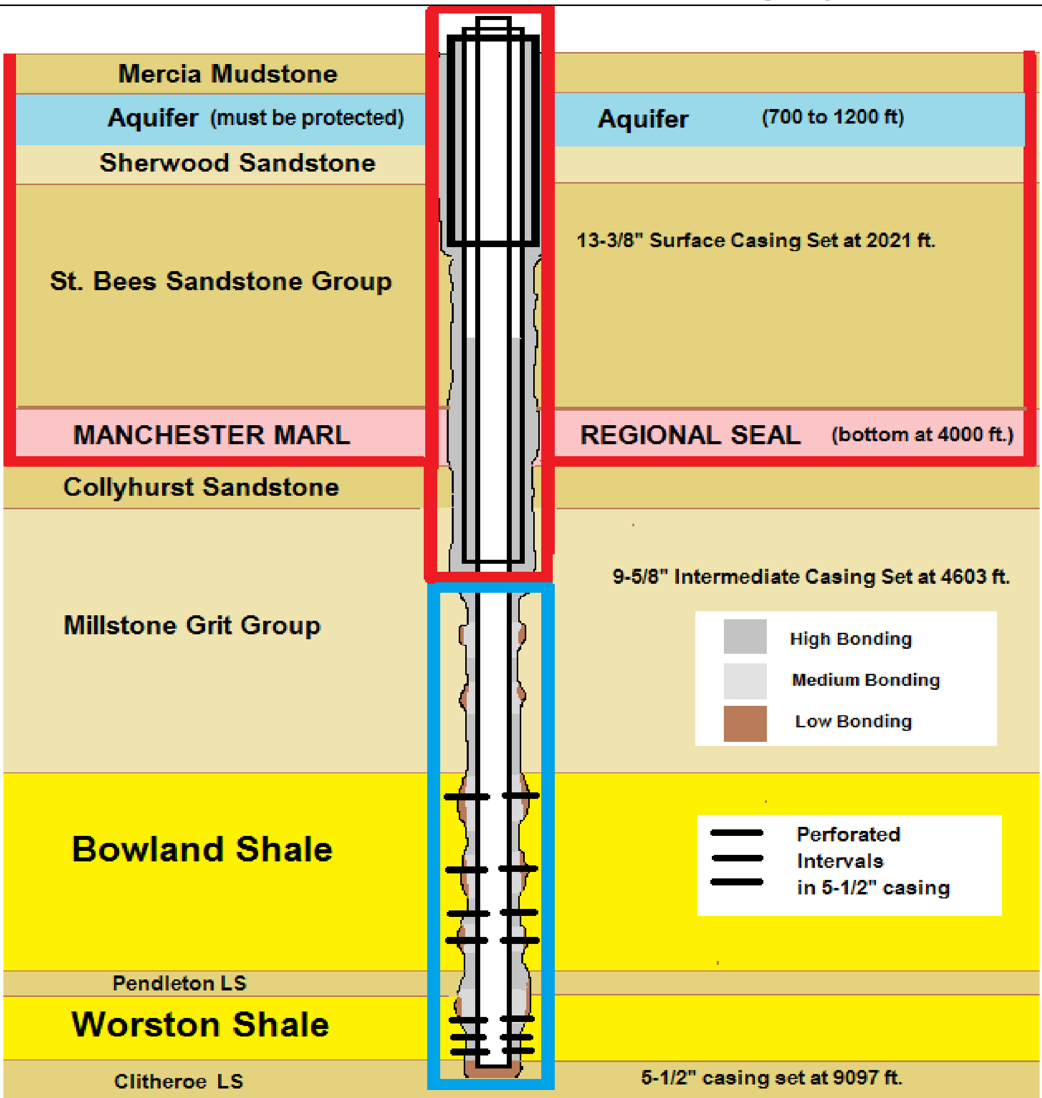
In the Preese Hall #1 the production hole section was drilled with an 8-1/2" bit to a measured depth of 9097 ft., and penetrated the Bowland and Worston Shale sections. A string of 5-1/2" P-110 casing was then cemented in place and the cement top (by design) goes up inside the 9-5/8" casing to a depth level of 2600 ft, and has a rated work pressure in excess of 10,000 psi. This exceeds the work pressure needed to conduct the hydraulic stimulation program and testing of the well. More importantly however, it provides a work pressure that is more than 2 times higher than the maximum wellbore pressure that could be seen during normal well operations.

3.0 Understanding Wellbore Integrity

The protection of the shallow groundwater zones is achieved through good wellbore integrity in the <u>upper half of the well</u> (i.e. surface casing and intermediate casing).

This statement is best demonstrated in **Figure 2** where we have shown the well as being divided into 2 sections. The **red box** surrounds the upper half of the wellbore and defines the wellbore integrity of the surface and intermediate hole sections. It also extends around the Manchester Marl formation, which is the regional seal formation that protects the upward migration of reservoir fluids or natural gas from the deeper formations. The primary concern here is protection of all shallow formations, including freshwater aquifers. The **blue box** surrounds the lower half of the well, and defines the wellbore integrity across the potential gas zones that we may want to test. Our primary concern here is to achieve good zone isolation for the purpose of completing and testing potential hydrocarbon intervals.

Figure 2
Preese Hall #1 - Wellbore Integrity



4.0 Achieving Good Wellbore Integrity in the Upper Part of the Well

Good wellbore integrity starts with the use of industry best practices for ensuring that we get a good cement job on the surface and intermediate casings. Here are several of the more important steps that we take to make certain we have good cement jobs.

4.1 Pre-cement Procedures

We design our cement slurries using all industry recommended slurry design standards for thickening time, setting time, compressive strength, free water, and fluid loss. For new slurry designs we run a full suite of cement tests, using the actual dry cement and the mix water that will be on-site for the cement job. The cement slurry design work is conducted days, and in some cases weeks, in advance of pumping the job. Additionally, when the hole section has been successfully drilled we run a hole calliper log (as often as possible), to detect any sections of enlarged hole. This information is used to calculate the correct volume of cement needed to fill the annulus (i.e. the space between the casing wall and the drilled hole) from the casing shoe back to surface. Once we have made that volumetric calculation we typically run additional "excess" cement, as a safety factor to ensure we get sufficient cement returns to the surface during the mixing and pumping operation.

4.2 Conducting the Cement Jobs

Achieving a good cement job starts with first preparing the hole, by circulating and cleaning it before casing is run, then again after the casing is on bottom. And it is highly important that we use the right grade of casing, the right amount of casing centralizers, and the right type of casing shoe and float assembly (which acts as a check valve to prevent any backflow of cement inside the casing).

Another very important point to mention here is that during our job design process we take into consideration the hydrostatic head pressure of the column of our cement slurry (before it hardens) to determine if it could potentially exert too much pressure on the exposed formations deeper in the hole section. If we determine that could potentially be a problem we will run a 2 stage cement job. This involves the addition of a specialized stage cementing collar assembly to our casing string, which helps us ensure that the cement column does not feed into an exposed formation.

The cement mixing and pumping equipment that we use was purpose built for us in 2010. The purchase price was in excess of £ 1 million, and it has fully automated controls so that we can program our job into the onboard computer, and the unit will mix the cement slurry to all the correct specifications. It also provides a continuous recording of all of the key parameters, so that we have a detailed record of things like cement density, rates for mix water and dry cement, injection pressures and rates, etc.

As part of the quality control procedures we physically measure the cement density using the industry standard mud balance scales (pressurized type). This provides a back up measurement to be compared with the onboard density calculation on the cement mixing unit. Additionally, we collect cement slurry samples every few minutes throughout the job and label them with the sample number, the time collected, and the measured density. These provide the very best indication that we have pumped good cement and they are retained for future inspection, should there ever be any questions about the quality of cement job that has been pumped.

Finally, we employ the basic quality control procedures including pipe centralization during the cement job. And we displace our cement at a flow rate that enhances mud removal. This also helps to ensure we get the good mud removal.

4.3 Cement Evaluation Procedures

When the cement slurry has been mixed and pumped, the operation is shut down for a period long enough to allow the cement slurry to harden to a compressive strength sufficient to hold the casing in place while the drilling operation re-starts, and continues through the next hole section. Typically this is a 24 hour period, but it should be noted that the cement continues to harden and build compressive strength and may require days, or in some cases weeks, to reach its maximum compressive strength. Prior to the re-start of drilling operations we closely examine the cement samples that were collected during the job, and no drilling commences until we have determined that the cement has hardened to a point that it is strong enough to withstand the drilling operation.

When we determine the cement has reached a sufficient compressive strength we rig up to start drilling the next hole section. The drill bit is lowered into the well until it comes to rest on the cement shoe at the bottom of the casing string that has just been cemented. We then drill through the casing shoe, and the cement in the bottom of the hole section, then we drill approximately 20 feet of new rock. At this point we stop drilling and perform a **Formation Integrity Test** (or **"FIT"**).

> **NOTE:** The **FIT** is one of the most important steps in the entire drilling and cementing operations with respect to proving that we have achieved good wellbore integrity.

The purpose of the FIT is to apply hydraulic pressure to the newly drilled formation, and to the hardened cement at the bottom of the casing string. It is conducted by closing the BOP at the surface (around the drill pipe), then applying fluid pressure in a step-rate manner, from lowest to highest pressures, so that we can determine that neither the exposed rock nor the cement will allow any fluid leakage at the maximum pressures that could be seen from the well, during drilling operations or during production operations. The FIT is designed around what we refer to as "equivalent mud weight", which is the industry standard method for equating the range of pressures we apply during the FIT to the mud weight that is needed to hold back the reservoir pressures as we drill deeper.

To put this in perspective, the average mud weight we used during the drilling of our Preese Hall well was 9.2 ppg (pounds per gallon) during the surface hole section, but the equivalent mud weight used during the surface FIT was 12.5 ppg, which gave us a 25% safety factor in terms of proving the pressure that our cement job and upper formation could withstand. For our intermediate hole section the average mud weight used was 10.5 ppg, but our intermediate FIT was conducted at 14.5 ppg, thus giving us a near 40% safety margin.

In the end, what the FIT proves to us is that once the well is put into service, the pressure from the natural gas in the deeper reservoirs absolutely cannot get past the bottom end of the 9-5/8" intermediate casing, or through the formation that the casing is cemented through. And because we cement the intermediate casing through the Manchester Marl, which is the regional seal to upward migration of oil or gas, we can say with full confidence that we have good wellbore integrity when we are finished with the well. Moreover, in the very unlikely event that the intermediate casing experiences a failure, our FIT done previously on the 13-3/8" casing ensures that no fluids or hydrocarbons can get past that casing shoe and reach the aquifer, 800 ft farther up the wellbore.

Note: *Because of the critical importance of the FIT on both the surface and intermediate hole sections in the wellbore, we do not continue drilling any new hole section until we have first established that we have full wellbore integrity on the hole section that we just finished.*

Note: *We are required to report the results of the surface and intermediate formation integrity tests to the HSE through our weekly reporting requirements to them.*

A second method used for cement evaluation is the use of a **Bond Log**, or sometimes referred to as a "CBL". A bond log is generated from a specialized instrument package that is lowered into the wellbore on multi-conductor wire. It uses sonic measurements to provide us with an indication of how well the cement slurry "bonds", or "adheres", to the steel casing once it has hardened. While the FIT ensures us that no pressurized fluids or hydrocarbons can get around the casing shoes for the intermediate and surface casing strings, it does not tell us anything about the cement quality behind the pipe. In that regard, the bond log provides a good backup to the FIT in that it allows us to obtain some estimate of how well the cement has bonded to the pipe and formation.

But the bond log by itself is not always a reliable indication of the amount or quality of cement that is present between the casing and rock formations. It is entirely possible to mix and pump a perfect cement job, and observe cement returns at surface, and still get a bond log that indicates that there are sections where there is low bonding. This can happen in cases where we have a "micro-annulus" which is an extremely thin gap (less than 0.05 mm) between the cement and the outside of the casing. This gap does not necessarily mean that we don't have good zone isolation, as it is typically too thin to transmit fluid flow. But if the bond log is not properly interpreted it can suggest (incorrectly) that there is no cement behind the pipe.

Another reason for indications of poor bonding can be an irregular or enlarged hole diameter, that occurred during the drilling operation. If the hole diameter is large enough it is possible that the cement will not remove all the drilling mud, as some of the mud can become trapped in the outer part of the enlarged hole. This would result in a low bond indicated on the bond log at that particular spot, even if good cement is present, fully hardened, and well bonded to the casing.

Note: *We are required (through our approved well design) to run a bond log in the upper casing sections if we observe any of the following issues during or after a cement job.*

- *Cement did not circulate to surface during the job*
- *There were significant problems encountered with mixing and pumping the cement*
- *The FIT indicates leakage past the casing shoe at pressures below expected reservoir pressures*

On the first 2 wells we did not run bond logs on the upper casing strings, as we had good cement circulated to surface, and we had good results from the FIT's. However, we have committed to run surface and intermediate bond logs as a standard practice on future wells, as often as is reasonably possible, starting on our 3rd well.

5.0 Wellbore Integrity in the Lower Part of the Well (across gas producing zones)

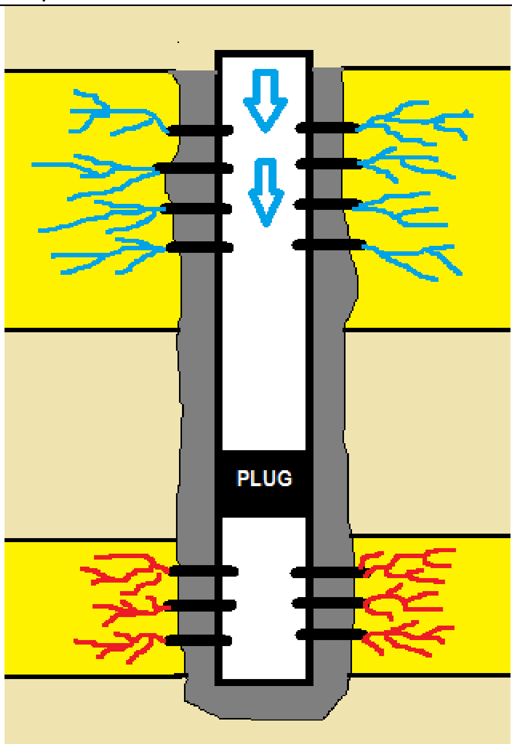
5.1 Wellbore Integrity Requirements

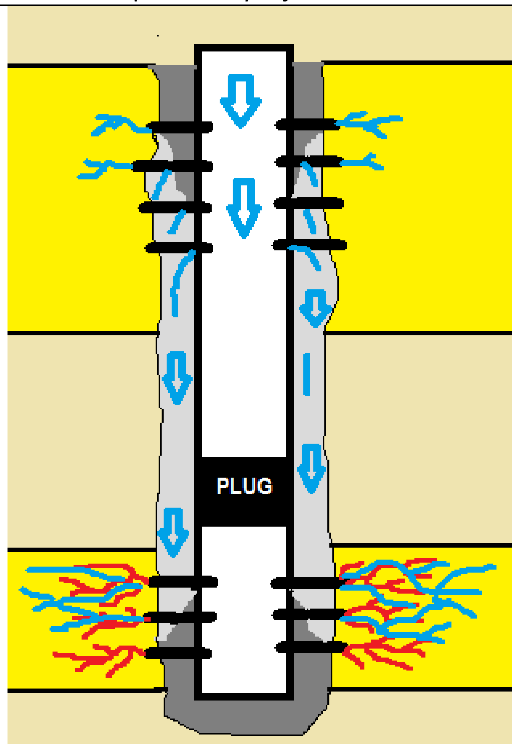
The main purpose of the cement job in the production hole section is to provide good isolation between the various potential gas zones that we may want to test. As an example of why this is needed, let's look at how we typically conduct a multiple-stage hydraulic fracture program.

The very first zone that we frac is the lowermost zone in the wellbore. We install perforations in the 5-1/2" casing adjacent to the interval where we want to inject water and sand. We conduct the hydraulic fracturing process, then we prepare for the next stage of the frac and test program. At this point we would set a "casing plug" above the perforated interval of the lowermost zone which was previously fraced. We then place a new set of holes above the plug, and adjacent to the second zone we intend to test. With good zone isolation behind the pipe, the only place the fluid can go is directly into the zone connected by the holes. **Figure 3** provides a comparison of how this process works for with good zone isolation vs poor isolation, due to inadequate cement placement behind the 5-1/2" casing.

Figure 3
The Importance of Zone Isolation For Multi-Stage Frac & Test Programs

Example 1 - Good Zone Isolation	Example 2 - Poor Zone Isolation
Water and sand on 2nd stage enters the correct zone, and does not go into a previously stimulated zone, or an unproductive zone	Very little water and sand goes into the upper zone, where it is needed. Most goes down into lower zone where we have previously injected fluid.





We do not conduct the **FIT** in the bottom of the 8-1/2" production hole section, because after we have cemented the 5-1/2" casing in place, the well drilling is complete and we do not enter the hole again with the drill string. But we still have the need to evaluate the cement job across the potential gas producing zones that we wish to test. To make this assessment we use **bond log** to evaluate the section of the 5-1/2" casing that is in the interval from the bottom of the intermediate casing to the bottom of the wellbore. The purpose of the bond log is to help us locate any areas where we may feel the cement behind the casing may need to be repaired to give us the level of zone isolation needed for our multi-zone frac and test program.

> **Note:** *The cement bond log in the production hole is <u>not</u> an indication of the wellbore integrity in the <u>top half</u> of the well, and therefore does not tell us anything regarding the protection of shallow groundwater. As stated before, the shallow groundwater is protected providing that we have good wellbore integrity in the upper half of the wellbore (ref:* ***Figure 2****).*

The bond log from the Preese Hall production hole section indicated that we had some intervals of low bond which coincide with some of these hole irregularities. From our quality control recording of the cement job, along with the cement samples collected during the pumping operation, we know we placed <u>good</u> cement behind the most of the 5-1/2"casing (except for a small interval at the very bottom 100 ft in the well). But the bond log revealed places where we felt we needed to repair the cement job to achieve better zone isolation.

> **Note:** *A copy of the Preese Hall bond log for the 5-1/2" casing is attached (see* ***Figure 5****). Because it covers nearly 4500 ft of hole section, it has been reduced in scale. The full digital record is also available upon request.*

5.2 <u>Cement Remediation Process</u>

Cement remediation is relatively easy, as demonstrated in **Figure 4**. But the first thing required is to determine if the areas of low bond are able to transmit fluid across the cemented area behind the casing. This is done by first placing a solid bridge plug in the casing above any perforations that may have previously been put into the well for the purpose of fracing and testing lower zones. Next we place a small number of perforations at the bottom end and top end of the area in question. Then we place small diameter tubing into the well with another special type of plug called a "cement retainer", which enables us to pump through the plug (via the inside of the tubing), but fluid cannot go up around the outside of the small diameter tubing.

When this is in place we apply water pressure to the inside of the tubing, and if the pressure does not leak-off, then we can determine that the bond behind the 5-1/2" casing is sufficient, and we remove the tubing and plugs. But if we can circulate water behind the 5-1/2" casing, then we switch to cement slurry, and pump through the section of low bond, to make the cement repair. When the cement operation is completed, and the new cement behind the casing has hardened, then we remove the tubing and clean out the wellbore. Then we can resume operations.

Figure 4

Cement Remediation Process

(same process as what was done at Preese Hall – 1)

Step 1 – LOW BOND	**Step 2 - REPAIR**	**Step 3 – HIGH BOND**
Use bond log to identify hole section to be repaired (low cement bond in repair area)	Place holes in casing <u>above</u> and <u>below</u> the repair area. Install downhole repair assembly. Pump new cement into the repair area	Remove repair assembly. Clean wellbore, restore well usage. (high cement bond left in the repair area)

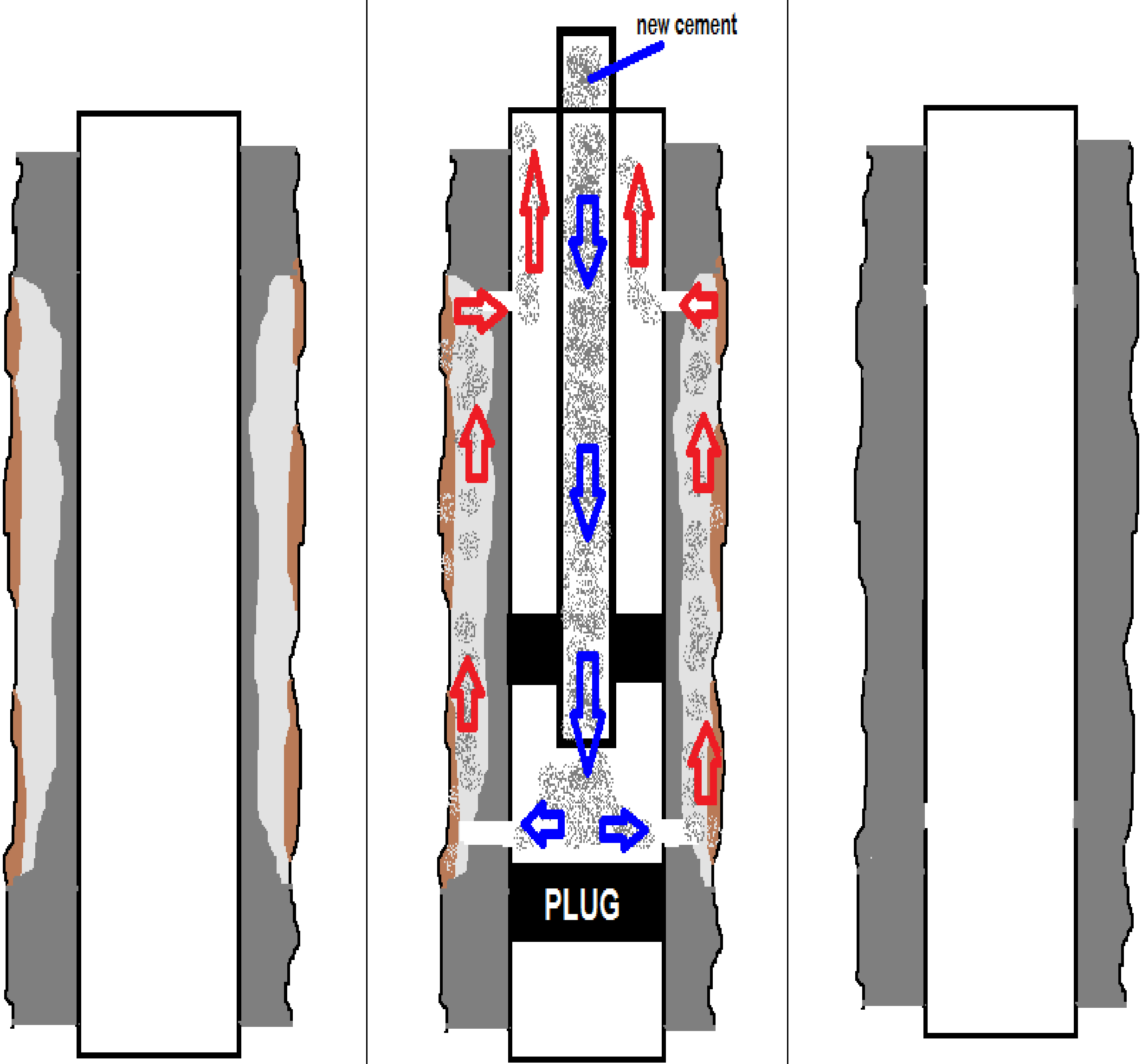
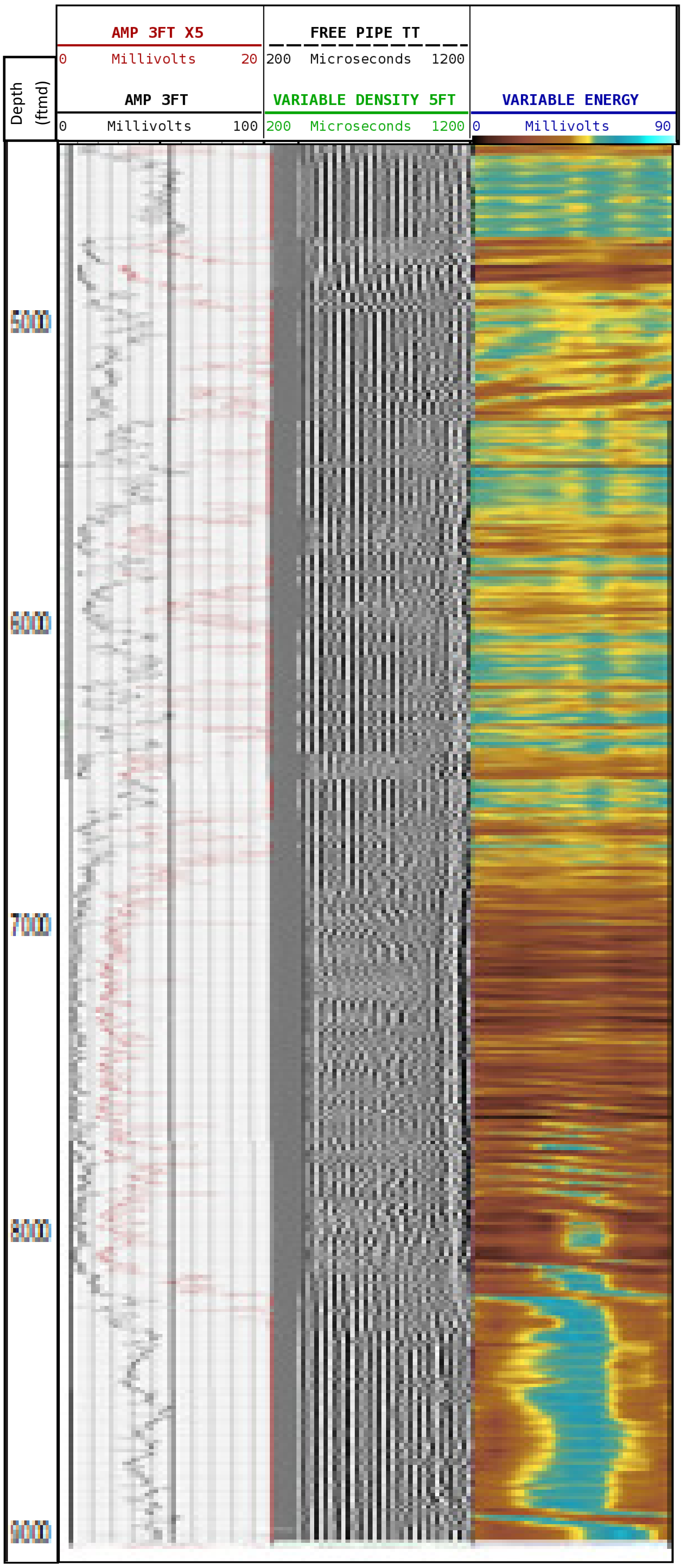


Figure 5

Bond Log Image – Preese Hall 1 – Production Hole Section with 5-1/2" Casing



6.0 Well Integrity at the Surface

Discussions to this point have been focused on wellbore integrity in the wellbore, and the figures have shown simple schematics of casing strings in the surface, intermediate and production hole sections. Equally important however is how we contain pressure and prevent leakage at the top of the well. **Figure 6** is a drawing of the wellhead that is installed during the drilling process. It is assemble progressively in sections, as each new casing string is cemented in place. The wellhead will be configured with additional valves if the well is put into production.

Figure 6

Standard Well Head Configuration At End Of Drilling Phase