Abstract:
The scope of this document is the safety of the West End Tower Vacuum Vessel which will be used at Virgo (Italy). The system has to comply with the Pressure Equipment Directive (PED) 97/23/CE. The French construction code for pressure apparatus CODAP (Code De Construction des Appareils a Pression) is used to verify the stresses. With a volume of 5500 liter and a design pressure of 0.5 bar, the vessel is not applicable to PED.
1 GENERAL DESCRIPTION

The current Virgo vacuum level needs to be improved by about a factor of hundred in order to be compliant with the required Advanced Virgo sensitivity. Such an improvement requires baking out the interferometer arms. To separate these arms from the towers that hold the mirrors and allow the bake-out, four cryogenic vacuum links will be installed. Cryogenic vacuum links are the classical solution to stop the migration of water from unbaked towers to interferometer (ITF) arms.

The outer vacuum vessel will be constructed from stainless steel 304L. Reinforcement ribs are welded to the outside of the vessel to avoid buckling of the structure. The vessel is equipped with pump-out and service ports. A stainless steel hydro-formed bellow is foreseen at one end of the vacuum vessel as a connecting piece between the trap and the tower. This bellow will have a 700 mm inner diameter and can accommodate expansion of the structure. The other connection is an existing DN1000 valve. See also Figure 6 at page 8

Inside the vacuum vessel a cold part of the cryogenic vacuum link will be constructed from aluminum. The inner surface of this link is cooled with liquid nitrogen. This cold part is isolated from the vessel by using two air springs and designed in such a way that thermal expansion does not induce stresses in the outside vacuum vessel.
The system will be building up and tested at an extern company. The final performance tests will be done at Nikhef before installing at Virgo. For this the cryogenic vacuum link will be closed with two end caps, and one extra the support will be added. See next Figure 2 and Figure 3:

Figure 2, the cryogenic vacuum link how it will build up for testing at Nikhef.

Figure 3, inside the vessel a cold part is mounted (cyan), supported on four ribs at the outside of the vessel.
2 SAFETY

To prevent failure of the system, the system has to equipped with a burst discs on the vacuum vessel and a relief valve for the nitrogen vessel. The calculations are done based on a burst discs which opens at a pressure difference of max. +0.5 bar. Both safety systems are venting through a stainless steel safety line for personal safety. See the following Figure 4:

![Figure 4, two burst discs preventing the vessels. Yellow = vacuum | red = nitrogen | blue = safety line.](image)
3 DEFINING PED CATEGORY

The Pressure Equipment Directive (97/23/EC) was adopted by the European Parliament and the European Council in May 1997. The PED is a European Single Market Directive that covers pressure equipment and assemblies with a maximum allowable pressure PS greater than 0.5 bar.

Pressure equipment: Pressure vessel
Media: Nitrogen (N)
Group: Non dangerous media
Phase: Gas
Vessel volume: V = 5500 Liter
Design Pressure (PS): 0.5 bar

\[ PS \cdot V = 2750 \text{ [bar.l]} \]

Tabel 1. defining the PED category for non dangerous gases. The red lines indicate the vessel properties.

Following Tabel 1, the vessel is not applicable to PED.
4 CALCULATIONS (FINITE ELEMENT ANALYSIS)

Finite element analyses are done to investigate the expected stresses and deformations. The French construction code for pressure apparatus (CODAP) is used to verify the stresses. Following the chosen construction class B and welding coefficient \( z = 0.7 \), the stress limits according to CODAP for austenitic stainless steels are:

- **Global zones:** \( f = f_3 = \frac{R_m}{3.5} \)
- **Weld regions:** \( f_w = z \cdot \frac{R_m}{3.5} \)
- **Peak regions:** \( f_p = 1.5 \cdot f_3 \)
- **Peak/Weld regions:** \( f_{pw} = 1.5 \cdot f_w \)

\( R_m \) = minimum guaranteed value ultimate tensile strength at room temperature

Finite element analyses are done with the finite element analysis module of Ideas™. Results of the stress analysis are presented in terms of Von Mises equivalent stress. In addition the calculated deformations from the stress analysis and the stability (buckling) are presented. The quality of the FEA is verified using the strain energy error norm. A value below 7% is recommended by the IDEAS™ software.

4.1 Operational conditions

Half of the pressure vessel is modeled, as the vessel is symmetric about YZ, see Figure 5.

![Figure 5. The vessel is symmetric about YZ.](image)

The design pressure PS of the vessel is between -1 bar (vacuum) and +0.5 bar. Normal operational condition is vacuum. The +0.5 bar differential pressure will be determined by a burst disc which opens at a max. pressure difference of +0.5 bar. This can be caused of a failure of the inner cold part
which is cooled with liquid nitrogen. The vacuum vessel will be baked out at 150°C. Operational temperature of the vessel will be 20°C. The main support of the vessel is the big valve at the left side, see Figure 6.

![Figure 6, supports of the vacuum vessel.](image)

This support on the left (valve) side can be considered as rigid. At the other end the vessel is supported in Z direction by two studs of 12mm and designed in such a way that thermal expansion does not induce stresses in the vessel. The vacuum vessel is connected by a stainless bellow which can accommodate thermal expansion of the structure.

The inner cold part, filled with liquid nitrogen, is hanging with air filled bellows on two ribs of the vacuum vessel; see Figure 7 and Figure 8. The total weight of this aluminum vessel (550 kg) with liquid nitrogen (± 300 Liter | 250 kg) on the four flanges is 800 kg (8000 N).
Figure 7. two suspensions of the cold part (nitrogen vessel) inside the vacuum vessel. Blue are the ribs and green are the suspensions of the inner cold part.

Figure 8. detail of the suspension.

Table 2, summary of the operational conditions

<table>
<thead>
<tr>
<th>Operational conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Pressure</td>
</tr>
<tr>
<td>Design Temperature</td>
</tr>
<tr>
<td>Additional load</td>
</tr>
</tbody>
</table>
4.2 The FEA model

The FEA model is built up from 3D solid parabolic tetrahedron and 2D Thin Shell parabolic quadrilateral elements. The design pressure is +0.5 bar (when the nitrogen vessel failures and the burst disc opens). Chosen is to have an additional load safety factor of 3 on this internal pressure. This means that the FEA simulation is done with +1.5 bar. The vacuum load and the external loads of the nitrogen vessel are applied without additional safety factors.

The vessel is verified for two conditions:

1. Pressure +1.5 bar | temperature 20°C
2. Pressure -1 bar | temperature 150°C

See for all FEA model constrains the following Figure 9:

![Figure 9, FEA model with constrains of the vacuum vessel.](image-url)
4.3  Material

The vessel will be made from AISI 304L. The material has been selected based on the corrosion requirements and the welding ability of the material. A summary of the mechanical properties is given in Tabel 3.

Tabel 3, properties AISI 304L (Battelle Structural Alloys Handbook)

<table>
<thead>
<tr>
<th>Property</th>
<th>SI unit</th>
<th>Value at 20-25 °C</th>
<th>Value at 150 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength $R_m$</td>
<td>[MPa]</td>
<td>520</td>
<td>482</td>
</tr>
<tr>
<td>Yield strength $R_{p0.2}$</td>
<td>[MPa]</td>
<td>193</td>
<td>186</td>
</tr>
<tr>
<td>Young’s modulus $E$</td>
<td>[GPa]</td>
<td>200</td>
<td>190</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>[g/cm³]</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>Poissons ratio $\nu$</td>
<td></td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>Elongation at break $A_5$</td>
<td>[%]</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Brinell hardness $HB$</td>
<td></td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

The stress limits according to CODAP are:

1. Pressure 1.5 bar | temperature 20°C

Global zones: $$f = f_3 = \frac{R_m}{3.5} = \frac{520}{3.5} = 148 \text{ MPa}$$
Weld regions: $$f_w = \frac{z \cdot R_m}{3.5} = \frac{0.7 \cdot 520}{3.5} = 103 \text{ MPa}$$
Peak regions: $$f_p = 1.5 \cdot f_3 = 1.5 \cdot 148 = 222 \text{ MPa}$$
Peak/Weld regions: $$f_{pw} = 1.5 \cdot f_w = 1.5 \cdot 103 = 155 \text{ MPa}$$

2. Pressure -1 bar | temperature 150°C

Global zones: $$f = f_3 = \frac{R_m}{3.5} = \frac{482}{3.5} = 137 \text{ MPa}$$
Weld regions: $$f_w = \frac{z \cdot R_m}{3.5} = \frac{0.7 \cdot 482}{3.5} = 96 \text{ MPa}$$
Peak regions: $$f_p = 1.5 \cdot f_3 = 1.5 \cdot 137 = 205 \text{ MPa}$$
Peak/Weld regions: $$f_{pw} = 1.5 \cdot f_w = 1.5 \cdot 96 = 144 \text{ MPa}$$
4.4 Tube calculation

Design Pressure: \( P S_{max} = 1.5 \text{ bar (0.15 MPa)} \)
Inside diameter: \( D_{in} = 1350 \text{ mm} \)
Outside diameter: \( D_{out} = 1360 \text{ mm} \)
Wall thickness: \( t = 5 \text{ mm} \)

The vessel can be considered as thin-walled vessel because the \( D_{in}/t \) ratio (1350/5=270) is higher than 10 (often cited as 20).

Radial (Hoop) stress:
\[
\sigma_r = \frac{F}{A} = \frac{P S \cdot D_{in}}{2 \cdot t} = \frac{0.15 \cdot 1350}{2 \cdot 5} = 20.3 \text{ MPa}
\]

Axial stress:
\[
\sigma_a = \frac{F}{A} = \frac{P S \cdot D_{in}^2}{D_{out}^2 - D_{in}^2} = \frac{0.15 \cdot 1350^2}{1360^2 - 1350^2} = 10.1 \text{ MPa}
\]
4.5 FEA results

4.5.1 Internal pressure analysis

Figure 10, internal pressure stress result | max stress = 161 Mpa | See details in next figures.

Figure 11, detail 1 stress at the right flange | max 161 MPa
Figure 12, detail 2 stress at the transition | max 113 MPa

Figure 13, limited stress to 103 MPa (CODAP limit weld regions).
Figure 14, internal pressure displacement result | max displacement = 1.7mm.

Figure 15, strain energy error norm = 4%.
4.5.2 Vacuum analysis

Figure 16, vacuum stress result | max stress = 144 Mpa | See detail in next figures

Figure 17, detail stress at the right flange | max 144 MPa
Figure 18, limited stress to 96 MPa (CODAP limit weld regions).

Figure 19, vacuum displacement result | max displacement = 1.2 mm.
Figure 20, vacuum first normal mode result | buckling factor = 6.8.
5 RESULTS OF THE ANALYSIS.

The results are compared with the requirements defined by the CODAP. The limitations of the analysis are presented, and the compliance with the code is verified.

Assuming the internal pressure analysis, simulation shows that the expected max stress (161 MPa) is well below the acceptable values of 222 MPa for Peak regions. Detail 1 in Figure 11 shows that the peak of 161 MPa is situated next to the weld region. Detail 2 in Figure 12 shows the transition part between the two diameters of the tube which has the highest (peak) stress in weld regions. Maximum is 113 MPa which is well below the limit of peak/weld regions (155 MPa). Stresses in other weld regions are well below the CODAP limit of 103 MPa. Tube calculation also shows that the general stresses (20.3 MPa) in the vessel are far below the acceptable value for global zones (148MPa) and in the same range as the simulation shows (17 – 25 MPa). The stainless steel hydro-formed bellow at one end of the vacuum vessel has to accommodate an expansion of 1.7 mm.

Assuming the vacuum analysis, the calculation shows that the expected max stress (144 MPa) is well below the acceptable values of 205 MPa for Peak regions. Same as said in the internal pressure result, Figure 17 shows that the peak of 144 MPa is situated next to the weld region. Figure 18 shows that all weld regions are below the CODAP limit of 96 MPa for weld regions. Buckling analysis shows a buckling factor of 6.8, where a factor of 3 is required, which can be considered as safe. The tolerances for the fabrication of the vessel will ensure that the shape of the vessel will be in accordance with the model. The stainless steel hydro-formed bellow at one end of the vacuum vessel has to accommodate a compression of 1.2 mm.

The global value for the strain energy error norm in the vessel of 4% is below the 7% which is recommended by the IDEAS™ software.
Presented is the safety analysis of the vacuum vessel which will be used at the Virgo institute in Italy. The system must comply with the Pressure Equipment Directive (PED) 97/23/CE. The French construction code for pressure apparatus (CODAP) is used to verify the stresses.

The vessel will be made of AISI 304L. The vessel has two design conditions. An internal pressure of +0.5 bar (nitrogen; in case of a failure of the inner cold part) at 20 °C and a vacuum (-1 bar; normal optional condition) at 150 °C (bake out of the system).

1. Pressure +0.5 bar | temperature 20°C
2. Pressure -1 bar | temperature 150°C

Chosen is that the finite element calculation are done with a safety load factor = 3 on the design pressure of 0.5 bar, which means an intern pressure of +1.5 bar at 20°C.

To prevent failure of the system, the system has to equipped with a burst disc which opens at max 0.5 bar difference pressure.

With a volume of 5500 liter and a design pressure PS of 0.5 bar, the vessel is not applicable to PED.

Analysis shows that the vessel is in compliance with the requirements put forth by the CODAP. Also the stability requirements (buckling) lay within the requirements of the CODAP.
7 APPENDICES

7.1 Main technical drawings
Detail B
Scale: 1:1

Section view A-A
Scale: 1:5

Isometric view
Scale: 1:5

*Clean all parts according to Nikhef cleaning procedures
*Leak rate less than 10^-10 mbar l/s helium
## 7.2 Contents of the PED modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Manufacturers attend to internal manufacturing control, themselves producing and storing the documentation. The authorized body not involved.</td>
</tr>
<tr>
<td>A1</td>
<td>Manufacturers attend to internal manufacturing control, themselves producing and storing the documentation. The authorized body monitors the final verification through unannounced visits.</td>
</tr>
<tr>
<td>B</td>
<td>Manufacturers draw up the technical documentation and provide samples. The authorized body examines the technical documentation and undertakes the necessary testing of the samples and issues an EEC type testing certificate.</td>
</tr>
<tr>
<td>B1</td>
<td>The manufacturer draws up the technical documentation. The authorized body examines the technical documentation and issues an EEC construction testing certificate.</td>
</tr>
<tr>
<td>C1</td>
<td>Manufacturers ensure that production conforms to the specifications of the type approval. The authorized body monitors the final verification through unannounced visits.</td>
</tr>
<tr>
<td>D</td>
<td>Manufacturers use a documented quality assurance system that covers production, final inspection and testing. The authorized body audits, approves and monitors the quality assurance system.</td>
</tr>
<tr>
<td>D1</td>
<td>As D but manufacturers must also draw up and file technical documentation for the equipment.</td>
</tr>
<tr>
<td>E</td>
<td>Manufacturers use a documented quality assurance system that covers final inspection and testing. The authorized body audits, approves and monitors the quality assurance system.</td>
</tr>
<tr>
<td>E1</td>
<td>As E but manufacturers must also draw up and file technical documentation for the equipment.</td>
</tr>
<tr>
<td>F</td>
<td>Manufacturers ensure that production conforms to the specifications of the type approval or the construction testing certificate. The authorized body inspects each product. The authorized body issues a certificate of conformity.</td>
</tr>
<tr>
<td>G</td>
<td>The manufacturer draws up and submits the technical documentation. The authorized body examines the technical documentation, manufacture and each individual product. The authorized body issues a certificate of conformity.</td>
</tr>
<tr>
<td>H</td>
<td>Manufacturers use a documented quality assurance system that covers construction, production, final inspection and testing.</td>
</tr>
<tr>
<td>H1</td>
<td>As H but manufacturers must also apply for construction approval from the same authorized body that monitors the quality assurance system.</td>
</tr>
</tbody>
</table>