

BEAM INDUCED DAMAGE – WHAT IS A SAFE BEAM?

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Abstract

The knowledge of damage levels is vital to define protection schemes, beam loss monitor thresholds, safe beam limits for setting up the machines, etc. This talk will try to revisit our present knowledge and assumptions on damage levels in the LHC in terms of lost beam intensity, beam momentum and emittance. It is clear that with the LHC's unprecedented energy reach, benchmark tests to cross-check energy deposition simulations for all possible energies before LHC start-up have not been possible. Also, the definition of when equipment is damaged is not always straight forward. In view of the obvious limitations to our knowledge of damage levels, operational commissioning and LHC running strategies will be re-discussed, open questions will be highlighted and proposals will be presented where possible.

INTRODUCTION

A prerequisite for the assessment of the damage potential of the LHC beams is the knowledge of the levels for beam induced damage of different equipment. With the current assumptions on damage levels and hence damage potential of the LHC beams, protection thresholds and beam commissioning strategies have been defined. A key concept of the LHC machine protection strategy is the LHC Safe Beam Intensity. This is an intensity limit below which equipment can be set up with relaxed machine protection constraints, for instance maskable user inputs to the beam interlock controllers can be masked. What is the basis of the definition of the LHC Safe Beam Intensity Limit?

MATERIAL DAMAGE LEVELS AND DEFINITION OF THE LHC SAFE BEAM LIMIT

In 2004 an experiment was carried out to study the effect of transient beam loss with LHC type beam on matter. The experiment is known under "TT40 material damage test" [1]. In view of the abundance of metal close to the beam in the LHC, the 30 cm long damage test target consisted of different metal plates (different stainless steel types, Cu, Zn), see Fig.1. The target was installed in TT40, a part of the TI 8 transfer line between the SPS and LHC Ring 2, see Fig. 2. Four intensities were extracted from the SPS onto the target. The chosen LHC beam intensities are summarised in Table 1. Damage was classified as "clear sign of melting". A typical example of one of the Cu plates after the irradiation can be seen in Fig. 3. The locations of the four intensities on the plates are indicated there as well.

Table 1: Intensities extracted onto the TT40 Material Damage Test target.

Intensity	# protons
A	1.3×10^{12}
B	2.6×10^{12}
C	5.3×10^{12}
D	7.9×10^{12}

Intensity A did not create any reaction on Cu plates. The conclusion of the test hence was that an intensity of 1×10^{12} protons lost at 450 GeV is safe. The simulations showed that this intensity corresponded to a maximum temperature in the Cu plates of $\sim 500^\circ\text{C}$, about a factor 2 below the melting point of Cu.

The result of the TT40 Material Damage Test was then used to define the LHC Safe Beam Intensity Limit [2]. At 450 GeV it is therefore $1 \times 10^{12} p^+$ for nominal

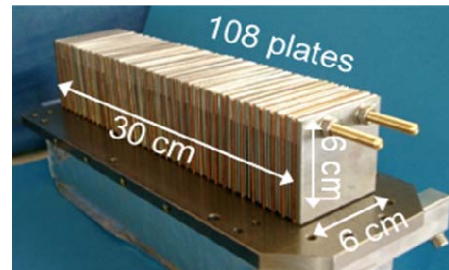


Figure 1: TT40 Material Damage Test target. 108 plates of different metals.

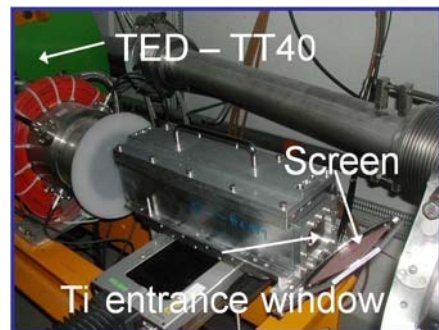


Figure 2: TT40 Material Damage Test target installed in TT40 enclosed in its Al confinement.

emittance. FLUKA simulations were used to find the scaling law for the dependence of the Safe Beam Limit on energy and emittance reduction. The derived scaling law for the peak energy deposition in Cu is $E_{\text{deposition}} \propto E_{\text{beam}}^{1.7}$ [3]. With the scaling law and the Safe Beam Intensity at 450 GeV, it could be defined for any intensity, see Fig. 5. For instance the Safe Beam Intensity at 7 TeV is 1×10^{10} protons.

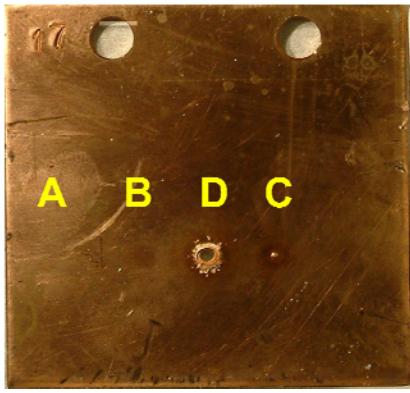


Figure 3: One of the Cu plates of the TT40 Material Damage Test target after the irradiation. Intensities D and C show clear sign of melting and even creation of holes. The impact location of intensity B shows signs of decolouration, whereas intensity A does not seem to have altered the material.

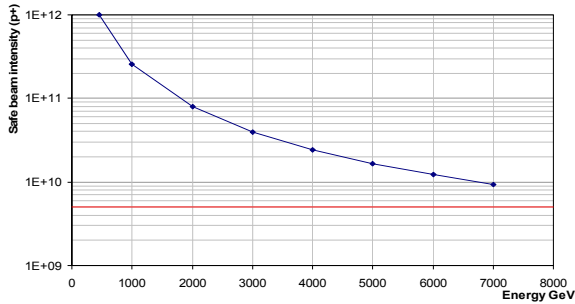


Figure 5: Assuming 1×10^{12} protons at 450 GeV to be safe at 450 GeV results at 1×10^{10} protons being safe at 7 TeV. Courtesy B. Goddard

DISCUSSION OF THE LHC “SAFE” BEAM LIMIT

Damage is not necessarily Melting

Damage at the TT40 Material Damage Test was defined as clear sign of melting. Transient heat deposition can however damage materials well below the melting point. Thermo-mechanical stress levels have to be taken into account. A typical example is Carbon-Carbon, the material of the LHC secondary collimators. Worst case impact scenarios on a collimator at 450 GeV and 7 TeV were studied with FLUKA. The energy deposition results were then used with ANSYS. During the impact scenario of a 7 TeV asynchronous beam dump the collimator would reach a maximum temperature of 551° C, a factor 7 below the material’s melting point. The material is however at the limit of its allowable stress. It reaches a stress level of 82 MPa, where the allowable stress is 86 MPa [4].

Materials are part of Equipment

The TT40 robustness test of the LHC secondary collimator demonstrated another important fact which has to be taken into account when assessing damage levels.

Materials are part of equipment and an ensemble of materials might have a lower damage level than the individual one. During the TT40 robustness test of the LHC secondary collimator in 2004, a collimator installed in TT40 was irradiated with an LHC full intensity injected batch (3.2×10^{13} protons) simulating a worst case injection error. The Carbon-Carbon collimator jaw survived as predicted. The Cu backplane reached 70° C. And this was enough to permanently deform the support bar – and with it the whole jaw - by a peak deformation of $\sim 300 \mu\text{m}$. This is outside the allowed setting-up tolerances of the LHC collimator jaws. (In the meantime Cu has been replaced by GlidCop® to avoid this effect in the future.)

Tungsten

The third weak point of the current Safe Beam Intensity concept is that is based on data obtained for Cu only. The tertiary collimators close to the experiments are made of tungsten [5] which has a higher Z value than Cu. Losing beam on a tertiary collimator was studied with FLUKA, assuming transient beam loss at top energy and worst case impact parameters:

- 5 mm impact parameter
- impact angle and beam sizes according to optics in point 5 fully squeezed and unsqueezed for different emittances ($1 \mu\text{m}$ to $3.5 \mu\text{m}$)

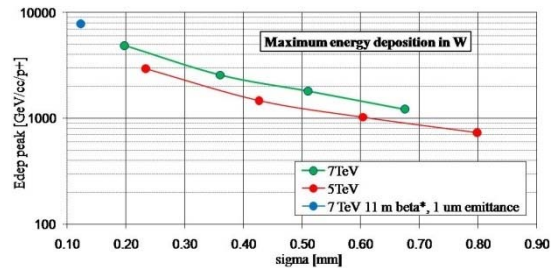


Figure 6: Peak energy deposition in a tertiary collimator for the parameters given above for 7 TeV squeezed (different emittances) and unsqueezed beam.

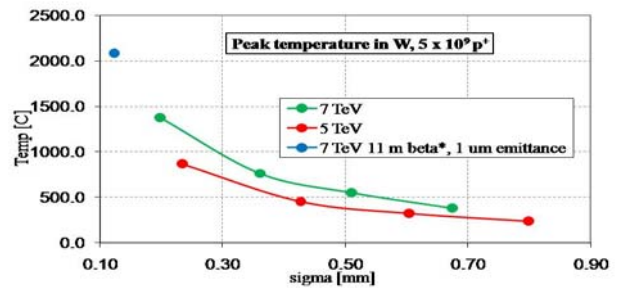


Figure 7: Peak temperature in a tungsten tertiary collimator for impact of pilot bunch.

The peak energy deposition in tungsten for the cases described above is shown in Fig. 6 and energy deposition

converted into peak temperature rise for an impact of one pilot bunch is shown in Fig. 7. In the case of a loss of a pilot bunch with unsqueezed optics at 7 TeV, the peak temperature would be more than 2000° C. This temperature is still below the melting point of W (3422° C). However, the shock waves travelling through the material caused by such a temperature increase within a few ns are most certainly non-negligible. The results of Fig. 6 were used to calculate the intensities required to reach the melting point in the tungsten part of the collimator, see Fig. 8. For unsqueezed optics losing 1×10^{10} protons at 7 TeV is enough. This number corresponds to the Safe Beam Intensity Limit at 7 TeV. The Safe Beam Intensity Limit is thus not necessarily safe for tertiary collimators.

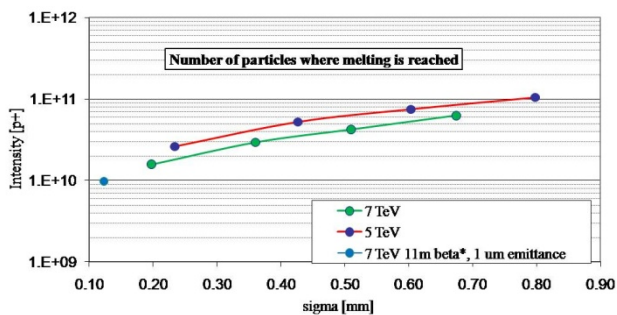


Figure 8: Number of particles required to reach melting point in W jaw.

Discussion

The usefulness of the LHC Safe Beam Concept with all these arguments from above not taken into account might seem doubtful. In summary it means that the LHC Safe Beam Intensity is not safe under all conditions. Still, the concept is not rendered useless. An intensity limit below which beam based interlock thresholds can be derived with beam without enabling the interlocking functionality is essential for collimators and absorbers. It is also essential for MD-like situations where apertures and optics are measured. Setting up the LHC would be practically impossible without it. Also, this intensity limit cannot be chosen arbitrarily low. Below pilot intensity (5×10^9 protons) the LHC beam instrumentation does not trigger anymore. The LHC Safe Beam Intensity at 7 TeV can thus not be much below what has been specified already. However to avoid confusion and carelessness in the future it is proposed to change the name from “Safe Beam Intensity” to “Set-up Beam Intensity”. For the rest of document the name Set-up Beam Intensity will be used.

PROTECTION DEVICES

For the design of the protection devices, definition of beam loss monitor thresholds and operational limits for some equipment (e.g. wire scanners and OTR screens), the damage limits of the equipment in question taking all

the arguments from above into account must be known. In some cases these limits are well-established, for example for the magnets in the transfer lines. Masks downstream of the transfer line collimators TCDI had to be introduced to protect the magnets from the collimator showers [6]. The damage limit of the magnet coils is 100° C. The masks are designed such that the magnet coils stay below this limit under all possible loss scenarios on the collimators.

A similar situation – a protection device being followed by a mask in front of the magnet downstream of the protection device – can be found in the LHC. For example, the TDI in the injection region is followed by the mask TCDD in front of the magnet D1 [7]. Another example is the absorber TCDQ in the dump region, followed by the mask TCDQM in front of the magnet Q4 [8]. The difference to the transfer lines is that the magnets in question are superconducting.

DAMAGE LEVELS OF SUPERCONDUCTING MAGNETS

How well are the damage levels of superconducting magnets known for transient beam loss? Are there different limits for different types of magnets, e.g. main bends and triplet magnets?

In the LHC project note 141 [9] a number for the damage limit of superconducting coils is calculated. The damage limit according to this evaluation corresponds to an energy deposition of $\Delta Q = 87 \text{ J/cm}^3$. Also an estimate for how many protons would have to be lost locally to damage is given in this note. For injection energy they predict 2.3×10^{12} protons and at top energy (7 TeV) 6.7×10^{10} protons. Note that these numbers are consistent with the results of the TT40 Material Damage Test and extrapolation to 7 TeV and are slightly above the Set-up Beam Intensity.

87 J/cm^3 has been used as damage limit for the design of all protection devices protecting superconducting elements. It is the assumed damage limit of the superconducting D1 for the design of the mask TCDD [7] and the assumed damage limit of the superconducting quadrupole Q4 for the design of the mask TCDQM [8]. Superconducting magnet experts at CERN, however, admit that no work has been carried out on the problem of transient beam loss and the reaction of the superconductor and that they can hence not comment on this number of 87 J/cm^3 . Damage limits of superconducting coils for steady state heat depositions are known [10]:

Table 2: Damage limits of superconducting magnets for steady state heat deposition.

Temperature [°C]	Component showing degradation	Effect
~ 180	Kapton	Mechanical degradation
~ 220	SnAg solder	Cross-contact

	material	resistance of strands degrading
~ 350	NbTi	Current carrying capacity degrading
~ 350	Kapton	Dielectric degradation
~ 800	Cu	

The temperature limit of $\sim 350^\circ\text{C}$ from Table 2 only has a degrading effect on the superconductor NbTi if it is exposed to this temperature for several days. It is not clear in general how and whether these numbers can be used to define damage limits for transient heat deposition in the time scales of μs . The effect of shockwaves for example has not been addressed at all.

As the design of protection devices has been based on this number of 87 J/cm^3 , it should be at least clarified whether this number can be regarded as conservative as most of the experts seem to indicate. In case the opposite is true the LHC protection systems might not be adequate. As a side remark, the number seems to be very low. The energy stored in a pilot bunch at 450 GeV is already 360 J.

Experimental verification of beam induced damage of superconducting magnets should be considered. The TT60 HiRadMat, a High Power Beam Test Facility [11], could address these questions. The objective of this test facility is to foster basic understanding of beam-induced shock waves in standard and advanced materials. The irradiation of a whole superconducting magnet could be envisaged, if possible even cooled.

SIMULATIONS OF ENERGY DEPOSITION IN SUPERCONDUCTING MAGNETS FOR TRANSIENT BEAM LOSS

Simulations have been carried out with Geant 4 to predict how much energy would be deposited in the superconducting coil of a main dipole magnet in case beam was lost with an impact angle of $250\ \mu\text{rad}$ in the horizontal plane [12]. This angle corresponds to the impact angle of the beam trajectory leading to the first beam induced quench in a main dipole during an injection test. Fig. 9 shows the results in mJ/cm^3 in different radial bins of the superconducting coil for 450 GeV. The energy deposition has been calculated for point-like losses and also for the more realistic case of distributed losses. The very small impact angle of $250\ \mu\text{rad}$ and a beam size of 1 mm lead to a longitudinal loss distribution corresponding to Fig. 10. The sigma of this distribution is about 4 m.

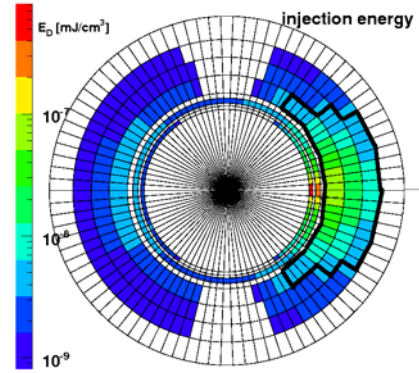


Figure 9: Energy deposition for point-like loss, impact angle of $250\ \mu\text{rad}$, in a main dipole magnet at 450 GeV.

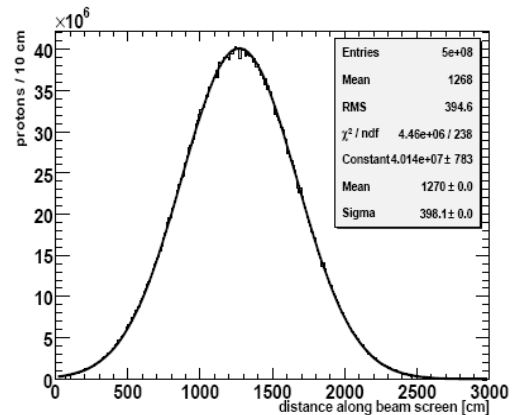


Figure 10: Longitudinal loss distribution for horizontal impact angle of $250\ \mu\text{rad}$ and beam size of 1 mm.

The results of the simulations are summarised in Fig. 11 for injection energy and Fig. 12 for 7 TeV, showing the energy deposition in different radial bins and the maximum closest to the cold bore for point-like losses and in dashed-line for distributed losses. The energy deposition per primary proton for distributed losses is about a factor 20 below the maximum of the energy deposition due to a point-like loss.

Assuming a point-like loss of the Set-up Intensity at 450 GeV, as the extreme case for very local losses, the maximum energy deposition in the superconducting coil would be about 150 J/cm^3 . This is already almost a factor 2 above the assumed damage limit of a superconducting coil (damage limit 87 J/cm^3). In case of a point-like loss of the Set-up Intensity at 7 TeV, the maximum energy deposition would amount to 50 J/cm^3 , slightly below the damage limit.

The energy deposition in the cold bore was also calculated. The results are shown in Fig. 13 and Fig. 14.

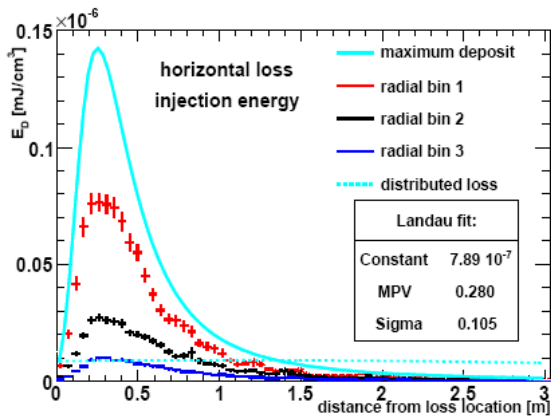


Figure 11: Energy deposition for point-like loss and distributed loss per primary proton at injection energy.

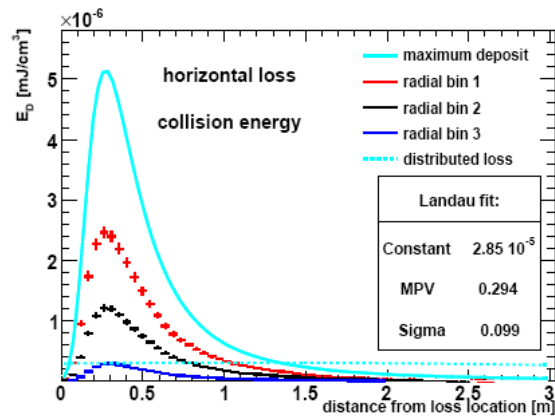


Figure 12: Energy deposition for point-like loss and distributed loss per primary proton at 7 TeV.

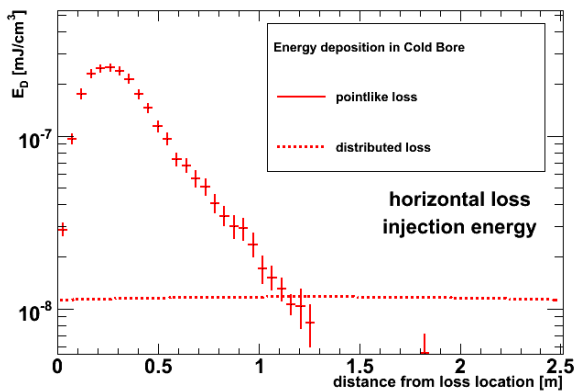


Figure 13: Energy deposition for point-like loss and distributed loss per primary proton at injection energy in cold bore.

From Fig. 13 and Fig. 14 it can be seen that for distributed losses the energy deposition in the cold bore stays about the same level for several meters. Assuming stainless steel 316 L (melting point 1398°C) the temperature rise in the cold bore can be calculated for a distributed loss of a full injected batch (3.2×10^{13} protons).

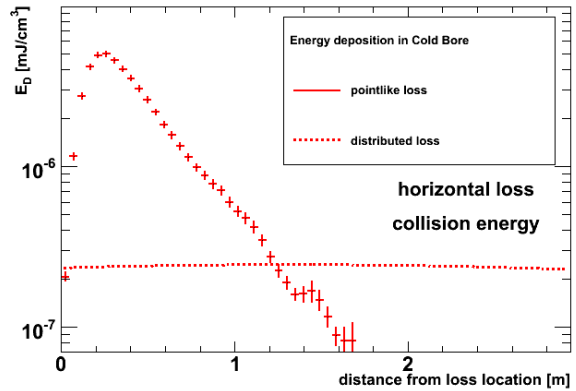


Figure 14: Energy deposition for point-like loss and distributed loss per primary proton at 7 TeV in cold bore.

The temperature rise would be $\sim 2100 \text{ K}$ over several meters. Even though such a scenario is very unlikely to happen with our present scheme of protection, it is not unconceivable [13]. The impact on He flow into the beam vacuum and such like has not been investigated yet. Also, the estimates for the energy deposition are very sensitive to impact angles, details of the geometry and aperture model. The results therefore have to be taken as preliminary numbers. More studies with more realistic assumptions are underway. The FLUKA model of the dispersion suppressor in IR7 originally set up for collimation studies will be used for that purpose.

SUMMARY

A change of name of the LHC Safe Beam Intensity Limit is proposed to account for the fact that this intensity limit is not safe under all conditions. The new name shall be Set-up Beam Intensity. The values for the Set-up Beam Intensity have been derived from the TT40 Material Damage Test in 2004 for 450 GeV and extrapolated to 7 TeV using FLUKA. The derived intensities are consistent with numbers derived from analytical calculations of the damage limit of superconducting coils.

The only damage limit number for transient beam loss available for superconducting magnets has been calculated analytically and is 87 J/cm^3 . The design of the LHC elements protecting superconducting magnets are all based on this number. There is no experimental verification for it. Simulations and possible experiments should be envisaged. The TT60 HiRadMat, high power beam test facility, has been mentioned as one possibility to study damage levels of superconducting magnets.

Geant 4 simulations of the energy deposition during transient beam loss in a superconducting coil of an LHC main dipole have been carried out for point-like and distributed losses. With the extreme case of point-like losses of intensities corresponding to the Set-up Beam Intensities, the assumed damage limit of 87 J/cm^3 is reached (at injection energy) or almost reached (at 7 TeV). In case of distributed losses the loss can occur over several meters. Thus for losses of large enough

intensities, holes of several meters could be cut into the cold bore. Preliminary numbers have been given. As the results are very sensitive to impact parameters and aperture models, more detailed studies will have to be carried out.

RECOMMENDATIONS

For some equipment damage limits are well-established. For others like the injection kickers, RF cavities, superconducting magnets it is less the case. Also, damage levels are not straight forward to derive, shock waves and phase transitions in the material have to be taken into account. Experimental verification is very useful in this regard but might not necessarily be possible any more.

In view of the lack of a full picture of damage levels and the fact that even pilot intensity at 7 TeV cannot be regarded safe under all conditions, no beam should be considered safe at top energy. Only going to 5 TeV will not significantly change the picture. Certain precautions have to be taken to commission the LHC for nominal intensities: avoidance, minimisation of consequences and continuous follow-up.

Avoidance: The agreed operational envelope (intensity, emittance, energy) has to be respected at every stage of the commissioning. Every effort has to be made to avoid operational errors using RBAC, the management of critical settings, sanity checks, etc. Commissioning procedures have to be thoroughly prepared and followed.

Minimisation of consequences: The passive protection system has to be set up as early as possible. Even if beam cleaning is not an issue yet, the collimators should be used as passive protection devices. Every new commissioning step should first be carried out with pilot intensity. Enough spares should be available. Minimisation of collateral damage should be envisaged (pressure relief valves, etc.).

Continuous follow-up: Any occurring problem during commissioning and beam operation has to be analysed and understood before carrying on. Post mortem analysis and post operational checks (XPOC, etc.) have to be taken seriously.

ACKNOWLEDGEMENTS

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