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Extending the Limits of the Shale Developments by Using a Fit-for-purpose OCTG Connection

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Abstract

Operators in the Shale plays are reaching some limitations with the current technology available on the premium connection market, specifically in Torque and Tension on integral connections. Many operators use a conventional Semi-flush connection in the lateral portion of the well with Tension efficiency in the 70-80% pipe body range. They then cross over to Threaded and Coupled (T&C) in the vertical portion to have higher Tension efficiency. But the preference is to have a single solution for the full string length that could be run both in the vertical and horizontal portions of the well.

VAM SG, a fit-for purpose Semi-flush connection with a gas-tight metal seal and 90% Tension rating, was developed to meet this need. It was designed and tested to a fit for purpose test program for the Shale plays in the US. It has increased Torque capacity to be able to rotate the string into the lateral section. It is targeting the key sizes of the production casing strings that are common to the Shale play well designs in the US, 4 ½", 5" and 5 ½".

The target of the fit for purpose test program was to demonstrate that the connection could withstand multiple frac (fracture treatment) cycles, inducing high Tension and Internal Pressure with water. Then the connection had to pass an ISO 13679 Series B test with gas Internal Pressure, combined with Tension, Compression, and Bending, proving that the connection would still be gas tight for the production cycles after the liquid frac cycles.

Introduction

Most operators in the Shale plays in the US utilize Semi-flush connections in the bend and lateral portions of the well to ease the installation of the string. However, the Semi-flush connections currently on the market do not have high enough Tension ratings to support running a full string from top to lateral, and in many cases do not have sufficient Torque and Fatigue capacity to safely rotate the string into the lateral section of the well.

A fit-for purpose Semi-flush connection was developed to extend the limits of the Shale development, through a detailed and severe project methodology that is described below. The result is a Semi-flush connection with a gas-tight metal seal and 90% Tension rating, offering an increased Torque capacity.

Typical Well Design

The typical well design in Haynesville, both in East Texas and in North Louisiana, is 10 ¾" surface casing, 7 5/8" intermediate casing, and 5" or 5 ½" production casing. The wells typically have a 10-12,000 ft vertical section, followed by a 4-6,000 ft lateral section. The build rate in the curve is generally targeted at 10 deg / 100 ft, with the actual build usually peaking at a max of 20 deg / 100 ft. Similar well designs are used in many of the other Shale plays, although the details can vary widely, particularly on string length.

The production casing is selected primarily based on the required frac pressures, which can range from 8,000 psi up to about 14,000 psi. Common sizes seen in many of the Shale plays are 5 ½" 23# & 26#, 5" 21.4# & 23.2#, and 4 ½" 15.1#.

Many operators utilize tapered string designs in order to reduce the overall weight of the string. It is common to see 5 ½" by 5", 5 ½" by 4 ½", or 5" by 4 ½". In many cases, a T&C connection is utilized in the vertical portion of the well on the larger size, in order to have a connection that is as strong as the pipe body and achieve a sufficient safety factor for Tension loads. A Semi-flush connection is often used in the bend and the lateral on the smaller size.

Production Casing Loads

The most severe loads seen by the production casing are during installation, and during the fracture treatment. Therefore the primary loads considered during the selection of the casing size, weight, and grade are:

- Tension from the weight of the string
- Compression from the weight of the vertical portion of the string pushing down during installation
- Tension and Compression induced by the curvature of the pipe in the build section
- Tension and Internal Pressures induced by the fracture treatment.

The load on the production casing during the production phase is relatively low. The flowing pressure at the start of the production cycle varies by Shale play from a few thousand psi to as much as 10,000 psi for more critical plays, such as the Haynesville Shale. This amount of pressure is generally not sustained for an extended period of time. Normally within a matter of months the producing pressures reduce to a fraction of what they were when the well first started producing.

Rotational Torque

The installation often involves rotating the pipe to get into the lateral section. The Torque required to rotate the string in place is often one of the primary considerations on connection selection.

Fatigue

Fatigue is also a major consideration, particularly if the string is rotated during cementing. A connection may be in the bend for as many as 100,000 cycles during the installation. For example, with a penetration rate of 40 ft / hour, it would take a connection 25 hours to get through a 1,000 ft build section (with a build rate of 9 degrees per 100 ft). If the string is being rotated at 60 rpm during installation, this is a total of 90,000 Fatigue cycles on a connection during the time it is in the build, which could be a significant portion of the connections predicted Fatigue life.

In this example, if the string is then rotated during cementation, all connections in the bend during the cementing process would be subject to additional Fatigue cycles. A connection in the build section but closer to the lateral portion of the well would take the full impact of Fatigue loading during installation, plus Fatigue during cementation.

A connection in an area of peak build rate will endure significantly more severe Fatigue loads. Rotating in a 20 degree dog-leg versus a 10 degree dog-leg doubles the Fatigue stress, which reduces the expected Fatigue life by a factor of 16! For example, if a connection is expected to fail after 160,000 cycles at a Bending stress induced by a 10 deg / 100 ft dogleg, then the same connection would be expected to fail at 10,000 cycles in a 20 deg / 100 ft dogleg. Therefore, it is very important to consider the ‘static’ rotation during cementing, and the Fatigue induced by the highest dogleg severity of the bend.

Fracture Treatment Loads

The loads during the fracture treatment are primarily Internal Pressure plus Tension. The frac fluid pumped into the casing string at ambient temperature at the surface is slowly heated as it sees the bottom hole temperature, which can easily push 250 degrees F in many plays. When this cold fluid hits the hot pipe, it starts to cool the pipe, causing contraction of the steel. Since most of these strings are cemented in place, the pipe is not allowed to contract, so that Tension loads increase due to the change in temperature. Of course this affect is exaggerated in the winter, when colder fluids are being pumped in.

Naturally the fluid warms up over time, once it is down-hole, but the frac process is constantly pumping cold fluid into the casing for hours at a time. The flow of fresh cold fluid continues in order to maintain the high pressure needed to fracture the formation, resulting in a continuous drop of the production casing temperature.

Connections

The Shale plays have historically used API connections due to the relatively low bottom hole and producing pressures. However, in some of the more severe plays like Haynesville and Fayetteville, there have been many failures with API connections, primarily attributed to the high pressures and induced axial loads from the multiple frac cycles. As a result, most operators in those areas have switched to using premium (gas-tight metal seal) connections.

As discussed previously, the primary considerations in connection selection are Torque required during installation, frac pressures, axial loads from the string weight, axial loads induced by the build rate, axial loads induced by the frac, and Fatigue loading. But the most important point is the fact that the connection must remain gas-tight after all of this loading, even if the gas pressures are relatively low compared to the liquid frac pressures.

Semi-flush connections are used to improve clearance in the annulus between the outside of the pipe and connection, and the ID of the intermediate casing, while maintaining high Tension strength. This stream-lined OD improves the ability to circulate drilling fluids while running the casing and in case of well control issues. It also improves the ability to run the pipe in the lateral section of the well.

Most operators prefer to use integral connections in the bend and in the lateral, to ease the installation process and prevent the risk of a coupling face ‘hanging up’ on the formation. The smooth profile of an integral connection slides into the lateral much easier by reducing contact with the well bore, and therefore requires less Torque as well as less reciprocating axial load to prevent the pipe getting stuck.

The Need for an Advanced Semi-flush Premium

A typical Flush premium connection has Tension yield strength in the range of 50-65% of pipe body. This generally is not enough Tension strength for the loads in the bend and induced by the frac. Typical expanded box or Semi-flush premium connections have Tension yield strength in the range of 65-80% of pipe body. This is typically sufficient to handle the loads, but can result in a safety factor that is border-line in some of the deeper, higher pressure wells. This also may not be enough axial load capacity to run the Semi-flush connection all the way to surface.

Currently many operators use a Semi-flush connection in the bend and lateral section and cross over to a T&C connection in the vertical section. This means that they either sacrifice annular space for circulation of fluids, or they have to go to a smaller size (5” compared to 5 ½”). The smaller size means less fluid weight inside the casing, resulting in higher pump pressures at the surface during the frac operation. Of course T&C premium is more costly than Semi-flush, so this is a strain on the well economics.

The rotational Torque needs vary by Shale play, and the specific needs and practices of each operator. However, when operators do need to rotate the string, the Torque they are using is generally in the range of 8-12,000 ft-lbs. Many Semi-flush connections have restrictions in Torque capacity in this range. Therefore, the ability to rotate depends on the exact need and the operator's willingness to push the Torque close to the connections theoretical limits.

There are advanced thread technologies that provide extreme Torque capacity, up to 30,000 ft-lb range for the typical Shale play sizes. But such technologies are more costly to produce than conventional premium thread forms, and may not fit the economic needs of some Shale plays. For most Shale play applications, this Torque capacity is considered to be overkill. Currently there is not a Semi-flush connection available in this extreme Torque segment that offers the higher Tension capacity required to run a full string.

The need for more Torque to rotate, combined with a desire to run a Semi-flush connection full string length, led to the need for connection development. For this reason, VAM USA pursued the development of a Semi-flush connection with greatly enhanced Tension rating and higher Torque capacity compared to existing technology.

Project Specification

The connection development was launched in January 2010. The primary components of the project specification were:

- Tension - 90% of pipe body.
- Compression – 63% of pipe body.
- Internal Pressure – equal to pipe body MIYP (Minimum Internal Yield Pressure).
- Bending – 40 deg / 100 ft
- Torque - 12,000 ft-lbs up to 16,000 ft-lbs on 5" & 5 ½" (depending on size, weight, and grade).
- Fatigue life – 90,000 cycles to failure at stress range equivalent to 10 deg / 100 ft Bending.

Fit for Purpose Test Program

The Shale plays do not require the same range of load conditions as offshore wells or even deep gas land wells. Therefore, the connection development was launched with a fit-for-purpose Shale test program that focused on simulating the multiple and severe frac cycles, followed by the combined loads that could be encountered during the gas production cycle.

Frac loading

The frac testing focused on several cycles with liquid to high pressures, combined with high Tension. Two primary frac load cases were identified:

- Frac 1 simulation - MIYP plus Tension to 95% VME.
- Frac 2 simulation - 95% Tension plus IP to 95% VME.

Figure 1 illustrates the frac 1 load cycles performed on 5 ½" 23# P110 pipe and connection. This VME ellipse shows the loads that were applied, based on actual material yield strength. It also provides the nominal loads, based on minimum specified material yield strength for reference.

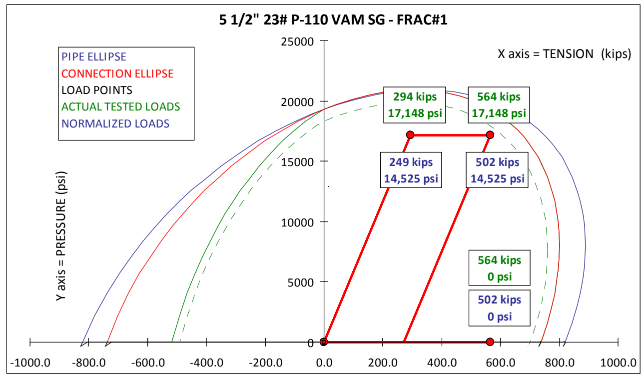

Figure 1 – Frac 1 liquid testing load cycles.

Figure 2 illustrates the same actual and nominal loads for the same test sample on the frac 2 load cycles.

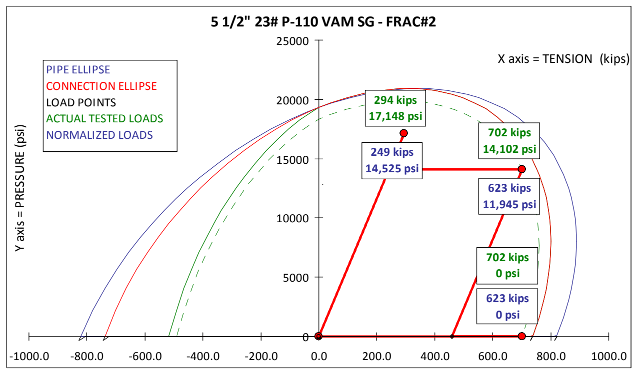

Figure 2 – Frac 2 liquid testing load cycles.

Twenty cycles were performed on each of the two frac loads. Each cycle consisted of:

1. Apply Tension load and Internal Pressure up to 95% VME
2. Hold for 15 minutes to an hour
3. Drop the load and pressure to zero

These three steps were each applied 20 times on each frac load.

The main reason for the two frac loads was that some end users would prefer to see the testing performed with higher pressures, while others would prefer to see higher Tension. Considering the shape of the VME ellipse, there has to be a trade off between Tension and Internal Pressure, to avoid overloading the connection. So two separate frac loads were identified. A total of forty frac cycles were achieved on a single sample by performing twenty cycles on each frac load. This replicated the Fatigue affect induced by applying and removing the loads.

Gas Testing for Production Phase

An ISO 13679 Series B test with internal gas pressure limited to 70% MIYP was performed after the frac cycles. The purpose of this test was to show that the connection remains gas-tight for the production phase after the severe multiple frac cycles. This test includes cycling from Tension to Compression with Internal Pressure, both with and without Bending applied. The loads for the 5 ½" 23# P110 sample are illustrated in Figure 3.

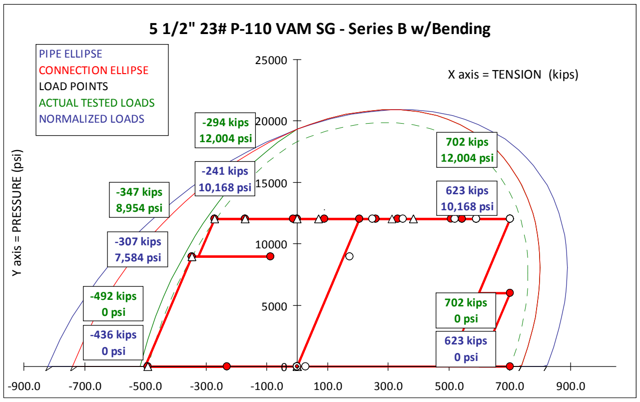

Figure 3 – Gas testing with combined loads.

Testing with Bending

When Bending is applied to the pipe and connection, axial Tension stress is induced on the outside of the bend, and axial Compression stress on the inside of the bend. For a load point with Tension plus Internal Pressure, the Tension load is reduced prior to applying Bending so that the Tension stress from the bend combined with the applied Tension load and Internal Pressure will achieve 95% VME stress on the outside of the bend. Likewise, the Compression load applied to the sample is reduced to compensate for the Compressive stress on the inside of the bend in order to achieve 95% VME stress on the inside of the bend.

The connection can support Bending up to the Tension and Compression ratings. For example, a Bending rate of 91.7 deg / 100 ft can be applied on 5 ½" 23# P110 pipe body. For a connection rating of 90% PBYS in Tension and 63% PBYS Compression, a Bending rate of 70.1 deg / 100 ft with an applied Tension load of 197 kips can be applied. However, such a high Bending rate can not be achieved with any Internal Pressure. This high bend rate subjects the outside of the curve to 100% VME stress in Tension and the inside of the curve at 100% VME in Compression. As Internal Pressure is added, the width of the VME ellipse is reduced, such that the Bending has to be reduced. Adding pressure requires reducing the Bending to keep the connection below 100% VME.

At MIYP, the Bending rating is 52 deg / 100 ft. But 40 deg / 100 ft is about the most Bending that still leaves a reasonable range of axial load capacity available for combined loads under Internal Pressure. This range of axial load capacity is needed to be able to withstand Compression at the bottom of the curve in the well and Tension at the top of the curve, and also to accommodate an increase in Tension load due to cold frac fluid injected into the string. This is why 40 deg / 100 ft Bending rate was selected for the testing. This is low enough to give a good range of axial load capacity at MIYP, but high enough to give a nice safety margin above the worst case bend, since most wells do not exceed 20 deg / 100 ft. Figure 4 illustrates the Bending loads, by explaining the three points used to express the stresses at one load point with Bending.

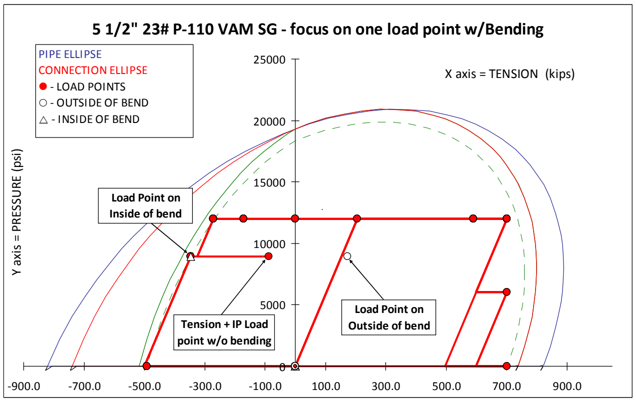

Figure 4 – Bending loads plotted on the VME ellipse.

Fatigue Testing

The final phase of the testing was Fatigue, to check that the connection could withstand the rotation under Torque, followed by frac cycles, and then remain gas-tight for the gas production stage.

The Solution

The connection development and internal validation testing was completed by the end of August, 2010. The connection met all the requirements of the specification.

The project consisted of first evaluating and testing different design concepts. Once the best design concept was selected, the design was extended to all size & weight combinations required. FEA was used to evaluate the design on all size & weight combinations, on high and low material grades. From the FEA results, R&D determined the 4 worst case combinations of size, weight, and grade that required physical testing. These 4 sizes were then subjected to the full test program of make and breaks, Frac #1 cycles, Frac #2 cycles, and gas production testing. Figure 5 illustrates an example output of the FEA analysis.

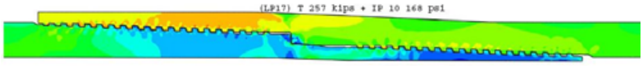

Figure 5 – FEA on the Fit-for-purpose Shale Connection

The existing Semi-flush connections utilize a tapered two-step thread with a center Torque shoulder. Most Semi-flush premium connections feature a primary pin nose metal seal, with a separate external metal seal at the box face. The solution for this project is a two-step connection, utilizing the same thread form concept, with a center Torque shoulder. However, the sealing is accomplished with a gas-tight metal seal in the center of the connection, next to the Torque shoulder. By moving the pin nose metal seal to the center of the connection, and removing the external metal seal, the critical cross section (CCS) at pin and box thread run-outs achieves the required 90% of pipe body. The resulting Torque shoulder is bigger in area, to achieve the increase in Torque capacity. Thread length also had to be increased, to carry the additional axial loads. Figures 6 and 7 illustrate the change in connection features from current Semi-flush connections to this fit-for-purpose Shale connection.

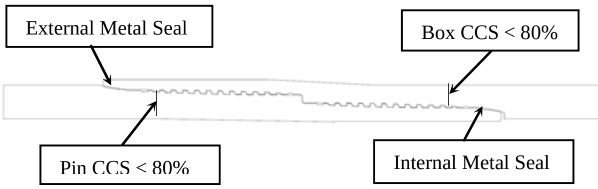

Figure 6 – Typical Semi-flush premium connection.

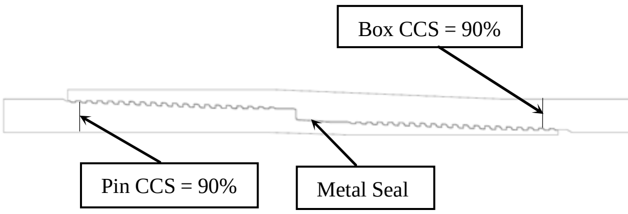

Figure 7 – Fit-for-purpose Shale Semi-flush premium.

Validation and Fatigue Testing on a "BIG Fish" Size

After completion of the R&D development project, additional testing was performed on 5 ½" 23# P110. This size was selected for additional testing because it is the most common size using premium connections in the US Shale plays, and it was not one of the sizes selected by R&D as being the most critical. This size was subjected to the full fit-for-purpose Shale test program.

Fatigue testing was also performed on 5 ½" 23# P110, since Bending stresses are higher on a larger OD, so that Fatigue testing is more critical on 5 ½" compared to 5" and 4 ½". Six samples were tested to failure at varying stress levels, corresponding to bend rates ranging from 5 deg to 17.5 deg / 100 ft dogleg. The results on these 6 Fatigue to failure tests showed that the connection is capable of far more than the specified 90,000 cycles at 10 deg / 100 ft dogleg.

A seventh sample was loaded to roughly 50% of the predicted Fatigue life (700,000 cycles at 10 deg / 100 ft), based on the results of the first 6 samples. This sample was then subjected to post-Fatigue combined load testing. It passed the Frac#1, Frac#2, and Series B gas production testing.

First Running

A field trial was successfully run at Weatherford in Broussard, using full length range 3 joints made up vertically. A round of make and breaks was performed, proving that the connection could withstand 3 make and breaks without thread or seal galling, even with rough rig conditions, like make up to high rpm, make up with misalignment, make up with excess thread compound or thread compound contaminated with oil, etc.

NFR ran the first 2 strings in the Haynesville Shale, during the last week of February, 2011. Both wells included about 6,500 ft of a conventional 5" Semi-flush connection in the lateral section, crossing over to 11,000 ft of 5 ½" 23# P110EC VAM SG in the vertical portion of the well. Both jobs ran smoothly, with only a few back-outs and zero rejects. Both strings were rotated through the bend and into the lateral, just as a precaution to get down safely without getting stuck.

No issues were faced, either with the make up of the connection or the running of the strings. In both cases, the company man on location was happy with the connection performance during the running. At the time of this writing, these 2 strings have been run and cemented in place, but have not yet been subjected to the fracture treatment. NFR was able to save money and clearance in the well by utilizing Semi-flush connections for the entire production casing string.

Conclusion

VAM SG is suitable for use in most Shale plays as production casing, to withstand the multiple frac stages, followed by gas production. In most cases, it can be run full string length with suitable design factors. It passed the specification, meeting the following performance properties:

- Tension - 90% of pipe body.
- Compression – 63% of pipe body.
- IP – equal to pipe body MIYP.
- Bending – 40 deg / 100 ft (with combined loading).
- Torque - 12,000 ft-lbs up to 16,000 ft-lbs on 5" & 5 ½" (depending on size, weight, and grade).
- Fatigue – rating on the product line of 1.5 SAF compared to DNV-B1 pipe body curve. On 5 ½", this corresponds to just over 270,000 cycles at stress equivalent to 10 deg / 100 ft Bending. This value would be much higher for the smaller sizes, 5" and 4 ½".

The make and breaks and combined load testing all passed successfully with no galling and no leaks, either on the two sets of frac load cycles or the combined load testing with gas Internal Pressure, Tension, Compression, and Bending.

The connection was validated to fully pass the project specification, and successfully extends the limits of the Shale developments.

Acknowledgments

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Nomenclature

VME = *Von Mises Equivalent stress*
FEA = *Finite Element Analysis (mathematic modeling of stresses and strains).*
CCS = *Critical Cross Section – cross sectional area of the connection at last engaged thread, expressed as a % of Pipe Body Cross Section.*
NFR = *NFR Energy, LLC*