EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2011-019

Risk analysis update of the LHC cryogenic system following the 19th September 2008 incident

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Abstract

On 19th September 2008, during powering tests of the main dipole circuit of the Large Hadron Collider, an electrical fault occurred producing an electrical arc and resulting in mechanical and electrical damage, release of helium from the magnet cold mass to the insulation vacuum enclosure and consequently to the tunnel, via the spring-loaded relief discs on the vacuum enclosure. The pressurization of the vacuum space exceeded significantly the allowed design value. Mathematical modeling based on a thermodynamic approach has enabled the revision of the helium discharge system protecting the vacuum enclosure against the over-pressurization in case of a redefined maximum credible incident (MCI) occurrence.

Presented at the International Cryogenic Engineering Conference 23–
International Cryogenic Materials Conference 2010 (ICEC23–ICMC2010)
19-23 July 2010, Wrocław, Poland.

Geneva, Switzerland,
August 2011

INTRODUCTION

The 19th September 2008 incident in the LHC sector due to an electrical arc in the main dipole bus-bar circuit has produced a large helium discharge in the cryo-magnet cryostats, about 6 tons of helium release in the LHC tunnel as well as blast impact on tunnel ventilation door [1]. A potential failure caused by the electrical arc in the superconducting cables joint was identified in the Preliminary Risk Analysis in 1998, but underestimated with respect to its consequences [2]. The maximum breach cross-section enabling the helium flow to the vacuum space has been assumed as equal to 5 cm^2. The resulting diameter of the safety valves (SV) protecting the vacuum vessel has been calculated to be of DN90 mm. The SV valves have been located at each LHC cell with the pitch of 107 m – Figure 1. During the 19th September 2008 incident the helium was discharged from the magnet cold-mass to the vacuum space through the total cross section of about 166 cm^2, instead of assumed 5 cm^2.

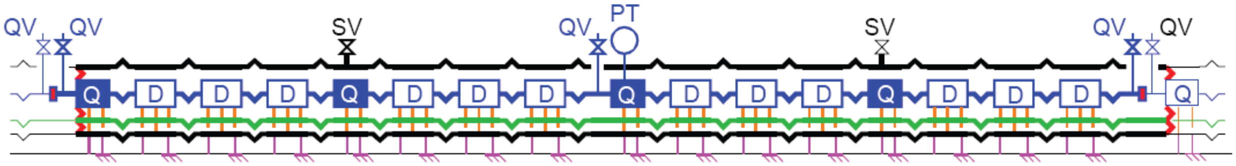

Figure 1. Original (prior to 19th September 08 incident) SV scheme, D – dipole, Q – quadrupole

The underestimated available safety valves cross-section has caused pressurization of the vacuum space to about 8 bar, resulting in severe direct and collateral damages. To avoid similar damages resulting from potential faulty electrical joint creating the electrical arc in the future, the maximum credible incident (MCI) has been redefined and assumed as a full cut of the interconnecting pipes in-between two magnet cold masses, taking into account a limiting factor which is the available free cross-section for longitudinal flow in the magnet cold-mass lamination, limited to about 60 cm^2.

MATHEMATICAL MODEL

A mathematical model enabling the calculation of the helium thermodynamic parameters in the cold mass and vacuum space, as well as corresponding helium flows, has been developed. The model is based on the scheme depicted in Fig. 2 and enables the helium parameter simulation from first principles, using a lumped parameter approach – to calculate helium parameters in the cold mass and vacuum space enclosures; and one-dimensional approach – to calculate longitudinal helium flows. The heat flux resulting from the magnet quench $q_{\mathrm{RateQuench}}$ has been scaled with the current from the experimental data registered for a 13 kA quench of the String 1 magnets – Figure 3 [3].

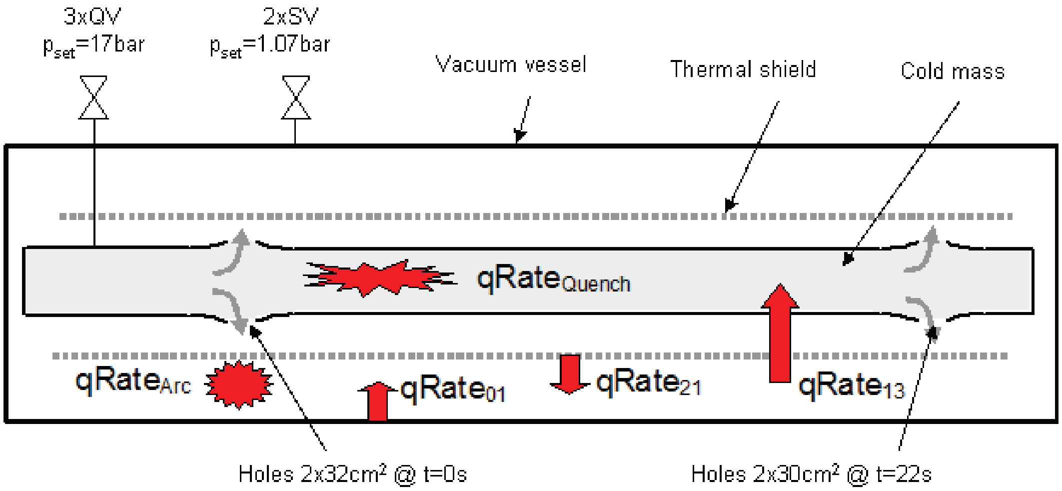

Figure 2. Scheme of the mathematical model describing the helium parameters evolution, $q_{RateQuench}$ – heat transfer from the quenched magnets to the cold mass helium, $q_{RateArc}$ heat transfer from electrical arc to the helium in the vacuum space, q_{Rate01} – heat transfer from the vacuum vessel to the helium in the vacuum space, q_{Rate21} – heat transfer from the aluminum thermal shield to the helium in the vacuum space,q_{Rate13} – heat transfer from the helium in the vacuum space to the cold mass helium

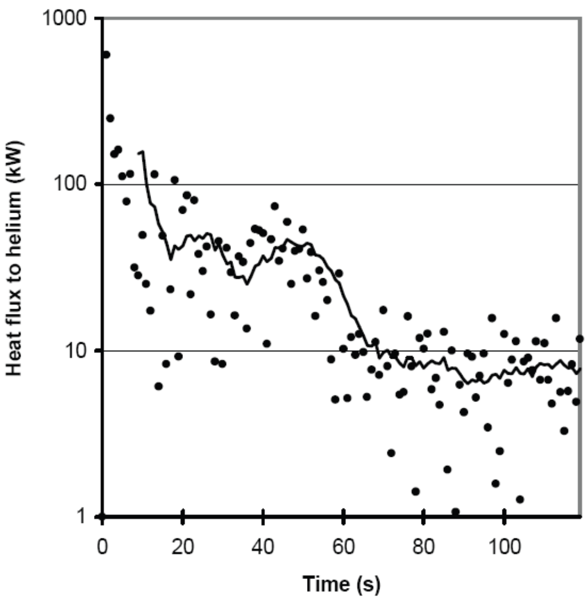

Figure 3. Heat flux transferred to cold mass helium after main dipole quench

Figure 4 shows the arc power resulting from the electrical arc during the 19th September 2008 incident for an initial arc current of 8.7 kA. In the mathematical model, the electrical arc heat flux has been conservatively scaled with the second power of the initial arc current I_{arc} according to Equation (1):

$$Q_{ele\_arc}(I_{arc}) = \left(\frac{I_{arc}}{8.7kA}\right)^2 Q_{ele\_arc}(8.7kA) \tag{1}$$

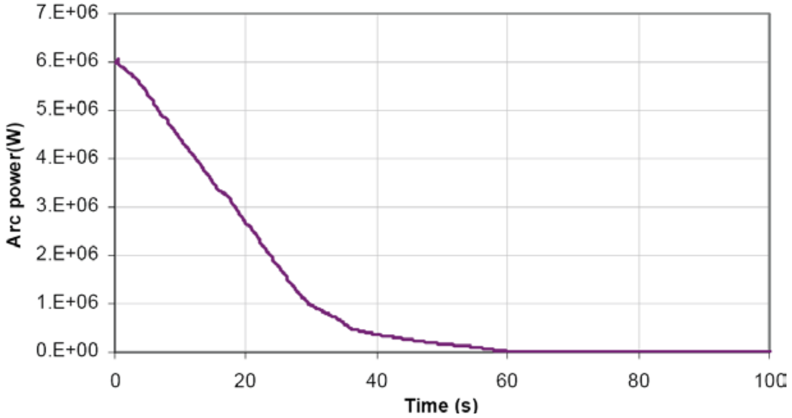

Figure 4. Heat flux resulting from electrical arc during the 19th September 2008 [1]

The scheme of convective heat transfer processes following the breach in interconnecting pipe or cold mass shrinking cylinder is depicted in Figure 5. This way of heat transfer is observed from the vacuum vessel to the helium in the vacuum space (q_{Rate01}), from the aluminium shield to the helium in the vacuum space (q_{Rate21}) and from the helium in the vacuum space to the cold mass helium (q_{Rate13}).

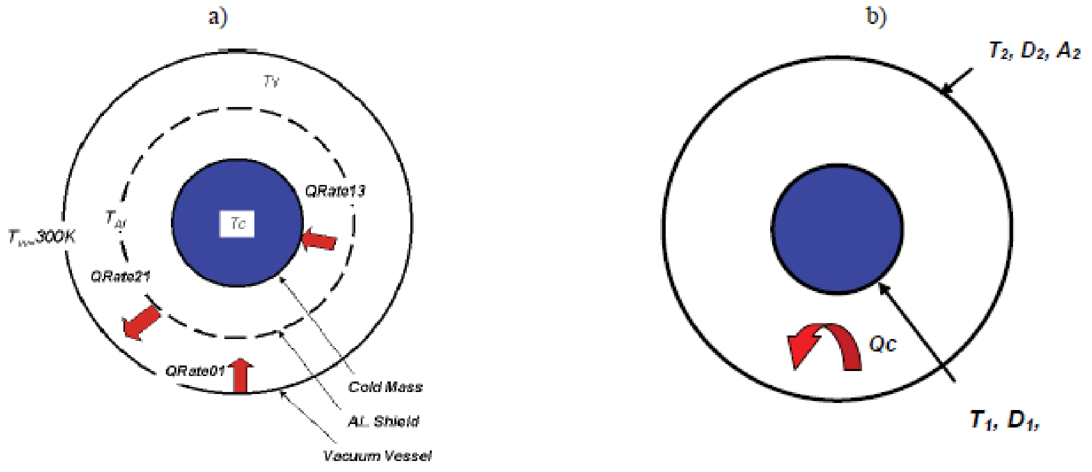
a)
b)

Figure 5. Scheme of the gas heat transfer in the LHC cryostat vacuum space – a, natural convection in a circular channel – b

The heat transfer between the helium filling the cold mass or vacuum space and the magnet construction element (vacuum vessel, aluminium shield, shrinking cylinder) have been assumed to be governed by natural convection mechanism – Eq. 2. In reality, due to the longitudinal helium flow, the process must lay somewhere between the natural and forced convection, hence the heat transfer coefficient h_c calculated for natural convection has been increased to fit the experimental data.

$$h_c = \frac{Nu \cdot k_{He}}{L} \tag{2}$$

where: Nu – Nusselt number, $L=D2 - D1$ – characteristic length, k_{He} – helium thermal conductivity.

The Nu has been calculated with respect to the adequate heat transfer conditions (suppressed or cellular motion, turbulent flow) and the model tuning, as described in [4], has been performed on the basis of the cold mass helium pressure evolution measured during the 19th September 2008 incident. A perfect match of the measured and calculated peak pressure value have been obtained for the free convection heat transfer multiplication coefficient f of 1.6, what justifies the assumption that the conditions of heat transfer process are in-between natural and forced convection – see Figure 6.

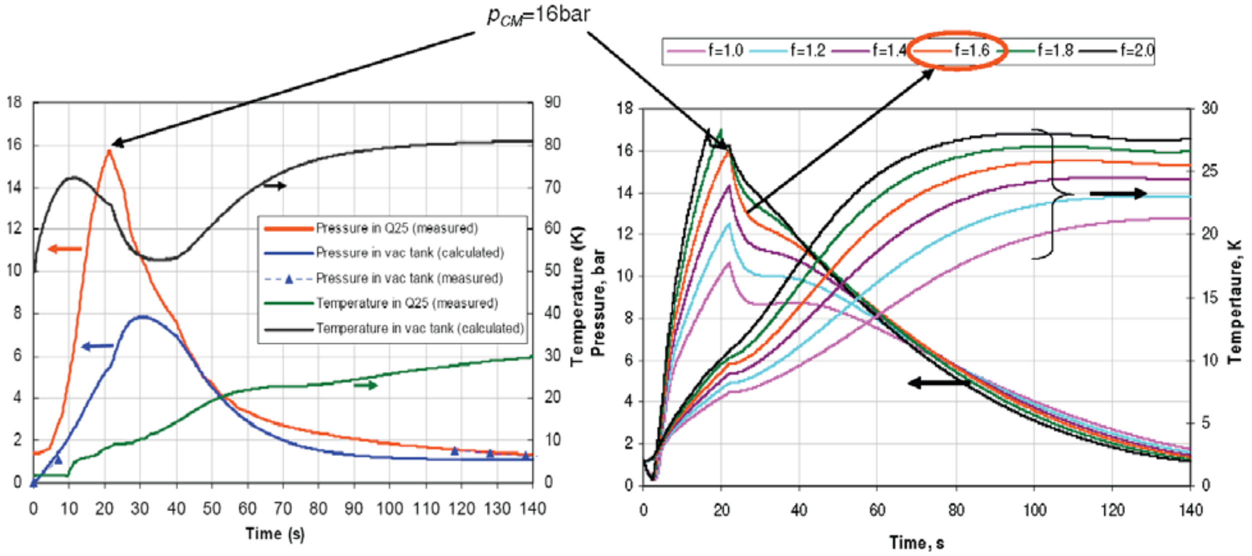

Figure 6. Model tuning by adjusting a free convection heat transfer coefficient, f – multiplication coefficient, experimental data – left, modelling results – right

MODELING OF THE 19TH SEPTEMBER 2008 INCIDENT

The model has been validated by the reproduction of the helium parameters following the 19th September 2008 incident. The comparison of modelling results with the directly (cold mass pressure, cold mass temperature) and indirectly (vacuum space pressure, vacuum space temperature) measured helium parameters evolution is given in Figure 7.

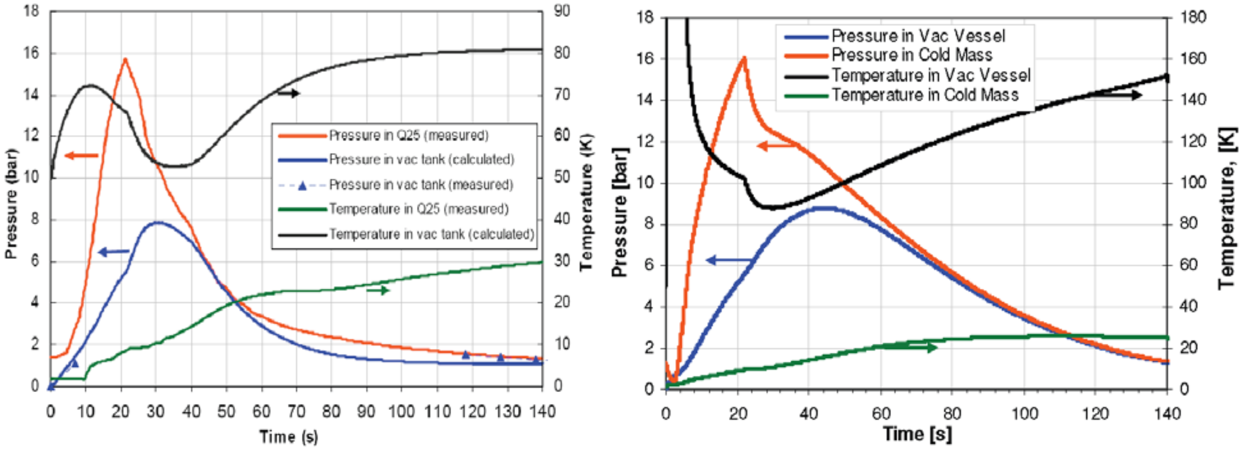

Figure 7. Measurements (left) and modelling (right) of the 19th September 2008 incident

The calculated pressure profile is in good accordance with the measured curve and some minor differences can be explained as follows. The change of slope of the measured pressure curve visible in the time instant of 40 s can be caused by further collateral damages and new breaches in the vacuum bellows of the interconnection region which have not been taken into account in the model calculations. A visible cold mass pressure drop in-between the origin of the breach of the interconnecting pipes in the calculated curve and not confirmed by the measurements (a slow pressure increase from the beginning, change of slope after the half-cell quench), can be explained by the assumption of instantaneous cut of the interconnecting pipes and the supposition that the arc heat is transferred to the vacuum space helium only. The measured delay in the increase of the cold mass temperature is most probably caused by the adiabatic compression of the helium following directly the magnet resistive transitions energy dissipation, according to two-volume thermo-hydraulic model described in [3]. The modelled maximal vacuum space helium pressure exceeds 8 bar and corresponds to the pressure estimated from the observation of mechanical damage of the vacuum barrier bellow. The modelled evolution of helium temperature in the vacuum space (Figure 9, right) differs significantly from the data shown in Figure 9 (left), but the parameter has not been measured and mere calculated with a simplified approach [1].

Figure 8 shows a parametric analysis of the vacuum-enclosure pressure evolution following redefined MCI and for different number of DN200 safety valves added to protect a sub-sector. To avoid over pressurization of the vacuum space at least 8 DN200 valves should be added in-between the vacuum barriers, at the length of 214 m.

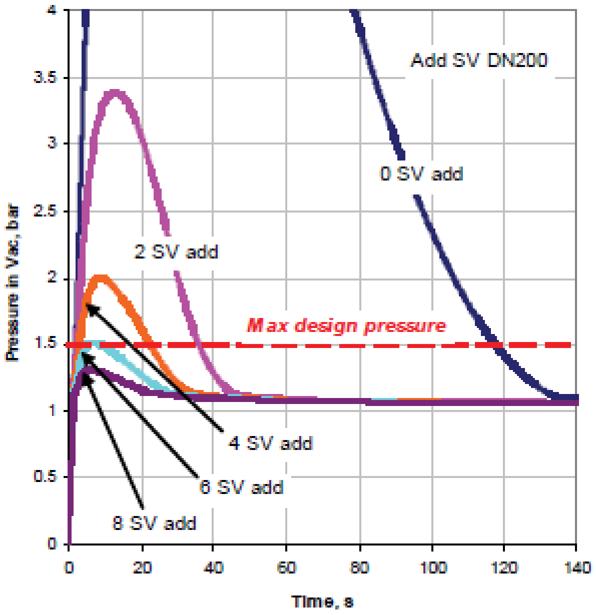

Figure 8. Helium pressure evolution in vacuum vessel for different number of additional DN200 SV per sub-sector

CONCLUSIONS AND RECOMMENDATIONS

The consequences of the redefined Maximum Credible Incident for the LHC cryogenic system have been modelled, enabling a proper scaling and configuration of the vacuum vessel safety valves. It has been assumed that the mechanical destruction of the interconnecting pipes according to the MCI has been accompanied by simultaneous occurrence of the following events:
– full break of the pipes resulting with the total area of the holes: 2 x 60 cm^2 = 120 cm^2,
– simultaneous quench of two cells (16 magnets) at the current of 13.1 kA.
The modelling enabled the formulation of safety valve scheme corresponding to the re-defined MCI (Figure 9) and temporary scheme, acceptable for low energy runs only (Figure 10).

The last issue was to specify protective means against the tunnel pressurization in case of relevant helium leakage. The helium of low temperature (about 160 K after 140 s – compare Figure 7 right) after leaving the vacuum enclosure, suddenly came into contact with “hot” tunnel walls, which temperature can be assumed to be of about 300 K. In the wake of it helium masses rapidly expanded. Consequently, its volume dramatically increased by the factor up to 2 orders of magnitude. The phenomenon can be expressed in terms of volume production and helium leakage can be considered as a volume source. When some amount of volume is released into confined space it causes a pressure rise. This can be dangerous if confinement walls can’t withstand the developed pressure. Such phenomenon is known as “physical explosion". During physical explosion no exothermic reaction takes place and pressure rise is basically a consequence of phase transition or cold gas expansion. The tunnel pressurization up to about 1.3 bar resulting from about 6-ton helium discharge has been a static process and no blasting has been observed. The recommendations concerning the mechanical properties of the doors installed in the tunnel have been formulated. To avoid the tunnel pressurization, self-opening doors or dedicated safety devices should be installed.

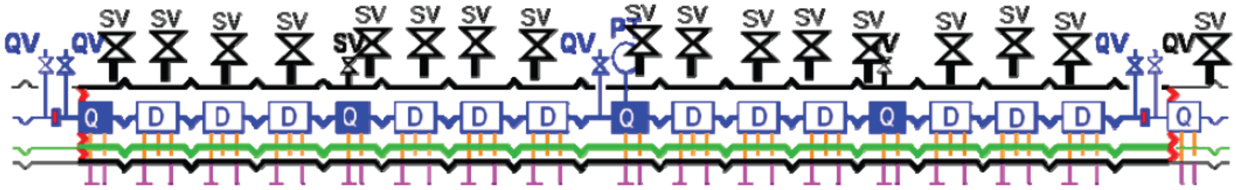

Figure 9. Verified SV scheme compatible to re-defined MCI

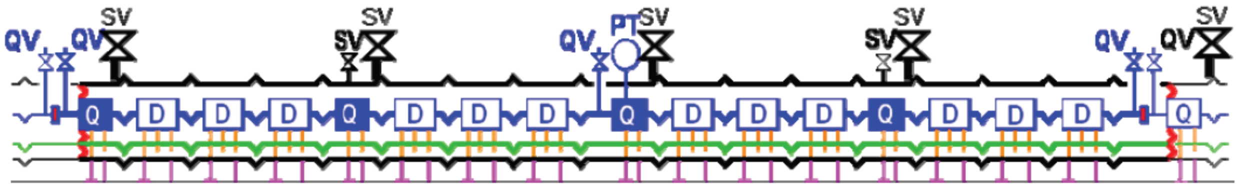

Figure 10. Temporary (acceptable for low energy runs) SV scheme

ACKNOWLEDGMENTS

This work was supported by CERN under the Agreement No. K1619. The authors would like to thank Philippe Lebrun and Antonio Perin for remarks and discussions.

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