PRESSURE TEST AFTER WAIT ON CEMENT (WOC): ANALYSIS IN OIL WELL CASING DESIGN

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Received: 09.12.2018 / Revised: 15.12.2018 / Accepted: 20.12.2018 / Published on line: 10.01.2019

ABSTRACT

This work discusses the load criteria known as pressure test after waiting-on-cement (WOC) through a detailed explanation of the calculation methodology and study cases. Well casing design is an important step on hydrocarbon exploration planning. New methodologies in this subject allows improvement on well structural integrity combined with time and costs reductions. In routine procedures, design may consider pressure test after WOC, which is an essential operation for cementation failures verification. During test pumping, additional loads are applied to the casing and, when combined, they must be lower than tubular resistances to ensure no failure, avoiding catastrophic consequences. The computational tool CWELL is used for analyzing a production casing string set next to the reservoir, submitted to the pressure test after WOC. Investigating different grades and linear weights on API tubes verifies the achievement of well safety requirements. Results indicate the importance of performing integrated analyzes to guarantee wells stability.

KEYWORDS

cementation; structures; casings; tubes; hydrocarbons

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doi:10.5419/bjpg2018-0022

1. INTRODUCTION

Nowadays, despite the energy matrix diversification, the demand for hydrocarbons continues to increase. This is an indication of the large global dependence on these fuels (BP, 2017). The growing complexity of oil well constructions for deep reservoirs is highlighted. Therefore, projects involving well construction need to be adapted to achieve efficiency in terms of time and cost (Aadnøy, 2010). When evaluating the importance of financial planning in the design of an exploratory program, casings expenses are among the costliest in the development of a well. In some situations, casing expenses account for 18% of the overall completion costs. If there are failures on the installation process or during the service, repair costs will make these costs even higher (Rahman & Chilingarian, 1995; Samuel et al., 2014).

Well casings are structures responsible for several functions, such as keeping the well open; preventing undesired fluid exchange between the well and the formation; being the conductor of fluids, from the formation to the surface, during production, and from the inverse path in the injection. Due to these factors, the casings can be considered important for hydrocarbon extraction in a safe and efficient way. The sizing step is one of the most relevant parts of the proper selection process of these components, and it has brought recurring challenges to drilling and completion engineers. This happens because those are

structures that are subjected to different types of loads that may compromise their integrity. The complexity of current wells requires a greater accuracy in the planning of casings, especially for applied load calculations (Rahman & Chilingarian, 1995; Samuel et al., 2014; Gholami et al., 2016; Wang & Taleghani, 2014).

The financial importance of the projects resides on the fact that sizing analyses generate references, including books and technical papers, proposing best practices to companies in oil and gas sector (Aadnøy, 2010; Allomax Engineering, 2000; ANSI/API TR 5C3, 2008; Shahvali et al. 2014, Peng & Wang 2012, Ma et al., 2009). These materials provide a theoretical basis for several investigations. They guide project improvements, such as the ones proposed by the authors of this in the implementation of a computational tool called Casign Well (Costa, 2016).

Thus, the objective of this is to verify the mechanical integrity of the well casing system by means of the critical forces generated during the wait on cement (WOC) pressure test. This test leads to evaluate the success of the cementation, being a fundamental step for structural evaluation of the well casing section. Based on mechanical integrity indicators, this work proposes the ideal configuration for the production casing system.

2. METHODS

The proposed analyses were developed on the software CWELL, which is a web application that performs the study of casing for oil wells. This mechanism was implemented within the Multidisciplinary Petroleum Engineering Applications System (SAEP), developed by the Federal University of Alagoas. The computational tool carries out the detailed analysis of the stability of the columns in several stages of the well (Costa, 2016).

Figure 1 illustrates the production casing. Among different kinds of well casings, it has the function of isolating producing zones to promote control over the fluid from reservoir. It also allows selective production when the well has several producing regions. It is through the production casing that the well completion is done (Aadnøy, 2010). The completeness of this structure depends

Figure 1. Casing program showing different casing sizes and their setting depths (Rahman & Chilingarian, 1995).

Figure 2. Modes of failures in tubes by: a - tension; b - burst; c - collapse (Bourgoyne et al., 1991.).

on the mechanical strength of the tubular installed. **ANSI/API TR 5C3 (2008)** standard indicates the calculations of how well the tube withstands different types of stress. The casing must withstand traction or compression, its failure (Figure 2-a) results in plastic deformation due to axial stresses. Similarly, it must withstand the burst produced by the excessive increase of internal pressure against external one (Figure 2-b). It must withstand the collapse, resulting from loads in which external pressure protrudes to internal, as shown in Figure 2-c.

2.1 Tubes resistance to internal loads

Equation (1) and Equation (2), respectively, indicate tube resistance to traction or compression R_t and to burst R_b . Tube outer D_o and inner D_i diameters, as well as its yield stress Y_p and thickness t are parts in the equation. The resistances are compared with the applied loads. If they exceed the tube load limit, it can indicate failure. For all types of applied loads, CWELL includes an extra portion to the cargoes. Those are the safety factors, which are common items in engineering projects, bringing them greater

reliability, from a percentage increase of the values of loads. These elements vary according to the characteristic design conditions and the company that conducts it.

$$R_t = \frac{\pi}{4} (D_o^2 - D_i^2) Y_p \quad (1)$$

$$R_b = 2Y_p \frac{0.875t}{D_o} \quad (2)$$

Aiming for a more realistic analysis, one must recognize that internal, external, and axial forces, acting simultaneously, can influence each other. Thus, for three-dimensional studies, it is prudent to consider a triaxial analysis, which can be applied through the von Mises plasticity criterion. The equivalent stress, σ_{VME} , relates the axial σ_a , radial σ_r , and tangential σ_t stresses, as presented in Equation (3) (ANSI/API TR 5C3, 2008). The pipe remains in linear elastic regime when $\sigma_{VME} < Y_p$. On the mentioned stresses, it is important to consider that the axial stress is given by the ratio of the axial force to the cross-sectional area of the pipe, since the radial and tangential stresses are given by the *Lamé* equations for perfect thick-walled pipes (Aadnøy, 2010; ANSI/API TR 5C3, 2008; Bourgoyne Jr. et al., 1991).

$$\sigma_{VME} = \frac{[(\sigma_a - \sigma_r)^2 + (\sigma_r - \sigma_t)^2 + (\sigma_t - \sigma_a)^2]^{0.5}}{\sqrt{2}} \quad (3)$$

Graphically, it is possible to describe an envelope created by Equation 3 and another one generated by the equations from **ANSI/API TR 5C3 (2008)**, known as the envelope (API-based security regulatory factors), as illustrated in Figure 3. These envelopes, penalized by the pipe safety factors, are

Figure 3. von Mises Ellipse and API Envelope generated for Casing tubes (Costa (2016), adapted).

basis for analyzing the tube structural safety. In this graphical area, the well loading scenario curves enable a visual comparison between resistance and loads to the pipe. That is, if the curves that represent the load applied to the tubes exceed the envelopes, the casing structural integrity is not guaranteed, since the flow stress of the material is achieved. In this case, one can state that the structural element reached the service limit state. It is worth noting that, even after exceeding these boundaries, the tube can also be used, however imperfectly, until it reaches the ultimate limit state, the structural failure, indicating the final stop of its use.

2.2 Pressure test after WOC

As for the axial loads, the string weight F_P , indicated by Equation (4), and the buoyancy F_E , indicated by Equation (5), are involved, reducing the weight action. These forces depend on the linear weight of the pipe W , in lbf/ft; the true vertical depth TVD , in m ; the hydrostatic pressure of the drilling mud P_{mud} , in psi ; and the external and internal areas, A_o and A_i , in pol^2 .

$$F_P = 3.28084W * TVD \quad (4)$$

$$F_E = P_{mud}(A_o - A_i) \quad (5)$$

Referring to the study of radial and tangential loads to the tube, the Pressure Test is set up after WOC. This is a test performed as soon as the cementation is completed after reaching the casing shoe, indicating the success or failure of the cement setting in the well. Cementation consists of a cement paste application process with the objective of hydraulically isolating different areas of interest (Bearden & Lane, 1961; Rabia, 1985). It is worth emphasizing that there are companies that carry out the pressure test of the casing even with the cement not cured (fresh cement), since, in some cases, micro channels have been created between the cement and the casing, allowing communication of the pressure in several areas (Rabia, 2011). During this event, one can interpret the interaction between internal and external pressures.

For the internal pressure P_i , in psi , one can see the influence, in Equation (6), of the pressure test on surface, P_{sp} , in psi , and of the drilling fluid, whose specific weight is given by ρ_{perf} , in lb/gal , in a certain TVD , in meters) (Allomax Engineering,

2000; Samuel et al., 2014).

$$P_i = 0.1704[\rho_{perf}TVD] + P_{sp} \quad (6)$$

External pressure calculation is based on two situations, observing the external pressure (P_o , in psi) applied by the cement after setting. Situation 1- looks at the pressure from the top of the well (TVD_{LDA} , which corresponds to the water depth in meters) to the top of cement (TVD_{cement} , in meters). It follows Equation (7), which involves the action of the drilling fluid and the seawater. Its specific mass is given by ρ_{sea} (in lb/gal). Situation 2- from the top of the cement to the base of the casing, including the specific mass of the cured cement ρ_{cement} (in lb/gal), according to Equation (8) (Allomax Engineering, 2000; Samuel et al., 2014).

$$P_o = 0.1704[\rho_{sea}TVD_{LDA} + \rho_{sea}(TVD_{cement} - TVD_{LDA})] \quad (7)$$

$$P_o = 0.1704[\rho_{sea}TVD_{LDA} + \rho_{sea}(TVD_{cement} - TVD_{LDA}) + \rho_{cement}(TVD - TVD_{cement})] \quad (8)$$

Depending on the operator, P_{sp} can be considered with values up to 80% of the burst strength pressure of the lowest grade used in the casing (Rabia, 1985, 2011). However, industry data show that, in robust casings, the suggested pressures are high (since they are survival loads), leading to the use of magnitudes that depend on the service loads that may act over the service life of the casing. Pipe leakage is deemed critical scenario of service, considering that the production casing must be prepared for the tube leakage, which is internal to the casing (Bourgoyne Jr. et al., 1991). In this scenario, the surface pressure value can be determined from Equation (9). In addition to ρ_{perf} , Equation 9 can provide the depth of the investigated casing shoe (TVD_{shoe} , in m) and the fracture gradient at this point, $\rho_{fracture}$, in lb/gal (Allomax Engineering, 2000). The surface pressure test also influences the axial load, generating the stress F_{sp} , Equation (10), in psi , adding to the axial stress of the column (Rabia, 1985).

$$P_{sp} = 0.1704(\rho_{fracture} - \rho_{perf} + 2)TVD_{shoe} \quad (9)$$

$$F_{sp} = P_{sp}A_i \quad (10)$$

The importance of proper cementation can be reflected in considerations about the damage of

Figure 4. Geometric configuration of the selected well, with the depths in TVD (Perez et al. (2017), adapted).

Brazilian offshore wells. The creation of flow channels in cement, which is one of the safety barriers of the well, allows the leakage of hydrocarbons after the cementation of the production casing. This leakage, besides causing significant economic losses to the company, due to deviation of production and increase of corrosion in some subsurface elements, can generate catastrophic environmental damages, because fluid exchange occurs with the formation (Perez et al., 2017). This work develops the sizing of a production casing adapted from Perez et al. (2017). According to Figure 4, the casing outer diameter is 9.625 in. True vertical depths of the top of the casing, the base of the casing, and the top of the phase cement are 161 m, 3045 m, and 2740 m, respectively. The well is simplified as vertical.

In addition to the basic data provided, other key information for the project was adopted in works with similar conditions (Allomax Engineering, 2000; Bourgoynne et al., 1991; Rahman & Chilingarian, 1995), generating the parameters

described in Table 1. For this purpose, load calculations are used to optimize casing costs. It is also necessary to investigate the linear weight and the grade (which determines the yield stress of the structure from the material of which it is formed) ideal for the situation, since the lower prices of the pipes are related to the lowest value of grades and the lighter linear weights (Rahman & Chilingarian, 1995).

Thus, grade C90 and linear weight, 47 lb/ft (thickness 0.472 in) were chosen considering their common use in production casing in several projects (Aadnøy, 2010; Allomax Engineering, 2000; Rahman & Chilingarian, 1995). Based on the standard (ANSI/API TR 5C3, 2008), two other grades (N80 and M65) were tested, submitted to two other linear weights (43.5 lb/ft, 0.435 in thick, and 40 lb/ft, 0.395 in thick). For all situations, a 12.5% casing wall thickness penalty was also applied. This penalty is used for casings not characterized as Premium by the manufacturer.

Table 1. Project input parameters.

Parameter	Value
Fracture gradient at 2740 m TVD	17.08 lbf/gal
Specific mass of the cured cement	15.88 lbf/gal
Specific mass of the drilling mud	9.5 lbf/gal
Specific mass of the mixture water	8.6 lbf/gal
Safety factor for tensile (traction/compression) loads	1.3
Safety factor for burst loads	1
Safety factor for collapse loads	1.1
Safety factor for triaxial loads	1.25

Figure 5. a: Loads representation for traction/compression scenario in tubes with the highest linear weight (47 lb/ft), i.e. axial load in blue and axial load with pressure test after WOC in green (TVD in m x tensile load in psi); and b: Loads representation for the burst scenario, i.e. pressure test after WOC in blue (TVD in m x burst load in psi).

3. RESULTS AND DISCUSSIONS

Equation 9 and the input data determined the surface pressure during the test, that is, 4970.75 psi. Then, as one can see in Figure 5, graphs were generated for the maximum traction/compression loads on the highest linear weight (47 lb/ft) pipe and for the burst load applied throughout the well in that order. In Figure 5-a, the image related to the action of the traction illustrates the major stresses applied in the structure located in the upper part of the well. This was an expected result due to the greater weight in this region. It is worth mentioning that the curve has the same tendency for different linear weights, which, while reduced, generate a lower traction load due to the application of a lower weight. The grade does not influence this value, since it only changes the stress flow (without influencing axial

loads). The maximum traction stresses calculated on the surface, in decreasing order, were 798.01 klbf (for 47 lb/ft), 770.29 klbf (for 43.5 lb/ft), and 743.75 klbf (for 40 lb/ft).

For the burst scenario, shown in Figure 5-b, the highest value load for all situations is 5503.17 psi and it is located at the top of the cement, presenting the same value close to the well's head (top of the liner). The curve behaved as expected in literature (Aadnøy, 2010; Allomax Engineering, 2000; Bourgoyne Jr. et al., 1991; Rabia, 2011; Rahman & Chilingarian, 1995), there was an increase in external pressure from the top of the cement to its base (in the casing shoe) and the burst differential assumed its smallest value.

For comparison, the uniaxial/biaxial strengths are given in Table 2. As expected, the more robust the pipe (either by the grade, leading to increased

Table 2. Results of the uniaxial/biaxial resistances of interest for the tubes analyzed.

Steel grade	Linear weight	Tensile resistance	Burst strength resistance
C90	47 lb/ft	1221.51 klbf	7723.64 psi
	43.5 lb/ft	1130.31 klbf	7118.18 psi
	40 lb/ft	1030.84 klbf	6463.64 psi
N80	47 lb/ft	1085.79 klbf	6865.45 psi
	43.5 lb/ft	1004.72 klbf	6327.27 psi
	40 lb/ft	916.30 klbf	5745.45 psi
M65	47 lb/ft	882.20 klbf	5578.18 psi
	43.5 lb/ft	816.33 klbf	5140.91 psi
	40 lb/ft	744.50 klbf	4668.18 psi

Figure 6. Results of triaxial scenarios for *C90* tubes with linear weights 47 lb/ft (a) and 40 lb/ft (b) displayed in a tensile load in klbf x collapse/burst strength in psi graph. Black and blue curves stand for VME and API envelope, green stands for the loads.

Figure 7. Results of triaxial scenarios for *N80* tubes with linear weights 43.5 lb/ft (a) and 40 lb/ft (b) displayed in a tensile load in klbf x collapse/burst strength in psi graph. Black and blue curves stand for VME and API envelope, green stands for the loads.

flow stress, or by linear weight, which increases the thickness), the greater the uniaxial/biaxial resistance is, being credited with greater safety in their use. Thus, the most critical values - the lowest strengths - were obtained for *M65* casings of 40 lb/ft and 43.5 lb/ft. Considering the burst failure criterion, one could observe that, for both, the load (5503.17 psi, like that one shown in Figure 5-b) would be higher than its respective resistances (4668.18 psi and 5140.91 psi, see Table 2). This indicates the possibility of rupture. It is possible to observe that, in the chosen scenario, these two pipes are no longer reliable for use.

The indication of greater integrity preservation for more robust pipes is maintained in the triaxial

study. Figure 6, Figure 7, and Figure 8, in that order, show the triaxial load analyses applied to *C90* (47 lb/ft and 40 lb/ft), *N80* (with 43.5 lb/ft and 40 lb/ft), and *M65* (47 lb/ft and 40 lb/ft). In all these graphs, the von Mises ellipse (VME) and API envelope are, respectively, in black and blue colors. If the loading (in green) exceeds any of them, casing failure is indicated. In this investigation, *C90* grade pipes proved to be reliable at all linear weights, as seen in Figure 6. Note that envelopes decrease (which makes loading closer to the limits thereof) is evident with the reduction of the linear weight, as with the *N80* and *M65* casings according to Figure 7 and Figure 8.

Figure 8. Results of triaxial scenarios for *M65* tubes with linear weights 47 lb/ft (a) and 40 lb/ft (b) displayed in a tensile load in klbf x collapse/burst strength in psi graph. Black and blue curves stand for VME and API envelope, green stands for the loads.

Although more reliable, *C90* is usually more expensive than the other tested grades. Thus, Figure 7 shows that under the proposed loading conditions, *N80* pipes and linear weights other than 40 lb/ft are safe. One can observe that the weight of 47 lb/ft is more robust than that of 43.5 lb/ft (Figure 7-a), which indicates near, but within limits, loading of the API envelope. It, however, is overcome for the 40 lb/ft *N80* casing (Figure 7-b). A similar situation occurs with the lower grade, *M65*, combined with the higher linear weight, as seen in Figure 8-a. This indicates that the *M65* is unsafe even in the best proposed situations for the chosen scenario. The problem is aggravated when the loading almost surpasses the von Mises envelope where the linear weight is reduced as shown in Figure 8-b.

Thus, it is evident that *C90* tests proved to be safe, whereas the casing that would be more financially viable (*M65*) in the triaxial analysis was not reliable. In the case of *N80* tubes, it is demonstrated that, due to their limitations, some applied forces, especially in a situation of low linear weight added to the thickness penalty, can make the use deficient when exceeding the limit state of service. Thus, the pipe can still be used, but inadequately, until the ultimate limit state is reached. The scenario chosen was limited to only one specific situation of the industry (pressure test after WOC), and other efforts could be made to render the intermediate grade completely useless.

4. CONCLUSIONS

The developed study indicates the most suitable pipes for the evaluated scenario among the options available. Grade *C90* pipes was indicated by the literature for the analyzed situation. However, *N80* pipes, less costly than the previous one, presented conditions of safe use, given the proposed scenario. To complement this work, new field scenarios and/or phases should be applied and investigated to address other possible scenarios. In addition, determining the ultimate limit state conditions of the structure would make it possible to determine more accurately how long the pipe could withstand, even with inadequate use due to imperfections along the structure.

Even so, it is evident the possibility of optimization in the use of casings based on their dimensions. Therefore, there is a possibility of an effective creation of a global well project with low costs that can also guarantee the structural integrity of the well. Thus, the industry can profit from the results, and, at the same time, can reduce potential damages caused by the oil and gas sector, benefiting society and the environment.

ACKNOWLEDGMENTS

The authors would like to thank the Laboratório de Computação Científica e Visualização (LCCV-UFAL) and its main institution UFAL, the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de Alagoas (FAPEAL) for

funding and research support along the SAEP project development.

NOMENCLATURE

A_i – Internal area
 ANSI – American National Standards Institute
 A_o – External area
 API – American Petroleum Institute
 CWELL – Casing well
 D_i – Inner diameter
 D_o – Outer diameter
 F_a – Axial force
 F_E – Buoyancy
 F_p – Casing string weight
 F_{sp} – Surface pressure test influence over axial load
 MASL – Meters above sea level
 P_i – Internal pressure
 P_{mud} – Hydrostatic pressure of the drilling mud
 P_o – External pressure
 P_{sp} – Pressure test value on surface
 R_b – Resistance to burst
 R_t – Resistance to tension or compression
 SAEP – Petroleum Engineering Applications System
 t – Thickness
 TR – Technical report
 TVD – True vertical depth
 TVD_{MASL} – Water depth in meters
 TVD_{Cement} – True vertical depth of the top of cement
 TVD_{shoe} – Casing shoe depth
 VME – von Mises ellipse
 W – Linear weight of the pipe
 WOC – Wait on cement
 Y_p – Yield stress
 ρ_{cement} – Specific weight of the cement
 $\rho_{fracture}$ – Fracture gradient
 ρ_{mud} – Specific weight of the mud
 ρ_{sea} – Specific weight of the sea water
 σ_a – Axial stress
 σ_r – Radial stress
 σ_t – Tangential stress
 σ_{VME} – Equivalent stress

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