Some mechanical aspects of the LAPLander experiment development

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Abstract

The LAPLander project aims to demonstrate a small recovery system for an ejectable sounding rocket payload. The system is being designed and built by a group of KTH students and has been selected by ESA for a flight test on board the REXUS-8 sounding rocket, which will be launched from Esrange, Kiruna, in March 2010. The payload will be ejected from the rocket and then undergo a free fall. During descent, it will deploy a structure combining airbags and parachute in order to brake the descent and be protected at landing impact. The airbags are filled up with gas $CO_2$, which is stored at high pressure in small cartridges. After impact, the LAPLander will send its position and be recovered. This document reports about some aspects of mechanical design and testing. After an overall presentation of the project, a simulation of the aerodynamic heating and the consequent thermal insulation design are presented. Then are listed a number of resistance and manufacturing tests that were performed to find a suitable fabric for the airbags. Follows a discussion about a test where a model of the payload was dropped from a tower to assess the parachute. Finally, a number of pressure, leakage and thermal tests of the cartridge are described together with the thermal properties of carbon dioxide are presented.
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Chapter 1

Introduction

The Light Airbag Protected Lander (LAPLander) project aims to demonstrate a small recovery system for an ejectable sounding rocket payload. The system is being designed and built by a group of Royal Institute of Technology (KTH) students at the Alfvén Laboratoriet at KTH and has been selected by the European Space Agency (ESA) for a flight test on board the sounding rocket REXUS 8, which will be launched from Esrange, Kiruna, in March 2010.

Multi-point measurements are the forefront of space research. However, the number of measurement points is still small: 4 satellites in the Cluster constellation and 5 sub-payloads in the case of Cascade-2 sounding rocket. In order to go a step further in the number of measurement points, two problems arise for sounding rockets: the telemetry bandwidth limits the amount of data which can be transmitted from all the measurement points and the amount of payload mass the sounding rockets can carry is obviously limited. That is why the LAPLander is designed to be much smaller and lighter than current payloads and by being recoverable down on ground, there is no need for data transmission.

The LAPLander is designed to provide housing, in the future, for the SCALE boom system for electric field measurements in the ionosphere by deploying four booms [1]. The LAPLander will also carry the SMILE fluxgate magnetometer [2] and a number of temperature, acceleration and attitude sensors. The total mass will be around 2 kg, which to be compared to the 25 kg of the Cascade-2 sub-payloads. It will be disc-shaped with a diameter of 25 cm and a height of 6 cm.

The LAPLander team has been divided into two sub-groups according to the nature of the tasks. The electronics group, formed by students with electrical engineering background, takes care of all electronic equipment and power supply and the one main critical issue is the localization system: after landing, the LAPLander will start transmitting its position in order to be found and recovered. The mechanical design is carried out by students with aeronautical and mechanical engineering background.

This project started before it was selected by ESA for a flight test. However, once the selection was confirmed, the experiment was oriented to meet goals directly related to the flight. The experiment success criteria is as follows:

1) The payload is successfully ejected from the main rocket, survives reentry and landing impact, and is localized and recovered.
2) The collected data are recovered and the payload’s behavior during flight is evaluated.

3) Payload dynamics are understood in terms of theoretical predictions and simulations.

4) The payload has suffered only a limited amount of damage and at least some parts can be reused in future missions.

The scope of this document is to report about the parts of mechanical development that I took upon myself between November 2008, at the very start of the project, until August 2009, when the project had passed the Critical Design Review and was undergoing the last stage of tests and the first stage of prototype manufacturing. The reader will find a number of chapters dealing with different topics, from thermal design or CO$_2$ physics to airbag, parachute and cartridge testing. I have tried to emphasize the reasons for design evolution and iteration because I believe that is one of the interesting and not so common aspects of this student project. In this way, the reader can understand some part of the LAPLander story and how some of its innovative and non-conventional solutions were reached.
Chapter 2

Experiment overview

2.1 Overall structure

The LAPLander is a prototype of future payloads aiming for multi-point measurements in the ionosphere. The biggest instrument these payloads will carry is the SCALE boom system. The LAPLander prototype is designed to carry a real electronics box and four full-scale dummy boom units of the SCALE boom system placed in a cross shape as shown in picture 2.1. In order to optimize the size, the LAPLander is built around the dummies and the electronics box. The structure is shaped as a flat cylindrical disc, with 24 cm in diameter and 8 cm in height. It will have a mass between 2 and 3 kg. Thanks to this shape and low mass, many of these payloads could be piled inside a sounding-rocket which will then eject them all with different directions. Once ejected from the sounding rocket, the payload undergoes a free fall. The LAPLander will be ejected with a spin of 4 Hz. Correct magnetic measurements need magnetic cleanliness from the payload and so every component must be non-magnetic. The cylinder is covered by top and bottom aluminium discs. This discs are covered by a thin resistant film of a thermal insulator like Kapton or Mylar. Two half-cylindrical hatches close the sides of the structure. An air-braking and impact protection system helps decelerate the payload during descent and protects it at landing impact. This system is detailed in section 2.2.

Finally, to recover the payload it has landed, a redundant radio system with a radio-beacon and a satellite transmitter will be utilized, where the GPS position of the payload is transmitted as e-mail and sms text message over the satellite link. During the flight, sensor data will be stored in an on-board memory, which is later to be recovered. The flight profile will be recreated in order to understand the aerodynamic properties of the payload.

2.2 Recovery system

The recovery system is a non-conventional combination of airbags and parachute.

The initial idea was that to use the four spaces available between the boom dummies to fit the recovery system. This would be very efficient in terms of size. But fitting a traditional parachute into four spaces was very complex. Moreover, the big disadvantage of a traditional parachute was that with a fast-tumbling...
payload, it is very difficult to guarantee that the parachute will deploy correctly and not get tangled with the payload. Stabilization could have been achieved by some techniques but altogether required too many elements which meant weight and room.

This is why the initial idea of four spherical airbags was preferred. These airbags would be inflated at a specified altitude during descent and they would both help decelerate the falling payload and protect it at landing impact from all sides. The attitude of the payload at deployment was not critical as the airbags would inflate anyway and stabilize the descent. However, initial estimations concluded that in order to obtain a touch-down speed lower than 10 m/s, each spherical airbag would need to be around 40 liter, see figure 2.2. A prospection of typical compressed gas cartridges showed that it was impossible to fit in the LAPLander a system that would provide with 160 liters of gas. As an example, a typical CO$_2$ cartridge -like those used for bicycle tyres- filled with 10 g of compressed CO$_2$ will provide with only 6 liters of gas at standard conditions and is 8 cm height. Thus it was concluded that spherical airbags were not a good lead.

The idea came to use tyre-shaped airbags. When inflated, the four airbags would form a cross-shape as shown in figure 2.2. These would require a small amount of gas and would protect the payload from all sides.

The problem was that with this shape, the airbags would have a very small drag area and they would not help decelerate much. It was then decided that the space between the airbags when deployed should be filled with some kind of membrane or textile and this would act as a parachute. Figure 2.2 shows one of the four membranes filling the space between two airbags. In this way, the recovery system would be a combination of non-conventional airbags and parachute.
At the beginning, it was thought that a small amount of a smokeless powder like nitrocellulose could be used to inflate the airbags because these powders are very efficient: 1 g would produce around 1 liter of gas at normal conditions. But a powder was judged too dangerous and with tyre-shaped airbags the amount of gas to produce was not critical. It was found that commercial CO\textsubscript{2} cartridges were almost exactly what LAPLander needed. They were small, had the right amount of gas and were very cheap. The first important disadvantage was that they are all made out of steel, which is a magnetic metal, and no aluminium cartridge could be found. The second disadvantage was that we needed a way of opening the cartridge to release the CO\textsubscript{2}. The common methods to open them require too much mechanical energy and this was not acceptable for us. Then it was decided to design and build our own cartridge out of aluminium and find
a suitable solution for opening it. To fill the cartridges with pressurized $CO_2$, one would just open the cartridge, introduce the right mass of ice $CO_2$, close the cartridge and then wait until $CO_2$ would reach high-pressure equilibrium inside the cartridge.

Another problem was how to open the structure to allow for airbag-parachute deployment. It was thought of getting rid of the top and bottom covers, but these surfaces are needed for antennas. Therefore it was decided that the best option was to get rid of the side hatches. MORABA (Mobile Rocket Base) experts recommended to use a wire or rope to hold the hatches together. When deployment is required, a wire-cutter cuts the wire and the hatches would be released allowing airbag-parachute deployment from the sides.

So, the recovery system consists of four $CO_2$ cartridges, each one connected to one airbag and four parachute membranes attached to the airbags, plus the hatches and wire-cutter structure. The following sections detail specific development of these devices.
Chapter 3

Aerodynamic heating and thermal insulation

3.1 Introduction

The LAPLander structure must keep an inside temperature such that no damage is caused to the carried devices and that they are all fully operational. As aerodynamic heating and cooling is a main external source of thermal changes, the outer structure of the LAPLander, mainly the covers and side hatches, are supposed to behave as thermal insulators. The covers will be composed very probably of an aluminium layer with a thickness of some millimeters, patch antennas on top of it and a thin layer of thermal insulator on top of everything.

A complete thermal model of the LAPLander is impossible at this stage. Consequently, this study presents a very simple approach to obtain some first estimations of the thermal problem and a first idea of the insulation need.

3.2 Thermal model of aerodynamic heat exchange

The only structure modeled here is the cover composed by the thermal insulator layer and the aluminium layer, as shown in picture 3.1. The effect of antennas is neglected at this stage. The goal is to obtain an estimation of the temperature of the aluminium layer. In this model, the structure is heated up and cooled down aerodynamically, i.e. by a convective heat flux. Thermal radiation is not considered. The problem is that the structure may become too hot. Radiation will cool down the structure so not including this mechanism in the model is a way of being conservative. The convective heat flux takes place only through the outer surface of the heat insulator, named surface 1 in picture 3.1.

The heat insulator is assumed to always be in thermal equilibrium. This means that the input convective heat flux is fully conducted through the thermal insulator, where the corresponding gradient of temperature has been immediately reached and is determined by the Fourier law. Again, this is a conservative choice because it means that all the flux is used to heat up the aluminium layer.

As aluminium and any other metal that could be used are very conductive, it is assumed that the layer has an homogeneous temperature. Thus, it is
assumed that the temperature of the aluminum layer is the temperature of the inner surface of the insulator layer, named surface 2 in picture 3.1.

The rate of convective heat flux (or convective power flux) through the surface 1 is

\[ H_1 = h(T_r - T_1) \]  \hspace{0.5cm} (3.1)

where \( H_1 \) is in \( W/m^2 \), \( h \) is the convective heat transfer coefficient, \( T_r \) is the recovery or stagnation temperature in degrees Kelvin and \( T_1 \) is the wall temperature or temperature at surface 1 of the thermal insulator in degrees Kelvin. It is important to understand that the difference \( T_r - T_1 \) forces the convective heat flux, so these two temperatures cannot be assumed to be equal. For this reason, neglecting radiation does not change the result so much: radiation direct effect is to decrease \( T_1 \), which means that \( T_r - T_1 \) increases, so the heat flux increases and consequently \( T_1 \) increases.

The power flux conducted by the heat insulator between the surfaces 1 and 2 follows the Fourier law

\[ H_{12} = \delta \frac{T_1 - T_2}{d} \]  \hspace{0.5cm} (3.2)

where \( H_{12} \) is in \( W/m^2 \), \( \delta \) is the thermal insulator conductivity in \( W \cdot m^{-1} \cdot K^{-1} \), \( T_{al} \) is the temperature of the inner side of the heat insulator in degrees Kelvin and \( d \) is the thickness of the insulator in m.

Finally, the power flux going into the aluminum structure follows the heating equation

\[ H_2 = C_{al} \frac{\partial T_2}{\partial t} \]  \hspace{0.5cm} (3.3)

where \( H_2 \) is in \( W/m^2 \), \( C_{al} \) is the total heat capacity of the aluminum structure per unit area in \( J \cdot K^{-1} \cdot m^{-2} \).

Given the assumption of thermal equilibrium of the heat insulator, the three fluxes are equal:

\[ H_1 = H_{12} = H_2 \]  \hspace{0.5cm} (3.4)

\[ h(T_r - T_1) = \delta \frac{T_1 - T_2}{d} = C_{al} \frac{\partial T_2}{\partial t} \]  \hspace{0.5cm} (3.5)
The first equality gives the wall temperature as a function of the recovery temperature:

\[ T_1 = T_r + T_2 \frac{\delta}{1 + \frac{\delta}{\delta_t}} \]  

(3.6)

Then the second equality is solved to give a first order differential equation on the aluminum temperature:

\[ \frac{\partial T_2}{\partial t} = \frac{h}{C_{al}} \frac{1}{1 + \frac{\delta}{\delta_t}} (T_r - T_2) \]  

(3.7)

This equation relates the rate of change of the aluminum temperature to the convective power flux. By integrating this equation during the whole descent, the temperature is obtained at each moment.

This integration is done by iteration using a first order backward finite difference method [4]. At each iteration step, the algorithm inputs information from the descent calculation, namely time, speed, atmospheric temperature and air density at corresponding altitude.

The stagnation temperature is estimated as usual:

\[ T_r = T(1 + \frac{\gamma - 1}{2} M^2) \]  

(3.8)

where \( T \) is the atmospheric temperature in degrees Kelvin, \( \gamma \) is the adiabatic index of air and \( M \) is the Mach number.

Following [3], as the Laplander speed does not exceed 900 m/s, the Reynolds analogy is assumed to be valid and the convective heat transfer coefficient can be written as

\[ h = \frac{1}{2} C_f C_p \rho V \]  

(3.9)

where \( C_f \) is the local skin-friction coefficient, \( C_p \) is the specific heat capacity of air, \( \rho \) is the air density and \( V \) the Laplander speed.

The local-skin friction coefficient of a flat plate in an axial flow depends both on the Mach and Reynolds number, as explained in [5] and shown in figure 3.2. As the values of the skin-friction coefficient times the Reynolds number for a flat plate differ from one book to another, but they all agree on a maximum value of 1.4 for Mach=0, this is the value chosen here, regardless of the Mach number. Finally, to run this model, the only necessary input data are atmospheric conditions (absolute temperature and air density) and the falling speed, all in function of descent time.

### 3.3 Results

Some simulation results of the aerodynamic heating and cooling are shown in figures 3.3(a), 3.3(b) and 3.3(c). They used a descent profile obtained from the simulations by Li Xin. The input parameters were as follows:

- insulator thickness: 0.2\( mm \)
- insulator conductivity: 0.1\( W \cdot m^{-1} \cdot K^{-1} \)
- thickness of the aluminium layer: 3\( mm \)
It is seen that the aluminium layer is kept within temperatures lower than 20°C during the whole descent except for around one minute following the peak of stagnation temperature. The aluminium layer reaches a maximum temperature of around 75°C, but stays between 50 and 75°C for only 25 seconds. Given that the calculations have been made with the worst-case scenario assumptions, it is considered that from the thermal point of view, 3\text{mm} of aluminium and 0.2mm of a thermal insulator with a conductivity of 0.1W \cdot m^{-1} \cdot K^{-1} is a sufficiently good design.
Figure 3.3: Results of a simulated LAPLander descent.
Chapter 4

Inflatable structure design and testing

4.1 Introduction

The function of the airbags is to protect the payload at landing impact from all sides and to provide the structure support to which the parachute is attached. As explained before, each airbag is connected to one CO\textsubscript{2} cartridge, folded and fitted in one of the four spaces between the boom units. At a specified altitude, the hatches are released and the airbags inflated and deployed. Therefore, the requirements for a good airbag design are:

- The subsystem airbag + cartridge must be airtight for at least 10 minutes.
- The fabric needs to be strong enough to stand the inside the pressure, to sustain the landing impact and not to be torn by dynamic pressure during descent.
- It has to be thin so it can fit easily in the available space.
- The inflatable structure must have an internal volume as small as possible when inflated in order to have a low requirement on gas generation.
- It must have a shape that can be easily manufactured.

The two last requirements were two of the reasons that decided the team to go for tyre-shaped (toroidal) airbags. A torus, although it is not a figure developable from a flat surface, is easier to build than a sphere. But finding a thin, non-elastic, strong, easily-folded, airtight fabric that can be glued to form an airtight closed torus was a challenging task. This chapter recounts the tests performed to find the fabric and the way to build a toroidal airbag.

4.2 Strength test of airbag fabric glued with Nusil MED 1511 glue

4.2.1 Introduction

Autoliv provided us with a sample of two fabrics that are among the most airtight airbag fabrics that can be found in the car industry. These were made out of polyamide filaments that provides strength coated with silicone that decreases porosity. This fabric was clearly sufficiently strong and the question was
if it could be glued strongly to form the toroidal structure and if the structure would be airtight.

The Nusil MED 1511 glue was found to provide a strong and airtight gluing of the airbag textile. The glued region needs to stand tensile stress produced by internal overpressure. The data sheet provided by the manufacturer accords the glue a tensile strength of 8 MPa. However, the real strength of a glued structure depends also on the glued fabric and the gluing procedure, specially the thickness of the glue film. The aim of the test presented here was to evaluate tensile strength of two pieces of airbag fabric glued with Nusil MED 1511 glue.

4.2.2 Experimental setup and procedure

One rectangular piece of airbag fabric was cut with the following approximate dimensions: 35mm x 45mm. Then it was cut in two similar halves. The ends of the two halves were glued with Nusil MED 1511. The gluing procedure was as follows:
- some glue was deposited on one of the parts, namely on a small zone in the end where the cut was performed. The deposition zone was about 35mm (corresponding to the whole width of the piece of fabric) x 10mm
- the end of the second piece of fabric was deposited over the zone with the glue
- a mass of about 8 kg was deposited over the fabric pieces in order to put a lot of pressure during drying of the glue
- the glue was let to dry until the following day

Once the two pieces were glued and formed one piece again, as shown in figure

![Glued zone](image)

Figure 4.1: Two pieces of airbag fabric glued with Nusil MED 1511 glue

4.1, the thickness of the glue layer was estimated to be 0.7mm by measuring the thickness of the zone with glue (0.53mm) and subtracting twice the thickness of the airbag fabric (0.23mm). Then the two ends of the fabric were strongly attached using two clamps and one machine vise in such a way that the textile is laying vertically and one of the clamps is hanging from the fabric, as shown in 4.2(b). As this figure shows, thanks to ropes, the big plate is hanging from the clamp which is hanging from the fabric. In both attachments, sufficiently large metal plates were used, as shown in the figure 4.2(a) the friction is distributed
along the whole width of the rectangle. This is important because it allows the stress to be uniformly distributed along the width.

(a) Both sides of the fabric are attached by friction.

(b) Overall view of the structure for testing fabric and glue tensile strength.

Figure 4.2: Experimental setup of the fabric strength test.
4.2.3 Results

The glue and the fabric resisted loadings up to 14 kg without showing any sign of damage. The following load was 19 kg and the glue could not stand it so the two pieces of fabric came unstuck. This means that the maximum load that the tested glue layer could stand was between 14 and 19 kg. A reasonable and conservative value of the maximum load the glue resisted is 15 kg which corresponds to 4600 N/m given a width of 35 mm or 60 MPa considering the thickness of 0.7 mm.

4.3 Manufacturing and testing of a straight cylinder: airbag fabric and Nusil MED1511 glue

4.3.1 Introduction

As the airbag fabric and the glue Nusil MED1511 were strong enough, the following step was to build a closed straight cylinder in order to check airtightness and to see if it really withstood internal pressure.

4.3.2 Experimental setup

A straight cylinder was built by cutting a rectangular piece of airbag fabric and gluing two sides. The approximate dimensions were 60 cm long and a diameter between 3 and 4 cm. Then one end was closed using the clamp. One side of the tube was connected to the helium tank and the other was introduced inside the airbag cylinder through the open end. This end was tied to seal the cylinder as much as possible. Then the crane on the tank was open and the cylinder was filled with helium. The cylinder was put under water so any leakage will show up by creating visible bubbles. The same experiment was performed with air from a pressurized air hose.

4.3.3 Results and discussion

It was observed that there were bubbles coming from all the cylinder surface. This meant that the fabric was leaking everywhere. This happened even at low pressures between 1 and 2 bar. The same was performed with air from a pressurized hose to see if the cylinder was airtight for bigger molecules, but it also leaked. It was concluded that the coating on the airbag fabrics is not sufficient for our purposes.

Another observation was that the straight cylinder resisted internal pressures up to 10 bar. As the leakage through the fabric was not fast enough, it was possible to maintain the internal pressure at a specified value up to 10 bar. Neither the fabric nor the glue broke.
4.4 Manufacturing and testing of a straight cylinder: airbag fabric, polyamide film and Nusil MED1511 glue

4.4.1 Introduction
As it was observed that the airbag fabric alone is not airtight, the idea came to test a cylinder with two layers: airbag fabric and polyamide film. The airbag fabric should provide with structural strength and the polyamide layer would seal it.

4.4.2 Experimental setup
A rectangular piece of airbag fabric with approximate dimensions 12 cm x 25 cm was cut. A piece of polyamide film with almost the same dimensions, just slightly smaller, was cut as well. This film was glued to the fabric only on the borders. The reason is that if the whole surface is glued, the result is a structure with poor flexibility. Then a hole of 9 mm is made on the two layers so the inlet can go through. The inlet was put through and its base was glued to the polyamide film, which was to become the inner side of the cylinder. Finally, to form the cylinder, the two long sides were glued together. The result is a straight cylinder, with two open ends, and consisting of two layers: an inner layer of polyamide film and an outer layer of airbag fabric.

The two ends were closed using the clamps and the cylinder was connected to an argon pressurized tank. The cylinder was filled with argon gas and put under water to observe if any bubbles would come from it.

4.4.3 Results and discussion
Once again, bubbles were observed to come through all the airbag fabric surface. It is not clear what was the reason for the leakage, but the conclusion was that making a two-layer cylinder was too complex because there would always be leakage from some point with bad gluing. The base of the inlet showed no leakage, so the procedure of gluing the inlet was satisfactory.

4.5 Manufacturing and testing of a straight cylinder: thermo-plastic elastomer material glued with Nusil MED1511 glue

4.5.1 Introduction
As the airbag fabric was not a good lead, it was decided to try to build the cylinder out of a thin plastic film. Nordbergs Tekniska AB sent samples of 9 different materials. One thermo-plastic elastomer (TPE) was chosen as the most suitable to try make a test, as it was thin, very flexible and glued well with Nusil MED1511.
4.5.2 Experimental setup

The procedure was similar to the ones before. Using the MED1511 glue, a straight cylinder was built out of the TPE material and also the same inlet was glued to the cylinder. The two ends were glued and clamped. The inlet was connected to the tank using an adapter. As usual, the bubbles were used to see if the cylinder was leaking.

4.5.3 Results and discussion

This time, the cylinder showed absolutely no leakage. The over-pressure was raised up to 2 bar (internal pressure of 3 bar) and at this point the cylinder exploded. The TPE material teared with a straight line. Again, the inlet did not leak. The cylinder had a diameter of 3 cm and broke with an internal over-pressure of 2 bar. This means that the yield strength of the TPE material is around 30 N/cm. It is to be observed that it did not break in the glued part. This is understandable as the glued part has 3 layers: 2 layers of TPE material and one layer of glue, and all together is stronger than one single layer of TPE.

4.6 Manufacturing and testing of a toroidal airbag using a thin PEEK film and Nusil MED1511 glue

4.6.1 Introduction

A strong airtight cylinder had been successfully built using a TPE thin film. This encouraged us to go one step further with thin plastic films: this meant to build a complete toroidal airbag. The main technical problem was how to give the torus-shape to the airbag. The material used this time was a thin film of PEEK because of stock availability and price. The PEEK film was also flexible and stronger than the TPE film.

4.6.2 Manufacturing procedure

Firstly, a straight cylinder was built exactly as described in chapter 4.5 with the inlet placed in the middle between the two ends. The cylinder was 120 cm long and had a diameter of 38 mm, see picture 4.3. This means that, if one counted with an overlap of 3 cm to close and glue the cylinder, the toroidal airbag was doing to have an outer diameter of about 37 cm. Then the inner side of the ring would be 93 cm. Therefore a ribbon of 5 mm x 95 cm was cut out of airbag fabric P6046056. This was placed inside the tube. Long pliers were introduced into the cylinder from one side to catch the ribbon, so both ends of the ribbon could be extracted from the cylinder. These two ends were then glued together using Nusil MED 1511 glue forming a closed circular structure. The PEEK cylinder was around it. It is important to understand that, as the ribbon had a length of less than 95 cm and the cylinder was 120 cm long, the PEEK film was wrinkled. Then the two ends of the tube were glued together using Nusil MED 1511 glue. Then a closed inflatable structure was built.
4.6.3 Experimental setup

Once again, the inlet was connected to an argon tank so the structure could be pressurized. In order to detect leakage, a liquid for leakage detection by bubbles was used. The complete setup is shown in picture 4.4.

4.6.4 Conclusion

Once the tube was pressurized, two problems became obvious. On one hand, the airbag did not take a circular shape: the structure presented some sharp angles instead of taking a smooth circular shape. Thus the form was more similar to a rectangle or other geometric figures with straight sides than to a torus. Moreover, the form changed a lot every time the tube was inflated because the angles appeared on different positions every time. On the other hand, the inner side of the film plastic became wrinkled as expected to match the shorter length. The problem was that the wrinkles provoked the glued region to leak from many different points. Even though the glued zone was reinforced with more glue, it went on leaking.

It was concluded that the plastic film was not suitable for building a ring-shaped airbag. The material was not flexible enough and the glued zones were weak points prone to leakage. An alternative solution should be found for the airbags. Building a torus from a non-elastic material such as the plastic films does not seem a good lead.
4.7 Gluing test of the two ends of a cut Continental Race 28 Supersonic tyre with Asperg Vulcaniser Glue

4.7.1 Introduction

One very promising idea to build the airbag was to use a bicycle tyre surrounded by a some kind of non-elastic strong cloth: for example thin glass fibers or parachute textile. The tyre would provide with perfect sealing and toroidal shaping of the whole structure, while the cloth would prevent the tyre from expanding and eventually exploding when pressurized. The most interesting tyres for the project are competition tyres because they are thin and lightweight. But one immediate practical problem arose: they are sold only with standard diameters from 630 to 700 mm and this is too big for LAPLander. One possible
solution was to cut a piece of it and close both ends to a smaller radius. A
graing test of the two ends of this kind of tyre was performed and is presented
in this section.

4.7.2 Experimental procedure

A piece of the tyre was cut with scissors. Without cleaning the tyre, the two
ends were glued together using the Asperg glue, which is supposed to vulcanize
the rubber. Then the tyre was connected to the argon tank using a proper
adapter and it was pressurized with an inner pressure between 1.5 and 2 bar.
Picture 4.5(a) shows the whole tyre after having been inflated and picture 4.5(b)
shows a close view of the glued ends. In order to determine whether the glued
ends were leaking, the tyre was put under water after having been pressurized.

4.7.3 Results and discussion

A first major result was that the glued region did not show any leakage when
put under the water. Given the fact that the gluing had been done without
extreme precaution, this meant that the Asperg Vulcanizer is a very efficient
gue in terms of sealing. After one whole day, the tyre was still completely
inflated.

Another important result is that the glue resisted pressures up to 1.5-2 bar.
Therefore it is concluded that gluing the two ends of an open Butyl tyre
using Asperg vulcanizer provides an airtight sufficiently strong sealing of the
structure.

4.8 Manufacturing and testing of a toroidal airbag

using a Continental Race 28 Supersonic tyre

surrounded by a nylon textile tube formed

by short tubes sewed together

4.8.1 Introduction

The goal was to build a ring with two layers: the inner one would be a bicy-
cle tyre, providing airtightness and torus-shape and the second one would be
parachute textile, which would provide with tensile strength. A main issue was
how to build the second layer, namely a ring-shaped tube.

4.8.2 Experimental procedure

First, seven pieces of nylon textile were cut with the right dimensions in order
to, once put together, form a heptagonal tube. Their ends were sewed. Then
the tyre was surrounded by this cloth and the nylon tube was closed by gluing
its sides with the silicone adhesive, see picture 4.6. The tyre inlet was connected
to the argon tank and the tyre was pressurized up to 1 to 1.5 bar overpressure
(the manometer was not very accurate). It must be remarked that as the nylon
tube was shorter than the tyre, a suplementary small piece of textile had to be
(a) The tyre, after having been cut and glued, was successfully inflated.

(b) The two ends were glued using a commercial rubber vulcanizer for bicycle tyres.

Figure 4.5: The tyre, after having been cut and glued, was successfully inflated.

Figure 4.5: The tyre, after having been cut and glued, was successfully inflated.

4.8.3 Results and discussion

The whole structure appeared to be strong and did not explode. However, the tyre became kinked in the sewed parts of the outer ring, see picture 4.7. Each nylon textile cylinder was moreover straight. It was observed that no kink appeared on the region where the supplementary piece of cloth had been glued, while every sewed position was kinked. This caused the tyre to have a very long
Figure 4.6: The two layers airbag connected to the argon tank.

straight portion corresponding to two cylinders. Therefore, the final shape of
the whole ring was not an heptagon as it should have been. Another drawback

Figure 4.7: Inflated airbag showing kinks where the textile had been sewed.

was that when the pressure was stepped up, the structure came out of its plane,
as it can be seen in picture 4.8. It was concluded that surrounding the tyre with
a tube made out of straight cylinders sued or glued together was not a suitable
solution.
Figure 4.8: After the pressure was increased, the airbag came out of its plane.
Chapter 5

Parachute design and testing

5.1 Introduction

The parachute function is to help decelerate the payload during descent to a speed lower than 10 m/s by drastically increasing the drag area of the falling object. The parachute is composed of 4 independent identical pieces of parachute textile. Each piece is attached to two airbags, as shown in figure 5.1. The parachute pieces will be attached or glued to the airbags and also fitted inside the LAPLander. For each piece of parachute, its two parts attached to the airbags will be fitted with the airbags in the two corresponding available spaces between the booms, but some part of the piece will obviously have to be fitted between the boom separating the two airbags and the top or bottom cover. For all these reasons, the parachute requirements are aerodynamic stability, low weight and strength. The following sections recount some test performed to

Figure 5.1: LAPLander full-scale model showing one of the four pieces of parachute attached to two dummy airbags.
5.2 Drop test from the KTH clock tower of a full-scale model

5.2.1 Introduction

The aim of this test was to get a first idea of the parachute performance in terms of drag and stability. A full-scale model allowing for different parachute configurations was built. Two different parachute configurations and different case scenario were tested by dropping the whole structure from the highest building at KTH: the clock tower. This provided with a good qualitative estimation of drag and stability.

5.2.2 Experimental setup and procedure

The wooden cylinder has a diameter of 25 cm and a thickness of 6 cm. Four hard plastic rings of 45 cm diameter were attached to the wooden cylinder to represent the four airbags in their deployed configuration. A number of holes was made on the rings in order to attach the parachutes.

The parachute was drawn using Matlab. This drawing was printed and used to cut the parachute from the textile roll. The figure 5.2 shows one 1/4 of parachute after being cut. The cutting was done with a hot knife, following a recommendation from the parachute textile provider, Airsafe. The hot knife melts the textile, which causes less damage to the textile than by using scissors.

Figure 5.2: 1/4 of parachute before attachment

Then the parachute was screwed to the rings, as shown in figure 5.3, and then the drop test could begin. The prototype was dropped from the highest building at KTH: the clock tower, from a height of about 25 m.
5.2.3 Results and discussion

All the drop tests were filmed.

<table>
<thead>
<tr>
<th>Parachute</th>
<th>Drop</th>
<th>Descent behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>180° see figure 5.4</td>
<td>Up side up</td>
<td>Turned up-side-down, stayed in this position until landing.</td>
</tr>
<tr>
<td>180°</td>
<td>Up side down</td>
<td>Stayed in this position until landing.</td>
</tr>
<tr>
<td>180°</td>
<td>Tumbling</td>
<td>Stopped tumbling, reached up-side-down stability.</td>
</tr>
</tbody>
</table>

It is clear that with the 180° design, the up side up position is unstable and up side down is stable. However, it can be seen in the videos that before
loosing stability, the up side up profile descends slower than the up side down configuration, which probably means that it has a higher drag coefficient. The descent speed for the stable position is estimated to be between 6 and 10 m/s.

Next step was to test the up-side-down configuration in the wind tunnel to see if this was really a stable position and also to obtain an experimental value of the drag coefficient.

5.3 Estimation of attachment forces at parachute deployment

5.3.1 Introduction

The parachutes are attached to the inflatable rings and the rings are attached to the disk. According to the aerodynamic simulation, when rings and parachute are deployed at an altitude of about 5 km, the LAPLander has a falling speed of moreover 25 m/s. Then one needs to make sure that the two attachments are sufficiently strong for the aerodynamic forces the parachute will transmit to the payload before this one is decelerated to lower speeds. A simple model has been developed to obtain a first approximation to the attachment forces.

5.3.2 Model

Let’s consider the parachute and rings together as a mechanical system with a mass $m_{ab}$. The forces applied on this system are the weight $W_{ab}$, the drag force $D_{ab}$ and the attachment force $F_a$ that keeps together the rings and the disk. The acceleration $a_{ab}$, counted positive upwards, of the airbags-parachute system is described by the following equation:

$$m_{ab}a_{ab} = D_{ab} - W_{ab} + F_a$$  (5.1)

An equivalent equation can be written for the disk alone:

$$m_d = D_d - W_d - F_a$$  (5.2)

As the rings and the disk are attached, it can be assumed that they have the same speed, thus the same acceleration. This is not completely true: first, the rings and parachute will probably flatter; secondly, if the whole system is tumbling when falling, then rotating acceleration should be considered as well. However, the maximum and most dangerous force, the one that can potentially break the attachments, is the drag pointed upwards caused by the vertical speed. Then, only the vertical acceleration is considered and flatter is neglected. Consequently, it is assumed that the accelerations of the disk and the rings+parachute are equal:

$$a_d = a_{ab}$$  (5.3)

This and equations 5.3.2 and 5.3.2 are used to obtain the following expression of the attachment force:
The drag coefficient of the whole LAPLander was measured experimentally in a wind tunnel and it is 1. A common value of the drag coefficient of disk falling flatly is 1.14 and parachutes have drag coefficients between 0.7 and 0.8. This means that if the LAPLander parachute was flying alone, without being attached to the disk, its drag coefficient would probably be lower than 1, possibly close to 0.8. Also, the drag coefficient of the disk flying alone would be close to 1.14. In order to make a conservative estimation, the drag force on the parachute alone will be estimated using a drag coefficient of 1. Thus, the drag forces, with a speed V at deployment, are respectively

\[ D_d = \frac{1}{2} \rho S_{ab} V^2 \]  
\[ D_{ab} = \frac{1}{2} \rho S_d V^2 \]  

Concerning the attachment between the parachute and the rings, it is assumed that the parachutes are attached uniformly along half the length of the rings. Then the force per unit length this attachment must stand is:

\[ F_{parachute-ring} = \frac{F_{ab}}{\pi \cdot \text{diameter}_{ring}/2} \]

5.3.3 Results

The calculations were performed for a disk with a diameter of 25cm. The force on each attachment is shown in figure 5.5 as a function of the ring diameter.

The attachment between the parachute and the rings must stand a maximum force of 1.7 N/cm. As the force is proportional to the diameter of the rings, the force per unit length is independent of the size of the rings.
Figure 5.5: Force (Newton) exerted by the parachute and rings on each of the four attachment points to the central disk as a function of ring diameter (cm)
Chapter 6

$CO_2$ cartridge testing

6.1 $CO_2$ thermal properties

6.1.1 Introduction

This section presents the thermal properties of $CO_2$ which are important for designing, testing and using the cartridge and the airbags. Firstly, a diagram is presented to explain how the $CO_2$ is used in the LAPLander project. Then, it is used to estimate the mass of $CO_2$ that can be safely introduced inside the cartridge.

6.1.2 Phase diagram

![Phase diagram for carbon dioxide.](image)

Figure 6.1: Phase diagram for carbon dioxide.

Figure 6.1 shows the phase diagram for carbon dioxide at any temperature and pressure. It shows the state of $CO_2$ at any temperature and condition. The lines are the temperature and pressure conditions at which $CO_2$ coexist at two different states. For example, at 1 bar and -78.5 °C, solid and gas $CO_2$ coexist.
A specified amount of solid CO$_2$ is introduced inside the cartridge, which is then closed. At a pressure of 1 atm and room temperature, carbon dioxide is gas. The dry ice is initially at a temperature lower than $-78.5^\circ C$. As soon as it is introduced in the cartridge, it begins to exchange heat with the medium. As the diagram shows, at 1 atm carbon dioxide can not be liquid, so the dry ice sublimates progressively inside the cartridge. While solid and gas coexist, the pressure inside the cartridge is given by the solid-gas line as a function of temperature. The initial point is the one corresponding to 1 atm and $-78^\circ C$ because the dry ice is at this temperature initially. As the gas is generated, the pressure inside the cartridge increases, so the point on the diagram giving the conditions moves along the solid-gas line towards the triple point. Then two things can happen: either the triple point is reached or all the dry ice has sublimated before reaching it.

In the latest case, only gas exists and warms up until it reaches room temperature. As it warms up, the pressure increases.

In the first case, once the triple point is reached, the solid CO$_2$ melts and disappears to be replaced by liquid. Then liquid and gas coexist and the conditions are those of the saturated gas given by the liquid-gas line. As the triple point is at $-56.6^\circ C$, the environment keeps on heating the CO$_2$ so the liquid evaporates progressively. As it evaporates, the conditions point move along the liquid-gas line towards the critical point: both the pressure and temperature increase. The final equilibrium is given by the room temperature and the amount of CO$_2$ that was introduced in the cartridge.

Then three things can happen: the CO$_2$ mass is such that not all the liquid has evaporated when the final temperature is reached. Then the final equilibrium is a saturated CO$_2$ vapor with a pressure depending on the temperature (57 bar at 20$^\circ C$). This is the typical condition for CO$_2$ cartridges. The proportions of liquid and gas depend on the total amount of CO$_2$ and the cartridge volume.

The second possibility is that all liquid has evaporated. For this to happen the amount of gas should be very small. In this case, the pressure will be lower than the corresponding pressure of saturated vapor.

The third possibility is that the amount of CO$_2$ is sufficiently high to be all liquid. This is very dangerous and must be avoided by introducing less CO$_2$ than the minimum required for this to happen.

6.1.3 Maximum CO$_2$ mass inside the cartridge

Firstly, one can estimate the maximum mass of dry ice that can be fitted inside the cartridge. The inner volume of the cartridge is $V_{\text{cartridge}} = 23mL$ and the dry ice density is $\rho_{\text{CO}_2,s} = 1.562g/ml$. Then the maximum mass $m_{\text{CO}_2,max}$ of CO$_2$ follows the condition

$$m_{\text{CO}_2,max} \leq \rho_{\text{CO}_2,s} \times V_{\text{cartridge}} = 36g \quad (6.1)$$

Another restriction comes from the fact that for safety reasons, the amount of CO$_2$ mass should be such that at equilibrium, the CO$_2$ is on the liquid-gas line, which means both liquid and gas CO$_2$ coexist. An equilibrium with only liquid CO$_2$ is very dangerous and may provoke an explosion of the cartridge because liquid is incompressible. Let $x$ be the fraction of the cartridge volume
occupied by gas $CO_2$. Then $1 - x$ is the fraction of volume occupied by liquid $CO_2$. Let $m_{CO_2}$ be the total mass of $CO_2$ introduced inside the cartridge. Call $\rho_{CO_2,g}$ and $\rho_{CO_2,l}$ the densities of gas and liquid $CO_2$ respectively. Then write the conservation of mass:

$$m_{CO_2} = x \cdot \rho_{CO_2,g} \cdot V_{cartridge} + (1 - x) \cdot \rho_{CO_2,l} \cdot V_{cartridge}$$ (6.2)

so the fraction of gas $CO_2$ is

$$x = \frac{\rho_{CO_2,l} - m_{CO_2}}{\rho_{CO_2,l} - \rho_{CO_2,g}}$$ (6.3)

As $0 \leq x \leq 1$, the total mass is

$$\rho_{CO_2,g} \cdot V_{cartridge} \leq m_{CO_2} \leq \rho_{CO_2,l} \cdot V_{cartridge}$$ (6.4)

If $m_{CO_2} \leq \rho_{CO_2,g} \cdot V_{cartridge}$ then all the $CO_2$ is gas and the pressure is given by the perfect gas law, but in any case, at a given temperature, the pressure is lower than the saturated vapour pressure at the same temperature. On the contrary, if $m_{CO_2} \geq \rho_{CO_2,l} \cdot V_{cartridge}$, all the $CO_2$ is liquid and this situation is dangerous. So, for safety reasons, the maximum mass of $CO_2$ introduced inside the cartridge should respect the following condition

$$m_{CO_2,max} \leq \rho_{CO_2,l} \times V_{cartridge}$$ (6.5)

$\rho_{CO_2,l}$ depends on the temperature and the previous condition must be respected at all temperatures, so one should estimate the worst case, which is given by the lowest value of $\rho_{CO_2,l}$. This is given at the highest possible temperature at which liquid can exist and this is $30^\circ C$, the critical point, as shown in figure 6.1. At this temperature, $\rho_{CO_2,l}(30^\circ C) = 0.5952g/mL$, so

$$m_{CO_2,max} \leq 13.69g$$ (6.6)

![Figure 6.2: Supercritical CO\(_2\) pressure in function of mass](image)

There is a third condition the amount of $CO_2$ mass should respect. The valve is supposed to open if heated up to a temperature of $62^\circ C$ so one should be sure that the cartridge will not explode before the valve opens. Above $31^\circ C$, $CO_2$
becomes a supercritical fluid as can be seen in 6.1. The supercritical pressure inside a cartridge of 23 ml is shown in figure 6.2 at 62°C and 70°C. This figure shows that at 62°C, a mass higher than 13 g would cause the internal pressure to be higher than 145 bar. This imposes the third condition

\[ m_{\text{CO}_2,\text{max}} \leq 13g \]  

(6.7)

Among the three conditions given by equations 6.1, 6.6 and 6.7, the most restrictive is 6.8 so this is the condition that must be respected when filling the cartridge. So the conclusion of this paragraph is the following restriction:

\[ m_{\text{CO}_2} \leq 13g \]  

(6.8)

6.2 High pressure and leakage test of the first Alfvén CO₂ cartridge prototype

6.2.1 Introduction

The aim of this test is to show that the valve and the devices used to house it in the CO₂ cartridge stand a pressure up to 145 bar. This pressure is approximately 2.5 times the maximum operation pressure expected inside the cartridge. This gives a sufficiently good safety factor.

6.2.2 Valve housing

The LAPLander electro-valve was housed in the cartridge as shown from figure 6.3(a) to figure 6.3(f). The outer and inner peek plates shown in figure 6.3(b) and figure 6.3(d) respectively are used to provide thermal insulation of the electro-valve.

6.2.3 Experimental setup and procedure

Once the valve was housed in the cartridge and the cartridge was closed, this was connected by means of its back swagelock connector to a stainless-steel tube, as shown in figure 6.4(a). This tube was connected to another tube, which was connected to the nitrogen tank. As the tube were long and could be bended, this provided a flexible and safe installation. The cartridge was put inside a room and the tank remained outside. The spray was used to make sure that none of the connections was leaking.

Firstly, the tank outlet was open to fill the cartridge with a pressure up to 20 bar, in order to check if there was any leakage. The spray showed that the cartridge was leaking from one of the cable holes.

Then, the cartridge was put into the big container filled with water, see figure 6.4(b), which was located inside the room, see figure 6.4(c), and the room was closed to avoid any accident, see figure 6.4(d). The pressure was increased slowly up to 145 bar, which was the maximum pressure the tank could provide. Then the pressure was released and the cartridge unmounted.
(a) Cartridge cover.  
(b) Outer peek plate and electro-valve.  
(c) Cartridge cover and valve O-ring  
(d) Inner peek plate.  
(e) Inner metal plate.  
(f) Cover and tank screwed together.  

Figure 6.3: Housing and sealing of the electro-valve in the $CO_2$ cartridge cover.
Figure 6.4: Experimental setup of the cartridge high pressure test.
6.2.4 Results and discussion

The leakage observed in previous tests persisted. As before, it was coming from one of the cable holes. After unmounting the valve, it was observed that one of the cable solderings was loose. The soldering may have broken during the test, but it is much more probable that it was loose since the beginning. This not only would explain the leakage but also the fact that the bubbles were observed to come only from one of the cable holes. This means that the leakage cannot be attributed with assurance to the o-ring design. A new leakage test with a proper soldering and the same o-ring design is needed to determine whether the o-ring must be redesigned.

Regarding the high pressure resistance, apart from the loose soldering, the valve was almost intact. The main body of the valve was intact and none of the holes was open. One of the four solderings was observed to be less deep than the other three but this is attributed to a lack of precision during manufacturing. It can be concluded that the valve and the devices used to house it can resist pressures up to 145 bar, which is 2.5 times the highest operational pressure in the cartridge. This is true for the external thread used to the cover to the cartridge.

6.3 Leakage test of the valve cable soldering with the first Alfvén $CO_2$ cartridge prototype

6.3.1 Introduction

It was pointed in 6.2 that a bad soldering of one cable to the valve was a possible cause of leakage from the cartridge. The leakage test was repeated using a valve where the cable soldering had been done carefully. Therefore this report is to be read as an attachment to 6.2. The material and experimental setup were exactly the one described in 6.2.

6.3.2 Results and discussion

The cartridge was found to be leaking through the two cable holes once again. The leakage was smaller than during the previous test, but this time it concerned both holes. It is to be concluded that the reason for this leakage is not the cable soldering, but probably a bad sealing of the o-ring. Consequently, the next step is to improve the o-ring sealing.

6.4 High pressure and leakage test of the first $CO_2$ A-MEK cartridge prototype

6.4.1 Introduction

A-MEK manufactured a cartridge prototype, shown in figure 6.5, according to design by Christian Westlund. At this stage, the cartridge had almost final dimensions which would only be modified if some test showed it to be necessary. The sealing had of course been reviewed and new silicone o-rings were going to be used. As this cartridge was optimized in terms of size and thickness, the
resistance to high pressure was an important test. A leakage test was also compulsory. The tests were performed as before in the Energy Department at KTH, following the same procedure.

![Figure 6.5: First A-MEK cartridge prototype](image)

6.4.2 Results and procedure

The immediate observation was that the big O-ring was not sealing and there were big losses of gas through the thread joining tank and cover. This happened at low pressures. The leakage was so big that it was impossible to see if the valve O-ring was also leaking or not. The test stopped there and a cartridge verification followed to find what was the reason of the leakage.

The first problem of this cartridge was that the bottom of the cover thread was not threaded. This prevented the tank to be screwed down to the bottom and press the O-ring. So the cover was machined in Alfvén and the bottom of the cover thread was offset in order to allow the tank to be screwed to the bottom. A new test showed that the O-ring was still leaking.

The groove where the O-ring was supposed to sit was considered to be too deep. The O-ring had a thickness diameter of $1.78\text{mm}$ and the groove was more around $1.5\text{mm}$. So the cover was machined again and the groove depth was reduced down to $1.25\text{mm}$. And the cartridge leaked again.

Finally, the outer diameter of the groove, $37\text{mm}$, was compared to the outer diameter of the O-ring, $36.5\text{mm}$. This was judged to be the main reason for the leakage because when the pressure comes from inside, those two diameter should be equal. The problem was that the inner pressure would push the O-ring against the outer wall of the groove. This is generally not good for an O-ring, but in this situation it was particularly bad because there the O-ring met the rounded outer edge of the tank. This meant that the O-ring was not pressed by a flat surface as it should be. This problem could not be arranged on the existing prototype so a new prototype was manufactured in Alfvén.
6.5 High pressure and leakage test of the second Alfvén CO$_2$ cartridge prototype

6.5.1 Introduction and procedure

At this stage, it was crucial to solve the big O-ring problem, so a cartridge with manufactured in order to test only the big O-ring. Because of time urgency, only the parts of the cartridge concerned by the O-ring sealing and the valve sealing had the right dimensions and form. The rest of it did not follow the final design but it was made in such a way that this prototype could be machined again according to the final design.

The big O-ring groove had an outer diameter of 36.5 mm, a depth of 1.25 mm and a width of 2.45 mm. This means that the O-ring, with its diameter of 1.78 mm, would undergo a compression down to 1.25 mm, i.e. a 30% compression, which the maximum recommended value. The big thread was 40 x 1.5, while in the CAD is 40 x 1.

Another difference was that the holes for the inner peek plate screws were made longer, 5 mm instead of 3 mm, because with 3 mm as in the A-MEK prototype the screws always reached the bottom of the hole and could not press the peek efficiently. This issue was crucial for the valve O-ring sealing.

6.5.2 Results and discussion

The standard test was performed in the Energy Department. The pressure was raised up to 160 Bar and the big O-ring never leaked. However, it must be noted that it is recommended to screw the tank and the cover strongly, generally by fixing the cover in the machine and turning the tank with a spanner. It is to be concluded that the new groove dimensions, mentioned above, are good to seal the cartridge.

On the contrary, the valve hole began leaking from 15-20 Bar. This was already an issue with the first Alfvén prototype and needed to be investigated properly. The leakage was very small.

6.6 Solving the valve sealing issue in the second Alfvén CO$_2$ cartridge prototype

6.6.1 Procedure

It was observed that the outer peek plate and valve together had a thickness of 3 mm and they were supposed to sit in a hole of 2.7 mm deep. The hole was machined down to 3 mm. Now the valve O-ring was supposed to be sitting over a flat surface. But the valve leaked again. The gas passes obviously between the valve edge and the wall of the cover hole.

Actually, the reason for the leakage is the following. The valve O-ring is supposed to provide sealing by sitting over too different parallel surfaces: the valve surface and one of the aluminium step surface on the valve hole. Then the O-ring is pressed by the inner peek plate, which is pushed by the screws. This presents already many difficulties:
- the valve should be perfectly flat. This is a very difficult issue because the
valve is a very thin and small fiberglass laminate plate and because it has circuits printed on it.
- assuming the valve is flat, its surface should lay exactly at the same height as the aluminium step surface in which the O-ring sits. This is also very very difficult to achieve because it depends on the outer peek, on the contact between valve and peek, and on the pressure one puts on this two.
- it is not obvious that the inner peek plate is pressing the O-ring correctly and is not bending on the center because the screws are far radially and it is impossible to know exactly what is happening in the center with the O-ring.

Moreover, this O-ring was receiving pressure both from the inner and outer side, which is extremely challenging. The outer pressure comes from the space between the inner peek plate and the aluminium surface and the inner pressure comes from the center hole on the plate. As it was explained for the big O-ring, when the pressure comes from inside, the outer diameter of the groove should be equal to the O-ring outer diameter. When the pressure comes from outside, the inner diameter of the groove should be equal to the O-ring inner diameter. Consequently, when the pressure comes from both sides the O-ring should sit exactly into the groove’s inner and outer diameter. Then the O-ring has no space to expand when pressed. The expansion is very important for sealing.

However, the leakage was very small and a quick and easy solution was needed. There was a possible and quick test: to put some silicone between the valve edge and the wall. Commercial "black" silicone was used and laid on the valve edge. Then the cartridge was tested without the O-ring. It leaked a lot. Then it was tested with the O-ring and peek plate and it was found to be sealed up to 130 bar. So it seems that the silicone is sufficient to avoid the small leakage. It should also be noted that strong screws are to be used to fix the inner peek plate, one can not force the peek plate to press the O-ring strongly.
Bibliography


