



BSI Standards Publication

Helium cryostats — Protection against excessive pressure

National foreword

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European foreword

This document (EN 17527:2021) has been prepared by Technical Committee CEN/TC 268 “Cryogenic vessels and specific hydrogen technologies applications”, the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2022, and conflicting national standards shall be withdrawn at the latest by June 2022.

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Introduction

Helium cryostats, other than cryogenic vessels used for storage of cryogenic liquids covered by EN ISO 21009-2 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 sudden excessive pressure rise, which strongly influences the design of pressure relief systems and is not covered by existing standards. Helium 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 rise cannot be standardized. Rather, the approach on how to obtain the state-of-the-art protection can be standardized and therefore is covered by this document, specifying the procedure and minimum requirements for the various aspects in the main part of the document. Additional information, example solutions and exemplary measures are provided in the extensive Annex, which mirrors the structure of the main part.

This document covers the typical sources that can lead to excessive pressure rise in helium cryostats and the conditions, which are relevant for the protection against excessive pressure rise during system failures, in order to harmonize risk assessments and design best practices. The document uses common SI-based units.

The user of this document can refer to CEN/CENELEC Internal Regulations Part 3, which deals with the use of verbal forms for the formulation of provisions.

1 Scope

This document specifies the minimum requirements for the protection of helium cryostats against excessive pressure rise, including the specific risks associated with cryostats for superconducting magnets and cryostats for superconducting radio-frequency cavities, coldboxes of helium refrigerators and liquefiers as well as helium distribution systems including valve boxes. It includes information on risk assessment, protection concepts, dimensioning of pressure relief devices, types of pressure relief devices, substance release and operation of helium cryostats.

In order to fulfil the aim of this document, the characteristics of pressure relief devices are taken into account.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 13445-2, *Unfired pressure vessels - Part 2: Materials*

EN 13445-3, *Unfired pressure vessels - Part 3: Design*

EN ISO 4126-1:2013, *Safety devices for protection against excessive pressure - Part 1: Safety valves (ISO 4126-1:2013)*

EN ISO 4126-3:2020, *Safety devices for protection against excessive pressure - Part 3: Safety valves and bursting disc safety devices in combination (ISO 4126-3:2020)*

EN ISO 4126-6:2014, *Safety devices for protection against excessive pressure - Part 6: Application, selection and installation of bursting disc safety devices (ISO 4126-6:2014)*

EN ISO 21013-3:2016, *Cryogenic vessels - Pressure-relief accessories for cryogenic service - Part 3: Sizing and capacity determination (ISO 21013-3:2016)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1

relevant national third party

inspection body authorized by national regulations

3.2**back pressure** p_b

pressure existing at the outlet of a pressure relief device during discharge as a result of the pressure in the downstream system

Note 1 to entry: The back pressure is the sum of the superimposed and built-up back pressures.

[SOURCE: EN ISO 4126-1:2013, 3.11, modified]

3.3**bath cooling**

cooling method in which the object to be cooled is submerged in a vessel filled with a liquid cooling medium

Note 1 to entry: The enthalpy of evaporation is used for cooling, with the phase change providing a nearly constant cooling temperature.

3.4**blowdown** Δp_{reseat}

difference between set and reseating pressure

[SOURCE: EN ISO 4126-1:2013, 3.15]

3.5**build up back pressure** Δp_{bb}

pressure existing at the outlet of a pressure relief device caused by flow through the device and the downstream system

[SOURCE: EN ISO 4126-1:2013, 3.12, modified]

3.6**bursting pressure** p_{burst}

value of the differential pressure between the upstream side and the downstream side of the bursting disc when it bursts

[SOURCE: EN ISO 4126-2:2019, 3.10]

3.7**chattering**

unstable discharge of a pressure relief valve characterised by high frequency opening and closing

3.8**coincident temperature**

temperature of the bursting disc associated with a bursting pressure

[SOURCE: EN ISO 4126-2:2019, 3.14, modified]

3.9

coldbox

cryostat of a helium refrigerator or liquefier, where the cooling power and the low temperatures are being generated

3.10

cryogenic fluid

fluid with a normal boiling point below 120 K respectively $-153\text{ }^{\circ}\text{C}$

3.11

cryogenics

subject of technologies, procedures and equipment for temperatures below 120 K

3.12

cryostat

vacuum-insulated device for the operation of components at cryogenic temperatures using cryogenic fluids

Note 1 to entry: A cryostat is considered as an assembly.

3.13

current lead

electrical connection between an ambient temperature power supply unit and a low temperature superconducting magnet for charging, operating and discharging the magnet

Note 1 to entry: In larger systems, current leads are actively cooled due to the high thermal conduction and the large temperature gradient. The current lead consists of e.g. a copper part as electrical conductor and a heat exchanger for cooling.

3.14

dewar

vacuum-insulated storage and transport container for cryogenic fluids

3.15

driven mode

<superconducting magnet> operation of a magnet by a power supply unit, where the magnet is always connected to the power supply unit or, in the event of quench, to an external protective circuit or a discharge resistor

3.16

full-lift pressure relief valve

PRV

PRV that opens instantaneously within 5 % of the pressure increase up to the design limited lift

Note 1 to entry: The proportion of the lift up to the instantaneous opening (proportional range) may not exceed 20 % of the total lift.

3.17

helium guard

barrier gas volume to avoid atmospheric gas leaks into sub-atmospheric helium systems

3.18**leak rate**

pV throughput of a specific fluid which flows through a leak under specific conditions

Note 1 to entry: In vacuum technology and cryogenics, a leak rate is commonly expressed in the unit mbar l/s.

[SOURCE: EN ISO 20484:2017, 4.3.5]

3.19**maximum allowable pressure**

p_s

maximum gauge pressure for which the equipment is designed, as specified by the manufacturer

[SOURCE: EN ISO 4126-1:2013, 3.6, modified]

3.20**maximum credible incident****MCI**

worst incident within the realm of possibility that has a propensity to cause significant damage

Note 1 to entry: The MCI is the design basis for the dimensioning of the primary pressure relief device (PRD).

3.21**multi-layer insulation****MLI**

very effective thermal insulation method used in cryogenics, which significantly reduces the heat transport caused by thermal radiation

Note 1 to entry: MLI consists of multiple layers of highly reflective films enclosing the cryogenic components. MLI is used along with vacuum insulation.

3.22**nominal operating pressure**

p_{operate}

pressure expected during nominal operation

3.23**overpressure**

Δp_{over}

pressure increase over the set pressure

[SOURCE: EN ISO 4126-1:2013, 3.7]

3.24**performance tolerance**

Δp_{burst}

range of pressure between the specified minimum bursting pressure and the specified maximum bursting pressure, or the range of pressure in positive and negative percentages or quantities which is related to the specified bursting pressure

[SOURCE: EN ISO 4126-2:2019, 3.15]

3.25

persistent mode

<superconducting magnet> magnet operation without connection to a power supply unit, where the power supply unit is disconnected after charging the magnet and the superconducting magnet operates in short-circuit mode

3.26

pV throughput

rate at which a volume of gas at specified pressure passes a given cross-section of the system

Note 1 to entry: The pV throughput is expressed in mbar l/s.

[SOURCE: EN ISO 20484:2017, 4.2.3, modified]

3.27

quench

<superconducting magnet> spontaneous transition of a superconductor from the superconducting state to the normal conducting state

3.28

relieving pressure

p_0

pressure used for the sizing of pressure relief devices

Note 1 to entry: For a pressure relief valve the relieving pressure is greater than or equal to the set pressure plus overpressure.

[SOURCE: EN ISO 4126-1:2013, 3.10, modified]

3.29

reseating pressure

p_{reseat}

value of the inlet static pressure at which the disc re-establishes contact with the seat or at which the lift becomes zero

[SOURCE: EN ISO 4126-1:2013, 3.8, modified]

3.30

set pressure

p_{set}

predetermined gauge pressure at which the pressure relief valve commences to open

Note 1 to entry: It is the gauge pressure measured at the valve inlet at which the pressure forces tending to open the valve for the specific service conditions are in equilibrium with the forces retaining the valve disc on its seat.

[SOURCE: EN ISO 4126-1:2013, 3.5, modified]

3.31**specified bursting pressure** $p_{\text{burst,sp}}$

bursting pressure quoted with a fixed coincident temperature when defining the bursting disc requirements, used in conjunction with a performance tolerance

[SOURCE: EN ISO 4126-2:2019, 3.11, modified]

3.32**specified maximum bursting pressure** $p_{\text{burst,max}}$

maximum pressure quoted with a fixed coincident temperature when defining the bursting disc requirements (used in conjunction with minimum bursting pressure)

[SOURCE: EN ISO 4126-2:2019, 3.12, modified]

3.33**specified minimum bursting pressure** $p_{\text{burst,min}}$

minimum pressure quoted with a fixed coincident temperature when defining the bursting disc requirements (used in conjunction with maximum bursting pressure)

[SOURCE: EN ISO 4126-2:2019, 3.13, modified]

3.34**superconducting magnet**

magnet whose coils are cooled to a temperature at which the conductor becomes superconducting, effectively removing electrical resistance

3.35**superimposed back pressure** p_{bs}

initial pressure existing at the outlet of a pressure relief device in the absence of flow at the time when the device is required to operate

[SOURCE: EN ISO 4126-1:2013, 3.13, modified]

3.36**test pressure** p_{test}

pressure to which the equipment is subjected for test purposes

[SOURCE: EN 764-1:2015+A1:2016]

3.37**thermal acoustic oscillation**

resonant gas oscillation building up spontaneously within a connecting tube between high and low temperature levels

3.38**vacuum jacket**

evacuated outer shell of a cryostat surrounding the cryogenic components, inhibiting the heat conduction by residual gas

Note 1 to entry: The vacuum jacket normally remains at ambient temperature.

3.39**valve box**

assembly for distributing cryogenic fluid to several cryostats and for controlling the flow in supply and return lines

Note 1 to entry: A valve box consists of a vacuum vessel with an arrangement of cryogenic valves and pipework.

4 Symbols

A_c	affected cryogenic surface area	m^2
a_i	initial filling level	–
A_{leak}	cross section of leak	m^2
A_{scd}	affected surface area of the superconducting device	m^2
A_{th}	minimum discharge area of the pressure relief device (PRD)	m^2
C	discharge function	–
c	specific heat capacity of the vessel/pipework material	$J/(kgK)$
c_p	specific heat capacity at constant pressure	$J/(kgK)$
c_{th}	velocity in the throat of the pressure relief device (PRD)	m/s
E_{mag}	electromagnetic energy stored in the magnet	J
E_{max}	maximum thermal energy of the electrical arc	J
E_{wall}	thermal energy transferred into the vessel/pipework wall in case of dielectric breakdown	J
h	specific enthalpy	J/kg
h'	specific enthalpy of saturated liquid	J/kg
h''	specific enthalpy of saturated vapour	J/kg
Δh	specific enthalpy change	J/kg
$h_{0,x}$	adjusted specific enthalpy	J/kg
Δh_{air}	enthalpy difference of air	J/kg
Δh_{fusion}	latent heat of fusion of vessel/pipework material	J/kg

h_{th}	specific enthalpy in the throat	J/kg
I	current	A
$\bar{k}$	average heat transfer coefficient	W/(m ² K)
K_d	discharge coefficient	–
K_{dr}	certified discharge coefficient	–
l	length	m
L	inductance	H
L_c	characteristic length of heat transfer problem	m
$\dot{M}$	relieving mass flow rate	kg/s
M_c	total mass of the cryogenic fluid in the system	kg
M_{He}	total mass of helium in the system	kg
$\dot{M}_{lvb}$	mass flow rate to vacuum space in case of LBV (loss of beamline vacuum)	kg/s
$\dot{M}_{lcf}$	mass flow rate to vacuum space in case of leak of cryogenic fluid	kg/s
$\dot{m}_{th}$	mass flux in the throat of the PRD	kg/(m ² s)
P	perimeter of the pipework section	m
P_{proj}	perimeter of the pipework for the heat transfer in flow direction	m
p_0	relieving pressure	bar(a)
p_0^*	relieving pressure from which on critical (sonic) flow occurs in the throat area A_{th}	bar(a)
$p_{0,x}$	adjusted relieving pressure, taking into account the upstream pipework	bar(a)
p_{amb}	ambient pressure	bar(a)
p_b	back pressure	bar(a)
Δp_{bb}	built-up back pressure along the downstream pipework	bar(a)
p_{bs}	superimposed back pressure	bar(a)
p_{burst}	bursting pressure	bar(g)
$p_{burst,max}$	maximum bursting pressure of the bursting disc	bar(g)
$p_{burst,min}$	minimum bursting pressure of the bursting disc	bar(g)

p_c	pressure in the cryogenic circuit	bar(a)
p_{crit}	thermodynamic critical pressure	bar(a)
Δp	pressure drop	bar
$p_{operate}$	pressure at operating level	
Δp_{over}	overpressure	bar
p_s	maximum allowable pressure	bar(g)
p_{set}	set pressure of pressure relief valve (PRV)	bar(g)
p_{test}	test pressure	bar(g)
p_{th}	pressure in the throat of the pressure relief device (PRD)	bar(a)
p_v	initial pressure in the vacuum chamber or in the beam line before the incident	bar(a)
p_x	sub-critical flash pressure	bar(a)
pd	pressure and gap distance product in Paschen curve	Pa m
$\dot{Q}$	heat load	W
$\dot{Q}_{liv}$	heat load caused by loss of insulating vacuum (LIV)	W
$\dot{q}_{liv}$	heat flux caused by loss of insulating vacuum (LIV)	W/m ²
$\dot{Q}_{quench}$	heat load caused by a quench	W
$\dot{q}_{quench}$	heat flux caused by a quench	W/m ²
$\dot{Q}_{lbv}$	heat load caused by loss of beamline vacuum (LBV)	W
Q_1	leak rate	mbar l/s
R	ideal gas constant	J/(mol K)
R_c	fluid-specific gas constant	J/(kg K)
$s_{0,x}$	adjusted specific entropy	J/(kg K)
T	temperature	K
T_{amb}	ambient temperature	K
T_{fusion}	melting temperature of vessel/pipework material	K
$T_{i,He}$	nominal temperature of He	K

T_0	relieving temperature	K
$T_{0,in,i}$	inlet helium temperature of pipework section i	K
$T_{0,x}$	adjusted relieving temperature, taking into account heat transfer in the upstream pipework	K
$T_{0,x,i}$	adjusted relieving temperature of pipework section i	K
T_c	temperature in the cryogenic circuit	K
T_{sat}	saturation temperature	K
T_{scd}	surface temperature of the superconducting device following a quench	K
T_{wall}	temperature of the cryogenic vessel/pipework wall	K
$T_{w,i}$	surface temperature of pipework section i	K
t	time	s
$U_{breakdown}$	breakdown voltage of Paschen curve	V
U_{ion}	ionization voltage of gas	V
ν	specific volume	m ³ /kg
ν'	specific volume of saturated liquid	m ³ /kg
ν''	specific volume of saturated vapour	m ³ /kg
$\nu_{0,x}$	specific volume upstream of PRD	m ³ /kg
ν_{amb}	specific volume of ambient air	m ³ /kg
ν_c	specific volume in the cryogenic circuit	m ³ /kg
V_{He}	helium volume of the cryostat	m ³
ν_i	initial specific volume	m ³ /kg
ν_0	specific volume at relieving conditions	m ³ /kg
ν_{th}	specific volume in the throat of the PRD	m ³ /kg
V_v	volume of the vacuum space	m ³
x	dimensionless vapour mass fraction (quality)	–
z	thickness of vessel/pipework wall	m
α	temperature ratio	–
ε	dimensionless void fraction	–

γ	secondary Townsend coefficient of discharge	–
η_c	critical pressure ratio for two-phase flow	–
κ	isentropic expansion coefficient	–
ξ	length ratio	–
ρ	density	kg/m ³
φ	relative humidity	%
ω	Omega parameter	–
ψ	discharge function	–

5 Process flow-charts

5.1 Process flow-chart concerning risk assessment and protection concepts

The process flow concerning the risk assessment and the protection concepts is shown in Figure 1.

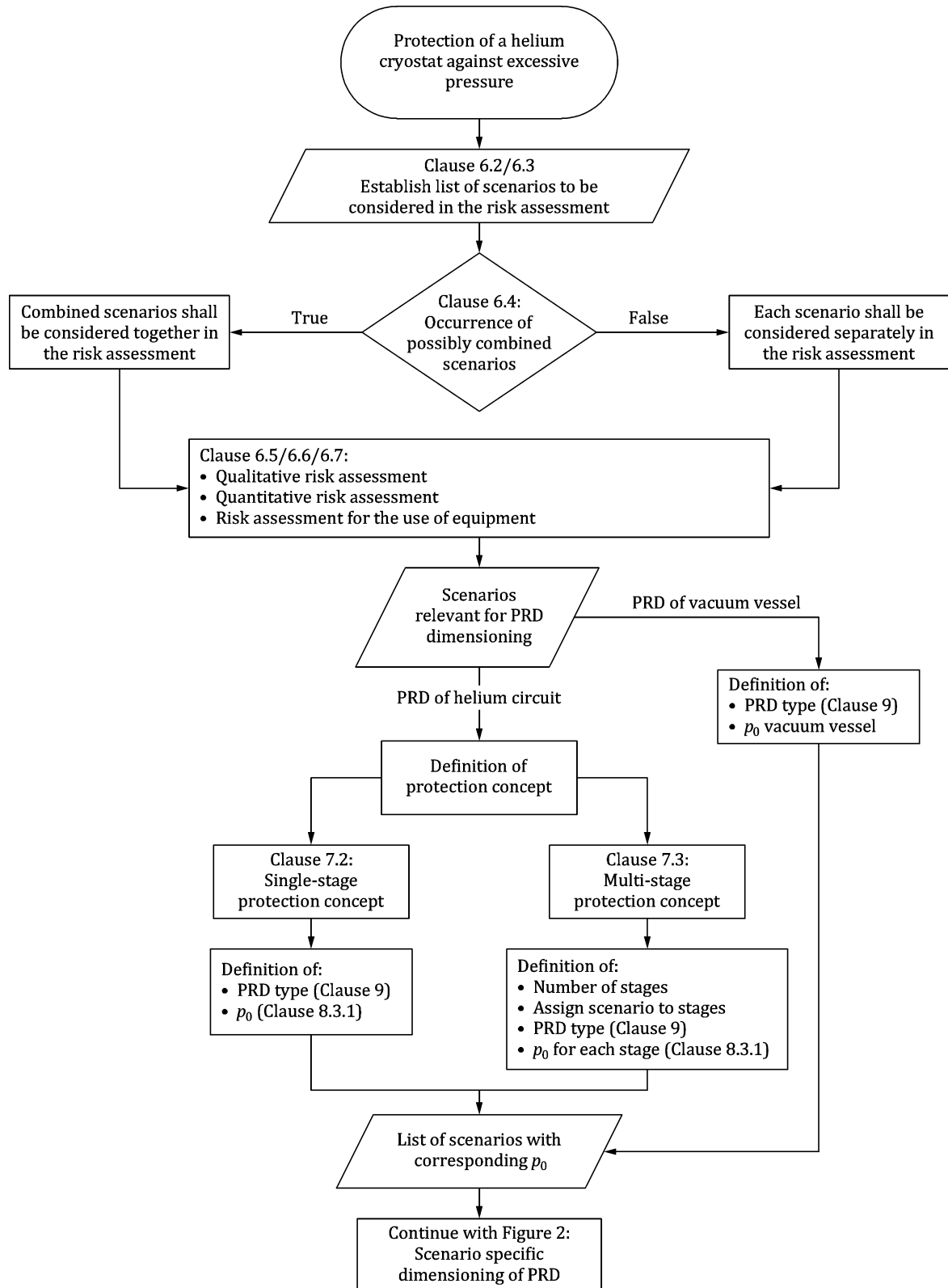


Figure 1 — Process flow-chart concerning risk assessment and protection concepts

5.2 Process flow-chart concerning scenario-specific dimensioning of helium circuit PRD

The process flow concerning the scenario-specific dimensioning of helium circuit PRD is shown in Figure 2.

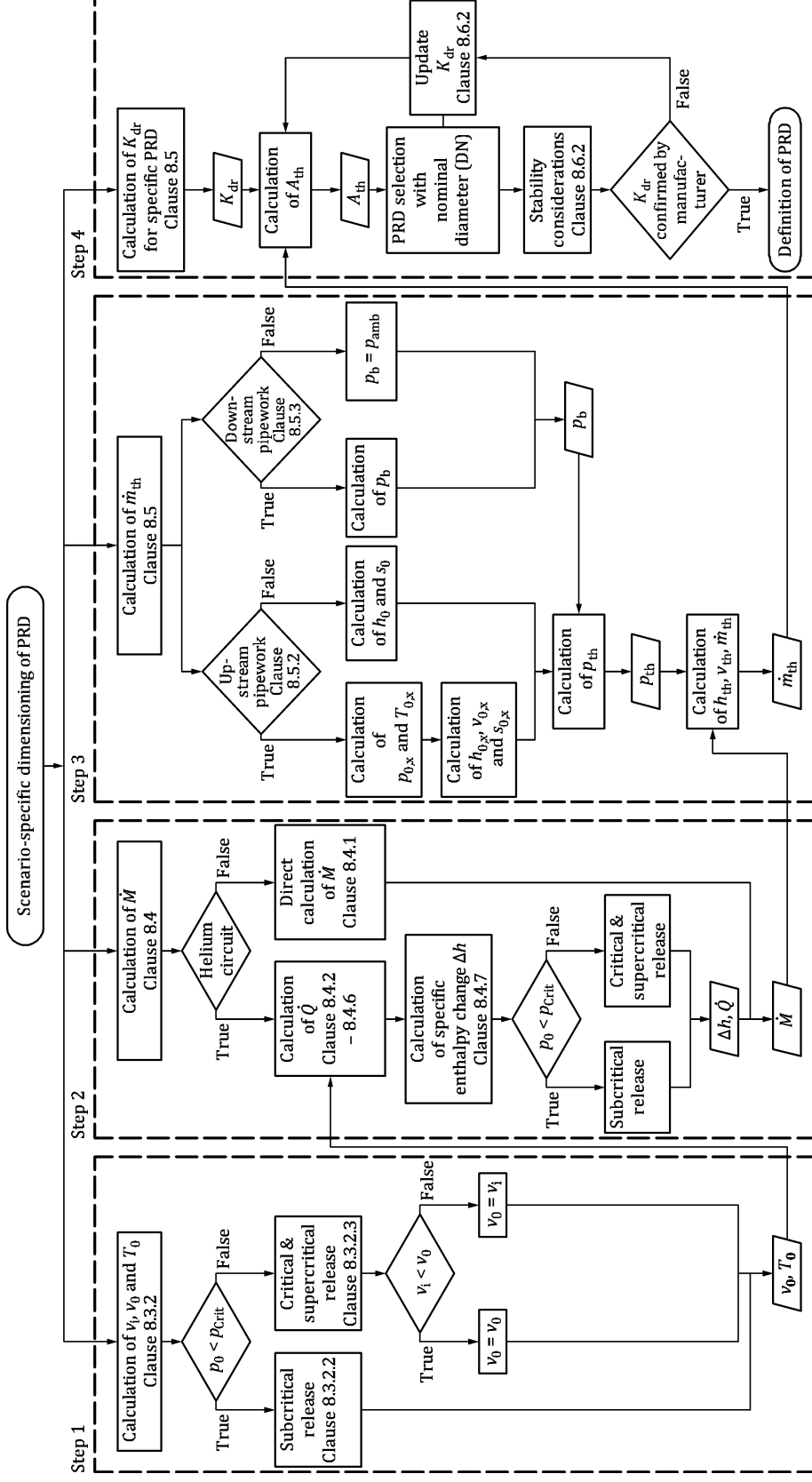


Figure 2 — Process flow-chart concerning scenario-specific dimensioning of helium circuit PRD

6 Risk assessment

6.1 General information on risk assessment

As a basis for the dimensioning of pressure relief devices (PRD) given in Clause 8, it is required to carry out a risk assessment given in Clause 6 and specify the protection concept based on Clause 7.

The sources of excessive pressure rise stated in 6.2 and 6.3 shall be considered in the risk assessment of a helium cryostat.

The sources of excessive pressure rise under 6.2 are relevant for the dimensioning of PRDs. The sources of excessive pressure rise under 6.3 shall be mitigated as a result of the risk assessment.

In contrast to conventional pressure equipment, helium cryostats include specific components such as superconducting magnets and cavities, electrical heaters, heat exchangers, bellows, circulation pumps and internal control valves.

NOTE The risk and hazard analysis according to Pressure Equipment Directive (PED) do not cover the risks of components, which are designed and fabricated according to other directives and regulations, e.g. Machinery Directive 2006/42/EC (MD), Low Voltage Directive 2014/35/EU (LVD) and Electromagnetic Compatibility Directive 2004/108/EC (EMC).

6.2 Sources of excessive pressure rise relevant for dimensioning

6.2.1 Loss of insulating vacuum

Helium cryostats are generally vacuum-insulated. During the loss of insulating vacuum (LIV), the vacuum system is vented with atmospheric air, yielding large heat loads on the helium system due to air desublimation and condensation. The heat load depends on the optional installation of multi-layer insulation (MLI) on the cryogenic surface. Loss of insulating vacuum often specifies the maximum credible incident (MCI) in helium cryostats that influences the dimensioning of pressure relief devices.

LIV shall be considered in the risk assessment of all vacuum-insulated helium cryostats.

The determination of the heat load due to LIV is specified in 8.4.2. Additional information on LIV is given in B.1.

6.2.2 Loss of beamline vacuum

The loss of beamline vacuum (LBV) by venting with atmospheric air is similar to the LIV scenario. It applies in particular to superconducting accelerator facilities, where the inner beamline surface cannot be covered with MLI in general. This yields maximum heat flux values due to desublimation and condensation of the vented air on the cryogenic surface. Such incidents can arise from the damage of interconnection bellows between two superconducting devices in a beamline.

This scenario shall particularly be considered in helium cryostats containing superconducting radio-frequency cavities.

The determination of the heat load due to LBV is specified in 8.4.3. Additional information on LBV is given in B.2.

6.2.3 Quench of superconducting device

A quench signifies the spontaneous transition of a superconducting device from the superconducting state to the normal conducting state (resistive). The normal conducting state implies resistive losses that dissipate, after Joule heating, electromagnetic energy in form of heat to the helium. The heat load resulting from the quench of a superconducting magnet coil induces a significant pressure rise of the helium. Quenches could be triggered deliberately in order to test or protect the superconducting device.

In systems, where the stored energy in superconducting devices can pressurize the cryostat to pressures near p_s , quenches shall generally be expected and shall be considered in the risk assessment.

The determination of the heat load due to the quench of a superconducting device is specified in 8.4.4. Additional information on quenches of superconducting devices is given in B.3.

6.2.4 Leak of cryogenic fluid

During leak of cryogenic fluid, either helium from the helium system, nitrogen from a liquid nitrogen insulation system (nitrogen guard) or any other system fluid leaks into the insulating vacuum space. This causes a pressure increase in both the vacuum and the cryogenic fluid system responsible for the leak.

This scenario shall be taken into account when dimensioning pressure relief devices for both the cryogenic fluid system(s) and the vacuum system.

The thermal shields typically present in helium cryostats shall foresee sufficient openings to ensure the nominal relieving capacity, apart from the vacuum requirements.

The risk that occurs when components made of carbon steel come into contact with cryogenic liquids shall be particularly emphasized.

The determination of the relieving mass flow rate due to leak of cryogenic fluid is specified in 8.4.5. Additional information on leak of cryogenic fluids is given in B.4.

6.2.5 Dielectric breakdown

Electrical insulators can become conductive if the voltage applied across exceeds the breakdown voltage. Depending on the electric energy stored in the system, dielectric breakdown can either cause small electric discharge following the Paschen law, or major electric arcs in high-current installations. Major electric arcs can destroy pipework and vessels of cryogenic fluid circuits, yielding pressure increases in both the fluid and the vacuum systems.

The risk of major electric arcs shall be considered in the risk assessment of superconducting devices involving large current densities and large stored energy. This risk should be mitigated by appropriate design and instrumentation of electrical circuits.

The determination of the relieving mass flow rate due to dielectric breakdown is specified in 8.4.6. Additional Information on dielectric breakdown is given in B.5.

6.2.6 Entrapment of cryogenic fluid

The entrapment of cryogenic fluid in a closed volume, e.g. in-between two closed valves, causes pressure increase due to ever-present heat leaks (natural losses), and in particular in case of LIV. Entrapment can also occur in-between the sheets of multi-layer bellows, causing rupture during warm up. This latter risk can be mitigated by e.g. holes in-between the outer layer(s) of such bellows.

Entrapment of cryogenic fluid shall be considered in the risk assessment of all helium cryostats. Respective sub-systems shall be protected by individual pressure relief devices.

The determination of the heat load is equivalent to LIV as specified in 8.4.2.

6.3 Sources of excessive pressure rise to be mitigated

6.3.1 Thermal acoustic oscillation

A thermal acoustic oscillation (TAO) is a resonant gas oscillation built-up under certain conditions in half-open connecting lines between a cryogenic helium reservoir and installations at ambient temperature, such as pressure gauges and pressure relief devices. TAO strongly increase the heat transport along the respective line, typically causing also ice formation at the ambient installation. In addition, the associated pressure oscillation can cause the activation of pressure relief devices.

The risk of thermal acoustic oscillation shall be considered in the design phase and be mitigated. Possibilities to mitigate TAO are explained in B.6.

6.3.2 Cryopumping

The cryogenic surface of a helium cryostat acts as a cryopump, on which any gases except helium are de-sublimated. Minor leaks of either ambient air or e.g. nitrogen from a nitrogen insulation system into the vacuum system do not necessarily increase the vacuum pressure, but accumulate as frost layer on the cryogenic surface throughout operation. During warm-up, the solidified gases evaporate and pressurize the vacuum system.

The risk of cryopumping shall be considered in the design phase and be mitigated. Possibilities to mitigate cryopumping are explained in B.7.

6.3.3 Power failure

Power failure can result in a lack of cooling power that compensates the heat load in cryostats during normal operation, thus causing pressure increase. In addition, power failure prevents the normal operation of control valves and other actuators.

Power failure shall be considered in the design of helium cryostats, in particular for the definition of fail-safe positions of control valves. Supply valves should be closed and return valves should be open in safe position, depending on the concerned processes.

6.3.4 Pressure surge

Pressure surge is created by a sudden fluid velocity change that causes unstable conditions. The fluid velocity change can be caused by e.g. starting/stopping pumps, opening/closing valves or reductions in line size.

The risk of pressure surge shall be mitigated by the mechanical design and the appropriate choice of time constants in the control system.

6.3.5 Freezing

Hazardous solidification of fluids both inside and outside of helium cryostats shall be mitigated by appropriate measures, including e.g. safety switches to avoid over-filling, leak tightness tests of pressure relief devices and helium guards for sub-atmospheric systems.

6.3.6 Backflow

Backflow can occur when connecting systems of different pressure, e.g. during transfer of liquid helium from storage vessels into cryostats. The backflow of warm gas can cause a sudden evaporation of liquid helium.

The risk of backflow shall be mitigated either by the installation of check valves, by appropriate design such as limiting the diameter of supply lines to a mass flow rate lower than the relieving mass flow rate, by control routines and by operating instructions.

6.3.7 Other sources of excessive pressure

Other sources of pressure increase in helium cryostat include, for example, the lack of cooling due to cryopump malfunction, human errors, control errors and non-standard operation of valves.

Provided that other potential sources of excessive pressure rise exist, they shall be considered in the risk assessment and appropriate measures shall be taken.

6.3.8 Earthquake

Earthquake scenarios typically affect the mechanical design of helium cryostats (regulated e.g. in EN 13445 (all parts)), rather than the design of pressure relief devices. Nevertheless, earthquakes can trigger a break of insulating vacuum and beamline vacuum through possible cryostat displacement and damage of connecting bellows.

If earthquake scenarios are to be considered for the installation area of a helium cryostat, the applicable Standards shall be considered.

6.3.9 Fire

The case of fire is not required to be taken into account for the design of pressure relief devices, as long as there is negligible fire load present within the meaning of this document.

NOTE The requirement given in the 2014/68/EU Pressure Equipment Directive (PED) for external fire refers to the damage limitation level (see Figure 3 and Figure 4) and is not intended to be used for the pressure protection in normal operation of helium cryostats.

A fire load is considered to be a combustible substance in the vicinity of a helium cryostat, which represents a potential risk to the pressure vessel in the case of fire. Due to the heat transfer in the event of a fire, hazards can arise from the fire load by the touch of flames or thermal radiation.

The consideration of fire would yield excessive oversizing of pressure relief devices, causing e.g. leaks and instable operation (chattering) with reduced discharge capacity and damage of spring-loaded pressure relief valves. It is therefore recommended to exclude the risk of fire in the vicinity of helium cryostats by appropriate measures such as fire prevention, fire protection and firefighting measures.

In the case of a residual fire load being present, EN ISO 21013-3 can be used for the dimensioning of pressure relief devices.

6.4 Combined scenarios

Generally, the causes of excessive pressure rise are considered to be unrelated (single jeopardy theory) if no process link exists between them, or if the time period between two possibly linked scenarios is sufficiently large.

Due to the process dynamics during incidents in helium cryostats, the risk assessment often involves the consideration of time constants of events following an incident. A quench of a superconducting magnet triggered by the loss of insulation vacuum or a power supply failure caused by the loss of beamline vacuum in particle detector and accelerator systems are examples involving a double event.

Combined scenarios shall be considered, as the negligence or the unrealistic superposition of incidents can lead to either undersized or oversized pressure relief systems.

6.5 Risk assessment before ordering

When ordering a helium cryostat, a qualitative risk assessment shall be issued by the end-user before procurement. This shall be accomplished by carrying out a Hazard and Operability Study (HAZOP, see IEC 61882:2016) or an equivalent recognized method. The risk assessment shall 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, such as magnetic fields;
- the nominal operating conditions.

For customized helium cryostats, the risk assessment should additionally include:

- the preliminary specification of a single- or a multi-stage protection concept;

— the downstream conditions and helium recovery systems.

This risk assessment shall be included in the technical specification of the helium cryostat.

Further information and an example on qualitative risk assessment methods are given in B.8.

6.6 Risk assessment in the design phase

A risk assessment shall be issued in the design phase, including at least the evaluation and verification of the sources of excessive pressure rise stated in 6.2. This is accomplished by carrying out a Failure Mode and Effect Analysis (FMEA, [32] [34]) or an equivalent recognized method. The risk assessment in the design phase shall include a detailed description of the operational safety of the cryostat. Risks shall be identified and measures shall be specified in order to reduce or mitigate the risks to an acceptable level.

The helium cryostat shall be designed, manufactured and documented according to this risk assessment, including also the dimensioning of the pressure relief devices.

7 Protection concepts

7.1 General

Based on the risk assessment described in Clause 6, the overall protection concept against excessive pressure rise shall be specified before the dimensioning and the selection of pressure relief devices.

In helium cryostats, hydrostatic tests are impractical and disadvantageous, so that in general only pneumatic tests are permissible.

7.2 Single-stage protection concept

A single-stage protection concept is the minimum requirement for pressure protection of a helium cryostat.

A single-stage protection concept shall include an operating level, a protection level and a damage limitation level.

Figure 3 shows an example of a single stage relieving system, with either a bursting disc (BD, Option 1) or a pressure relief valve (PRV, Option 2) in the protection level.

Operating parameters of the helium cryostat such as pressure, flow rates, filling quantity and temperature shall be controlled in the operating level to remain within an acceptable range.

In case of an incidental scenario, the protection level prevents the pressure from exceeding the acceptable limit, using a pressure relief device (PRD). Protection against excessive pressure rise shall be achieved by either non-reclosable PRD, e.g. bursting discs (BD) with the bursting pressure p_{burst} smaller than or equal to the maximum allowable pressure p_s , or by reclosable PRD, e.g. spring-loaded or magnetic pressure relief valves (PRV) with the set pressure p_{set} smaller than or equal to p_s . Standardized tolerances of non-reclosable PRD and opening characteristics of reclosable PRD shall limit the momentary pressure surge to a maximum of 10 % of p_s .

The damage limitation level includes additional requirements in addition to the pressure protection level against external hazards, e.g. safe guards, fire prevention, oxygen monitoring, barriers, access restriction and helium recovery systems.

Further information is given in C.1.

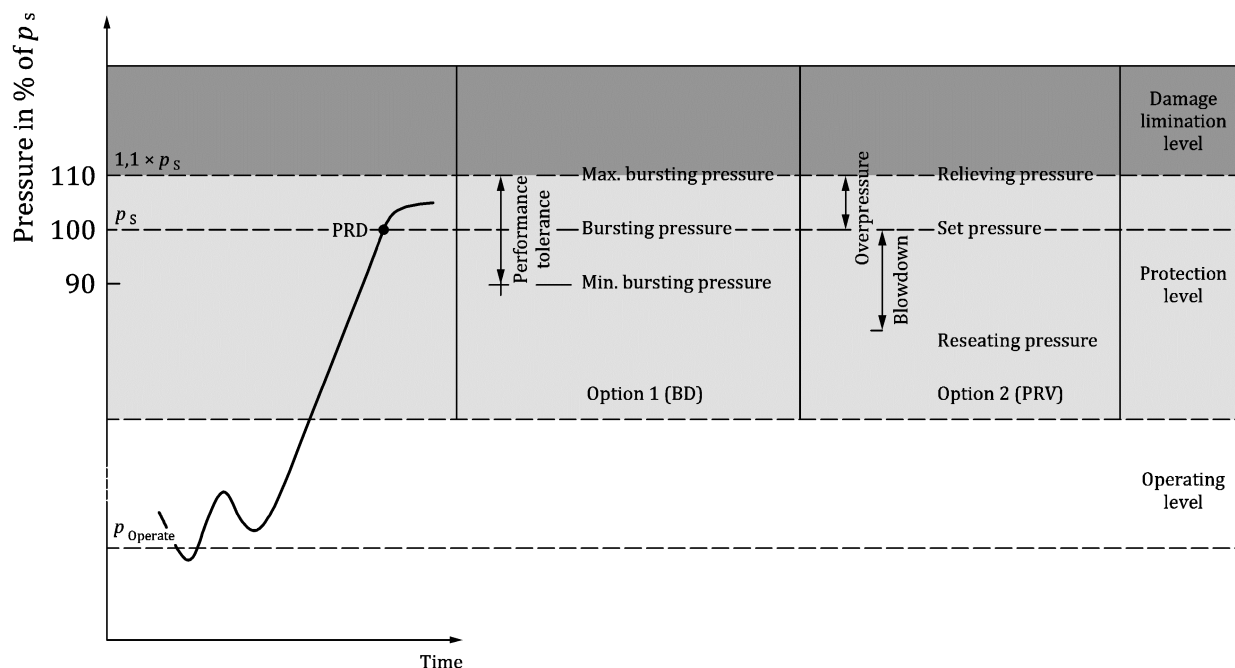


Figure 3 — Example of a single-stage relieving system, using either a bursting disc (BD) as non-reclosable pressure relief device (Option 1, $p_{\text{burst}} = p_s$), or a pressure relief valve (PRV) as reclosable pressure relief device (Option 2, $p_{\text{set}} = p_s$)

7.3 Multi-stage protection concepts

7.3.1 General

According to EN ISO 4126-3:2020, combinations of reclosable and non-reclosable PRD, specifically the combination of pressure relief valves (PRV) and bursting discs (BD) in series, are allowed for the following reasons:

- a) protection of the PRV against corrosion, fouling or conditions that can compromise its functionality
- b) prevention of leaks
- c) prevention of the loss of the content of the protected system after bursting of the bursting disc (BD)

In addition, multi-stage protection concepts are allowed in helium cryostats, either in series or in parallel:

- d) for helium retention in general, and
- e) for the protection of delicate and expensive equipment

Multi-stage protection concepts may be applied in helium cryostats, where a primary PRD completely fulfils the pressure protection at the maximum allowable pressure p_s and based on the maximum credible incident (MCI) as specified by the risk assessment in Clause 6.

With regard to the primary PRD, secondary PRD may be applied at either lower or higher relieving pressure p_0 . The secondary PRD shall not compromise the functionality of the primary PRD.

Secondary PRD, however, can influence the definition of the maximum allowable pressure p_s in multi-stage protection concepts of helium cryostats. The values of p_0 of the primary and the secondary PRD, respectively, shall be carefully specified, considering the tolerances and the opening characteristics in order to prevent unintended activation of the primary PRD.

Figure 4 depicts an exemplary multi-stage relieving system with a bursting disc (BD) as non-reclosable primary pressure relief device and a pressure relief valve (PRV) as reclosable secondary pressure relief device.

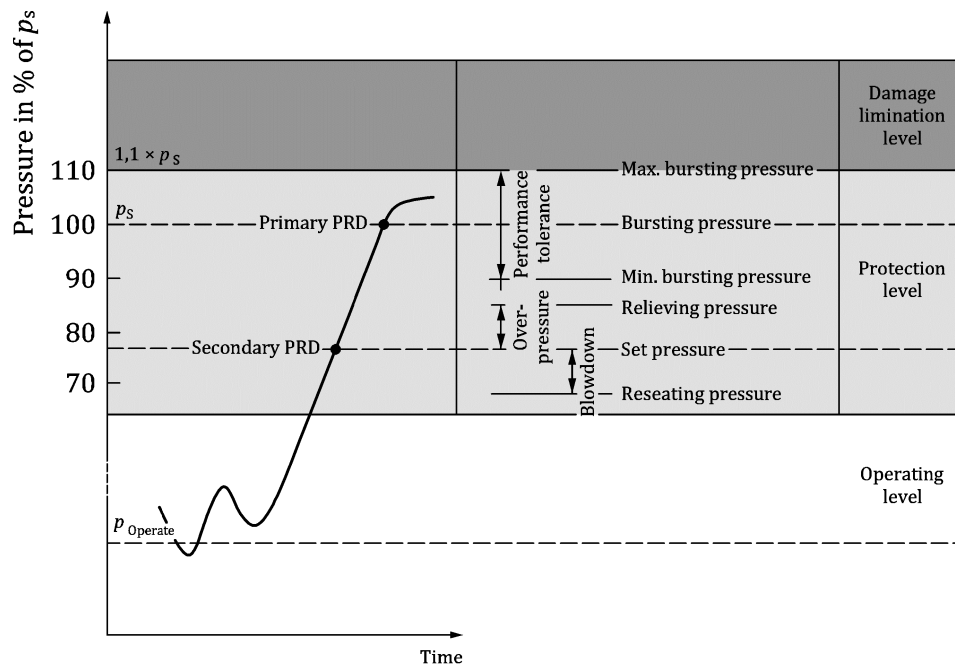


Figure 4 — Example of a multi-stage relieving system, using a bursting disc (BD, $p_{\text{burst}} = p_s$) as non-reclosable primary pressure relief device and a pressure relief valve (PRV) as reclosable secondary pressure relief device

7.3.2 Pressure protection of high-pressure helium cryostats

High-pressure helium cryostats refer to systems with a maximum allowable pressure larger than or equal to the critical pressure of helium, i.e. $p_s \geq p_{\text{crit}} = 2,3 \text{ bar(a)} - p_{\text{amb}}$.

With regard to 6.2.3, quenches shall be considered in superconducting magnet cryostats.

In cases where quenches or other scenarios induce a lower risk and a lower heat load compared to the MCI, secondary PRD may be used as quench relief valve (QRV) with a relieving pressure $p_0 < p_s + p_{\text{amb}}$.

Further information is given in C.2.2.

7.3.3 Pressure protection of low-pressure helium cryostats

Low-pressure helium cryostats refer to systems with a maximum allowable pressure lower than the critical pressure of helium, i.e. $p_s < p_{\text{crit}} = 2,3 \text{ bar(a)} - p_{\text{amb}}$. In such systems, it is barely possible to implement a secondary PRD at $p_0 < p_s + p_{\text{amb}}$.

For the purpose of damage limitation in low-pressure helium cryostats, it is allowed to set the relieving pressure p_0 of a secondary PRD to the actual test pressure of the pressure equipment. Whenever a secondary PRD at $p_0 \geq p_s + p_{\text{amb}}$ has been activated, the pressure equipment shall be subjected to a new acceptance test, which can include a pressure test.

Further information is given in C.2.3.

7.3.4 Pressure protection of sub-atmospheric helium cryostats

Primary PRD of sub-atmospheric helium cryostats may be protected by helium guards, constituting a serial combination of PRD in order to prevent leaks into the helium system.

It is recommended that either the primary or the secondary PRD is non-reclosable.

In case of two reclosable PRD connected in series, the functionality of the PRD combination shall be proven.

Further information is given in C.2.4.

7.3.5 Pressure protection of He-II cryostats

He-II cryostats can include additional restrictions for the relieving mass flow, in particular a lambda plate for the thermal insulation between the He-II phase and the He-I phase.

If a restriction is installed, it shall be equipped with an orifice (e.g. a lambda valve) through which the helium can escape in order to prevent excessive pressure. The orifice shall ensure the same relieving capacity as the primary PRD.

Further information is given in C.2.5.

7.3.6 Pressure protection of ultra-low temperature refrigerator systems

Ultra-low temperature refrigerator systems can be either a fixed or a removable part of helium cryostats, allowing the closed-loop circulation of ^3He . Refrigerator systems operating with pure ^3He can reach temperatures of $T \sim 300 \text{ mK}$ and dilution refrigerators operating with $^3\text{He}/^4\text{He}$ mixtures temperatures as low as $T \geq 2 \text{ mK}$. Depending on the type of refrigerator, the ^3He can be stored either inside an integrated circulation pump, or in an external low-pressure vessel.

Ultra-low temperature refrigerator systems can operate in several ways. Configurations with a blocked Joule-Thomson valve on the inlet often specify the maximum credible incident. This type of system can be subject to both high inlet pressure of $p \geq p_{\text{crit}} = 2,3 \text{ bar(a)}$ and low outlet pressure in the order of mbar (a).

Ultra-low temperature refrigerator systems should be equipped with at least one reclosable primary PRD. A secondary PRD should allow the ^3He or $^3\text{He}/^4\text{He}$ mixture to return safely to its storage without loss.

Further information is given in C.2.6.

8 Dimensioning of pressure relief devices

8.1 Method for the dimensioning of pressure relief devices

The dimensioning of pressure relief devices (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 behaviour are considered by correction factors. Different models are available in literature, however, the Homogeneous

Equilibrium Model (HEM or G-model) ^[26] of Clause 8 should be used for the dimensioning of PRD as it is valid for the entire pressure and temperature range relevant for helium cryostats.

A flowchart summarizing the dimensioning process is given in 5.2.

NOTE A comparison to the dimension-dependent Formulae in EN ISO 4126-7:2013 and in EN ISO 21013-3:2016 and the conversions are explained in D.1.

As alternative to the HEM of Clause 8, the case-specific model in D.2 may be used for the dimensioning of PRD.

8.2 Calculation of the minimum discharge area

The general Formula for the calculation of the minimum discharge area A_{th} (the so-called throat) of PRD is

$$A_{th} = \frac{\dot{M}}{\dot{m}_{th} \times K_{dr}} = \frac{\dot{M}(p_0, v_0)}{\dot{m}_{th}(p_{0,x}, s_{0,x}) \times K_{dr}} \quad (1)$$

where

A_{th} is the minimum discharge area of the PRD in m²;

p_0, v_0 are the relieving pressure p_0 in bar(a) and the specific volume v_0 of the helium inside the cryostat in m³/kg as specified in 8.3;

$\dot{M}$ is the relieving mass flow rate in kg/s as specified in 8.4;

$p_{0,x}, s_{0,x}$ are the relieving pressure ($p_{0,x}$) in bar(a) and the specific entropy ($s_{0,x}$) in J/kg/K adjusted to the pressure drop and temperature increase in the pipework upstream of the PRD as specified in 8.5;

$\dot{m}_{th}$ is the mass flux in the throat in kg/(m²s) as specified in 8.5; and

K_{dr} is the dimensionless certified discharge coefficient as specified in 8.6.

NOTE 1 The index "0" refers to the relieving conditions of the cryostat, "0,x" refers to the fluid states upstream the PRD adjusted to pressure drop and temperature increase in the upstream pipework, and "th" refers to the states in the throat. Therefore, the minimum discharge area is labelled as A_{th} in contrast to the nomenclature in EN ISO 4126-7:2013 and EN ISO 21013-3:2016, where A_0 is used as symbol for the minimum discharge area.

NOTE 2 If there is no pipework installed, i.e. the PRD is directly mounted on the cryostat, the relieving conditions "0" are equal to the adjusted relieving conditions "0,x".

8.3 Calculation of the fluid state properties at relieving conditions

8.3.1 Calculation of the relieving pressure

The relieving pressure p_0 results from the protection concept in Clause 7. For primary PRD, the relieving pressure p_0 shall be

$$p_0 \leq (1,1 \times p_s) + p_{amb} \quad (2)$$

Using secondary PRD in a multi-stage protection concept according to 7.3, the relieving pressure p_0 of secondary PRD shall be chosen such that the function of primary PRD is not compromised.

Using pressure relief valves as reclosable PRD, the relieving pressure is equal to the set pressure plus overpressure.

$$p_0 = (p_{\text{set}} + p_{\text{amb}}) + \Delta p_{\text{over}} \quad (3)$$

Using bursting discs as non-reclosable PRD, the relieving pressure is equal to the maximum bursting pressure

$$p_0 = p_{\text{burst,max}} + p_{\text{amb}} \quad (4)$$

Using secondary PRD for damage limitation in low-pressure helium cryostats (7.3.3), the relieving pressure shall be smaller than or equal to the actual test pressure, to which the pressure equipment was subject to.

$$p_0 \leq p_{\text{test}} + p_{\text{amb}} \quad (5)$$

8.3.2 Calculation of the specific volume

8.3.2.1 Initial specific volume

The initial specific volume v_i depends on the filling quantity and is defined as

$$v_i = \frac{V_{\text{He}}}{M_{\text{He}}} \quad (6)$$

In two-phase systems, the initial specific volume shall be determined from the masses both in the vapour phase and in the liquid phase.

8.3.2.2 Specific volume at subcritical relieving pressure

With regard to Figure A.1 in Annex A, the fluid state upstream of the PRD at subcritical relieving pressure ($p_0 < p_{\text{crit}}$) can be either liquid, two-phase or vapour, depending on the isochoric process path following the initial specific volume v_i .

During discharge, the specific volume increases. An exemplarily process path is shown in Figure 5 (a). The evolution of the minimum discharge area per watt of heat load shall be calculated by taking into account all relevant inlet conditions into the PRD during discharge, starting with the initial specific volume v_i , cf. Figure 5 (b). The worst case with the maximum value of A_{th} shall be assumed for dimensioning the PRD.

$$v_0 = v \left|_{v \geq v_i}^{\max} [A_{\text{th}}(v)] \quad (7)$$

with

$$T_0 = T_0(p_0, v_0) \quad (8)$$

If the specific volume v_0 cannot be determined due to missing information on v_i , $v_0 = v'$ yields the maximum value of A_{th} .

NOTE ISO 21013-3 uses $v_0 = v''$, which does not consider the possibility of liquid or two-phase inlet conditions at small initial specific volumes v_i (i.e. at large initial filling quantities).

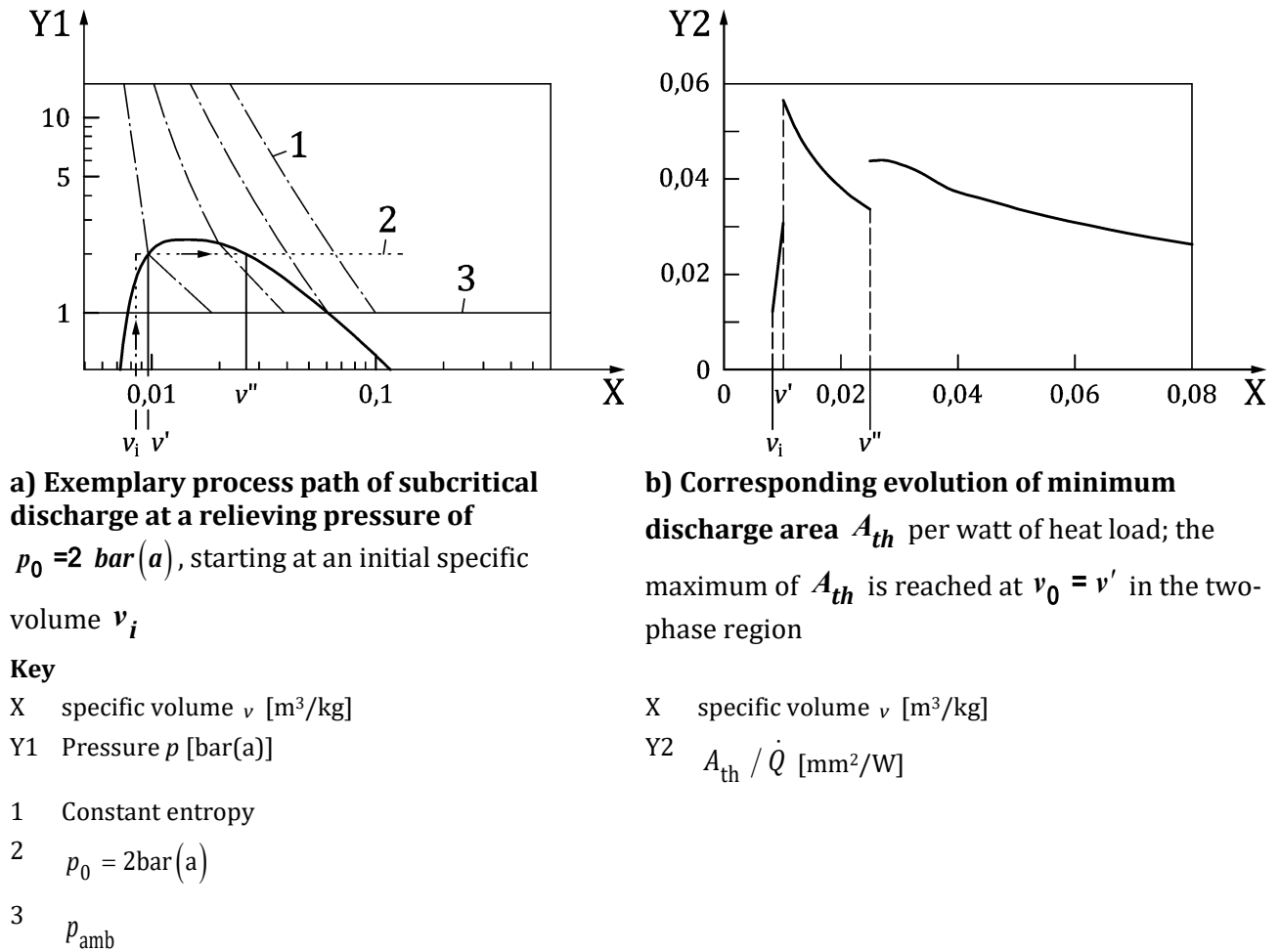


Figure 5 — Typical evolution of the minimum discharge area at subcritical relieving pressure

8.3.2.3 Specific volume at critical and supercritical relieving pressure

The specific volume v at critical and supercritical relieving pressure $p_0 \geq p_{\text{crit}}$ is given by

$$v = f(p_0, T_0) \quad (9)$$

where

T_0 is the temperature in $\left\{ \begin{array}{l} v = f(p_0, T_0) \\ h = f(p_0, T_0) \end{array} \right\}$ when the coefficient

$$\frac{\sqrt{v}}{v \times \left(\frac{\partial h}{\partial v} \right)_{p_0}} \quad (10)$$

reaches its maximum [46].

NOTE 1 See example in D.5

Depending on the initial specific volume v_i , two cases shall be distinguished:

- a) $v_i < v$: v_0 is calculated by Formula (9) at the maximum of expression (10)
- b) $v_i \geq v$: $v_0 = v_i$

NOTE 2 During discharge, the specific volume increases continuously and Case a) corresponds to the state that requires the maximum discharge area. In Case b), the use of $v_0 = v_i$ is justified as the specific volume cannot decrease below v_i .

8.4 Calculation of the relieving mass flow rate

8.4.1 General

For the dimensioning of PRD, the relieving mass flow rate $\dot{M}$ shall be calculated from the energy balance applied to an open system at constant relieving pressure p_0 . In case the risk assessment concludes that other sources of excessive pressure rise cannot be mitigated (see 6.3), the resulting mass flow rates $\dot{M}_{\text{other}}$ shall be taken into account.

$$\dot{M} = \frac{\dot{Q}}{\Delta h} + \dot{M}_{\text{other}} \quad (11)$$

where

- $\dot{M}$ is the relieving mass flow rate in kg/s;
- $\dot{M}_{\text{other}}$ is the relieving mass flow rate in kg/s from other scenarios (see 6.3);
- $\dot{Q}$ is the heat load in W for the relevant scenarios according to 8.4.2 to 8.4.6; and
- Δh is the specific enthalpy change of the helium in J/kg according to 8.4.7.

All steps relevant for the mass flow rate calculation according to Formula (11) shall be performed considering the relieving conditions of the cryostat (index "0").

For the variety of specific and advanced design solutions of helium cryostats, an overall algorithm for calculating the heat load $\dot{Q}$ cannot be specified. The determination of the heat load for a particular incidental scenario may hence be based on either

- the algorithm given in 8.4.2 to 8.4.6,
- literature data shown in Annex B,
- unpublished experimental data obtained for the particular cryostat design including detailed documentation, or
- numerical modelling of the processes during the incidental scenario including detailed documentation.

8.4.2 Loss of insulating vacuum

Loss of insulating vacuum can be relevant for the dimensioning of the PRD of the helium cryostat.

The heat load caused by the loss of insulating vacuum $\dot{Q}_{\text{liv}}$ is defined as

$$\dot{Q}_{\text{liv}} = \dot{q}_{\text{liv}} \times A_c \quad (12)$$

The maximum heat fluxes $\dot{q}_{\text{liv}}$ to blank vacuum-insulated cryogenic surfaces without multi-layer insulation (MLI) in case of free convection and relevant for the dimensioning of PRD are:

- Subcritical relieving pressure $p_0 < p_{\text{crit}}$

$$\dot{q}_{\text{liv}} = 3,8 \times 10^4 \text{ W / m}^2 \quad (13)$$

as given in [19].

- Critical and Supercritical relieving pressure $p_0 \geq p_{\text{crit}}$

$$\dot{q}_{\text{liv}} = 2,0 \times 10^4 \text{ W / m}^2 \quad (14)$$

In the case of forced convection at both sub- and supercritical relieving pressure, numerical modelling of the heat flux should be carried out.

In case of MLI-insulated surfaces, values of $\dot{q}_{\text{liv}}$ depend on the type and the particular implementation of MLI. In absence of specific experimental data, the heat flux as a function of MLI layer numbers as specified in EN ISO 21013-3 can be used. Further example values are given in Annex B.

In cases where the heat flux is limited by the ratio between the leak area and the affected cryogenic surface area according to Formula (15), the procedure in 8.4.3 may be applied.

8.4.3 Loss of beamline vacuum

Loss of beamline vacuum can be relevant for the dimensioning of the PRD of the helium cryostat, e.g. accelerator components.

In case of loss of beamline vacuum by venting with atmospheric air, the heat flux transferred in the helium yields maximum values due to the absence of thermal insulation. Heat flux values to blank vacuum insulated surfaces given in 8.4.2 shall be applied, provided the venting of air into the vacuum space is sufficient to yield the maximum value.

For small leaks into the beamline vacuum, where the ratio between the leak area and the affected cryogenic surface area follows

$$\frac{A_{\text{leak}}}{A_c} < 8,0 \times 10^{-4} \quad (15)$$

the heat load is limited by the energy stored in the venting air flow. The following procedure shall be applied in this case:

1. Determine the size of the incidental leak area as a result of the risk assessment.
2. Calculate the mass flow rate through the leak (depending if the flow is subcritical or critical) according to the Bernoulli-equation for adiabatic and compressible flow through short nozzles:

$$\dot{M}_{\text{lbv}} = A_{\text{leak}} \times \sqrt{2 \times 10^5 \times \frac{p_{\text{amb}}}{v_{\text{amb}}}} \times \begin{cases} \sqrt{\frac{\kappa}{\kappa-1} \times \left(\left(\frac{p_v}{p_{\text{amb}}} \right)^{\frac{2}{\kappa}} - \left(\frac{p_v}{p_{\text{amb}}} \right)^{\frac{\kappa+1}{\kappa}} \right)}, & \frac{p_v}{p_{\text{amb}}} < \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} \\ \sqrt{\frac{\kappa}{\kappa+1} \times \left(\frac{2}{\kappa+1} \right)^{\frac{1}{\kappa-1}}}, & \frac{p_v}{p_{\text{amb}}} \geq \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} \end{cases} \quad (16)$$

where κ is the isentropic expansion coefficient of ambient air at T_{amb} and p_{amb} .

3. Determine the specific enthalpy difference of humid air Δh_{air} in J/kg, including the sensible heat and the latent heat of both vaporization and sublimation.

NOTE 1 Table B.2 in B.2 provides a list of values of Δh_{air} for a range of cryogenic wall temperatures, which can be considered equal to the helium temperature inside the cryostat.

4. Calculate the heat load dissipated onto the beamline wall by multiplying the specific enthalpy difference with the mass flow rate

$$\dot{Q}_{\text{lbv}} = \Delta h_{\text{air}} \times \dot{M}_{\text{lbv}} \quad (17)$$

NOTE 2 The value in (15) is based on experiments in the test facility [27].

NOTE 3 The factor 10^5 in Formula (16) corresponds to the conversion from bar to Pa.

8.4.4 Quench of a superconducting device

A quench of a superconducting device (SCD) can be relevant for the dimensioning of PRD of a helium cryostat.

In order to reduce the risk of excessive pressure rise caused by a quench, the liquid-to-gas ratio of helium in the cryostat should be reduced to a minimum and/or an electromagnetic energy extraction system (e.g. dump resistor) should be implemented.

The heat load on the helium system caused by the quench of a SCD is defined as

$$\dot{Q}_{\text{quench}} = \dot{q}_{\text{quench}} \times A_{\text{scd}} \quad (18)$$

The heat flux transferred to the helium is

$$\dot{q}_{\text{quench}} = \dot{q}_{\text{quench}}(p_0, (T_{\text{scd}} - T_0)) \quad (19)$$

where

p_0 is the relieving pressure according to 8.3.1;

T_{scd} is the surface temperature of the superconducting device following a quench in K; and

T_0 is the relieving temperature in K defined as

$$T_0 = T_s(p_0) \text{ in case } p_0 < p_{\text{crit}} \quad (20)$$

$$T_0 = T_0 \text{ according to 8.3.2.3 in case } p_0 \geq p_{\text{crit}} \quad (21)$$

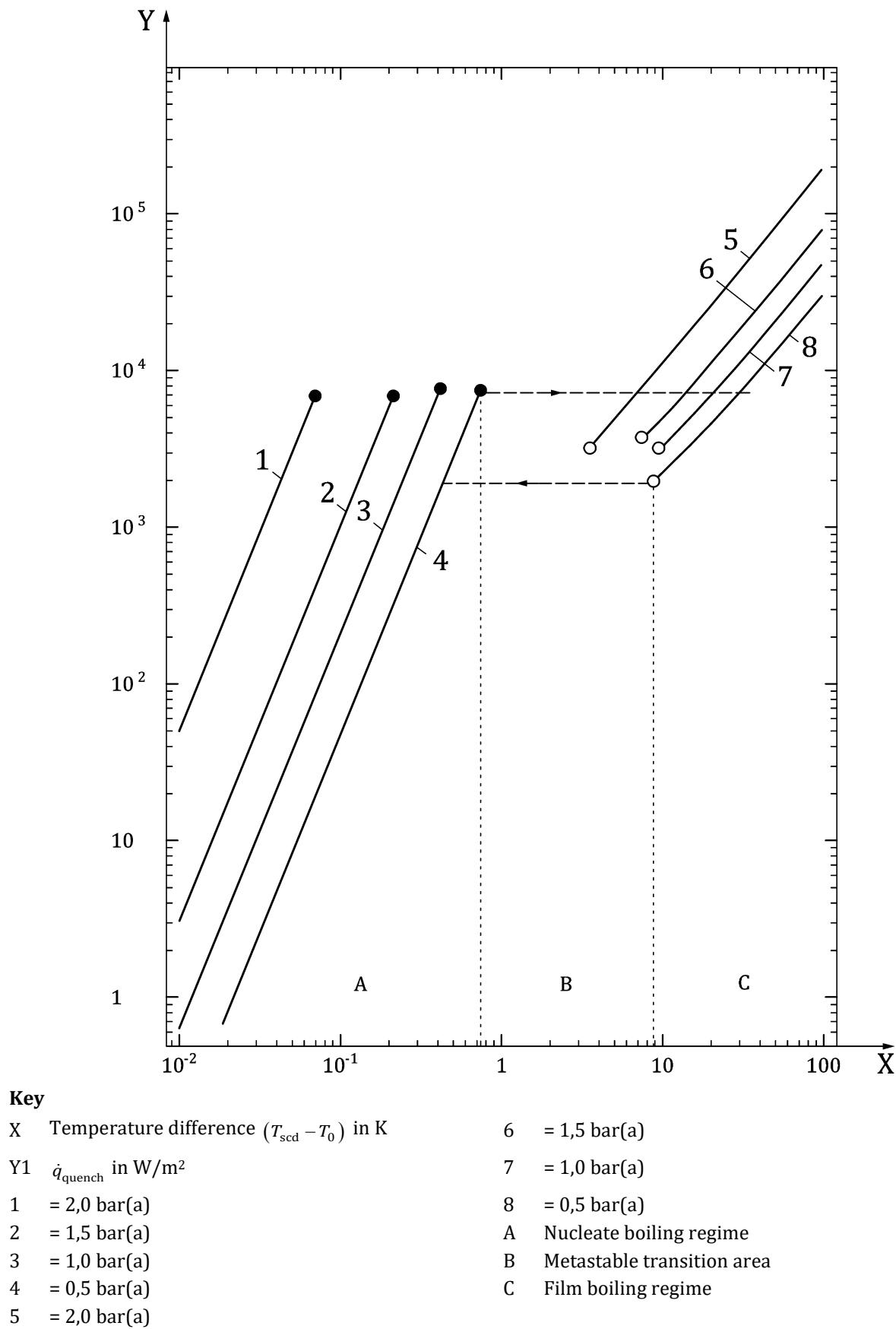


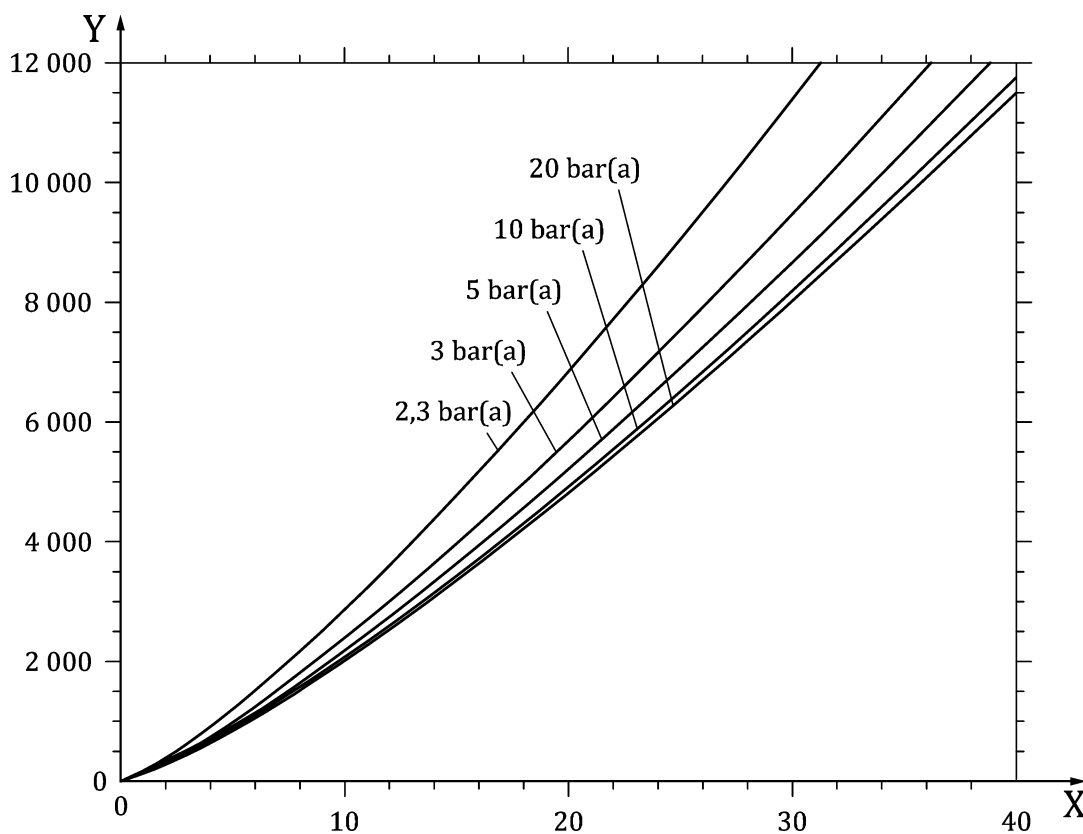
Figure 6 — Heat flux $\dot{q}_{\text{quench}}$ versus temperature difference at subcritical relieving pressure

At subcritical relieving pressure $p_0 < p_{\text{crit}}$ and with T_0 according to Formula (20), the heat flux $\dot{q}_{\text{quench}}$ shall be determined from Figure 6, whereby the evolution of the surface temperature T_{scd} should be determined together with the designer of the superconducting device. Nucleate boiling occurs up to the maximum nucleate boiling heat flux, followed by a spontaneous transition to film boiling [30].

At critical and supercritical relieving pressure $p_0 \geq p_{\text{crit}}$, the heat flux $\dot{q}_{\text{quench}}$ shall be determined from Figure 7 in case of free convection, whereby the characteristic length L_c of the heat transfer problem shall be specified according to the specific geometry [11].

$$L_c = \frac{A_{\text{scd}}}{P_{\text{proj}}} \quad (22)$$

In the case of forced convection at both sub- and supercritical relieving pressure, numerical modelling of the heat flux should be carried out.



Key

X Temperature difference ($T_{\text{scd}} - T_0$) in K

Y $\dot{q}_{\text{quench}} / L_c^{-0,226}$ in $\text{W} / \text{m}^{1,774}$

Figure 7 — Heat flux $\dot{q}_{\text{quench}}$ per characteristic length $L_c^{-0,226}$ versus temperature difference at supercritical relieving pressure in case of free convection

NOTE 1 The exponent of the characteristic length $L_c^{-0,226}$ is derived from the used correlation for free convection heat transfer to supercritical helium [18].