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INDUSTRIAL VALVES FOR THERMAL APPLICATIONS AT LOW TEMPERATURES: LITERATURE REVIEW AND CASE STUDY

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Abstract. *Industrial valves are mechanical devices used to manipulate and manage fluids in an industrial plant. They are used in several applications, being considered of high criticality, those that involve the use in low temperatures. For these applications, so-called cryogenic valves are used, which are designed with specific geometry. The metallic and polymeric materials used are carefully selected to suit the contact with cryogenic fluids, where temperatures can vary from -46 °C to -254 °C. This article presents a literature review on the main concepts of a cryogenic ball valve design, presenting constructive aspects, normalization, related works, and finally, a case study related to a product approval test is presented. Thus, this work presents itself as complementary and auxiliary literature for students and professionals in the field related to the project, qualification tests, and the use of cryogenic valves, contributing yet to a better specification and use of these devices, aiming at a longer useful life and safety for the operation and the environment.*

Keywords: *Cryogenic valves, Pipe fittings, Thermal applications, Literature review, Case study.*

1. INTRODUCTION

Industrial valves are mechanical equipment designed to direct, initiate, block, control, mix, and regulate the flow, pressure, or temperature of a process fluid. They are applied in all industries that need to manage liquids and gases in their production process, such as oil and gas, pulp and paper, chemical, nuclear, food, among others (Skousen, 2011).

The thermal applications of valves for cryogenic services are extremely important for several industrial segments and require the use of special materials and adequate designs to meet such conditions. Also required for these valves are product qualification tests according to international standards and user specifications (Welsford, 2021).

Several industries use cryogenic valves, Figure 1, such as petrochemical, chemical, industrial gas manufacturers, pharmaceutical, food, among others. According to IOGP S-562 (2019), cryogenic services are those where the temperature is below -46 °C. Table 1 shows the temperature of fluids considered cryogenic under a pressure of 1 atm (Cameron, 2015).



Figure 1. Example of the cryogenic valve (adapted from Micromazza, 2022).

Table 1. The temperature of cryogenic fluids at 1 atm (adapted from Cameron, 2015).

Cryogenic Fluids	Temperature (°C)
Carbon dioxide	-78
Ethylene	-104
Methane	-162
Oxygen	-183
Argon	-186
Nitrogen	-196
Hydrogen	-254

Nowadays, the development of cryogenic products is still a challenge for the equipment industry. By its definition, cryogenic services imply being used at extremely low temperatures. An application example is liquefied natural gas (LNG); the liquefaction process reduces the volume of the gas by about 600 times, making it much more economical to transport onboard ships to various destinations around the world. The temperature required to liquefy this gas is -162 °C, which requires adequate tubes, valves, and connections to meet these conditions (Andersen & Shifrin, 2022).

Cryogenic valves have special designs, although they use the same basic concepts of functionality as general-purpose valves. The most used valve categories, customized for cryogenic applications, are ball, gate, globe, and butterfly. These designs have some differences in geometry and material selection compared to conventional valves, such as using an extended stem and materials from the austenitic stainless-steel group (Smith & Zappe, 2004).

According to BS 6364 (1984) or MSS SP 134 (2012) standards, these projects must undergo qualification tests when adapted for cryogenic services. These tests simulate valve operation in a cryogenic application at a temperature of -196 °C, where leakage rates, working pressures, test system temperatures, actuation torques, and the number of cycles are monitored. After the tests have been carried out and compliance with the acceptance criteria present in the standards and specifications has been demonstrated, the valve is approved and considered suitable for use in cryogenic services.

Although currently there are standards and designs for cryogenic valves available on the market, there are still flaws in the specifications and uses of valves for such purposes. In this context, this work aims to present the main concepts of the ball valve for cryogenic thermal applications. Aspects of projects, groups of materials used, normative specifications, and citations of recent articles are discussed, and finally, a case study related to the approval of a ball valve, according to MSS SP 134 (2012), is presented.

2. CRYOGENIC VALVE DESIGN

Although using the same operating concepts as general-purpose valves, like: ball, gate, globe, and butterfly, the projects developed for cryogenic services have some specific details, such as using an extended stem. The stem extension can distance the valve actuation system from the pipeline. In this way, a gas column formed inside the extension is generated, which isolates the cryogenic temperature of the operation to the valve actuation device. The actuation of the valve can be of the manual type through a lever or automatic activation using pneumatic, electric or hydraulic actuators.

The extension distance is defined by MSS SP 134 (2012) according to the pipe diameter in two conditions called Cold Box and Non-Cold Box, i.e., the distance from the gas column varies according to the application. Figure 2 outlines a ball valve design for cryogenic service, identifying the main components. Next, each valve part or component details are presented, presenting their characteristics and functions.

- 1) **Body** and **Cover** are the components that make up the valve housing. They are elements that contain the fluid pressure and house the sealing system between the seat and the ball. The Covers can be manufactured with different ends for connection to the pipe, such as flanged, threaded, socket, and extension nipples for welding. The most used materials for the manufacture of these items are austenitic stainless steels. The BS 6364 (1984) standard specifies cast and forged steels, as shown in Table 2.

Table 2. Austenitic steels indicated for the manufacture of cryogenic valves (adapted from BS 6364, 1984).

ASTM Standard and Grades	
Forgings	Castings
ASTM A182 GR F304	ASTM A351 GR CF8
ASTM A182 GR F316	ASTM A351 GR CF8M
ASTM A182 GR F304L	ASTM A351 GR CF3
ASTM A182 GR F316L	ASTM A351 GR CF3M
ASTM A182 GR F321	ASTM A351 GR CF8C

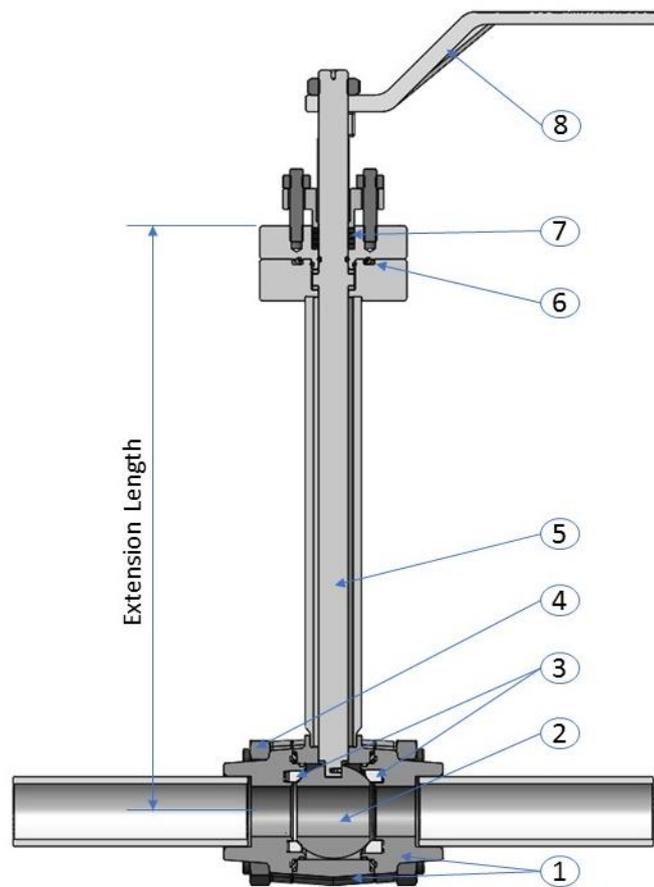


Figure 2. Sketch of a cryogenic ball valve and its main components (adapted from Micromazza, 2022).

- 2) **Ball** is the valve obturator. Its function is to block the flow of fluid in the process. This element has a through-hole with the same diameter as the pipe, allowing the fluid's passage when parallel to the flow. Generally, for cryogenic valves, the balls also contain a relief hole perpendicular to the passage, preventing pressure retention in the internal cavity of the body. With the use of the relief hole in the ball, the valve to have a preferential flow direction; in this way, the body is marked with an indicative arrow to indicate with the mounting position in the line. If the ball valve concept is of the trunnion type, the sealing occurs upstream, and if it is of the floating type, the fluid-tightness occurs in the downstream seat (Teles et al., 2022). The balls are manufactured from the same body and cover material groups, as shown in Table 2.
- 3) **Seat** is the element that seals through contact with the ball. It has a ring shape and can be manufactured in polymeric materials such as PTFE and PCTFE. They can also be manufactured in stainless steel coated with a material with greater hardness like Stellite[®]. Seats can be designed to be energized by springs to compensate for material contractions when subjected to cryogenic temperatures. The contact geometry between the seat and ball is developed by the valve manufacturer (Hoeffner, 2021).
- 4) **Bolts and Nuts** are specified in materials compatible with the valve body and cover. The manufacture of bolts usually is according to ASTM A320 GR B8M, and the nuts to ASTM A194 GR 8M.
- 5) **Stem** has the function of interconnecting the ball and the valve actuation system and is manufactured according to groups of materials presented in Table 2. The minimum height of the extension is presented in Table 3 for two applications called Cold Box and Non-Cold Box. The extension of the stem for cryogenic valves is of paramount importance, as a column of steam is formed in it, which prevents the cryogenic temperature from reaching the stem sealing system and the actuation, thus preserving these elements.
- 6) **Body Sealing System** is considered a static type seal. This system can be composed of primary seals of the resilient type like PTFE and secondary seals based on graphite of the Spiral Wound Gasket type, mainly to meet qualifications such as Fire Test according to ISO 10497 (2010).
- 7) **Stem Sealing System** is a dynamic seal used due to the ¼ turn movement of the stem to open or close the valve. This system can be composed of primary and secondary seals likewise to the body sealing system, however with the use of Gasket Rings of square sections. It contains components like a Packing Gland and Fasteners that can be adjusted until the fluid is sealed.

- 8) **Lever** is a component fixed to the stem with the function of opening or closing the valve. Turning clockwise closes the valve and counterclockwise opens it. In addition to the use of levers, the valves can be designed for automatic activation using actuators of the following types: pneumatic, electric or hydraulic.

Table 3. The extension length of stem (adapted from MSS SP 134, 2012).

Quarter-Turn Valves			
Size (NPS)	Size (DN)	Cold Box (mm)	Non-Cold Box (mm)
1/2	15	400	200
3/4	20	400	200
1	25	400	200
1 1/2	40	500	225
2	50	500	250
3	80	550	300
4	100	600	350
6	150	600	425
8	200	650	450
10	250	700	600
12	300	800	700

3. CASE STUDY

3.1 Prototype Specification

This case study presents the approval tests of a floating ball valve according to the requirements of MSS SP 134 (2012). The project characteristics are presented in Table 4.

Table 4. Specifications of the valve prototype tested according to MSS SP 134 (2012).

Specifications	Standards
Floating Ball Valve NPS 1" Class 800	ISO 17292 (2015) and ASME 16.34 (2020)
Extension Length of the Stem	Non-Cold Box
Body and Cover Materials	ASTM A182 GR F316
Internal Components	ASTM A182 GR F316
Bolts and Nuts	ASTM A 320 GR B8M / ASTM A 194 GR 8M
Seats	PCTFE
Body Seals	Primary PTFE and Secondary Spiral Wound Gasket (316+Graphite)
Stem Seals	Primary PTFE and Secondary Gasket (Graphite+Inconel)
Ends for the Pipe	Parallel ends extension nipple for welding.

3.2 Test Methodology

The test methodology used was the MSS SP 134 (2012) standard. Figure 3 presents an outline of the test apparatus for cryogenic valves. The test instrumentation involves connecting the test valve (1), by flanges or welding, in a fluid/pressure inlet pipe and an outlet pipe. Throughout the test stages, the latter is connected to a Flow Meter (5), equipment that checks the valve's leakage rate between the seat and the ball. The valve is fixed inside a Tank (2), where it is submerged in liquid nitrogen to reach a temperature of -196 °C, where it will remain throughout the test. The valve should be submerged about 25.4 mm above the intersection of the body with the extended stem system. The drive system and the packing must not be submerged in liquid nitrogen and must be free to access to carry out the drives. The test fluid used is helium (3) with about 99% purity. According to the valve class, the pressure inlet piping must contain pressure gauges calibrated to meet the test pressure range. Thermocouples (4) are installed in the region of the stem seals, in the lower part of the valve body where it is submitted, and at the end of the outlet pipe at the location of the leakage rate measurement. The acceptance criteria for seat leakage are shown in Table 5.

The leakage to the external environment of the valve is monitored by the Sniffing Method (Figure 4). In this case, the helium concentration present close to the regions of the seals to the valve's external environment is verified. For this verification, a Helium Mass Spectrometer (2) connected to a Probe (3) is used, being moved around the valve manually by the test operator.

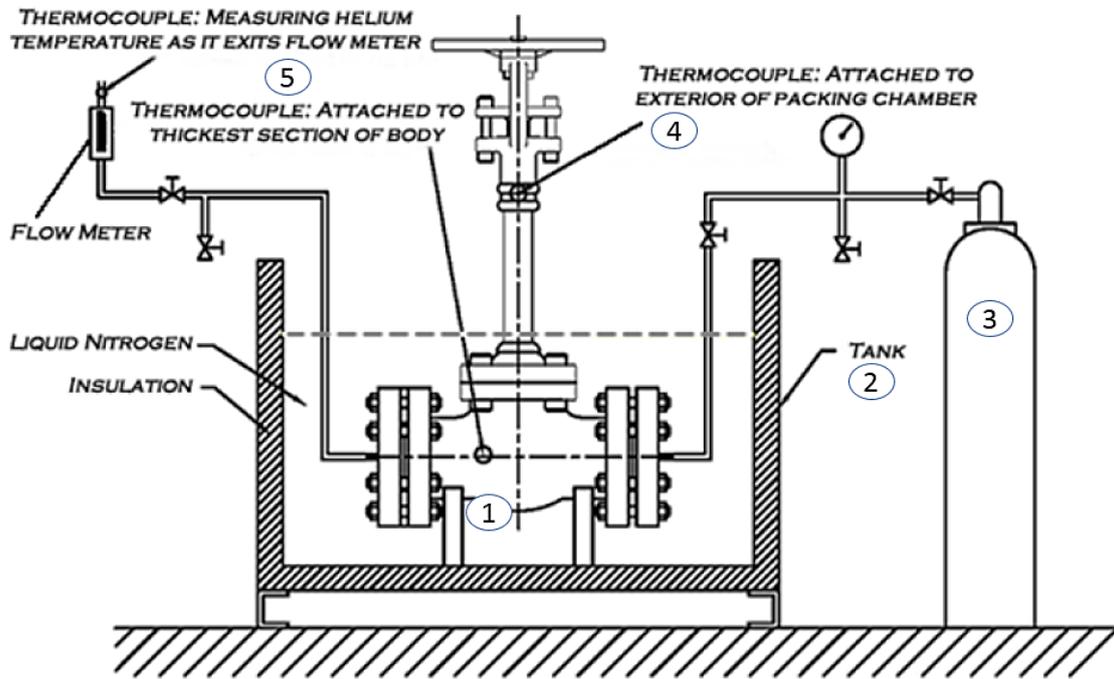


Figure 3. Sketch the test setup (adapted from MSS SP 134, 2012).

Table 5. Allowable helium seat leakage rates for cryogenic closure tests (adapted from MSS SP 134, 2012).

Seat Test	Allowable Leakage (scc/minute/NPS) Gate, Globe, Butterfly, and Ball	
	Soft Seat	Metal Seat
Low-pressure seat test (5,5 bar)	25	50
High-pressure seat test for classes 150, 300 and 600	75	150
High-pressure seat test for classes 800, 900 and 1500	100	200

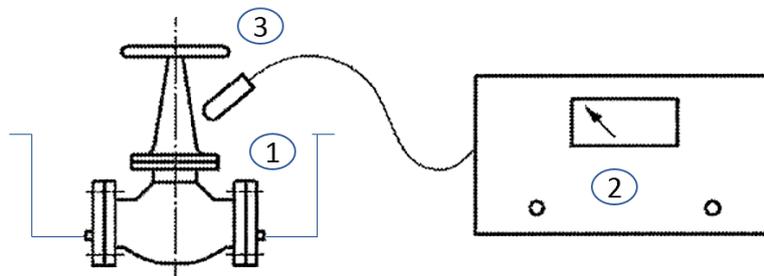


Figure 4. Sketch the sniffing test (adapted from ISO 15848-1, 2015).

3.3 Results and Discussions

Initially, the valve was kept fully open. Subsequently, the valve was immersed in the tank with liquid nitrogen (Fig. 5). At the time of immersion, the valve was kept under a pressure of 1 bar using helium fluid. A small leak was maintained downstream in the system. The valve was submerged with liquid nitrogen fluid at least 25.4 mm above the bolted joint of

the body and cover. Three opening and closing cycles were performed after the valve stabilized at cryogenic temperature $-196\text{ }^{\circ}\text{C}$ according to MSS SP 134 (2012) requirements.

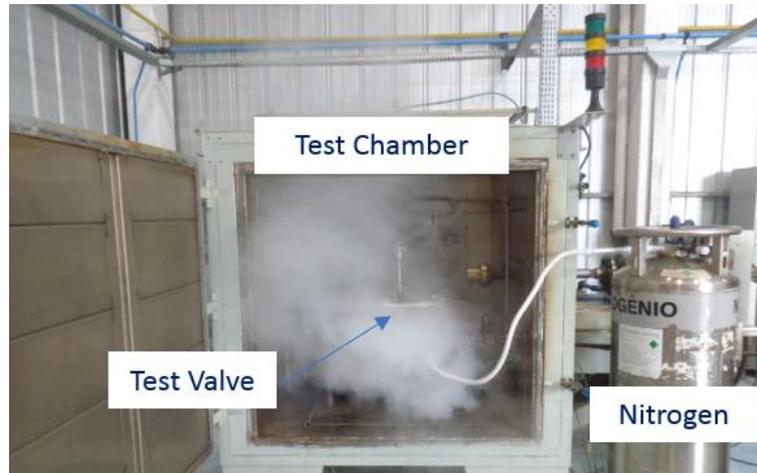


Figure 5. Valve under test.

After the initial steps, the first seat tightness test was carried out at a low pressure of 5.5 bar for 10 minutes. No visible leaks were witnessed. The system temperatures were recorded in this step: $-196\text{ }^{\circ}\text{C}$ at the valve body, $16\text{ }^{\circ}\text{C}$ at the bonnet, and $20\text{ }^{\circ}\text{C}$ at the valve outlet piping near the flow meter. Subsequently, the high-pressure test of the seat was carried out considering the valve's pressure class 800. According to MSS SP 134 (2012) standard, a pressure of 110.3 bar was used. In this step, visible leaks in the flow meter were also not evidenced.

After approval of the tightness test between seat and ball, the body pressure test was carried out using the Sniffing Method. The test was performed with the valve still at cryogenic temperature, where it was pressurized with 13.8 bar in the semi-open position. The valve was removed from the nitrogen tank (Fig. 5a), where the probe connected to the Helium Mass Spectrometer (Fig. 5b) was passed. The concentration of helium gas in the environment around the valve was verified. The acceptance criterion is up to 50 PPM, found around 21 PPM (Fig. 5c).

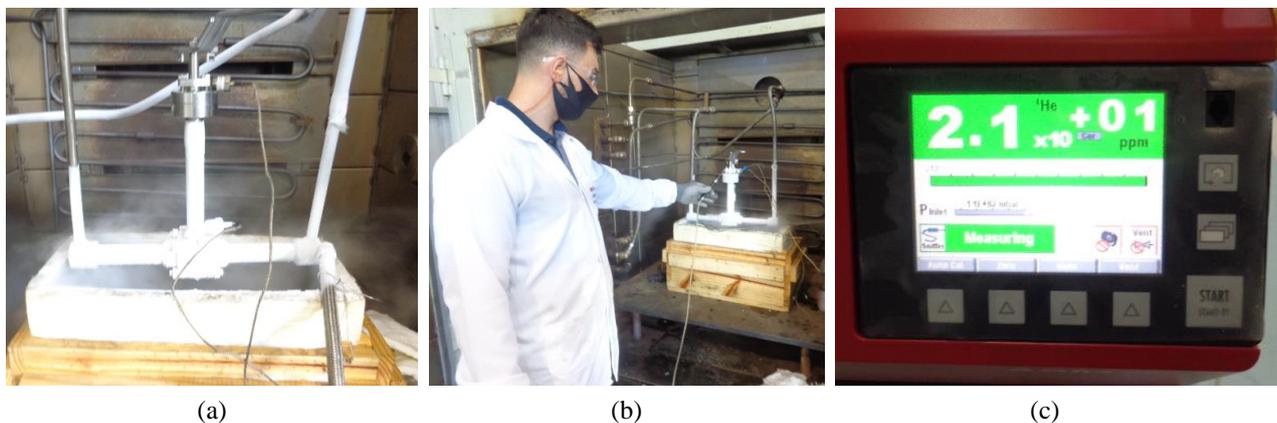


Figure 5. Sniffing test at cryogenic temperature.

After the cryogenic tests, the seat tightness test was carried out at low pressure, where no visible leakage was observed. The body test was also carried out with the Sniffing Method at room temperature, where approximately the same value of the local concentration of helium gas in the environment of the previous test was verified.

A relevant fact was the increase in the valve actuation torque at cryogenic temperatures. At room temperature, before and after the cryogenic tests, torques were found to open the valve with the maximum working pressure, around 20 N-m. In the seat pressure test at cryogenic temperature, it was found that the maximum torque at the moment of opening reached approximately 36 N-m, about an 80% increase. After completing the tests, the valve was dismantled, and a visual and dimensional inspection of the components was carried out. No faults were found in the elements, and the valve is ready for use even after the approval tests.

4. CONCLUSION

The main conclusions of this work are summarized in the following topics:

- Cryogenic valves play a fundamental role in several industrial segments, so it is of paramount importance that professionals in the environment know the main concepts of operation of these valves and what the main qualification standards are applicable. In this way, it can be ensured the proper specification of the product for the required application.
- The use of cryogenic valves tends to increase with the advent of natural gas transport and storage worldwide, which will increase the consumption and use of this equipment.
- It is essential for professional manufacturers and users of these devices to know the most suitable metallic and polymeric materials for cryogenic applications;
- In the case study, no visible leaks were found between the seat and ball and also by Sniffing Method. It was verified that the leakage from the valve body and cover seals were within the acceptance criteria of the MSS SSP 134 (2021) standard. However, there was a considerable increase in the value of the valve actuation torque in the cryogenic situation. This increase in torque comes from the contractions of the materials used to manufacture the components. Although this increase in torque did not affect the valve's performance, the drive system dimensioning is worth noting. In cases of specification of automated drive, a possible increase in torque must be considered the lower the operating temperature. Therefore, the valve manufacturer must be consulted to verify the percentage of torque increase; in this way, perform the correct specification and dimensioning of the actuation system.
- It also verified the gas column efficiency from the extension of the stem regarding the temperature of the actuation system, which remained close to room temperature, even with the valve body submerged in liquid nitrogen at -196 °C. This arrangement allows simple manual actuation of the valve.
- It is concluded that, when properly designed and tested, cryogenic valves can provide longer life and safety in applications to operators and the environment.

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