

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particles Physics

Task Force Report

Safety of Personnel in LHC underground areas following the accident of 19th September 2008

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Abstract

In January 2009, the "Task Force on Safety of Personnel in the LHC underground areas following the accident in sector 3-4 of 19th September 2008" (Safety Task Force) received from the CERN Director General the mandate to investigate the impact of the accident of 19th September 2008 on the safety of personnel working in the LHC underground areas. This mandate includes the elaboration of preventive and/or corrective measures, if deemed necessary. This report gives the conclusions and recommendations of the Safety Task Force which have been reviewed by an external advisory committee of safety experts.



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1. Introduction

Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have confirmed that the cause of the accident was a faulty electrical connection between two of the superconducting magnets [1]. This resulted in electrical and mechanical damage and release of helium from the magnet cold mass into the LHC tunnel. The "Task Force on Safety of Personnel in the LHC underground areas following the accident in sector 3-4 of 19th September 2008" (Safety Task Force) received the mandate to investigate the impact of this accident on the safety of personnel working in the underground areas of LHC (see Annex F). The mandate includes the elaboration of preventive and/or corrective measures, if deemed necessary.

The Safety Task Force was chaired by the Head of the Safety Commission and composed of representatives from the Beams Department, the Engineering Department, the Physics Department, the Technology Department, the Safety Commission and the Staff Association. The participation of a representative of the Radiation Protection group of the Safety Commission was omitted since no radiological risk existed during the accident of 19th September 2008.

The Safety Task Force collected all data presented in the meetings in a restricted EDMS folder; status reports were given in an intermediate report to the CERN Director General (EDMS 991361) as well as in different CERN internal meetings Hardware Commissioning Day (HWC Day), 19th March 2009, EDMS 991897; LHC Machine Committee (LMC), 25th March 2009, EDMS 993975; LMC, 29th April 2009, EDMS 997675).

2. Methodology

In order to elaborate the conditions for safety of personnel in the LHC underground areas during the accident, the Safety Task Force went through the following steps:

- (1) **Establish the sequence of facts related to the safety of personnel**
based on level 3 alarm records and the CERN Fire Brigade emergency intervention records;
- (2) **Analyse the LHC underground environmental conditions and explain their development**
in relation with original risk analyses (incl. tests) performed;
- (3) **Recommend preventive and/or corrective measures**
for the safety of personnel in the LHC underground.

Priority was given to the definition of constraints for the long shutdown works and the access conditions for the powering test.

3. Listing of Available Input Data – Fact Finding

In the accident of 19th September 2008, a faulty electrical connection between two of the superconducting magnets of the LHC caused a major loss of helium containment (helium leak into the magnet insulation vacuum) and thereby a rapid discharge of approximately 2 tons of helium into the LHC machine tunnel within the first 2 minutes [1]. Over the following several hours, a total release of about 6 tons of helium accumulated into the sector 3-4.

For the reconstruction of the development of the environmental conditions during and directly after the accident, the following input data were considered.

- Alarm level 3 data (from Oxygen Deficiency Hazard (ODH) sensors, Automatic Fire Detection system (AFD) detectors, and their location).

- Fire brigade intervention report and eye-witness report of members of the Fire brigade intervention team.
- Video surveillance taken at access control post UJ43 at Point 4.
- Eye-witness report from CERN personnel working in the SD surface building at Point 4.
- Helium mass flow estimates as reported by the Cryogenic Group of the Technology Department (TE/CRG).
- Manual actions on ventilation system and air measurements as reported by the Cooling and Ventilation Group of the Engineering Department (EN/CV).
- Sequence of facts as reconstructed by the Technical Task Force [1].
- Geometry of LHC tunnel (volume and length).
- Location of equipment (safety valves, ventilation doors, ducts for air inlets/outlets).

In addition, available simulations and tests concerning helium releases in the tunnel were considered [2, 3, 4, 5, 6].

The details about the reconstruction of the accident, the data on which the analysis of the Safety Task Force is based, and the concurrent development of the environmental conditions in the LHC tunnel is given in the different Annexes. The positions in the LHC tunnel are given as the cumulated distances in meters from the Point 1 of the LHC to the location to be identified. This cumulated distance (DCUM) runs from 0 to 26658. This localisation is used in the re-construction of the environmental conditions.

Even though not all input data could be explained in details, the Safety Task Force is confident about a sequence of events that can be derived from the input data as follows.

- At 11:19, a first arc occurred at the half-cell 24R3 and at DCUM 7793, approximately in the middle of the arc of sector 3-4. The electrical fault resulted in a loss of helium containment and a helium release into the machine tunnel of approximately 2 tons within the first 2 minutes.
- The Oxygen Deficiency Hazard (ODH) sensor closest to the first release points triggered immediately; the time stamp given by the system is 11:19:05 (see Fig 1).
The Automatic Fire Detection system (AFD) sensor closest to the first release points triggered a few seconds later due to the helium/water cloud; the time stamp given by the system is 11:19:10 (see Annex A).
- A helium mass-flow of 15 to 26 kg/s for about 40 seconds increased the static pressure in the "closed"¹ ventilation area of sector 3-4.
- The helium cloud resulting from the release propagated with a velocity of ~5 m/s close to the accident area (D-area) and ~0.4 m/s when reaching the vicinity of Points 3 and 4 (see Fig 1).
- When a maximum static overpressure of 135 mbar was reached, the ventilation sectorisation door in UL44 gave in resulting in a release of the overpressure (air and helium) via UL44, US45 and the PM shaft into the SD4 surface building and further to the environment through the open door of the building.
- The sudden opening of a release path produced a pressure drop, and thus creating a flushing of the entire sector 3-4. This flushing raised dust all over the sector and thus triggered the optical fire detection sensors of the Automatic Fire Detection system (AFD) almost simultaneously along the entire sector from TZ32 to US45 (except the one in RE42); the time stamp of the AFD system is 11:19:27 - 11:19:38 and corresponds to the collapse of the ventilation door in UL44. This flushing accelerated the helium cloud propagation towards Point 4 and decelerated the helium cloud propagation towards Point 3. The flushing effect caused dust clouds that could be observed on the surveillance video taken by the access system at the access Point UJ43 at Point 4.

¹ Considering the huge helium discharge into the machine tunnel ventilation sector, the nominal ventilation rate of 18'000 m³/h and the openings in the ventilation doors (see Annex 5) can be neglected.

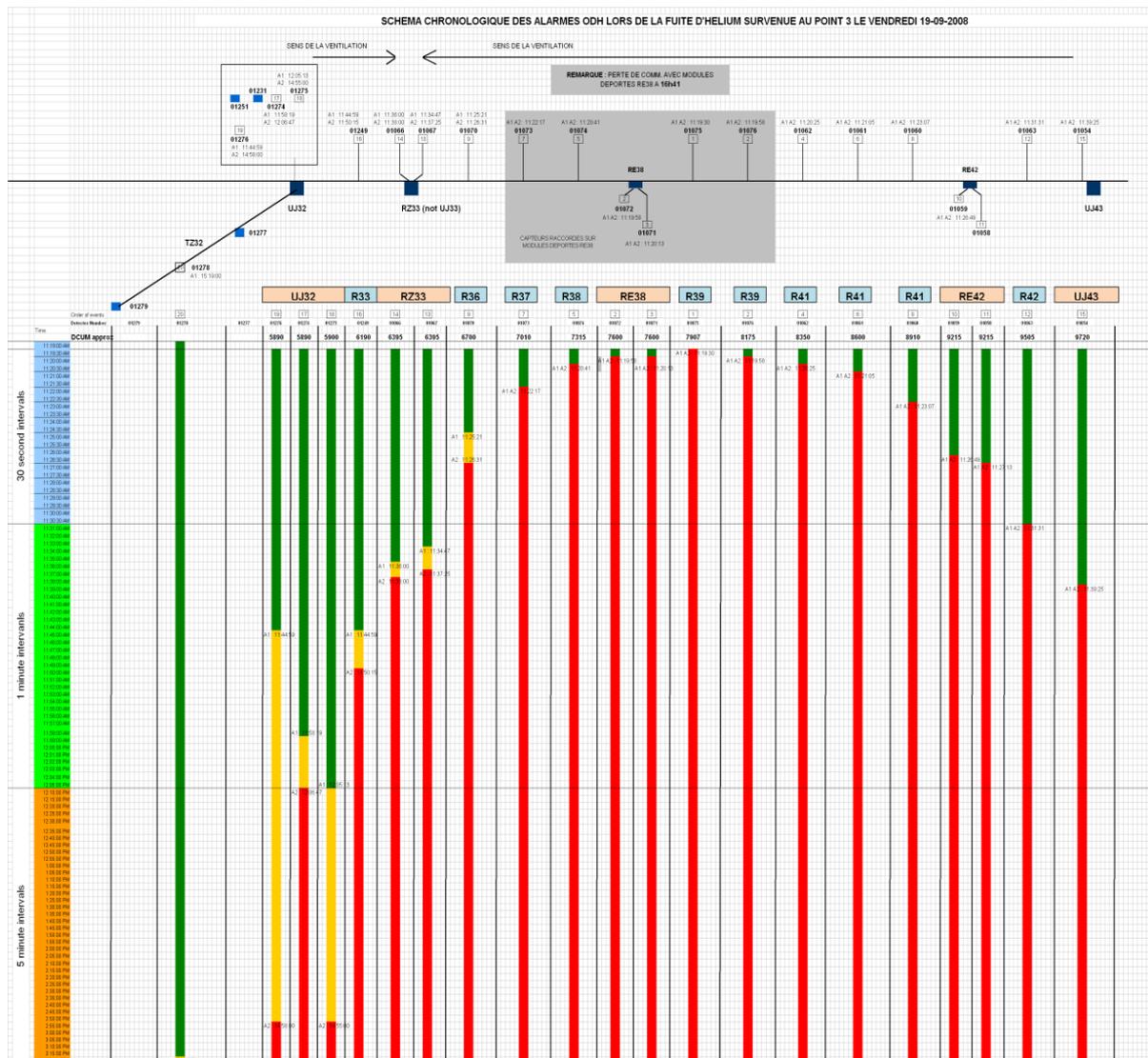


Fig. 1: Chronological scheme of the ODH alarms in sector 3-4 after the accident on 19th September 2008. Time runs vertically from top to bottom. The horizontal axis gives the localisation of the detectors in the area. The colour coding indicates values as follows: green = O₂ level above 19%, yellow = O₂ level between 19% and 18%, red = O₂ level below 18%.

4. Analysis of the LHC Underground Environment and its Development during the Accident

The Safety Task Force considers that the available data is sufficiently well understood to draw conclusions on the development of the environmental conditions in sector 3-4 during the accident of 19th September 2008.

The localisation of the helium release close to the mid-sector position, together with the availability of a wide release path via the collapsed ventilation door in UL44 and the PM shaft to the surface limited the oxygen deficiency hazard to Sector 3-4 and to the directly connected access area at Point 4 directly connected to sector 3-4.

Ventilation System

The Safety Task Force assumes that neither the air flow produced by the LHC ventilation system nor the tunnel slope had any sizable impact on the helium flow during the accident of 19th September 2008. The functioning of the ventilation system was nevertheless required in case of an emergency intervention of the CERN Fire Brigade.

Light

The 2-person-team of the CERN Fire Brigade (so-called *binôme*) reported that there was light in the tunnel. There was normal light in the first several hundred meters, but only emergency lights in the area of the accident.

Noise

The noise levels in the LHC tunnel created during the accident of 19th September 2008 are unknown. Considering the estimated helium flow and compared to earlier experiences at CERN where high noise levels were observed at lower flow rates, it is to be expected that the noise levels could have caused a damage or potential loss of hearing.

Pressure in the LHC Tunnel during the Accident 19th September 2008

For the estimate of the static pressure increase in the "closed" ventilation area of sector 3-4 within the first minute of the helium discharge, the following assumptions were made.

- A clear interface between air and helium remains, i.e. the gases do not mix.
- The sectors of the LHC tunnel are sufficiently tight such that neither air nor helium escapes.
- The air remaining in the tunnel during the helium release is compressed. This process could be considered as adiabatic or isothermal, depending on how fast the compression took place.
- The pressure p is uniform along the tunnel.
- The initial air temperature in the tunnel is $T_o = 300$ K, and the initial pressure is atmospheric, i.e. $p_o = 1$ bar.
- The temperature of the helium in the tunnel is uniform.

Fig. 2 shows the assumed helium mass flow of the helium discharge from the various vacuum subsectors of the string of magnets. Assuming a maximum of 40 seconds before the ventilation door in UL44 gave in, a maximum total amount of ~820 kg of helium was released into the "closed" sector 3-4 causing the overpressure.

A rough mechanical calculation for the overpressure at which the ventilation door collapsed, gives a maximum pressure of 135 mbar.

Fig. 3 shows the pressure as a function of the accumulated amount of helium discharged and the mean helium temperature as the parameter (100 K, 200 K or 300 K) for a tunnel volume of 33'000 m³.

The Safety Task Force considers the fast change as an adiabatic rather than an isothermal process.

All the above given assumptions and information correspond to a worst case scenario giving a maximum attainable pressure of 135 mbar for ~820 kg of helium discharge, a temperature of 200 K for the helium in the tunnel and a total volume of 33'000 m³ for sector 3-4.

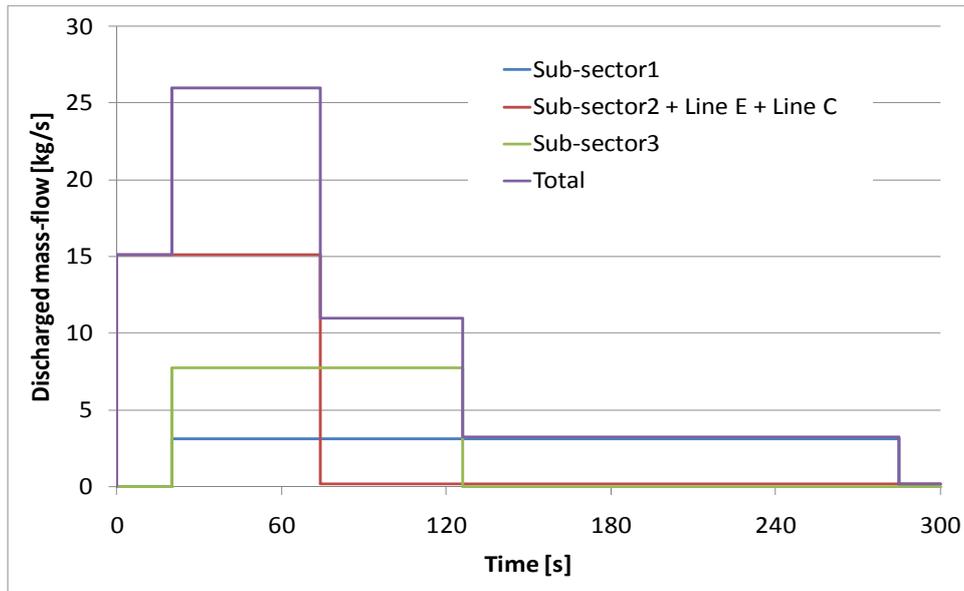


Fig. 2: Helium mass flow due to the discharge of the different vacuum sub-sectors.

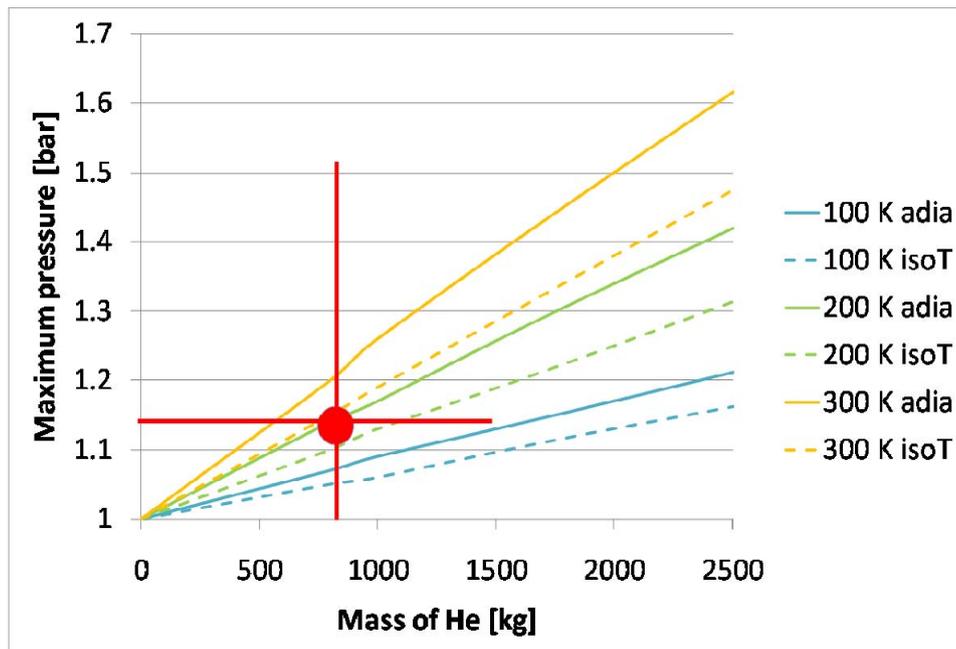


Fig. 3: Estimated pressure development in sector 3-4 assuming the flow rates given in Fig. 2.

D-area and Immediate Surroundings

Several studies have shown that cold helium releases provoke low levels of oxygen, low temperatures and lack of visibility due to vapour clouds.

From the alarm level 3 data obtained (ODH and AFD) as well as from the simulations carried out in the past, it is expected that the helium most probably filled the entire cross section of the tunnel in the D-

area and its direct vicinity. Therefore, in the D-area and the immediate surroundings, an oxygen deficiency was created with oxygen levels approaching zero (see Annex A).

Further to the oxygen deficiency and due to the cryogenic helium release (the estimated temperature at the moment of release are 40-60 K [1]), very low ambient temperatures (~200 K for the above presented scenario) were generated in the D-area and the immediate vicinity.

In addition, the formation of a vapour cloud in the vicinity of the helium release would impair all visibility. During the accident of 19th September 2008, the optical sensors of the fire detection in the electrical alcove RE42 were triggered at the same time as the ODH sensor in RE42. In line with this analysis, the binôme of the CERN Fire Brigade reported a visible vapour cloud close to the ceiling around RE42 some two hours after the onset of the helium release.

Following the above analysis, it is assumed that no one would have survived in the D-area or in its close vicinity due to oxygen deficiency. Most probably the temperature development was lethal as well. It should be noted that during the operational conditions of the LHC machine on the 19th September 2008, by definition nobody was allowed to be in the machine tunnel.

Validity of the Preliminary Risk Assessment from 1999

In 1999, a risk assessment was carried out for the LHC to identify the risks to personnel resulting from cryogenic failure [7]. This risk assessment comprises the case of an electrical arc where helium is vented through the quench relief valves (scenario R1.9), expecting a total amount of helium loss of 475 kg with a flow rate below 2 kg/s. During the accident of 19th September 2008, a flow rate of approximately 20 kg/s took place resulting from an opening of up to 64 cm² during the accident.

The risk analysis from 1999 has clearly underestimated the possible size of an opening and consequently the flow generated to the magnet's vacuum enclosures in case of electrical arc failures. The present protection system against pressure build up in the vacuum enclosure is therefore undersized. Consequently, in January 2009, the Safety Task Force has supported the installation of additional overpressure relief valves on the LHC magnet cryostats and related cryogenic equipment.

The Safety Task Force has therefore questioned whether the existing Maximum Credible Incident MCI scenario remains valid. During the accident of 19th September 2008, the electrical arc destroyed the M3 pipe, the E line (partially), the V2 line and the V1 line (partially) [1]. The Technical Task Force assumes that an electrical arc at a higher current could also destroy the M1 line and/or the M2 line simultaneously and thus produce an even larger helium flow. These considerations resulted in a redefinition of the MCI in the LHC arcs that based on a total cross-section of a breach of 120 cm² and taking into account a specific flow-rate of 0.33 kg/s per cm² would yield a maximum mass-flow of 40 kg/s.

The conclusion of both Task Forces is that for a worst case scenario, an electrical arc in the mid-arc sub-sector is identified which would give this maximum flow of 40 kg/s, a fast release of 1.5 tons of helium and a total loss of 5 tons. A detailed description and the derivation of the worst case scenario can be found in the Annex B.

In the preliminary risk analysis of 1999, the worst case scenario for helium release while the LHC tunnel is in access mode was related to a break of a jumper connection of the cryogenic distribution line (QRL), due to the collapse of a tunnel ceiling. This scenario gives an initial flow-rate of 20 kg/s and a total helium discharge of 4.3 tons with 600 kg in the first minute. This was and remains a very improbable scenario, although the probability of occurrence cannot be distinguished from zero.

5. Results and Conclusion

For the recommendation of preventive and corrective measures for the safety of personnel, the Task Force has considered all LHC underground, i.e. the LHC machine tunnel with its service areas, including the large UX caverns at P4 and P6, the four large experimental underground areas, and the corresponding access areas.

The Safety Task Force has restricted itself to the scenario of a major cryogenic incident with release of cryofluid caused by any sources.

The environmental conditions and their development during the accident of 19th September 2008 in sector 3-4 are sufficiently well understood to draw conclusions.

Source of the accident

The Safety Task Force understands from the conclusion of the Technical Task Force as well as the conclusions of the Chamonix 2009 workshop that the recurrence of an electrical arc cannot be excluded. However as a consequence of the improved machine protection systems the immediate He-release would be limited to a maximum amount of:

- 1110 kg if the leak occurs in a standard subsector;
- 1520 kg if the leak occurs in the mid-arc position;
- 970 kg if the leak occurs in the dispersion suppressor area of the accelerator (for details see Annex B).

For the standalone and semi-standalone magnets, as well as the superconducting links in the long straight section, the respective values are considerably smaller (less than 260 kg).

The Safety Task Force understands that such an electrical arc /MCI can occur in any part of the cold machine; consequently no distinction is made with respect to where inside a sector the MCI may occur.

The MCI would release an initial mass flow rate of ~40 kg/s or ~166 m³/s of helium gas at 200 K. The MCI initial mass flow rate would be about double the mass flow rate experienced in September 2008.

Considering the accident of 19th September 2008, the Safety Task Force has not identified additional credible failure modes that would result in a helium release incompatible with the machine tunnel in access mode.

Concerning the experimental superconducting magnets in the ATLAS and CMS experiments, no evidence was found that a similar scenario to that of the 19th September 2008 is likely to reoccur.

Conclusion

From these considerations, the Safety Task Force concludes the following.

- 1. All efforts have to be made to limit an incidental helium release and the resulting overpressure.**
- 2. Any incidental helium release shall be confined to the ventilation sector where it occurs.**
- 3. This confinement must be carried out in combination with a controlled release of overpressure to the surface.**
- 4. No access shall be allowed to any ventilation sector of the LHC in which a large helium release has a non-negligible probability to occur. A ventilation sector is defined as the**

area directly affected by the overpressure resulting from the helium release. A large helium release is defined as being at least of the same order of magnitude as the release of 19th September 2008 accident.

6. Recommendations

The Safety Task Force thus recommends as **measures following conclusion #1**.

1. The consolidation/repair of potentially faulty bus-bar interconnects in the LHC machine together with the implementation of the improved machine protection systems (e.g. quench protection system, overpressure relief valves, etc.) shall be completed before repowering the magnets.
2. In addition, to limit incidental release at lower flow-rates the liquid helium shall be removed from the LHC machine before going into machine shutdown mode.

The Safety Task Force further recommends as **measures following conclusion #2**.

3. The sealing of the LHC tunnel towards other underground areas to protect them from Oxygen Deficiency Hazard (ODH) and from possible overpressure.
4. Precedence shall be given to overpressure limitation over structural reinforcement.
5. A detailed calculation of the overpressure values is recommended. This calculation should be done by means of Computational Fluid Dynamics software tool offering the possibility to take into account time dependant flow rates, helium gas expansion, thermal exchange with tunnel components, He/O₂ concentrations etc..

The Safety Task Force provides in Annex C a conservative estimate of the static overpressure values in the LHC tunnel based on steady state calculations. The estimate is given for the configuration of the intermediate solution (see measure in recommendation number 7) using the existing ventilation door(s) as pressure relief device(s) allowing the air/He to be released via the UL and US service areas, the PM shafts and finally the SD buildings.

Based on the MCI characteristics the following improvements are required for the ventilation sector confinement:

- a. Adequate sealing to allow for pressure differential conditions according to the confinement requirements for radiation protection;
- b. The structure of the ventilation sector concerned shall withstand an incidental low ambient temperature (see chapter 4);
- c. The structure of the ventilation sector concerned shall withstand an incidental overpressure (details for the intermediate solution are given in the Annex C);
- d. For the intermediate solution, the surface buildings which form an integral part of the ventilation path to the atmosphere shall be protected against overpressure.

The Safety Task Force further recommends as **measure following conclusion #3**.

6. For the guided release of static overpressure from the LHC tunnel to the surface, the Safety Task Force recommends the implementation of a study group to propose possible options. One such option is to use the existing ventilation ducts equipped with overpressure relief devices and reinforced to withstand the high mass-flow rates.

7. As an intermediate measure, the Safety Task Force recommends to use existing ventilation doors as relief devices or to equip them with relief valves to allow a pressure release like in 19th September 2008 via the UL area and a shaft to the surface building. This implies in case of an incidental large helium release that the ventilation sector concerned expands beyond the machine tunnel and includes the service areas. The consequences of this short term approach for the accessibility of the LHC underground areas and the PM shafts as well as the SD buildings are explained in greater detail on a specific example in the Annex D.

The Safety Task Force further supports the proposed **measures following conclusion #4**.

8. 2-phase approach for machine powering [7]
While the accelerator is in "powering phase I", the current in the electrical circuits shall be limited and the probability for massive incidental helium release shall be negligible, such that the cryogenic hazard due to the powering does not require particular access restrictions. During "powering phase II" no access shall be allowed to the ventilation sector concerned as well as in the ventilation sectors affected by the helium release in case the above intermediate measure is applied (see measure in recommendation number 7).

In addition, the Safety Task Force recommends the **following general measures**:

9. For the level 3 alarm systems
 - a. From the time stamps of the evacuation alarm system given in Annex A, it can be seen that a confirmed ODH alarm triggered only the evacuation alarms on a half-sector basis of the respective sector. The Safety Task Force notes that this is in disagreement with the layout principle of the LHC ventilation system. Therefore, the Safety Task Force requests to change rapidly the configuration of the evacuation alarm systems such that an entire ventilation sector is warned.
 - b. In the reconstruction of the event, it could not be explained why the AFD detection in RE42 did not trigger simultaneously with the other AFD detection. A testing of the AFD installation in RE42 is thus recommended.
10. The Safety Task Force has identified that the loss of helium containment to the beam pipe vacuum, e.g. caused by an electrical fault in the magnet powering circuits, might result in structural damage to the beryllium beam pipes of the experiments, or to other equipment. The Safety Task Force recommends setting up a working group to study this scenario, and in particular to answer whether access to the experimental caverns shall be granted only when the beam pipe gate valves are closed.
11. Heavy handling, works and transport restrictions have been defined for the LHC tunnel in November 2008 following the accident; the Safety Task Force recommends formalizing these restrictions in an appropriate way.
12. Equip machine tunnel sectors with sensors to monitor air temperature and pressure, as well as air speed in the tunnel.
13. Carry out a risk assessment of particularities such as the He-Ring line and the cryogenic installations in the UX45, UX65, and UX85 caverns.
14. The Safety Task Force considers that the ventilation system is relevant for the safety of personnel and thus recommends to set-up a study of the LHC ventilation system with respect to monitoring and reliability of the system.

7. References

- [1] Report of the Task Force on the Incident of 19th September 2008, P. Lebrun (chair) *et al.*, LHC-Project-Report-1168 (2009)
- [2] An Experimental Study of Cold Helium Dispersion in Air, M. Chorowski, G. Konopka and G. Riddone, LHC-Project-Report-508 (2001)
- [3] Experimental simulation of helium discharge into the LHC tunnel from the supercritical helium supply header in the LHC cryogenic distribution line, M. Chorowski, G. Konopka, G. Riddone and D. Rybkowski, LHC-ACR Internal Note 2002-01, EDMS N° 361608 (2002)
- [4] Experimental Simulation of Helium Discharge into the LHC tunnel, M. Chorowski, G. Konopka, G. Riddone and D. Rybkowski, LHC-Project-Report-611 (2002)
- [5] Conclusion of the He spill simulations in the LHC tunnel, M. Vadon and J. Manteca, CERN-TIS-2003-013-GS-CF, EDMS N° 426030 (2003)
- [6] Safety oriented analysis of cold helium-air mixture formation and stratification, M. Chorowski, G. Konopka-Cupial and G. Riddone, *Cryogenics*, 46, 262-272 (2006)
- [7] Preliminary risk analysis of the LHC cryogenic system, M. Chorowski, P. Lebrun and G. Riddone, LHC-Project-Note-177, (1999)
- [8] LHC-MPP-ES-0002, M. Solfaroli *et. al.*, EDMS N°1001985 (2009)

Annex A

G. Lindell

Listing of Available Input Data – Fact Finding

The schematic layout of the tunnel of sector 3-4 is shown in Figure A1 including the identification of the different areas.

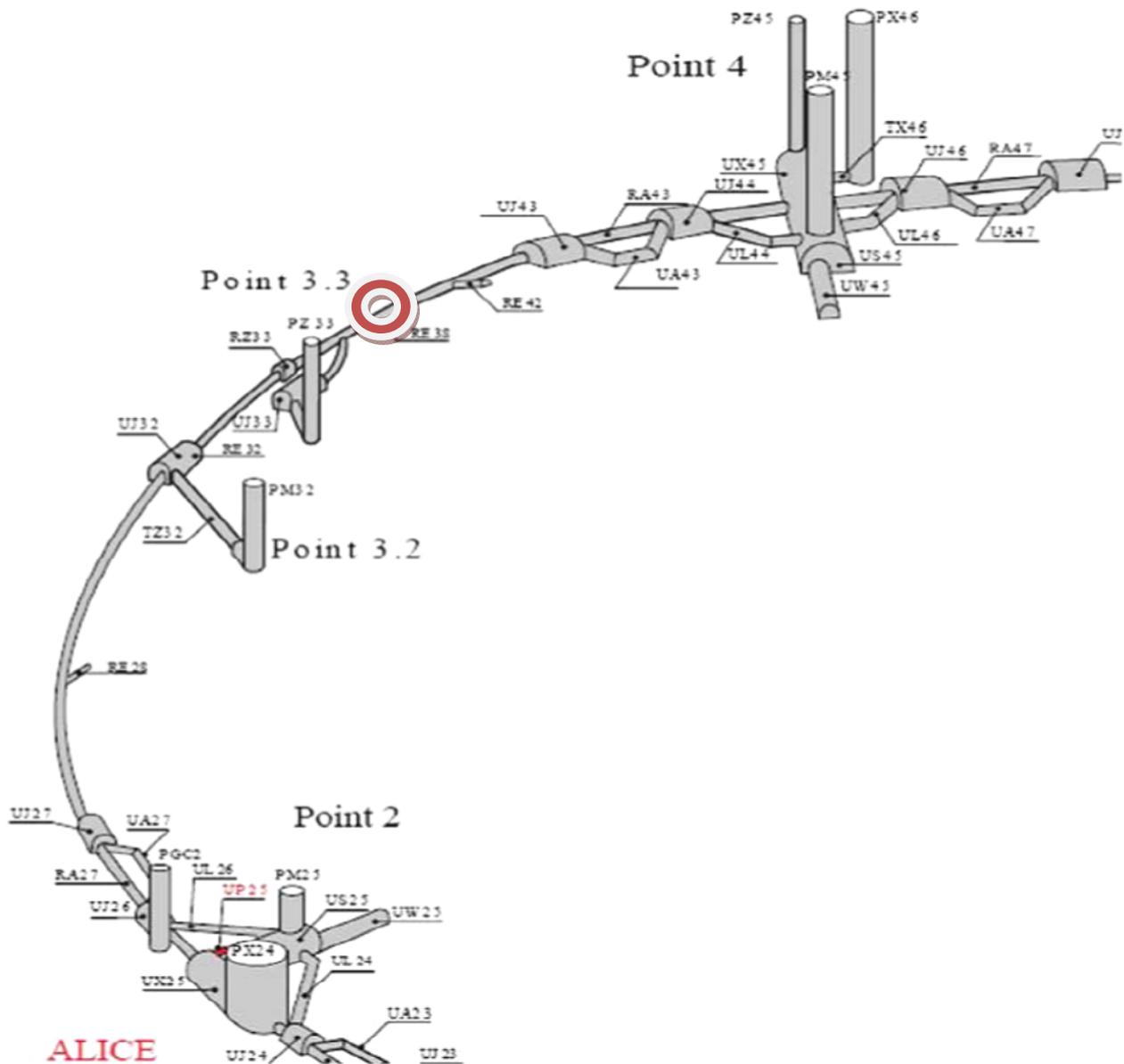


Fig. A1: Schematic layout of the LHC tunnel of sector 3-4. The red dot indicates the approximate position of the accident.

For the identification of an exact location in the LHC tunnel, a so-called *DCUM number* is given, covering the entire tunnel starting at Point 1 and running clockwise. In the current report, this number is used in the re-construction of the environmental conditions directly after the accident for the estimation of, e.g. the helium propagation velocity etc..

During the accident of 19th September 2008, a total of six safety valves opened and released helium into the LHC tunnel. The positions of the outermost safety valves were DCUM 7536 and DCUM 8060. The *damaged area* (D-area) was defined by the Technical Task Force by the position of the 3 damaged cryogenic sub-sectors stretching from DCUM 7477 to and DCUM 8119, i.e. covering a length of 642 m.

In normal operating conditions, the air flow produced by the ventilation system in sector 3-4 goes from Point 4 towards Point 3 with a speed of approximately 0.55 m/s. The injection point is at UJ44 and the extraction point is on the surface of P32 via TZ32.

Oxygen Deficiency Hazard (ODH)

Oxygen (O₂) sensors are placed all along the LHC machine tunnel, mounted on the ceiling with a maximum distance of 300 meters between two individual sensors. Alcoves and extensions are equipped with two sensors. In case a sensor detects oxygen levels below 18%, a so-called level 3 alarm will be automatically triggered which means that flashing lights will be activated at roughly 300 meters on each side of the detection point together with an automatic alarm which will be sent to the CERN's Safety Control Room (SCR) in order to alert the CERN fire brigade. The definition of a level 3 alarm and its handling is defined in the Safety Instruction No. 37, "*Level-3' Safety Alarms and Alarm Systems*" [1]; ODH systems are declared as Safety Systems, submitted to the functional specification "*Systèmes Généraux de Sécurité du LHC*" [2].

An ODH alarm is considered as *confirmed* alarm if two adjacent O₂ sensors detect oxygen levels below 18%. In this case, the evacuation alarm system for the sector will be activated automatically. The timeline for ODH detection is shown in Table A1.

Table A1: Time stamps (software alarms except the first alarm which is hard wired) of the ODH system given during the accident of 19th September 2009

Time stamp given by the system	ODH Alarm detection
11:19:05 (Hard wired alarm)	First ODH detection triggered in location R39 (DCUM 7907).
11:19:58	ODH triggered at DCUM 7600 - RE38 (further towards Point 3) and DCUM 8175 (further towards Point 4)
11:20:25	ODH triggered at DCUM 8350 (further towards Point 4)
11:20:41	ODH triggered at DCUM 7315 (further towards Point 3)
11:22:17	ODH triggered at DCUM 7010 (further towards Point 3)
Up to 14:58:00	ODH detection triggered all along the sector from UJ43 to UJ32. No detection in UJ44, which could be explained by the fact that the sensors are installed upstream (or very close to) the ventilation injection unit.
11:39:25	ODH detection at UJ43 (close to Point 4). DCUM 9720.
12:06:47	ODH detection in UJ32 (close to TZ32). DCUM 5890.
15:19:00	ODH pre-alarm (less than 19% O ₂ but above 18% O ₂) triggered in TZ32.

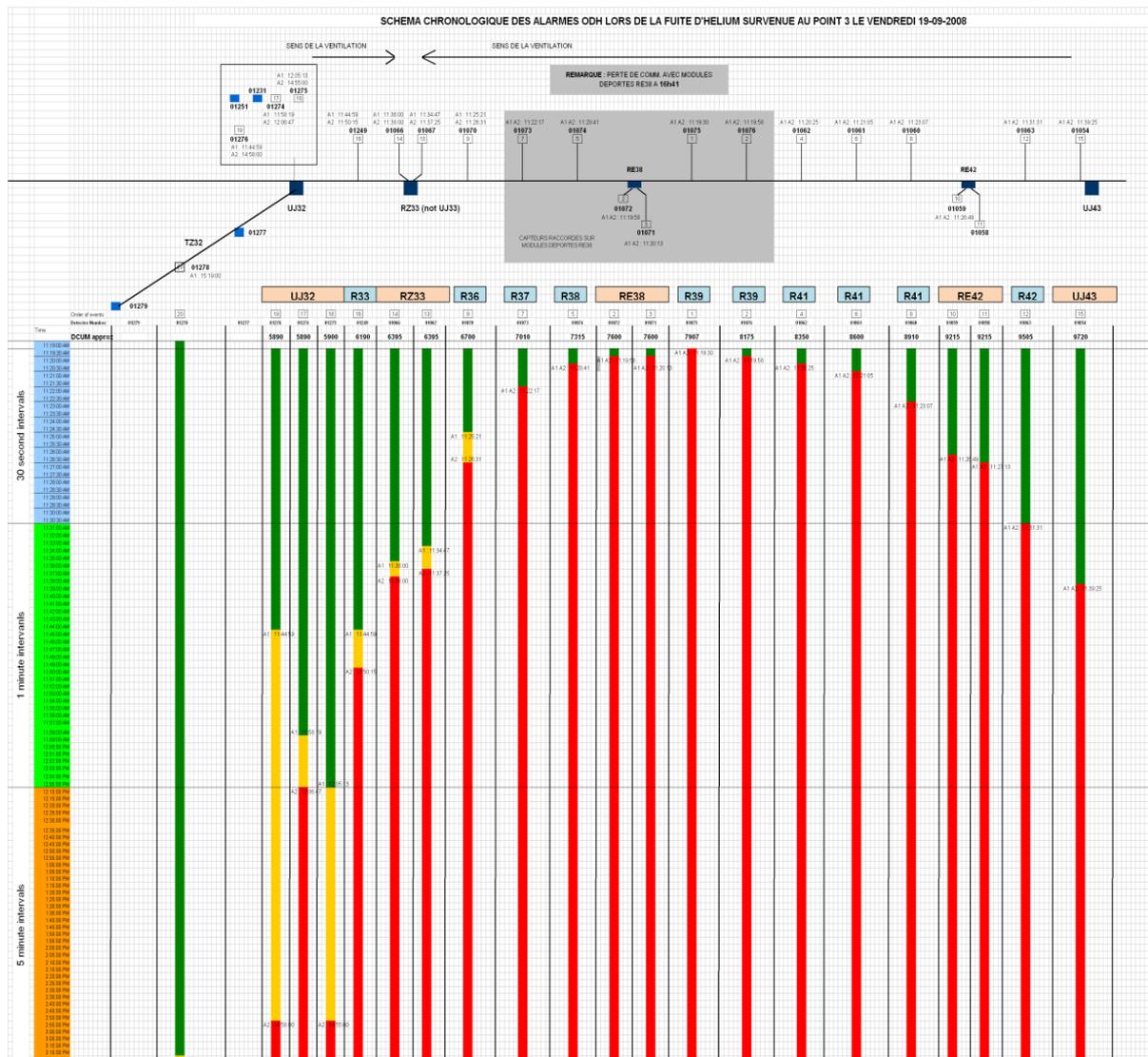


Fig. A2: Chronological scheme of the ODH alarms in sector 3-4 after the accident on 19th September 2008. Time runs vertically from top to bottom. The horizontal axis gives the localisation of the detectors in the area. The colour coding indicates values as follows: green = O₂ level above 19%, yellow = O₂ level between 19% and 18%, red = O₂ level below 18%.

From the time stamps of the alarm detection of the ODH system, two propagation speeds have been determined for the ODH propagation for the different directions from the D-area towards Point 4 and from the D-area towards Point 3.

The ODH propagation speed from outside the D-area towards Point 3 is estimated to be approximately 3.1 m/s for the first 300 meters (up to DCUM 7010) then subsequently go down to approximately 1.2 m/s for the following 300 meters, to approximately 0.5 m/s for the following 300 meters, and finally to approximately 0.3 m/s for the last 500 meters up to location UJ32.

Similarly, the ODH propagation speed from D-area towards Point 4 is estimated to be above 6 m/s for approximately the first ~500 m (up to DCUM 8600), then subsequently goes down to approximately 2.5 m/s for the following 300 m, to approximately 1.4 m/s for the next 300 m, to approximately 1.0 m/s for the following 300 m, and finally to 0.4 m/s for the last 200 meters up to location UJ43.

The normal evacuation speed when walking calmly is in the order of 1.2 m/s (4-5 km/h).

The oxygen concentration as a function of time is shown in Fig A3. The ODH sensors are positioned at the ceiling level.

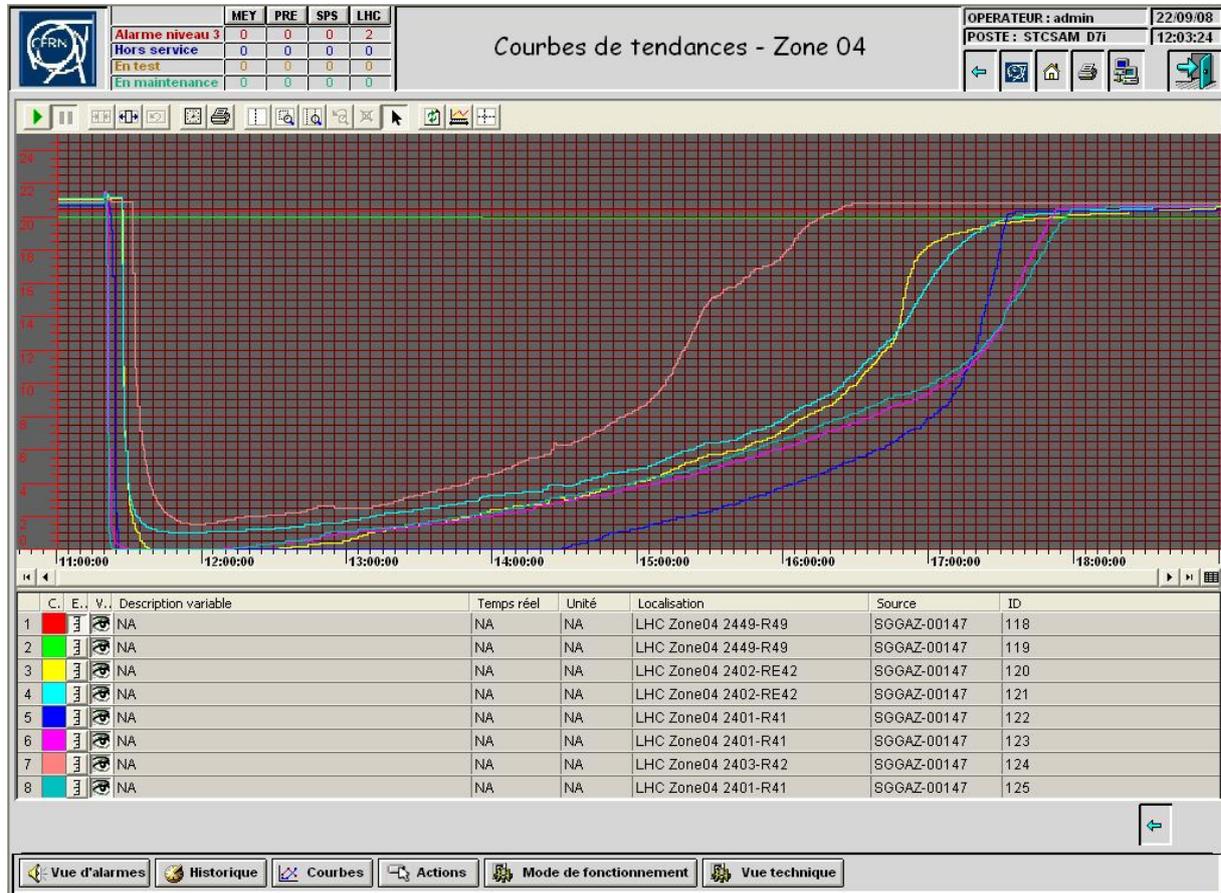


Fig. A3: Oxygen concentrations as a function of time for the ODH sensors of the half sectors 4-3

Automatic Fire Detection

The system for Automatic Fire Detection (AFD) depends on optical fire detectors that are installed in the TZ32, UJ32, UJ33, TZ33, RE38, RE42, UJ43, RA43, UJ44, UL44 & US45 areas. The system operates by aspiration of air from the detection areas by means of perforated pipes to the end of the pipe where the sensor is placed. In case a signal is triggered, a fire alarm from this sensor sends an automatic alarm to the Safety Control Room (SCR). The system does not activate any local alarms as sirens, flashing lights, etc..

Table A2: Time stamps of the AFD system given during the accident of 19th September 2009

Time stamp given by the system	AFD Alarm detection
11:19:10	The first Fire detection was triggered in RE38 (DCUM 7600) due to a vapour cloud some five seconds after the ODH detection in the same area.
11:19:27 – 11:19:38	Fire detection triggered simultaneously along the entire sector from US45 to TZ32 (except for RE42 which is not understood). The time stamp corresponds to the collapse of the ventilation door in UL44, which created a sudden pressure drop in the entire sector. At this moment, dust was stirred up and triggered the optical fire detection sensors.
11:26:49	Fire detection triggered in RE42 (DCUM 9215) due to vapour cloud. The first ODH sensor in RE42 was triggered at the same time.

Evacuation Alarm System

The evacuation alarm is automatically triggered in case of confirmed ODH alarm. The Automatic Fire Detection will not trigger any evacuation alarm in the LHC tunnel. Table A3 gives the time stamps of the triggering of the evacuation alarms during the accident of 19th September 2009.

Table A3: Time stamps of the triggering of the evacuation system during the accident of 19th September 2009

Time stamp given by the system	Evacuation Alarm system
11:19:39	Evacuation alarm triggered for half sector 3-4.
11:20:45	Evacuation alarm triggered for half sector 4-3.
11:37:33	Evacuation alarm triggered for half sector 3-2, when the helium arrived at Point 3.

Witness Statements

Members of the CERN Fire brigade Entering the LHC Tunnel

In addition to the time stamps given by the different alarm systems, the Safety Task Force used as a source of information the intervention report of the CERN Fire Brigade and an eye-witness report of a Fire brigade assistant operator who participated in the intervention of 19th September 2008.

It could be re-constructed that at their Safety Control Room (SCR) the CERN Fire Brigade observed ingoing alarms of the AFD system and the ODH system almost simultaneously. The eye-witness reported that it was quickly understood that nobody was present in the tunnel, that radiation protection was not an issue, and that a large quantity of helium was to be expected in sector 3-4.

Due to the direction of the air flow provided by the ventilation system in the LHC tunnel, it was decided to access at Point 4 instead of Point 3. On request of the CERN Fire Brigade, the ventilation was manually switched to high extraction speed in sector 3-4 at approximately 12:20.

First Fire Brigade Team

At approximately 13:15, the CERN Fire Brigade sent a 2-person-team (so-called *binôme*) entering the tunnel at Point 4, the infrared-camera was used to determine both the ambient temperature, and the temperature of the magnets' vacuum vessels. The registered temperature levels were communicated to

the *chef d'intervention*¹ at the surface. O₂-levels between 20% and 19% at a height of approximately 1.80 meters were read with a portable detector. The highest level of O₂ was found close to Point 4 and decreased going further into the tunnel.

At 14:20, the team had to return to the surface due to loss of communication after having covered approx. 1200 m starting from Point 4, corresponding to some 400 meters from the D-area. The binôme reported to have seen a vapour/helium cloud coming from the location RE42.

The ambient temperature in the tunnel was measured between +20° C and +15° C, the warmest location being close to Point 4. The temperature readings decreased when the team went further into the tunnel towards Point 3.

Second Fire Brigade Team

At approximately 16:15, the CERN Fire Brigade sent a second binôme to enter the tunnel at Point 4. The second binôme covered the entire D-area and beyond, by going up to DCUM 7312 (corresponding to some 170 meters beyond the D-area). They reported measurements for temperature and oxygen levels for the area DCUM 8381 to DCUM 7312. At DCUM 7954, an ambient temperature of +12° C and a magnet surface temperature of -27° C was measured.

Oxygen levels are given between 18% and 17%, measured at a height of approximately 1.80 m (DCUM 8381-7419). The highest level of O₂ was found close to Point 4 and the values decreased when the team went further in to the tunnel. The team did not report any visible vapour helium cloud.

Witnesses working in SD4 Surface Building

Two eye witnesses observed a vapour/helium cloud escaping from the tunnel through the PM45 shaft into the surface building SD4. The exact time is not known.

Measurements and Actions Taken by the Team in Charge of the Ventilation System

The group technically in charge of the LHC ventilation system carried out different changes of the ventilation modes, following requests given by the CERN Fire Brigade. The modifications made were the followings.

- At approximately 12:20 the ventilation was changed from normal mode to emergency extraction mode. This means an increase of air speed from 0.55 m/s to 0.88 m/s.
- At approximately 13:30, the air inlet temperature of the ventilation system was increased from 24° C to 32° C.
- At approximately 15:30, the air flow of the ventilation system was increased by another 10%.

In addition, measurements were taken with a mass spectrometer at the ventilation extraction duct at Point 3 (see Table A4 for details).

Table A4: Measurements taken at the ventilation extraction duct at Point 3.

Time stamp	Nitrogen level [%]	Oxygen level [%]	Helium level [%]
14:30	49	12	39
14:55	39	9	51
15:13	44	10	46
17:55	43	11	46

The summary of the available level 3 alarm data is provided in Table A5, while Fig. A3 summarizes all the available data for the D-area.

¹ A copy of the hand-written notes taken during the intervention between 13:15 – 14:20 o'clock was provided to the Safety Task Force and was used for the reconstruction of the sequence of events.

Table A5: Summary of level 3 alarms during the first hours following the helium release

Time stamp given by the CSAM system	Event	Comment
11:19:05	First ODH triggered in R39 (DCUM 7907)	
11:19:10	First AFD triggered in RE38	Triggered by vapour helium cloud
11:19:25	AFD triggered in UL44	Triggered by dust when the door in UL44 collapsed
11:19:27	AFD triggered in UJ33 (DCUM 6400)	Triggered by dust when the door in UL44 collapsed
11:19:30	AFD triggered in TZ33 (DCUM 6400)	Triggered by dust when the door in UL44 collapsed
11:19:33	AFD triggered in RA43	Triggered by dust when the door in UL44 collapsed
11:19:34	AFD triggered in US45 (DCUM 10000)	Triggered by dust when the door in UL44 collapsed
11:19:35	AFD triggered in UJ43 (DCUM 9720)	Triggered by dust when the door in UL44 collapsed
11:19:38	AFD triggered in TZ32 (UJ32 side) (DCUM 9700)	Triggered by dust when the door in UL44 collapsed
11:19:39	Evacuation alarm triggered for half sector 3-4	
11:19:58	ODH triggered in R39 (DCUM 8175) & RE38 (DCUM 7600)	
11:20:13	2 nd ODH triggered in RE38 (DCUM 7600)	
11:20:25	ODH triggered in R41 (DCUM 8350)	
11:20:41	ODH triggered in R41 (DCUM 7315)	
11:20:45	Evacuation alarm triggered for half sector 4-3	
11:21:05	ODH triggered in R41 (DCUM 8600)	
11:22:17	ODH triggered in R37 (DCUM 7010)	
11:23:07	ODH triggered in R41 (DCUM 8910)	
11:26:31	ODH triggered in R36 (DCUM 6700)	
11:26:49	ODH triggered in RE42 (DCUM 9215)	
11:27:13	2 nd ODH triggered in RE42 (DCUM 9215)	
11:31:31	ODH triggered in R42 (DCUM 9505)	
11:37:25	ODH triggered in RZ33 (DCUM 6395)	
11:37:33	Evacuation alarm triggered for half sector 3-2	
11:38:00	2 nd ODH triggered in RZ33 (DCUM 6395)	
11:50:15	ODH triggered in R33 (DCUM 6190)	
12:06:47	ODH triggered in UJ32 (DCUM 5890)	
14:55:00	ODH triggered in UJ32 (DCUM 5900)	
14:58:00	ODH triggered in UJ32 (DCUM 5890)	

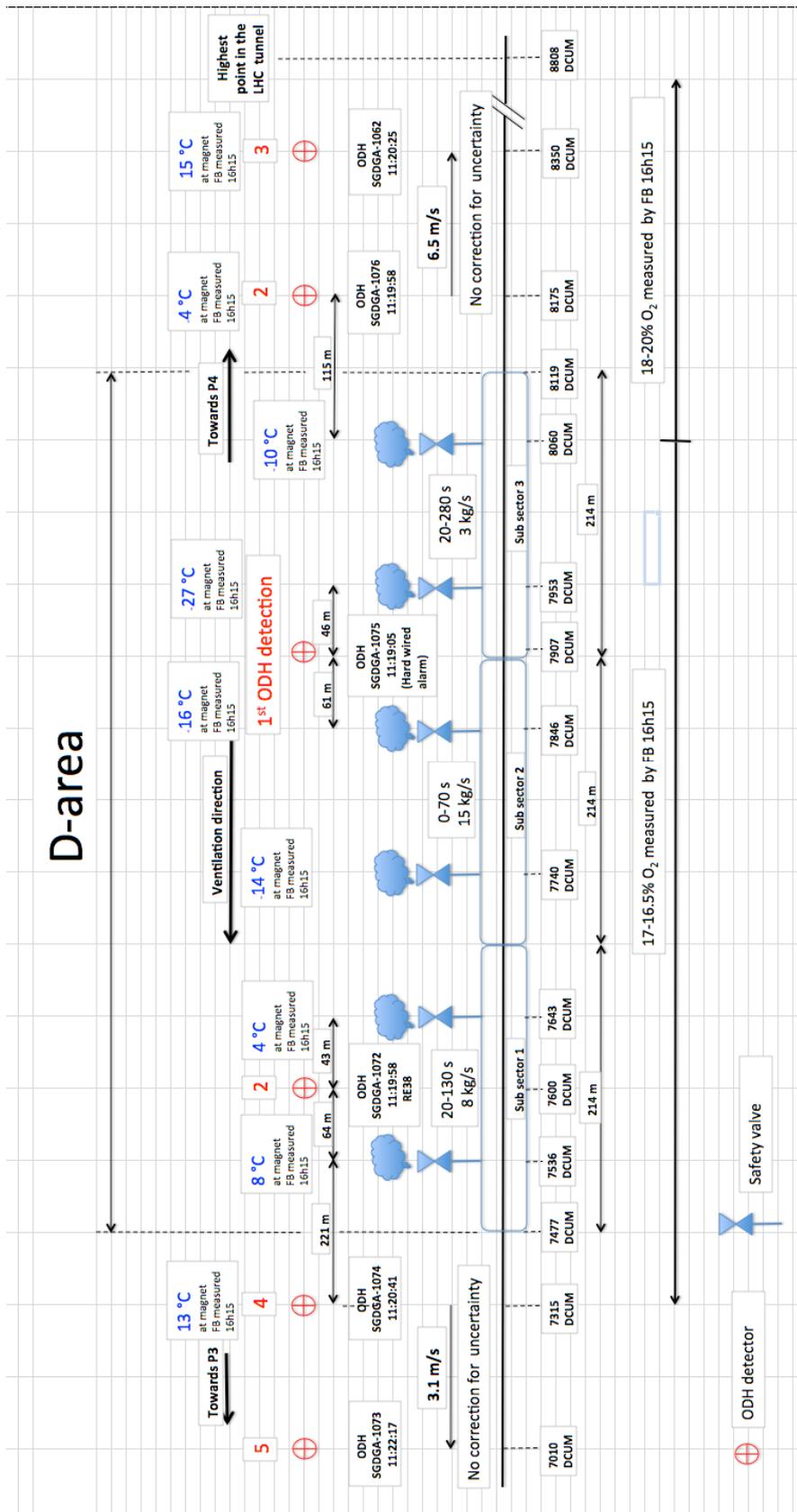


Fig. A4: Summary of the data for the D-area including ODH data and observations by the fire brigade

Reference

- [1] IS 37, Alarms and alarm systems, EDMS N°335802 v.4, (2003)
- [2] Systèmes Généraux de Sécurité du LHC, Functional Specification, LHC Project Document (2002)

Annex B

L. Tavian

Validity of the Preliminary Risk Assessment and redefinition of the Maximum Credible Incident (MCI)

MCI from preliminary risk analysis

The maximum credible incident (MCI) was defined in 1999 in the preliminary risk analysis of the cryogenic system [1]. At the time, in case of electrical arcs, the maximum flow which could be discharged from the magnet cold mass into the insulation vacuum enclosure of the readout cryostats was assessed to be 2 kg/s. This value was based on a maximum breach cross-section of 5 cm². It also corresponds to the average flow discharge through a quench valve having a larger section passage (~12 cm²), as measured after a magnet resistive transition [2] (see Fig.B1). This figure shows at the very beginning a mass-flow peak exceeding 2 kg/s, whereas in case of helium release, the insulation vacuum acts as a buffer volume. This volume of about 80 m³ is able to buffer about 60 kg of helium at 60 K. An experiment was also performed on a 107 m test-cell of the cryogenic distribution line (QRL) [3], equipped with a bursting disk of 5 cm² cross-section on header C, to stimulate a helium discharge via the vacuum enclosure into a simulated tunnel. During this experiment, a maximum flow of 1 kg/s was deduced (see Fig. B2), validating the hypothesis.

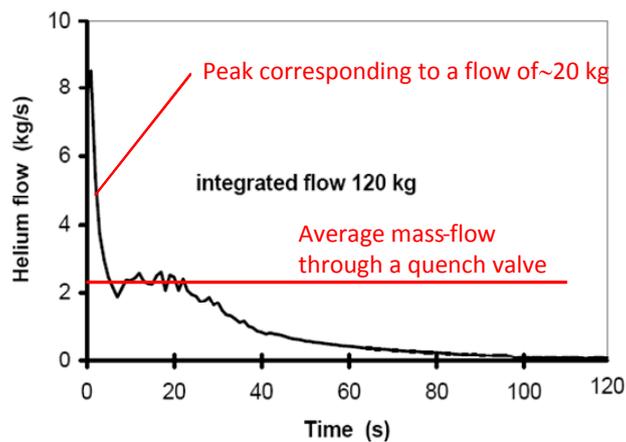


Fig. B1: Helium flow measured after a magnet resistive transition through a quench valve

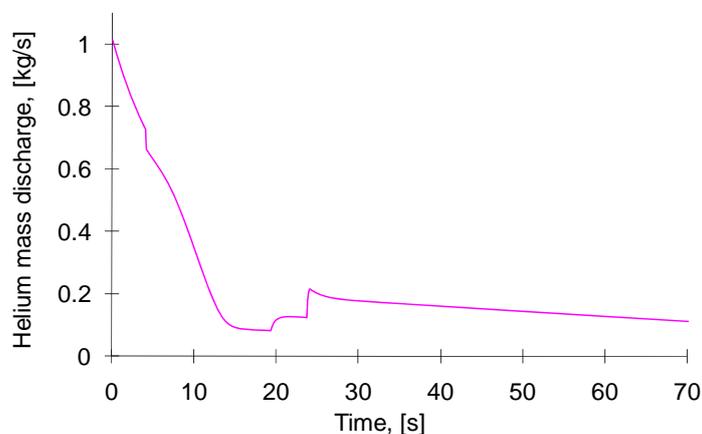


Fig. B2: Helium discharge during the QRL test-cell experiment

Concerning the inventory of helium released in the tunnel, a maximum amount of 475 kg was assessed based on a standard cryogenic sub-sector of 214 m with a filling factor of 15 l/m.

Concerning helium release in the tunnel, the preliminary risk analysis had also identified the worst case scenario corresponding to a complete break of a jumper connection of the cryogenic distribution line (QRL). In this case, up to 4250 kg of helium were discharged directly (i.e. without passing via the vacuum enclosure) into the tunnel, including 600 kg discharged during the first minute.

Outcome from the LHC accident on 19 September 2008

On 19th September 2008, helium breaches of 2 x 32 cm² were first created between the magnet cold-mass and the insulation vacuum enclosure by the electrical arc at the interconnection of the quadrupole 24R3. 22 seconds later, additional breaches of 60 cm² were created as collateral damage due to magnet displacement, producing the complete rupture of the Q26 interconnection. A total flow cross-section of 124 cm² was therefore eventually produced. Estimation of the mass flow of helium out of the magnet helium enclosure yields a maximum value of about 20 kg/s with the first breach (64 cm²) and later up to a maximum of 40 kg/s with the additional breaches (+ 60 cm²). In the first approximation, the specific flow-rate is about 0.33 kg/s per cm² of cross-section.

With respect to the preliminary risk analysis, the order of magnitude of the specific flow-rate is confirmed. The main difference in absolute numbers resides in the assumption made on the flow cross-section of the breach which could be created by an electrical arc. The 19th September 2008 accident showed that a factor 25, i.e. more than one order of magnitude than foreseen. This large difference explains the over-pressurization of the insulation vacuum enclosures of the magnet sub-sector which were equipped with relief devices too small to accommodate the mass-flow, and consequently the collateral damage on the concerned sub-sector as well as on the adjacent ones.

During the first minutes following the accident, up to 2700 kg of helium corresponding to the inventory of 3 standard sub-sectors having a filling rate of 26 l/m and of the line E were released in the tunnel. Moreover, the helium inventory of the line C corresponding to 3400 kg of helium were released during several hours at a lower flow-rate (~0.2 kg/s). Line C is located in the QRL distribution line but directly connected to the machine via small-diameter pipes without separation valves. In total about 6 tons of helium were lost.

Redefinition of MCI for standard sub-sectors in LHC arcs

On 19th September 2008, the initial electrical arc has fully destroyed the interconnection line M3 and the beam vacuum line V2, and has perforated the line E (thermal shield cooling) and the beam vacuum line V1 (see Fig. B3). A similar electrical arc with a different development could potentially destroy two bus-bar lines, opening breaches of 4 x 32 cm² (i.e. 128 cm² in total). It should also be remembered that the accident on 19th September 2008 occurred at a current of 8.7 kA, lower than the nominal value. Therefore, it is credible to envisage that an electrical arc at nominal current (~12 kA) could destroy the three bus-bar lines of the magnet interconnection, thus opening breaches of 6 x 32 cm² (192 cm² in total).

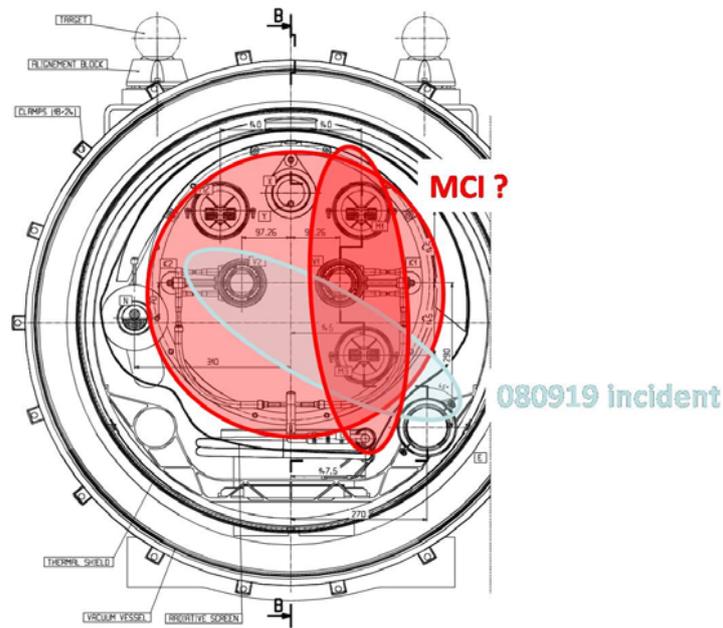


Fig. B3: Damages caused by an electrical arc

A limiting factor which has to be taken into account is the available free cross-section for longitudinal flow in the magnet cold-mass lamination, limited to about 60 cm^2 . Therefore, even in case of a total breach of an interconnect between two magnets, when both sides are opened, the magnet laminations will limit the total effective opening to 120 cm^2 ($2 \times 60 \text{ cm}^2$). Moreover, the new protection system to be implemented will limit the pressurization of the magnet cryostat and consequently will prevent the collateral damage and additional flow due to secondary breaches provoked by magnet displacement.

In conclusion, the redefinition of the MCI in LHC arcs, based on a total breach cross-section of 120 cm^2 yields a maximum mass-flow of 40 kg/s , taking into account the (confirmed) specific flow-rate of $0.33 \text{ kg/s per cm}^2$.

Concerning helium released in the tunnel, the inventory of the concerned sub-sector (820 kg for a standard sub-sector) and of the line E (290 kg) will be lost during the first minutes. The inventory of the line C (3400 kg) will also be lost but at a lower rate ($\sim 0.2 \text{ kg/s}$) during several hours.

Redefinition of MCI for other cryogenic sub-sectors

In addition to standard sub-sectors, the LHC contains other cryogenic sub-sectors having various lengths, helium inventory, bus-bar configuration especially in the mid arc and in long straight section. For each type, the maximum breach section has been assessed in order to define the corresponding mass-flow using the specific flow-rate of $0.33 \text{ kg/s per cm}^2$. Table B1 gives the MCI conditions for the different cryogenic sub-sectors. The worst case scenario corresponds to an electrical arc in the mid-arc sub-sector giving a maximum flow of 40 kg/s , a fast release of 1.5 tons of helium and a total loss of 5 tons . Table B2 compares this new worst case scenario with the one defined in the preliminary risk analysis showing a factor 2.5 on the fast-released losses which are critical for the tunnel pressure build-up.

Table B1: MCI conditions for different cryogenic sub-sectors

Sub-sector	Maximum flow [kg/s]	Helium inventory loss [kg]	
		Fast release (During the first minutes)	Total
Standard sub-sector	40	1110	4510
Mid-arc sub-sector	40	1520	4920
DS sub-sector	40	970	4370
Stand-alone magnet	8	30	3900
Semi-stand-alone magnet	15	60	3930
Inner triplet	20	180	3870
Superconducting link (P3)	13	260	3950
Superconducting link (P1, P5)	8	30	3720

Table B2: Worst case scenario comparison

Worst case scenario	Maximum flow [kg/s]	Helium inventory loss [kg]	
		Fast release (During the first minutes)	Total
1999 analysis (Break of jumper connection)	20	600	4250
2009 analysis (Electrical arc in mid-arc sub-sector)	40	1520	4920
Ratio	2	2.5	1.2

Reference

- [1] Preliminary risk analysis of the LHC cryogenic system, M. Chorowski, *et al.*, LHC-Project-Note-177, (1998)
- [2] Experimental Simulation of Helium Discharge into the LHC tunnel, M. Chorowski *et al.*, LHC-Project-Report-611 (2002)
- [3] Thermohydraulics of Quenches and Helium Recovery in the LHC Magnet Strings, M. Chorowski *et al.*, LHC-Project-Report-154 (1997)

Annex C

B. Delille

Estimates of overpressure values due to Maximum Credible Incident (MCI)

The analysis carried out and described in this Annex aims at estimating the maximum pressure which can be encountered in the LHC tunnel due to the MCI (see Annex B).

Hypotheses

What follows is an estimate of the static overpressure values in the LHC tunnel based on steady state calculations. The estimate is given for the configuration of the intermediate solution using the existing ventilation door(s) as relief devices allowing the air/He to be released via the UL, PM shafts and SD buildings. A detailed calculation of the overpressure values, based on Computational Fluid Dynamics (CFD) analysis, would nevertheless be more appropriate for considering time dependant flow rates, helium gas expansion, thermal exchange with tunnel components, He/O₂ concentrations etc..

Results given in this Annex are based on the following assumptions.

- **Mass-flow Discharge**

A mass flow discharge of 40 kg/s of He was taken into account. This maximum mass flow has been defined for the MCI and is limited by the longitudinal hydraulic impedance of the magnets (see Annex B).

- **Location of the MCI**

The location of the MCI (with a maximum flow of 40kg/s) is chosen the closest to where the overpressure must be known.

- **Helium release path**

The Table below gives the assumptions taken into account for the assessment of pressure drops. The following must be considered as a proposal, coherent with the access matrix defined in Annex D.

Table C1: basic assumption for the helium release path configuration shown in Fig. C1

Location of MCI	Air-He released at	Door(s) open	Pressure resistant door(s)
S81	P1 and P8	UL14 and UL86	
S12	P1 and P2	UL16 and UL24	
S23	P2	UL26	UJ32
S34	P4	UL44	UJ32
S45	P4 and P6	UL46, UL64 and UL56	
S56	P4 and P6	UL46, UL64 and UL56	
S67	P6	UL66	UJ76
S78	P8	UL84	UJ76

As example, the case of an MCI close to Point 1 in sector 1-2 is illustrated below. Both the air and helium will be released at Points 1 and 2, through the corresponding PM shafts.

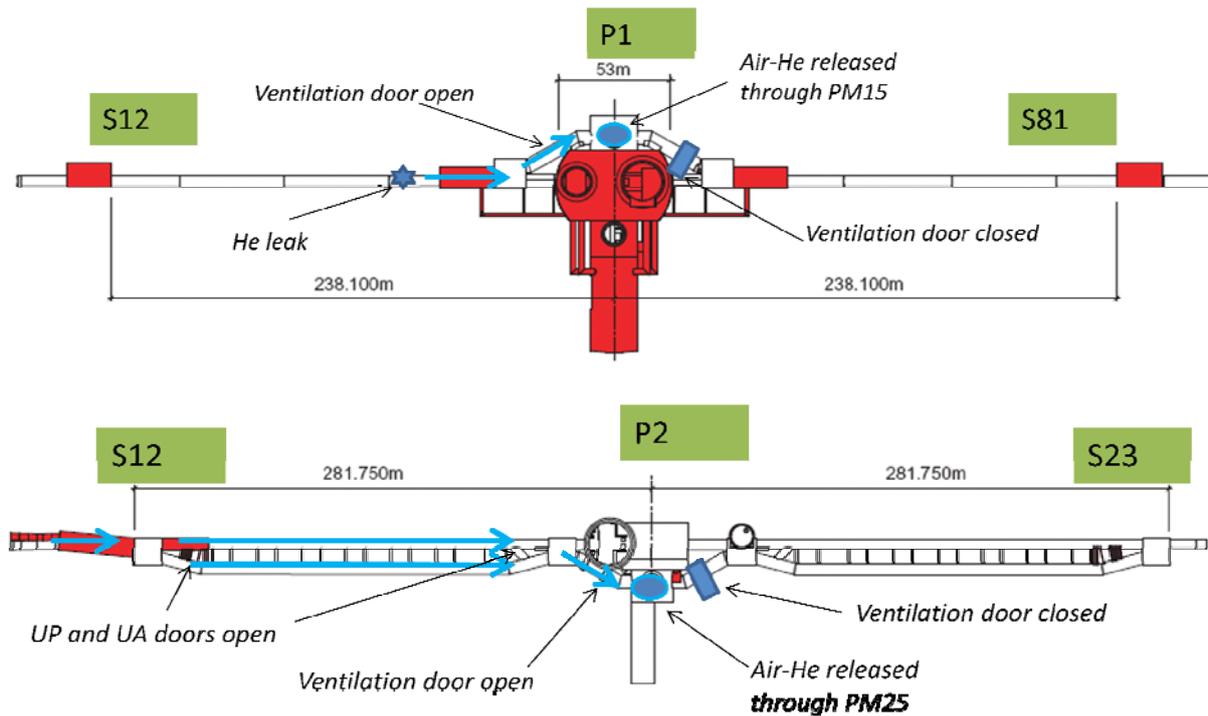


Fig. C1: Configuration for helium release path – Illustration for S12 and MCI close to Point 1

It is assumed, at Points 2, 4, 6 and 8 that the doors (with a surface of 2 m² each) between UA and RA are open (the UP door and the door at the end of UA).

- **Fluid properties**

Although helium is released in the tunnel during the MCI, one took as conservative assumption that Air is extracted from the tunnel.

Considering the density of helium at 200 K ($\rho = 0.24 \text{ kg/m}^3$), the mass flow of 40 kg/s gives a volumetric flow of 166 m³/s.

Pressure drop calculations were carried out considering a volumetric flow of Air at 300K of 166 m³/s with the following properties: $\rho = 1.16 \text{ kg/m}^3$ and $\mu = 1.85e^{-5} \text{ Pa.s}$

- **Pressure drop calculations**

The total pressure drop, from the point where the accident occurs to the SD building, is expressed as

$$P = \sum_i \Delta P_i$$

$$\text{With } \Delta P_i = C_i \times \frac{\rho m \dot{V}^2}{2S_i^3}$$

For tunnel singularities, Ci coefficients are defined according to rules given by the SMACNA (Sheet Metal and Air Conditioning National Association) and depend on local geometry.

Doors in the UP and at the end of the UA's are considered open.

Along the tunnel, the coefficient Ci is given by

$$C_i = f(d) \times \frac{l}{d}$$

with $f(d)$ the friction factor, l the length of tunnel and d the hydraulic diameter of the tunnel

$$f(d) = \frac{0.25}{\log \left[\frac{e}{3.7d} + \frac{5.74}{\text{Re}(d)^{0.9}} \right]^2}, \text{ for Reynolds numbers higher than 2300}$$

$e = 1\text{mm}$, roughness considered as average between polished surfaces (machine, floor) and concrete

$$d = \frac{4S}{P}$$

$S = 7,15 \text{ m}^2$ is the tunnel free area

$P = 20,5 \text{ m}$ is the total "wetted perimeter"

The approximate free area of the tunnel of 7.15 m^2 is given by the whole cross section from which the coloured areas are subtracted (see Fig. C2).

The approximate value of the so-called "wetted perimeter" is given by the sum of perimeter of the pieces of equipment coloured in blue (see Fig. C2).

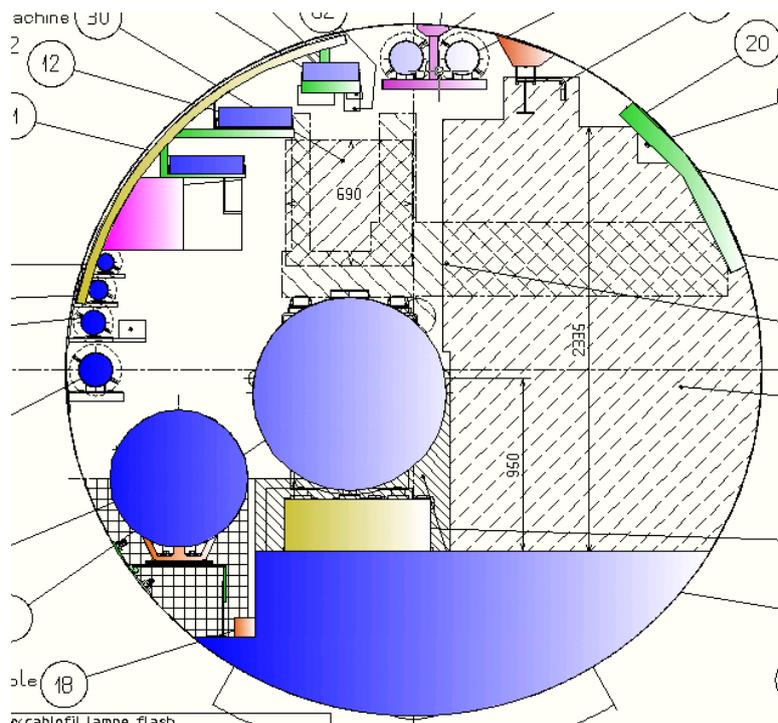


Fig. C2: Standard cross-section of the tunnel [for the colour code see text]

The value of pressure drop in the SD building is assumed constant at 10 mbar and is given by the pressure build up by an air flow of $166 \text{ m}^3/\text{s}$ passing through an opening of 4 m^2 .

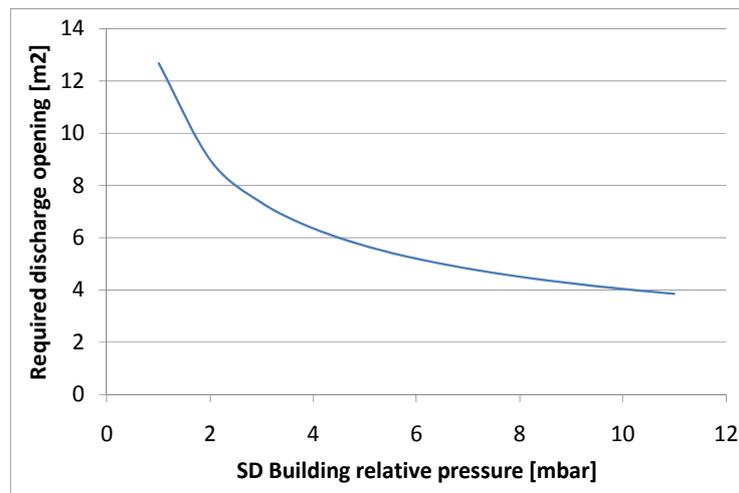


Fig. C3: Required discharge opening v/s pressure build-up in SD building for an air flow of 166 m³/s

Summary of results

Table C1: Estimated static overpressure in the different locations depending on the location of the accident and as a function of the conditions for the air restriction (ventilation doors, etc.)

Pressure at	Incident in	Air-He released at	Door(s) open	Maximum flow [m ³ /s]	Maximum pressure in the US [mbar]	Maximum pressure in the tunnel [mbar]
P1	SD area of S81 close to P1	P1 and P8	UL14 and UL86	59.9 (P8) 106.1 (P1)	10.2 (US85) 10.7 (US15)	31.6
P1	SD area of S12 close to P1	P1 and P2	UL16 and UL24	59.8 (P2) 106.2 (P1)	10.2 (US25) 10.7 (US15)	31.7
P2	SD area of S12 close to P2	P1 and P2	UL16 and UL24	98.8 (P2) 67.2 (P1)	10.5 (US25) 10.3 (US15)	34.6
P2	SD area of S23 close to P2	P2	UL26	166	11.5 (US25)	76.1
P3	SD area of S23 close to P3	P2	UL26	166	11.5 (US25)	145.4
P3	SD area of S34 close to P3	P4	UL44	166	12.5 (US45)	203.4
P4	SD area of S34 close to P4	P4	UL44	166	12.5 (US45)	76.7
P4	SD area of S45 close to P4	P4	UL46	110.6 (P4) 55.4 (P6)	11.2 (US45) 10.3 (US65)	39.9
P5	SD area of S45 close to P5	P4 and P6	UL46 and UL64	83.9 (P4) 82.1 (P6)	10.6 (US65) 10.7 (US45)	51.8
P5	SD area of S56 close to P5	P4 and P6	UL46 and UL64	82.7 (P4) 83.3 (P6)	10.6 (US65) 10.7 (US45)	51.8
P6	SD area of S56 close to P6	P4 and P6	UL46 and UL64	110.8 (P6) 55.2 (P4)	11.1 (US65) 10.3 (US45)	39.7
P6	SD area of S67 close to P6	P6	UL66	166	12.2 (US65)	76.6
P7	SD area of S67 close to P7	P6	UL66	166	12.2 (US65)	176.0
P7	SD area of S78 close to P7	P8	UL84	166	11.8 (US85)	175.4
P8	SD area of S78 close to P8	P8	UL84	166	11.8 (US85)	75.8
P8	SD area of S81 close to P8	P8 and P1	UL14 and UL86	100.3 (P8) 65.7 (P1)	10.7 (US85) 10.3 (US15)	34.0

Detailed Results

Tables showing in detail the pressure loss coefficients (C) as well as the local pressure drops (ΔP) for all calculations performed are documented and available on request.

Additional Results –Point 8

On request of the LHCb experiment, the pressure at Points 6, 7 and 8 was re-computed considering the door in UJ76 opened in case of MCI. The opening of the doors is connecting both Sectors 6-7 and 7-8 (solution similar to Point 5 connecting Sector 4-5 and Sector 5-6 in case of MCI in one of these Sectors). The concerned part of the summary tables for this alternative configuration can be found below. Should this proposal be accepted, the access matrix would need to be changed accordingly.

Table C2: Estimated static overpressure at Points 6, 7 and 8 with door in UJ 76 open

Pressure at	Incident in	Air-He released at	Door(s) open	Maximum flow [m ³ /s]	Maximum pressure in the US [mbar]	Maximum pressure in the tunnel [mbar]
P6	SD area of S67 close to P6	P6 P8	UL66 UL84	113.0 (P6) 53.0 (P8)	11.0 (US65) 10.2 (US85)	40.8
P7	P7	P6 P8	UL66 UL84	85.7 (P6) 80.3 (P8)	10.6 (US65) 10.4 (US85)	54.2
P8	SD area of S78 close to P8	P6 P8	UL66 UL84	52.8 (P6) 113.2 (P8)	10.2 (US65) 10.9 (US85)	40.6

Annex D

E. Thomas

Access Restrictions

A controlled and direct release of the overpressure within a machine tunnel ventilation sector to the surface, i.e. without flow through other underground ventilation areas, is at present not implemented. The Safety Task Force proposes as temporary compensatory measure to allow access only to areas which are *sealed off* from the machine tunnel ventilation sector in which an MCI might occur, and in which there is no risk to personnel, i.e.:

1. The separating structures (walls, doors...) resist to the overpressure,
2. The helium leak rate is sufficiently low to exclude the creation of an Oxygen Deficiency Hazard,
3. The evacuation of the personnel is safe.

The local implementation of these compensatory measures will depend on various factors like the local topology, the stiffness of the existing structures, the helium relief possibilities, the expected overpressure, and the access needs.

An illustrative example is given in Figure 1. For sector 1-2 during Phase II powering test, both UL 14 and UL24 doors shall open freely to release the helium via the UL area, the PM shaft and out of the SD surface building thus limiting the overpressure. There is no access to the US15 and US25 because it is on the way of the helium evacuation path to the PM shaft. Working at height restrictions apply to the SD buildings because of the ODH risk.

In this example it is assumed that the necessary work has been made to get the experimental halls tight (condition 1 and 2 fulfilled) and therefore access to UX15 and UX25 is allowed. In case of ODH alarm in a machine tunnel ventilation sector, the implemented evacuation matrix will activate the evacuation alarm up to the UA included of the adjacent sectors. The natural behaviour of the personnel there would be to evacuate to the nearest PM shaft and be at risk. Therefore the access in the adjacent sectors is permitted only up to the nearest inter-site door (condition 3). It should be noted that additional constraints may arise from access control requirements.

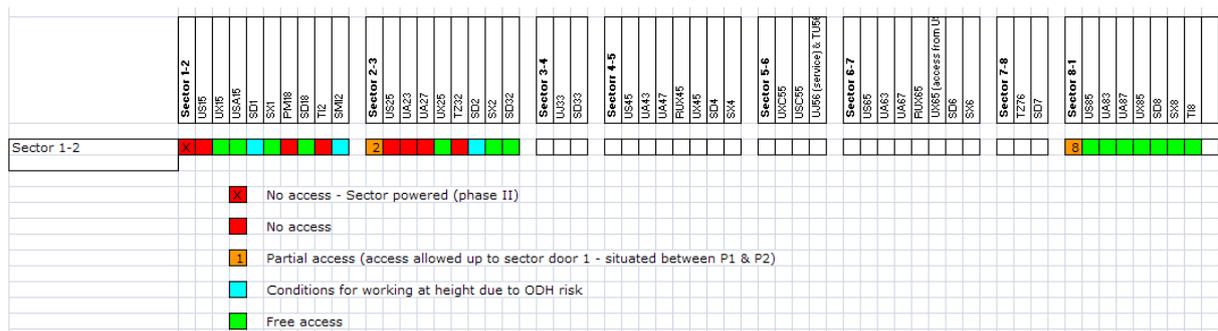


Fig. D1: Example of access matrix while sector 1-2 is in phase II powering

Annex E

Pictures of the ventilation doors of sector 3-4



Fig. E1: Pictures of the UJ32 doors



Fig. E2: Picture of the RB44 door



Fig. E3: Picture of the UL44 door

Annex F

Mandate of the “Task Force” on Safety of Personnel in the LHC underground areas following the accident in sector 3-4 of the 19th September 2008

1. *Mandate*

- a. Establish the sequence of facts related to safety of personnel, based on AL3 data and FB emergency intervention records.
- b. Analyse the LHC underground environmental conditions with respect to Safety of personnel and explain their development in relation with original risk analyses (incl. tests) performed.
- c. Recommend preventive and corrective measures for the Safety of Personnel in the LHC underground.

2. *Membership*

TF composed of safety and cryogenic experts

- a. Beam Department: Ghislain Roy (DSO BE dept.)
- b. Safety Commission: Benoit Delille, Gunnar Lindell, Ralf Trant (Chair), Christine Vollinger (scientific secretary)
- c. Technology Department: Laurent Tavian (group leader EN/CR)
- d. Physics Department: Eric Thomas (LHCb GLIMOS)
- e. Engineering Department: Joaquin Inigo-Golfin (Group Leader EN/CV)
- f. Staff Association: Sebastien Evrard

3. *Communication*

- a. Reporting to the Directorate (milestones)
- b. Informing Department Heads concerned (BE, EN, TE, PH) & relevant committees (SAPOCO/BFSP)
- c. Sensitive information will be gathered, exchanged and interpreted by the TF, therefore:
 - i. Members of the TF subject to confidentiality
 - ii. Working documents available on restricted EDMS site

4. *Organisation*

- a. Confirmed mandate right after the Christmas shutdown (5th of January 2009)
- b. Starting after the Christmas shutdown (First meeting at 21st of January 2009)
- c. Aim at concluding within 30 working days
- d. Frequency, time and place of the meetings:
 - iii. Wednesday, Friday mornings (2h)
 - iv. Bldg. 24, SC Conference room
- e. No minutes, but slides & documents on protected EDMS site, write final report
- f. Forward documents to C. Vollinger managing the EDMS site
- g. Priority actions
 - v. Long shut down works constraints
 - vi. Powering test access constraints
- h. The preliminary conclusion will be reviewed by an external advisory committee of safety experts (e.g. from BNL, DESY, FNL, JFL).