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STRUCTURAL INTEGRITY ANALYSIS OF THE HEAVY WATER REFLECTOR TANKS OF THE IPEN/MB-01 REACTOR

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ABSTRACT

The IPEN/MB-01 is a zero power research reactor designed and built by IPEN in partnership with the Brazilian Navy. This reactor is located in IPEN and began operating in 1988. IPEN/MB-01 has been used as an experimental facility for studies on neutron parameters of nuclear reactors moderated by light water. In 2016, a project to modify the core structure of IPEN/MB-01 Reactor was initiated. This project aims the replacement of the rod-type fuel structure for a plate-type one. In order to optimize the performance of the experiments, four tanks filled with D_2O were installed around the core. This new core will contain fuel elements that are similar to the ones that will be used in the Brazilian Multipurpose Reactor. In this paper, a complete structural integrity analysis of the four heavy water reflector tanks installed in IPEN/MB-01 Reactor is presented. A numerical analysis was performed applying the finite element method, using ANSYS software and considering ASME Code VIII, division 2.

1. INTRODUCTION

IPEN/MB-01 Nuclear Research Reactor is an open tank zero power one, with a core formed by rod-type fuel elements, which is used to simulate and investigate neutron parameters of nuclear reactors moderated to light water.

The original project of the Nuclear Research Reactor IPEN/MB-01 is being refurbished with the introduction of a set of heavy water reflecting tanks (D_2O), which are part of the group of components related to the replacement of the current core, with its rod-type fuel elements, by a core with plate-type fuel elements.

This work evaluates the structural integrity of the four heavy water reflector tanks by applying the Finite Element Method of the , using the ANSYS structural analysis computer program, and checking if ASME code, Section VIII, Division 2 requirements are met.

Figura 1 shows the current core of the IPEN/MB-01 Nuclear Research Reactor and the future core, after the refurbishment.

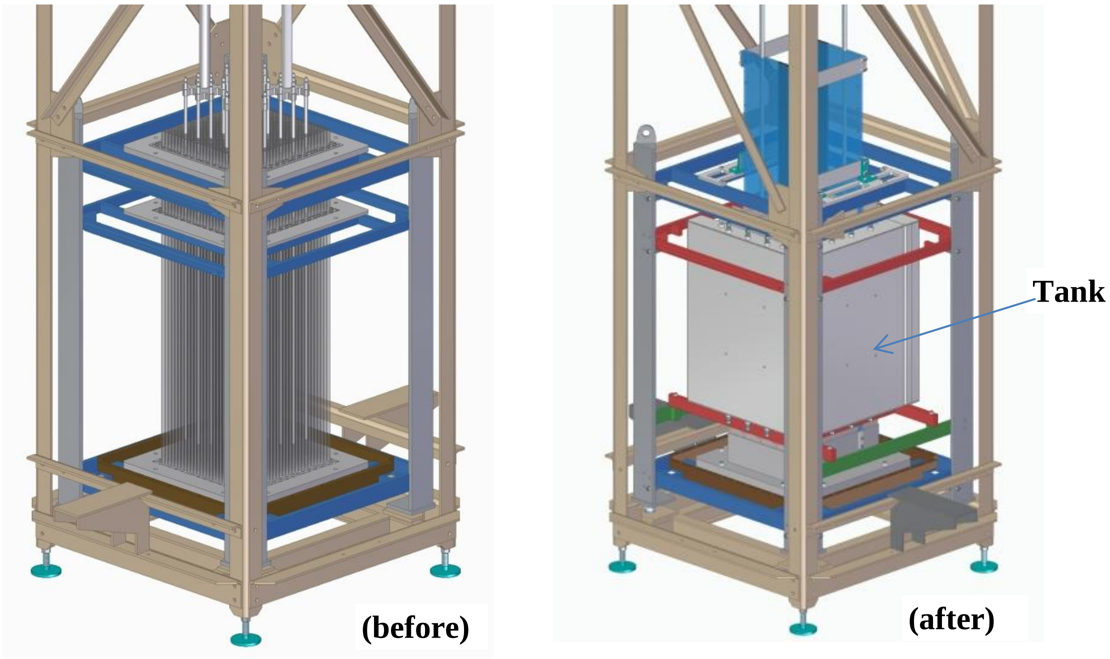


Figure 1 – Core of the Reactor IPEN/MB-01 before and after refurbishment

2. HEAVY WATER REFLECTOR TANKS

The set of Heavy Water Reflector Tanks is formed by four aluminum boxes, filled with heavy water (D_2O), and identified as:

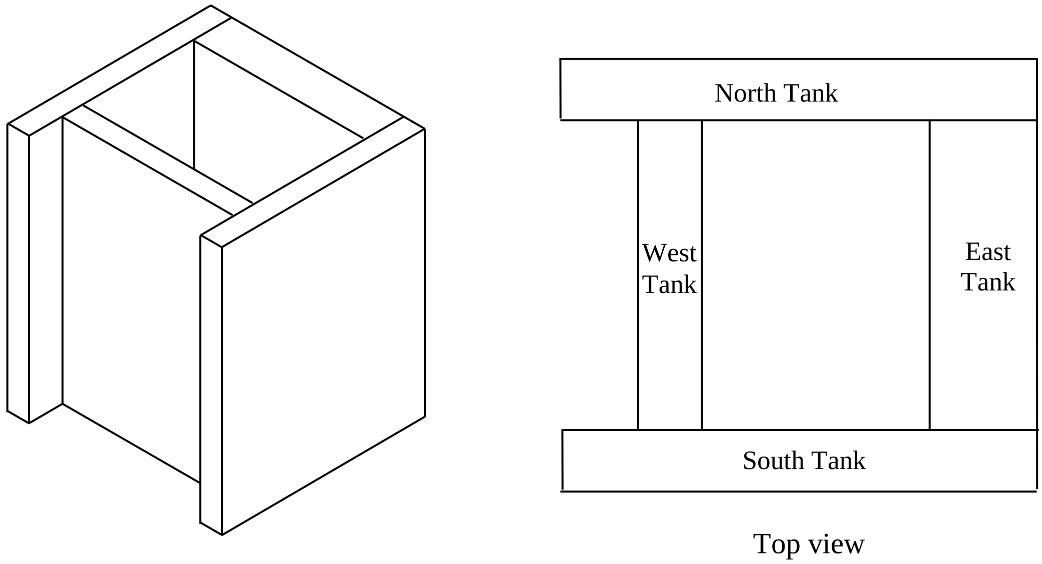
- North & South Tank ([2] [4]);
- East Tank ([2] [5]);
- West Tank ([2] [3])

Heavy Water Reflector Tanks are rectangular pressure vessels constructed of folded and welded aluminum plates with flat tops welded for closure. Spacers, fixed to the lateral plates, are used as structural reinforcements [6].

The North and South Tanks are identical. The arrangement and geometric layout of the Heavy Water Reflector Tanks assembly are schematically shown in Figure 2.

The process data [1] applied to Heavy Water Reflector Tanks are:

- Internal Pressure = 0.0326 N/mm^2;
- Maximum Allowable Working Pressure (MAWP) = 0.05 N/mm^2;
- Hydrostatic Test Pressure = 0.057 N/mm^2;
- Operating Temperature = 30ºC.



Isometric view

Top view

Figure 2 - Heavy Water Reflector Tanks model

The mechanical properties of aluminum 6061 [9] used in the construction of the Heavy Water Reflector Tanks are shown in Table 1 for room temperature. The allowable stresses of the materials were obtained with the following correlation:

$$\mathbf{S_H = minimum\ [S_U /3.5 : S_Y /1.5].}$$

Table 1 – Aluminium mechanical properties (N/mm^2)

Item	Material	S_U	S_Y	Allowable Stress (N/mm^2)
Plate	SB209 6061 T6	289.0	241.0	S_{H1} = 82.6
Cover	SB211 6061 O	151.7	124.1	S_{H2} = 43.4
Spacer	SB221 6061 O	151.7	124.1	S_{H3} = 43.4

[$\mathbf{S_U}$: $\mathbf{S_Y}$] – [Ultimate Stress : Yield Stress].

The load cases applied to the Heavy Water Reflector Tanks are: Deadweight, Design Pressure and Hydrostatic Test Pressure. The combination between the load cases in order to simulate the Design and Hydrostatic Test conditions of the Tanks are:

Design Condition ⇨ Deadweight + Design Pressure
Hydrostatic Test condition ⇨ Deadweight + Hydrostatic Test Pressure

The simplified geometry of the heavy water reflector tanks, with main dimensions, is shown in Figure 3 and Table 2.

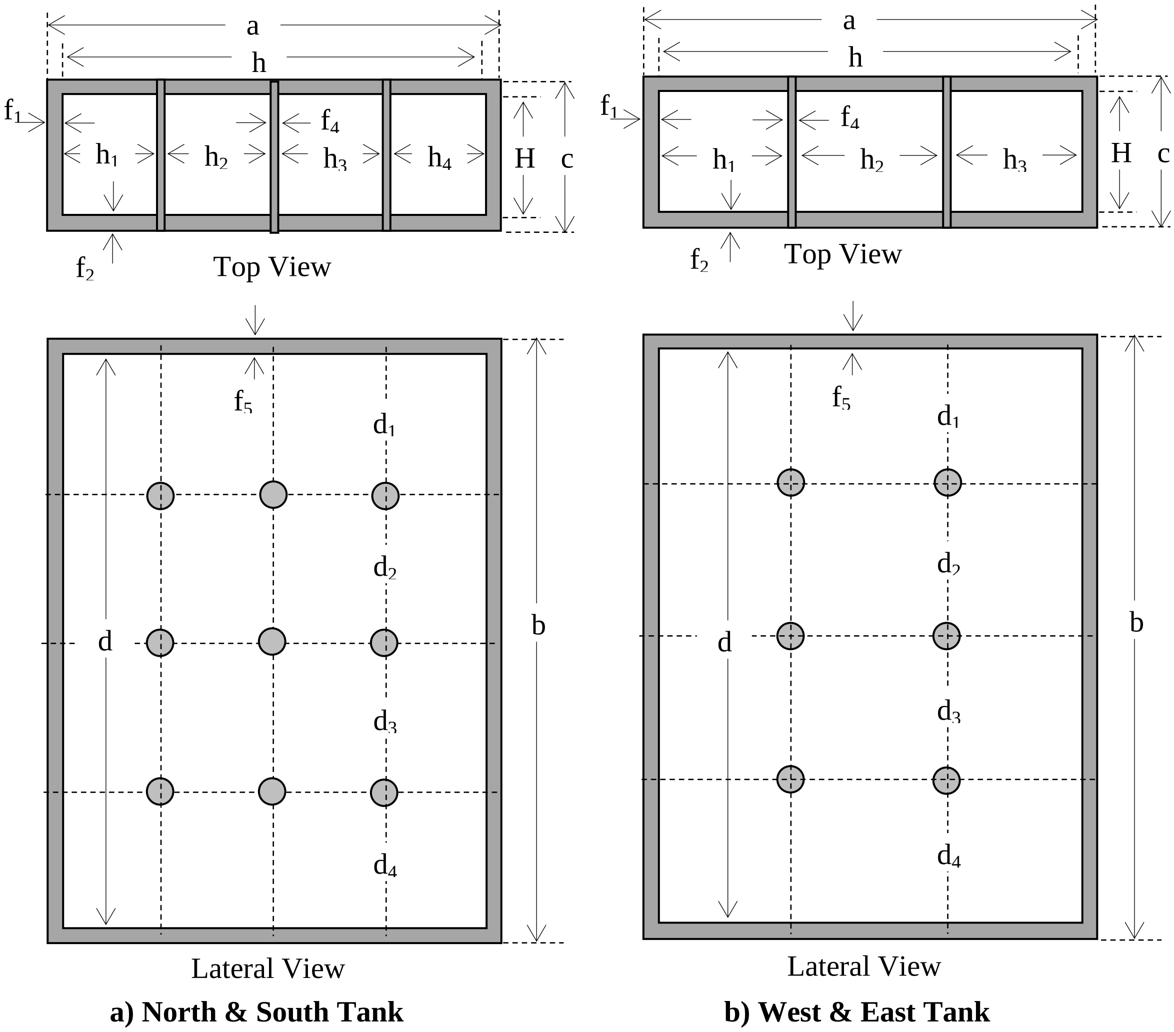


Figure 3 – Dimensional drawing of Heavy Water Reflector Tanks

Table 2 – Dimensional data of Heavy Water Reflector Tanks (mm)

	a	**b**	**c**	**d**	**d_1**	**d_2**	**d_3**	**d_4**	**h**
North	608.0	709.0	76.24	703.0	171.5	180.0	180.0	171.5	601.65
South	608.0	709.0	76.24	703.0	171.5	180.0	180.0	171.5	601.65
East	452.85	709.0	140.0	703.0	171.5	180.0	180.0	171.5	446.5
West	452.85	709.0	58.0	703.0	171.5	180.0	180.0	171.5	446.5
	h_1	**h_2**	**h_3**	**h_4**	**H**	**f_1**	**f_2**	**f_4**	**f_5**
North	155.82	145.0	145.0	155.82	69.89	3.175	3.175	7.0	3.0
South	155.82	145.0	145.0	155.82	69.89	3.175	3.175	7.0	3.0
East	150.75	145.0	150.75	-	133.65	3.175	3.175	7.0	3.0
West	150.75	145.0	150.75	-	51.65	3.175	3.175	7.0	3.0

3. METHODOLOGY

The structural integrity of the Heavy Water Reflector Tanks will be evaluated by performing a linear and elastic stress analysis, using the computer program for structural analysis that uses the Finite Element Method: ANSYS [8] for numerical simulations. The evaluation will be done in accordance with the requirements of ASME code, Section VIII, Division 2, [10].

In order to evaluate the plastic collapse protection, the calculated stresses should be categorized according to:

- General Primary Membrane Stress – P_m;
- Local Primary Membrane Stress – P_L;
- Primary Bending Stress – P_B;
- Secondary Stress – Q.

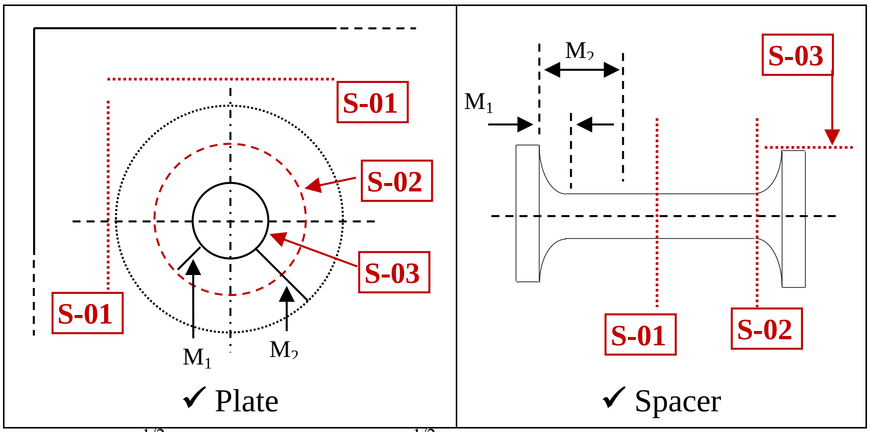
The equivalent stress is calculated according to the theory of the maximum distortion energy or Von Mises criterion, in chosen regions of the component, and compared to the proper equivalent stress limit.

$$[P_m \leq S_H : P_L \leq 1.5\ S_H \text{ and/or } P_L + P_B \leq 1.5\ S_H : P_L + P_B + Q \leq 3.0\ S_H]$$

The equivalent stresses in the Reflecting Tanks will be analyzed in the following regions:

- Cover plates – the stresses will be linearized and categorized in the section where the maximum stress occurs;
- Lateral plates – the stresses will be linearized by calculating the mean stress based on the set of colors shown beside the figures, in sections S-01, S-02 and S-03, starting in the hole where the maximum stress occurs;
- Spacers – the stresses will be linearized by calculating the mean stress based on the set of colors shown beside the figures, in sections S-01, S-02 and S-03.

Figure 4 shows the sections of the side plates and spacers which will be analyzed.



[$\mathbf{M_1} = (R_2 \times e_1)^{1/2}$: $\mathbf{M_2} = 2.5 \times (R_2 \times e_1)^{1/2}$: $\mathbf{R_2}$ (hole radius) : $\mathbf{e_1}$ (plate thickness)]

Figure 4 –North & South Tank - Plates and Spacers Cross Section

The resulting equivalent stresses in the regions described in the previous paragraph for the Design and Hydrostatic Test conditions shall meet the stress limits to avoid plastic collapse, according to:

- S-01 ⇨ $P_m \leq S_H$
- S-02 ⇨ $P_L \leq 1.5 x S_H$ e/ou $P_L + P_b \leq 1.5 x S_H$
- S-03 ⇨ $P_L + P_b + Q \leq 3.0 x S_H$

4. RESULTS

The stress analyses of the Heavy Water Reflector Tanks North, South, East and West were performed according to the following steps:

- To develop the solid 3D model for each tank;
- To enter the solid 3D model in the ANSYS program;
- To apply the finite element with 20 nodes and 3 Degrees of Freedom;
- To search for the finite element mesh suitable for each tank;
- To apply the boundary conditions to the calculation model, simulating the connection of the tank with the metallic platform in the building;
- To perform the numerical simulation with the ANSYS program for the following load cases: Deadweight, Design Pressure, Hydrostatic Test Pressure;
- To post-processing to obtain the resulting stresses from the combinations: design condition and hydrostatic test.

The mapping of the calculated equivalent stresses can be seen in Figures 5 through 13 for the North, South, East and West Reflector Tanks, as well as the maximum values found for the cover, lateral plate and spacers of each tank (see items 4.1 to 4.3). Table 3 shows the value of the maximum equivalent stress in each tank.

Table 3 – Lateral Plate Maximum Stresses for the Heavy Water Reflector Tanks

		Equivalent Stresses (N/mm^2)					
Tank	**Condition**	**S-01**		**S-02**		**S-03**	
		P_m	S_H	P_L	$1.5\ S_H$	$P_L + P_B + Q$	$3.0\ S_H$
North & South	Design Hydrostatic Test	67.5 81.0	82.6	105.0 117.0	124.0	128.0 153.0	241.0
East	Design Hydrostatic Test	46.8 53.0	82.6	70.0 80.0	124.0	99.5 113.0	241.0
West	Design Hydrostatic Test	54.0 61.0	82.6	71.8 74.5	124.0	101.7 116.0	241.0

As can be seen in Table 3, the maximum calculated stresses comply with the limits prescribed by the ASME code, Section VIII, division 2.

4.1. North & South Tank

The distribution of the resulting equivalent stresses in the North Reflecting Tank, for the Design and Hydrostatic Test conditions, can be seen in Figures 5 to 7. Table 4 briefly shows the equivalent maximum stresses.

Table 4 – North & South Tank Equivalent Stresses (N/mm²)

<table>
<tr><td colspan="2">-</td><td colspan="2">$P_L + P_B$</td><td>$1.5\ S_H$</td><td colspan="2">$P_L + P_B + Q$</td><td>$3.0\ S_H$</td></tr>
<tr><td rowspan="2">Cover Plate</td><td>Design</td><td colspan="2">44.9</td><td>65.1</td><td colspan="2">51.8</td><td>65.1</td></tr>
<tr><td>Hydrostatic Test</td><td colspan="2">44.9</td><td>130.2</td><td colspan="2">51.8</td><td>130.2</td></tr>
<tr><td colspan="2" rowspan="2">-</td><td colspan="2">S-01</td><td colspan="2">S-02</td><td colspan="2">S-03</td></tr>
<tr><td>P_m</td><td>S_H</td><td>P_L</td><td>$1.5\ S_H$</td><td>$P_L + P_B + Q$</td><td>$3.0\ S_H$</td></tr>
<tr><td rowspan="2">Lateral Plate</td><td>Design</td><td>67.5</td><td>82.6</td><td>105.0</td><td>124.0</td><td>128.0</td><td>241.0</td></tr>
<tr><td>Hydrostatic Test</td><td>81.0</td><td>82.6</td><td>117.0</td><td>124.0</td><td>153.0</td><td>241.0</td></tr>
<tr><td rowspan="2">Spacer</td><td>Design</td><td>23.4</td><td>43.4</td><td>29.1</td><td>65.1</td><td>99.0</td><td>130.0</td></tr>
<tr><td>Hydrostatic Test</td><td>25.9</td><td>43.4</td><td>32.2</td><td>65.1</td><td>109.1</td><td>130.0</td></tr>
</table>

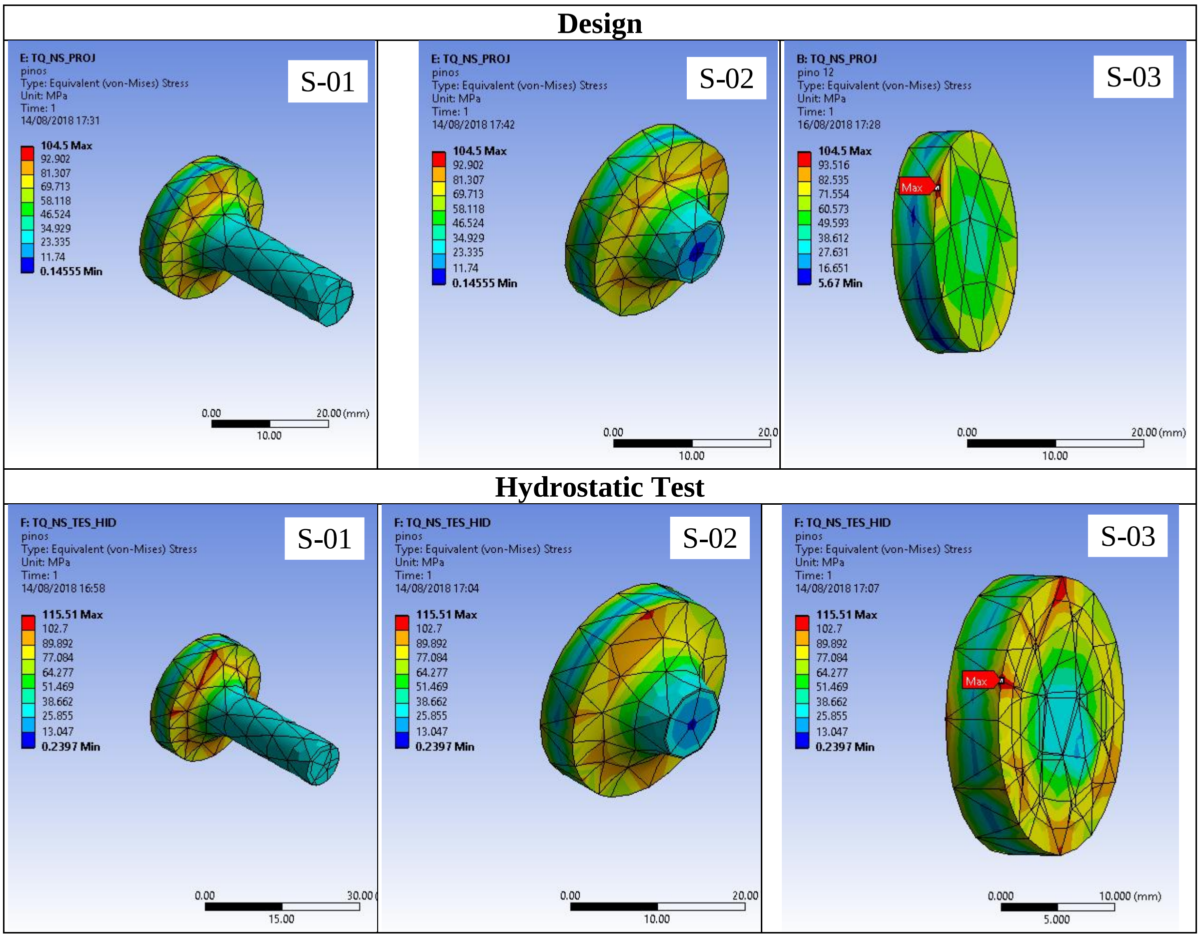


Figure 5 – North & South Tank Equivalent Stresses - Spacer (N/mm²)

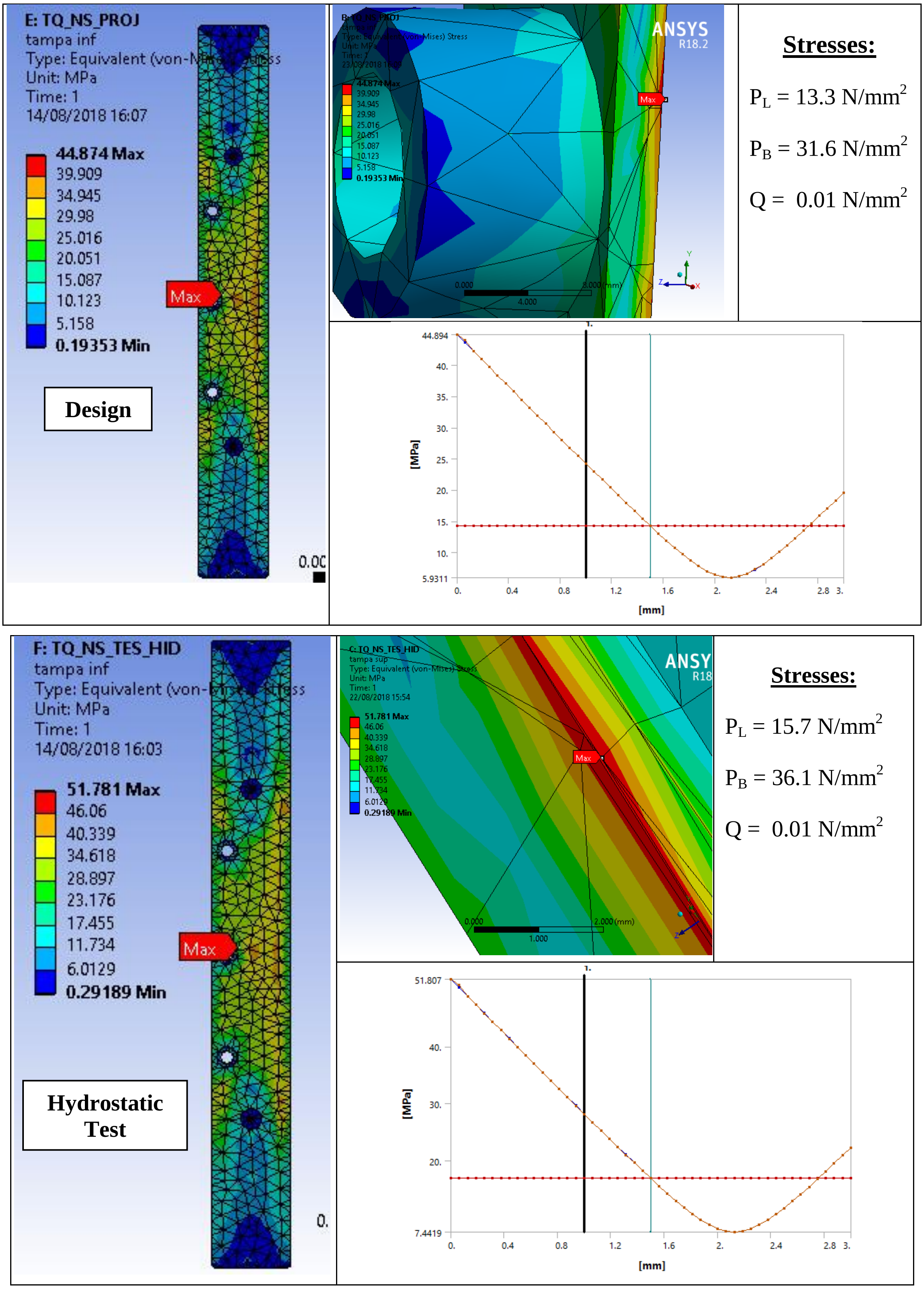


Figure 6 – North & South Tank Equivalent Stresses – Cover Plate (MPa)

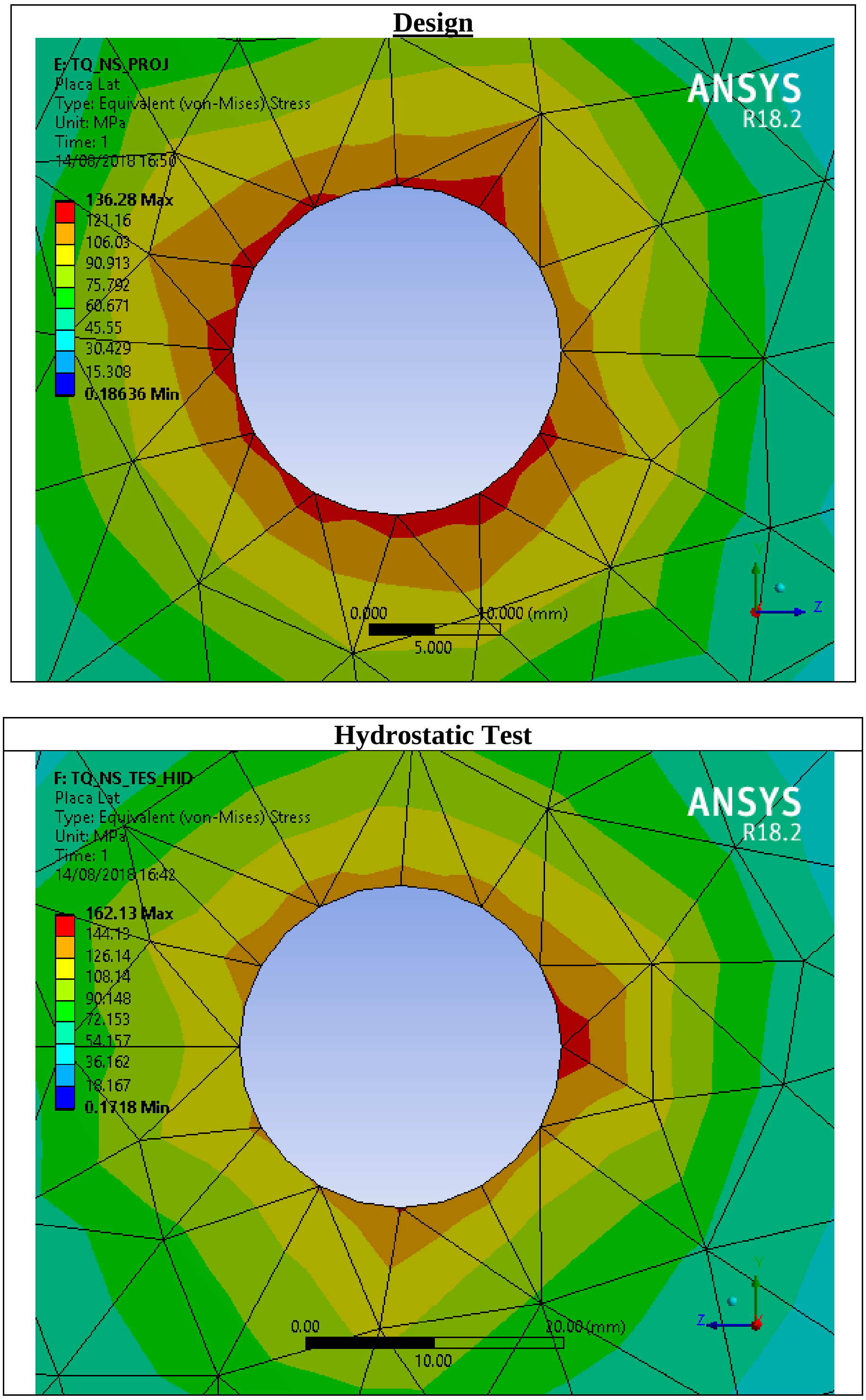


Figure 7 – North & South Tank Equivalent Stresses – Lateral Plate (MPa)

4.2. East Tank

The distribution of the resulting equivalent stresses in the East Reflecting Tank, for the Design and Hydrostatic Test conditions, can be seen in Figures 8 to 10. Table 5 briefly shows the equivalent maximum stresses.

Table 5 – East Tank Equivalent Stresses (N/mm²)

<table>
<tr><th colspan="2">-</th><th colspan="2">$P_L + P_B$</th><th>$1.5\ S_H$</th><th colspan="2">$P_L + P_B + Q$</th><th>$3.0\ S_H$</th></tr>
<tr><td rowspan="2">Cover Plate</td><td>Design</td><td colspan="2">35.0</td><td>65.1</td><td colspan="2">39.7</td><td>65.1</td></tr>
<tr><td>Hydrostatic Test</td><td colspan="2">35.0</td><td>130.2</td><td colspan="2">39.7</td><td>130.2</td></tr>
<tr><td colspan="2" rowspan="2">-</td><td colspan="2">S-01</td><td colspan="2">S-02</td><td colspan="2">S-03</td></tr>
<tr><td>P_m</td><td>S_H</td><td>P_L</td><td>$1.5\ S_H$</td><td>$P_L + P_B + Q$</td><td>$3.0\ S_H$</td></tr>
<tr><td rowspan="2">Lateral Plate</td><td>Design</td><td>46.8</td><td>82.6</td><td>70.0</td><td>124.0</td><td>99.5</td><td>241.0</td></tr>
<tr><td>Hydrostatic Test</td><td>53.0</td><td>82.6</td><td>80.0</td><td>124.0</td><td>113.0</td><td>241.0</td></tr>
<tr><td rowspan="2">Spacer</td><td>Design</td><td>21.7</td><td>43.4</td><td>21.3</td><td>65.1</td><td>46.3</td><td>130.0</td></tr>
<tr><td>Hydrostatic Test</td><td>24.7</td><td>43.4</td><td>24.7</td><td>65.1</td><td>56.7</td><td>130.0</td></tr>
</table>

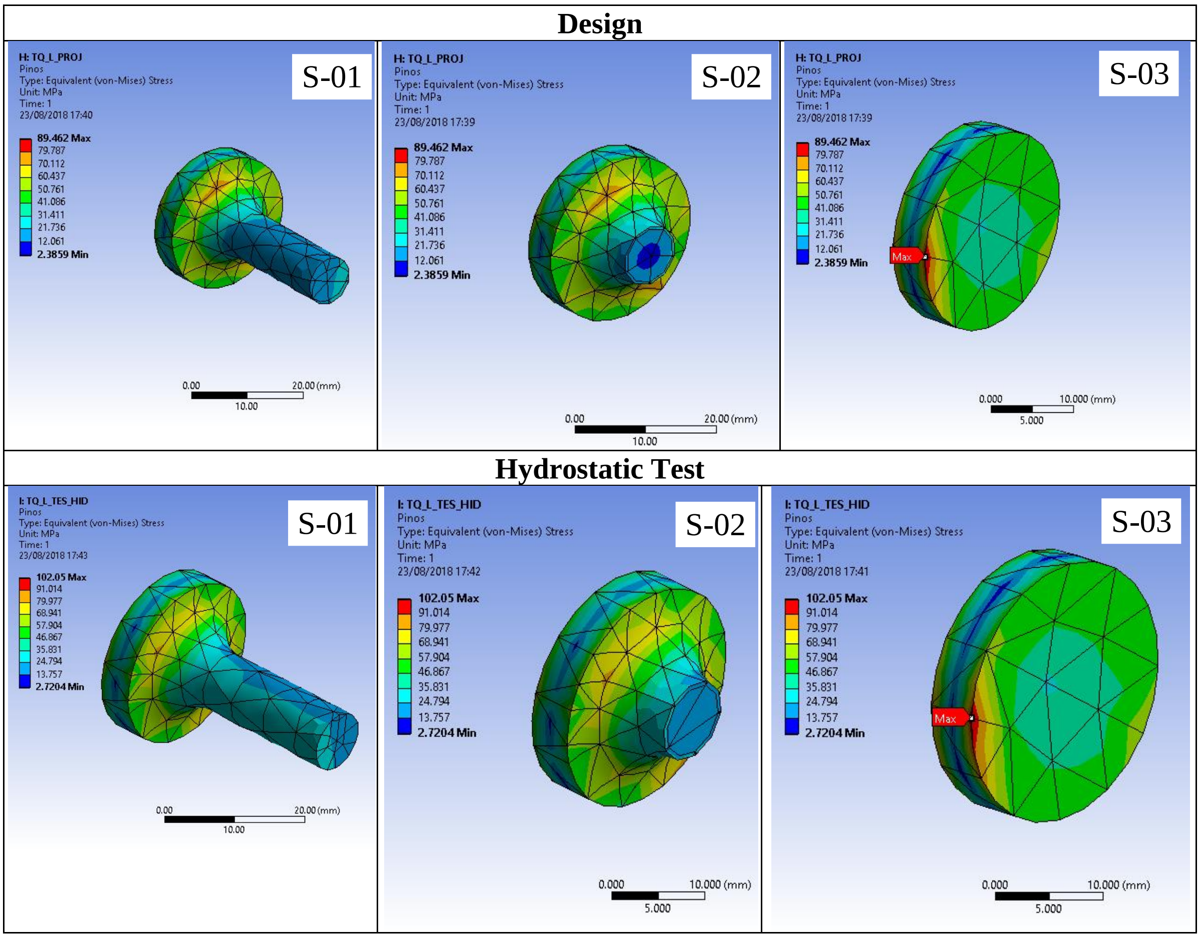


Figure 8 – East Tank Equivalent Stresses - Spacer (N/mm²)

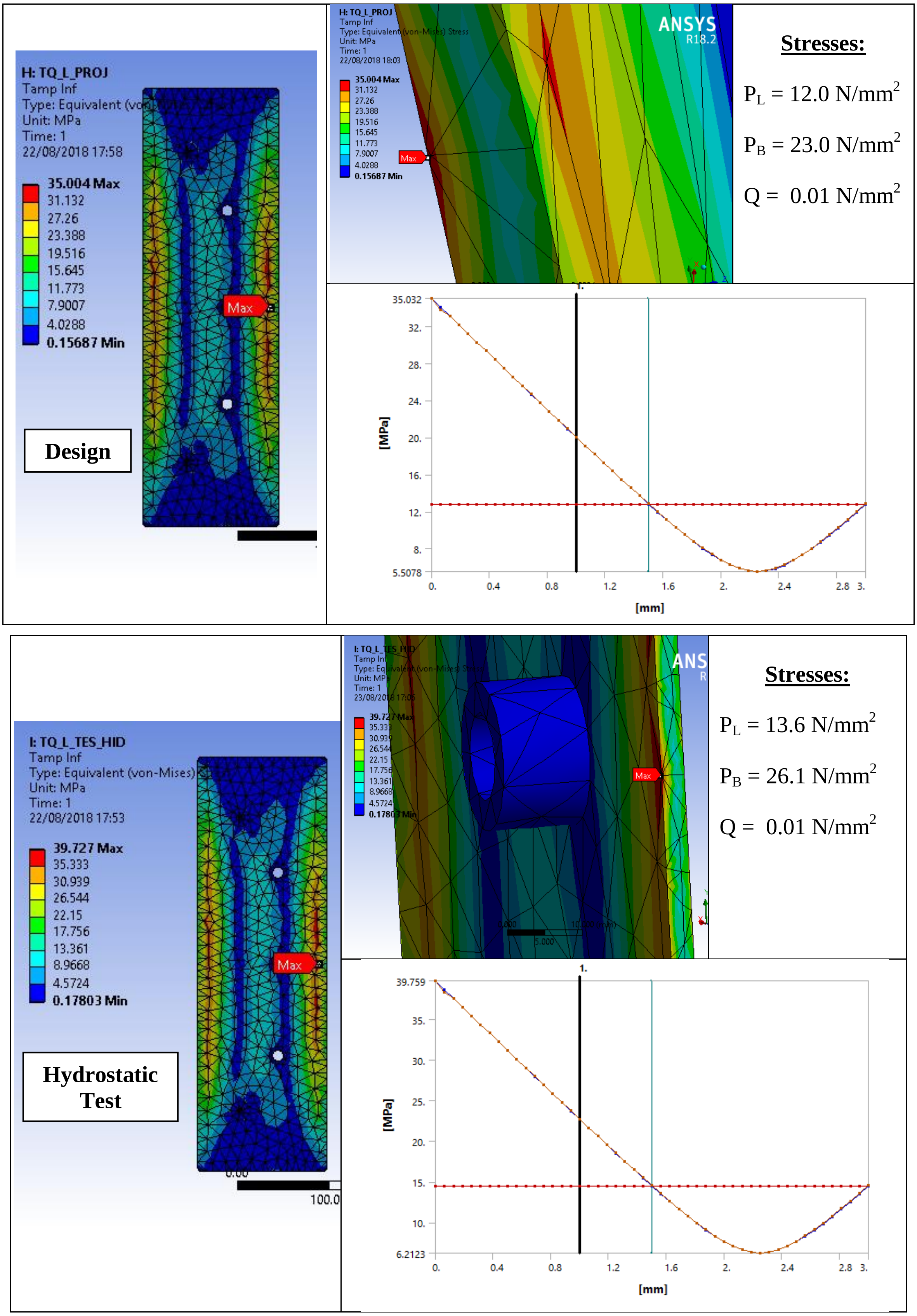
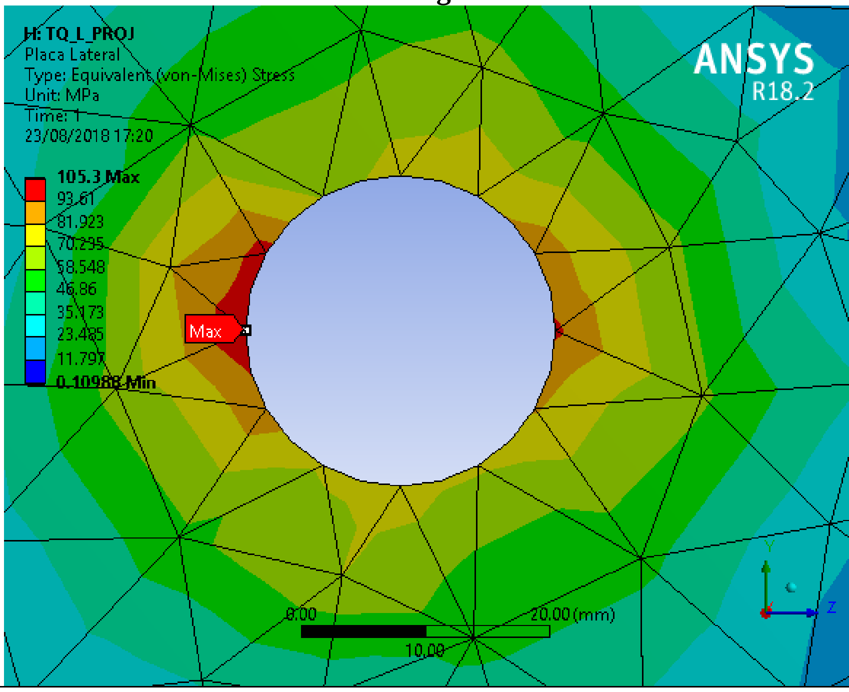


Figure 9 – East Tank Equivalent Stresses – Cover Plate

Design



Hydrostatic Test

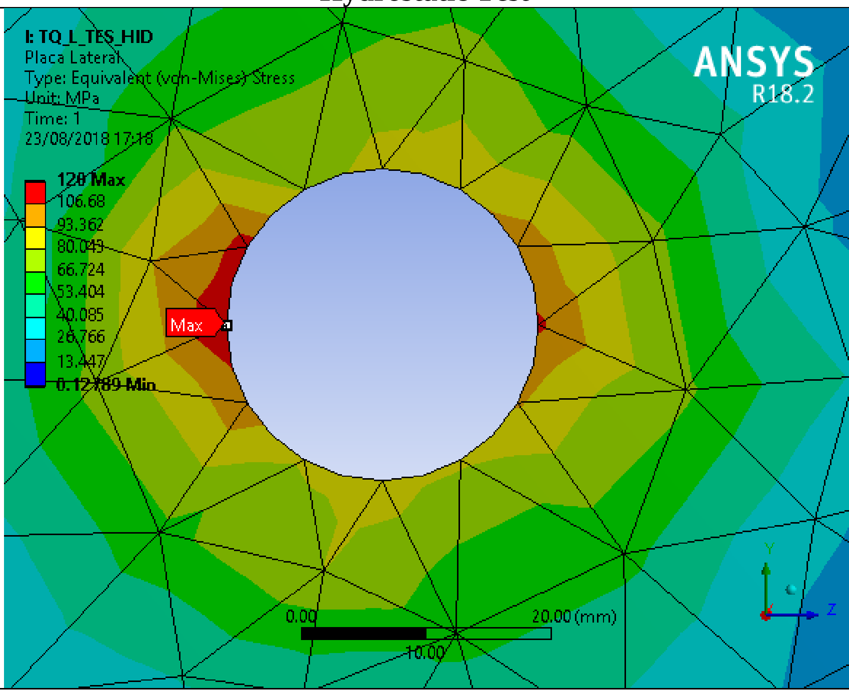


Figure 10 – East Tank Equivalent Stresses –Lateral Plate (MPa)

4.3. West Tank

The distribution of the resulting equivalent stresses in the West Reflecting Tank, for the Design and Hydrostatic Test conditions, can be seen in Figures 11 to 13. Table 6 shows the equivalent maximum stresses.

Table 6 – West **Tank Equivalent Stresses (N/mm^2)**

-		$P_L + P_B$	$1.5\ S_H$		$P_L + P_B + Q$	$3.0\ S_H$	
Cover Plate	Design	55.5	65.1		63.2	65.1	
	Hydrostatic Test	55.5	130.2		63.2	130.2	
-		**S-01**		**S-02**		**S-03**	
		P_m	S_H	P_L	$1.5\ S_H$	$P_L + P_B + Q$	$3.0\ S_H$
Lateral Plate	Design	54.0	82.6	71.8	124.0	101.7	241.0
	Hydrostatic Test	61.0	82.6	74.5	124.0	116.0	241.0
Spacer	Design	20.4	43.4	20.4	65.1	42.1	130.0
	Hydrostatic Test	23.3	43.4	23.3	65.1	48.1	130.0

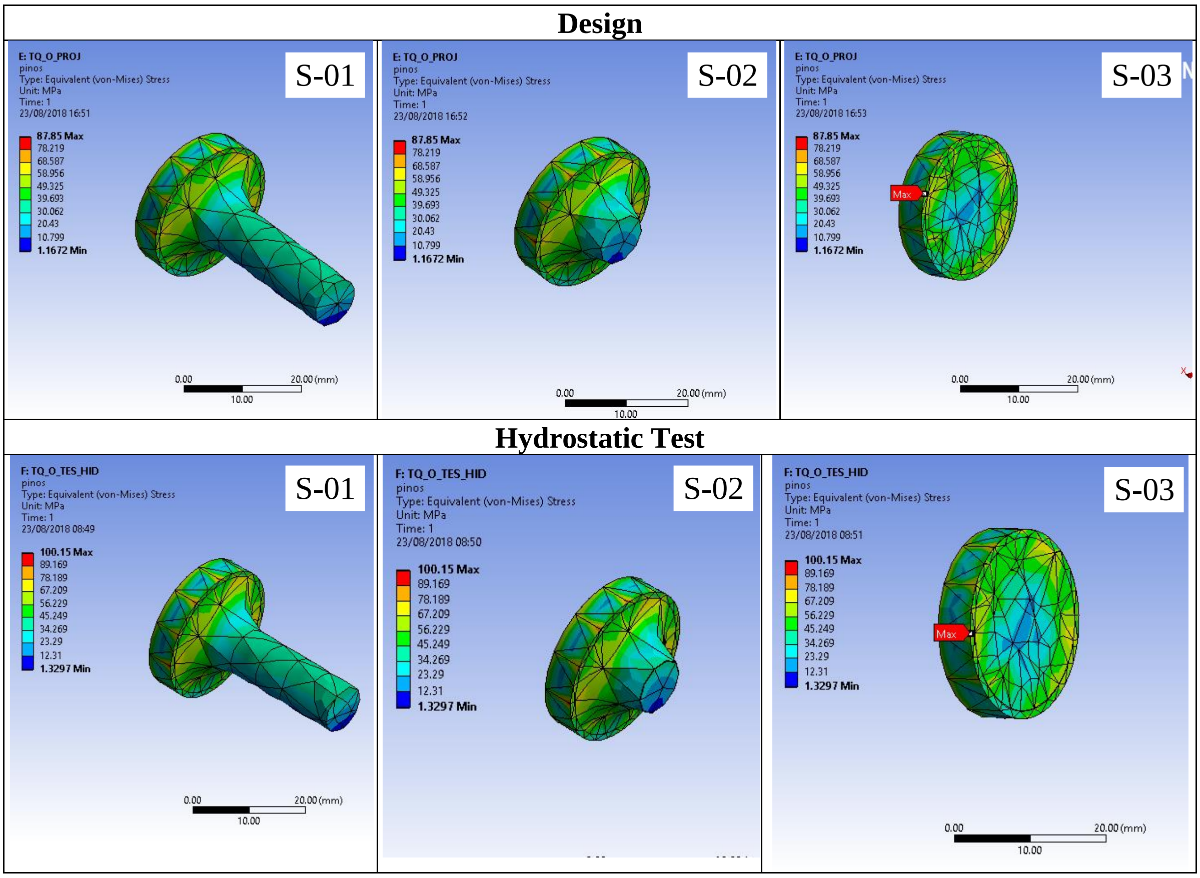


Figure 11 – West Tank Equivalent Stresses - Spacer (N/mm^2)

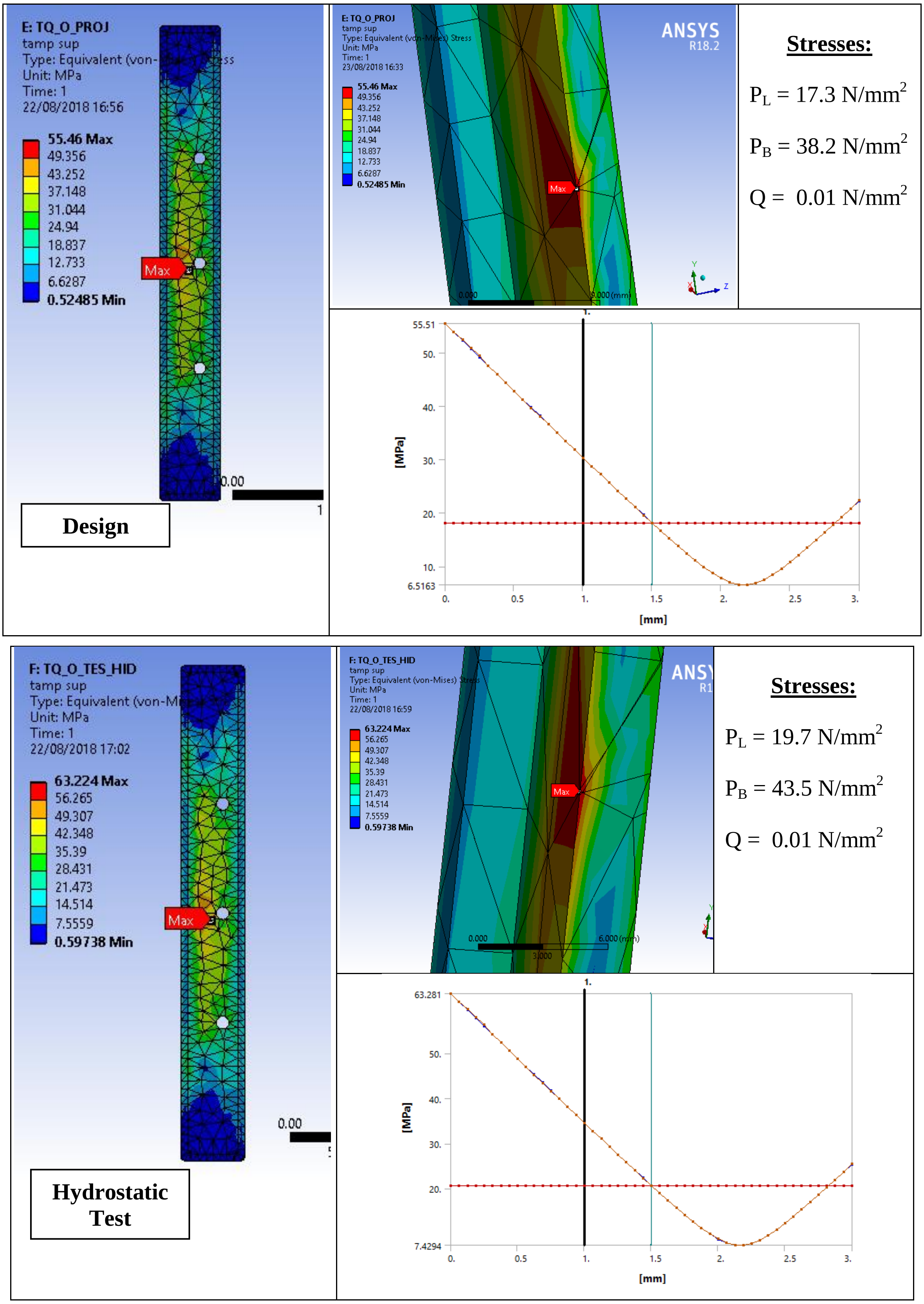


Figure 12 – West Tank Equivalent Stresses – Cover Plate

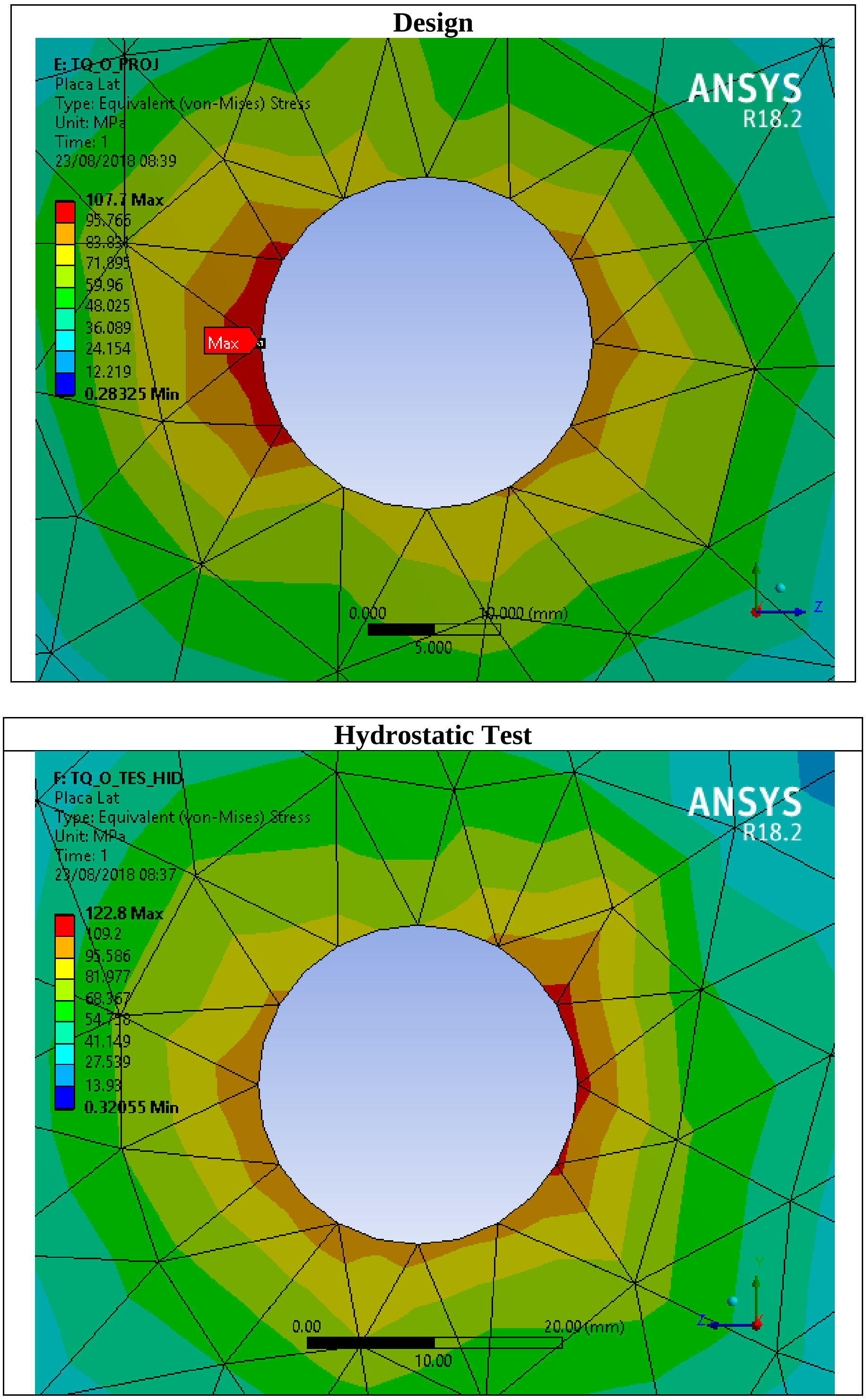


Figure 13 – West Tank Equivalent Stresses –Lateral Plate (MPa)

5. CONCLUSIONS

The North, South, East and West Heavy Water Reflector Tanks of the IPEN/MB-01 Nuclear Research Reactor were analyzed by applying the ANSYS computer program for structural analysis using the finite element method.

The results of the stress analysis of each tank show that the limits for plastic collapse established by the ASME code, Section VIII, division 2 are met.

Therefore, the structural integrity of the North, South, East and West Heavy Water Reflector Tanks is guaranteed.

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