Preliminary risk analysis of the LHC cryogenic system

M. Chorowski*, Ph. Lebrun**, G. Riddone**

* Wroclaw University of Technology – Faculty of Mechanical and Power Engineering
Institute of Heat Engineering and Fluid Mechanics

** LHC-ACR Group

Summary

The objective of the study is to identify all risks to personnel, equipment or environment resulting from cryogenic failures that may accidentally occur within the cryogenic system of Large Hadron Collider in any phase of the machine operation, and that could not be eliminated by design. We then formulate recommendations concerning lines of preventive and corrective defence, as well as further, more detailed studies.

Table of contents

1. Preliminary risk analysis method.....	5
2. Identification Phase	7
2.1 LHC cryogenic system nodes	7
2.2 Failure modes of the LHC cryogenic system	10
2.3 Operation modes of the Large Hadron Collider.....	15
3. Risks associated to failures at LHC cryogenic system nodes located in the tunnel.	18
3.1.LHC cryogenic system nodes located in the tunnel.....	18
3.2.Potential and credible failures at the nodes located in the tunnel.....	22
3.3.Analysis of and recommendations for credible failure modes at the nodes located in the tunnel	25
4. Risks associated to failures of LHC cryogenic system nodes in caverns and shafts	32
4.1 LHC cryogenic system nodes located in the caverns and shafts.....	32
4.2 Potential and credible failure modes at the nodes located in the caverns and shafts	37
4.3 Analysis of and recommendations for credible failure modes at the nodes located in the caverns and shafts.....	40
5. Risks associated at failures of LHC cryogenic system nodes at the surface.....	46
5.1 LHC cryogenic system nodes located at the surface (buildings and open space)	46
5.2 Potential and credible failures at the nodes located at the surface	51
5.3.Analysis of and recommendations for credible failure modes at the nodes located at the surface	55
6. Worst case scenario failures	66
7. Conclusions	67
8. Acknowledgments.....	67
9. Glossary	67
10. References	68

List of tables

Table 1:	Cryogenic failure modes	12
Table 2:	Operation modes of Large Hadron Collider.	17
Table 3:	LHC cryogenic system nodes located in the tunnel.....	18
Table 4:	Maximum He masses and volumes in the tunnel.....	21
Table 5:	Potential and credible (Y) failure modes of LHC nodes located in the tunnel (part 1)	23
Table 6:	Credible failures of the cryogenic elements located in the tunnel and their causes ..	25
Table 7:	Recognized failures of the LHC elements located in the tunnel and their consequences (part 1)	26
Table 8:	Gravity 3b failures at the nodes located in the tunnel.....	31
Table 9:	LHC cryogenic system nodes located in caverns and shafts	32
Table 10:	Maximum He masses and volumes in the QURC.....	35
Table 11:	Maximum He masses and volumes in the QUL.....	35
Table 12:	Maximum He masses and volumes in the QURA.....	35
Table 13:	Maximum He masses and volumes in the insulated transfer lines and uninsulated pipes in the caverns and shafts.....	36
Table 14:	Potential and credible (Y) failure modes of LHC nodes located in caverns.....	38
Table 15:	Potential and credible (Y) failure modes of LHC nodes located in the shafts.....	39
Table 16:	Credible failures of the machine elements located in caverns and shafts, and their causes	40
Table 17:	Recognized failures of the LHC elements located in caverns and shafts, and their consequences (part 1)	41
Table 18:	Gravity 3b failures at the nodes located in caverns and shafts	45
Table 19:	LHC cryogenic system nodes located at the surface	46
Table 20:	Maximum He masses and volumes in the QSRA	48
Table 21:	Maximum He masses and volumes in the QSRB	48
Table 22:	Maximum He masses and volumes in the QSCA or QSCB.....	48
Table 23:	Maximum He masses and volumes in the QSCC	49
Table 24:	Maximum helium and nitrogen masses and volumes in the storage vessels.....	49
Table 25:	Maximum helium and nitrogen masses and volumes in interconnecting cryogenic lines and warm piping at the surface	50
Table 26:	Potential and credible (Y) failure modes of LHC nodes located at the surface (part 1).....	52
Table 27:	Credible failures of the cryogenic elements located at the surface and their causes (part 1)	55
Table 28:	Credible failure modes of the LHC elements located at the surface and their consequences (part 1).	57
Table 29:	Gravity 3b failures of the nodes located in surface	65
Table 30:	Worst case scenario failures for the LHC cryogenic system nodes located in the tunnel, caverns, shafts and at the surface.	66

List of figures

Figure 1: Schematic representation of the risk analysis method.....	6
Figure 2: General view of the LHC cryogenic system.....	8
Figure 3: Architecture of the LHC cryogenic system.....	9
Figure 4: Flow-scheme of LHC elementary cooling loop.....	11
Figure 5: Simplified LHC flow-scheme showing safety relief valve locations.....	13
Figure 6: Generic flow (a) and technical (b) scheme of the LHC cryogenic system nodes with failure modes shown.....	14
Figure 7: LHC yearly operation schedule.....	16
Figure 8: LHC machine components located in the tunnel.	19
Figure 9: Vacuum and cold mass sub-sectorization (QRL and LHC machine cryostat) in the LHC regular arc.....	20
Figure 10: Layout of cryogenic equipment in a typical cavern (P8).....	33
Figure 11: Typical layout of piping at an even-numbered point (P4, P6, P8).....	34
Figure 12: Typical layout of cryogenic equipment at the surface (P8).....	47

1. Preliminary risk analysis method

The Preliminary Risk Analysis (PRA) presented in this paper is performed in three steps, conceptually shown in Figure 1.

- The first step, called Identification is focused on listing of all the machine components, called later nodes, cryogenics-related failures and operation modes. Data have been collected through dedicated hearings, discussions and experience gathered at CERN.
- The objective of the second phase, called Combination is to list all potential failures for every node in any mode of the collider operation.
- The third phase, called Analysis is conducted in two steps. First for each potential failure a YES/NO decision is made to retain credible failures only. Then a descriptive analysis of the causes and consequences of each credible failure is made and a gravity number of 1 to 3 is assigned to each event. Failures of gravity 1 do not create any risk, neither to personnel nor to environment. For the failures of gravity 2 and 3, the associated risks are described and recommendations are formulated. Finally worst case scenarios for the nodes located in the tunnel, caverns, shafts and surface are identified and a descriptive probability for each of the mishaps is assigned.

The technique used for performing the PRA of the LHC cryogenic system is compatible with FEMECA (Failure Mode and Effect Criticality analysis) [1]. It fulfils the general requirements of Preliminary Risk Analysis of a complex technical system and in particular of a cryogenic system auxiliary to a large superconducting device [2, 3].

Figure 1: Schematic representation of the risk analysis method

2. Identification Phase

2.1 LHC cryogenic system nodes

For the purpose of this analysis the cryogenic system of LHC is treated as composed of separate helium enclosures, called later on nodes. Each node is characterised by the amount and thermodynamic parameters of the helium enclosed. For the enclosures that are vacuum insulated, the volume of the vacuum space is the relevant parameter.

The general view of the LHC cryogenic system is shown in Figure 2, and its architecture in Figure 3. The LHC cryogenic nodes are classified according to their locations [4]:

- Nodes in tunnel, related later as R (e.g. LHC cryomagnets, cryogenic distribution line QRL),
- Nodes in caverns, related later as U (e.g. cold compressor boxes QURC),
- Nodes in shafts, related later as P (e.g. cryogenic interconnecting lines QPLA),
- Nodes at surface (buildings and free space), related later as S (e.g. helium compressor stations QSCA, QSCB, QSCC).

Figure 2: General view of the LHC cryogenic system

2.2 Failure modes of the LHC cryogenic system

The safety philosophy of the LHC cryogenic system rests on some specific design features, listed in the following:

- the presence of a high-capacity, cold recovery header D which has a nominal working pressure of 1.3 bar (design pressure of 20 bar), a nominal working temperature of 20 K and a volume of about 60 m³ per sector. Helium expelled from the magnet cold mass after a loss of insulation vacuum or magnet resistive transitions will flow into header D. The header will also accommodate helium relieved from other cryogenic distribution line QRL headers after insulation vacuum degradation (see Figure 4 and Figure 5). The only header protected with safety valves venting directly to caverns is header B because of low design pressure. A warm helium recovery line (see Figure 3) accommodates helium leaving the DFB after cooling the HTS current leads.
- the absence of nitrogen (liquid or gaseous) in the tunnel (see Figure 4 and Figure 5), in any operating mode. Liquid nitrogen is used only for helium pre-cooling at ground surface during cool-down.
- the absence of forced helium flow by mechanical devices (pumps) in cooling loops, resulting in quasi-static behaviour of fluid in case of header rupture (see Figure 4).

These features differ from the options chosen for the cryogenic systems of other large superconducting accelerators [5], and contribute to make the LHC cryogenic system inherently safe, with a limited number of credible risks and failures.

We define a cryogenic-related failure mode as an accidental event that involves helium or air mass transfer between helium enclosure, insulation or beam vacuum space and environment, in result of any constructional element break or malfunctioning (e.g. broken bellows, broken pipe or leaking valve). An unexpected energy release to cold mass helium as result of an extended magnet resistive transition or electrical arc is also a cryogenic failure mode.

We assume that within the LHC cryogenic system, only a single failure mode can occur at a given time.

A generic scheme of the LHC cryogenic system nodes is shown conceptually in Figure 6. Based on this scheme we can define the following potential failure modes for any of the system nodes (see Table 1). Depending on the node a list of potential failures may comprise all the events named in Table 1 (e.g. for LHC cryomagnets) or only a few of them (e.g. for medium-pressure helium storage tanks the only possible failure is helium flow to environment).

Figure 4: Flow-scheme of LHC elementary cooling loop

Table 1: Cryogenic failure modes

No.	Cryogenic failure
1	Air flow to insulation vacuum
2 ⁽¹⁾	Helium flow to insulation vacuum
3	Air flow to sub-atmospheric helium
4 ⁽¹⁾	Helium flow to environment
5	Air flow to beam vacuum
6	Helium flow to beam vacuum
7	Pressurised helium flow to sub-atmospheric helium
8	Energy release to cold mass helium due to a sector quench
9	Energy release to cold mass helium due to electrical arc
10	Oil flow to environment (in case of helium compressors only)

⁽¹⁾ in case of nitrogen tanks on surface the failure mode deals with “nitrogen flow” instead of “helium flow”

From their consequences, the LHC cryogenic related failures will be classified into three groups of different gravity, numbered from 1 to 3.

Gravity 1. Failure does not involve helium relief from the machine, or risk either to personnel or to environment.

Gravity 2. Helium⁽¹⁾ is blown out of the machine directly to atmosphere at the surface.

Gravity 3. Helium⁽¹⁾ is blown out of the machine to the confined area (tunnel, cavern, shaft, surface building):

Gravity 3a – while access to the tunnel is forbidden

Gravity 3b – while access to the tunnel is allowed, under controlled conditions

According to the conclusions of AIWG (Access and Interlock Working Group), endorsed by the LHC Technical Committee (TCC Minutes 3.07.1998), access to the LHC will always be controlled.

Figure 5: Simplified LHC flow-scheme showing safety relief valve locations

Figure 6. Generic flow (a) and technical (b) scheme of the LHC cryogenic system nodes with failure modes shown.

2.3 Operation modes of the Large Hadron Collider

The LHC operation modes have been defined on the basis of the tentative machine yearly operation schedule as shown in Figure 7 [6]. Additionally, the operation modes that will not happen on a regular basis have been taken into account. A list of LHC operation modes is given in Table 2. The helium temperature and the presence of magnetic field and beam define each operation mode. As a remark, the access condition to the tunnel is also given.

The part of a ring between two successive insertion points, which corresponds to $1/8$ of the machine circumference, is called a sector [7]. Cryogenic installations for each sector can be operated independently. During the machine installation and commissioning phases, different operation modes may be encountered even in adjacent sectors [8].

Figure 7: LHC yearly operation schedule

Table 2. Operation modes of Large Hadron Collider.

No.	Operation mode	Temperature [K]	Magnetic field	Beam	Remarks
1	Warm	300	No field	No beam	Access to the tunnel controlled
2	Drifting	< 300	No field	No beam	Passive warm up of the machine, access to the tunnel controlled
2	75 K stand-by	75	No field	No beam	Active cooling of the shield 75 K, helium flow through 75 K cooling loop, access to the tunnel controlled
3	Cool - down	300 - 1.9	No field	No beam	Access to the tunnel controlled
4	1.9 K stand-by	1.9	No field or very low field	No beam	Access to the tunnel controlled
5	System test or ramp down	1.9	Nominal field or ramp down	No beam	Access to the tunnel restricted.
6	Normal operation	1.9	Injection field, ramp up or nominal	Injection, Fill, Nominal	No access to the tunnel
7	Warm up	1.9 - 300	No field	No beam	Access to the tunnel controlled
9	Short intervention	1.9 mostly, locally 300	No field	No beam	E.g.: during a cold diode change, access to the tunnel controlled
10	Limited quench	1.9 mostly, locally 30	No field	No beam	Access to the tunnel restricted

3. Risks associated to failures at LHC cryogenic system nodes located in the tunnel.

3.1. LHC cryogenic system nodes located in the tunnel

A typical LHC tunnel cross-section is shown in Figure 8. The accelerator will be composed of the LHC machine cryostat paralleled by the cryogenic distribution line QRL. Both will be linked by a jumper connection every 107 m.

The nodes of LHC cryogenic system located in the tunnel are listed in Table 3.

Table 3. LHC cryogenic system nodes located in the tunnel.

Node	Node description	Remarks
R1	LHC cryomagnets (including stand-alone units)	Along the machine
R2	Cryogenic distribution line QRL (including jumper connections)	Along the machine
R3	Helium ring line (QRP ; see figure 8)	Along the machine
R4	Warm helium recovery line (QRP ; see figure 8)	Along the machine
R5	Electrical feed box DFB	At the ends of each sector
R6	Radio-frequency RF cavities	In straight sections, on each side of PM4

Each node located in the tunnel may be characterized by the amount of helium enclosed and vacuum insulation volume. The values depend on vacuum and cold mass sub-sectorization (see Figure 9). Based on the distances between QRL vacuum barriers (four cells), LHC machine cryostat vacuum barriers (2 cells) and cold mass tight plugs (two cells), the highest amount of helium and length of vacuum insulation involved in the failures are calculated and listed in Table 4 [9]. The operation modes when the helium quantities in the specified helium enclosures are the highest are: 1.9 K stand-by, Normal operation, System test and Ramp down. The exception is QRL header D, which has the highest helium density after a limited quench.

Figure 8: LHC machine components located in the tunnel.

Insulation Vacuum sub-sectorization:

Cold-mass sub-sectorization:

Figure 9: **Vacuum and cold mass sub-sectorization (QRL and LHC machine cryostat) in the LHC regular arc**

Table 4: Maximum He masses and volumes in the tunnel

	P [bar]	T [K]	Mass-flow [kg/s]	Mass per sub-sector [kg]	Residence time ⁽³⁾ [s]	Volume per sub-sector [m ³]	He sub-sectorisation [m]	Vacuum sub-sectorisation [m]
QRL:								
Header B	0.016	4	0.125	37	296	195	3300	428
Header C	3	4.6	0.141	3300	23400	26	3300	428
Header D ⁽⁴⁾	3	10	0.114	917 ⁽⁴⁾	8043	60	3300	428
Header F	19	75	0.234	195	833	17	3300	428
LHC cryomagnets:								
Cold mass	1.3	1.9	0	475	∞	3.21	214	214
Header E	19.5	75	0.234	195	833	17	3300	214
DFB	1.3	4.4	0	79	∞	0.65 ⁽¹⁾	15	300
RF cavities	1.3	4.4	0	34	∞	0.28 ⁽²⁾	13	13
He ring line	20	300	0.15	321	2140	104	26400	=
Warm recovery line	1.05	300	0.05	9	180	58	3300	=

(1) Longest DFB at Point 2 Left

(2) volume per module

(3) residence time is calculated as element length divided by the fluid velocity

(4) helium parameters in header D – as after a limited quench

3.2. Potential and credible failures at the nodes located in the tunnel

All potential failures at the cryogenic nodes located in the tunnel, which may happen at any phase of the collider operation, are listed in Table 5.

We identify a failure at a node by the following code:

$R_{x,y}$

The first identification character [R], as shown in Figure 2, defines a node location [4].

The second identification character [x], as listed in Table 3, defines a node.

The third identification character [y], as listed in Table 1, defines a failure mode.

In Table 5 all failures listed in Table 1 for every node located in the tunnel are combined with the machine operation modes given in Table 2, creating a full list of potential failures. Subsequently for each potential failure a YES/NO decision is made to eliminate events that are not credible. Finally some of the credible failures are qualified as worst case scenarios on the criterion of mass of helium involved and access to the tunnel as shown in darker cells in Table 5.

Table 5a: Potential and credible (Y) failure modes of LHC nodes located in the tunnel (part 1)

Node	Failure mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
R1	R1.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R1.2.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R1.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	R1.4	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R1.5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R1.6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R1.7	N	N	N	Y	Y	Y	Y	Y	Y	Y
R2	R1.8	N	N	N	N	N	Y	Y	N	N	N
	R1.9	N	N	N	N	N	Y	Y	N	N	N
	R2.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R2.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R2.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	R2.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R2.5	N	N	N	N	N	N	N	N	N	N
R3	R2.6	N	N	N	N	N	N	N	N	N	N
	R2.7	N	N	N	N	N	N	N	N	N	N
	R2.8	N	N	N	N	N	N	N	N	N	N
	R2.9	N	N	N	N	N	N	N	N	N	N
	R3.1	N	N	N	N	N	N	N	N	N	N
	R3.2	N	N	N	N	N	N	N	N	N	N
	R3.3	N	N	N	N	N	N	N	N	N	N
	R3.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R3.5	N	N	N	N	N	N	N	N	N	N
	R3.6	N	N	N	N	N	N	N	N	N	N
	R3.7	N	N	N	N	N	N	N	N	N	N
	R3.8	N	N	N	N	N	N	N	N	N	N
	R3.9	N	N	N	N	N	N	N	N	N	N
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

Table 5b: Potential and credible (Y) failure modes of LHC nodes located in the tunnel (part 2).

Node	Failure mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
R4	R4.1	N	N	N	N	N	N	N	N	N	N
	R4.2	N	N	N	N	N	N	N	N	N	N
	R4.3	N	N	N	N	N	N	N	N	N	N
	R4.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R4.5	N	N	N	N	N	N	N	N	N	N
	R4.6	N	N	N	N	N	N	N	N	N	N
	R4.7	N	N	N	N	N	N	N	N	N	N
	R4.8	N	N	N	N	N	N	N	N	N	N
	R4.9	N	N	N	N	N	N	N	N	N	N
R5	R5.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R5.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R5.3	N	N	N	N	N	N	N	N	N	N
	R5.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R5.5	N	N	N	N	N	N	N	N	N	N
	R5.6	N	N	N	N	N	N	N	N	N	N
	R5.7	N	N	N	N	N	N	N	N	N	N
	R5.8	N	N	N	N	N	N	N	N	N	N
	R5.9	N	N	N	N	N	N	N	N	N	N
R6	R6.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R6.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R6.3	N	N	N	N	N	N	N	N	N	N
	R6.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	R6.5	N	N	N	N	N	N	N	N	N	N
	R6.6	N	N	N	N	N	N	N	N	N	N
	R6.7	N	N	N	N	N	N	N	N	N	N
	R6.8	N	N	N	N	N	N	N	N	N	N
	R6.9	N	N	N	N	N	N	N	N	N	N
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

3.3. Analysis of and recommendations for credible failure modes at the nodes located in the tunnel

The detailed analysis is performed and recommendations are formulated for the failures involving the highest helium amounts during the operation modes with access to the tunnel allowed or restricted. In Table 6 the credible cryogenics-related failures are gathered and their potential causes are specified. In Table 7 physical consequences of the credible failures are described, the method of failure detection is proposed (column Information/Detection), as well as preventive and corrective defence measures.

Table 6: Credible failures of the cryogenic elements located in the tunnel and their causes

Element	Failure	Failure causes
R1. LHC machine cryostat	R1.1. Air flow to cryostat insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	R1.2. Helium flow to cryostat insulation vacuum	Bellows failure Weld non-tight
	R1.3. Air flow to sub-atmospheric helium Venting to helium of cryostat insulation vacuum	Break of instrumentation capillary
	R1.4. Helium flow to environment	Break of instrumentation capillary
	R1.5. Air flow to beam vacuum	Break of warm beam tube e.g. due to beam escape. Bellows failure
	R1.6. Helium flow to beam vacuum	Break of beam screen cooling pipe or cold beam tube e.g. due to beam escape.
	R1.7. Pressurized helium flow to sub-atmospheric helium	Bellows failure
	R1.8. Energy release due to a sector quench	Control system failure Utilities failure
	R1.9 Energy release due to electrical arc	Low dielectric resistance of helium
R2. Cryogenic distribution line QRL with jumper connection	R2.1. Air flow to QRL insulation vacuum	Mechanical impact on a vacuum gauge Bellows failure Weld non-tight
	R2.2. Helium flow to QRL insulation vacuum	Bellows failure Weld non-tight
	R2.3 Air flow to sub-atmospheric helium	Break of helium guard
	R2.4. Helium flow to environment	Break of jumper connection due to mechanical impact or geotechnical problems
R3. Helium ring line	R3.4. Helium flow to environment	Mechanical impact on helium ring line
R4. Warm helium recovery line	R4.1. Helium flow to environment	Mechanical impact on warm helium recovery line
R5. Electrical feed box DFB	R5.1. Air flow to DFB insulation vacuum	Mechanical impact on a vacuum gauge
	R5.2. Helium flow to DFB insulation vacuum	Bellows failure Weld non-tight
	R5.4 Helium flow to environment	Break of instrumentation capillary
R6. RF cavities	R6.1. Air flow to RF cavities insulation vacuum	Mechanical impact on a vacuum gauge Bellows failure Weld non-tight
	R6.2. Helium flow to RF insulation vacuum	Bellows failure Weld non-tight
	R6.4 Helium flow to environment	Break of instrumentation capillary

Table 7a: Recognized failures of the LHC elements located in the tunnel and their consequences (part 1)

Failure	Events	Danger to personnel	Risk to equipment	Information/detection	Preventive defence	Corrective defence
R1.1. Air flow to insulation vacuum of LHC machine cryostat [10, 11] Gravity 1	Pressurisation up to 1 bar of LHC cryostat vacuum insulation at the length of 214 m. Oxygen enriched air condensation on the cold mass Heat load to cold mass and header E, helium flow to header D through safety valves	No	Air contamination of the cryostat MLI at the length of 214 m Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R1.2. He flow to insulation vacuum of LHC machine cryostat Gravity 3b	Pressurisation of LHC cryostat vacuum above 1 bar Heat load to the headers, helium flow to header D through safety valves Break of rupture disc protecting vacuum space Helium flow to the tunnel from cryostat vacuum space	Freezing of tissue Asphyxiation	Contamination with He of cryostat MLI at the length of 214 m Cold jet and embrittlement of the cryostat vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R1.3. Air flow to sub-atm. He Gravity 1	Air condensation and freezing, 1.9 cooling loop blockage	No	Air contamination of 1.9 K cooling loop	1.9 K cooling loop temperature and flow sensors	Helium guard	Intervention necessary
R1.4. He flow from LHC machine cryostat to air Gravity 3b	Break of instrumentation feedthrough or cryogenic valves will result in cold helium flow to the tunnel	Freezing of tissue	Embrittlement of carbon steel wall of the vacuum vessel	Malfunctioning of the sensor, flow disturbance in the corresponding cryogenic loop	Low diameter of instrumentation feedthrough	Intervention necessary

Table 7b: Recognized failures of the LHC elements located in the tunnel and their consequences (part 2)

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
R1.5. Air flow to beam vacuum Gravity 1	Air propagation to the cold bore. Air condensation and heat flow to the cold mass. A quench may be provoked.	No	Contamination of the beam vacuum space	Beam vacuum gauges	Actively cooled beam screen	Intervention necessary
R1.6. He flow to beam vacuum Gravity 3b	Beam vacuum filling with cold helium along whole machine. The pressure may rise above the set pressure for rupture disc and helium may flow to the tunnel. A quench may be provoked.	Freezing of tissue	Contamination of beam vacuum space	Beam vacuum gauges	Actively cooled beam screen	Intervention necessary
R1.7. Press. He flow to sub-atm He Gravity 1	Increase of the saturation He pressure and cold mass temperature. A quench may be provoked.	No	No	Temperature and pressure sensors	Redundancy of cold compressors capacity	Intervention necessary
R1.8. Sector quench [12 ,13] Gravity 1	Dissipation of magnetic energy in the cold mass, helium expulsion to header D through SRV valves Pressurisation of header D to 20 bar, helium flow to HP storage	No	No	Rise of magnet temperature	High capacity cold header D	Not linked to the cryogenic system
R1.9. Energy release – electrical arc Gravity 3b	Electrical arc between superconducting cables or busbars may result in local thermal energy release of MW order. Cold mass helium will pressurise and vent through quench relief valve. It may be followed by destruction of cold mass enclosure and helium flow to insulation vacuum (see R1.2).	See R1.2	See R1.2	Voltage taps, voltage across current leads	High dielectric resistance of pressurised He II	Not linked to the cryogenic system

Table 7c: Recognized failures of the LHC elements located in the tunnel and their consequences (part 3)

Failure	Events	Danger to personnel	Risk to equipment	Information/detection	Preventive defence	Corrective defence
R2.1. Air flow to QRL insulation vacuum [14] Gravity 1	Pressurisation up to 1 bar of QRL vacuum insulation at the length of 428 m Oxygen enriched air condensation on the headers Heat load to QRL headers, pressurisation of the headers, helium flow to header D through safety valves.	No	Air contamination of QRL vacuum space at the length of 428 m Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R2.2. Helium flow to QRL insulation vacuum Gravity 3b	Pressurisation of QRL vacuum space above 1 bar at the length of 214 m Heat load to the headers, helium flow to header D and to the vented QRL vacuum space Break of rupture disc protecting QRL vacuum Helium flow to tunnel from QRL vacuum space	Freezing of tissue Asphyxiation	Contamination of vacuum space with He at the length of 428 m Cold helium jet from headers on the vacuum vessel and its embrittlement	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R2.3. Air flow to sub-atm. He Gravity 1	Air condensation and freezing	No	Contamination of header B and sub-atmospheric circle	Pressure sensor monitoring He guard	Helium guard	Intervention necessary
R2.4. He flow to air, worst case – break of jumper connection Gravity 3b	Heat load to cold mass helium, oxygen enriched air condensation on the cold mass Helium expulsion from the cold mass to the tunnel (470 kg or 940 kg) Venting of 428 m of QRL MLI to air/helium mixture Oxygen enriched air condensation on the headers Helium flow from the headers to the tunnel (3300 kg) Filling the confined volumes in the tunnel and shafts with helium	Freezing of tissue Asphyxiation	Contamination of MLI of QRL at the length of 428 m and of machine cryostat at the length of 214 m Chemical burning of MLI insulation Embrittlement of the cryostat and QRL vacuum vessel	Vacuum gauges	Efficient tunnel ventilation	Intervention necessary

Table 7d: Recognized failures of the LHC elements located in the tunnel and their consequences (part 4)

Failure	Events	Danger to personnel	Risk to equipment	Information/detection	Preventive defence	Corrective defence
R3.4. He flow from He ring line to air Gravity 3b	Break of He ring line will result in warm He flow to the tunnel	Asphyxiation	No	Oxygen concentration sensor	Efficient tunnel ventilation	Intervention necessary
R4.4 He flow from He recovery line to air Gravity 3b	Break of warm helium recovery line will result in warm He flow to the tunnel	Asphyxiation	No	Oxygen concentration sensor	Efficient tunnel ventilation	Intervention necessary
R5.1 Air flow to DFB insulation vacuum Gravity 1	Pressurisation up to 1 bar of DFB cryostat vacuum insulation. Oxygen enriched air condensation on the cold mass Heat load to cold mass and header E, helium flow to header D through safety valves	No	Air contamination of the cryostat MLI at the length of 214 m Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R5.2. He flow to DFB insulation vacuum Gravity 3b	Pressurisation of DFB vacuum above 1 bar Heat load to the DFB cold mass, helium flow to header D through safety valve Break of rupture disc protecting vacuum space Helium flow to the tunnel/cavern from DFB vacuum space	Freezing of tissue Asphyxiation	Contamination of DFB vacuum space with He Cold helium jet from DFB cold mass on the vacuum vessel and its embrittlement	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary

Table 7e: Recognized failures of the LHC elements located in the tunnel and their consequences (part 5)

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
R5.4. He flow from DFB to air Gravity 3b	Break of instrumentation feedthrough or cryogenic valves will result in cold helium flow to the tunnel	Freezing of tissue	Embrittlement of carbon steel wall of the vacuum vessel	Malfunctioning of the sensor, flow disturbance in the corresponding cryogenic loop	Low diameter of instrumentation feedthrough	Intervention necessary
R6.1. Air flow to insulation vacuum of RF cavities Gravity 1	Pressurisation up to 1 bar of insulation vacuum of RF cavities Oxygen enriched air condensation Heat load to helium cooling cavities, helium flow to header D through safety valves	No	Air contamination of MLI of RF cavities. Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R6.2. He flow to insulation vacuum of RF cavities Gravity 3b	Pressurization of RF cavity vacuum above 1 bar Heat load to the cold mass of the RF cavities, helium flow to header D through safety valve Break of rupture disc protecting vacuum space Helium flow to the tunnel/cavern from RF vacuum space	Freezing of tissue Asphyxiation	Contamination of vacuum space of RF cavities with He Cold helium jet from cold mass of RF cavities on to the vacuum vessel and its embrittlement	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
R 6.4. He flow from RF cavities to air Gravity 3b	Break of instrumentation feedthrough or cryogenic valves will result in cold helium flow to the tunnel	Freezing of tissue	Embrittlement of carbon steel wall of the vacuum vessel	Malfunctioning of the sensor, flow disturbance in the corresponding cryogenic loop	Low diameter of instrumentation feedthrough	Intervention necessary

There are 12 events of the gravity 3b identified in Table 7. Table 8 lists the 3b gravity events, gives the highest amounts of helium that might be relieved to the tunnel together with approximate mass-flow rates and formulates the recommendations. Generally the highest value of the mass-flow rate occurs in a period of about 100 seconds. After reaching this value the mass-flow rate reduces at least by an order of magnitude within a similar period of time.

Table 8: Gravity 3b failures at the nodes located in the tunnel

Failure	Maximum amount of helium relieved to the tunnel [kg]/ approximate flow rate [kg/s]	Recommendations
R1.2 LHC cryomagnets: He flow to cryostat insulation vacuum	475 / below 2	Further analysis necessary
R1.4 LHC cryomagnets: He flow to air	475 / He flow of a leak order	Consequences of the failure fully covered by R1.2 and R2.4
R1.6 LHC cryomagnets He flow to beam vacuum	475 / to be calculated	Further analysis necessary
R1.9 LHC cryomagnets energy release – electrical arc	475 kg / flow rate similar to R1.2	Not directly related to cryogenics, consequences covered by R1.2
R2.2 He flow to QRL insulation vacuum, assumption of header C break	3300 kg / lower than 2	Second, after R2.4 worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary
R2.4 He flow to air, assumption of jumper connection break	4250 / about 20. About 600 kg are discharged in the first 60 s. After this time the mass flow-rate reduces by an order of magnitude.	Worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary
R3.4 He flow to air, He ring line break	321 kg / below 7	Further analysis recommended
R4.4 He flow to air, warm He recovery line break	9 kg / He flow of a leak order	Consequences negligible in comparison with other cases
R5.2 He flow to DFB insulation vacuum	79 kg / below 2	Further analysis recommended
R5.4 DFB He flow to air	79 kg / He flow of a leak order	Consequences of the failure fully covered by R5.2
R6.2 He flow to RF cavities insulation vacuum	34 kg / below 2	Further analysis recommended
R6.4 RF cavities cooling He flow to air	34 kg / He flow of a leak order	Consequences of the failure fully covered by R6.2

As it follows from Table 8, two worst case scenarios can be identified based on the criterion of mass of helium involved and flow rate to the tunnel: helium flow to QRL insulation vacuum (assumption of header C break) and break of jumper connection.

4. Risks associated to failures of LHC cryogenic system nodes in caverns and shafts

4.1 LHC cryogenic system nodes located in the caverns and shafts

The elements of the cryogenic system located in caverns and shafts are listed in Table 9. A layout of a typical cavern is shown in Figure 10.

The interconnecting warm pipes and cryogenic lines are schematically shown in Figure 11. Each pipe or line is identified by its corresponding equipment code and tag numbering.

Table 9: LHC cryogenic system nodes located in caverns and shafts

Node	Description	Remarks
U1	Cold compressor boxes (QURC)	In the caverns
U2	Cryogenic interconnection boxes (QUI)	In the caverns
U3	Underground Lower Cold Boxes (QURA)	In the caverns
P4	Interconnecting cryogenic lines (QPLA, QPLB, QULA and QULC)	In the caverns and shafts
P5	Interconnecting warm pipes (QPP, QPPD and QRP)	In the caverns and shafts

The amount of helium and volume of vacuum space involved in case of failure of the elements in the caverns and shafts are given in Tables 2 to 5 [15, 16, 17].

Figure 10: Layout of cryogenic equipment in a typical cavern (P8)

Figure 11: Typical layout of piping at an even-numbered point (P4, P6, P8)

Table 10: Maximum He masses and volumes in the QURC

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
VLP ⁽¹⁾ +HX ⁽²⁾	0.016-0.4	4-300	0.126	12	95	0.351
LP	1.3	20	0.126	0.06	0.5	0.02
HP	20	300-30	0.126	0.6	5	0.02
Sub-cooler	0.016	1.8	=	60	=	0.5
Absorber	20	80	0.126	2.3	20	0.4

(1) VLP = Very Low Pressure

(2) HX = heat exchanger

Table 11: Maximum He masses and volumes in the QUI

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
Header B	0.016	4	0.126	0.1	1	0.6
Header C	3.6	4.6	0.126	10	80	0.1
Header D	1.3	20	0.126	0.6	4	0.2
Header E	19.5	50	0.234	0.9	4	0.05
Header F	18	75	0.234	0.6	2	0.05
Sub-cooler	1	4.2	=	63	=	0.5

Table 12: Maximum He masses and volumes in the QURA

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
HP	20	20-4.5	0.8	88.17	110	1
LP	1.3	4.5-20	0.8	176.34	220	2
Sub-cooler	1.3	4.5	=	120	∞	1

Table 13: Maximum He masses and volumes in the interconnecting cryogenic lines and interconnecting warm pipes in the caverns and shafts

Pipe			P	T	Mass-flow	Mass	Residence time	Volume
from	To	code	[bar]	[K]	[kg/s]	[kg]	[s]	[m ³]
QUI	QURC	720 (header B)	0.016	4	0.126	0.04	0.3	0.2
		720 (header C)	3.6	4.6	0.126	3.6	28	0.03
		720 (header D)	1.3	20	0.126	0.2	1.5	0.06
QUI	QURC	760 (header B)	0.016	4	0.126	0.04	0.3	0.2
		760 (header C)	3.6	4.6	0.126	3.6	28	0.03
		760 (header D)	1.3	20	0.126	0.2	1.5	0.06
QUI	QURB	750 (header C)	3.6	4.6	0.235	174	740	1.3
		750 (header D)	1.3	20	0.165	9.4	48	3
		750 (header E)	19	50	0.24	15	60	0.8
		750 (header F)	18	75	0.24	9.5	38	0.8
QUI	QURA	710 (header C)	3.6	4.6	0.126	10	81	0.1
		710 (header D)	1.3	20	0.165	0.5	3.3	0.2
		710 (header E)	19	50	0.24	0.9	3.7	0.05
		710 (header F)	18	75	0.24	0.6	2.3	0.05
QUI	Surface ⁽¹⁾	000	1	4	=	=	=	5.3
QUI	QSV_ ⁽¹⁾	210	20	4	=	=	=	12.3
QURC	QSCC	121	15	300	0.126	5	36	2
		122	1	300	0.126	2	15	12.3
QURC	QSCC	161	15	300	0.126	5	36	2
		162	1	300	0.126	2	15	12.3
QURC	QSCA	141	15	300	0.031	3	97	1.3
		142	1	300	0.031	0.2	6.5	1.3
QURC	QSCB	181	15	300	0.041	3	73	1.3
		182	1	300	0.041	0.2	5	1.3
QURA	QSRA	210 (HP)	20	20	0.69	63	91	1.3
		210 (LP)	1.3	20	0.66	9.4	14	3
		210 (header E)	19.5	50	0.225	15.3	68	0.9
		210 (header F)	18	75	0.225	9.5	42	0.9
QURA	QSCA	131	20	300	0.042	6.6	158	2.1
		132	20	300	0.050 ⁽²⁾	1.0	20	0.3
		133	1	300	0.042	0.3	8	2.1
		134	1	300	=	=	=	3.0
QRP (warm recovery line)	QSCA	110	1.5	300	0.037	2.0	51	7.8
QRP (warm recovery line)	QSCB	150	1.5	300	0.042	2.0	54	7.8
QRP (He ring line)	QSV_	030	20	300	=	25	=	7.8

(1): pipe used in case of emergency

(2): pipe used only during warm-up

4.2 Potential and credible failure modes at the nodes located in the caverns and shafts

All potential failures at the cryogenic nodes located in the caverns and shafts, which may happen at any phase of the collider operation, are listed in Table 14 and Table 15. In a similar ways as for the nodes located in the tunnel, we identify a failure at a node by the following code: $Ux.y$ or $Px.y$, where U and P stand for location [4], x stands for element number (see Table 10) and y stands for failure mode number (see Table 1).

Table 14: Potential and credible (Y) failure modes of LHC nodes located in caverns

Node	Failure mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
U1	U1.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U1.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U1.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	U1.4	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U1.5	N	N	N	N	N	N	N	N	N	N
U2	U1.6	Y	Y	Y	Y	N	N	N	N	N	N
	U1.7	N	N	N	Y	Y	Y	Y	Y	Y	Y
	U2.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U2.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U2.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	U2.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U2.5	N	N	N	N	N	N	N	N	N	N
	U2.6	N	N	N	N	N	N	N	N	N	N
U3	U2.7	N	N	N	N	N	N	N	N	N	N
	U3.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U3.2	N	N	N	Y	Y	Y	Y	Y	Y	Y
	U3.3	N	N	N	N	N	N	N	N	N	N
	U3.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	U3.5	N	N	N	N	N	N	N	N	N	N
	U3.6	N	N	N	N	N	N	N	N	N	N
	U3.7	N	N	N	N	N	N	N	N	N	N
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

Table 15: Potential and credible (Y) failure modes of LHC nodes located in the shafts

Node	Failure mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
P4	P4.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	P4.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	P4.3	N	N	N	N	N	N	N	N	N	N
	P4.4	N	N	N	N	N	N	N	N	N	N
	P4.5	N	N	N	N	N	N	N	N	N	N
	P4.6	N	N	N	N	N	N	N	N	N	N
	P4.7	N	N	N	N	N	N	N	N	N	N
P5	P5.1	N	N	N	N	N	N	N	N	N	N
	P5.2	N	N	N	N	N	N	N	N	N	N
	P5.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	P5.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	P5.5	N	N	N	N	N	N	N	N	N	N
	P5.6	N	N	N	N	N	N	N	N	N	N
	P5.7	N	N	N	N	N	N	N	N	N	N
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

4.3 Analysis of and recommendations for credible failure modes at the nodes located in the caverns and shafts

The credible failures of the LHC cryogenic elements located in caverns and shafts and their probable causes are listed in Table 16.

Table 17 gives physical consequences of the failures, proposes the means of failure detection, as well as preventive and corrective defence measures.

Table 16: Credible failures of the machine elements located in caverns and shafts, and their causes

Element	Failure	Probable causes
U1. Cold compressor boxes (QURC)	U1.1 Air flow to QURC insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	U1.2 Helium flow to QURC insulation vacuum	Bellows failure Weld non-tight
	U1.3 Air flow to sub-atmospheric helium	Break of helium guard
	U1.4 Helium flow to environment	Break of instrumentation capillary
	U1.7 Pressurised helium flow to subatmospheric helium	Break of heat exchanger, leaking valve
U2. Cryogenic interconnection boxes (QUI)	U2.1 Air flow to QUI insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	U2.2 Helium flow to QUI insulation vacuum	Break of a bellow Weld non-tight
	U2.3 Air flow to sub-atmospheric helium	Break of helium guard
	U2.4 Helium flow to environment	Break of instrumentation capillary
U3. Underground Lower Cold Boxes (QURA)	U3.1. Air flow to QURA insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	U3.2 Helium flow to QURA insulation vacuum	Bellows failure Weld non-tight
	U3.4. Helium flow to environment	Break of instrumentation capillary
P4. Interconnecting cryogenic lines	P4.1 Air flow to the transfer line insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	P4.2 Helium flow to the transfer line insulation vacuum	Bellows failure Weld non-tight
P5. Interconnecting warm pipes	U5.3 Air flow to subatmospheric helium	Break of pipe
	U5.4 Helium flow to environment	Break of pipe due to e. g. ice condensation

Table 17a: Recognized failures of the LHC elements located in caverns and shafts, and their consequences (part 1)

Failure	Events	Danger to personnel	Risk to equipment	Information/defection	Preventive defence	Corrective defence
U1.1. Air flow to QURC insulation vacuum Gravity 1	Pressurisation of QURC insulation vacuum up to 1 bar Oxygen enriched air condensation on the cold parts of QURC Heat load to helium in VLP HX, LP, HP+HX, Sub-cooler and Absorber, helium pressurisation and discharge to helium collector through safety valves	Freezing of tissue Asphyxiation	Air contamination of the MLI of QURC Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U1.2. He flow to QURC insulation vacuum Gravity 3b	Pressurisation of QURC insulation vacuum above 1 bar Heat load to helium in VLP HX, LP, HP+HX, Sub-cooler and Absorber, helium pressurisation and discharge to cavern through safety valves Break of rupture disc protecting vacuum space Helium flow to the cavern from QURC vacuum space	Freezing of tissue Asphyxiation	He contamination of the MLI of QURC Cold jet and embrittlement of the QURC vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U1.3. Air flow to sub-atm. He Gravity 1	Air condensation and freezing, subatmospheric He flow blockage	No	Air contamination of cold compressors	Flow gauges	Helium guard	Intervention necessary

Table 17b: Recognized failures of the LHC elements located in caverns and shafts and their consequences (part 2)

Failure	Events	Danger to personnel	Risk to equipment	Information/defection	Preventive defence	Corrective defence
U1.4. He flow to air Gravity 3b	Break of instrumentation capillary will result in cold helium flow to a cavern or shaft	Freezing of tissue	No	Malfunctioning of the sensor,	Low diameter of instrumentation feedthrough	Intervention necessary
U1.7. Press. He flow to sub-atm He within QURC cold box Gravity 1	Increase of the subatmospheric He pressure	No	No	Temperature and pressure sensors	Redundancy of cold compressors capacity	Intervention necessary
U2.1. Air flow to QUI insulation vacuum Gravity 1	Pressurisation up to 1 bar of QUI vacuum insulation space Oxygen enriched air condensation on the QUI pipes Heat load to QUI pipes, pressurisation of the headers, helium flow to header D in cryogenics distribution line through safety valves.	No	Air contamination of QRL vacuum space Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U2.2. Helium flow to QUI insulation vacuum Gravity 3b	Pressurisation of QUI insulation vacuum space above 1 bar Heat load to the headers in QUI, increase in helium flow to QUI vacuum space Break of rupture disc protecting QUI vacuum Helium flow to a cavern from QUI vacuum space	Freezing of tissue Asphyxiation	Contamination of QUI vacuum space with He Cold helium jet from headers on the vacuum vessel and its embrittlement	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U2.3. Air flow to sub-atm. He within QUI Gravity 1	Air condensation and freezing	No	Contamination of header B and sub-atmospheric circle	Pressure gauges	Helium guard	Intervention necessary

Table 17c: Recognized failures of the LHC elements located in caverns and shafts, and their consequences (part 3)

Failure	Events	Danger to personnel	Risk to equipment	Information/defection	Preventive defence	Corrective defence
U2.4. He flow to environment Gravity 3b	Break of instrumentation capillary will result in cold helium flow to a cavern or shaft	Freezing of tissue	Embrittlement of carbon steel wall of the vacuum vessel	False indication of a gauge with a broken capillary	Low diameter of instrumentation capillaries	Intervention necessary
U3.1 Air flow to QURA insulation vacuum Gravity 1	Pressurisation up to 1 bar of QURA insulation vacuum space Oxygen enriched air condensation on the QURA pipes Heat load to QURA pipes, pressurisation of the headers, helium flow to header D in cryogenics distribution line through safety valves.	No	Air contamination of QURA vacuum space Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U3.2 Helium flow to QURA insulation vacuum Gravity 3b	Pressurisation of QURA insulation vacuum space above 1 bar Heat load to the headers in QURA, increase in helium flow to QUI vacuum space Break of rupture disc protecting QURA vacuum Helium flow to a cavern from QURA vacuum space	Freezing of tissue Asphyxiation	Contamination of QURA vacuum space with He Cold helium jet from headers on the vacuum vessel and its embrittlement	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
U3.4. He flow to air Gravity 3b	Break of He ring line will result in warm He flow to the tunnel	Asphyxiation	No	Pressure gauges, oxygen concentration sensors	Efficient tunnel ventilation	Intervention necessary

Table 17d: Recognized failures of the LHC elements located in caverns and shafts, and their consequences (part 4)

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
P4.1 Air flow to transfer line insulation vacuum Gravity 1	Pressurisation up to 1 bar of transfer line insulation vacuum Oxygen enriched air condensation on the inner pipe in transfer line Heat load to helium in inner pipe, helium pressurisation and discharge to cavern through safety valves	Freezing of tissue Asphyxiation	Air contamination of MLI Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
P4.2 He flow to transfer line insulation vacuum Gravity 3b	Break of warm helium recovery line will result in warm He flow to the tunnel	Asphyxiation	No	Pressure and flow gauges oxygen concentration sensors	Efficient tunnel ventilation	Intervention necessary
P5.3 Air flow to subatmospheric helium, VLP pipe connecting cold compressors with Warm Compressor Station Gravity 1	In case of a subatmospheric pipe break, air will flow into the pipe	No	Contamination of helium with air	Pressure and flow gauges	Helium guard on all connections	Intervention necessary
P5.4 He flow to environment Gravity 3b	Direct helium flow to a cavern or shaft	Freezing of tissue Asphyxiation	No	Pressure and flow gauges	Good ventilation of caverns and shafts	Intervention necessary

There are 8 events of gravity 3b identified in Table 17. Table 18 lists the 3b gravity events, gives the highest amounts of helium that might be relieved to the caverns and shaft together with an approximate mass flow rates and formulates the recommendations.

Table 18: Gravity 3b failures at the nodes located in caverns and shafts

Failure	Maximum amount of helium relieved [kg] / approximate flow rate [kg/s]	Recommendations
U1.2. He flow to QURC insulation vacuum Gravity 3b	60 / below 2	Consequences of the failure mode fully covered by U3.2
U1.4. He flow from QURC to environment Gravity 3b	60 / of the leak order	Consequences of the failure mode fully covered by U3.2
U2.2. Helium flow to QUI insulation vacuum Gravity 3b	63 / below 2	Consequences of the failure mode fully covered by U3.2
U2.4. He flow from QUI enclosures to environment Gravity 3b	63 / of the leak order	Consequences of the failure mode fully covered by U3.2
U3.2 Helium flow to QURA insulation vacuum, LP circuit break	176 kg / below 2	Worst case scenario
U3.4. He flow from QURA to environment	176 kg / of the leak order	Consequences of the failure mode fully covered by U3.2
P4.2 He flow from header C of the interconnecting cryogenic line between QUI and QURB to its insulation vacuum	174 kg / below 2	From the consequences failure similar to U3.2
P5.4 He flow from QRP (warm recovery line) to environment	2 kg / of the leak order	Consequences of the failure mode fully covered by U3.2

As it follows from Table 18, the worst case scenario that may happen in a cavern or a shaft, is helium flow to QURA insulation vacuum due to the break of low pressure circuit (1.3 bar). The event will be followed by relief of about 176 kg of helium directly to the atmosphere of a cavern or shaft.

5. Risks associated at failures of LHC cryogenic system nodes at the surface

5.1 LHC cryogenic system nodes located at the surface (buildings and open space)

The elements of cryogenic systems, which are located at the surface are listed in Table 19.

Table 19: LHC cryogenic system nodes located at the surface

Node	Description	Remarks
S1	Surface upper cold boxes (QSRA)	Buildings
S2	Surface integrated cold boxes (QSRB)	Buildings
S3	Helium compressor stations (QSCA, QSCB, QSCC)	Buildings
S4	Interconnecting cryogenic lines (QSL_N, QSL_H)	Buildings
S5	Interconnecting warm pipes (QSPA, QSPB, QPPA, QPPB, QSPD)	Buildings
S6	Helium storage medium-pressure tanks (QSVA, QSVB)	Open space
S7	Liquid nitrogen storage (QSD_N)	Open space
S8	Liquid helium storage (QSD_H)	Open space
S9	Interconnecting cryogenic lines (QSL_N, QSL_H)	Open space
S10	Interconnecting warm pipes (QSPD)	Open space

A typical surface layout showing the buildings housing the cold boxes and the helium compressor stations, as well as the helium and nitrogen storages is presented in Figure 12. The amount of helium and volume of vacuum space involved in case of failure of the elements at the surface are given in Table 20 to Table 25.

Figure 12: Typical layout of cryogenic equipment at the surface (P8)

Table 20: Maximum He masses and volumes in the QSRA

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
LP	1.3	20-300	0.800	3.33	4	8
MP	4.5	20-300	0.800	5.75	7	4
HP	20	300-20	1.600	18.89	1	3
Adsorber 1	20	80	1.200	11.62	10	1
Adsorber 2	20	20	0.800	9.41	1	0.2

Table 21: Maximum He masses and volumes in the QSRB

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
LP	1.3	4.5-300	0.740	4.17	6	10
MP	4.5	20-300	0.960	6.74	7	5
HP	22	300-4.5	1.700	27.65	2	4
Adsorber 1	22	80	1.460	15.29	10	1.2
Adsorber 2	22	20	0.740	5.14	7	0.1
Sub-cooler	1.3	4.5	0.490	190.35	388	2

Table 22: Maximum He masses and volumes in the QSCA or QSCB

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
LP	1	300	0.800	3.05	3.809	19
MP	4	300	0.800	2.88	3.604	4.5
HP	20	300	1.600	14.31	8.945	4.5
Oil separator 1	20	360	1.600	31.86	19.911	12.0
Oil separator 2	4	360	0.800	3.74	4.673	7.0
Coalesher	20	300	1.600	22.26	13.914	7.0
Adsorber	20	300	1.600	3.18	1.988	1.0

Table 23: Maximum He masses and volumes in the QSCC

	P	T	Mass-flow	Mass	Residence time	Volume
	[bar]	[K]	[kg/s]	[kg]	[s]	[m3]
LP	4	300	0.126	0.06	0.493	0.1
HP	0.34	300	0.126	0.03	0.210	0.5
Oil separator	4	330	0.126	1.92	14.786	3
Coaleser	4	300	0.126	0.32	2.464	0.5
Adsorber	4	300	0.126	0.32	2.464	0.5

Table 24: Maximum helium and nitrogen masses and volumes in the storage vessels

	P	T	Mass	Volume
	[bar]	[K]	[kg]	[m3]
HP	20	300	795.08	250
LN2	3	80	40000	50
LHe	3.5	4.5	6582.74	50

Table 25: Maximum helium and nitrogen masses and volumes in interconnecting cryogenic lines and warm piping at the surface

Pipe			P	T	Mass-flow	Mass	Residence time	Volume
from	To	code	[bar]	[K]	[kg/s]	[kg]	[s]	[m ³]
QSRA	QSCA	111 (HP)	20	300	1.4	10	7	3.1
		112 (MP)	4.5	300	0.75	2.3	3	3.1
		113 (LP)	1.3	300	0.77	2.6	3	12.6
QSRB	QSCB	151 (HP)	22	300	1.65	16.5	10	4.7
		152 (MP)	4.5	300	0.85	3.4	4	4.7
		152 (LP)	1.3	300	0.8	3.9	5	18.8
QSRA	QSCA	131	20	300	0.042	3.9	93	1.2
		132	20	300	0.050 ⁽²⁾	0.62	12.4	0.2
		133	1	300	0.042	0.20	5	1.2
		134 ⁽¹⁾	1	300	=	=	=	3.0
QSCA	QSCB	101	20	300	1.65	0.39	0.24	0.1
		102	4.5	300	0.85	0.23	0.27	0.3
		103	1.3	300	0.8	0.07	0.08	0.3
QSCA	QSV	011	20	300	0.2	0.16	0.80	0.05
QSD_N	QSRA	421	3	77	1.1	122	111	0.15
QSD_N	QSRB	461	3	77	1.1	122	111	0.15
QSD_N	QSCA	411	3	77	0.15	406	2708	0.50
QSD_N	QSCB	451	3	77	0.15	406	2708	0.50
QSD_H	QSRB	051	3.5	4.2	0.5	32	64	0.24

(1): pipe used in case of emergency

(2): pipe used only during warm-up

5.2 Potential and credible failures at the nodes located at the surface

All potential failures at the cryogenic nodes located at the surface, which may happen at any phase of the collider operation, are listed in Table 26. In a similar way as for the nodes located in the tunnel, caverns and shafts, we identify a failure at a node by the following code: Sx.y, where S stands for location, x stands for node number (see Table 19) and y stands for failure mode number (see Table 1)

Table 26a: Potential and credible (Y) failure modes of LHC nodes located at the surface (part 1)

Node	Failure Mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
S1	S1.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S1.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S1.3	N	N	N	N	N	N	N	N	N	N
	S1.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S1.7	N	N	N	N	N	N	N	N	N	N
	S1.10	N	N	N	N	N	N	N	N	N	N
S2	S2.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S2.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S2.3	N	N	N	N	N	N	N	N	N	N
	S2.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S2.7	N	N	N	N	N	N	N	N	N	N
	S2.10	N	N	N	N	N	N	N	N	N	N
S3	S3.1	N	N	N	N	N	N	N	N	N	N
	S3.2	N	N	N	N	N	N	N	N	N	N
	S3.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	S3.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S3.7	N	N	N	N	N	N	N	N	N	N
	S3.10	N	N	Y	Y	Y	Y	Y	Y	Y	Y
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

Table 26b: Potential and credible (Y) failure modes of LHC nodes located at the surface (part 2)

Node	Failure Mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
S4	S4.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S4.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S4.3	N	N	N	N	N	N	N	N	N	N
	S4.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S4.7	N	N	N	N	N	N	N	N	N	N
S5	S4.10	N	N	N	N	N	N	N	N	N	N
	S5.1	N	N	N	N	N	N	N	N	N	N
	S5.2	N	N	N	N	N	N	N	N	N	N
	S5.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	S5.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S5.7	N	N	N	N	N	N	N	N	N	N
	S5.10	N	N	N	N	N	N	N	N	N	N
	S6.1	N	N	N	N	N	N	N	N	N	N
	S6.2	N	N	N	N	N	N	N	N	N	N
	S6.3	N	N	N	N	N	N	N	N	N	N
S6	S6.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S6.7	N	N	N	N	N	N	N	N	N	N
	S6.10	N	N	N	N	N	N	N	N	N	N
	S7.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S7.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
S7	S7.3	N	N	N	N	N	N	N	N	N	N
	S7.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S7.7	N	N	N	N	N	N	N	N	N	N
	S7.10	N	N	N	N	N	N	N	N	N	N

Access to the tunnel	Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Controlled	Restricted
----------------------	------------	------------	------------	------------	------------	------------	-----------	------------	------------	------------	------------

Table 26c: Potential and credible (Y) failure modes of LHC nodes located at the surface (part 3)

Node	Failure Mode	Warm	Drifting	75 K stand-by	Cool-down	1.9 K stand-by	System test, ramp down	Normal operation	Warm-up	Short intervention	Limited quench
S8	S8.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S8.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S8.3	N	N	N	N	N	N	N	N	N	N
	S8.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S8.7	N	N	N	N	N	N	N	N	N	N
	S8.10	N	N	N	N	N	N	N	N	N	N
S9	S9.1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S9.2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S9.3	N	N	N	N	N	N	N	N	N	N
	S9.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S9.7	N	N	N	N	N	N	N	N	N	N
	S9.10	N	N	N	N	N	N	N	N	N	N
S10	S10.1	N	N	N	N	N	N	N	N	N	N
	S10.2	N	N	N	N	N	N	N	N	N	N
	S10.3	N	N	N	Y	Y	Y	Y	Y	Y	Y
	S10.4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	S10.7	N	N	N	N	N	N	N	N	N	N
	S10.10	N	N	N	N	N	N	N	N	N	N
Access to the tunnel		Controlled	Controlled	Controlled	Controlled	Controlled	Restricted	Forbidden	Controlled	Controlled	Restricted

5.3. Analysis of and recommendations for credible failure modes at the nodes located at the surface

Credible failures at the nodes located at the surface are listed in Table 27.

Table 28 gives physical consequences of the failures, proposes the means of failure detection, as well as preventive and corrective defence measures.

Table 27a: Credible failures of the cryogenic elements located at the surface and their causes (part 1)

Element	Failure	Causes
S1. Surface upper cold box (QSRA)	S1.1. Air flow to QSRA insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	S1.2. Helium flow to QSRA insulation vacuum	Bellows failure Weld non-tight
	S1.4. Helium flow to environment	Break of instrumentation capillary
S2. Surface integrated cold boxes (QSRB)	S2.1. Air flow to QSRB insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	S2.2. Helium flow to QSRB insulation vacuum	Bellows failure Weld non-tight
	S2.4. Helium flow to environment	Break of instrumentation capillary
S3. Helium compressor station (QSC_[A, B,C])	S3.3. Air flow to sub-atmospheric helium	Break of helium guard
	S3.4. Helium flow to environment	Mechanical damage to the valves
	S3.10. Oil flow to environment	Break of oil pipe
S4. Interconnecting cryogenic line in confined space	S4.1. Air flow to the transfer line insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	S4.2. Helium/nitrogen flow to the transfer line insulation vacuum	Bellows failure Weld non-tight
	S4.4. Helium/nitrogen flow to environment	Break of instrumentation capillary
S5. Interconnecting warm pipe in confined space	S5.3. Air flow to sub-atmospheric helium	Break of pipe
	S5.4. Helium flow to environment	Break of pipe

Table 27b: Credible failures of the cryogenic elements located at the surface and their causes (part 2)

Element	Failure	Causes
S6. Helium storage medium-pressure tank (QSVA, QSVB)	S6.4. Helium flow to environment	Overpressure in HP storage tanks
S7. Liquid nitrogen storage vessel (QSL_N)	S7.1. Air flow to QSL_N	Break of QSL_N outer tank
	S7.2 Nitrogen flow to (QSL_N) insulation vacuum	Break of QSL_N inner tank
	S7.4. Nitrogen flow to environment	Mechanical damage to LN2 storage vessel
S8. Liquid helium storage vessel (QSL_H)	S8.1. Air flow to QSL_H	Break of QSL_H outer tank
	S8.2 Helium flow to (QSL_H) insulation vacuum	Break of QSL_H inner tank
	S8.4. Helium flow to environment	
S9. Interconnecting cryogenic line in open space	S4.1. Air flow to the transfer line insulation vacuum	Mechanical impact on a vacuum tapping Bellows failure Weld non-tight
	S4.2. Helium flow to the transfer line insulation vacuum	Bellows failure Weld non-tight
	S4.4 Helium flow to environment	Break of instrumentation capillary
S10. Interconnecting warm pipe in open space	S10.3 Air flow to sub-atmospheric helium	Break of instrumentation capillary
	S10.4. Helium flow to environment	Break of pipe Mechanical damage to the pipes

Table 28a: Credible failure modes of the LHC elements located at the surface and their consequences (part 1).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S1.1. Air flow to QSRA insulation vacuum Gravity 1	Pressurisation up to 1 bar of QSRA insulation vacuum Oxygen enriched air condensation on the cold parts of QSRA Heat load to cold helium, helium pressurisation and discharge to cavern through safety valves to warm helium collectors and buffers	No	Air contamination of MLI Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum Outlet of safety valves located in open space	Connect to vacuum pump If pumping is not enough, intervention necessary
S1.2. He flow to QSRA insulation vacuum Gravity 3b	Pressurisation of QSRA insulation vacuum above 1 bar Heat load to cold helium, helium pressurisation and discharge through safety valves to warm helium collectors and buffers Break of rupture disc protecting vacuum space Helium flow to the building from QSRA vacuum space	Freezing of tissue Asphyxiation	He contamination of the MLI Cold jet and embrittlement of the QSRA vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
S1.4. He flow to environment Gravity 3b	Break of instrumentation capillary will result in helium flow to a building (flow of a leak order)	Freezing of tissue	No	Malfunctioning of the sensor	Low diameter of instrumentation feedthrough	Intervention necessary

Table 28b. Credible failure modes of the LHC elements located at the surface and their consequences (part 2).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S2.1. Air flow to QSRB insulation vacuum Gravity 1	Pressurisation up to 1 bar of QSRB insulation vacuum Oxygen enriched air condensation on the cold parts of QSRB Heat load to cold helium, helium pressurisation and discharge to cavern through safety valves to warm helium collectors and buffers	No	Air contamination of MLI Chemical burning of MLI Embrittlement of carbon steel wall of the vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
S2.2. Helium flow to QSRB insulation vacuum Gravity 3b	Pressurisation of QSRB insulation vacuum above 1 bar Heat load to cold helium, helium pressurisation and discharge through safety valves Break of rupture disc protecting vacuum space Helium flow to the building from QSRB vacuum space	Freezing of tissue Asphyxiation	He contamination of the MLI Cold jet and embrittlement of the QSRB vacuum vessel	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
S2.4. Helium flow to environment Gravity 3b	Break of instrumentation capillary will result in helium flow to a building (flow of a leak order)	Freezing of tissue	No	Malfunctioning of the sensor	Low diameter of instrumentation feedthrough	Intervention necessary
S3.3 Air flow to sub-atmospheric helium Gravity 1	Air leak into sub-atmospheric helium	No	Helium contamination with air	Pressure gauge in helium guard	Helium guards	Intervention necessary

Table 28c. Credible failure modes of the LHC elements located at the surface and their consequences (part 3).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S3.4 Helium flow to environment Gravity 3 b	Helium will gather in confined spaces creating oxygen deficiency hazard	Asphyxiation	No	Pressure, flow gauges and oxygen concentration meters	Good ventilation	Intervention necessary
S3.10 Oil flow to environment Gravity 1	Oil spreading in form of mist (high pressure oil pipe broken), or liquid (low pressure oil pipe broken)	BREOX can be cancerous when heated above 200 °C	Lack of lubrication	Oil pressure gauges	No temperatures higher than 200 °C in the process Smoking forbidden	Intervention necessary
S4.1 Air flow to transfer line insulation vacuum Gravity 1	Pressurisation up to 1 bar of transfer line insulation vacuum Oxygen enriched air condensation on the inner tube of transfer line Heat load to cold helium, helium pressurisation and discharge to cavern through safety valves to warm helium collectors and buffers	Freezing of tissue Asphyxiation	Air contamination of transfer line MLI Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Intervention necessary

Table 28d. Credible failure modes of the LHC elements located at the surface and their consequences (part 4).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S4.2 Helium flow to transfer line insulation vacuum Gravity 3 b	Pressurisation of transfer line insulation vacuum above 1 bar Heat load to cold helium/nitrogen in the inner tube of the transfer line, helium/nitrogen pressurisation and discharge through safety valves Break of rupture disc protecting vacuum space Helium/nitrogen flow to the building from transfer line vacuum space Helium will gather in confined spaces creating oxygen deficiency hazard Nitrogen may fill the pit.	Freezing of tissue Asphyxiation	He contamination of the MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
S4.4 Helium flow to environment Gravity 3b	Break of instrumentation capillary will result in helium/nitrogen flow to a building Helium/nitrogen will gather in confined spaces creating oxygen deficiency hazard Nitrogen may fill the pit.	Freezing of tissue Asphyxiation	No	Malfunctioning of the sensor,	Low diameter of instrumentation feedthrough	Intervention necessary
S5.3. Air flow to sub-atm. Gravity 1	Air leak into sub-atmospheric helium	No	Helium contamination with air	Pressure gauge at helium guard	Helium guards	Intervention necessary
S5.4. He flow to environment Gravity 3b	Helium will gather in confined spaces creating oxygen deficiency hazard	Asphyxiation	No	Pressure and flow gauges	Good ventilation	Intervention necessary

Table 28e: Credible failure modes of the LHC elements located at the surface and their consequences (part 5).

Failure	Events	Danger to personnel	Risk to equipment	Information/defection	Preventive defence	Corrective defence
S6.4 Helium flow to environment Gravity 2	Due to low density, helium will reach upper layers of the atmosphere	No	No	Pressure gauges, noise	Low helium density	Repair HP
S7.1 Air flow to QSL_N insulation vacuum Gravity 2	Pressurisation up to 1 bar of QSL_N insulation vacuum space Oxygen enriched air condensation on the QSL_N inner tank Heat load to and pressurisation of nitrogen, nitrogen discharge through safety valve	No	Air contamination of MLI Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Change/repair of liquid nitrogen storage vessel
S7.2 Nitrogen flow to QSL_N insulation vacuum Gravity 2	Pressurisation of QSL_N insulation vacuum space above 1 bar Heat load to and pressurisation of nitrogen, nitrogen discharge through safety valve Break of rupture disc protecting QSL_N insulation vacuum Nitrogen flow to environment from QSL_N vacuum space	Freezing of tissue Asphyxiation	Contamination of MLI with nitrogen Vacuum vessel embrittlement	Pressure and level gauges, cold nitrogen mist visible	MLI still efficient at broken vacuum	Change/repair of liquid nitrogen storage vessel
S7.4 Nitrogen flow to environment Gravity 3b	Due to high cold density, nitrogen will cover the surface and may flow down the shafts	Freezing of tissue Asphyxiation	Embrittlement of carbon steel elements	Pressure and level gauges, cold nitrogen mist visible	Liquid nitrogen used only at the surface, good visibility of cold nitrogen vapours in open space	Change/repair of liquid nitrogen storage vessel

Table 28f: Credible failure modes of the LHC elements located at the surface and their consequences (part 6)

Failure	Events	Danger to personnel	Risk to equipment	Information/defection	Preventive defence	Corrective defence
S8.1 Air flow to QSL_H insulation vacuum Gravity 1	Pressurisation up to 1 bar of QSL_H insulation vacuum space Oxygen enriched air condensation on the QSL_H inner tank Heat load to and pressurisation of helium, helium discharge through safety valve to a warm collector and buffer	No	Air contamination of MLI Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Change/repair of liquid helium storage vessel
S8.2 He flow to QSL_H insulation vacuum Gravity 2	Pressurisation of QSL_H insulation vacuum space above 1 bar Heat load to and pressurisation of helium, helium discharge through safety valve Break of rupture disc protecting QSL_H insulation vacuum Helium flow to environment from QSL_H vacuum space Due to a low helium density it will go to upper layers of the atmosphere	Freezing of tissue	Contamination of MLI Vacuum vessel embrittlement	Pressure and level gauges, cold nitrogen mist visible	MLI still efficient at broken vacuum	Change/repair of liquid helium storage vessel
S8.4 He flow to environment Gravity 2	Due to a low density helium will go to upper layers of the atmosphere	Freezing of tissue	Embrittlement of carbon steel elements	Pressure and level gauges, cold helium mist visible	Liquid nitrogen used only at the surface	Change/repair of liquid helium storage vessel

Table 28g. Credible failure modes of the LHC elements located at the surface and their consequences (part 7).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S9.1 Air flow to transfer line insulation vacuum Gravity 1	Pressurisation up to 1 bar of transfer line insulation vacuum Oxygen enriched air condensation on the inner tube of transfer line Heat load to cold helium, helium pressurisation and discharge to cavern through safety valves to warm helium collectors and buffers	Freezing of tissue Asphyxiation	Air contamination of transfer line MLI Chemical burning of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Intervention necessary
S9.2 Helium flow to transfer line insulation vacuum Gravity 2	Pressurisation of transfer line insulation vacuum above 1 bar Heat load to cold helium in the inner tube of the transfer line, helium pressurisation and discharge through safety valves Break of rupture disc protecting vacuum space Helium flow to the building from transfer line vacuum space Helium will gather in confined spaces creating oxygen deficiency hazard	Freezing of tissue Asphyxiation	He contamination of MLI	Vacuum gauges	MLI still efficient at broken vacuum	Connect to vacuum pump If pumping is not enough, intervention necessary
S9.4 Helium flow to environment Gravity 2	Break of instrumentation capillary will result in helium flow to a building Helium will gather in confined spaces creating oxygen deficiency hazard	Freezing of tissue Asphyxiation	No	Malfunctioning of the sensor,	Low diameter of instrumentation feedthrough	Intervention necessary

Table 28h. Credible failure modes of the LHC elements located at the surface and their consequences (part 8).

Failure	Events	Danger to personnel	Risk to equipment	Information/ detection	Preventive defence	Corrective defence
S10.3 Air flow to sub- atmospheric helium Gravity 1	Air leak into sub-atmospheric helium	No	Helium contamination with air	Pressure gauge at helium guard	Helium guards	Intervention necessary
S10.4 Helium flow to environment Gravity 2	Due to low density, helium will reach upper layers of the atmosphere	No	No	Pressure and flow gauges	Low helium density	Intervention necessary

There are 9 events of gravity 3b identified in Table 28. Table 29 lists the 3b gravity events, gives the highest amount of helium that might be relieved to confined space as well as an approximate mass-flow rate and formulates the recommendations.

Table 29: Gravity 3b failures of the nodes located in surface

Failure	Maximum amount of helium relieved [kg] / approximate flow rate [kg/s]	Recommendations
S1.2 Helium flow to QSRA insulation vacuum	19 / below 2	Consequences of the failure mode fully covered by S.2.2.
S1.4. He flow to environment from QSRA helium enclosures	19 / of the leak order	Consequences of the failure fully covered by R1.2.
S2.2. Helium flow to QSRB insulation vacuum	190 / below 2	Worst case scenario, further modelling of helium propagation in a confined space is recommended
S2.4. Helium flow to environment from QSRB helium enclosures	190 / of the leak order	Consequences of the failure fully covered by R2.2.
S3.4. He flow to environment from helium compressor stations	32 / of the leak order	Consequences of the failure mode fully covered by R2.2
S4.2 Helium flow to insulation vacuum of interconnecting cryogenic lines	32 / below 2	Consequences of the failure fully covered by R2.2.
S4.4 Helium flow to environment from interconnecting cryogenic lines	32 / of the leak order	Consequences of the failure fully covered by R4.2.
S5.4 Helium flow to environment from interconnecting warm pipes	16.5 / below 1	Consequences of the failure fully covered by R2.2.
S7.4 Nitrogen flow to environment	40000 / instantaneous flow of the order of 100	May be catastrophic if nitrogen fills the shafts. Analysis of the N2 vapour propagation (including filling buildings and shafts) is recommended.

6. Worst case scenario failures

Based on the criterion of the amount of helium or nitrogen relieved to confined space, worst case scenarios have been identified for the machine components located in the tunnel, caverns, shafts and surface buildings. The worst case scenarios are summarised in Table 30. For each worst case scenario an attempt to assign a probability of occurrence is made. The following scale of probability is used [18]

- A (Frequent) – likely to occur repeatedly during the life-cycle of system.
- B (Occasional) – likely to occur several times in the life-cycle of system.
- C (Occasional) – likely to occur sometimes in life-cycle of system
- D (Remote) – not likely to occur in life-cycle, but possible.
- E (Improbable) – probability of occurrence cannot be distinguished from zero.

Table 30: Worst case scenario failures for the LHC cryogenic system nodes located in the tunnel, caverns, shafts and at the surface.

Location	Failure	Prob.	Max. amount of helium relieved [kg] / max. flow rate [kg/s]	Recommendations
Tunnel	R2.2. He flow to QRL insulation vacuum (break of header C)	D	3300 / below 2	Analysis of helium flow rate to the tunnel following QRL insulation vacuum break. Analysis of helium propagation in the tunnel. Based on the analysis results implementation of TIS Safety Instruction[19]
Tunnel	R2.4. He flow to air (jumper connection break)	E	4250 / below 20	Analysis of helium flow rate to the tunnel following break of jumper connection. Analysis of helium propagation in the tunnel. Based on the analysis results implementation of TIS Safety Instruction [19]
Cavern/ shaft	U3.2. He flow to QURA insulation vacuum, LP circuit break	D	176 / below 2	Analysis of helium flow rate to caverns and shafts. Analysis of helium propagation in caverns and shafts. Based on the analysis results implementation of TIS Safety Instruction [19]
Surface	S2.2. He flow to QSRB insulation vacuum	D	190 / below 2	Analysis of helium flow rate to the buildings. Based on the analysis results implementation of TIS Safety Instruction [19]
Surface	S7.4. Break of LN2 storage vessel (QSL_N). Nitrogen flow to environment	D	40000 / may be of the order of hundreds	Analysis of nitrogen propagation following break of LN2 storage vessel. Based on the analysis results implementation of TIS Safety Instruction [19]

7. Conclusions

- Due to its specific design features (cold recovery header, absence of nitrogen down the tunnel, no forced flow in cooling loops) the LHC cryogenic system is inherently safe, with a limited number of possible risks and failures, usually associated with cryogen relief to a confined space.
- Out of almost 1000 analysed failure modes there are only 29 events that may be followed by helium discharge to a confined space.
- Worst case failure modes have been identified and the potential amount of helium or nitrogen that might be vented into the machine tunnel, caverns, shafts and surface building, as well as maximum fluid flow rate, have been found. Further, more detailed studies are recommended to estimate the fluid flow rate over a time domain, cryogen propagation in a confined space (tunnel, caverns, shafts buildings) and to implement general safety rules in accordance with TIS Safety Instruction *The Use of Cryogenic Fluids*. [19].

8. Acknowledgments

The authors would like to thank S. Claudet, L. Taviani, U. Wagner and M. Barranco, W. Erdt, G. Rau, V. Sergo, R. Trant and R. van Weelderen for their help during preparation of this study.

9. Glossary

The following definitions are applicable:

- Risk:** Risk is a possibility or chance of meeting danger, suffering loss or injury
- System:** System is a group of things or parts working together in a regular action
- Location:** Location of the LHC cryogenic system node according to the code used for civil engineering of the LEP machine, R – ring tunnel (on beam path), U – underground caverns & galleries, P – access shafts, S – surface
- Cryogenic system node:** Separate enclosure, characterized by thermodynamic state of fluid content
- Cryogenic failure mode:** Accidental event that involves helium or nitrogen mass transfer between helium enclosure, insulation or beam vacuum space and environment in result of any constructional element break or malfunctioning. An unexpected energy release to cold mass helium as result of an extended magnet resistive transition or electrical arc, is also a cryogenic failure mode.

10. References

- [1] H. Garin, AMDEC, MADE, AEEL, L'essentiel de la méthode, AFNOR, Paris (1994)
- [2] S. W. Malasky, System safety, Hayden Book Company, Rachelle Pack, N.J., Inc., ISBN 0-87671-559-5 (1974)
- [3] B. G. Blyukher, L.E. Reznikov, Design phase safety and risk assessment for superconducting cryogenic system, ASME International (1997), pp 74-80.
- [4] S. Claudet, U. Wagner, Equipment TAG Code System for Accelerator Cryogenics, rev. 2.1, LHC-ACR internal note 98-03, Rev. (1998)
- [5] G. Horlitz, Refrigeration of large scale superconducting systems for high energy accelerators, Cryogenics, Vol 32, ICEC Supplement (1992), pp. 44-49
- [6] L. Bottura, P. Burla, R. Wolf, LHC main dipoles proposed baseline current ramping, LHC-Project-Report-172 (1998)
- [7] The LHC Study Group, The Large Hadron Collider Conceptual Design, CERN/AC/95-05 (LHC) (1995)
- [8] Benda, V., et al., Conceptual design of the cryogenic system for the Large Hadron Collider (LHC), in Proc. EPAC-96, Institute of Physics Publishing, Bristol, UK (1996) 361-363.
- [9] G. Riddone, L. Tavian, R. van Weelderen, Dimensions, pressures, temperatures and sizing of valves and piping in the LHC machine cryostat and cryogenic distribution line, Engineering Specification LHC-Q-ES-0001.00 rev. 0.1 (1998)
- [10] P. Cruikshank, N. Kos, G. Riddone and L. Tavian, Investigation of Thermal and Vacuum Transients on the LHC Prototype Magnet String, LHC Project Report 50, Cryogenics, Proc. ICEC/ICMC 16, Elsevier Science (1997), 681-684
- [11] Ph. Lebrun, B. Szeless, L. Tavian, L.R. Williams, Experimental investigation of accidental loss of insulation vacuum in an LHC prototype dipole cryostat, Adv. in Cryo. Eng. 41a, Plenum Press (1995), 799-804
- [12] M. Chorowski, Transient behaviour and helium recovery in the LHC cryogenic system following magnet resistive transition, LHC Project Note 77 (1996)

- [13] M. Chorowski, B. Skoczen, Thermo-mechanical analysis of cold helium injection into medium-pressure (MP) gas storage tanks following resistive transition of a LHC sector, LHC Project Note 119 (1996).
- [14] M. Chorowski, Transient behaviour and helium discharge in cryogenic distribution line (QRL) headers following breakdown of insulation vacuum, LHC Project Note 120 (1996).
- [15] S. Claudet, private communication
- [16] U. Wagner, private communication
- [17] L. Tavian, private communication
- [18] B. L. Hendrix, Application of system safety engineering techniques for hazard prevention at the superconducting super collider, Supercollider 3, Plenum press, New York, (1991), 1005-1015.
- [19] Instruction de Sécurité, Safety Instruction, TIS IS 47, CERN (1998)
- [20] F. J. Edeskuty, W. F. Stewart, Safety in the Handling of Cryogenics Fluids, Plenum Press, New York, ISBN 0-306-45161-1 (1996)