Design and analysis of a large transportable vacuum insulated cryogenic vessel

Bachelor Degree Project in Mechanical Engineering
22.5 ECTS
Spring term 2010

Alejandro Unda García
Carlos Muñoz Alonso

Supervisor: M. Sc. Tomas Walander
Examiner: Ph. D. Karl Mauritsson
ABSTRACT

This project has been undertaken by Alejandro Unda García and Carlos Muñoz Alonso for Veprox AB (www.veprox.se), a Swedish engineering company, in collaboration with the School of Technology and Society at the University of Skövde (www.his.se). This thesis represents the final project for the Bachelor Degree Exam in Mechanical Engineering during the academic year 2009-2010.

To achieve this project, we were helped and supported by Peter Höglund, Veprox AB Office Manager; Tomas Walander, Supervisor and M. Sc. student and Karl Mauritsson, Examiner and Lecturer, both belonging to the Department of Mechanical Engineering at the School of Technology and Society of the University of Skövde.

This project is aimed to study, design and analyze a large transportable vacuum insulated cryogenic vessel that will be attached to a truck in order to keep, maintain and transport by road liquid methane at a temperature of -162 °C.

Considerations such as different pressure loads, dimensions, materials as well as their mechanical properties, constraints, masses, insulation systems and weather-environmental conditions (Northern Europe) are made in the mechanical analysis. Furthermore, calculations and dimensions satisfy the requirements given by the Swedish Standards Institute (S.I.S) following the standards SS-EN 13530-1: Cryogenic vessels - Large transportable vacuum insulated vessel; Part 1: Fundamental requirements [1] and SS-EN 13530-2: Cryogenic vessels - Large transportable vacuum insulated vessel; Part 2: Design, fabrication, inspection and testing [2].

The CAD software Pro/Engineer Wildfire 4.0 is used to visualize the models for the chosen designs. In addition, the finite element module Pro/Mechanica is used to obtain results of mechanical analyses in order to determine if the stresses are within margins.
## TABLE OF CONTENTS

1. INTRODUCTION AND OVERVIEW ................................................................. 1

2. BACKGROUND INFORMATION ..................................................................... 2
   2.1. Methane ............................................................................................... 2
   2.2. Truck and hook-lift mechanism .......................................................... 3
   2.3. Insulation system ................................................................................ 4

3. DESIGN AND ANALYSES OF THE PARTS OF THE CRYOGENIC VESSEL
   .................................................................................................................. 6
   3.1. Frame .................................................................................................. 8
   3.2. Main vessel .......................................................................................... 11
       3.2.1. Inner vessel .................................................................................. 11
       3.2.2. Outer jacket .................................................................................. 15
       3.2.3. Supports ....................................................................................... 16
       3.2.4. Beams ......................................................................................... 19
       3.2.5. Pipes ........................................................................................... 21
   3.3. Other elements .................................................................................... 25
       3.3.1. Cabinet ......................................................................................... 25
       3.3.2. Valves ......................................................................................... 26
       3.3.3. Vacuum gate ............................................................................... 27

4. CONCLUSIONS ............................................................................................ 29

5. REFERENCES .............................................................................................. 31
1. INTRODUCTION AND OVERVIEW

The denotation “cryogenics” is defined as the study of a liquefied gas at very low temperature (below −150°C), as well as how materials perform at the aforementioned temperature. In this case, the cryogenic fluid is methane, which presents very good flammable qualities allowing it to be used as a new fuel and energy source. By being liquefied, methane reduces its volume approximately 580 times at room pressure (1 bar), which makes it possible to transport a large quantity of methane in a small tank, which can be transported by a truck.

Cryogenic vessels could be transportable (by road, by train or by boat) or stationary (set on a gas plant, for instance). Moreover, vessels could be insulated by vacuum or by special insulation material (foam, for example).

This project is aimed at the design and analysis of a transportable cryogenic vessel composed of several parts. Methane is kept in an inner vessel covered by an outer jacket of the same shape. Between both vessels, a vacuum insulation system is located. There are also beams which are used as connections between the inner vessel and the outer jacket and these are designed, analyzed and optimized in order to obtain stress values within margins. Apart from this, the project also addresses the frame to which vessels are attached, as well as its supports, which are the connections between the vessels and the frame. Finally, pipes and valves are taken into consideration in order to complete the design of the cryogenic vessel.

This project is structured around two parts. The first part contains a background on methane, the truck with the hook-lift mechanism and the insulation system. The second part focuses on the design and finite element analysis of the cryogenic vessel assembly.
2. BACKGROUND INFORMATION

The vessel is intended to carry methane. Therefore, in order to gain a better knowledge of this element, some characteristics are mentioned below. Since the properties of methane affect the design and analysis of the vessel, a truck with a hook-lift mechanism is intended to transport the vessel and thus an overview of them is studied.

Vacuum is selected as the insulation system. There are various kinds of methods for vacuum insulation. The description of these appears below.

2.1. Methane

Methane is a chemical compound with the chemical formula CH₄ [3]. It is the principal component of natural gas (about 87 % by volume). The relative abundance of methane makes it an attractive fuel. However, given that methane is a gas at normal temperature and pressure, it is difficult to transport. Methane in a gas state is flammable only when its concentration in air fluctuates between 5 and 15 %. Liquid methane does not burn unless subjected to a high pressure of 4 – 5 atmospheres normally.

Regarding potential health hazards, methane is not toxic. However, it is highly flammable and may form explosive mixtures on contact with air. It is violently reactive with oxidizers, halogens and some halogen-containing compounds. It is also suffocating and it may displace oxygen in an enclosed space. A decrease in its oxygen concentration down to or below 19.5 % by displacement may result in asphyxia.

Methane is important for the generation of electricity by burning it as a fuel in a gas turbine or steam boiler. Compared to other hydrocarbon fuels, burning methane produces less carbon dioxide for each unit of released heat. With 891 kJ/mol, methane's heat of combustion is lower than any other hydrocarbon, but the ratio of the heat of combustion regarding the molecular mass (16 g/mol) shows that methane, being the simplest hydrocarbon, produces more heat per mass unit (55.7 kJ/g) than other hydrocarbons. In many cities, methane is distributed into homes for domestic heating and cooking purposes. In this context it is usually known as natural gas and it is considered to have an energy content of 39 MJ/m³ at a temperature of 0 ºC and a pressure of 1 bar.

Methane in the form of compressed natural gas is used as a vehicle fuel and it is claimed to be more environmentally friendly than other fossil fuels such as gasoline/petrol and diesel.

Methane is often kept in the transportable vessel in a liquid state (denoted “liquefied methane gas”, LMG), given that it is possible to keep more liquefied methane than gas methane within the same volume space, as the ratio of volumes is 1/580. Methane is in a liquid state at a temperature of -160 ºC and a pressure of 1 bar. It has a density of 415 kg/m³. Methane is also less dangerous in a liquid state regarding fire and explosions matters.
2.2. Truck and hook-lift mechanism

It is necessary to find a truck which fulfils the requirements regarding dimensions, maximum payload and the possibility of attaching a hook-lift mechanism onto it, to load and unload the vessel on the truck chassis.

The chosen truck is the Volvo 6x4 T Ride Tractor, which belongs to the Volvo FM13 range [4]. Its main dimensions are shown in figure 1 and some other specifications of the truck are listed below.

![Figure 1. Dimensions of the Volvo 6x4 T Ride Tractor given in millimetres.](image)

Chassis dimensions:

- Wheelbase (WB): 3600 mm
- Overall chassis length (A): 7137 mm
- Centre of rear axle to back of cab (D): 2604 mm
- Theoretical wheelbase (T): 4285 mm

Plated weights:

- Gross vehicle weight: 34000 kg
- Gross combination weight: 44000 kg
- Maximum payload: 10000 kg

The hook-lift system is a mechanism used to load and unload containers by using a hook. There are many companies specialized in manufacturing different hook-lift systems depending on the model of the truck.

A sketch of a hook-lift mechanism is shown in figure 2 [5]. The hook-lift system in figure 2 has a mass of one ton and it is able to load approximately eight tons.
2.3. Insulation system

There are two main insulation methods regarding cryogenic vessels: vacuum and non-vacuum insulation. Non-vacuum insulation uses special materials with very low heat conductivity. A good example of such a material is the insulation polyurethane foam, whose heat conductivity is 0.028 W/m·K. Nevertheless, the use of vacuum is the most efficient method, since it has almost no heat conductivity. This is why a vacuum insulated system is selected.

Vacuum insulation method consists of creating a vacuum between the surfaces which are at different temperatures. Also, special materials can be added within the space between the two vessels to obtain lower heat conductivity and to also get a load carrying capacity that separates the vessels. There are two different methods depending on the added material. The first method is denoted multi-layer insulation (MLI) [6], and is also denoted as super insulation (SI). The second method is the expanded perlite insulation [7].

Multi-layer insulation consists of creating many radiation shields (normally aluminum foil) stacked in parallel as close together as possible without having actual contact. It typically contains about 60 layers per inch. MLI structures are anisotropic by nature, which makes it difficult to analyze them. It is also very sensitive to mechanical compression and edge effects, so careful attention to detail during all phases of its installation is mechanically required. Heat conductivity is not as good in practice as it is in theory.

In MLI, each layer is isolated from the other by spacer material such as polyester, polyamide or Mylar. Aluminum foil is carefully wrapped around the container in such a way that the entire surface of the inner vessel is covered. Spacer material is placed between the
layers to completely prevent the separate coverings of foil from making contact. If they are in contact, a thermal short circuit would occur and increase the heat transfer. The layers can be applied manually as blankets. These are hand cut to fit and are wrapped over the vessel and vessel ends. Tape of low out-gassing properties is then used to hold the blanket layers in place.

Multi-layer insulation can only be used if the vacuum pressure is below 1 mTorr, which is approximately 1 mbar. To obtain this vacuum, pumping for a long time is generally required along with heating and purging cycles. Chemical gettering materials are required to absorb the out-gassed molecules to maintain the vacuum over extended periods.

On the other hand, perlite insulation that is suitable for vacuumed cryogenic vessels has a low thermal conductivity throughout a wide range of temperatures, pressures, and densities [8]. The operating pressure for perlite is about 10 mTorr, which is approximately 10 mbar. Perlite is relatively low in cost, easy to handle and install and does not shrink, swell, warp or slump in comparison to other added materials. It is also non-combustible.

Perlite must be dry. During operating service, the normal moisture limit is 0.1 weight percent relative to the mass itself and this normal moisture limit greatly increases the pump-down time necessary to achieve the required vacuum. As a result, perlite must be fresh and packaged in moisture-proof bags or in a sealed tank.

A vacuum insulation system that fulfils specific mechanical requirements is needed. MLI is generally very sensitive to mechanical compression and edge effects. Since the vessel is loaded and unloaded from a truck, it is exposed to movements that would cause critical stresses on the unit when using MLI. These stresses could affect the multi-layer insulation system, breaking its internal bonds between layers that might cause its insulation properties to decrease. For this reason, and also due to the high quality of vacuum that MLI requires, this insulation method is rejected for the vessel that is being designed. Thus, the best insulation system for this project is the perlite insulation.
3. DESIGN AND ANALYSES OF THE PARTS OF THE CRYOGENIC VESSEL

This chapter focuses on the study of the parts of which the cryogenic vessel assembly is composed. Firstly, the frame that the cryogenic vessel is standing on is analyzed. Secondly the main vessel which is composed of an inner vessel, wherein the cryogenic fluid is kept, an outer jacket (in charge of covering the inner vessel), four supports (attachment between the vessels and the frame), twenty four beams (in charge of separating the inner vessel and the outer jacket), and finally three pipes for letting some flows of gas or air going in and out of the vessels. A third main part deals with other elements that complete the whole assembly. These are the cabinet (located on one side of the frame), the valves and the vacuum gate. In figure 3, the assembly is shown, although some of the parts such as the inner vessel, the pipes, the valves and the beams are not visualised.

![Figure 3. Overview of the cryogenic vessel assembly.](image)

The study, in turn, is divided into two major steps: firstly, the design and modelling of each of the mentioned parts; and secondly, the verification through finite element analysis that the stresses of each part are within margins. For modelling, the CAD software Pro/Engineer Wildfire 4.0 is used, and for finite element analysis the finite element module Pro/Mechanica is used.

Some specifications and clarifications for the analysis are listed below:

- All parts are modelled as surface models in order to idealize them with shell elements in the finite element analysis.
- All pipes and all connections between the inner vessel and the outer jacket are idealized as beams with a specified cross-section for each one of them.
• Since all mechanical analyses are made for the whole unit, it is necessary to set constraints in one of the parts. As the frame is the part in contact with the truck, the frame is the one that has the constraints. These constraints are located in one place or another depending on the position of the assembly.

• In finite element analysis, considerations such as “numerical singularities” (they come up in the meeting point of several sharp edges or corners) and “incompatibilities” (locations with large concentration of stresses that come from the union or connection of the beam idealization with the shell idealization) are taken into account, but they are ignored due to the fact that they are not physically real. Regarding incompatibilities, the finite element module does not take into account the whole section of the beam, rather only taking into consideration one single point. Thus, the same stress values are obtained by using different beam cross-section values within the same conditions (loads and constraints).

• The mechanical analysis of the complete assembly is performed with three different loads. These loads are the gravity (9.81 m/s²), an incoming pressure load of 2 bar affecting the outer surface of the outer jacket and an outgoing pressure load of 5 bar affecting the inner surface of the inner vessel. These loads are explained in detail later on. The finite element analysis results are shown independently for each part, including the effects caused by the interaction of each part with the others.

• Three different analyses are performed, depending on the position of the cryogenic vessel in order to analyze and check the stresses of the assembly in different situations. These positions are horizontal (frame parallel to the ground), vertical (in case of an accident where the truck could overturn) and with an angle of inclination (loading and unloading of the whole assembly from the truck). This last case begins when the assembly leans on the truck. Then the hook-lift mechanism acts, lifting the whole assembly through the front side (the one which has the hook attachment), giving it an angled position and getting new constraints: one in the contact location between the hook-lift and the frame, and two more in the two locations where the truck and the frame rails are in contact. This is the worst case due to the fact that the constraints are three little locations instead of locations such as the bottom surfaces of the frame rails. Therefore, higher stress locations are obtained.

• In each part, the value of the safety factor, which comes from the ratio between the yield strength and the maximum stress value, is given. The tensile strength is not considered for this calculation as criteria for failure, because the finite element module only considers the lineal behaviour of materials. Therefore, it is assumed that if the model stands the stresses and loads with the yield strength as criteria, it stands them with the tensile strength, since the yield strength is lower than the tensile strength. Below, the properties of the chosen materials are shown in Table 1.
Table 1: Main properties of stainless steel and carbon steel.

<table>
<thead>
<tr>
<th></th>
<th>Stainless steel</th>
<th>Carbon steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UNS S30400</td>
<td>AISI 1040</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>8030</td>
<td>7845</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>193</td>
<td>200</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>290</td>
<td>353.4</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>515</td>
<td>518.8</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (°C⁻¹)</td>
<td>1.69x10⁻⁵</td>
<td>1.36x10⁻⁵</td>
</tr>
<tr>
<td>Specific heat capacity (0-100 °C) (kJ/kg·K)</td>
<td>0.5</td>
<td>0.49</td>
</tr>
<tr>
<td>Thermal conductivity (100 °C) (W/m·K)</td>
<td>16.2</td>
<td>54</td>
</tr>
</tbody>
</table>

- The union of each part with another is supposed to be obtained through welding processes, which are considered as multi-point constraints. These constraints set the nodes of a surface to have the same displacement as the nodes of another surface. Thus, the final assembly is considered as one unit.

3.1. Frame

3.1.1 Design

The frame is the part that connects the main vessel and its accessories to the truck. Its function is to carry and maintain the main vessel fixed to it. The frame is shown from two different orientations in figures 4 and 5:

![Figure 4. Overview of the frame.](image-url)
As can be seen in figure 4, the frame is composed of two plates, one horizontal and one vertical. The rails of the horizontal plate are in contact with the truck and hold the total weight of the vessels that the frame carries on top. The vertical plate has the function of carrying a hook attachment to the top part. This hook attachment is used to unload and load the whole assembly from the truck through the hook-lift mechanism. Both plates are joined by two rails (see figure 5). The frame is symmetric, which results in symmetric stress distribution.

The total mass of the frame is 554 kg and it is made of the AISI 1040 carbon steel [9], which has a yield strength of 353 MPa. This fact allows the different thicknesses of the frame not to be very high in comparison to other materials whose yield strength is lower. Its dimensions are influenced by the dimensions of the truck because the frame must be able to fit into the truck. For more details of the dimensions of the frame, see Appendix I.

3.1.2. Mechanical analyses and results

In figure 6, the result of the finite element analysis in the angled position is shown. This occurs when the frame is being loaded or unloaded. In that position the frame has constraints at three different locations (this situation being the worst case): two of them in two separate locations in the rails and the third one in the top part of the hook attachment. The number of elements used in this shell simulation is 367.
Figure 6. Result of the finite element analysis in the frame. The colour legend values represent the von Mises stresses in MPa.

The maximum value of von Mises stress is between 166.6 and 177.7 MPa (see further figures 6 and 7). This is a factor much lower than the yield strength of the carbon steel, which is 353 MPa. It is stated that the safety factor (in aspect of the yield strength) is 1.98.

The locations with more concentration of stresses are the ones surrounding the constraints, which are in the rails and in the hook attachment. There are also stress concentrations in the location where the hook attachment connects with the rails and where the supports of the outer jacket are welded (see figure 6).
3.2. Main vessel

The main vessel is divided into five parts: the inner vessel, the outer jacket, the supports, the beams (in charge of separating the inner vessel and the outer jacket) and the pipes (the ones which let some gas or air flow in and out the vessels). The width, the length and the height of the vessel are influenced by the dimensions of the frame. The outer jacket has an elliptical shape in order to take advantage of the space within the frame as much as possible. Consequently, a larger quantity of methane can be stored within the vessel.

The shape of the inner vessel and the outer jacket is the same. The only differences are the dimensions. Within the space between them, there is the insulation system and the pipes/beams. The distance between the vessels is 150 mm.

3.2.1. Inner vessel

3.2.1.1. Design

The main function of the inner vessel is to keep the methane at a temperature of -162°C. Figure 8 shows an overall view, where it is possible to observe the symmetric shape of the inner vessel. It has three symmetry planes. The main dimensions are a length of 3320 mm, a width of 1900 mm and a height of 1100 mm. In order to see all the dimensions, see Appendix I.
Figure 8 shows two rounds in the edges. The purpose of these features is that the rounds reduce the stress concentrations where the inner vessel has sharp corners.

In the internal part of this vessel there are five surge plates that reduce the effect of moving waves of liquid while the truck accelerates. They have a thickness of two millimetres and they are placed with a distance between them of 550 mm (see further figure 9). Due to visualization errors in figure 9, it appears that some surfaces are broken. This is, however, not the case. The shape of the surge plates follows the shape of the vessel but ends with horizontal edges at the top and bottom part (see figure 10). The purpose of the horizontal end at the bottom part is to still make it possible to fill the vessel from one position. The space between the horizontal edge at the top part of the surge plate and the inner vessel is an opening whose function is to let gases flow through. Thus, the pressure has the same value at all positions in the inner vessel. The distance from the top edge to the horizontal edge of the surge plate is 700 mm. The surge plates cover an area of approximately 70% of the cross-section area of the inner vessel, according to the Swedish standard SS-EN 13530, Part 2.

Figure 9. Surge plate placements.
The volume capacity of the inner vessel is approximately 6000 l. However, it is never filled to its maximum capacity. According to Swedish standard SS-EN 13530, Part 2, the inner vessel must be filled at most at 95% of its volume capacity. This means that the vessel can not be filled with more than 5700 l.

The inner vessel is made of the UNS S30400 stainless steel [10]. This material is selected due to its good corrosion resistance. Its yield strength at room temperature is 290 MPa. At -196 °C the metal has a yield strength of 386 MPa. In order to be conservative, the lowest yield strength is used in all mechanical analyses. The inner vessel has a mass of 2800 kg and it has a volume of 0.349 m³.

3.2.1.2. Mechanical analyses and results

Applied loads on the inner vessel come from the Swedish standard SS-EN 13530, Part 2. In this procedure, several pressures are taken into consideration, such as the test pressure ($p_T$), the maximum allowable pressure ($p_S$), the pressure during operation ($p_C$), the pressure exerted by the mass of the liquid contents when the vessel is filled to capacity ($p_L$) and the internal design pressure ($p$). The interesting pressure in the mechanical analysis is the internal design pressure ($p$), which is the pressure applied on the model. To obtain the value of this pressure, some previous steps are needed. Operating conditions of the used material such as the yield strength at room temperature ($K_{20}$) and the yield strength at cryogenic temperature ($K_T$) are taken into consideration.

Firstly, the maximum allowable pressure ($p_S$) is selected. If this pressure is reached in the inner vessel, the relief system will work. This pressure has a value of 4 bar. The reason of this value is to have a margin of 3 bar for the stored liquid methane, which is at 1 bar, in case of the methane boiling and expanding within the inner vessel.
Then, the calculation of the pressure exerted by the mass of the liquid contents when the vessel is filled to capacity \( (p_L) \) is developed. The value of this pressure is 0.14 bar. This calculation is made considering the mass of the methane acting on the inner surfaces of the inner vessel.

The next step is to calculate the values of test pressure and the pressure during operation. The equations that give these values are the following:

\[
\begin{align*}
\text{p}_T &\geq 1.3(p_S + 1\text{bar}) = 6.5 \text{ bar} \\
\text{p}_C & = p_S + p_L + 1\text{bar} = 5.14 \text{ bar}
\end{align*}
\]

The 1 bar added in both equations comes from the effect of the vacuum. Since vacuum has no pressure, it is necessary to add an extra pressure of 1 bar acting on the outer surface of the inner vessel in the opposite direction of the atmospheric pressure direction in order to equilibrate the gradient of pressures between the vacuum and the inside of the inner vessel. This extra pressure, in turn, comes into the inner vessel following the same direction as the other pressures (test pressure and pressure during operation).

According to the Swedish standard \textit{SS-EN 13530, Part 2}, the internal design pressure shall be the greater of \( p_T \) and \( p_C \) corrected for operating conditions \( (K_{20}/K_T) \) to take into account the cold properties of the used material. In this case, as \( p_T > p_C \), the final internal design pressure \( (p) \) is:

\[
p = p_T \cdot \frac{K_{20}}{K_T} = 4.88 \text{ bar}
\]

The value of 5 bar is taken in order to be conservative. The values of material properties taken in equation (3) are:

- \( K_{20} = 290 \text{ MPa} \)
- \( K_T = 386 \text{ MPa} \), at a temperature of \(-196^\circ\text{C}\)

The mechanical results show the von Mises stresses of the inner vessel positioned horizontally. The constraints are set in the bottom surface of the rails of the frame. Figure 11 shows an overview of the inner vessel with its stresses.
Figure 11. Result of the finite element analysis of the inner vessel. The colour legend values represent the von Mises stresses in MPa.

The number of shell elements used for this simulation is 89. As it is possible to see in figure 11, the considered maximum stress location is placed on the rounded edge. The locations around the beam and pipe connections are not considered due to incompatibilities. The maximum von Mises stress value on the rounded edge is 210 MPa. Therefore, the safety factor (in aspect of the yield strength) is 1.24.

3.2.2. Outer jacket

3.2.2.1. Design

The outer jacket is intended to hold the inner vessel and the vacuum insulation system. It presents the same shape as the inner vessel; therefore its characteristics are similar. To see all dimensions see Appendix I.

The chosen material for this part is the AISI 1040 carbon steel. It is selected because it has high yield strength (353 MPa), which is translated for a smaller thickness than if a weaker material were used. Owing to the use of this material, the outer jacket has a mass of 1440 kg and it has a volume of 0.184 m³.

3.2.2.2. Mechanical analyses and results

The applied load on this model is an incoming pressure of 2 bar acting on the outer surface. This value results from one bar of the atmospheric pressure and another bar from the vacuum.
The mechanical results show the stresses of the outer jacket positioned horizontally. The constraints are set along the bottom surface of the rails of the frame. Figure 12 shows an overview of the whole model upside-down with its stresses:

![Figure 12. Result of the finite element analysis of the outer jacket. The colour legend values represent the von Mises stresses in MPa.](image)

The number of shell elements used for this part is 52. According to figure 12, the stress behaviour of the outer jacket is quite similar to the inner vessel, due to their similar shape. Therefore, the considered maximum stress location is placed on the rounded edges, and it has a von Mises stress value of 215 MPa. The safety factor (in aspect of the yield strength) is 1.64. Apart from the incompatibilities resulting from the beam connections, there are numerical singularities due to the support connections. These numerical singularities are not taken into consideration because they come from sharp edged connections that concentrate high stresses, and this is not physically realistic.

3.2.3. Supports

3.2.3.1. Design

The supports are intended to join the vessels to the frame. They hold the weight of the entire unit (inner vessel, outer jacket, beams and pipes) including methane weight. They also maintain the vessels fixed, stopping them from being displaced by the movement of the truck. Figure 13 shows an overview of one of the four supports.
As a result of its shape, the supports are made up of straight surfaces with the exception of one of them, which presents the same shape as the outer jacket (see figure 13). This curved surface is welded to the outer jacket at its four edges. The remaining surfaces (except the top one) are welded to the frame at the edges located on the lower part of each one (there is no bottom surface as this would not be necessary since it would not suffer any stress).

The dimensions have to be appropriate. Since the curved surface is welded to the outer jacket, it has to have a proper value, while the rest of them depend on this one. To know all dimensions of the supports, see Appendix I.

Regarding mass and material, each support has a weight of approximately 50 kg. These supports are made of the AISI 1040 carbon steel.

Regarding their position within the frame, they are centred with respect to the right and top symmetry planes of the vessels (see figure 8), which are centred within the frame as well. The distances between each can be seen in figure 14:

Figure 13. Overview of one support.

Figure 14. Top view of the disposition of the supports within the frame. Units in mm.
3.2.3.2. Mechanical analyses and results

Figure 15 shows the result of the finite element analysis in the worst situation for one of the supports, namely when the whole unit is in a vertical position. Since these are designed to stand the weight horizontally, the supports do not work properly when the assembly is positioned vertically. The constraints are set in the bottom surface of the rails of the frame. Since the four of them are placed symmetrically within the assembly, they hold the same weight, same loads and therefore, the same concentration of stresses. The number of shell elements used for each support is 8.

The considered maximum von Mises stress value is 91.7 MPa. The safety factor (in aspect of the yield strength) is 3.85. Apart from this, the maximum stress location is placed in the upper-left corner of the support, reaching a value of 184.6 MPa. Although this stress concentration occurs in reality, it is still a numerical singularity due to the sharp edge connections. Therefore, this last stress value is not considered.
3.2.4. Beams

3.2.4.1. Design

The beams are intended to join the inner vessel and the outer jacket, in other words, to keep them attached. As a result, they transmit the forces from one to the other. The distribution around the vessels can be seen in figure 16.

![Figure 16. Overview of disposition of beams along the inner vessel.](image)

Beams can be classified in two groups: firstly, the group formed by the beams which are on the top and on the bottom of the inner vessel; and secondly, those which are on the sides of it. Regarding the first group, the total number of beams is 16, distributed symmetrically in four different rows: two of them on the top of the inner vessel and the other two on the bottom of it. The distance between each beam is 664 mm and each one has an angle of inclination of 45° from the horizontal symmetry plane of the inner vessel (front plane). Regarding the second group, the total number of beams is 8, four on each side. They are placed symmetrically around each surface and they are perpendicular to the surfaces of the inner vessel and the outer jacket.

Each beam in each group has the same mass and dimensions. The beams belonging to the first group have a mass of 4.65 kg each (mass of group one is 74.4 kg) and those belonging to the second group have a mass of 6.15 kg each (mass of group two is 49.2 kg). Therefore, the total mass of both groups of beams is 123.6 kg. With regard to dimensions, each beam has the same cross-section (see figure 17) but differs on length, which is 164 mm for beams belonging to the first group, and 216 mm for beams belonging to the second one.
Each beam is welded to the outer jacket and to the inner vessel. The beams are made of the UNS S30400 stainless steel because they are influenced by the inner vessel, which is exposed to the liquid methane at a temperature of -162 °C.

3.2.4.2 Mechanical analyses and results

Figure 18 and figure 19 show the result of the finite element analysis in the worst situation, namely, when the whole assembly is in a vertical position. In this position, they suffer higher stresses than in the horizontal one, because in this last case the beams mostly suffer traction and compression stresses. Otherwise, they suffer large bending moments when the assembly is positioned vertically. The constraints are set along the bottom surface of the rails of the frame. Figure 18 shows the result of the analysis for a beam belonging to the first group and figure 19 shows the result of the analysis for a beam from the second group.

Figure 18. Result of the finite element analysis in one beam of the first group. The colour legend values represent the von Mises stresses in MPa.

Figure 17. Cross-section of beams. Units in mm.
Figure 19. Result of the finite element analysis in one beam of the second group. The colour legend values represent the von Mises stresses in MPa.

The maximum von Mises stress value for a beam from the first group is 232.1 MPa, giving a safety factor (in aspect of the yield strength) of 1.25. For beams belonging to the second group the maximum von Mises stress value is 20.7 MPa and therefore the safety factor (in aspect of the yield strength) is 14.

In both figures, the lower part of the beam would be in contact with the inner vessel and the upper part would be in contact with the outer jacket.

3.2.5. Pipes

3.2.5.1. Design

There are three pipes going through the vessels: for filling purposes, for draining purposes and another one for the relief system. The two first ones are situated on the side of the vessel where the cabinet is. The one for the relief system is placed on the top-back part of the vessel. Figure 20 shows an overview from the back side of the inner vessel with the pipes attached to it.
The relief system pipe is vertical and it is centred with respect to one of the vertical symmetric planes of the vessel denoted “TOP” plane (see figure 20). With regard to the other vertical symmetric plane denoted “RIGHT” plane (see in Figure 20), the axis of this pipe is displaced from that plane with a value of 1400 mm.

Regarding the filling and the draining pipes, these are parallel (the distance between them is 300 mm) and they are situated symmetrically with respect to the vertical symmetric plane called “RIGHT” in figure 20. The next picture shows a view in detail (figure 21), where it is possible to see the angle that they have with respect to the inner vessel surface and the distance from the horizontal symmetric plane.

Figure 20. Overview of pipes attached to the inner vessel. Units in mm.

Figure 21. Detail of position of filling and draining pipes. Units in mm.
The length of the filling and draining pipes is the same at 146 mm. The length of the relief system pipe is 150 mm. All these pipes have the same cross-section, see figure 22. The inner diameter of all the pipes has a standard value of 25.4 mm.

![Figure 22. Cross-section of pipes. Units in mm.](image)

The material used for the pipes is the same used for the inner vessel, namely, the UNS S30400 stainless steel. This is because these parts are in direct contact with methane, so they need a good corrosion resistance. The sum of the masses of the filling and draining pipes is 2.7 kg. The mass of the relief system pipe is 2.8 kg. Therefore, the total mass of the three pipes is 5.5 kg. It is assumed that the pipes are welded to the inner vessel and the outer jacket.

### 3.2.5.2. Mechanical analyses and results

These parts are analysed in the worst case, which occurs when the whole unit is situated vertically. In this position, the parts suffer higher stresses than in the horizontal one, because in this last case the three pipes suffer traction and compression stresses mostly. Otherwise, they suffer large bending moments when the assembly is positioned vertically. The constraints are set along the bottom surface of the rails of the frame. The following pictures (figure 23 and 24) show their stresses.
Figure 23. Result of the finite element analysis of the relief system pipe. The colour legend values represent the von Mises stresses in MPa.

Figure 24. Result of the finite element analysis of the filling and draining pipes. The colour legend values represent the von Mises stresses in MPa.
Figure 23 represents the relief system pipe in which the end point, where the maximum von Mises stress value occurs, is the union with the inner vessel and the other end point is the union with the outer jacket. The maximum von Mises stress value is 192 MPa and the safety factor (in aspect of the yield strength) is 1.51.

Figure 24 represents the filling and draining pipes in which the end points, where the maximum von Mises stress values occur, are the unions with the inner vessel and the other end points are the unions with the outer jacket. The maximum von Mises stress value is 157 MPa and the safety factor (in aspect of the yield strength) is 1.84.

3.3. Other elements

In this chapter, some other parts belonging to the cryogenic vessel are described. Although they do not belong to the main target of the project, they are important with a view to develop the vessel. These aforementioned parts are the cabinet, the valves and the vacuum gate. Moreover, no mechanical analyses are done for these elements; it could be a future study for Veprox AB.

3.3.1. Cabinet

The cabinet is intended to cover and protect the piping and valve system. Figure 25 shows an overview of the cabinet. It is placed on the right side of the vessel, this is, the right side of the truck. This position allows the vessel to be as long as possible. Moreover, this is because of transport features. The truck is intended to drive on European roads, so the driving side is the right one. If an accident occurs, it is more probable that a vehicle collides with the truck on the left side and not on the right. In addition, if the truck stops accidentally on the road while other vehicles are moving, it is safer for the piping system to be on the right side in case the driver needs to manipulate it. Its shape is symmetric and its dimensions are mentioned in Appendix I.
The cabinet does not have a bottom surface as this is unnecessary. It is welded to the frame and attached with a non-welding procedure to the outer jacket (silicone, plastic or a similar material). This last connection would avoid the increase of stresses between the outer jacket and the cabinet. The material used for this model is the AISI 1040 carbon steel, which gives a mass of 11.8 kg to the cabinet.

3.3.2. Valves

Below, some overviews of valves involved in the development of the cryogenic vessel are shown. These are the safety or relief valve (figure 26), the check valve (figure 27) and the actuated globe valve (figure 28) [11].

Figure 26. Overview of the relief valve.

Figure 27. Overview of the check valve.
Figure 28. Overview of the actuated globe valve.

All valves have the same standard inner diameter, which is 25.4 mm.

3.3.3. Vacuum gate

The vacuum gate is the element through which the vacuum insulation system is performed. Figure 29 shows an overview of this component:

Figure 29. Overview of the vacuum gate.
The mass of the vacuum gate is 160 g, it is made of the AISI 1040 carbon steel and the dimensions are the ones shown in figure 30.

Figure 30. Dimensions of vacuum gate. Units in mm.
4. CONCLUSIONS

Nowadays, many new technologies and advances concerning the field of energy have appeared. Regarding cryogenics, it is easy to find elements such as cryogenic fluid hydrogen, oxygen or argon, but the use of methane as cryogenic gas has resulted in the appearance of a new way of obtaining high quality energy for different applications. Although the use of liquefied methane is a fairly new procedure, it has been in development for several years and therefore, meets the requirements of the standards institutes.

Referring to this cryogenic vessel and apart from the fact that it has been analysed and designed to transport liquid methane at a temperature of -162 °C and attached to a truck, it can also be used as a stationary vessel, due to the fact that the frame is part of the entire unit and this is the part allowing the vessel to be loaded or unloaded. Therefore, in the case where the customer considers it appropriate, the whole unit can be unloaded and kept somewhere, so that it would be ready to be used again without losing any of its mechanical properties, thanks to the chosen materials and its insulation system.

It can be said that the sum of each one of the parts constitutes the whole unit resulting from welding processes between the parts that are in contact with each other. This welding attachment is explained by the loading and unloading process of the unit. The hook-lift mechanism moves the unit into non-desirable situations, that is, angled positions (as the desirable position is the horizontal one). In these situations, the unit has to be perfectly as well as strongly attached. Otherwise, it would break and cause irreparable damage.

Concerning the design, it had to meet the appropriate requirements for the truck in question. These requirements included dimensions (the whole unit would be able to fit into the truck) and the maximum payload (maximum weight that the truck could carry), which had a value of 10 tons. Once the mass of every part was known, it was possible to know the total mass of the entire unit, taking into account the mass of the maximum quantity of liquid methane which was inside the inner vessel. This total mass reached a value of 8.5 tons, which gave a margin of 1.5 tons with respect to that maximum payload.

Regarding materials, the same material could have been used for every part. Nevertheless, not every part works under the same conditions, so it was better to choose the appropriate one for each part. Materials could be divided into two groups: the ones that are directly exposed to a very low temperature and the others that are not directly exposed to a very low temperature. Thus, a material with a very good corrosion resistance (stainless steel) was chosen, as well as another material which did not have to present such corrosion resistance but fulfilled some other basic mechanical requirements (carbon steel). To conclude, given that the thickness of the outer jacket does not have to be as high as that of the inner vessel, it was possible to economize on material.

With regard to mechanical analyses, each part was analysed independently as part of the whole assembly. In both cases all parts held perfectly under all the stresses they suffered when loads (gravity, an incoming pressure load of 2 bar affecting the outer jacket and an outgoing pressure load of 5 bar affecting the inner vessel) and constraints were applied.
Regarding safety factors in aspect of the yield strength, those of the inner vessel and the outer jacket seem to be low. However, they come from narrow locations where the used software is not very accurate. By taking a look at big locations one could observe some stresses much further away from the yield strengths in question. Anyway, this report has shown that every part works properly, as expected.
5. REFERENCES


http://www.technifab.com/resources/cryogenic_information_library/insulation/index.html


http://www.perlite.net/redco/pvs_07.pdf


APPENDIX I: DRAWINGS

In some drawings, due to the fact that thicknesses are much lower than main dimensions and in many cases the thickness is the same for all the surfaces, it is considered appropriate to write a note at the bottom of the drawing page clarifying the thickness value. In other cases (models with different thicknesses depending on the surface), the thickness dimension has been placed in the correct position. The units of all dimensions shown in the following drawings are in millimetres.
SCALE 1:40
FRAME
Note: Thickness of 18 mm in every surface

SCALE 1:25
INNER VESSEL
Note: Thickness of 7 mm in every surface

SCALE 1:25
OUTER JACKET
ELLIPSE, R1:700, R2:1100

Note: Thickness of 7 mm in every surface

SCALE 1:12.5
SUPPORT
Note: thickness of 1 mm in every surface

SCALE 1:12
CABINET