Grant Agreement No: 731086

AMICI

Accelerator and Magnet Infrastructure for Cooperation and Innovation

Horizon 2020 / Coordination and Support Action (CSA)

DELIVERABLE REPORT

GENERAL HARMONISED GUIDELINES FOR THE SAFETY OF CRYOGENIC EQUIPMENT

DELIVERABLE: 5.3

Document identifier:	AMICI-D5.3
Due date of deliverable:	End of Month 30 (June 2019)
Report release date:	17 September 2019
Work package:	WP5:3 - Harmonisation - Cryogenic Safety Procedures
Lead beneficiary:	KIT
Document status:	Final

Delivery Slip

	Name	Partner	Date
Authored by	S. Grohmann (WP5.3 Task Leader)	KIT	17 September 2019
Reviewed by	P. Fabbricatore (WP5 Coordinator)	INFN	18 September 2019
Approved by	O. Napoly (AMICI coordinator)	CEA	23 September 2019

Deliverable:

D5.3 Harmonisation - Cryogenic Safety Procedures

Executive summary:

The overpressure protection of various types of cryogenic vessels is covered by a number of International Standards. Helium cryostats, however, include additional components such as superconducting magnets and cavities, electrical heaters and control valves with associated piping, which significantly influence the potential risk. At the European Committee for Standardization CEN, a new working group was hence founded as CEN/TC 268/WG6, dealing with 'Specific helium technology applications'. Supported by the AMICI project, its aim is to develop a European Standard for the protection of helium cryostats against excessive pressure that will be harmonized with the European Pressure Equipment Directive. It will cover the typical conditions in accidental scenarios in order to harmonize the risk assessment as well as design practices for the pressure relieving systems.

Beyond the actual state-of-the art, the status of available modelling codes is described that are able to consider and analyze the process dynamics of cryogenic incidents. In addition, the scope of future experiments and model developments is defined in order to implement dynamic models in a common Standard.

1 INTRODUCTION

Helium cryostats, other than cryogenic vessels used for storage of cryogenic liquids covered by ISO 21009 and EN 13458, include additional specific components such as superconducting magnets and cavities, electrical heaters, heat exchangers, bellows, circulation pumps and internal control valves. These components imply additional risks for excessive pressure increase, which are not covered by existing Standards and strongly influence the design of helium cryostats including their pressure relieving systems. A new working group was hence founded in July 2017 at the European Committee for Standardization CEN, dealing with *"Specific helium technology applications"*. This working group, CEN/TC 268/WG6, is formed by experts from international and national research laboratories and from industry in Europe together with their related national standardization bodies. Its aim is to develop a European Standard for the protection of helium cryostats against excessive pressure that will be harmonized with the European Pressure Equipment Directive (PED) [1].

In section **Erreur ! Source du renvoi introuvable.** of this report, we explain the overall scope and content of the new European Standard. This is followed by the plans to harmonize this Standard with the PED in section 3. Beyond the state-of-the-art, section 4 gives an overview on the status of dynamic modelling and on the plans to integrate such models in a future update of this Standard. A final summary is given in section 5.

2 THE NEW EUROPEAN STANDARD "HELIUM CRYOSTATS – PROTECTION AGAINST EXCESSIVE PRESSURE"

2.1 Scope and structure of the new Standard

The new European Standard *"Helium cryostats – Protection against excessive pressure"* will be applicable to superconducting magnet cryostats and cryostats for superconducting radio-frequency cavities, to coldboxes of helium refrigerators and liquefiers, to ultra-low temperature refrigerator systems using ^{3}He and ^{3}He/^{4}He mixtures as well as to helium distribution systems including valve boxes. Such cryostats are characterized by a variety of complex and individual design solutions, often exploiting small design margins for cutting-edge performance. Therefore, a common and specific technical solution for the protection against excessive pressure cannot be standardized. Rather, the *approach* of how to obtain a state-of-the-art protection is covered by this Standard, specifying the procedure and the minimum requirements for the various aspects in the main part of the Standard. Alternative and/or advanced methods, additional information, example solutions and exemplary measures are provided in an extensive Annex that mirrors the structure of the main part.

The new Standard is structured as follows:

- The technical part starts with a clause on "Risk assessment" whose content is described in section 2.2. It includes a pre-defined list of "Sources of excessive pressure" as risk scenarios to be considered in the risk assessments "– before ordering" and "– in the design phase". The "Evaluation of risks by the equipment owner/employer" is also covered.
- Risk assessment is the prerequisite for the following clause on "Protection concepts" further explained in section 2.3. It distinguishes between single- and multi-stage protection concepts and defines particular requirements for 5 different types of systems.
- The "Dimensioning of pressure relief devices" in the succeeding clause is based on a pre-defined protection concept. The Standard allows two alternative methods, which is shown in section 2.4.
- Further clauses address requirements on "Pressure relief devices", "Substance release" and "Operation of helium cryostats". Their content is briefly summarized in section 2.5.

2.2 Risk assessment

Risk assessment is the basis of any preliminary and detailed design process of helium cryostats. The new Standard defines 15 risk scenarios as “Sources of excessive pressure” (Table 1), which shall be considered in the risk assessment process. For each of these risk scenarios, common data and examples are given in the Annex.

Table 1: Sources of excessive pressure

Loss of insulating vacuum	Loss of beamline vacuum	Leak of cryogenic fluid
Quench of superconducting device	Thermal acoustic oscillation	Cryopumping
Entrapment of cryogenic fluid	Dielectric breakdown	Power failure
Pressure surge	Freezing	Backflow
Other sources of excessive pressure	Earthquake	Fire

In a first step, the Standard requires a qualitative risk assessment before procurement, typically accomplished by carrying out a Hazard and Operability Study (HAZOP) or an equivalent recognized method. This may typically include:

- the process integration of the helium cryostat in the environment where it will be installed;
- the boundary conditions and the influence of associated installations, e.g. magnetic fields;
- the nominal operating conditions;
- the preliminary indication of a single- or a multi-stage protection concept;
- the discharge conditions and helium recovery systems.

In a second step, a quantitative risk assessment shall be issued in the design phase, including at least the evaluation and verification of the risks in Table 1. This is accomplished by carrying out a Failure Mode and Effect Analysis (FMEA) or an equivalent recognized method.

In a final step, the equipment owner/employer shall perform a risk evaluation for the use of the equipment, in its foreseen environment, before commissioning and final acceptance in accordance with the national implementation of the provisions of the European Health and Safety at Work Directive [2].

2.3 Protection concepts

The new Standard defines a single-stage protection concept as the minimum requirement for pressure protection according to the PED. In addition, multi-stage protection concepts may be applied in helium cryostats, where a primary pressure relief device (PRD) completely fulfills the pressure protection at the maximum allowable pressure p_S in compliance with the PED and based on the maximum credible incident (MCI) as defined by the risk assessment. With regard to the primary PRD, secondary PRD may be applied at either lower or higher relieving pressure p_0, either in series or in parallel. The secondary PRD shall not compromise the functionality of the primary PRD. However, secondary PRD may influence the definition of the maximum allowable pressure p_S in multi-stage protection concepts.

The values of p_S and p_0 of the primary and the secondary PRD, respectively, shall be carefully defined, considering their tolerances and opening characteristics in order to prevent unintended activation or deactivation of the primary PRD.

The new Standard defines particular requirements for multi-stage protection concepts and provides example solutions for the following types of systems:

- high-pressure superconducting magnet cryostats;
- low-pressure helium cryostats, e.g. superconducting radio-frequency cavities;

- sub-atmospheric helium cryostats;
- cryostats for superfluid He-II;
- ultra-low temperature refrigerator systems.

2.4 Dimensioning of pressure relief devices

The dimensioning of PRD is based on mass-specific energy and momentum conservation as well as the continuity equation for one-dimensional, frictionless, compressible, steady-state and adiabatic fluid flow through short nozzles, where deviations from ideal fluid behavior are considered by correction factors. The following two methods are established to evaluate the thermo- and fluid dynamic relations, yielding similar results:

a) Homogeneous Equilibrium Model (HEM or G-model);

b) Case-specific model.

The HEM used in the main part of the new Standard does not require a pre-definition of the fluid state (i.e. liquid, two-phase or vapor) in the minimum discharge area (called the throat) of PRD, yielding a more compact algorithm.

The case-specific model presented in the Annex may be applied as alternative. In contrast to both ISO 4126-7:2013 and ISO 21013-3:2016, the algorithm uses SI-units without hidden scaling factors (the conversions are explained). This enables the use of one basic equation for the minimum discharge area, both for vapor flow, liquid flow and two-phase flow. Differences due to different fluid states are contained in the parameters of the basic equation.

In order to calculate the relieving mass flow rate following accidental scenarios, the new Standard only defines the maximum heat flux to cryogenic surfaces without multi-layer insulation (MLI), as a general algorithm for the variety of specific and advanced design solutions does not exist. For such cases, the determination of the heat load shall be based on either:

- experimental data given in the Annex or published elsewhere in literature for the respective conditions;
- unpublished experimental data obtained for the particular cryostat design including detailed documentation; or
- numerical modeling of the processes during the accidental scenario including detailed documentation.

2.5 Further aspects

The new Standard includes further clauses on

- Pressure relief devices;
- Substance release;
- Operation of helium cryostats.

The clause on “Pressure relief devices” gives reference to ISO 4126 as the relevant product Standard for pressure relief valves and bursting disks, emphasizing operating characteristics and tolerances that are particularly relevant for the combination of PRD in multi-stage protection concepts. It further contains requirements and examples of PRD for insulating vacuum vessels, support structures and materials.

The clause on “Substance release” deals with the requirements for discharge lines and helium recovery systems, as well as safety aspects for direct helium release to the environment.

The final clause on “Operation of helium cryostats” covers user requirements regarding the inspection before commissioning along with periodic inspections and maintenance of pressure relief devices.

3 HARMONIZATION OF THE NEW STANDARD WITH THE EUROPEAN PRESSURE EQUIPMENT DIRECTIVE

The applicable legislative reference for helium cryostats operated at pressures above 0.5 bar(g) is the European Pressure Equipment Directive (PED) [1]. There are several Standards for different kind of pressure equipment, which provide the technical implementation of the requirements defined in the PED. Although a user is free to apply any existing Standard(s), he/she will generally have to prove, in parallel to the application of the Standard(s), its/their compliance with the essential safety requirements of the European Directives. This additional verification procedure is not necessary, if the applied Standard is a *"Harmonized Standard"* [3].

The harmonization of the new Standard "Helium cryostats – protection against excessive pressure" is an important innovation tool for both European Research and Technology Infrastructures (RIs, TIs) as well as for European industry. It will assure that helium cryostats are designed with an equivalent safety level that is determined by the PED. This enables a better cooperation and exchange between the Research/Technology Infrastructures and industry, for instance during prototyping.

The process of harmonizing the new Standard with the PED is a special procedure, conducted by an external agency mandated by CEN (HAS Consultants) upon request of the European Commission. As there is no particular request from the European Commission, the new Standard will first be published in the form provided by the CEN/TC 268/WG6 working group. Only after the publication, the harmonization procedure may be triggered through the CEN Technical Board (CEN/BT). In the harmonization procedure, all Clauses of the Standard will be cross-checked with the essential safety requirements of the PED, which implies a certified revision lead by the HAS Consultants in cooperation with the technical experts.

4 DYNAMIC MODELLING OF CRYOGENIC INCIDENTS

A basic dynamic model for the loss of insulating vacuum in helium cryostats is published in [4]. As the model contains simplifying assumptions to be verified by experiments, the test facility PICARD was constructed and commissioned within a PhD project at KIT [5].

Based on experiments in PICARD, the basic model [4] has been further developed for bare cryogenic surfaces within a common project among KIT and CERN [5], [6], [7]. Experiments with multi-layer insulated surfaces and their first model implementation are described in [8]. Details of the experiments and the entire dynamic model development will be published in early 2020 in the dissertation [9].

In the frame of a further KIT-CERN cooperation and a third PhD project, it is planned to advance the present model into a robust *dynamic helium cryostat safety* model. This will require additional 20-30 tests in PICARD with different types of multi-layer insulation, as well as a probabilistic modelling approach. Although the option of numerical modeling is already contained in the new European Standard (see section 2.4), the possibility of a normative dynamic algorithm and a normative solution strategy for application in a future update of this Standard will be investigated.

5 SUMMARY

Supported by the AMICI project, the working group CEN/TC 268/WG6 was formed in July 2017 at the European Committee for Standardization CEN, dealing with "Specific helium technology applications". Its aim is to develop a new European Standard on "Helium cryostats – Protection against excessive pressure" that shall be harmonized with the European Pressure Equipment Directive (PED). The Standard will be applicable to superconducting magnet cryostats and cryostats for superconducting radio-frequency cavities, to cold boxes of helium refrigerators and liquefiers, to ultra-low temperature refrigerator systems using ^{3}He and ^{3}He/^{4}He mixtures as well as to helium distribution systems including valve boxes. The draft of this European Standard is planned to be published in late 2019.

The harmonization of the new Standard with the PED is planned in a subsequent step after publication of the Standard. This is an important innovation tool for both European Research and Technology Infrastructures (RIs, TIs) as well as for European industry, assuring that helium cryostats are designed with an equivalent safety level that is determined by the PED. This enables a better cooperation and exchange between the Research/Technology Infrastructures and the industry, for instance during prototyping.

In the frame of a further KIT-CERN cooperation, it is planned to evolve the present model into a robust *dynamic helium cryostat safety model*. The need of additional 20-30 tests with different types of multi-layer insulation has been identified. The possibility of a normative dynamic algorithm and a normative solution strategy for application in a future update of the Standard will be explored.

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