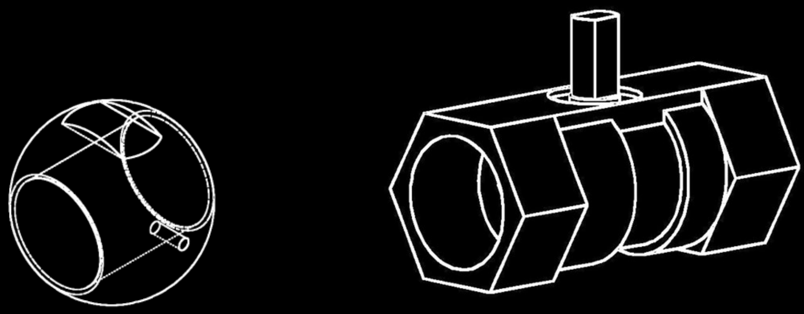

Modification of a Ball Valve for Cryogenic Application

EPFL ROCKET TEAM

TECHNICAL NOTE

Title:	Modification of a Ball Valve for Cryogenic Application	Prepared by:	Name Surname
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1. ABBREVIATIONS

ERT	EPFL Rocket Team
FEA	Finite Elements Analysis
LOx	Liquid oxygen
LN_2	Liquid nitrogen
Ox	Oxidizer
Fu.	Fuel
O/F ratio	Oxidizer over fuel ration
P.	Pressure
CC	Combustion chamber
Di	Valve Diameter
Q	Flow Rate
SW	SolidWorks
CAD	Computer Assisted Design

2. INTRODUCTION

2.1. Context

In the summer 2021, the EPFL Rocket Team (ERT) defined a long-term vision of reaching space with a student-made sounding rocket. Additionally, after the successful development of a hybrid propulsion system, the team was willing to gain knowledge on liquid propellants rocket engines. In order to reach those ambitious goals, the Hyperion research project was created.

Its objective is to develop liquid propellants rocket engines, with each new model integrating more complex technologies, and ultimately providing the engine that will propel the ERT's launch vehicle above the Karman's line.

This year the team's focus is on the **Demo-B1 engine**, which will be pressure fed and will use ball valves to control the flow of propellants (fuel and oxidizer). In a near future, the oxidizer used will be liquid oxygen (LOx), at a temperature of -183°C.

This project specifically targets the ball valve mechanism and aims to study how a cryogenic application affects a valve's performance. Ultimately, the goal of this project is to modify the mechanism of ***a general use ball valve*** and adapt it to a cryogenic use.

The valve will be automatically operated using an electric motor. Also, tests and qualifications will be performed with liquid Nitrogen on the valve since its thermal and physical properties are analogous to LOx, but its handling remains much more secure.

2.2. Valve Specification

The Valves current specifications are listed below.

Specification	Value	Units	Comments
P_tank	40	Bar	Max operating pressure
P_cc	25	Bar	At 5000 N
P_valve	40	Bar	Max pressure considering no losses
Q_Ox	1.133	L/s	
Ox_density	1152	Kg/m^3	
m_dot_Ox	1.305	Kg/s	
T_vap_LOx	-182.97	°C	= 98.18 K
T_vap_LN_2	-198.8	°C	= 74.35 K
Oxidizer	LO	-	Oxyggen thermophysical properties
Di	1/2	Inch	For the pipe, Di_valve = 9 mm

Table 2.1 - Valve Specification

3. CRYOGENIC CONSTRAINTS

Our starting point is identifying the constraints imposed by cryogens. A liquid is considered cryogenic when its boiling point is below -100°C. For this project, we are dealing with LN_2 and LOx which have respectively boiling points of -195.8°C and -183°C (77,3 K and 90.2 K).

For this reason, we must consider all the constraints that those specific temperatures involve. Thus, we identified **4 main issues** that we must deal with to design a functional ball valve.

3.1. Pressure hazards due to high expansion ratio.

The first one is the **expansion ratio** during the vaporisation of a cryogenic liquid. $Expansion\ ratios\ of\ liquid\ oxygen\ and\ liquid\ nitrogen$:.

$$\mathrm{LO}x_{expansion\ ratio} = 1{:}\,861$$

$$\mathrm{LN}_{2_{expansion\ ratio}} = 1{:}\,694$$

This property requires careful attention, as any cryogenic liquid heating up in a closed system could result in considerable internal pressure forces, which often lead to rupture. Our ball valve could be subject to this problem; as it closes after operation, the valve chamber could be filled with liquid oxygen. Even if the volume of liquid that can be enclosed in the system is small, the resulting pressure after its vaporisation would have disastrous consequences.

To prevent this danger, the solution is to drill a hole in a strategic location on the valve, which will act as a pressure relief point. This problematic is further explored in *Section 5.3*.

3.2. Cryogenic Material Compatibility & Ductile to brittle transition temperature

The second one is the **ductile to brittle properties of metals**. A vast majority of materials show a sudden transformation below a temperature threshold that can lead to a big drop in their stiffness. The most famous material is steel. It can witness a brittle transformation at 0°C. We have studied all the material that keep good stiffness below -180°C. In order to build a resistant valve, we need a metallic material and a polymer that can be used as a joint.

In the class of metals, at these temperatures, only the ones with a face centered cubic system hold. We thus have copper, its alloys and the austenitic stainless steel (with a low carbon content (<1.2% by mass) and a good chromium content (>10.5% by mass)).

Among the class of polymers, the only one with a reasonable price is the **PTFE:**

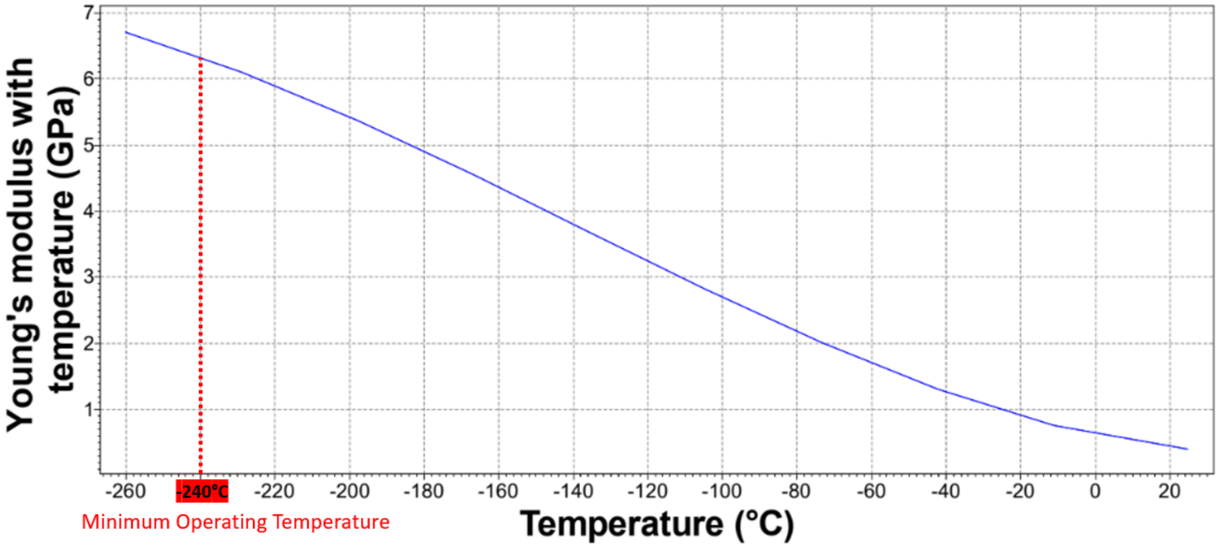


Figure 3.1 - PTFE's Young's Modulus as a function of Temperature and its Minimum operating temperature. Source: Ansys

The choice of materials is therefore highly important and needs to be considered when purchasing a valve which we intend to use in a cryogenic situation.

3.3. Temperature drop of the valve assembly by conduction

The third one is the connection between the valve and any component likely to freeze. Since the valve is metallic, the cold temperatures are easily transmitted to the rest of the system by conduction. Knowing that we have a motor on top of the stem to actuate the ball valve, we must make sure that the frame holding the valve and the motor is well designed, to keep the motor above its nominal temperature range. This problematic is further explored in *Section 6.3.*

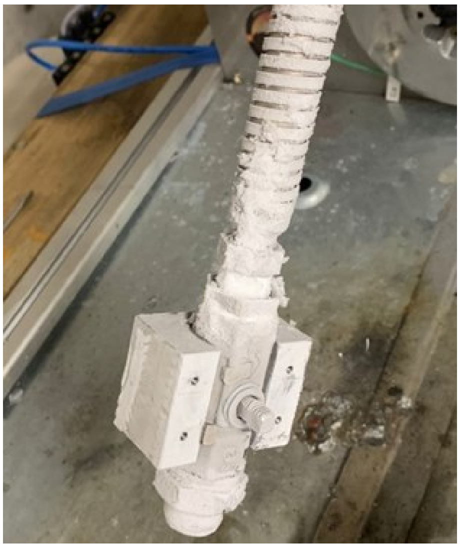


Figure 3.2 - Frozen valve after being connected to LN_2 for 10 minutes.

3.4. Increasing torque at cryogenic temperatures

Finally, we must ensure that the torque necessary to activate the valve remains reasonable, even with the ice that might be generated from the sublimation of humid air, which can lead to an increase of the necessary torque to actuate the valve. It is important to precisely determine to what degree the torque increases from an ambient temperature actuation to a cryogenic temperature actuation.

The testing for this purpose is developed *in Section 7.4*.

4. CRYOGENIC VALVES VS GENERAL USAGE VALVES

Cryogenic valves are built to sustain high pressures under extremely cold conditions. They can cost up to CHF 1500.- and differ from conventional valves on several points:

- **Material Selection:** Cryogenic ball valves are constructed using materials specifically chosen for their ability to withstand extremely low temperatures. Common materials include stainless steel, brass, or alloys with excellent low-temperature properties, such as austenitic stainless steel. (*cf Section 3.2.)*
- **Stem Extension**: Cryogenic ball valves often incorporate an extended stem design to position the stem seal away from the extremely low-temperature environment. This helps prevent the stem seal from becoming brittle or failing due to the cold. If the valve is motor-actuated, the stem prevents the motor from going below its operating temperature. However, having an elongated stem is not a suitable solution since our valve assembly will need to be as compact as possible. A discussion on how to prevent thermal conduction in low volumes can be found in *Section 6.3*.
- **Insulation and Heat Transfer Prevention:** To minimize heat transfer and maintain the low temperature inside the valve, cryogenic ball valves may incorporate insulation or heat-resistant coatings. These measures prevent heat from entering the valve, reducing the risk of ice formation, operational inefficiencies, and potential damage due to thermal stresses.
- **Low-Temperature Lubrication**: Standard lubricants used in normal ball valves can thicken or solidify under cryogenic conditions, hindering smooth operation. In cryogenic ball valves, special low-temperature lubricants are employed to prevent the lubricant from solidifying.
- **Enhanced Sealing Mechanisms:** Advanced sealing mechanisms are used to ensure tight shut-off and prevent leakage at extremely low temperatures. These sealing mechanisms can include double or triple seals, spring-loaded seats, or metal-to-metal seals that can withstand the thermal contraction of materials without compromising the integrity of the valve.
- **Pressure Relief Mechanisms:** Cryogenic valves have special pressure relief mechanisms such as a vented ball to prevent pressure build-up in the ball cavity due to the potential vaporization of the cryogenic liquid.
- **Testing and Certification**: Ball valves designed for cryogenic applications undergo rigorous testing to ensure their suitability and reliability, as dictated by the norm ISO 21011. This certification is expensive which partly explains the high price of cryogenic valves on the market.

Below you will find an exploded view of a cryogenic-rated Valve, provided by Avco. All the elements mentioned above are present:

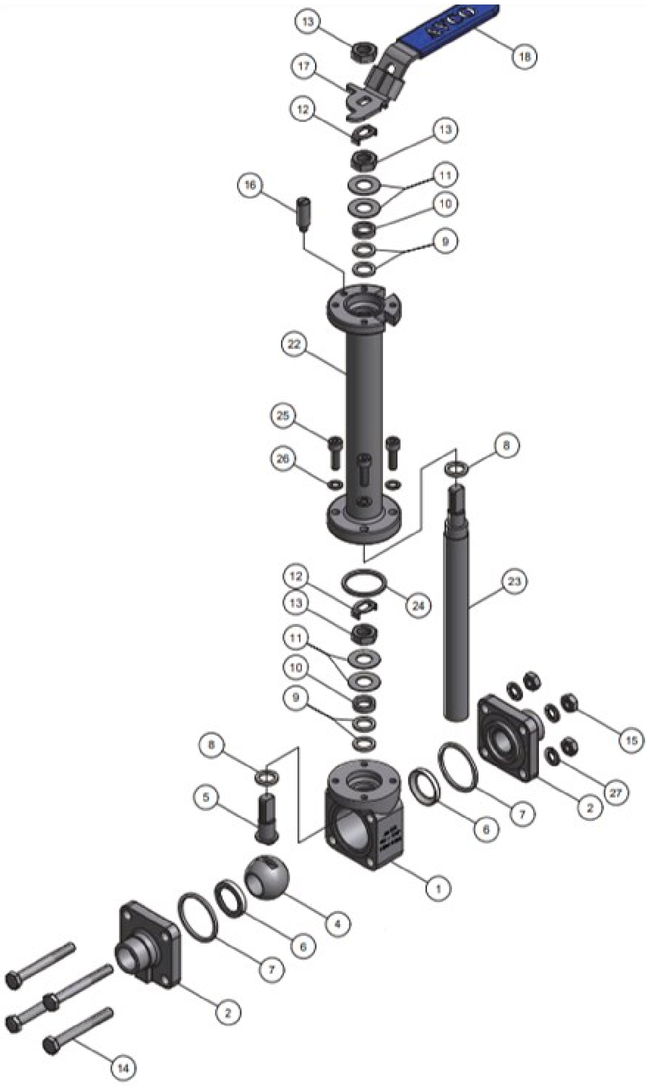


Figure 4.1 - Exploded view of the 1500 Series cryogenic ball valve, provided by Avco.

Given these facts, building a cryogenic valve from a simple supermarket valve may seem ambitious. But many problems can be avoided: all we need to do is find a valve with the right materials with similar thermal expansion coefficients to limit thermal stresses. An affordable PTFE seal would do the trick and spare us the need for expensive lubricants. Heat Transfer Prevention can be solved with a clever Valve Assembly (*cf Section 6.3*) and the pressure relief mechanism can be manufactured in-home (*cf Section 5.3*). Finally, as for the testing, we do it ourselves (*cf section 7*).

5. VALVE'S MODIFICATION

5.1. Purchase of a ball valve

Now that we know what the cryogenic constraints are and how cryogenic valve manufacturers deal with them, we know what to look for when buying our own valve.

The main searching criteria is the valve's materials: we need to make sure that all the pieces present in the valve are made from cryogenic-compatible materials. As soon as the valve meets this criterion, it represents a good starting point to eventually modify it and create our own cryogenic valve.

After a few weeks of reading literature about materials and ball valves, we have found a ball valve that met all the criteria imposed by a cryogenic operation: the *stainless-steel ball valve DN15 - 1/2" inch GK03 Manufactured by Neiruf* (*cf* Appendix for the Datasheet), which can operate with up to 40 bars of pressure withing a small temperature range (-20°C ; +125°C), according to the manufacturer.

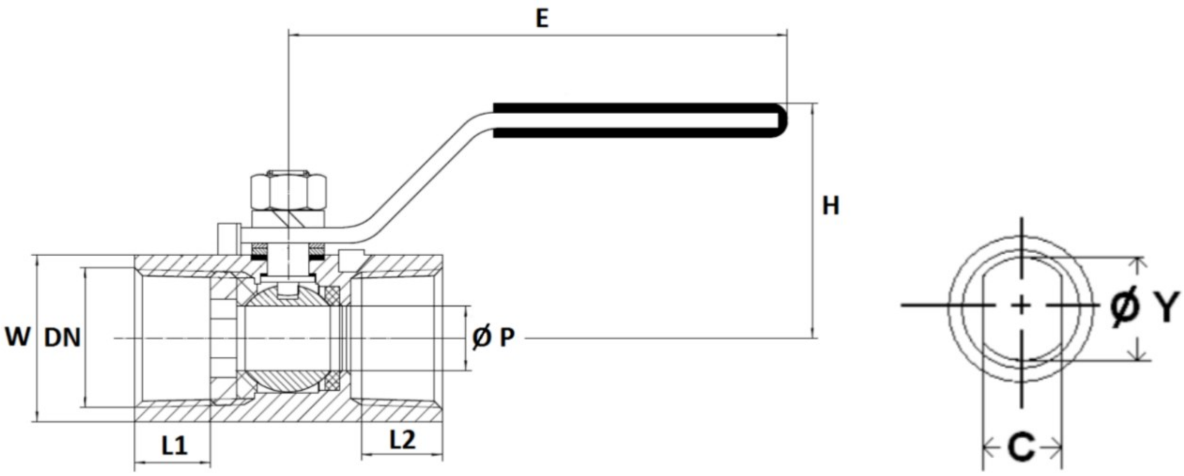
The advantage of this valve is that's it's made entirely from stainless steel (type 1.4408) and PTFE and has a rather simple yet effective structure: which means less potential leaking points, and easier to disassemble. In fact, we have been able to disassemble the valve into all of its components in order to better understand its functioning. Once the valve disassembled (*cf Section 5.4 for the Disassembly Procedure*), we have been able to create a reproduction of the model in CAD on SW. This allowed us to visualize in detail the distances and volumes inside the valve.

Below you will find an exploded view of this valve that we managed to model on a CAD software.

5.2. Parts list

Number	Name	Material
01	Chassis	Stainless steel 1.4408
02	Ball	Stainless steel 1.4408
03	Stem	Stainless steel 1.4408
04	Nut	Stainless steel 1.4408
05	Joint	PTFE
06	joint	PTFE

Table 5.1 – Parts list.



DN	ØP	L	ØD	E	H	L1	L2	W	C	ØY	weight
15	9	56,5	8	96	45	16	14	25	5	7	0,19

Figure 5.1 - Technical Drawing of the Valve, provided by the manufacturer.

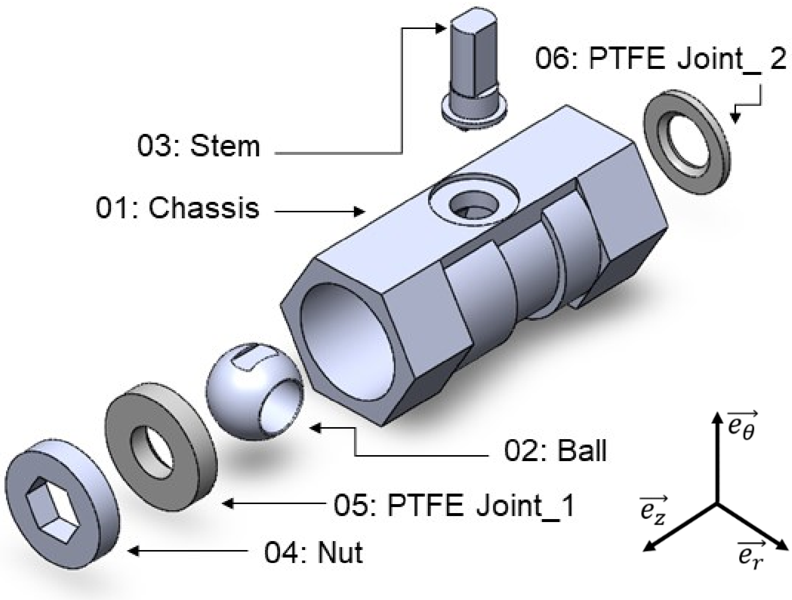


Figure 5.2 - exploded view of the Valve, modeled on Solidworks.

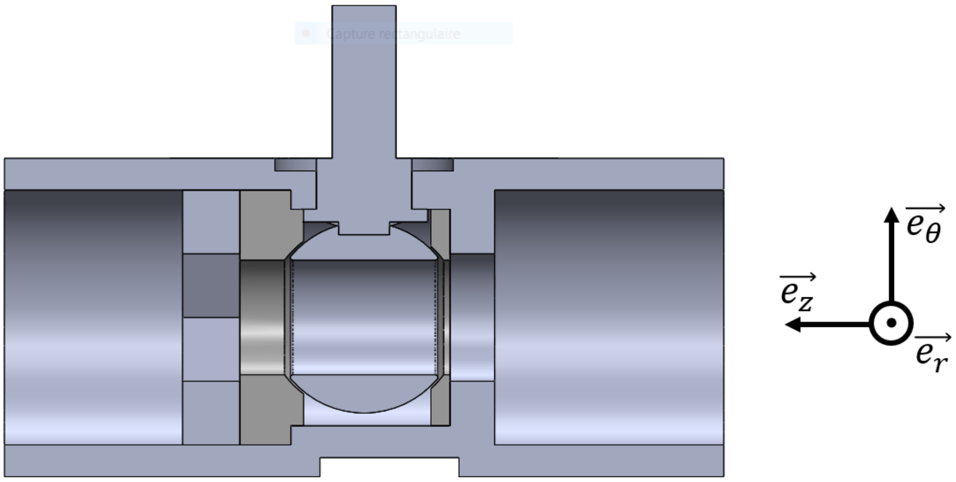


Figure 5.3 - sectional view of the Valve, modeled on Solidworks.

5.3. Adaptations made to the valve.

The main modification that we need to bring is a hole to allow the gas to escape once all the liquid has vaporized (*cf Section 3.1*). We first thought of piercing the valve's chassis on its side with a small hole (1 to 2mm of diameter). This modification has been disapproved by the CAD analysis and later with experiments (*cf Section 7.2)*.

During the experiment we conducted in Professor Mari's laboratory, we have been able to prove the utility of this hole. It worked as intended: once the valve was closed the hole on the side of the chassis allowed the trapped gas in the ball to escape. However, this experiments also showed us that during the opening and closing stage of the valve, at around 45°, the hole lets the gas escape the valve with its initial pressure. Indeed, the joints being thinner than the 9mm diameter from the ball hole, there exists a position in which the liquid could pass through the entrance, the exit, and this hole at the same time; as shown in Figure 5.4 and explained in Section 7.2.

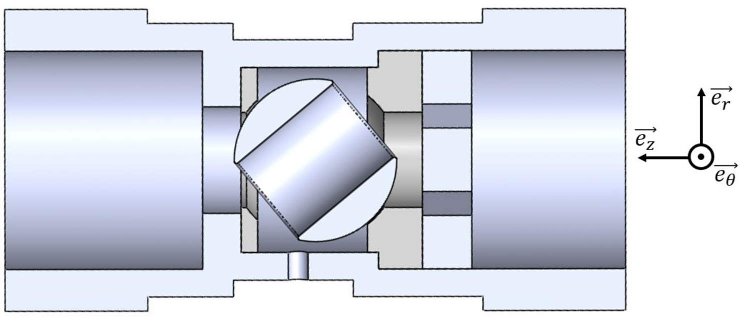


Figure 5.4 - Cross-sectional view of the valve from the top, opened at 45°.

As a consequence, in this configuration the liquid can escape through the machined cavity at high speed rather than following the intended path. This makes the control of the incoming flow in the combustion chamber very difficult and most importantly we are worried that this ejection on the side of the valve could reach supersonic speeds when testing at higher pressure, which could potentially damage the surrounding mechanics.

To make this design work, we would need to link the drilled hole to a tube and a control valve. This would result in a complex and large system on the side of the valve. We have let this option on the side as we have realized the only way to assemble the tube to the chassis was by welding, which is most definitely a delicate operation to perform on a stainless-steel valve as it could compromise its sealing due to the heat produced.

For these reasons the hole on the chassis is not a viable solution.

The last option we considered is piercing the ball itself on the side. Since the ball is made of the same stainless steel as the chassis, we have been able to machine a hole of 1mm diameter with a conventional drilling machine. This hole has in addition the benefit of creating a connection between the enclosed vaporized liquid, and the tube linking the valve to the CC.

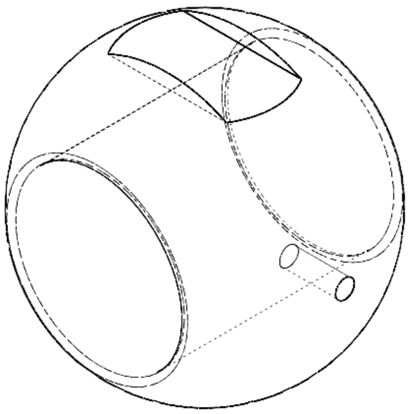


Figure 5.5 - ¾ view of the modified ball.

Hole on spherical ball manufacturing instructions	
Step 1	Disassemble your valve following the procedure described in Section 5.4 and retrieve the spherical ball.
Step 2	Make sure you use a pilot drill beforehand. By doing so the 1mm drill bit will be correctly guided and will make a clean hole through the stainless-steel ball. Note that without the pilot drill it is impossible to drill such a hole on a spherical surface.
Step 3	Drill the final hole using a 1mm drilling bit. The smaller the better.
Step 4	Polish the ball if needed to prevent damages on the joint.

Table 5.2 – Ball machining's procedure.

5.4. Disassembly procedure

1st step:

Use an Allen key of 10 to unscrew nut (Part # 04). Carefully hold the valve to make sure it stays cylindrical. The valve is thin around the screw pitch.

2nd step:

Use a tool to remove the PTFE joint (Part # 05). The best method is to push it from the opposite side using a flat screwdriver. But be gentle as you might damage the joint and therefore compromise the quality of the seal.

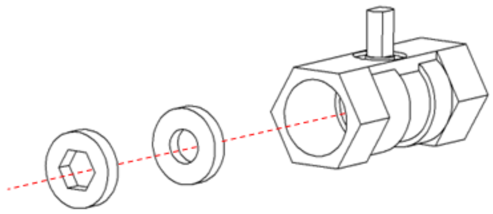


Figure 5.6 – Exploded view of one side of the valve, 2nd step.

3rd step:

The ball is kept in place by the stem thanks to a groove. You need to correctly rotate the stem so that the groove is aligned with the valve's body. Once you do so, the ball should easily fall, shake the assembly if needed.

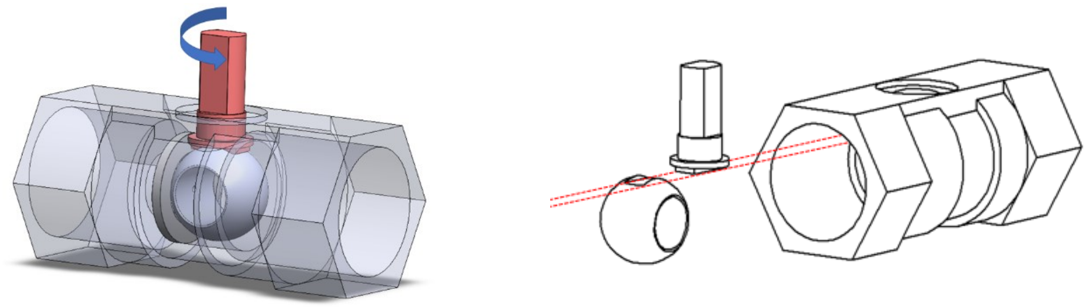


Figure 5.7 – Exploded view of the inside of the valve, 3rd step.

4th step:

Once the ball is out, simply remove all the nuts and washers on the stem, and it will fall.

6. TEST BENCH ASSEMBLY

Intensive testing played a crucial role in the development of this project, particularly in ensuring the reliability of the ball valve under cryogenic conditions. In fact, they pose unique challenges, which can significantly impact the performance and functionality of mechanical components. A more thorough discussion on the tests performed can be found in *Section 7*.

But before performing the testing it was important to set up a reliable and safe test bench.

6.1. Warning for manipulating Liquid Nitrogen

Most of our experiences involve the manipulation of liquid nitrogen. When working with liquid nitrogen, it is crucial to prioritize safety. Always wear the necessary protective gear, including insulated gloves and safety goggles. Ensure you work in well-ventilated areas to avoid a lack of Oxygen to breath caused by the release of nitrogen gas during evaporation. And most importantly, be aware of pressure hazards due to its vaporization.

6.2. General overview of the test bench

The test bench is composed of few elements:

- The pressurized **dewar** filled with LN_2, (cf *Section 6.4* for detailed information about its operating instructions).
- The ball valve, which could either be manually actuated, using protective gloves, or which could be mounted into the **motor assembly** to remotely actuate it using a Maxon motor (*cf Section 6.3*).
- **Piping and connectors**. Note that every connection should be sealed by putting Teflon on the threads. A ½'' thread adapter from BSP to NPT is necessary to connect the ball valve to the flexible steel tube through which LN_2 is conveyed.

6.3. Ball Valve Motor Assembly

The aim of this assembly is to actuate the ball valve using a Maxon motor reliably and remotely, controlled by a computer. This configuration is the closest to what the final assembly will look like, ready to be assembled into the rocket.

However, the focus here was on safety and reliability, and discussions on weight and volume optimization were not considered. For instance, a lighter motor could be used for the in-rocket assembly, as long as it can deliver a torque sufficient to actuate the valve. A more thorough discussion on the required torque can be found in *Section 7.3 and 7.4.*

Below you will find a parts list of the assembly as well as an assembly procedure diagram.

Number	Name	Material
01	Lower_Chassis	Aluminium
02	Ball_Valve	Stainless Steel
03	Main_Chassis	Aluminium
04	Valve_to_spring_adapter	Aluminium
05	Spring_adapter	-
06	Maxon Motor	-

Table 6.1 - Parts List of the Motor Assembly.

The main purpose of the assembly is to keep the motor steady and concentric relative to the ball valve.

Since the stem needs to be vertical to facilitate the handling, the ball valve needs to be milled on the sides in order to perfectly fit onto the Lower_Chassis (cf Figure 6.2). It is important to keep a low tolerance to produce a clamping connection between the chassis and the valve. The Lower_Chassis can then be securely fastened using a vice to proceed to the testing.

One of the main concerns for this assembly was the conduction of cold temperatures from the valve to the motor, which could cause its failure. To prevent the motor going below its operating temperature, the solution is to make a "sandwich-like" structure, by inserting parts between the valve and the motor, with materials having low conduction coefficients, in order to reduce the thermal conduction. This solution is also more compact than adding a long stem between the motor and the valve.

For example, the Valve_to_spring_adapter, which is currently in aluminium could be machined using PTFE, which has a lower thermal conductivity coefficient.

Note however that the time the valve stays in open position is relatively short to the time it takes the valve to completely freeze (more about the cooling of the valve in *Section 7.1*) and when the valve is in closed position, the thernal conductivity is even further reduced. Therefore, with this geometry the motor remains unharmed througout all the cooling process. (See *Section 7.5* for further details)

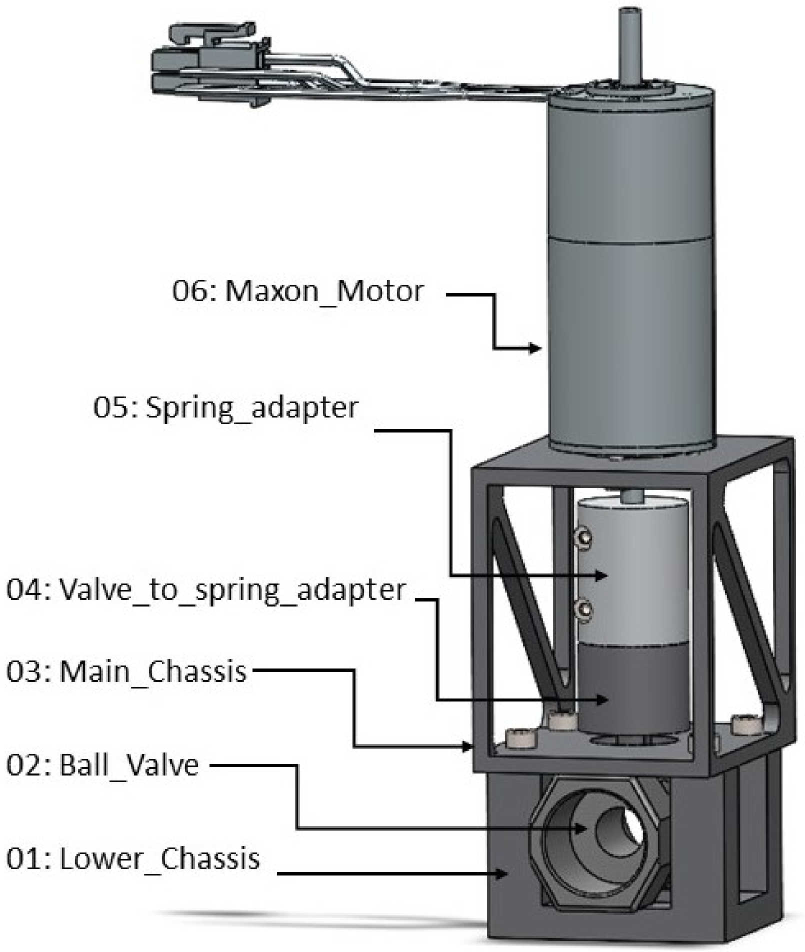


Figure 6.1 - ¾ view of the ball valve motor assembly.

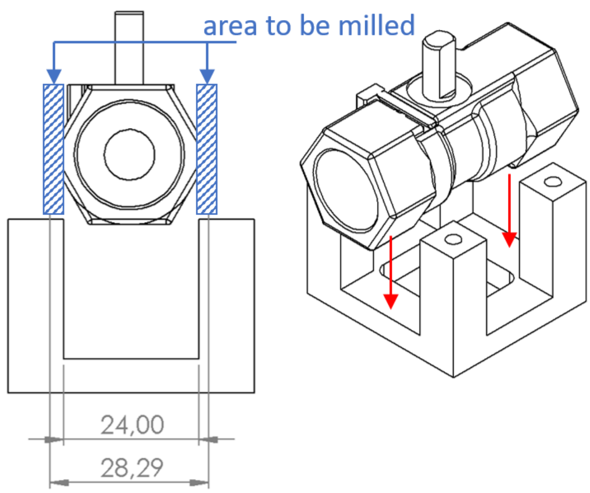


Figure 6.2 - Instructions for Valve Manufacturing (Milling Procedure).

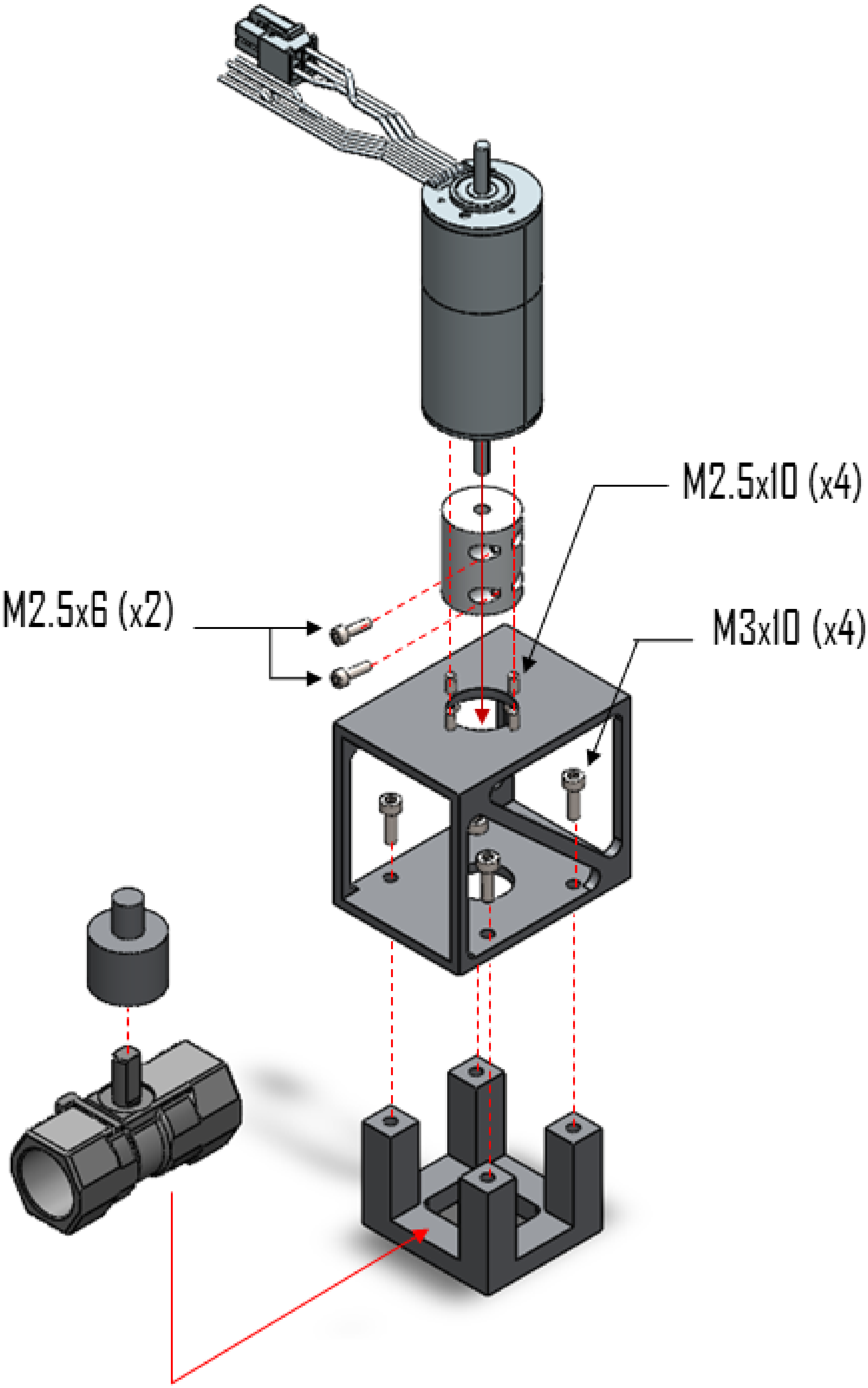


Figure 6.3 - Assembly Instructions.

6.4. The Cryogenic Dewar: Principle of Operation

A cryogenic storage dewar (named after James Dewar) is a specialized type of vacuum flask used for storing cryogens.

The deware used at rocket team is a 127L vacuum tank made by Cryo Diffusion in 1976, type RBP 120 VLR, which can sustain a maximum pressure of 2.9 bars. It has the ability to be filled with a cryogenic product, build pressure inside the vessel, and deliver either liquid or gas for a specific application.

A good amount of this project's time was spent ensuring that the dewar, which is relatively old and hadn't been reviewed since its production, can be safely and reliably operated. For this purpose, a filling and emptying test was carried out, this also permitted us to understand more thoroughly its principle of operation. (cf Figures 6.4 & 6.5).

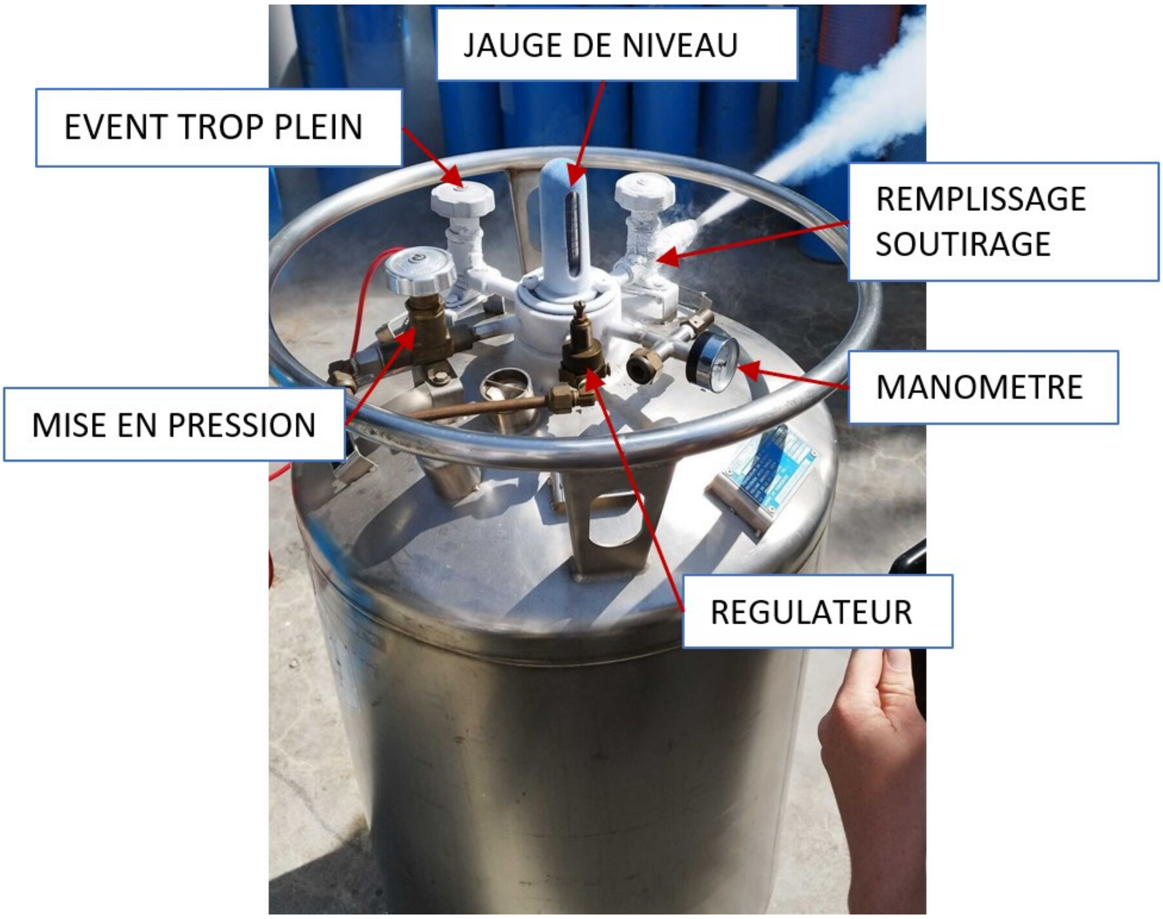


Figure 6.4 - Filling and emptying the dewar with LN_2, all the valves are labelled on the tank.

The dewar operation is done completely with the control valves located on the top of the tank:

- REMPLISSAGE SOUTIRAGE: This valve is connected to a pipe that goes to the bottom of the tank. Use this valve when you want to fill the tank or proceed to a liquid withdrawal. This valve can be adjusted to obtain the proper liquid flow rate. Note that for a filling procedure you need to connect this valve to a ***pressurized*** container of LN_2 and open the “event trop plein”. This will guaranty a minimum pressure inside the Dewar to allow a maximum of liquid to get in.

- EVENT TROP PLEIN: This valve is directly connected to the top of the tank: open this valve when you want to proceed to a gas withdrawal (which naturally stays in the top of the tank) or when you want to lower the pressure inside the tank by letting some gas out. When doing so, always make sure you are with an oxygen captor, in a well-ventilated area or preferably outside.

- MISE EN PRESSION: The dewar is equipped with a pressure building coil that runs the full length of the tank from the bottom. Inside this coil the liquid nitrogen vaporizes and climbs to the top of the tank. You can therefore open the “mise en pression” valve if you want to inject that gas back into the dewar in order to pressurize it. This is particularly useful as it allows us to withdraw Liquid Nitrogen from the dewar without the need of an external pressurized tank of gaseous nitrogen.

- REGULATEUR: The “regulateur” is basically a screw-driven tuneable pressure relief valve, which is directly connected to the “Mise En Pression” valve and allows you to control how pressurized you want your dewar to be. The more you screw it down the more pressure will build up into the tank. If you wish to slowly lower the pressure, simply unscrew a little the “regulateur” and gas will start leaking from its side. Note that the screw is not graduated so after moving the screw just wait a little bit for the pressure on the manometer to stabilize.

- MANOMETRE: The manometer is where you can read the pressure inside the tank. Note that on the side of the manometer there is a safety pressure relief valve which is not tuneable and that will open if pressure ever goes over 3 bar. This is a single use valve that mechanically break if the inside pressure of the Dewar reaches 3 bars. This will be necessary is there is an anomaly in the “regulateur”.

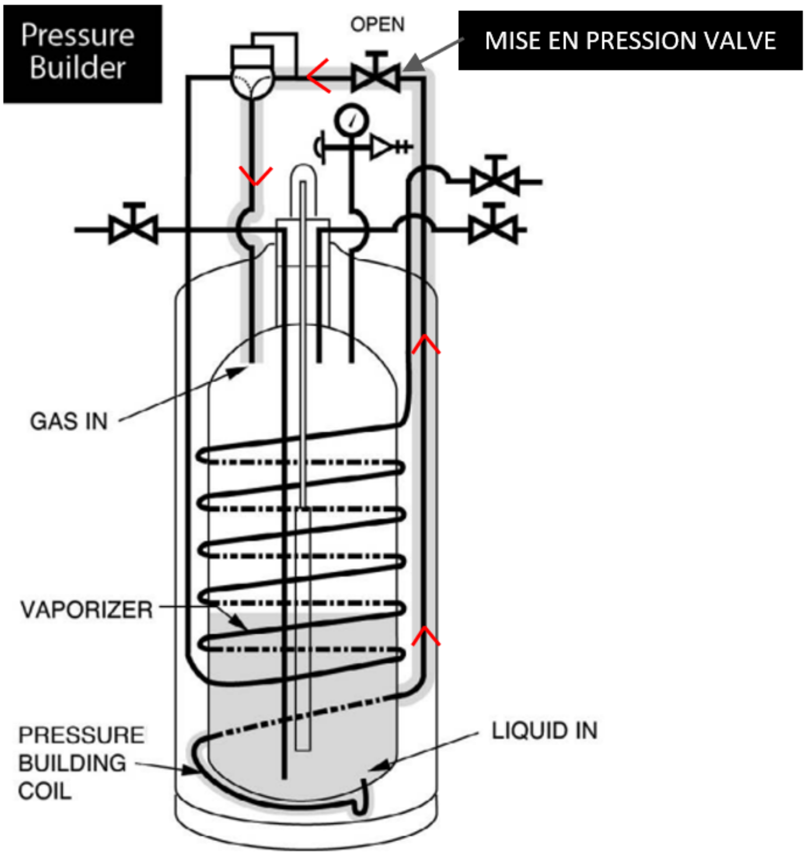


Figure 6.5 - Schematics of the dewar and flow during the "mise en pression" operation.

6.4.1. LN_2 Withdrawal

Warning: Before making a liquid transfer, be sure that protective eyeglasses and gloves are being worn. Also, any time liquid can be entrapped in a pipe between two valves, the pipe must be linked with a safety relief device.

Cryogenic liquid can be pressure transferred from the dewar to other cryogenic equipment that operates at a lower pressure than the tank. To make a liquid withdrawal follow this procedure:

1. Connect the transfer hose to the "Soutirage" Valve and to the cryogenic equipment that will receive the liquid.
2. Open the "mise en pression" valve and adjust the regulator's screw to build up the desired pressure inside the tank. Once the pressure is stabilized, as seen on the manometer, you can proceed to the next step.
3. You can now open the "Soutirage" Valve. This valve can be adjusted to obtain the proper liquid flow rate.
4. Once you are done you can close the "Soutirage" valve. But make sure that no liquid remains trapped in between the valve and the cryogenic equipment you

are using. Either open the equipment's valve first or equip the transfer hose with a safety relief device.

5. If you wish to lower the pressure inside the tank after operating, simply open the "Event trop plein" Valve and let the gas out. Make sure to be with an oxygen captor, in a well-ventilated area or preferably outside.

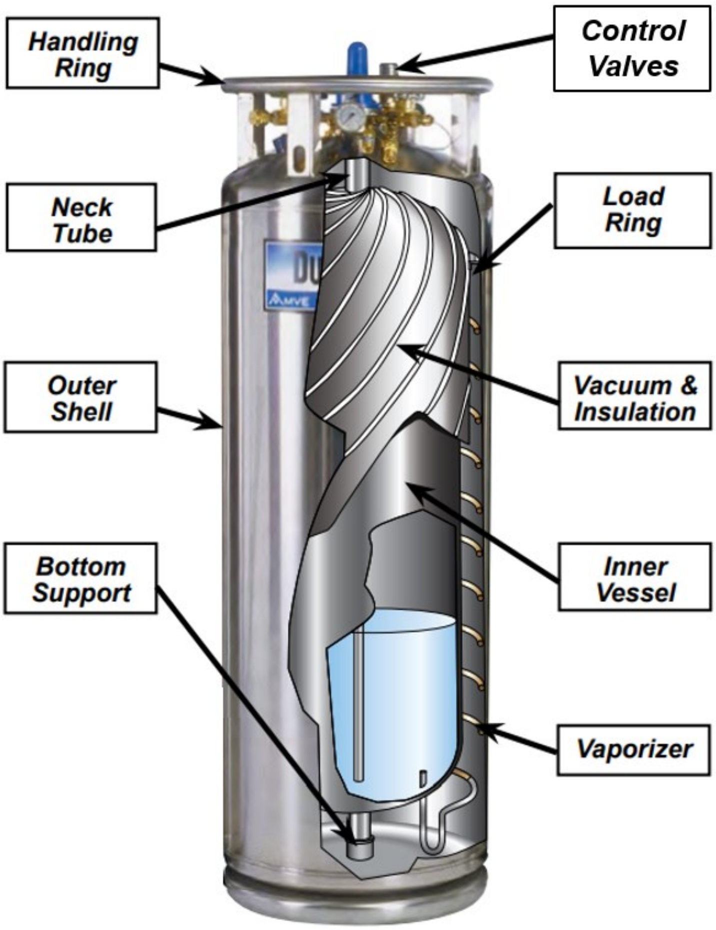


Figure 6.6 - Major components of the dewar.

7. TESTING

Throughout this project we led various tests to best determine the valve's behavior to both high pressures and low temperatures.

Test n°	Description of the test
1	Dipping the valve into LN_2
2	Manually operated Valve on LN_2 Dewar @ 0.4 Bars
3	High pressure torque test with water
4	Manual torque test with LN_2 1.8 Bars
5	Automated assembly connected to LN_2 Dewar @ 2.0 Bars

Table 7.1 – List of tests performed.

7.1. Results from the 1st experience: dipping the valve into LN_2:

This test was the first opportunity for us to see and manipulate liquid nitrogen, and to get familiar with the safety measures. We have been able to plunge the valve into an open dewar filled with LN_2.

Once we immerge the valve its temperature drops abruptly until it reaches the temperature of liquid nitrogen. During the cooling process, we can see formation of nitrogen bubbles on the surface of the valve. When the valve reaches thermal equilibrium whit the LN_2 , the bubbles stop. This way me we saw that the time required to get the whole valve frozen was *8 minutes*, while being fully immerged.

Therefore, as the valve will be in contact with LN_2 only through the pipes, the risks of getting the motor damaged due to the cold temperatures is low. Indeed, during the valve will be closed for most of its time in contact with LN_2, as the rocket will remain static on the launch pad for a few minutes. Then the time with which the liquid will be at the heart of the valve is only a matter of a few seconds (it corresponds to the time of engine burn). This is thus not enough to cool down the entire valve setup and endanger the motor.

We have also been able to test the behavior of the PTFE joint when frozen. As expected, it becomes much more brittle and was easy to break when stressed in the radial direction, but this will not be a problem as the joint mostly sustains loads in the z-direction (cf Figure 5.2 for the axis-system).

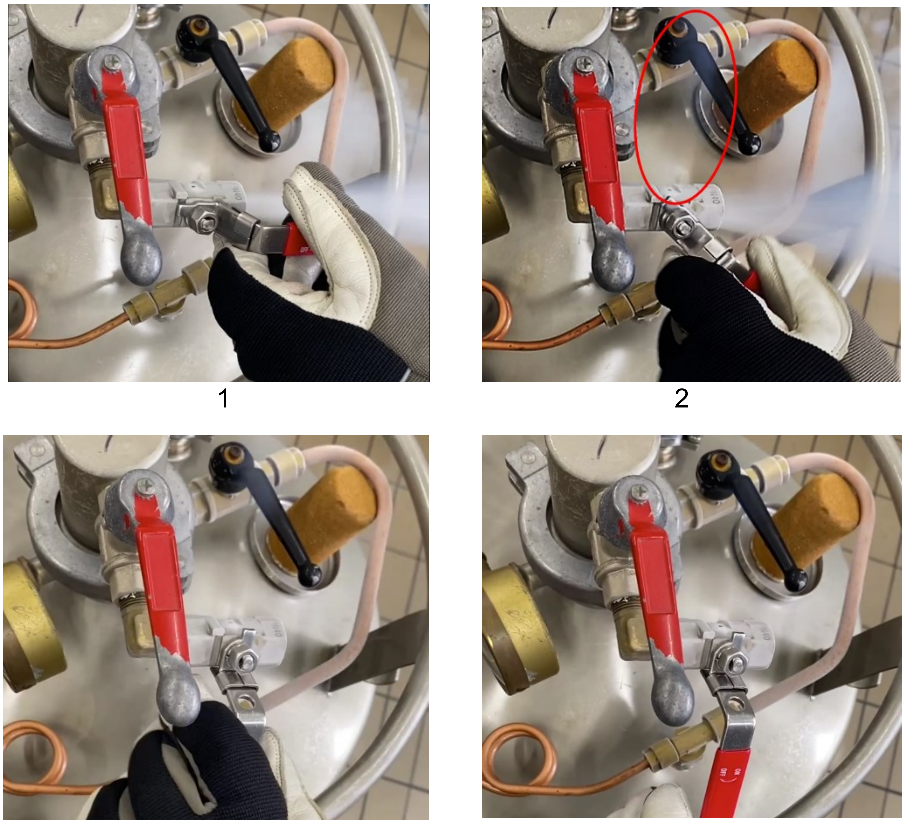
Figure 7-1 - Valve in and out of the dewar.

7.2. Results from the 2nd experience, open and close a valve connected to a dewar with 0.4 bar:

This test has been conducted in the physics laboratory thanks to Professor Mari. We have been able to test the first iteration of the modified valve, with a hole machined on the side of the chassis. The setup consisted of the ball valve connected to a deware filled with liquid nitrogen, pressurized at 0.4 bars.

Figure 7.2 - Image of the valve opened.

The objective of this test was to study the effect and the feasibility of the modification we have made at low pressure and evaluate the possibility to keep it for a test at high pressure.



1 2 3 4

Figure 7.3 - 4 images showing the liquid nitrogen flow when the valve is open and closed.

This test has allowed us to visualize the fact that if the frame is drilled, there is an angle at which the liquid flows through both the valve and the drilled hole (cf *Section 5.3* for sectional view on CAD). This can be seen on images 2 and 3 of Figure 7.3, the flow can be seen at the top of each image, above the black handle.

Note that the experiment was conducted with a pressure of 0.4 bar and the side flow was already considerably high. Therefore, the option of drilling the frame has been moved aside.

This test has also allowed us to get a first estimation of the need to drill a hole to avoid an excessive pressure in the frame once the cryogenic liquid vaporize, as mentioned in Section 5.3. After closing the valve, a jet of vaporized liquid nitrogen was visible for 2 seconds escaping from the side of the valve (visible at the top of the third image above).

7.3. Results from the 3rd experience, estimation of the raise for the opening torque function of the pressure change:

This experience has been conducted with a dynamometer and a water pump to be able to reach a high pressure safely. The objective of this experience was to determine the coefficient with which the pressure would rise with the increasing incoming pressure.

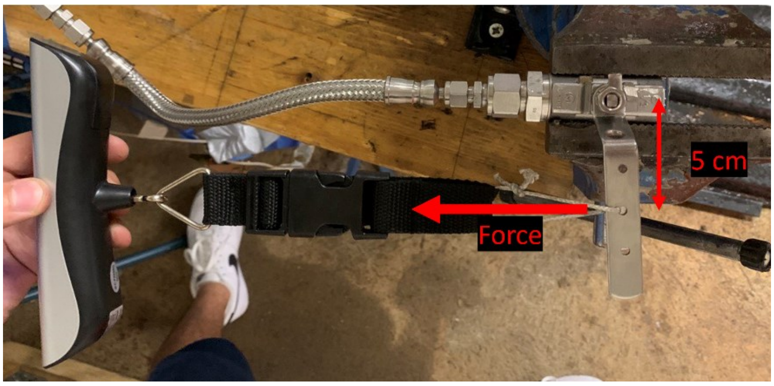


Figure 7.4 - Test set up.

From this experience, we have been able to get three informations:

- The torque necessary to open the valve decrease with time. We have collected data for the opening torque with 0 bars within the pipe. We have notice that after being opened around 50 times, the torque necessary to open the valve decrease of 0.1 Nm.
  This tells us that we can either use thread lock after having modified the valve. Or the joint moving or deforming itself. Nevertheless, we have noticed no anomaly when disassembling the valve.

incoming pressure [bar]	weight measured [kg]					Average wight	Average Torque [Nm]
0	3	2.95	3			2.98	1.46
0	2.7	2.85	2.8	2.7	2.8	2.77	1.36

Table 7.2 - Data collected before and after 50 valve actuations.

- Although the coefficient of torque increase is visible on the graph, it is equal to 0.0042 Nm/bar, which is negligible for this ball valve. For a pressure difference of 40 bars, it represents an increase of 0.2 Nm to open the valve.
  This calculation has been made without considering the torque reduction detailed in the previous point. Therefore, this 0.2 Nm is an overestimation.

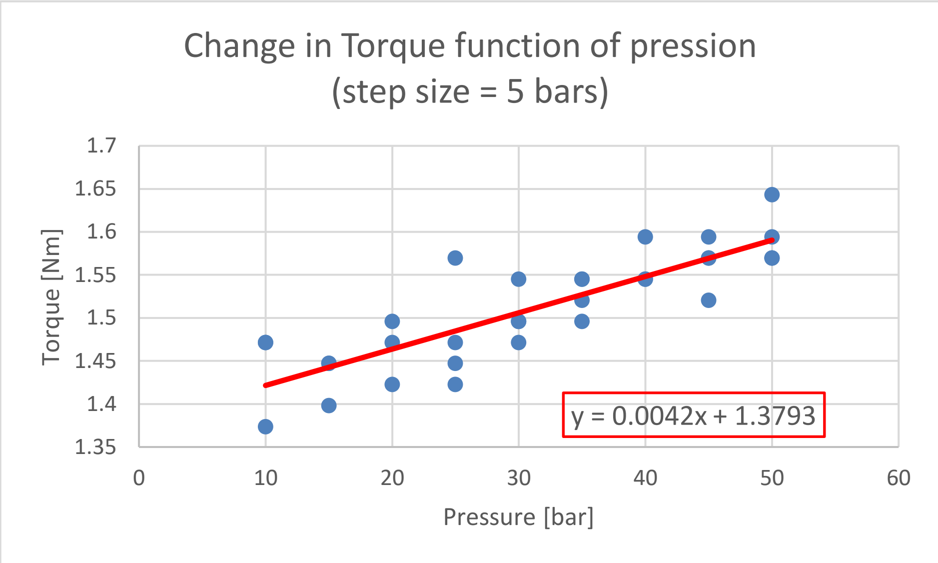


Figure 7.4 – Graph showing the torque function of the applied pressure.

- During the data collection, we have noticed a rise in the weight measured after opening the valve of 15 degrees. It corresponds to the angle at which the liquid in the pipe accesses the ball. This led to an instant raise in the torque of 0.1 Nm. Which could bring a servo motor to its limit if no safety factor has been considered.

Finally, this test has been conducted to measure the rise in the necessary torque to open the valve and not to measure a precise opening torque. Indeed, we have seen a substantial leak in the flexible pipe leading to an important pressure drop in the system. Therefore, we have set a minimum of 3 measures per pressure stage to get the most accurate response possible.

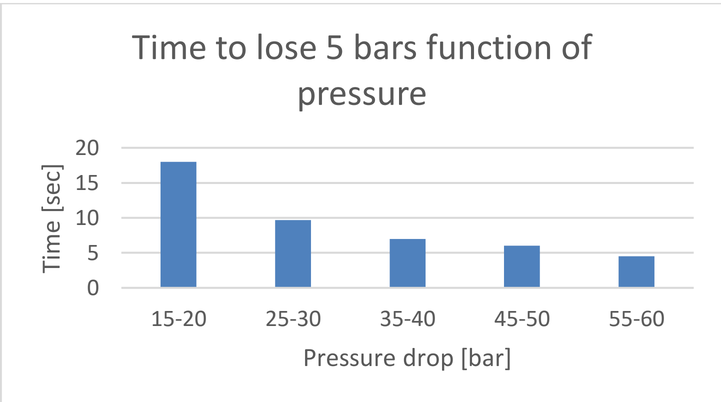


Figure 7.5 – Plot of the time related to the pressure drop.

7.4. Manual torque test with LN_2 at 1.8 Bars

This experience has been conducted in similar condition to the previous test. This time, we have placed the valve into the lower_chassis to keep the valve steady while opening it.

Firstly, we have performed a test with water at 0 and 10 bars. This gave us the torque necessary to open the valve at ambient temperatures.

pressure [bar]	weight measured [kg]			average weight [kg]	average torque [Nm]
0	3.6	3.55	3.45	3.53	1.73
10	3.65	3.45	3.45	3.52	1.72

Table 7.3 - Data collected with a water pump and a dynamometer.

We then have connected the pipe to our dewar to get a flow of LN_2. The dewar has been self-pressured with the “Mise en Pression” valve and limited to 1.8 bar with the “Regulateur”. Without unscrewing any nut, we have dried the valve to decrease the risk of having ice in it and set it up to the dewar.

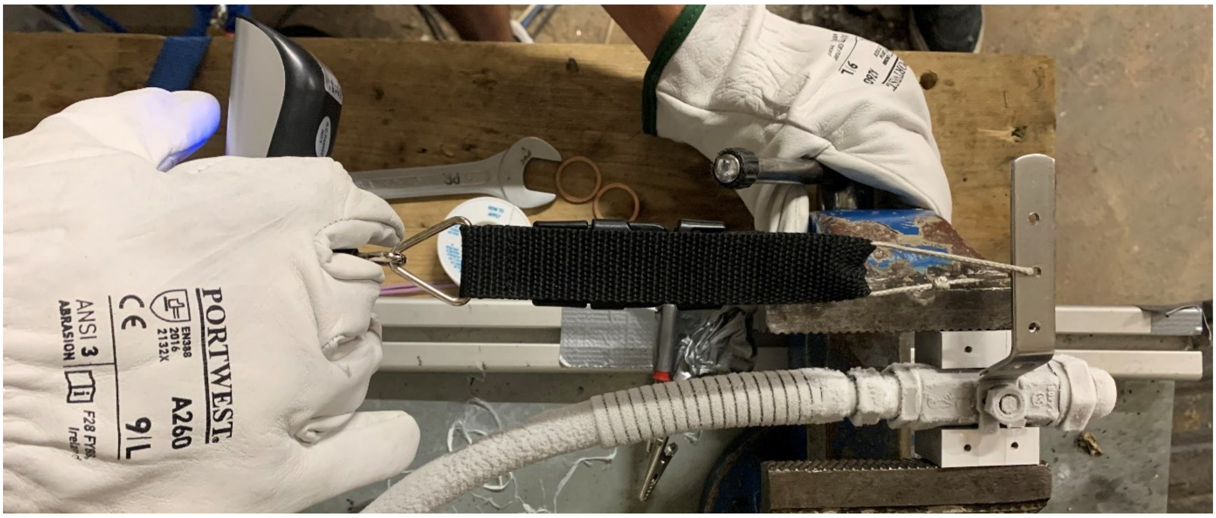


Figure 7.6 – Frozen valve installed in the vise.

From this experience we have been able to see an increase in the torque necessary to actuate the valve once everything is frozen by about 50% of its value at ambient temperatures. This is a warning to use a motor able to withstand a torque of minimum 4 [Nm].

pressure [bar]	weight measured [kg]				average weight [kg]	average torque [Nm]
2	5.75	6.05	5.3	4.9	5.50	2.70

Table 7.4 - Data collected on the frozen valve.

7.5. Automated assembly connected to LN_2 Dewar at 2.0 Bars

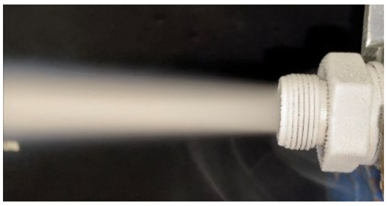
This is the final experience conducted this semester. It consists of opening and closing the valve with LN_2 on its end, through a computer driven motor. We have been able to iterate this experience many times, with satisfying results on every iteration.

The valve has shown no sign of fatigue nor leaks, and the flow has been always controlled.

Figure 7.7 – LN_2 leaving the valve.

Furthermore, we have been able to evaluate the time needed to evacuate the vaporized liquid trapped inside the valve's frame.

Figure 7.8 - Sequence of image after cooled valve closure.



Time T + 0 sec.

Time T + 0.5 sec

Time T + 5 sec.

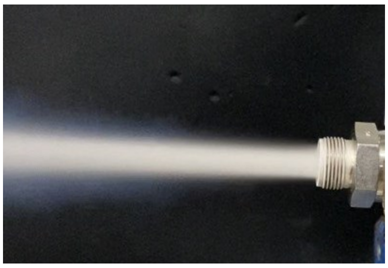
Time T + 9 sec.

Time T + 13 sec.

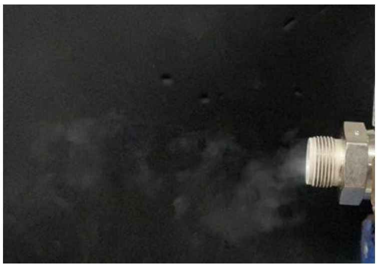
This sequence of images shows how the jet induced by the 1mm wide hole drilled in the hole evacuates the gas blocked. We see that the jet is effective until 13 seconds after the valve closes. From there, the flow is not horizontal and we can suggest the remaining smoke comes from the evaporation of the water frozen on the cold metal.

This experiment was carried out approximately 6 minutes after the first LN_2 flow through the valve. On the first flow, the jet induced by the vaporization was almost instantaneous as the pipes and the valve was at ambiant temperature.

Figure 7.9 - Sequence of 3 images after ambient temperature valve closure.



Time T + 0 sec



Time T + 0.5 sec.

Time T + 2 sec.

Despite being not clearly quantified, the effectiveness of the hole inside the ball has been proved. Indeed, whether it's on a freshly use valve of on a cold valve, the maximum volume filled with liquid is 2820 mm^3 (see calculation in appendix 12.1). Which correspond to a volume of 2 428 020 mm^3 or 2.42 Liters.

8. ANALYTICAL RESULTS

The aim of this section is to provide some analytical results to corroborate the empirical findings mentioned above, or to explore some other problematics.

8.1. Effects of high pressure on the ball valve.

It is specified by the manufacturer that the valve should be able to withstand up to 40 bars of pressure, even though it is not graded for lower temperatures than -20°.

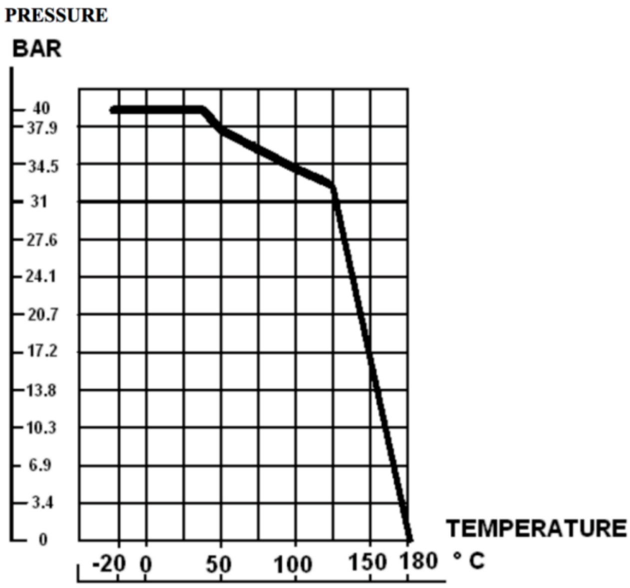


Figure 8.1 - Operative Pressure vs Temperature graph provided by the ball valve manufacturer for a range of $T \in [-20°\,C\,;\,+180°C]$ *.*

In this Section we want to make sure that the ball valve can sustain a pressure of 40 bars, even at lower temperatures, which implies considering the behavior of its materials under cryogenic conditions. To do so we look at the valve's material's properties: Stainless Steel 1.4408 which is equivalent to AISI 316 (depending on the norm used). Below you will find a graph displaying the Steel's Yield Strength (elastic limit) as a function of temperature. All the following calculations will therefore be carried out using the value of the yield strength at LN_2's operating temperature: -196°C.

$$\sigma_{el-316\ @-196°C} = 450\ Mpa$$

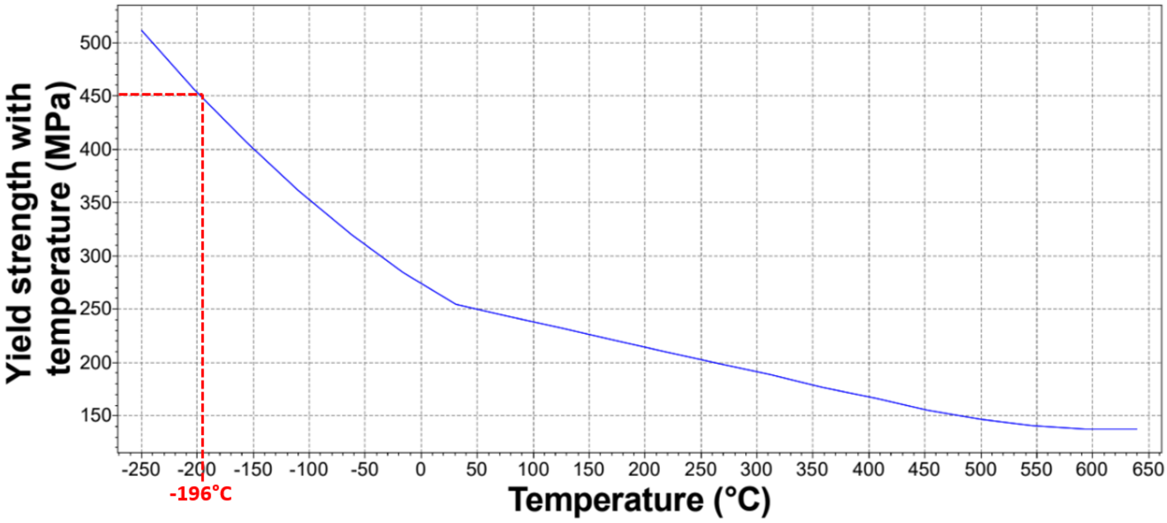


Figure 8.2 - Stainless-Steel 316's Yield Strength as a function of Temperature. Source: Ansys

Note that as the temperature drops, the metal becomes more rigid and resistant, but also more fragile, as its Young Modulus E also increases, which could lead to catastrophic fracture, especially if the fracture is initiated by the propagation of micro fissures. In that case the effective yield strength could be lower than the theoretical value shown above, a large safety factor will be needed when performing our resistance calculations.

When talking with Pr. Daniele Mari, we were told that the neck of the valve, and more specifically the threads were the first point of failure of the valve due to high pressure, which could lead to a premature leaking while the valve is in closed position.

Therefore, we now compute the stress on the cross-sectional area of the valve's neck.

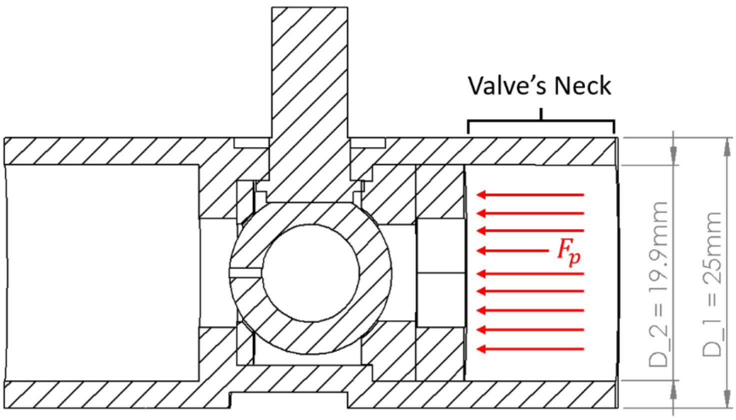


Figure 8.3 - Axial load on the valve's cross-sectional area in closed position.

$$F_p = \frac{\pi D_2^2}{4} p = 1244\ N \text{ , with } D_2 = 19{,}9mm \text{ and } p = 40\ Bar\ =\ 4\ Mpa$$

$$A_s = \pi \frac{D_1^2 - D_2^2}{4} = 180mm^2, \text{ with } D_1 = 25mm$$

$$\sigma_{Neck} = \frac{F_p}{A_s} = 6.9\text{Mpa}$$

A_s is the cross-section area of the thread.

F_p is the normal force applied on the threads.

Therefore, the stress on the cross-sectional area is much lower than the valve's Yield strength at operational temperature:

$$\sigma_{el-316\ @-196°C}\ >\ \sigma_{Neck}$$

We can therefore be sure that the connection on the neck will hold.

9. CONCLUSION AND REMARKS

Our project began with an extensive literature review and research phase focused on understanding the properties of materials under cryogenic conditions and the constraints that cryogens impose on any objects. This knowledge formed the foundation for selecting appropriate materials and modifying our ball valve to make it cryogenic rated.

Next, we proceeded with experimentation and testing to assess the valve's behaviour and performance under cryogenic conditions. We developed a comprehensive test plan and setup a dedicated test bench. The final step of our project involved the interpretation of the results obtained from testing. We carefully analysed the data, comparing it with our initial expectations in order to determine if the modifications were effective.

A good number of hours and energy has been spent in mail exchanges with EPFL regarding safety consideration, especially when it came to handling LN_2. As annoying as it may be, this step proved crucial to the progress of the project and will now allow the EPFL to gain independence for future testing. In particular, thanks to M. Madlinger we were able to assert that the dewar ERT owns, works properly and managed to put in place safe operational procedures. Most importantly, this project helped us gain knowledge on cryogens handling.

However, the aim of this project was to develop a valve that could sustain a pressure of 40 bars under cryogenic conditions, to meet the Rocket's requirements.

To do so, one last test would have to be done on the valve at high-pressure (40 bars) with liquid oxygen, to prove its resistance and its impermeability.

Unfortunately, the dewar we experimented with is simply meant to *store* LN_2 and cannot therefore be used to extract LOx at high pressure. An experiment like this requires a complex test bench with special tanks meant to withstand cryogenic temperatures and high-pressures. Such a test bench is being developed among the ERT and should be operational late 2023. In the meantime, our valve cannot be certified for high pressure cryogenic operations.

Nonetheless, we have performed the first cryogenic test withing the association, which remains a good first step forward our quest to deliver a cryogenic liquid engine that could send a sounding rocket to space by 2027.

10. USEFUL CONTACTS

Those are the useful contacts that helped us during the project and that might remain useful in the future.

- M. Madliger: Responsible for facilities and equipment of CMi (Center of MicroNano Technologies). He has access and knowledge about Liquid Nitrogen.
  patrick.madliger@epfl.ch

- M. Mari: Teacher in the physics department, responsible of the laboratory of quantum mechanics. He has access and knowledge about cryogenic liquids.
  daniele.mari@epfl.ch

- M. Deutsch: Responsible for the relations between EPFL and Carbagas, a gas company with a sales point in Lausanne (Rue du Grand-Pré 4, 1007 Lausanne). Carbagas offers the possibility to deliver liquid nitrogen.
  manuel.deutsch@carbagas.ch

11. REFERENCES

- PINHO, Jorge, PEVERONI, Laura, VETRANO, Maria Rosaria, *et al.* Experimental and numerical study of a cryogenic valve using liquid nitrogen and water. *Aerospace Science and Technology*, 2019, vol. 93, p. 105331.

- Liquid_Cylinder_Product_Manual Dura-Cyl

- Software Ansys Granta EduPack 2021

12. APPENDIX

12.1. Calculations for the volume trapped inside the valve

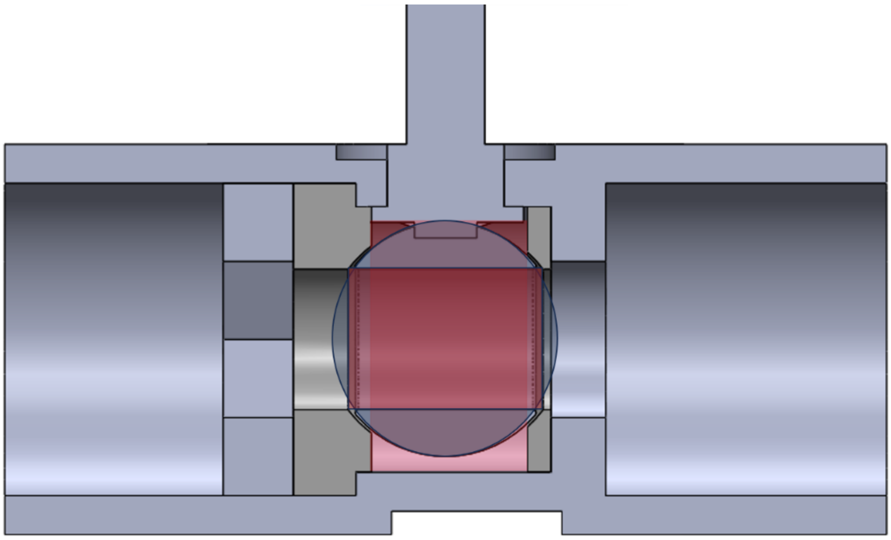


Figure 12.1 – Volume likely to keep some liquid.

$Frame_{length} = 17mm$

$Frame_{radius} = 8.5mm$

$Ball_{radius} = 7.5mm$

$Ball\ Hole_{radius} = 4.5mm$

$Ball\ Hole_{length} = 11.5mm$

$$Volume_{Ball} = \frac{4}{3} * Pi * Ball_{radius}{}^{3} - Pi * Ball\ Hole_{radius}{}^{2} * Ball\ hole_{\ length}$$
$$= 1767 - 731$$
$$= 1036mm^3$$

$$Volume_{Frame} = Pi * Frame_{radius}{}^{2} * Frame_{length} = 3859mm^3$$

$$Volume_{total} = Volume_{frame} - Volume_{ball} = 3859 - 1036 = 2823mm^3$$