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Cryogenic safety in helium cryostats at CERN

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Abstract. Cryostats contain large cold surfaces, cryogenic fluids, and sometimes large stored energy (e.g. energized magnets), with the potential risk of sudden liberation of energy through thermodynamic transformations of the fluids, which can be uncontrolled and lead to a dangerous increase of pressure inside the cryostat envelopes. The consequence, in the case of a rupture of the envelopes, may be serious for personnel (injuries from deflagration, burns, and oxygen deficiency hazard) as well as for the equipment. Performing a thorough risk analysis is an essential step to identify and understand risk hazards that may cause a pressure increase and in order to assess consequences, define mitigation actions, and design adequate safety relief devices to limit pressure accordingly. Lessons learnt from real cases are essential for improving safety awareness for future projects. We cover in this paper our experience on cryostats at CERN and the design-for-safety rules in place.

1. Introduction

At CERN, helium is the coolant of choice for operating high field superconducting magnets and accelerating radio-frequency cavities in particle accelerators like the LHC, as well as for the superconducting magnets of its particle detectors like ATLAS and CMS. It is also widely employed in the laboratories and testing facilities where magnets and cavities are developed and tested.

Cryostats for a variety of applications have been designed and constructed at CERN for which an expertise in the field of cryogenic safety has been established, also based on lessons learned from experience, and which is now being capitalized on the design and construction of new equipment. Figure 1, depicts some examples of helium cryostats in use or under design, and Table 1 summarizes a few of the parameters relevant to cryogenic safety. The large variety in geometries, helium inventory and stored energy, requires dedicated safety designs. Cryostats range from bulky and containing large helium inventories as for the High Field Magnets (HFM) test cryostat, to longer and more slender geometries as in the LHC machine cryostats, or the superconducting link for cold powering now under developed for the High Luminosity LHC (HL LHC) upgrade. The resulting pressure drops during helium discharge, either in normal operation or during accidental events, are very different, affecting the sizing and number of overpressure limiting safety devices [1-3]. Magnet cryostats also contain large stored energies, and are designed to withstand pressure increase and helium discharge following quenches. Still, accidental scenarios from electrical faults like shorts and the development of high-power arcs have to be included as possible events, for which exceptionally high helium flow-rates can be expected, leading to the design of large diameter safety devices. In some special applications, like in the cryo-modules for the HIE Isolde [4], cavity cleanliness requires assembly in clean rooms and therefore multi-layer insulation cannot be employed for thermal insulation, hence large bare cold surfaces remain exposed to the highest heat fluxes and helium boil-off in case of accidental venting of the cryostat to atmosphere.

Figure 1. Some examples of helium cryostats for accelerator devices at CERN: (from left to right): the LHC dipoles, the HFM vertical test cryostat, the HIE Isolde cryo-module (before insertion in its cryostat), a 60-m prototype of a SC link for HL LHC.

Table 1. Selected properties for some helium cryostats at CERN.

	LHC single dipole	String of 6 LHC dipoles in a 106 m cryogenic sector of the machine	HFM Vertical Test Cryostat	HIE Isolde Cryo-module	SC link for cold powering in HL LHC (100 m length)
Helium vessel volume [l]	375	2650	6100-7000 (depending on magnet) of which 3000-4000 LHeII	270 (of which 150 LHeI)	800
Helium vessel surface [m^2]	33	200	22.4	4.9	50
Stored energy [kJ]	8600	51600	1300-6000 depending on magnet	19	
Helium phase(s)	LHeII	LHeII	LHe I / LHeII	LHe I/vapor	vapor
Operating temperature [K]	1.9	1.9	1.9	4.5	4.5
Operating pressure [bar]	1.3	1.3	1.3	1.3	1.3

The thermo-physical properties of helium (Table 2) lead to a number of useful observations related to pressure hazards. Owing to the low latent heat of evaporation of helium as compared to other cryogens (~10 times lower than N_2) even low heat in-leaks lead to high boil-off rates (~50·10^{-3} g/s per W), so special care has to be taken to minimize them by appropriate thermal management. Furthermore, when comparing latent heat per unit volume, being a more relevant property for heat transfer through surfaces, a same vessel containing helium, of lower density, would require about 60 times less heat to evaporate as compared to nitrogen. The comparison with nitrogen is particularly appropriate as one of the driving hazards in sizing the safety devices against overpressure is an accidental venting to atmosphere of the insulation vacuum of a cryostat. In this case an air inrush from a breach in the vessel condenses essentially nitrogen onto the cold surfaces with heat power depositions, mainly from latent heat, in the order of a 1 to 4 kW/m^2, depending on the thermal insulation at the cold surface. So, roughly speaking, the inrush of 1 liter of air at room temperature causes the boil-off of about 60 liters of helium. Another special property of helium is the high density of its vapors with respect to the liquid phase (only about 7.4 times lower at boiling temperature and 1 bar), and which is also almost 4 times higher than the density of nitrogen vapors (but the latter being at 77 K). As a consequence, the residual helium content after evaporation of the liquid in a reservoir cannot be neglected as it retains a residual potential for expansion and pressure rise. This is why long transfer lines like the SC link, though containing only helium vapors, still need to be equipped with safety devices to protect against overpressure in the case of accidental venting of the insulation vacuum or bursting of the helium line.

Finally, helium has very special properties when in its superfluid state: the very high apparent conductivity of helium provides a beneficial *quasi*-isothermal heat deposition in the bulk helium and the

extraordinarily high specific heat while crossing the lambda line to normal liquid moderates the temperature increase in the very beginning of a heat deposition process, before the enthalpy of materials takes over. All these properties have to be taken into account when including safety aspects in the design of helium cryostats.

Table 2. Thermo-physical properties of selected cryogens.

	^{4}He	N_2	Ne	Ar
Boiling temperature (at 1'013 mbar) [K]	4.2	77.3	27.1	87.3
Latent heat of evaporation [kJ/kg]	21	199	87.2	163.2
Latent heat of evaporation per unit volume at 1 bar [kJ/litre]	2.6	160	104	220
Liquid density, at boiling temperature [kg/m^3]	125	804	1'204	1'400
Density ratio, ρ_{liquid}/ρ_{gas} (gas at boiling temperature and 1 bar)	7.4	175	126	240
Gas/liquid volume ratio (gas at 273 K and 1 bar)	702	652	1'356	795
Specific heat ratio LHeII/Cu per unit mass (and unit volume) at 2 K	$\sim10^6$, ($\sim2\cdot10^4$)	N.A.	N.A.	N.A.

2. Safety prescriptions for cryostats at CERN

Helium cryostats, as well as all cryogenic equipment in use at CERN, have to satisfy to the safety instructions and requirements in force in the Organization. Having an intergovernmental status, CERN establishes its own safety policy and underlying rules. Nonetheless, CERN's safety policy is based on the enforcement, as far as practically possible, of European directives and standards. As a general rule this also applies to cryogenic equipment and cryostats. Nevertheless, some specific applications do not fall under the scope of the directives and for these cases *ad-hoc* measures have to be taken in order to give proof of safety to CERN's safety authority.

2.1. Pressure safety prescriptions for cryostats

Cryogenic equipment, including cryostats, generally fall under the category of *pressure equipment*, as defined in the European Pressure Equipment Directive (PED) 2014/68/EU of the European Parliament [5] (and proceeding releases), for which the conformity assessment, covering the design, manufacturing, and qualification testing is a legal obligation in the EU since 2002. It applies to all equipment with an internal maximum allowable pressure ≥ 0.5 bar, therefore considered to be pressure vessels.
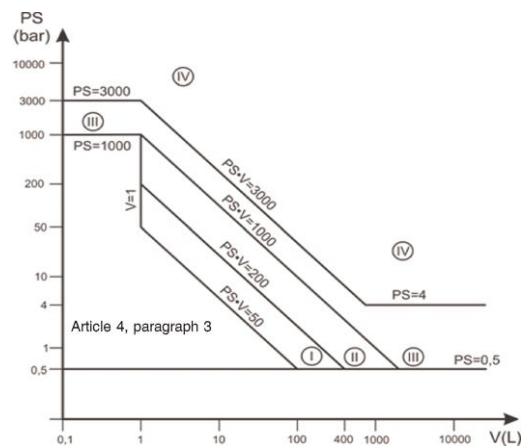

Figure 2. Category of pressure vessels according to stored energy, expressed in bar.l (extract of Directive 2014/68/EC).

Four categories of pressure vessels, Cat.I to Cat IV, are identified according to increasing pressure stored energy in the vessel, expressed by the design pressure multiplied by the volume (bar.l), and have to undergo increasingly stringent levels of conformity assessments. From Cat. I and above, a certification process, with a visible marking (CE marking) of the equipment becomes obligatory.

Cryostat vacuum vessels do not fall under these categories provided their pressure relief devices have been designed to limit overpressure to 0.5 bar gauge, and are simply designed in accordance with sound engineering practice. Nevertheless, it is often a good practice to enforce manufacturing requirements for Cat.I while still not being bound to the formal certification process.

2.1.1. Special equipment. Following the PED is not always possible for special applications. As an example the cryogenic helium vessels for superconducting magnets, like those of the LHC dipoles, owing to their size and high design pressure (in case of quench), would fall under Cat.IV (an LHC dipole, containing a helium volume of about 300 l and designed for 20 bar pressure, has a pressure stored energy of 6'000 bar.l) requiring the highest level of conformity assessment which cannot be completely complied with; for instance some geometries of welds do not conform to the norms, and some other cannot undergo NDT inspections. As a matter of fact, the predominant mechanical requirement of the helium vessel is the containment of the electromagnetic Lorentz forces developing in the structure of the magnet when energized, rather than pressure forces; the azimuthal membrane stress levels taken by the vessel is of the order of 150 MPa, about 3 times higher than the same type of stress induced by a 20 bar pressure during a magnet quench. Another example of vessels non-conforming with PED are the helium vessels for RF superconducting cavities made in bulk niobium. The cavity is part of the helium vessel but niobium is not, according to the norms, a certified material for pressure equipment. Furthermore, due to the low mechanical properties of niobium at room temperature, elliptical cavities may not be able to withstand pressure testing as specified; this is, for example, the case of the 1.3 GHz cavities for the European XFEL, for which pressure testing could be made, and had to be replaced by the implementation of a very strict and detailed quality assurance plan, covering all critical steps including design, qualification of raw materials, and monitoring of all manufacturing and assembly phases [6].

It is clear that in similar cases, cryogenic devices have to provide presumption of conformity with safety by undergoing assessments following non-conventional paths, and applying additional quality control and inspection procedures. At CERN the safety prescriptions for special equipment have to be agreed on a case-to-case basis with the internal safety authority.

2.2. *Applicable European Standards*

Within the PED legal frame, the use of harmonized European standards ensures presumption of conformity. A complete suite of European standards exist and are widely used for pressure vessels, for example the EN 13445 series covering the choice of materials, design rules, fabrication, inspection and testing. The use of other national or international standards is also allowed, but subject to the approval of CERN's safety unit.

Compliance with pressure regulations for cryogenic equipment involves a thorough understanding of the requirements for which the device is designed, including off-nominal operating conditions and accidental scenarios. This task can be quite difficult in cryogenic devices for accelerators considering the complexity of the systems involved, the cryogenic fluid thermodynamics phenomena as well as the mechanics at cryogenic temperature. Once the requirements are understood, well established standards exist which are a useful aid in the mechanical design of cryogenic equipment; for instance the European standards of the EN 13458 series, which provides rules for the mechanical design, fabrication, inspection and testing and operation of static vacuum insulated cryogenic pressure vessels.

As part of the design of cryogenic devices, the selection of the appropriate safety devices for the protection against excessive pressure has to be made. Safety valves and bust disks are commonly employed protection devices, and their design and certification testing is covered in the European standard of the EN 13648 and EN 4126 series (now being replaced by ISO 210013-3). The standards

also provide calculation methods for determining the mass flow to be relieved through the safety devices under accidental conditions.

Despite the abundance of guidelines and design rules provided by the above standards, mainly destined to industrial applications, liquid helium cryostats have specificities that are not sufficiently covered. For example the nearly instantaneous boil-off due to low latent heat, or the containment of non-conventional equipment like superconducting magnets with large stored energies regularly dumped to helium during quenches. For this reason the European cryogenic community, including CERN representatives, has recently agreed to elaborate, in the frame of the European technical committee CEN/TC/268, a new standard specifically devoted to *safety of liquid helium cryostats.*

3. Pressure hazard and safety in helium cryostats

The use of codes and standards illustrated above, though being an undoubted aid, should not exclude the good understanding of the principles and specific physical phenomena involved, especially for new and special applications and prototypes not covered by past experience. Good engineering practises, based on a good understanding of the underlying phenomenological description, supported by mathematical modelling and experimentation, remain essential. Cryogenic safety in helium cryostats is not an exception to this rule.

Probably the most difficult part of the design for safety process is in making a sound and thorough risk analysis, compiling the risk assessment matrix with identified risk hazards, likelihood versus severity, and deciding the acceptance level of risk. In the absence of reliable statistics on the occurrence of hazards and their consequences, the risk assessment exercise may slide into biased subjective judgements. Nonetheless, structuring a risk assessment process from the early stage of the design, is beneficial because it allows making design changes to introduce mitigation measures on most of the identified hazards. Residual risks involving injury to personnel (for example injury from blasts, ODH, cold burns), even if considered unlikely to happen, must be systematically addressed and lead to preventive measures (zone access limitations, use of personnel protective equipment, safety training). For the remaining risk hazards involving the integrity of the equipment, the *credible* worst-case scenario is the one for which safety devices should be designed. The level of acceptance of the residual uncovered risk remains under the responsibility of the stakeholders of the installation to which the equipment belongs.

When making the risk assessment related to overpressure hazards in cryostats, a variety of operating conditions have to be included. A non-exhaustive list of potential sources of overpressure, includes:
-    Compressors or pressure reservoirs, connected to the cryostat through cryogenic lines;
-    Heating of "trapped" volumes during warm-ups (e.g. enclosed volumes between valves);
-    Additional heating from degraded performance of insulation vacuum due to helium leaks;
-    Sudden vaporization of cryo-condensed gasses on cold surfaces during warm-ups, with consequent additional heating from degraded thermal performance;
-    Heating/vaporization of cryogens from sudden release of stored energy in SC device (e.g. quench or arcing in a SC magnet circuit);
-    Accidental air venting of insulation vacuum with sudden condensation on cold surfaces;
-    Accidental release of cold helium through a breach in the vessel, subsequent heating and expansion with a consequent pressure increase and further convective heating;

The last three of the sources of overpressure listed above are generally the ones defining the design conditions for the pressure relief devices in cryostats.

3.1. Design of pressure relief devices

The sizing rules are well described in EN 13648 "Safety devices for protection against excessive pressure". Pressure relief devices have to be designed to protect each enclosed volume in the circuits of the cryostat, including as a minimum those of the vacuum vessel, the helium vessel and the thermal shield cooling. Once the *credible worst-case scenario* event is identified, the safety relief system must

be designed to ensure that the pressure rise remains, within 10% according to the norms, of the design pressure (PS) for each circuit.

The design process can be split according to the following steps:

- **Step 1.** Appreciation of the worst-case scenario, estimation of the heat flux power deposition and calculation of the mass flow rates to be discharged;
- **Step 2.** Check the sizing of piping (generally designed for normal operation) to the relief device and increase if necessary;
- **Step 3.** Choice of the type of safety device (burst disks, valves, plates) and size the safety device (minimum relief area and set pressure). Include the use of safety device manufacturers formulas and charts;
- **Step 4.** Sizing of the exhaust piping downstream of the safety device and check open venting needs in the buildings and risk for ODH, or the use of closed recovery lines;

3.1.1. Case study. Pressure relief devices for the HIE Isolde Cryo-modules [7]. In the following we consider the case of the helium cryostat of the HIE Isolde cryo-module, which integrates five niobium sputtered copper quarter-wave resonators and one superconducting solenoid, all operated in 4.5 K boiling helium.

Two worst-case scenario are considered, *worst-case I* sizing the relief device protecting the helium vessel, and *worst-case II* sizing the one of the vacuum vessel.

Worst-case I is the consequence of a breach in one of the vacuum vessel's beam ports, possibly caused by rupture of a bellows due to an accidental mechanical operation; a sudden air inrush calculated to be equivalent to 0.15 kg/s of choked flow, and cryo-condensing on the bare cold surfaces (not having MLI protection) creates a maximum heat flux of 76 kW to the liquid through the helium vessel walls. Due to the choked flow, the heat flux remains lower than the maximum specific value of 38 kW.m^{-2} reported in literature [8]. This heat flux converts in a maximum vaporization rate of the liquid helium of about 30 l/s or 4 kg/s. After a fast transient of a few seconds, pressure builds up to become supercritical, then reaches the design pressure of 3.5 bar absolute equivalent to the set pressure of the safety device. A 25% mass flow margin is added to account for potential obstructions of the relief area by stripped instrumentation wires and insulating materials during the flow discharge. Helium is exhausted and routed outside the tunnel roof shielding to atmosphere via a 2-m long low-impedance collector not to reduce the peak mass flow. Figure 3, left, illustrates the sequence of events. The selected safety device is a DN50-mm burst disk (Figure 4, left), protected by a safety valve rated at a lower pressure to cope with operational mishaps exhausting limited quantities of helium.
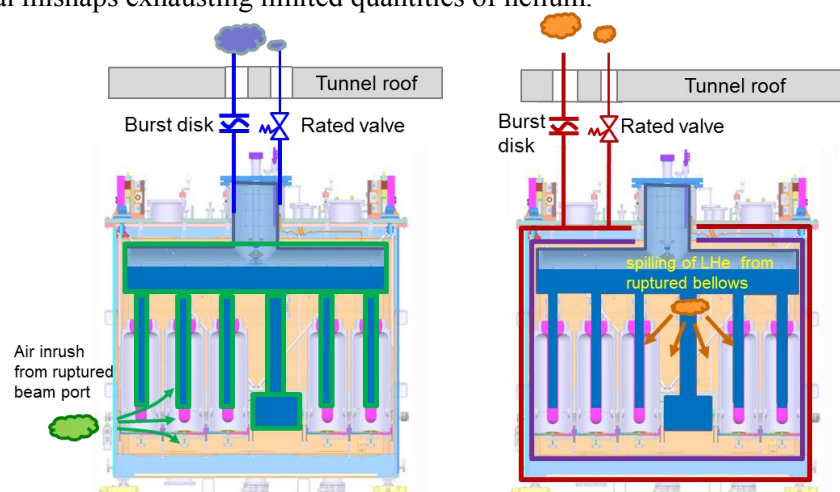

Figure 3. *Worst-case I* (left): sudden air inrush to the insulation vacuum, helium boil-off and pressure increase in the helium vessel, relieving through its safety device. *Worst-case II* (right): breach in internal

bellows, liquid helium spill to the vacuum vessel, vaporisation and expansion of the gas up to the burst disc relief pressure of the vacuum vessel.

Worst-case II is the consequence of the internal rupture of one of the six bellows connecting the solenoid and cavities to the helium reservoir, due to an excessively high torsion applied during an uncontrolled and poorly monitored mechanical adjustment of their internal position at cold. A cold helium spill, estimated at about 5 kg/s, floods the vacuum vessel and suddenly vaporized and expands in contact with the warmer surfaces. The loss of insulation vacuum adds convective heat transfer which further accelerates the gas expansion and pressure build-up until the safety relief device opens relieving helium to atmospheric pressure. Figure 3, right, illustrates the sequence of events.

The vacuum vessel safety device is designed to relieve a mass flow equal to the highest flow from the cryogenic vessel, but at a warmer temperature. This relief area is highly dependent on the relief temperature, which is difficult to estimate. In a first instance one should consider the most conservative assumption of discharging at room temperature. If the sizing results to be excessively large (often the case), one should review this assumption by taking into account more realistic (but still conservative) assumptions limiting the warm up of the fluid along the evacuation path.

A minimum calculated relief area corresponding to 112-mm diameter burst disk keeps overpressure of the vessel within a PS of 1.5 bar absolute (i.e. $\Delta p < 0.5$ bar with respect to atmospheric pressure) so that the vacuum vessel is not to be considered a pressure vessel according to the PED directives. The resulting helium peak mass flow is calculated to be 5 kg/s at an exhaust temperature which has been calculated to be 12 K after heating along the exhaust path from the breach, along the thermal shield up to the bust disk. The full rupture of a stainless steel bellows is considered a conservative scenario, and as a design mitigation measure, a protection cover is added around all bellows which also limits the maximum size of helium breach, limiting the mass flow. A larger burst disk, a DN180-mm, was finally selected for a matter of standardisation (Figure 4, right).
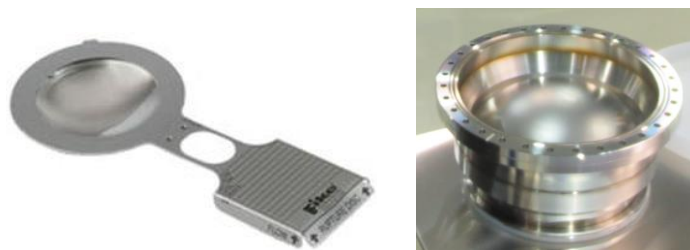

Figure 4. DN50-mm (left) and DN180-mm (right) bust disks for the protection of the helium vessel and vacuum vessel of the HIE Isolde cryo-modules.

4. The LHC accident in 2008

In September 2008, during the final machine commission tests, the LHC suffered a major accident when a faulty electrical joint between magnets developed an arc of about 4 MW bursting large breaches in the helium enclosure. The combined effect of additional power reaching the helium vessels from the arc, from the quenching of magnets, and from the degraded insulation of the cryostat, led to the development of pressure in these vessels over a time scale of several tens of seconds resulting in a massive release of liquid helium through the breaches into the insulation vacuum of the cryostats. Though the pressure rise in the helium enclosure was contained below the design pressure of 20 bar by the opening of the self-actuated quench relief valves, the helium release, with a peak mass flow estimate up to 20 kg/s, could not be discharged by the vacuum vessel-mounted spring-loaded relief discs, resulting in a pressure increase up to about 8 bar absolute, exerting large axial forces on the insulation vacuum barriers, causing mechanical failure of the ground supports of the magnets and large longitudinal movements creating secondary electrical arcs and helium breaches, resulting in a cascade effect on about 800 m of the machine [9]. Nobody was injured as machine access is forbidden during operation, but the damage to the equipment was severe, with about 50 magnets replaced.

The original worst-case scenario, for which the spring-loaded relief discs had been sized (two DN90 disks protecting a vacuum subsector of about 200 m of machine), was for a 2 kg/s mass flow resulting from a much smaller estimate breach, largely underestimated as compared to the accident. Following this event, the worst-case scenario was redefined considering that an arc could develop an even larger breach than the one which occurred, developing an even larger mass flow of up to 32 kg/s. The configuration of safety relief devices on the vacuum vessels was drastically upgraded, introducing DN200 plate disks on every dipole, i.e. multiplying by a factor of 30 the discharge area with respect to the original configuration.

Figure 5. The original DN90-mm spring-loaded relief disk after the 2008 accident (left) and the newly developed DN200-mm (right) plate disks for the up-graded protection of the LHC cryostats.

5. Summary
In this paper an overview is given of applications making use of helium cryostats at CERN, emphasizing aspects related to cryogenic safety. The safety prescription and the directives in force as well as the guidelines and design rules provided by European norms and standards have been outlined, as well as some limitations in their application for special equipment. Design principles for the protection of cryogenic devices against overpressure and the design of the protection devices have been presented and their application is illustrated through a real-case. The overpressure accident in the LHC in 2008 is reported as an exemplary case underlining the difficulty in making a thorough risk assessment on systems of high complexity where cryogenics safety is one of the elements in the chain but with the potential of sudden liberation of a large energy resulting in an uncontrolled cascade of events causing serious collateral damage.

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