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ML South: Innovation at work to push the limits and to deliver.

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Abstract

In 2012, TOTAL E&P BORNEO decided to continue the Maharaja Lela South Field (MLS) development by drilling wells with up to 15,000psi on the south panel. This project required the installation of the third well head platform on the field is knowns as the ML South project. In 2016, the new wells drilled were among the most challenging development wells ever drilled in Ultra HP/HT domain, with reservoir pressure up to 17,000psi, well head pressure close to 15,000psi, reservoir temperature up to 165°C, all combined with CO_2, H_2S and shallow reservoir.

The MLS field is operated by TOTAL E&P BORNEO B.V for the association with Shell Deepwater Borneo Ltd and PB ExPro Sdn Bhd. Mud optimization, drilling procedures and adaptation of the well architecture have been intensively prepared and developed in partnership with Vallourec in order to overcome the extreme field conditions. A 10-½" Premium production casing with 125ksi sour service material was tailor made and qualified for this project in order to withstand the extreme load cases but also to optimize the string weight and maintain similar minimum clearance as with a 10" casing in a 12-¼" hole. On the completion side, the latest generation of premium connection has been intensively tested for the production tubing according to ISO 13679 FDIS:2011 CAL IV protocol, the most severe protocol available in the Industry. A fine-tuned chemistry of the Super 13 Chromium material which successfully passed the corrosion tests as per TOTAL requirements without pitting nor cracks has been developed, industrialized, delivered and finally run in the MLS South wells.

This paper describes how Vallourec and TOTAL have worked together on the development of innovative connection designs; new generation of materials and how the combination of both was able to solve several of the well architecture design challenges historically faced by operators embarking into HP/HT projects.

Introduction

The further development of Maharaja Lela South (MLS) field with the Ultra HP/HT conditions was made possible thanks to the long term collaboration of Vallourec and TOTAL E&P BORNEO teams all along the project life: intial Research and Development activities were jointly initiated as soon as 2010 and led to a successful completion on the drilling campaign in 2016. The R&D expertise of both companies, combined with manufacturing excellence of Vallourec and Field Services support, all of these organized through a Project Management approach, were key to deliver innovative and cost effective solutions to overcome the technical challenges. By overcoming these challenges, operations were simplified and streamlined to reduce risks and improve safety.

The MLS field was already producing 10,000psi wells from two unmanned platforms MLJ1 & MLJ2. TOTAL E&P BORNEO made the decision to pursue the field development with two main reservoir types to be jointly operated from the new single plateform, MLJ3:

- **10,000psi reservoirs** with highly corrosive environment with H_2S of max 7ppm and CO_2 ranging between 0-3.2%. For these wells, Vallourec developed a metallurgy with high strength properties demonstrating a superior corrosion resistance at higher temperature compared to the standard Super 13Cr 13-5-2 grade and which is a cost effective solution compared to Duplex grades. Also, in order to withstand high pressure, high temperature and high combined loads, Vallourec developed an innovative connection design in order to pass the severe connection qualification tests to the full pipe body performance envelope (up to 100% compression). This premium thread was developed by using Finite Element Analysis (FEA) and physical protocol testing in order to deliver high strength and high seal integrity to comply with the severest protocol available at that time of ISO 13679 FDIS:2011 CAL IV, within the full pipe body envelope. It provides also excellent handling and running ability on the actual rig site to enhance operational performance.

- **15,000psi reservoirs** have originaly HP/HT conditions with surface pressure close to 15,000 psi. However the shallow reservoir depth including some reservoir pressure ranging from 10kpsi to over 17kpsi, shifted MLS reservoirs to Ultra HP/HT conditions. The typical architecture for such well use thick-wall 10-¾" top sections in 110ksi Sour Service (SS) before crossing-over to 10" 125ksi/140ksi casings, the target being to balance between resistance to H_2S and resistance to the load cases. However, there are some drawbacks when using this architecture such has one-way casing running operation due to the single string production casing being at the limit of the rig capacity. Vallourec developed for TOTAL a single diameter 10-½" production casing in 125ksi, with a gas tight threaded & coupled premium connection combining maximum external pressure resistance and internal pressure resistance with increased compression. This High Pressure (HP) connection was specifically designed and qualified to overcome problems associated with annulus pressure build-up and high collapse load cases such as on MLS well toward end of field life. To further increase the pressure resistance in the most sollicitated depth, wall thickness segregation has also been used. This tailor-made connection has been designed using Finite Element Analysis (FEA) and physically validated to ISO13679:2002 / API RP 5C5:2003 modified CAL IV and additional requirements that were later incorporated into the future revisions of API RP 5C5 standard. This innovative 10-½" 125ksi production casing has been able to bring benefits to the well design thanks to a stronger but lighter string with better clearance compared to the traditional 10-3/4" in 110ksi. For the Production Liner and the Completion, the proprietary 22 Chromium grade from Vallourec has been supplied in accordance with latest edition of API 5CRA / ISO 13680 specification - group 2 - category 22-5-3. This material has been tested and used in wells where a corrosion resistance is required regarding CO_2 and chloride for temperature up to 232°C (450°F).

In addition to the above conditions, some upper reservoirs in the block have already depleted. This leads to a drop in the formation frac pressures (requiring mud optimization efforts) leading to high risk of total losses and extreme collapse load cases, but also a drop in the formation pore pressures for which drilling procedures had to be optimized and which increased the criticality of any burst load cases. Overall, it was necessary to tailor make a new HP/HT architecture to overcome the field challenges.

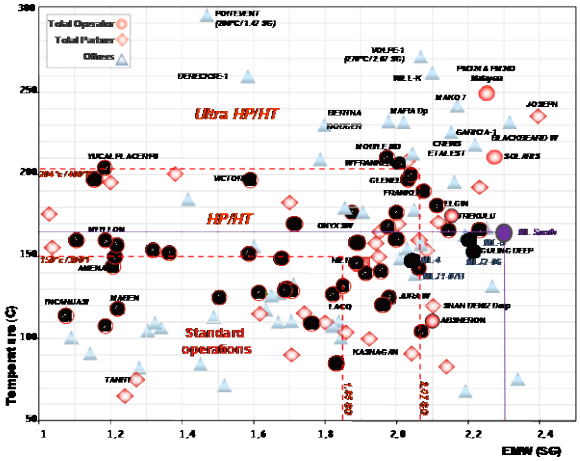

Figure 1: MLS field benchmark

Statement of Theory and Definitions

Qualification methodology for Materials:

TM0177-2005 standard has been used to test the materials of the Production Liners and the Completion of the 10,000psi and 15,000psi wells. This standard addresses the testing of materials for resistance to cracking failure under the combined action of tensile stress and corrosion in aqueous environments containing hydrogen sulfide (H_2S). This phenomenon is generally termed sulfide stress cracking (SSC) when operating at room temperature and stress corrosion cracking (SCC) when operating at higher temperatures.

In sour environments, the presence of H_2S can trigger Sulphide Stress Cracking (SSC) at stresses below the elastic strength limit (YS) of the material until its rupture. SSC of metals exposed to oilfield environments containing H_2S, even extremely low concentrations of H_2S, may be sufficient to lead to SSC failure of susceptible materials. In presence of H_2S, SSC can occur during or after production shut in (at ambient temperature) or closer to the wellhead (gradient of temperature).

SSC resistance is mainly assessed through NACE method A (standard tensile test) or C (standard C-ring test). For this project, SSC was tested using NACE method A with TOTAL E&P BORNEO SSC test conditions in both condensed and formation water as described in the Results section of this paper. NACE Method A, Standard Tensile Test, evaluates material resistance under uniaxial tensile loading. It offers a simple unnotched test specimen with a well-defined stress state. The cracking susceptibility with Method A is usually determined by time-to-failure. Tensile test specimens loaded to a particular stress level give a failure/no-failure test result.

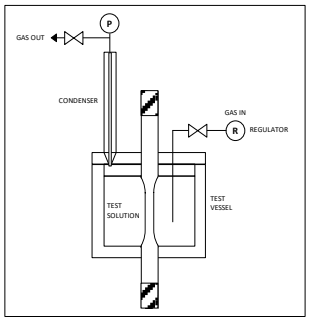

Figure 2: Test Equipment for Method A—NACE Standard Tensile Test

The Stress Corrosion Cracking (SCC) is a combination of corrosive environment and a mechanical stress at high temperature. It can lead to the creation of crack with multiple branches and progressive cracking with delayed failure. It starts from localized corrosion, which is a common for passivable material such as stainless steel and requires presence of Cl- (or Cl- + O_2) and H_2S in high temperature (often localized bottom hole).

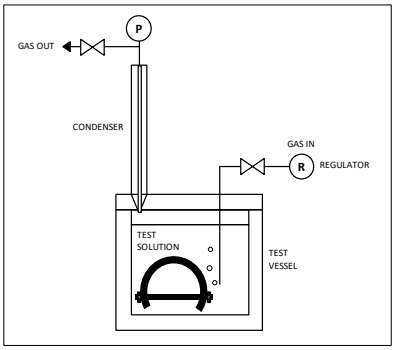

Figure 3: Test Equipment for Method C—NACE Standard C-Ring Test

SCC resistance is mainly assessed through NACE method C or 4 Point Bending (4PB). For this project, SCC was tested using NACE method C with TOTAL E&P BORNEO SCC test conditions described in the Results section of this paper. NACE Standard C-Ring Test (Method C) evaluates the cracking resistance of the materials under conditions of circumferential loading (hoop stress). It is particularly suitable for making transverse tests of tubing and bar. Cracking susceptibility with the C-ring test specimen is usually determined by time-to-cracking during the test. C-ring test specimens give a failure/no-failure result

To be noted that beside the SSC (at room temperature) and SCC (at elevated temperature) other failure modes (e.g., hydrogen blistering, hydrogen induced cracking [HIC], chloride stress corrosion cracking [SCC], pitting corrosion, and mass-loss corrosion) have also been considered to select and test the materials for this project with TOTAL E&P BORNEO in sweet (CO_2) and sour (H_2S) environments.

Qualification methodology for Premium Connections

Since 2002, ISO13679 1st edition/ API RP 5C5 3rd edition have been the industry standard for premium connection testing in OCTG. The objective of ISO 13679:2002 is to provide a standard for the evaluation of premium connection performance including testing procedure, measurement, load points and definitions. ISO does not define the size of the envelope and it is the connection designer to set the connection performance envelope.

In the last years, ISO and API committees worked on revising this standard to improve it and to attempt to replicate as close as possible OCTG downhole conditions. Some drivers were:

- to have combined loads at elevated temperature, whereas ISO13679:2002 was only proposing thermal cycles in Q1

quadrant of VME (Series C) whereas IP combined loads with bending (Series B) and Q1Q2Q3Q4 cycles (Series A) were always done at ambiant.
- to have external pressure at elevated temperature tests,
- to add Q1 (ambient) - Q3 (elevated temperature) cycles reflecting worst case discharge condition,
- to test connections as per clearely defined and accurate material characterization and connection in the very extreme tolerance range.

A first draft standard, the ISO13679:DIS2009 was issued in 2009 but was not adopted; it introduced elevated temperature Series B. A subsequent version in 2011 became a FDIS (final draft) but was rejected during ISO country vote. This ISO13679:FDIS2011 keeps Series B at elevated, but also adds the requirement of elevated temperature Series A (IP & EP at elevated temperature, and tighter extreme tolerances, as well as modified load calculation formula that make the testing more severe).

This ISO13679:FDIS2011 is the most severe test protocol developed, of all subsequent drafts up to the current API RP 5C5:2017 4th edition's continuously reduced qualification criticality. The ISO13679:FDIS2011 was used for Vallourec Premium connection qualification on ML South project, and able to pass the severe qualification tests to the full pipe body performance envelope (up to 100% compression).

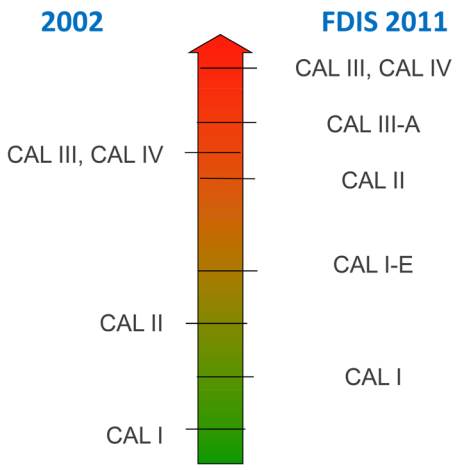

Figure 4: Comparison of ISO 13679: 2002 with FDIS:2011

Presentation of Data and Results

Materials: Super martensitic stainless steel Enhanced S13Cr in 110ksi as per UNS S41426

For the 10,000psi wells, a metallurgy demonstrating superior corrosion resistance at higher temperature compared to the standard Super 13Cr 13-5-2 grade has been developed. The environmental limit defined for Super martensitic stainless steel as per UNS S41426, also called Super 13Cr grade, is defined in Table A.19 of Annex A of NACE MR0175/ISO 15156-3 standard, but the information provided are very limited. For instance it does not describe in detail the Sulfide Stress Cracking (SSC) limits for the multiple combinations of pH, H_2S partial pressure (ppH_2S) and chloride contents; therefore product qualification is needed to define the SSC limits for different combinations of these parameters and to guarantee final product performance. The minimum requirements for qualifying Corrosion Resistant Alloy (CRA) material for Sour Service application by laboratory testing is defined in annex B of the same standard.

SSC performance of a proprietary Super 13Cr grade was qualified in several environments with different pH (from 3.0 to 6.0), ppH_2S (from 0.01 to 0.1 bar) and chloride levels (from 1g/l up to 200g/l of NaCl) using the most stringent requirements, such as applied stress of 90% AYS using uniaxial tensile (UT) test in solution C of NACE standard TM0177.
TOTAL E&P BORNEO approached Vallourec to determine if Super 13Cr 110ksi grade was suitable for the MLS project. Both, corrosion tests and subsequent analysis of the test samples of the Super 13Cr, showed that the existing product didn't pass the TOTAL E&P BORNEO 's criteria of shiny pass[(1)] in SSC corrosion tests to check the suitability of the material during shut-in phase. Therefore, a switch to a costly duplex (22-5-3) or Super duplex grade (25-7-3) would have been required.

#	Method	Material	Initial pH	Cl- (ppm)	Temp (°C)	H_2S (mbar)	Load	Results
1 SSC	NACE A	S13 110ksi	3.00	1 000	24	10	90% AYS at 24°C	Pass
2 SSC	NACE A		4.60	20 000	24	10	90% AYS at 24°C	Pits

Figure 5: Test results of S13Cr 110ksi as per SSC testing conditions from the customer

The detailed analysis showed that Super 13 grade was just at the limit of the application domain. By increasing the alloying elements (Chromium, Molybdenum and Nickel), it could reach a better corrosion resistance performances. New chemistries were first defined based on numerical simulation, using several alloying concepts and then tested through lab-scale prototyping. Several iterations and design loops were performed in order to converge towards the final optimized material.

(1) Pits are allowed according to NACE MR 0177:2005 acceptance criteria

The enhanced chemistry successfully passed the SSC corrosion tests as per the customer requirements without pits nor cracks. Additional SCC tests at well reservoir temperature have been performed to confirm the suitability of the material during production phase. The successful qualification allowed to provide a tailor made chemistry, safe, fit for reservoir condition and cost effective for the ML South development campaign, this is line with TOTAL "good enough" engineering approach in field development.

#	Method	Material	Initial pH	Cl- (ppm)	Temp (°C)	H_2S (mbar)	Load	Results
3 SSC	NACE A	**Enhanced** S13Cr 110ksi	3.00	1 000	24	10	90% AYS at 24°C	Pass
4 SSC	NACE A		4.60	20 000	24	10	90% AYS at 24°C	Pass
5 SCC	NACE A		4.60	20 000	141	10 + 27bar CO_2	100% AYS at 141°C	Pass

*Figure 6: Test results of **Enhanced** S13Cr 110ksi as per SSC testing conditions from the customer*

The development of the new metallurgy will be beneficial for other oil & gas operators. It allows optimizing material selection by choosing a grade specifically designed for their application.

Materials: Duplex 22Cr 125ksi grade as per UNS S31803

For the Production Liner and the Completion, a proprietary 22Cr 125ksi grade from Vallourec (UNS number S31803) was successful following intensive testing. SSC and SCC performance of a proprietary 22Cr 125ksi grade was tested on a sample with actual yield strength of 149 ksi at 20°C. As cracking sensitivity can be highest at a temperature below the maximum service temperature, tests were performed at 24°C, 80°C, 150°C and 175°C as requested by TOTAL E&P BORNEO. Tests has been made with applied stress of 90% AYS using uniaxial tensile (UT) test as per NACE standard TM0177 most stringent requirements.

Testing condition	Method	T (°C)	Solution			Pressure of gas at test temperature	Load	Results
			pH	[Cl-] en ppm	AcNa en g/l			
SSC-24-1	NACE A	24°C	pH 3.3 acidification by HCl	10000	-	100 mbar H_2S	90%AYS at 24°C	Pass
SSC-24-2	NACE A	24°C	pH 4.5 acidification by HCl	20000	0.4 g/L AcNa	20 mbar H_2S	90%AYS at 24°C	Pass
SSC-80-1	NACE A	80°C	pH 3.0 acidification by HCl	1000	0.4 g/L AcNa	56 mbar H_2S	90%AYS at 80°C	Pass
SSC-80-2			pH 4.7 acidification by HCl	20000		17 mbar H_2S		Pass
SCC-150-1	NACE C	150°C	pH 3.3 obtained by CO_2 addition	10000	-	20 mbar H_2S + 30 bar CO_2	90%AYS at 150°C	Pass
SCC-150-2	NACE C					50 mbar H_2S + 30 bar CO_2		Pass
SCC-150-3	NACE C					100 mbar H_2S + 30 bar CO_2		Pass
SCC-175-1	NACE C	175°C	pH 4.8 acidification by HCl	20000	2.4 g/L $NaHCO_3$	17 mbar H_2S + 38 bar CO_2	90%AYS at 175°C	Pass

Figure 7: Test results of 22Cr 125ksi grade as per SSC and SCC testing conditions from the customer

After one month of test, specimens were examined with up to 50X magnification and no evidence of corrosion nor cracking were observed. Finally to evaluate SCC resistance, tests were performed at 175°C with a pH 4.8 and 20 000ppm of chlorides. The material passes successfully the tests, neither corrosion nor cracking were observed.
The proprietary 22Cr 125ksi has been qualified in several environments with different temperatures: the proprietary 22Cr

125ksi passed the SSC and SCC tests as per TOTAL E&P BORNEO requirements without pits or cracks.

Connections: Production Casing connection

The Maharaja Lela South (MLS) field led also to several challenges on the connection development to overcome the Ultra HP/HT conditions. At design phase, several options were evaluated for the 15,000psi wells productions casing string. Due to the anticipated well conditions, the only viable "conventional" casing format would have been a 10-¾" C110 heavy walled pipe (110.2 lb/ft – 1.05" wall thickness). This product had already been used in other HP/HT projects in North Sea.

OD (in)	ppf	Wall (in)	Grade	Connection		MIYP (psi)
				Thread	OD (in)	@ 90%
9 7/8	66.9	0.668	VM125HY	Vam TOP NA	10.978	17 050
10	73.9	0.732	VM125HY	VAM21	11.213	18 451
10 1/2	96	0.94	VM125SS	VAM HP	11.2	20 148
10 3/4	110.2	1.05	VM110SS	VAM HP	11.491	19 344
				VAM HWST-NA	11.72	

Figure 8: Production Casing comparisons in dimensions and performances

However, other solutions using tailor-made casing sizes were explored, with the objective to improve safety factors on a several critical load cases. 10-½" 96 lb/ft (0.94" wall thickness) with a 125ksi Sour Service or Controled Yield material was identified to improve the axial and triaxial design safety factors for design cases such as "Cold kill: Bull heading surface tubing leak" and allowed to maintain an acceptable 10% minimum wear margin. Among the other benefits of the 10-½" Casing size was the reduction of the casing string cost by saving OCTG tonnage and the ±90 tons weight reduction (taking into account buoyancy) thanks to ±15% wall thickness reduction vs 10-¾" joints. The advantages of this tailor made casing size were deemed sufficient to design and qualify a 10-½" premium connection.

10-½" 96 lb/ft High Pressure (HP) connection with proprietary 125Ksi Sour service (SS) grade was extrapolated from TOTAL approved 10-¾" 110.2 lb/ft 110ksi Sour Service (SS) grade connection with specific OD and ID clearance, targetting full connection envelope and torque values so as to be able to use conventional field power tongs in Brunei. This connection had been validated to ISO13679:2002 / API RP 5C5:2003 CAL IV plus additional requirements that were later incorporated into the future revisions of API 5C5 standard such as combined load tests under internal pressure and external pressure performed at elevated temperature (180°C). As per TOTAL guidelines, it was agreed to perform an abbreviated test especially by adding testing cycles compared to the standard protocol – while maintaining the criticity of the tests – to reduce qualification costs (±1 MUSD) and test duration (±4 months). Physical tests were successfully completed in July 2013. Timing was critical as pipes rolling were already on-going in Germany to secure the delivery in time of those long lead critical items to the operation site.

Thanks to a close cooperation between Vallourec and TOTAL, a 10-½" 96 lb/ft 125 ksi Sour service (SS) High Pressure (HP) connection was successfully developed and qualified in time for the MLS development campaign by interpolation with an existing connection developed for a TOTAL exploration project. 10-½'' 96# development generated an approximate 350 kUSD saving per well in terms of OCTG with improved design safety factors.

Connections: Production tubing and production liner connection

Unlike for production casing, where a bespoke design development was agreed, it was decided to strictly follow the most stringent standard for production tubing and production liner qualification (ISO 13679:2011 FDIS CAL IV). 3 formats were considered for a full qualification:

- 6 5/8" 28ppf 110ksi 13%Cr 21st century connection,
- 5 ½" 23ppf 110ksi 13%Cr 21st century connection,
- 5 ½" 26.8ppf 125ksi 22%Cr 21st century connection.

Anticipated well loads covered almost the full Service Load Envelope of the Pipe Body (as depicted below by the Von Mises Envelope for a 5 ½" 26.8ppf (22%Cr 125ksi). Qualification Testing Envelope was defined to fit the entire Von Mises ellipse to validate all potential load cases that the project might encounter. To provide a magnitude of the loads that were applied for those full-scale testing, the maximum internal pressure reached 22665 psi and max applied Tension reached 933 000 lbs.

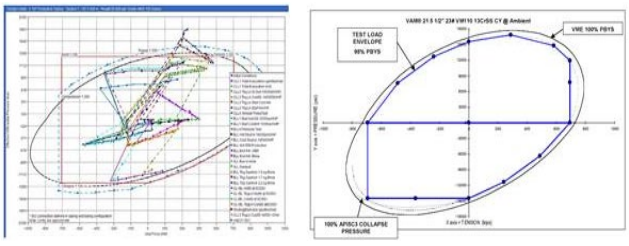

Figure 9: Von Mises Envelope for a 5 ½" 26.8ppf VM22 125

As explained earlier in this paper, ISO13679 standard was under revision process. Project managers ended up selecting the most stringent revision with the most critical Connection Application Level – ISO 13679:2011FDIS CAL IV – as it reflected load cases evaluated during casing and tubing design. Severity of the standard has been reduced since then, so it can be highlighted that TOTAL E&P Borneo has probably validated to the highest standards ever for a HP/HT project.

Taking the example of 6 5/8" 28ppf 110ksi 13%Cr 21st century connection, 5 samples were tested as per the recommendations of ISO13679:2011FDIS CAL IV, with a sequence of: Make-Up / Break-Out for galling resistance, Combined loads under internal and external pressures at ambient or 180°C, test to failure (see chart below):

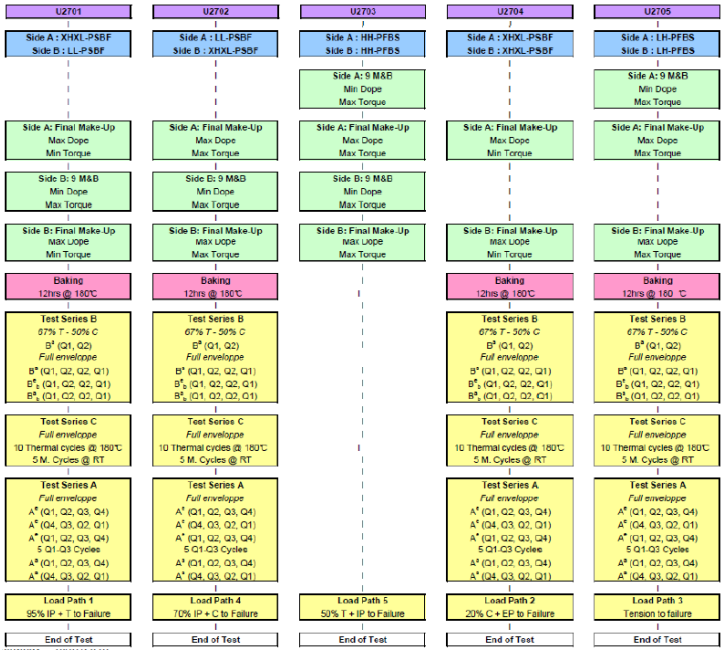

Figure 10: ISO13679:2011FDIS CAL IV testing sequence

Each qualification test lasted from 4 to 6 months, as specific mill rolls had to be run to source representative material that was to be run downhole. Estimated cost for those qualification tests exceed 1 MUSD per format, hence a real effort from both sides to conduct this exceptional validation process in due time for the project.

All qualification tests were successful and Tubings have been run downhole with success since then. This project allowed to provide to the industry a field proven and validated solution to the most stringent standard a set of Production Tubing and Production Liner for Ultra HP/HT development.

Conclusions

This challenging MLS project turns out to be a success for TOTAL and Vallourec to the implementation of a Project management organization leading to the development of innovative technical solutions. Vallourec had a dedicated team from Project Manager to Technical Manager located in Asia involved in monthly face to face meetings with TOTAL engineering team in Brunei to settle all contractual and technical aspects of the project. The collaboration between TOTAL E&P BORNEO and Vallourec was pushed down to the IT side with integration of Vallourec and TOTAL E&P BORNEO ERP systems to generate PO.

The MLS project was well anticipated, Vallourec and TOTAL worked together in order to design and develop innovative technical solutions bringing the following benefits. The new alloy developed by Vallourec is a cost effective solution to replace Duplex grade depending the severity of the well conditions. On the safety aspects, the 10-½'' lighter weight offered better margin of overpull for casing running. On operational aspects, running time was improved thanks to the 10-½'' lower torque needed and support of Vallourec Field Services on the rig. The design of Vallourec Premium connections with protected seal gave higher confidence in handling to the casing crew with reduced deck reject rate compare to convention premium connections.

Thanks to this "good enough" approach, TOTAL E&P BORNEO has been able to generate significant savings on the Oil Country Tubular Goods (OCTG) procurement and to deliver safely the 6 uHP/HT wells of the MLS development campaing.

Acknowledgments

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- Philippe Deletombe (Vallourec Oil & Gas France)

Vallourec woud like also to acknolewdge the contribution of Ronan Brignoli to the MLS project.

Appendix

Material evaluation

The objective is to assess whether a given material is suitable for Sour Service conditions. NACE TM 0177 has defined and

normalized 4 tests of which methods A to D are the most used for OCTG. Specimens are generally tested in a critical and normalized Sour Service environment called “environment A”. In fit for purpose conditions, modified environments called “environment C” may be used.

To be considered suitable for Sour Service environments, a material has to pass at least one of these tests.

Test methods	A	B	C	D
Stress application	Tension % of SMYS	Flexion 3 points bent	C ring % of SMYS	Wedge
Standard environment	P H2S = 1 bar (14,5 psi) pH = 3 NaCl = 50g/l (except test B) Temperature = 24°			
Duration	720 Hours			336 Hours
Results	Rupture / No rupture	Sc (Not used anymore)	Rupture / No rupture	Stress Intensity Factor