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CONCEPTION OF A PRESSURIZED ELECTROCHEMICAL CELL FOR CORROSION STUDIES

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Abstract. *Corrosive phenomena are responsible for significant losses to various industry sectors, especially petrochemical. Based on that, it is of great interest to develop a wear model for predictive maintenance based on experimental evidence. In order to provide conditions closer to reality, in environments with pressures higher than the atmospheric pressure, a bench-scale pressure vessel with electrochemical cell features was designed according to ASME Section VIII with analysis and selection of geometry, head, instruments and material manufacturing.*

Keywords: *Corrosion, Pressure Vessel, Electrochemical Cell, Petrochemical Industry, Predictive Maintenance.*

1. INTRODUCTION

The high cost of damages caused by tribological phenomena, such as corrosive wear, for example, in any national economy, is motivated mainly because of the great energy demand and material losses that occurs simultaneously in nearly all operating mechanical devices (Johnsen and Von Der Ohe, 2011; Choi and Nešić, 2011). When reviewed based on a single structure, the losses are small. However, when the same loss is replicated over millions of similar structure types, then the costs become significant (Stachowiak and Batchelor, 2006), justifying the need of a wear model for predictive maintenance based on experimental evidence.

The best exemplification is on the annual cost of corrosion processes in the oil and gas industry, estimated in $ 1,372 billion; $ 589 million in pipeline and surface installing costs, $ 463 million in subsurface pipeline and $ 320 million in capital expenses related to corrosion (Simmons, 2008). It is widely known in the petrochemical industry that effective corrosion management will not only contribute to its reduction, but also to accomplish safety, health and environmental policies (Johnsen and Von Der Ohe, 2011).

Several factors influence this wear phenomenon in ways that create an adverse environment, propitious to damage metallic structures; such factors are mainly high concentration of CO_2 and H_2S, high pressures and temperatures (Perez, 2013). Therefore, it is of great importance the experimental analysis considering these environments.

Materials and equipment for corrosion controlling to be used in these locations and in such conditions, must be highly reliable due to the damage associated with their failure (Nahal *et al.*, 2015). The main concern with downhole piping is related to problems of uniform or localized corrosion and formation of propitious environments to crack propagation to its materials (Nunes *et al.*, 2016).

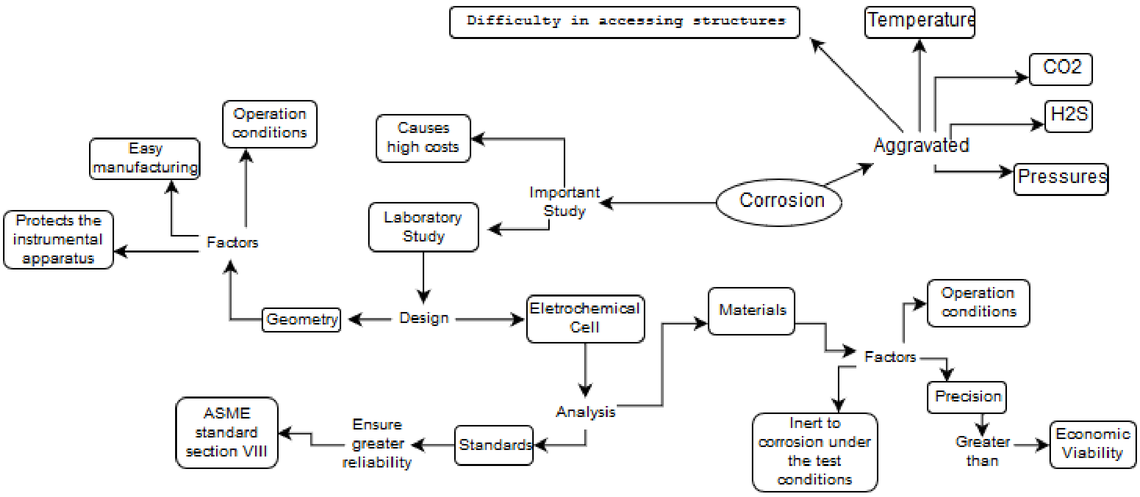
Finally, high pressure corrosion studies in laboratories become essential. Thus, the objective of this paper is to achieve a comparative analysis of geometries, design parameters and materials to apply in the conception of a pressurized electrochemical cell, proposing to simulate real environment situations in the industry field.

2. METHODOLOGY

The design procedure of a pressurized electrochemical cell for corrosion studies, the methodology for the theoretical calculation and the simulation software is presented here.

2.1 Technical standards

To ensure safety when working with any pressurized equipment, it is important to consider the adoption of specific standards. These standards allow the designer to work with a pre-set safety factor, in order to ensure reliability to the project. The project design was based on the most widespread pressure vessel code in Brazil, Section VIII of ASME (Telles, 2005).



2.2 Geometry

Figure **1.** Project procedure fluxogram

According to Telles (2005), the shape of a pressure vessel is, for the most part, determined by its purpose. Thus, in the case of pressurizing of an electrochemical cell, there was a main focus in adapting geometries that would better accommodate the whole instrumental apparatus, in addition to avoiding an approach by little practicality in terms of fabrication of the vessel's structural components. In general, the purpose of the equipment is to target corrosive studies by simulating an ambient under pressure in order of magnitude higher than atmospheric pressure

2.3 Materials

A key factor for any pressure vessel project is on the selection of constructing materials. In addition, to analyze structural compatibility with all the stresses acting on the equipment under predetermined conditions, it is also important to check the chemical nature of the substance(s) in contact with the structure of the vessel, whether liquid or gas. For this specific study, where the quantification of the corrosive processes is involved, it is important to ensure that the interaction between the fluid in which the corrosion coupons are being subjected and the electrochemical cell walls, is not a factor that changes the characteristics in the testing environment. The search for more precise results was prioritized, although economic viability is a determining factor. Having said that, a more in-depth study was sought in the group of stainless steels, from AISI 420 to Hastelloy and super-duplex.

2.4 Methodology for the theoretical calculation

The calculation for thickness required for the shell was made in anticipation that it is a thin walled pressure vessel that meets the requirements, according to UG-27 of the ASME VII code div. I, where the thickness must not exceed the half of the value of its internal radius. The nozzles minimum thickness was determined using the UG-45 paragraph of ASME VII div. I standard code and ASME B36.10M, respectively. The presence of the nozzles result in a concentration of load, in the vicinity of the aperture (Falcão, 2008). Thus, to compensate for material withdrawal and maintain load at the same initial magnitude, a reinforcement with area exactly equal to the area removed is sufficient to maintain the uniform stress level throughout the vessel wall extension. For this purpose, the methodology presented by Falcão (2008) was adopted.

The calculation of maximum allowable working pressure (MAWP) were done through a methodology presented by Telles (2005), considering a welding efficiency of 0.6 for non-inspection and flanges according to the ASME B16.5, for class 150, DN 12".

The Taylor Forge method, which the ASME code, appendix 2 is based, was utilized for the sizing of the sealing system (bolts and joints) and the method of Budynas and Nisbett (2015) for theoretical calculation of the tensions in the screws. Additionally, the number of bolts in critical (operating) condition and preload were calculated according to ASME B16.5 (2010).

2.5 Simulation (FEA)

For comparative and didactic purposes, the cell was simulated using the ANSYS Workbench software. With this tool, an estimate of the structural behavior of the vessel and its components was obtained to verify its proximity or distance with regard to theoretical hand calculations, and also to raise hypotheses and justifications for values that diverged significantly (over 10%) from the expected result of the theoretical calculation.

3. RESULTS AND DISCUSSION

The conception of a pressurized electrochemical cell for corrosion studies is presented here.

3.1 Geometry and material

The vessel is cylindrical in shape with two blind flanges attached by screws, as shown in Figure 2, and a consideration was made to the need for inlet and outlet nozzles of aqueous solution and CO_2 injection for pressurizing, and both quantity and distribution of the devices to be accommodated on the top, in addition to the volume of liquid acceptable for analysis based on the project presented and used by Nunes da Silva (2012), besides Távora (2007) and Cunha (2008).

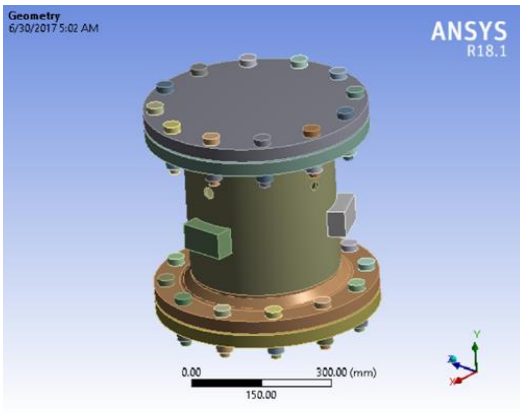


Figure 2. General geometry of pressurized electrochemical cell

The set value for the nominal diameter was approximately 12" (300 mm), which is also accepted for the length of the cylindrical body, as shown in Figure 3.

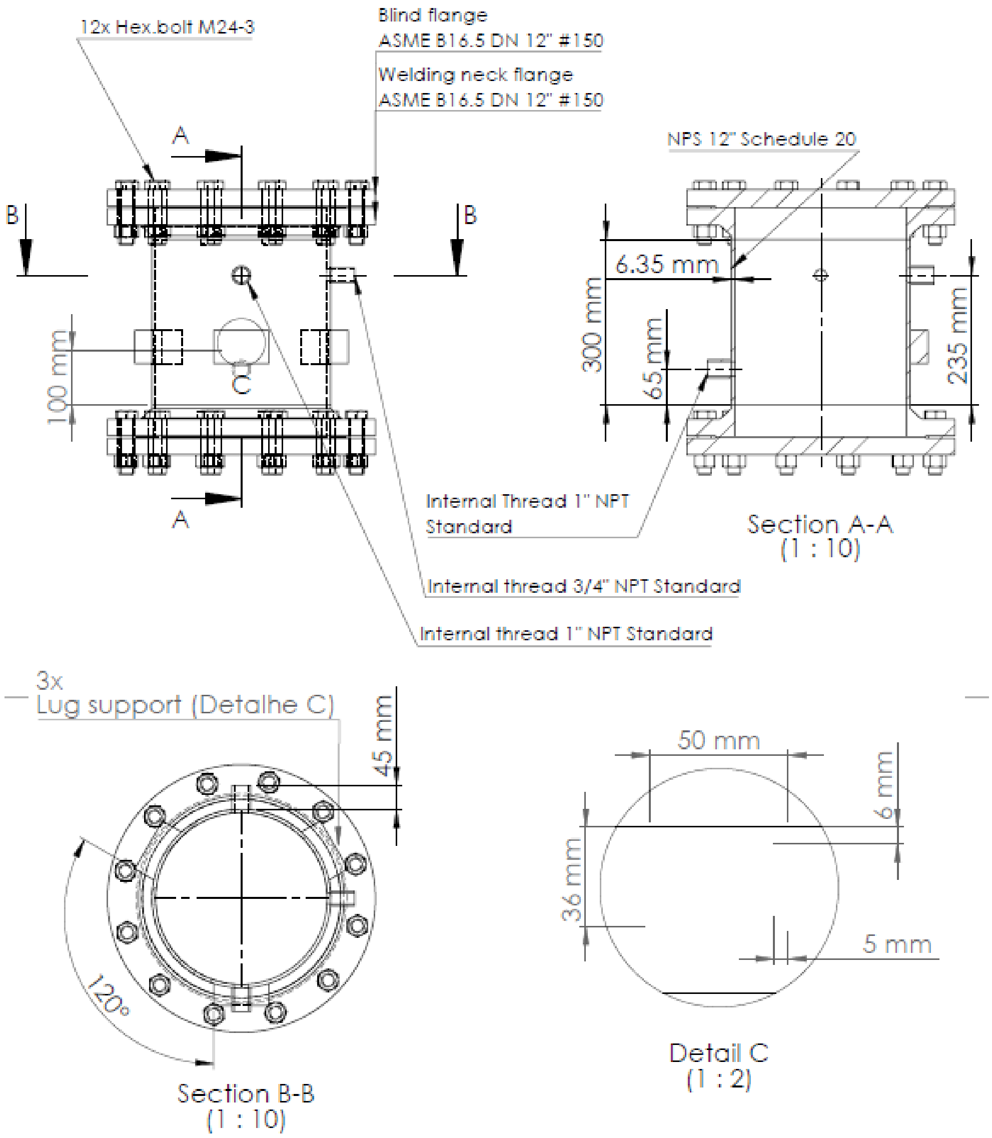


Figure 3. Commercial dimensions of the cell

The dimensions chosen were based, preferably, on commercial values. Values well below those specified may interfere with instrument accommodation and values much above may leave the vessel considerably heavier for handling.

The operating conditions of the pressurized electrochemical cell were established according to Table 1.

Table 1. Operating parameters

Design pressure (P)	0.55 MPa
Design temperature (Tp)	200°C
Nominal diameter	12” (300 mm)

For the material of the cell components, after a brief selection analysis, Hastelloy C276, a nickel-molybdenum-chromium super alloy with the addition of tungsten, was adopted in order to improve corrosion resistance to the most severe environments. The presence of nickel and molybdenum increases the resistance to pitting and cracking. For simplicity, it was considered that the material is free from corrosion under the conditions laid down. Table 2 lists the main characteristics and properties of the material, according to ASME Section II, Part D, Table 1B.

Table 2. Properties of Hastelloy C276

Commercial name	Hastelloy C276
Composition	54Ni-16Mo-15Cr
UNS Number	N10276
Density	8885 kg/m³
Minimum tensile stress	690 MPa
Minimum yield stress	285 MPa
Allowable stress - 30 to 40 °C	160 MPa
Allowable stress until 65 °C	152 MPa
Allowable stress until 200 °C	126 MPa

The material chosen, despite being resistant to aggressive environments, has a density close to 8,885 kg/m³, within the average for metallic materials, but it causes the cell to be approximately 150 kg, making it difficult to handle in the laboratory.

3.2 Results of theoretical calculation

According to the described methodology, the following results for the nozzles' commercial dimensions are according to Table 3:

Table 3. Dimensions of water and CO_2 nozzles

	Water nozzle (2x)	**CO_2 nozzle**
NPS	1" (25 mm)	¾" (20 mm)
External diameter	33.4 mm	26.7 mm

As per ASME recommendation B16.5, table 7, and the operational condition, twelve A307 carbon steel structural bolts, nominal size 7/8", close to an M24-3, length L = 100 mm, and established mechanical properties by ASME Section II, Part D, were selected only for calculation purposes. Thus, according to the described methodology, the theoretical stress in the screws are 32.34 MPa in average.

3.3 Results of the FEA simulation

Figure 4.A shows the circumferential stress calculated by the computational simulation using the ANSYS Workbench software. An average value was adopted between the chosen points of tension. The Figure 4.B shows the longitudinal stress calculated by the computer computational simulation using the ANSYS Workbench software.

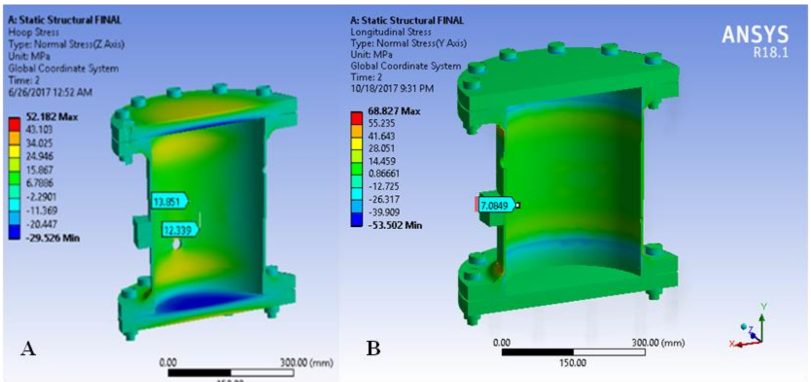


Figure 4. Circumferential stress on shell by finite element analysis

The maximum stress in the adjacencies of the nozzle openings was computed by choosing two points in the longitudinal plane of the vessel, since they contain their highest values, as shown in Figure 5.

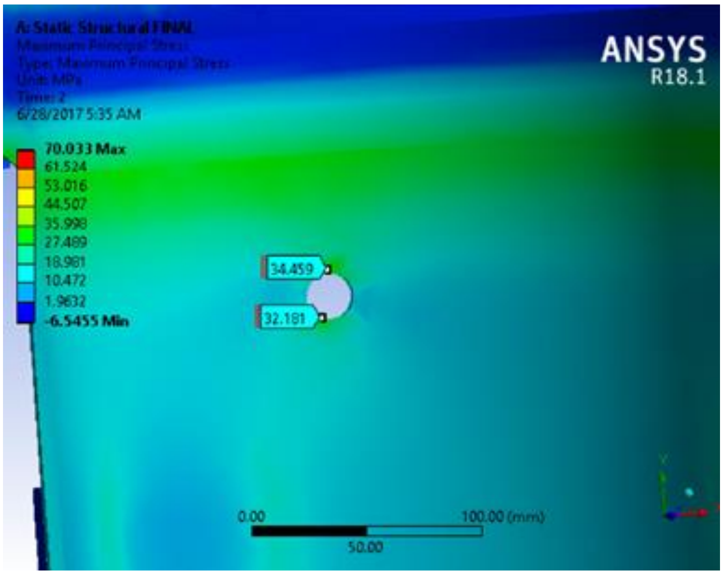


Figure 5. Longitudinal stress on opening by finite element analysis (FEA).

Figure 6 shows the maximum stress resulting from flange bending, computed by the software, to which the screw is subjected, the average between this value and the minimum being approximately 31.84 MPa.

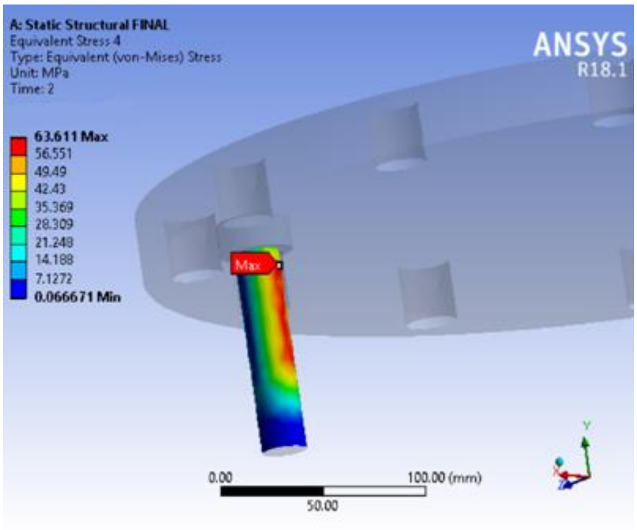


Figure 6. Bolt stress by finite element analysis (FEA)

Table 4 summarizes the values compared, including the percentage difference between them.

Table 4. Comparison between the stress results

	Theoretical value (MPa)	**FEA value (MPa)**	**Percental Difference (%)**
Circumferential stress	13.20	13.10	0.7
Longitudinal stress	6.60	7.07	6.7
Stress in the longitudinal plane in the vicinity of the aperture	33.0	33.32	1.0
Bolt stress	32.34	31.84	1.55

In addition to the theoretical and computational results of the stress, the linearization of the stresses in the shell and flange, primary stress zones, was adopted in order to separate their types according to the classification of ASME Section VIII division I, and to validate them with the established criteria by paragraph UG-23 of the standard.

The stress linearization throughout the shell (Figure 7), shows that the membrane tension (P_m) is predominant in this place, as the values in Figure 8. Then it can be simplified as the only acting on the shell elements, away from the discontinuities and opening of nozzles. This is due to the fact that the thickness is small compared to the radius of the cylinder (thin-walled vessel).

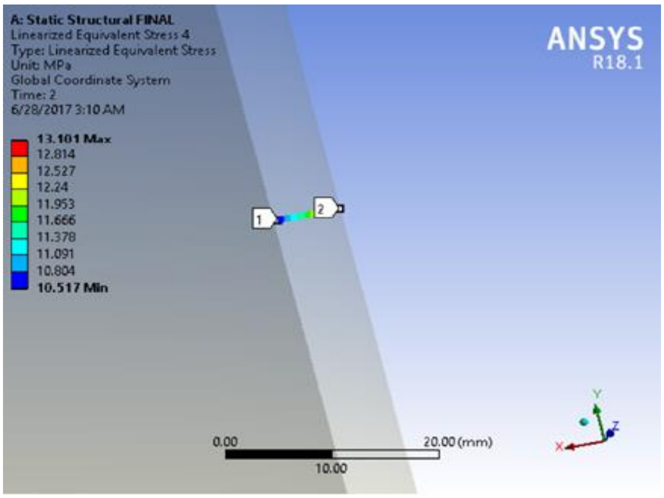


Figure 7. Shel stress linearization

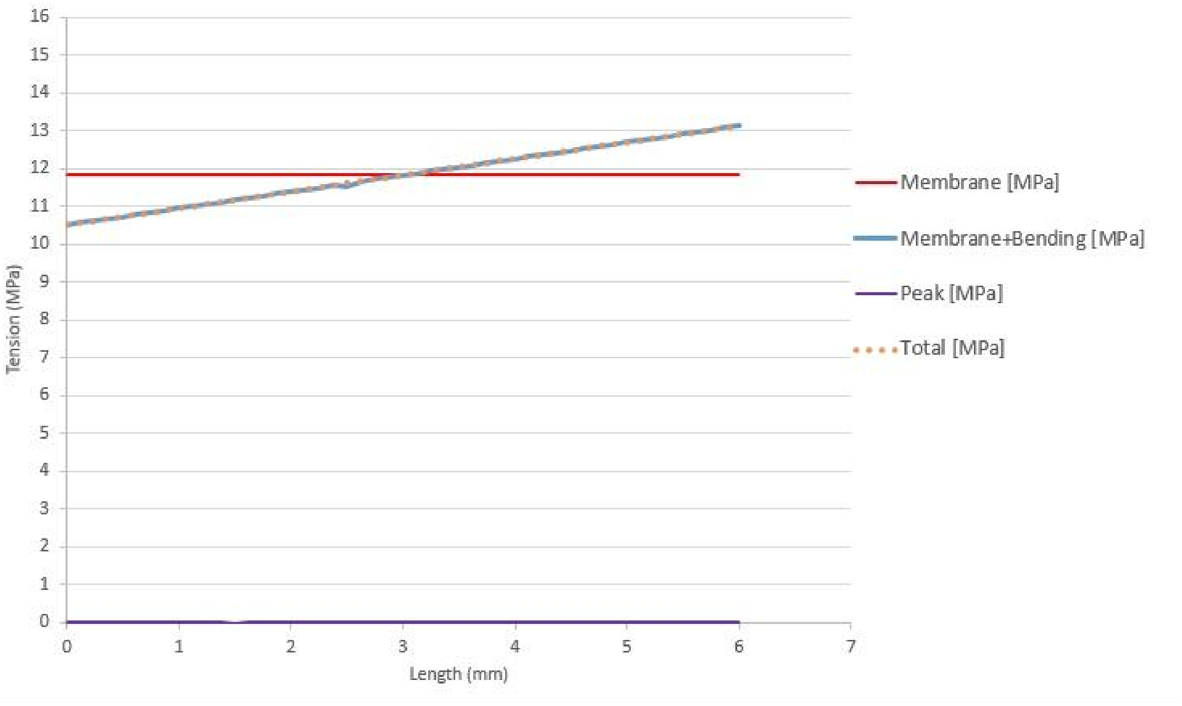


Figure 8. Linearization of the cylindrical shell

At the center of the flange (Figure 9), it occurred, predominating as primary bending stresses (P_b), due to the bending of the top caused by the action of internal pressure.

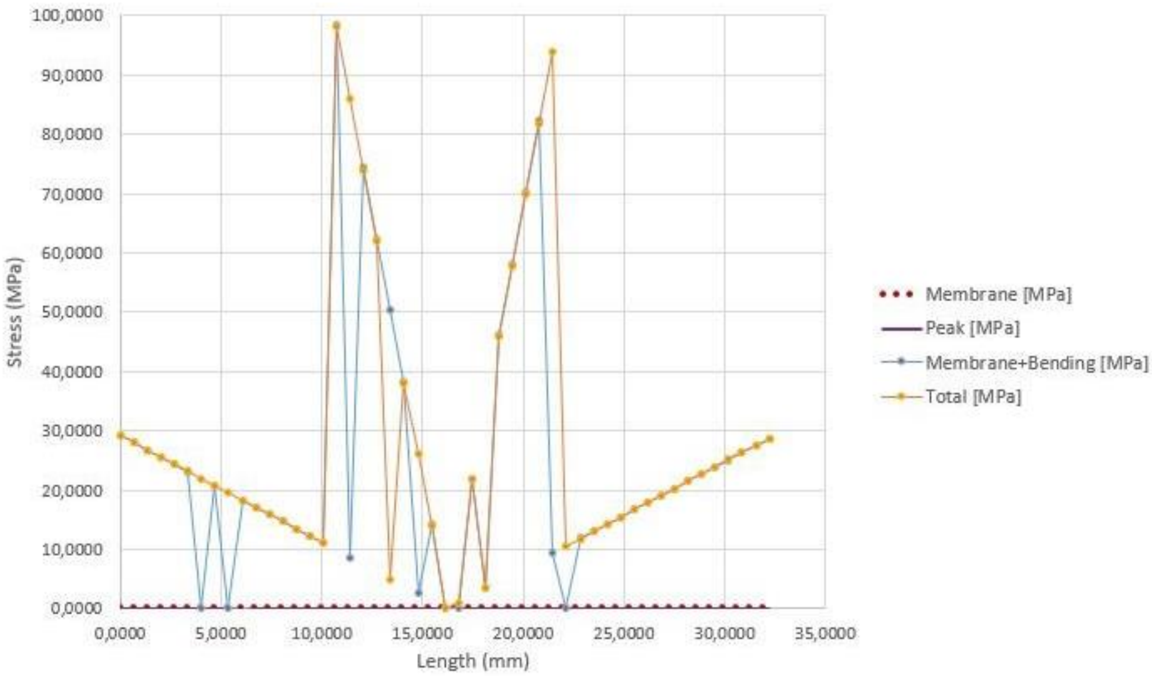


Figure 9. Separation of stresses by linearization, for blind flange region

The stress data obtained by linearization and the limit values established by the ASME code Section VIII div.1 for Hastelloy C276 are presented comparatively in Table 5, where S = 52 MPa.

Table 5. primary stresses computed through the linearization of stresses and limits established by the ASME code Section VIII div.1

Cylindrical shell		**ASME VIII Div.1 criterion (UG-23)**	
P_m	11,82	< S = 126	MPa
$P_m + P_b$	-	< 1,5 S = 189	MPa
Blind flange		-	
P_m	-	< S = 126	MPa
$P_m + P_b$	29,13	< 1,5 S = 189	MPa

4. CONCLUSION

With the results of the studies and with the purpose described previously, it was possible to have the design of a pressure vessel based on the ASME section VIII Division I for laboratory experiments, with functionalities of an electrochemical cell. This vessel should have a thin, cylindrical shape, vertical arrangement, flanged upper and lower tops, and be instrumented with pH meter thermometer, RPL (linear polarization resistance) and gravimetric probes, manometer and oximeter. In addition, we consider an environment subject to the action of chloride ions (Cl^-) and carbonic acid (H_2CO_3), as wetted parts of the vessel, preferably be made of stainless steel containing, for example, elements such as molybdenum in its composition, or characteristics that renders it resistant to pitting and cracking. It was also observed the convergence between the results of the theoretical calculations and those of the computational simulation with the application of finite element analysis (FEA).

Therefore, the pressurized electrochemical cell must be treated as a pressure vessel design by the code/standard, because, in this way it guarantees that the safety and reliability criteria are followed and the tribocorrosion tests will be performed in a way that does not influence in the equipment on studies of this phenomenon.

5. ACKNOWLEDGEMENTS

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