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Premium Connection Design, Testing, and Installation for HPHT Sour Wells

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Abstract

Drilling and completing wells deeper, and in HPHT sour environments, magnifies the importance of having reliable threaded casing and tubing connections. High pressure/high temperature wells present many critical challenges for threaded tubular connections. Through design, proof testing, and installation, premium connections are meeting these requirements in a number of ways. With coupling stock for thick walled tubulars and sour service environments often being the limiting factor as the pipe wall increases, integral connections, and threaded and coupled designs with pin to pin contact allow the use of production casing over one inch in wall thickness. The incorporation of resilient seals into threaded and coupled connections can offer secondary back-up seals to the primary metal to metal seals.

Premium connection designs are often required to be validated or pass a qualification test program before acceptance by the users. Two fundamental approaches exist for qualification testing; product line testing and project specific testing. Product line testing is used to “qualify” a range of dimensions and wall thickness within a given design and is often accompanied by Finite Element Analysis (FEA). Project specific testing is used for very critical applications and when the connection designs are tailored to meet specific requirements. The ISO 13679[1] test procedure is most commonly used as the basis for qualification testing although “modified” ISO and other qualification test procedures are also used.

The design and qualification of HPHT connections determine that the connections are fit for purpose and that they provide reliability for HPHT well applications. The installation process is also a critical issue in the successful drilling and completion of such wells. Computer controlled make-ups, low stress or non-marking dies in handling equipment and even the application of the proper thread compound and quantity can be critical components in the successful completion of HPHT sour wells.

Introduction

Designing a casing or tubing string for High Pressure High Temperature wells requires the designer or engineer to evaluate and select critical components for every phase of the drilling and completion phases. Typically the tubulars and connections are a critical component in the design and selection process. Once the tubulars are selected, the threaded connections to be used must be evaluated and selected based on designed performance, validation testing, and field reliability. This paper is offered to provide additional insight into the key design parameters, proof testing methodologies, and some discussion on the appropriate field installation practices required to ensure the performance of threaded connections in HPHT applications.

Premium Threaded Connection Designs for HPHT

HPHT applications experience extreme loads that require threaded connections with performance capabilities exceeding those of standard API connections. These load cases include extreme axial loading in tension and/or compression, sometimes high torque, and possibly reduced hole clearance. The thermal effects of high temperature wells may also subject the tubular connections to high compression loads during production and high external pressures due to annular fluid expansion due to temperature. These loads are not applied uni-axially but rather in a three dimensional state and connection designs must be based on tri-axial performance criteria, the same as the pipe body. This tri-axial criterion is commonly referred to as von Mises equivalent stress (VME). The primary design features of a premium connection; threads, seals, and torque shoulders if present must work together to provide gas sealing within the required domain. Metal-to-metal (MTM) gas tight seals which provide reliable sealing under extreme load cases are the most significant design features required for HPHT wells. Additionally, the connections must be compatible with elevated temperature and sour service well designs and materials.

High pressures and high temperatures experienced in severe applications necessitate particular design requirements for premium connections. High pressures must be addressed with heavy wall tubulars which require specific heavy wall (HW) connections. For sour service, the yield strengths of qualified materials are limited which means that the pipe wall thickness must be increased to handle the higher pressures. These thicker wall pipes require special HW designs with features such as steeper tapered threads to minimize the connection length, and seal designs that are designed to seal against high internal and external pressures without risk of galling on thicker pin seals. In addition to the high pressures encountered, high compressive loads may be experienced due to thermal expansion of tubing strings during production phases. Current threaded and coupled connection designs with slightly swaged pins are available that can pass ISO testing up to 100% pipe body compression.

Threads

The threads for premium metal seal connections serve not only to mechanically connect two lengths of pipe in the field but also contribute to the connection's overall performance with respect to axial loading and sealing. Since metal seal connections do not rely on the threads to seal, connection designers have a great deal of latitude in the thread form design. Premium connection threads are generally of a modified buttress thread form with the following design possibilities:

- Thread interference
  - Flank to flank thread interference (F-F)
  - Crest to root interference (C-R)
- Thread form
  - Positive load flank + Positive stab flank
  - Zero degree load flank + Positive stab flank
  - Negative load flank + Positive stab flank
  - Negative load flank + Negative stab flank (not a modified buttress)
- Crest – Root design
  - Thread crests and roots parallel to the axis of the pipe
  - Thread crests and roots parallel to the taper of the thread, (thread cone).

Each specific thread form has advantages and disadvantages that must be considered in connection designs. The various types of thread form designs are depicted in **Figs. 1 through 3**.

Thread Interference

Interference fit threads fall into two categories; flank to flank, and crest to root versions. Originating from the API buttress thread form, the crest to root (C-R) interference thread normally has clearances between the crest of the pin thread and the root of the box thread and between the stabbing flanks of the threads. This configuration allows for good thread compound distribution during make-up and also is less sensitive to thread galling than a flank to flank (F-F) interference fit. With the stab flank clearance, the C-R thread has a greater possibility to move under high compressive loads and must rely more on the torque shoulder for compression resistance. Flank to flank (F-F) interference threads have contact on both load and stabbing flanks and may have reduced clearances in the roots of either or both pin and box threads. Due to the contact on both thread flanks, F-F thread forms restrict movement under compressive loads but can be more sensitive to galling of the thread flanks. In either case, the connection must have sufficient radial thread interference to develop sufficient stored energy to prevent backing off downhole, without the radial thread interference reducing the seal contact pressure of the metal seal(s).

Thread Forms

Premium threaded MTM connections employ one of several thread forms. The four most common can be categorized as positive load flank, zero load flank, negative load flank, and "dovetail" threads, with both negative load and stabbing flank angles. Positive load flank thread forms are a direct descendent of API Buttress thread forms with both the stabbing and load flanks having a positive angle with respect to the thread axis. The principle advantage of positive load flank threads is that they are easier to machine and can be threaded or repaired using both NC and manual lathes. Using the API Buttress equation 42[2] for pipe thread strength, it can be shown that positive load flank threads in sizes 10¾" and larger are weaker than the pipe body yield strength. This limitation can be overcome with the use of negative load flank angle threads. These negative load flank thread forms have connection yield strengths equal to or greater than that of the pipe body. It should be noted that the connection yield strength is the load at which the connection may start to plastically deform and may no longer seal as designed. Design limits for connections therefore should be considered on a basis of joint yield strength rather than parting load.

The joint yield strength of a negative load flank connection is a function of three factors: the cumulative thread load flank areas, the cumulative thread shear areas, and the minimum critical cross section between the pin and box at the last engaged thread root of the pin (or the box). Designing the thread such that the load flank and shear areas are greater than the critical cross section of the pin ensures that under tension, the pin will fail in the pipe body at the critical cross section rather than by thread failure.

Negative load flank threads must be machined with NC threading lathes which may limit repair facilities, although this is much less of an issue today since most all thread and machine shops now have NC machines. The third thread form used today, is the "dovetail" thread form which has both the load and stabbing flanks at a negative angle. This type of thread profile is generally used with variable width threads. This makes the dovetail type thread able to handle extremely high torque loads during make-up or rotation downhole. The disadvantage of the dovetail type thread is that it can only be machined on NC machines and is more difficult to manufacture than the two other types discussed.

Crest-Root Design

The third feature of the thread forms which should be considered is the thread crest and root design. This feature while not contributing to the connection joint performance does have an impact on the stabbing and running characteristics of the connection. Based on previous buttress designs, many premium connections feature crests and roots that are parallel to the thread cone. These thread forms are commonly used with success but it is possible to have a crest to crest contact during stabbing and may require extra care to avoid make-up problems. The other possibility is to have the crests and roots parallel to the axis of the pipe. This thread form avoids the crest to crest contact during running and is easier to stab during rig make-ups, but can be less efficient to withstand tension loads for a given thread height than comparable threads with crests and roots parallel to the thread cone.

Seals

Most premium gas tight connections for HPHT applications utilize at least one radial metal seal, and some have multiple metal seals, and still others have resilient seals that act as back-ups to the primary metal seal. Radial metal seals are the critical component for isolating or containing the high formation pressures encountered in HPHT well drilling and completions.

The ability of the metal seal to control the pressures encountered is a function of the contact pressure between the two sealing surfaces. The seal contact energy in excess of the pipe ratings, or in excess of the expected well pressures determine the sealing performance of the connection. This contact pressure must also be balanced against the potential of the metal seal to gall during make-up. Simply put, more contact pressure provides more sealing but also increases the sensitivity to galling, particularly with sour service alloys and corrosion resistant alloy (CRA) grades. The actual effective seal contact pressure is a function of the mechanical interference fit of the two seal surfaces and the additional energy from the internal or external applied pressures. This is particularly true where an internal seal near the pin nose is used to contain internal pressure and an external seal is used near the end of the box to seal against external pressure as in many integral connections. Threaded and coupled connections may also have a second metal seal at or near the coupling face to seal against high external pressures. A 10¾" 101# (0.960"wt) VM110SS VAM HP, as shown in **Figure 4**, was qualified for North Sea service with dual metal seals

In addition to radial metal seals, some connections incorporate resilient seals as a back up to the metal seals, as shown in **Figure 5.** Resilient seals are normally placed in a groove in the connection box member and are manufactured from fiberglass reinforced polytetrafluoroethelene (PTFE). Again, there is a balance that must be achieved when using resilient seals. Since stresses are induced by the resilient seal, the designer must incorporate sufficient compression of the resilient seal to maintain an effective seal without creating too much radial stress that could reduce the interference fit of the metal seal. It is important to note that when connections with metal and resilient seals are tested with internal pressure, the two seals should be tested independently rather than in series, as mentioned in ISO 13679 Annex J.[1] This is to ensure that the resilient seal is truly working as a back-up to the metal seal. Recent tests with a 7.97" OD 1.123" wt VAM PRO RS connection have qualified resilient seals up to 25,000 psi and 425°F as shown in **Figure 6**.

Other elements of a premium connection that must be considered by the designer are torque shoulders, anti-galling treatments for threads and seals, and thread compounds used for make-up of the connections. It is the connection designer's responsibility to incorporate each of the possible elements into a reliable premium metal seal connection for HPHT and sour service applications.

HPHT Sour Service Designs

There is a lot of history with metal sealing HPHT connections for pipe wall thickness in the range of ≤ 0.650". For these more common tubulars, connections such as VAM TOP have been qualified and used for years in HPHT sour wells in the USA, North Sea, and other parts of the world. This document will focus more on technologies related to connections for heavier wall (≥ 0.750") sour service tubulars.

While general HPHT connection design fundamentals apply to sour service conditions, limitations on the availability of sour service rated thick walled coupling stock may dictate the use of alternate designs of various types. As a general rule, a typical shouldered metal seal premium connection requires coupling stock that is two times the wall thickness of the pipe. So for a pipe with a 1.00" wall thickness, a coupling stock with a 2.00" wall thickness would be required. With the availability of such thick walled coupling stock meeting the requirements for sour service such as NACE Method D**[3]** being limited at best, integral connections and threaded and coupled connection designs that use lighter wall coupling stock become very attractive.

Integral connection designs eliminate the need for coupling stock and therefore can be used on thicker walled casing for sour service applications. Two considerations for integral connection designs are reduced tensile efficiency compared to the pipe body yield strength and loss of sour service performance in the cold formed ends of semi-flush (SF) integral connections. **Figure 7** shows a typical expanded box semi-flush connection. Expanding the box and swaging the pin members of SF connections increase the joint strength up to 80% or more compared to the pipe body. This cold forming increases the joint strength but can alter the material properties sufficiently to degrade the sour service performance of the connection. Thermal stress relieving the formed area restores the yield strength and material properties of the mother tube. Sulfide Stress Cracking tests have demonstrated that this process does not adversely affect the cracking resistance of sour service material grades**[4]**. Although it has been demonstrated that a minimum induction stress relieve temperature of 1100°F restored the material properties to that of the original unformed pipe body**[5]** , the thermal stress relieving temperature should never exceed the original mill tempering temperature of the mother pipe. To avoid exceeding the mill tempering temperature, the thermal stress relieving temperature should kept at least 50°F below the tempering temperature.

One possibility to deal with the wall thickness limitations of sour service qualified coupling stock is to use the available qualified thinner wall thickness coupling material with a special clearance (reduced tension) threaded and coupled design. Although this will achieve a sour service design, the limits on tension may be unacceptable for a given application. An alterantive approach to overcome the limitations of available sour service coupling stock is by utilizing a threaded and coupled connection design with a pin nose to pin nose such as a VAM PRO concept as depicted in **Figure 8.** Using the pin nose of one pin as a torque shoulder for the second pin eliminates the torque shoulder in the coupling and allows a thinner walled sour service coupling stock to be used while maintaining 100% pipe body yield strength. Full gas pressure rating is maintained with the internal metal to metal radial seals. This type of design has a very controlled mill make-up position to ensure that the field pin is properly positioned and metal seals are engaged. VAM PRO connections have been successfully tested and qualified on tubes with wall thicknesses over 1.00" and pressures well over 27,000 psi., see **Figure 6**. In addition to the radial metal seal, a resilient seal may be incorporated as a gas tight back up seal, as with VAM PRO RS, shown in **Figure 9**. A photo of an actual VAM PRO RS ISO test sample for a 7.97" OD casing with 1.123" wall thickness is shown in **Figure 10**.

With the various thread design, metal seals, and elements of premium connections available, it is up to the connection designer(s) to weigh the benefits and negatives of each feature to develop a balanced connection with reliable HPHT performance.

Qualification Testing

Once a design is finalized and offered to the industry, it is advisable to substantiate the designed performance with either Finite Element Analysis (FEA) physical testing or both. Finite Element Analysis is a valuable tool in both connection design and qualification. Modeling the connection and applying material properties and load scenarios can be used to select the more robust designs for testing to reduce testing costs and time. The ability of a radial metal seal to contain the required pressures is a function of the contact pressure and length of contact. A common method of evaluating seal performance is to consider the length of contact in excess of the required pressure and also the total area under the contact pressure curve as shown in **Figure 11**. In general, the greater the area under the curve, the more reliable the seal. A comparison of the seal performance of various sizes and load cases can be used to select the more critical dimensions among a product line for physical testing.

FEA is also valuable for the user to compare various connection designs under defined loading conditions and for reducing the total number of designs to be considered for testing. It is also possible to use FEA to extrapolate or interpolate around sizes and grades that have completed physical testing.

While FEA is valuable in sorting and selecting connections for testing, there is no substitute for physical tests, particularly for severe applications. There are two basic philosophies for physical testing: product line testing and project specific testing. Product line testing is used to qualify a family of connections according to some defined set of criteria. Testing the extremes of a design family can produce a range of tested dimensions with additional dimensions being qualified through interpolation, usually with FEA on all sizes. A family of connections can be sub-divided into groups based on the connection features. Generally, a sub-group is those connections with similar design elements. For example, a "group" of metal seal connections would have the same thread pitch, seal profile, and general design characteristics. An example of this type of connection grouping is given in **Figure 12.** The principle advantage of a product line qualification is that more connections can be qualified with lower costs than testing individual connections for a specific project. The disadvantage of product line is that no physical testing may be available on a specific OD, weight, and material grade required for an application and either interpolation or some reduced supplemental testing may be required.

The second physical testing philosophy is more point specific and is usually based on the ISO 13679 procedures, commonly referred to as "ISO" testing. It is also possible to use to use ISO testing as part of a product line qualification program. ISO 13679 is an international industry standard for connection testing which provides guidelines for the effective testing of premium connections[3]. ISO testing is divided into four classes with defined samples and procedures for each class. The principle difference in ISO testing compared to other procedures is that ISO requires the connection to be tested to the manufacturer's rating and to be tested through cycles around the four quadrants of the VME envelope as depicted in **Figure 13**. This testing has identified the criticality of connections to remain gas tight under various combinations of pressure and axial loadings. It has been found that this cyclic loading can identify connection problems that may not be detected with more simplistic testing procedures. ISO CAL IV eight sample tests, as shown in **Figure 14**, are the most critical and are often performed for HPHT projects with severe load cases. The downsides of project specific ISO testing are the cost and the time required for testing numerous samples. A full eight sample ISO CAL IV test can cost several hundred thousand dollars and take several months to manufacture samples and complete testing.

Faced with the high cost of ISO testing, and still needing validation testing of a given connection, many operators and manufacturers are working together to accomplish the required proof testing with reduced testing costs. This is accomplished by combining ISO samples and testing series so that more information is gained with fewer samples. For example to a full ISO Level IV would require eight samples with four samples seeing internal pressure and bending and four seeing internal and external pressure with no bending. By combining some samples such as 1 & 5[1] and 4 & 7[1] so that each sample sees all four quadrants and bending, two samples can be eliminated. Combining other samples can further reduce total testing time and costs. While it is possible to reduce the total number of samples by as much as half, some compromises must be made since every sample configuration can be tested to the full ISO program. Since the individual samples of a reduced test program receive more testing, it should not be assumed that a given reduction of total samples reduces the testing costs proportionally.

Physical connection testing is a valuable tool in qualifying connections for HPHT applications but there are no specific connection testing parameters that pertain to sour service conditions. This aspect is addressed by qualifying the base pipe and coupling material according to industry procedures such as NACE TM0177[3].

In addition, since HPHT applications push the limits of testing to the extremes, special care should be taken with regards to material mechanical properties characterization. It is important to fully capture material behaviors and limits, which will be introduced into the testing load calculation. For example, elevated temperature material tests should be performed and the data used to calculate the appropriate elevated testing or thermal cycle loads. For the same reason, it is important to perform physical connection testing with samples from the actual or equivalent material that will be used for the HPHT application.

Field Installation

Even with a sound design and adequate validation testing, the reliability of a premium metal seal connection can be compromised unless proper running and installation procedures are followed. For a given string of threaded and coupled connections, 50% of the make-ups are performed on location and for an integral connections, 100% are made-up on location. Thread compounds, running equipment, and computer controlled make-up equipment should be selected with regard to the reliability of the individual connections as well as the total tubing or casing string in an HPHT sour environment.

Thread compounds can be divided into two general classes: API Modified according to API 5A3[6] Appendix A, and environmentally friendly “green dopes”. API Modified compounds are the generally preferred thread compounds for making up premium connections as well as API connections due to their excellent anti-galling characteristics. However, in many environments there is a desire to eliminate the lead and heavy metals from the well and associated environments. This has lead to the development of many non-leaded, non-metallic, “green dopes”. While these thread compounds are environmentally friendlier, many contain PTFE particles that can interfere with the sealing performance of the metal seals. Thread manufacturers should be consulted and only those “green dopes” tested and approved by the manufacturer should be used. Recently several premium connection vendors have developed the technology of eliminating conventional thread compounds from the connections altogether. These “dope free” connections accomplish the main objective of eliminating any discharge to the environment, while preserving the other performances of the connection, including galling resistance and sealing performance. In addition, “dope free” concepts are usually applied one time in the mill or threading facility, as an integrated system. This eliminates adverse variations in the make-up graphs due to variances in thread compound application. Cost savings can also be realized by eliminating the thread compound from the connections by reducing dope contamination in the well bore, eliminating cleaning and re-doping costs, and reducing costs for protector disposal.

Running and handling equipment are also critical for dependable connection performance in HPHT sour applications. Elevators, slips, and handling equipment should be non-marking or low stress designs to avoid work hardening or sharp gouges that could contribute to stress corrosion cracking of sour service materials. The make-up equipment should also inflict as little mechanical marking as possible. Most service companies offer various types of completely non-marking tongs and back-ups for sour service materials. Use of such equipment should be standard practice for HPHT sour service wells.

In addition to sour service running equipment, computer controlled make-up equipment is essential in running premium metal seal connections. The computer torque graph provides valuable information about the make-up of the connections at the mill and on the rig. **Figure 15** depicts an acceptable computer torque graph. Computer plots of torque and turns give evidence of proper distribution of the torque between the threads, seal, and shoulder. Should galling occur, the thread portion of the torque chart will show a continuous increasing slope with little or no evidence of seal or shoulder contact, as shown in **Figure 16**. The torque chart also provides evidence of proper loading of the torque shoulder during make-up. Sufficient torque on the shoulder ensures that the metal seal(s) are in proper position and that the seals will remain engaged under high axial loads. Too much torque applied to the shoulder will result in yielding of the shoulder and reduce seal contact pressure. This over torqued condition is evident by a loss of linearity of the make-up graph at final torque, as depicted **in Figure 17**. While torque graphs are extremely valuable for detecting torque distributions and potential problems, they are not a guarantee of sealability of the connection. It is therefore essential to have qualified personnel on location and to adhere to the manufacturer’s running recommendations.

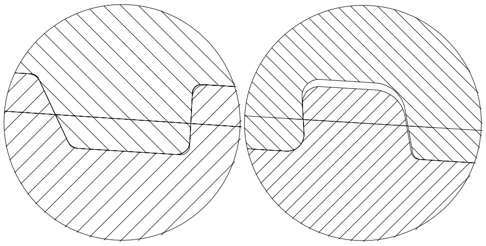
Conclusions

1. A properly designed premium connection for HPHT and sour service applications must contain a thread design that has reliable make-up characteristics.
2. The thread interference should be controlled to sufficient levels to prevent back off but not to induce radial stresses sufficient to disengage the metal seal(s).
3. The metal seal shape and interference should be designed to resist galling, and to maintain sufficient contact pressure distribution to meet the required sealing performance(s).
4. Several options exist to overcome the limitations for thick walled coupling stock for sour service applications.

5. “Modified” ISO testing can qualify threaded connections with reduced costs.
6. Accurate materials properties and behaviours are required for meaningful connection testing.
7. Thread compounds are a key component in connection performance and should conform to the connection manufacturer’s recommendations.
8. Proper handling and running are essential for tubular connections in HPHT sour service applications.

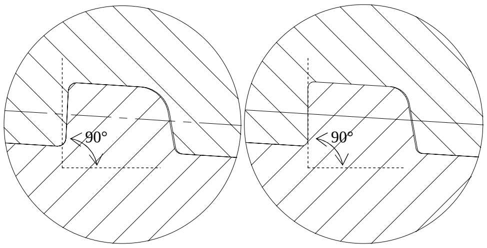
References

1. ISO 13679:2002 *Procedures for testing casing and tubing connections*, International Organization for Standardization, (2002)
2. American Petroleum Institute: *Bulletin on Formulas and Calculations for Casing, Tubing, Drill pipe, and Line Pipe Properties*, Sixth Edition, (1994)
3. NACE International, *ANSI/NACE Standard TM0177-96*, Revised 1996, (1996)
4. Jellison, M., DAVILA, M. A., : ”*How to Evaluate and Select Premium Casing Connectors*”, IADC/SPE 35037, presented in 1996 IADC/SPE Drilling Conference, Neew Orleans, Louisiana, (1996)
5. Badrak, R. P,: “*THE EFFECTS OF COLD WORKING AND STRESS RELIEVING ON SULFIDE STRESS CORROSION CRACKING RESISTANCE*”, Paper No. 49, Presented at the Corrosion 95 NACE International Annual Conference and Corrosion Show. (1995)

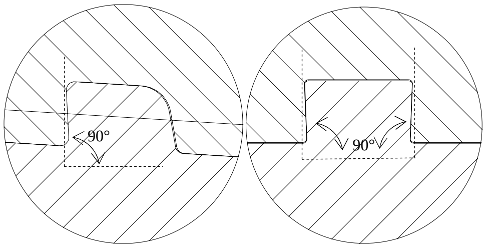


Flank to Flank **Crest to Root**

Figure 1. Thread iInterferences

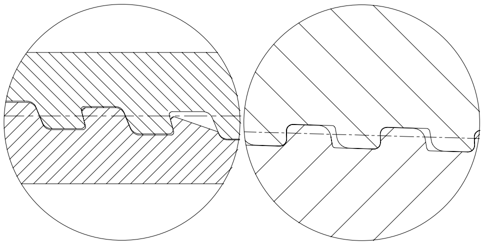


Positive Load Flank **Zero Load Flank**



Negative Load Flank **Negative Load and Stab Flanks**

Figure 2. Thread forms



Parallel to pipe axis **Parallel to thread cone**

Figure 3. Crest – root designs

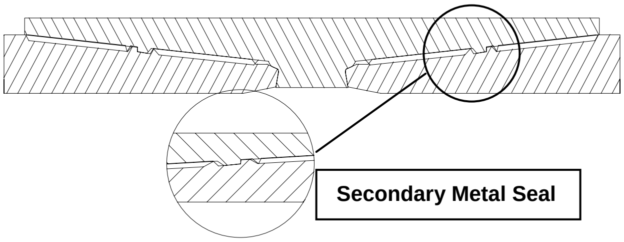


Figure 4. 10¾" x 101 lb/ft VM110SS VAM HP SC80 Threaded and coupled connection with secondary external metal seals.

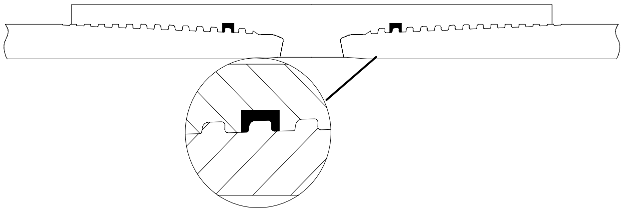


Figure 5. Resilient seal in threaded and coupled connection.

7.97" 1.123"-wall P110 VAM PRO RS						
Sample	Seal Tested	IP				EP
		A Series	B Series	C Series		A Series
		(psi)	(psi)	(psi)	(deg-F)	(psi)
1	MTM	27500	-	25000	425	15000
	RS	25000	-	25000	425	15000
2	MTM	27500	-	25000	425	15000
	RS	25000	-	25000	425	15000

Figure 6. ISO testing with metal and resilient seals.

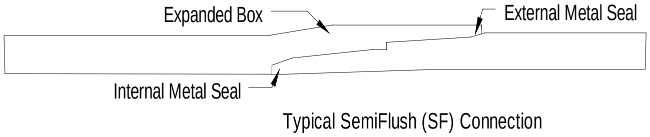


Figure 7. Typical expanded box semi-flush connection.

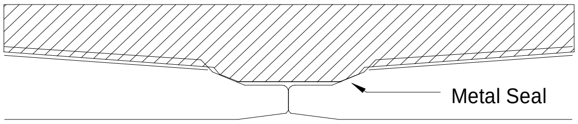


Figure 8. VAM PRO - Pin nose to pin nose with radial metal seal connection.

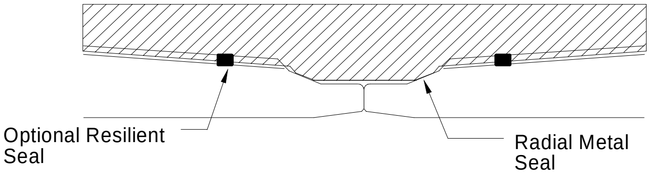


Figure 9. VAM PRO RS - Pin nose to pin nose radial metal seal connection with optional resilient seal.

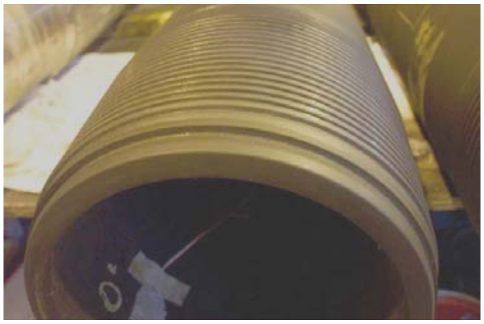


Figure 10. 7.97" OD x 1.123"wt VAM PRO RS connection with pin nose to pin nose shoulder.

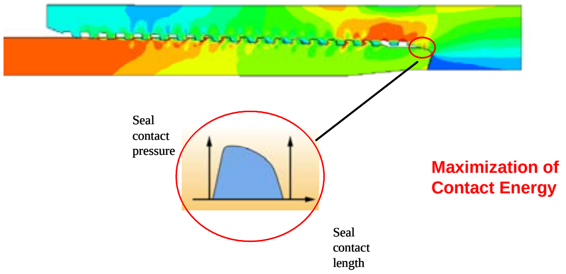


Figure 11. Example of Finite Element Analysis showing seal energy distribution.

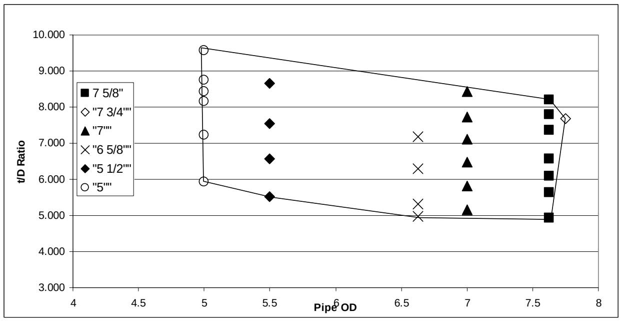


Figure 12. Example of product line connection grouping.

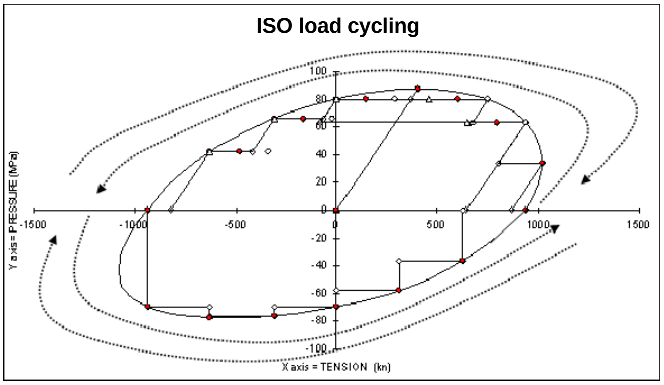
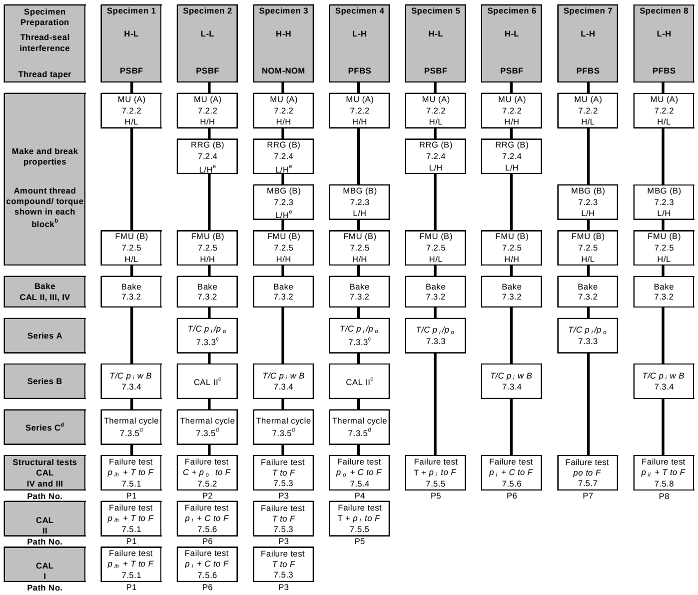


Figure 13. ISO 13679 loading cycles.



Specimen Preparation	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8
Thread-seal interference	H-L	L-L	H-H	L-H	H-L	H-L	L-H	L-H
Thread taper	PSBF	PSBF	NOM-NOM	PFBS	PSBF	PSBF	PFBS	PFBS
Make and break properties Amount thread compound/ torque shown in each block[b]	MU (A) 7.2.2 H/L	MU (A) 7.2.2 H/H	MU (A) 7.2.2 H/H	MU (A) 7.2.2 H/H	MU (A) 7.2.2 H/L	MU (A) 7.2.2 H/H	MU (A) 7.2.2 H/L	MU (A) 7.2.2 H/L
		RRG (B) 7.2.4 L/H[e]	RRG (B) 7.2.4 L/H[e]		RRG (B) 7.2.4 L/H	RRG (B) 7.2.4 L/H		
			MBG (B) 7.2.3 L/H[e]	MBG (B) 7.2.3 L/H			MBG (B) 7.2.3 L/H	MBG (B) 7.2.3 L/H
	FMU (B) 7.2.5 H/L	FMU (B) 7.2.5 H/H	FMU (B) 7.2.5 H/H	FMU (B) 7.2.5 H/H	FMU (B) 7.2.5 H/L	FMU (B) 7.2.5 H/H	FMU (B) 7.2.5 H/L	FMU (B) 7.2.5 H/L
Bake CAL II, III, IV	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2	Bake 7.3.2
Series A		*T/C* p_i/p_o 7.3.3[c]		*T/C* p_i/p_o 7.3.3[c]	*T/C* p_i/p_o 7.3.3		*T/C* p_i/p_o 7.3.3	
Series B	*T/C* p_i *w B* 7.3.4	CAL II[c]	*T/C* p_i *w B* 7.3.4	CAL II[c]		*T/C* p_i *w B* 7.3.4		*T/C* p_i *w B* 7.3.4
Series C[d]	Thermal cycle 7.3.5[d]	Thermal cycle 7.3.5[d]	Thermal cycle 7.3.5[d]	Thermal cycle 7.3.5[d]				
Structural tests CAL IV and III	Failure test p_{ih} + *T to F* 7.5.1	Failure test *C* + p_o *to F* 7.5.2	Failure test *T to F* 7.5.3	Failure test p_o + *C to F* 7.5.4	Failure test T + p_i *to F* 7.5.5	Failure test p_i + *C to F* 7.5.6	Failure test *po to F* 7.5.7	Failure test p_{il} + *T to F* 7.5.8
Path No.	P1	P2	P3	P4	P5	P6	P7	P8
CAL II	Failure test p_{ih} + *T to F* 7.5.1	Failure test p_i + *C to F* 7.5.6	Failure test *T to F* 7.5.3	Failure test T + p_i *to F* 7.5.5				
Path No.	P1	P6	P3	P5				
CAL I	Failure test p_{ih} + *T to F* 7.5.1	Failure test p_i + *C to F* 7.5.6	Failure test *T to F* 7.5.3					
Path No.	P1	P6	P3					

Figure 14. ISO 13679 eight sample CAL IV testing.

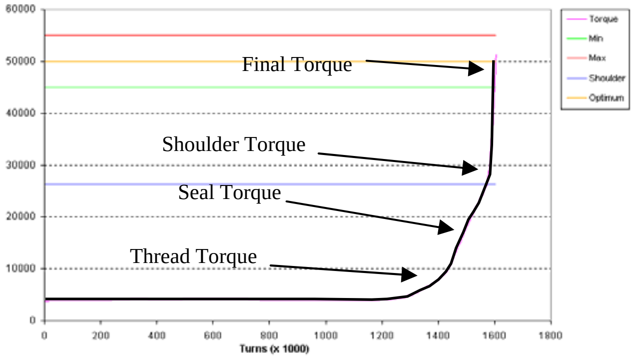


Figure 15. Acceptable torque turn graph.

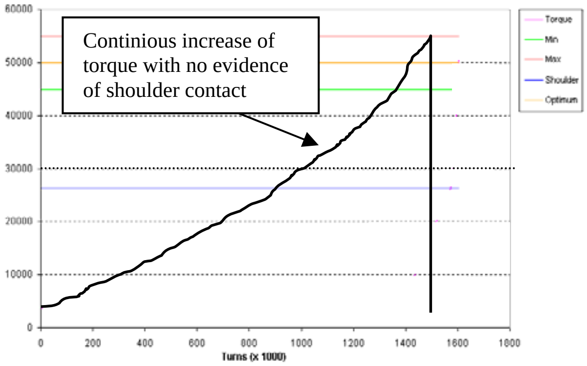


Figure 16. Torque graph showing thread galling.

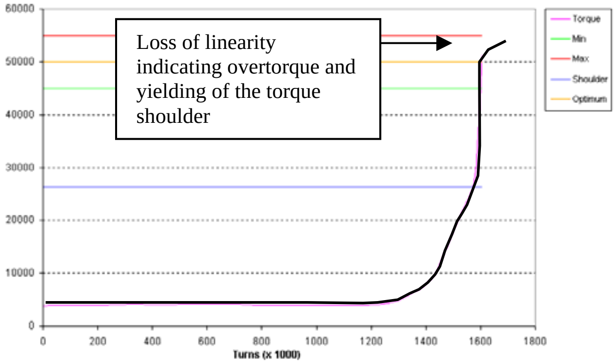


Figure 17. Torque graph showing overtorque connection.