2012
22nd International Lightning Detection Conference
2 – 3 April • Broomfield, Colorado, USA
4th International Lightning Meteorology Conference
4 – 5 April • Broomfield, Colorado, USA

LIGHTNING SAFETY OF HIGH CONSEQUENCE FACILITIES AND PRODUCTS

D Newton, M Jones*, J Pottage
AWE Aldermaston, Berkshire, UK

ABSTRACT

It has long been the tradition that safety (with the attendant minimisation of costs and complexity) should be built into facilities and products from the start of any design and development process and lightning safety falls very much into this category. It is of particular importance when the products, and the contents within such facilities, have a potential susceptibility to lightning strike and where failure is deemed unacceptable. However, not only should the safety rationale be laid down and agreed early but that it is maintained during the inevitable changes that will occur during the design, development, production and maintenance phases. Ensuring that this is effectively done for a complex facility, where many organisations with different interests are involved, requires close integration /communication amongst the various players. For example an 'improvement', as seen by a civil engineer or a facility manager, may well turn out to be detrimental to lightning safety. The message here is that the lightning protection experts need to be closely embedded into the facility or product over its lifetime.

This paper sketches out the lightning safety rationale laid down for a major high consequence facility which is based not only on international recognised standards but additionally on the enhanced requirements expected of a high consequence nuclear facility. It further identifies some of the changes that needed further assessment during the design and construction phases. In addition the paper covers some of the theoretical work that has been undertaken to get a better understanding of the processes that occur when high consequence products are struck by lightning.

1. LIGHTNING SAFETY RATIONALE FOR HIGH CONSEQUENCE FACILITY

At the early stages in the development of a High Consequence Facility, (concept to Initial Design), protective safeguards are defined to limit the susceptibility of the components that are to be processed as the inherent protection of the final products will be compromised, (particularly during assembly and disassembly phases).

Typical safeguarding aspects of the facility design would be to minimise the internal electromagnetic environment, ensure that direct lightning attachment to the sensitive assets is not credible, minimise structural damage, and ensure that lightning induced arcing in the high consequence areas are either eliminated or minimised to acceptable limits by defining an adequacy of separation of sensitive components from the facilities conductive structures.

The techniques used in the early phases of the development to determine the adequacy of the safeguards can be a combination of; predictive synthesis, adherence to recognised Codes of Practice, and computational modelling, the latter having importance in the quantification of the expected environmental parameters. The assessment processes used the worst case lightning strike criteria as defined in Section 4 of this paper. On completion of this phase of the development others become involved whose accountabilities include the build-ability, detailed constructional aspects of the facility, and the development of the detailed design. Coordination of this phase with the early phases and the safeguarding development is essential as the defined safety criterion can easily be compromised. Constructional techniques that aid the build-ability can if not fully understood, destroy or defeat the safeguarding design intent. The use of propriety products such as 'Hi-Rib' that is commonly employed by Civil Engineers to aid bonding at concrete pour intersections can provide a conductive path for direct lightning into protected zones. The use of conductive encast products to aid the installation of Plant and Equipment can if either directly or fortuitously connected to the constructional concrete steel reinforcement can lead to an unacceptably high internal electromagnetic environment under direct lightning strike conditions. Furthermore arc penetration distances can be compromised as such components bypass the protective layer of the concrete cover from the construction rebar.

Some typical examples relating to where building requirement had the potential for at least partially undermining the lightning safety rationale are given below:

1.1 Deployment of Hi-Rib

The deployment of Hi-Rib to aid the bonding of vertical concrete joint intersections had to be assessed and the computational model re-run to identify the effects of direct lightning attachment. Modelling of this feature indicated a need to assure during construction that the Hi-Rib component was recessed below the surface concrete and did not protrude beyond the installed structural rebar to preserve the defined safeguarding of the protected area.

1.2 Roof Trusses

Another post concept design being the replacement of structural roof trusses with structural 'I' section columns whereby the need for a dedicated earth bond connection to the structural rebar was questioned. Again it was necessary to re-run the computation model to demonstrate that connecting the bond or removing the dedicated bond had no detrimental effect on the level of protection afforded.

1.3 Fuse Link

A final example being that an air termination system (catenary) with an exceptionally large span which when detail design was developed by the Structural Engineers incorporated a 'Fuse Link' to mechanically protect the support pylons under extreme weather condition, (ice loading, wind, etc). It was subsequently found by modelling that the link's mechanical properties could become compromised by ohmic heating from a worst case lightning strike to the catenary cable. Further analysis showed that this could be mitigated by applying either thick copper plating or hot-dip galvanising to the outer surfaces of the link to provide a low impedance path, with unity magnetic permeability, for the lightning current path. This resulted in a significant reduction in ohmic heating of the device to a level that would not compromise its mechanical properties.

As a consequence of the examples given above it can be seen that it is essential when developing the overall safety theme for such structures that all of the stakeholders are involved in the process. That constructional drawings etc, are of sufficient detail to ensure that Contractor short-cuts/ preferences/quick-fixes are not covertly installed. That constructional detail is appropriately Design-reviewed to assure the safeguarding Design Intent, and that an appropriate level of quality control is applied throughout the constructional phase to maintain the safeguarding features.
All phases of the design, development, construction, and the installation of the required Plant and Equipment must be adequately coordinated to prevent late stage installation defeating early stage safeguarding design intent.

2. PROTECTION OF SENSITIVE ASSETS

3. NATURE OF THE PROBLEM

Not only are sensitive assets protected by the facilities in which they are manufactured and stored but also by their intrinsic design. For example such assets will be enclosed in conducting structures and any potential conducting ingress into such structures should have protection through combinations of surge arresting devices, faraday cages, screening and insulting barriers. However, such 'external' faraday / conducting barriers may well, of themselves, sustain damage from the direct lightning attachment. The damage assessment will depend on structure design and on the scale of the lightning attachment – noting that the flash may consist of a number of strokes. As such it is necessary to scope damaging effects and the related potential vulnerability of sensitive internal components.

4. WORST CASE STRIKE CRITERIA

There are a number of sources available for specifications for 'worst case' lightning assessment. For example BS EN 62305-1:2006 (Protection against Lightning) provides the following data:

1st negative short stroke – IPeak 200kA (99% of strokes lying below this value)
Q Flash 300C
dI/dt 20kA/µs
In fact only 0.1% of strokes have a peak value of >326kA.
Subsequent negative worst case short stroke:
IPeak 50kA
In fact only 0.1% of strokes have a peak value of >26kA.
dI/dt 200kA/µs
Long Stroke or follow-on current:
QLong 200C
TLong 0.5s

Figure 1 shows a typical lightning flash profile applied in the damage assessment undertaken below. It contains a first negative short stroke, a subsequent short stroke and a follow on current.

5. TYPICAL ASSET CONFIGURATION UNDER CONSIDERATION

There are well established standards for protection afforded by simple external conducting structures such as Al to ensure limited or no internal consequence for strokes of the order quoted above. However for items where mass is at a premium and where additional layers are necessary to protect against the hostile environment associated with high speed re-entry into the atmosphere, relatively 'thin' composite structures are necessary.

The 'for example' external structure under consideration here is typical of a re-entry aeroshell. It will consist of an outer heatshield of composite organic materials (of reasonably electrical conducting nature), an inner layer of a good conductor such as A1 alloy coupled with an insulating adhesive interlayer. Typical thicknesses are of the order of 10mm for the heatshield and 1mm, for the inner layer.

The safety concerns for the asset will relate to the degree of physical damage that occurs, the degree of electrical internal coupling that can arise and the resulting thermal and mechanical internal effects.

Electrical coupling can be a concern for sensitive internal items and this concern is enhanced if the outer envelope is damaged to the extent that holes are produced by the stroke. Thermal and mechanical effects may also be important if the stroke gives rise to significant distortions of the outer envelop such that it come into contact with sensitive inner components. In the limit these distortions can manifest themselves as free flying fragments which will lead to impact on internal components.

6. DAMAGE EFFECTS

Although the conducting layer on its own may have an intrinsic capability for dealing with a lightning attachment, it is the insulating adhesive layer which may turn out to be the seat of any damage problem. Current heating of the organic based adhesive can result in a thermodynamic explosion whose pressure may well be sufficient to damage the structure. Because the 'explosion' is sited within the structure, the event is tamped and the weakest layer either side of the adhesive interface will suffer the greater damage. For example, the configuration under consideration here will have a more substantial outer layer and as such the inner conducting layer will sustain the major damage. If this inner layer is deemed the main EM protection element then its capability against follow on strokes might be compromised. In addition, any distortion inwards of this layer may result in contact with internal sensitive circuitry which can be affected by the flowing current. In the limited this distortion can give rise to significant internal impacts, especially if the inner layer fragments. Even if none of these latter effects occurs, a hole in the inner conducting structure can give rise to enhanced internal electrical coupling in the presence of a follow on stroke.

7. THE ANALYSIS

Any approach benefits from both experimental and theoretical elements. The former does test directly but may have limitations in not being able to ideally replicate the worst case because of technical limitations and the approach is also resource intensive. It does have the secondary purpose of benchmarking a complementary, more flexible and less resource intensive theoretical modelling approach. The latter allows assessment over regimes which may prove difficult for experimental coverage and also allows one to carry out parametric and optimisation studies. It is this latter approach which is reported on in this paper.

There are two distinct phases in such an overall analysis.

(1) The estimation of damage that occurs as a result of the initial (worse case) stroke.

(2) The safety consequence of this damage and particularly in association with subsequent strokes.

8. PHASE 1

Experiments have benchmarked the theoretical approach based on the application of an EM MHD code named ALEGRA. The structure is modelled as a heatshield material with reasonable conducting properties and an inner Al alloy layer, with an interfacing adhesive layer. The interface adhesive is one commonly used in such applications. The heatshield is represented by an inter-layered composite with a C framework backbone and phenolic filler.

Typical results are given for profiles for the form shown in Figure 1.

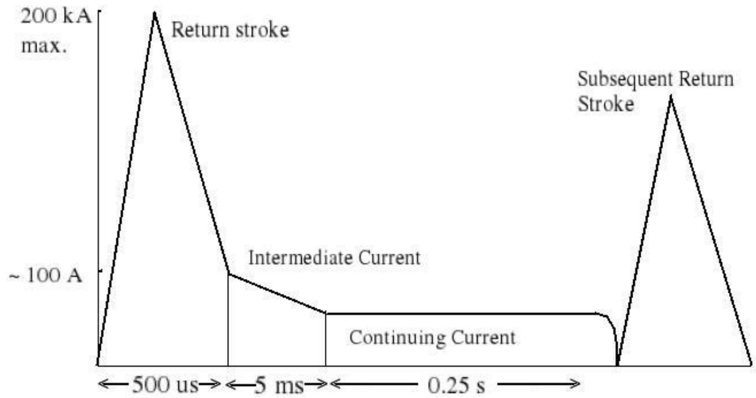

Figure 1: Typical pulse shape. Note: a standard aircraft testing pulse uses a 200kA peak current and a 20 microsecond rise time for the first return stroke.

The analysis shows that there is little damage to the heatshield layer for peak currents up to ~ 200kA and for the Al alloy layer for peak currents up to ~ 50kA (which covers about 95% of typical negative strokes). However, for peak currents approaching 200kA (the 1% stroke level) the damage to Al is more extensive with significant bowing in, and possible fragmentation of the inner Al alloy layer.

The seat of the damage lies in the breakdown and the subsequent thermal explosion in the adhesive layer which produces driving pressures of kb order. The associated EM forces are some 3 orders of magnitude lower and play a minor role. Initial breakdown in the adhesive is caused by the MV/m fields associated with the approaching step leader immediately prior to the occurrence of the return stroke. In fact modelling for the case where breakdown is assumed only to occur as a result of charge build-up (which is insufficient below ~ 80kA), shows damage levels which are greatly enhanced and which are not replicated by experimental results. It is interesting to note that if the adhesive layer is given a reasonable (artificial) degree of electrical conductivity (~10^5mho/m) then the damage is considerably reduced. A 0.1% worst case stroke of 362kA produces qualitatively similar damage to the 1% case. It is worth mentioning that the rise time of first return strokes increases in proportion to the peak current, thus mitigating the mechanical effects of higher currents. The worst case subsequent short stroke produces a similar level of damage to the 1% first stroke. The general analysis shows that the damage is not influenced by the follow on current. In order to assess the affect of potential flaws in the adhesive, a variety of 'air gaps forms' were inserted into the layer at the attachment point. This appears to cause a small increase in Al alloy velocity, but otherwise the results were similar to the non air gap case.

Typical results for the two possible breakdown mechanisms are shown in Figures 2 and 3.

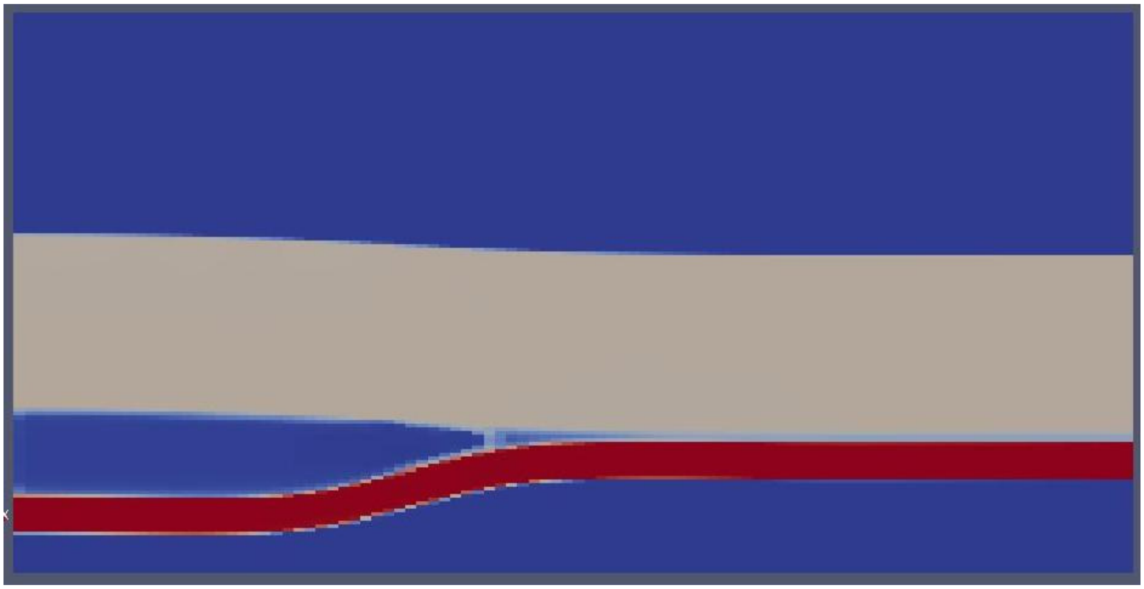

Figure 2: Pre-breakdown of adhesive in external electric field. Peak current 200kA, rise time 20 microsec. Plotted at time 33 microsec.

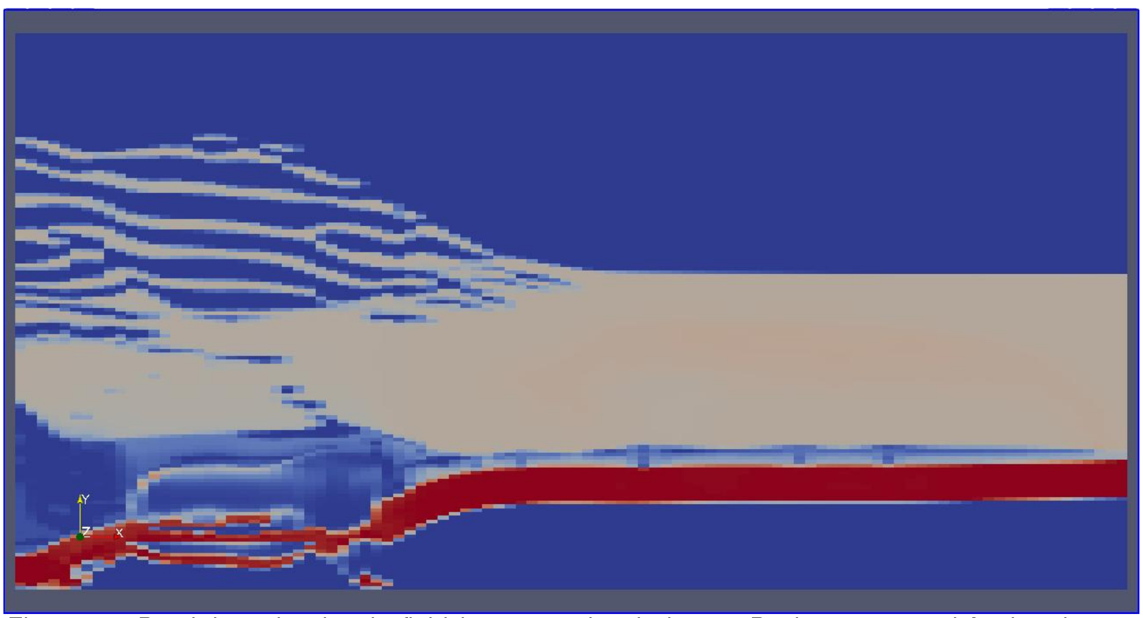

Figure 3: Breakdown in electric field by accumulated charge. Peak current 200kA, rise time 20 microsec. Plotted at time 7 microsec.

9. PHASE 2

Distortion on the inner conducting layer could in principle result in contact with inner components with potential concern relating to mechanical impact, thermal heat transfer or current transfer from that flowing in the Al alloy layer. In fact the damage can result in holes with resultant inward free flying Al fragments. Holes can be typically a few cm^2 with fragments of similar dimensions. The consequence of inward distortions and free fragments obviously depends on the location of and nature of the items that are contacted.

The consequence of a hole produced by the first stroke is of concern because of the potential for enhanced coupling into the interior given a follow on stroke. The consequence will be related to the size of the follow on stroke, its attachment position with respect to the hole, the size of the hole and the position of the hole with respect to internal components.

9.1 Mechanical Consequences

Fragments are expected to have velocities in the few tenths of km/s range with areas of a few cm^2 and masses of no more that a few g. For example, impacts of this nature are unlikely to cause significant response from relatively insensitive energetic materials. This judgement is further strengthened if these materials have some level of protection.

9.2 Thermal Consequences

The temperature associated with the deformed Al alloy will come from two sources, the arc and thermal explosion in the adhesive and the current flowing in the Al. The former has the ability to produce transient and localised temperatures of order 10^4 K, but the current densities observed for the latter (10^8 – 10^9 A/m^2) will not result in significant temperature enhancements. The overall judgement is that the thermal consequence for internal components will not be significant, particularly if internal components are not initially in contact with the Al alloy layer.

9.3 Current Diversion

Diversion of current flowing on the deformed Al alloy layer will only be transferred to underlying items if the distortion is sufficient to make contact with these items. Also, these diverted currents will be associated with the screens of single point grounded circuits.

9.4 Coupling Consequences

If the current flows uniformly on a close conducting surface then there will be no internal field. This will not be true in the region of the stroke impingent because of lack of uniformity and this will certainly not be true if there are holes in the conducting structure. The restive fields generated by current flowing along the Al surface of a typical cylindrical envelope are relatively small ~V/m but the inductive voltage will be of ~kV/m order. Although coupling to internal cabling can take place through both capacitive and inductive coupling, the former effect if very small and the latter is also not significant for intact surfaces with relatively uniform current flow. However, the latter can be more significant in the presence of holes in the Al alloy layer. For example the magnetic field H_E on the surface of a cylinder of radius r with a current of 200kA will be:

$$H_E = 2x10^5/2\pi r = 2.1x10^5 \text{ A/m for r typically of order 0.15m}$$

In turn the field H_I inside the hole is related to H_E by a relation of the form

$$H_I(q)/H_E = \alpha_\beta \beta_1^3/(4\ \pi q^3)$$

Where β_2/β_1 is the ratio of the minor to major dimensions of the hole, q the distance from the centre of the hole and the shape factor α_β varies from >0.1 for β_2/β_1<0.1 to 1.3 for $\beta_2/\beta_1 = 1$. For the typical tares seen in the experimental work a value of $\alpha_\beta = 0.1$ serves for the purpose of giving realistic estimates. With β_1<0.3, and q typically varying between 0.03 and 1m, the field ratio ranges from 1 to $2.2x10^{-4}$ and H_I covers the range $2.1x10^5$ to 44A/m.

In turn the current coupled into a circuit is given by:

$$I = (\mu_0 A/R_c).dH_I/dt$$

With $\mu_0 = 4\pi x10^7$(H/m), circuit resistance R_c typically 250mΩ, circuit coupling area A of order $10^{-3}m^2$ and dI/dt = $2x10^{11}$ A/s (taking the worst case subsequent negative short stroke), I ranges from 1.07kA to 0.23A. In order to comply with the former case, the cable will need to be located very near to the surface with its whole length near to the centre of the hole. Although not impossible, this represents a somewhat unlikely situation. For cases where this does not apply only relatively small currents will be coupled under worse case lightning conditions because of the q^3 relation. In addition typical cables are single point grounded and screened which will lead to further attenuation of the effective circuit current. These currents decrease by a factor of 10 for the worst case negative first short stroke condition.

BIOS

Dave Newton MBE, BSc, CEng, FIET, FIMechE, Atomic Weapons Establishment, Reading Berkshire, United Kingdom, Postal Code RG7 4PR
Fax UK 01189824821, Phone UK 01189826950, email: David.Newton@awe.co.uk
David is a Distinguished Specialist at AWE and Senior Electrical Authority for the Company and has more than 40 years experience at both AWE and Ministry of Defence Establishments.

*Malcolm Jones *(Corresponding Author)* MBE, BSc, CEng, PhD, F Inst P, FSSS, Atomic Weapons Establishment, Reading, Berkshire, United Kingdom, Postal code RG7 4PR.
Fax UK 01189827589, Phone UK 01189855495, e-mail Malcolm.Jones@awe.co.uk.
Malcolm is a Scientific Advisor and a Distinguished Scientist at AWE and has more than 40 years of wide ranging technical experience at that establishment.

James Pottage, MSci, PhD, Atomic Weapons Establishment, Reading, Berkshire, United Kingdom, Postal code RG7 4PR.
Fax UK 01189827589, Phone UK 01189824526, e-mail James.Pottage@awe.co.uk.
James is a Nuclear System Analyst and modeller of radiation transport at AWE.