# Lightning and Electrostatic Charge Effects And Protection Design Approaches For Large Transport Airships

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**ABSTRACT**

Airships are necessarily exposed to the atmospheric electrical environment, which includes electric fields, electrostatic charges, and lightning. Protection from hazards presented by these environments is necessary. One of the main issues is protection of the envelope, which is usually filled with helium. Helium poses special problems in this regard, even though it is an inert gas, because electrical breakdown of helium occurs at about $1/3^{rd}$ the electric field required for air. This means that it is possible to have thunderstorm induced electrical discharges in the helium volume before discharges occur in the surrounding air. Therefore, it is possible to have initial lightning attachment to structures inside the envelope resulting in envelope puncture. It is therefore necessary to include the presence of helium in the lightning protection design.

This paper offers lightning and static electricity protection concepts for a large semi-rigid airship based on simulated lightning tests of simple $1/25^{th}$ scale model envelope enclosures combined with laboratory testing and numerical simulations of thunderstorm electric field interaction with the airship geometry and materials. The relevant properties of helium compared to air are provided based on laboratory testing. A description of how the examples of the scale model laboratory tests of simple helium filled envelope shapes, combined with numerical electric field analyses approach and test results can be used to verify adequacy of protection of a full size airship will be presented, as well as correlated numerical simulations.

Additional concerns related to potential lightning and electrostatic effects on airship propulsion, flight control and electrical and avionic systems will be described, together with approaches with addressing them. Proposed new transport airship certification requirements, adapted from transport aircraft certification requirements, will also be reviewed. Airships and balloons in tethered or free flight have been struck by lightning and have experienced effects of static charge accumulations. Often the details of these encounters have not been fully understood or investigated, and there has been uncertainty as to whether the event was associated with static charge accumulations, or with an actual lightning strike to the envelope. Lightning strikes to tethered airships (i.e. aerostats) seem to have been reported more frequently than have strikes to free flying airships, but this may be only coincidental, or it may be because the free flying airships usually have the option of avoiding thunderstorm (and other electrified cloud regions), whereas a tethered craft may be exposed to whatever conditions pass by. Also, the electric field environments and charge distributions about tethered and non-tethered balloons (for example) may differ, and this may render the tethered variety somewhat more susceptible to lightning strike attachment. More importantly, envelope lightning protection methods that have been successful for (comparatively) small tethered balloons may not be as effective or applicable at all, when employed on larger, free flying airships. Moreover, future airships intended for commercial and/or industrial roles may be more susceptible to lightning and static charge encounters than have present airships utilized for advertising or recreational functions.

**AIRSHIP LIGHTNING EXPERIENCE**

Previous large airships, such as the Zeppelins (Graf, Hindenburg, Los Angeles) contained the lifting gas within balloons within rigid metal frames. When lightning strikes occurred the lightning current entered the metal framework and did little damage to envelope materials. The Hindenburg is a possible exception, where it is believed that an electrical discharge of some sort, either a strong streamer (100's of A) or a lightning strike (1000's of A) flowed within or across the partially conductive fabric and set it afire. A conductive coating had been provided to protect this fabric from degradation due to sunlight. The more ubiquitous advertising blimps seen today usually avoid known lightning conditions and are struck only infrequently by lightning. These are usually equipped with a single conductor routed lengthwise along the top of their non-rigid envelopes. Such an arrangement offers significant protection for small airships, but not for larger ones whose dimensions are larger than the striking distances of some lightning leaders. Since these blimps have had only a minimum lightning protection requirement imposed on them by the certifying agencies [1] and since they are operated largely in fair weather conditions, no attempts have been made to equip them with complete lightning protection. Occasional lightning strikes, and other atmospheric electric field effects have produced pin-holes in envelopes. There are a few reports of more extensive damage, but details of lightning related damage are obscure.

Aerostats electrically connected to earth via conductive tethers have had more lightning strikes due to their longer station-keeping roles in more varied weather conditions. Most of these are no larger than 30 m long, and their envelopes are also protected with single conductors along the centerlines. Sometimes these conductors are elevated from the envelope surface to minimize fire hazards during lightning strikes to the conductors. Being unmanned, there have been no airworthiness certification requirements applicable to aerostats. Sometimes, tethers have been struck and severed, with resultant loss of the aerostat.

In 1999, CargoLifter, GmbH (Germany) began design of a large airship (the CargoLifter CL-160) intended for heavy lift transport for which a Transport Airworthiness Requirement (TAR) was developed by German and Dutch authorities for certification purposes [2]. The TAR was based largely upon US and European requirements applicable to transport aircraft. Due to its large physical size (260 m long, 65 m diameter) this non-rigid airship would require a network of lightning diverters spaced strategically around the envelope to reduce the electric fields within the helium-filled envelope to non-ionizing levels. Development of this had been largely completed by the time the CL-160 project was terminated for financial insolvency [3].

Thus the CargoLifter was intended to be the first airship to be designed and certified to meet airworthiness certification requirements similar to those applicable to modern commercial aircraft. Lightning protection of the non-rigid, helium filled envelope was considered one of the key technologies to be mastered in this project, and a potential impediment to airworthiness certification. The technical challenges related to lightning protection were significant because:

Airship envelope materials are often potentially flammable, especially when exposed to electric arcs. This envelope was to be non-rigid and therefore not provided with a metal framework. The lifting gas (helium) ionizes (i.e. flashes over) at 1/3 the ionization potential of air, meaning that lightning would 'prefer' to exist within a helium volume as compared with air. There has been no legacy (i.e. prior) experience for protection of non-rigid airships this large Damage to the envelope could be catastrophic.

Much of the lightning and static electricity protection development and design work for the CL-160 had been accomplished between 1999 and 2002, when the project was terminated, including a significant amount of lightning protection verification testing, using facilities at Lightning Technologies, Inc. in the US and a new high voltage laboratory at the nearby Brandenburg Technical University in Cottbus, Germany. The lightning protection design for the CargoLifter envelope was essentially complete by the time the project was terminated. The authors of this paper were key members of the CargoLifter CL-160 Lightning and Electromagnetic Effects (EME) protection design team. Since the CL-160 project involved several technical challenges for which legacy data was not available the team employed a combination of laboratory tests of materials and small models with numerical simulation of lightning electric field effects, since it would never be possible to verify the full size airship protection by tests alone. Additional protection was required for electronic control systems and avionics since the airship was to be fully "fly by wire" and would necessitate some unusually long electrical circuits whose exposure to onboard and external electromagnetic environments would be higher than the usual aircraft EMI environments.

One of the technical achievements in the Cl-160 lightning/EME design project was successful agreement of lightning test and numerical simulation results on both 1/65 and 1/25 scale models of the CL-160 airship, which provided confidence that protection designs proved on the 1/25 model (which could be fit into a High Voltage laboratory for test) would be representative of full scale protection design effectiveness, which would have to be verified solely by numerical simulation (and, of course, subsequent flight test in the real lightning environment). This same approach is applicable to other large airships being contemplated today.

## AIRSHIP LIGHTNING ENVIRONMENT

The lightning environment up to commercial aircraft flight altitudes (i.e. 44,000 ft) has been experienced by aircraft for many years and is now well understood and standardized in standards [4] for use in protection design and certification of aircraft. At altitudes from earth to ~10,000 ft most lightning strikes to aircraft also reach the ground. Most lightning aircraft lightning strikes that happen above 10,000 ft are initiated at the aircraft and not all of these reach the earth. The standards referenced above encompass important aspects of the cloud-to-earth and aircraft initiated lightning strikes, including details of the currents, charge transfers and specific energies of lightning currents. These standards are also applicable to airships operating in the airspace occupied by aircraft, i.e. up to ~44,000 ft. What is less similar is the likelihood of a large airship triggering lightning. The large physical size, and also the slower speed, as compared with most aircraft do influence the propensity for triggering lightning (larger air vehicle size and is known to increase the likelihood of an aircraft triggering lightning, and this must also apply to an airship. Also, the slower speeds of airships as compared with aircraft mean that longer times are necessary for avoidance of lightning strike conditions. The standard lightning environment that airships are expected to experience

**Airship Lightning Exposure.** Since early airships operated at low altitudes (i.e. 1000 – 10,000 ft) most of the lightning strikes that an airship will experience will be of the cloud to earth variety. Such flashes usually lower negative charge to the earth and begin with a stepped leader that originates in the cloud and propagates toward the earth. Meanwhile negative charge is repelled from areas beneath the cloud and leader, leaving these areas positively charged, as shown in Figure 1. When the leader approaches within 50m (or so) of the earth, a junction leader originates from the earth and propagates upward to connect with the lightning leader. When this happens, electric charge in the leader is conducted rapidly from the leader to the earth. The rate of charge flow reaches 20,000 A (on average) and above 100,000 A 1% of the time. This is known as the first stroke (or 'return stroke" a misnomer since charge is not in fact returned to the cloud). Once the leader charge has been conducted to the earth, the charge remaining in the cloud flows more slowly to earth in the continuing current which can last up to one second at a rate of several hundred amperes. Negative charges entering the earth neutralize the positive charges in the region below the cloud. The process just described is often repeated several times before all of the charge in a cloud or cluster of cloud charge centers has been conducted to earth. This results in a multiple stroke flash. Most cloud to earth flashes produce 3 or 4 strokes, but as many as 27 have been recorded in a single cloud to earth flash.

If an aircraft or airship is nearby when a lightning leader originates, the leader may attach to the aircraft on its way to earth. In this event, all of the stroke and continuing lightning flash currents are conducted through the aircraft. The same thing would happen if an airship were struck, so that the lightning current would (most likely) enter at an upper location on the top of the airship and exit at another spot on a lower surface.

The currents would find their way through or across the airship, following any electrically conductive structural or system elements such as rigid envelope and gondola frames, control and electrical cables, and fuel or propulsion system components. Unlike an aircraft, much of an airship may be made of non-conductive materials, so lightning currents in system components may be substantially higher than in the same systems aboard a conventional metal airplane. The effects of lightning currents in these systems may be hazardous and special methods may be required to protect them from these hazards. A possible lightning strike scenario is illustrated in Figure 1.

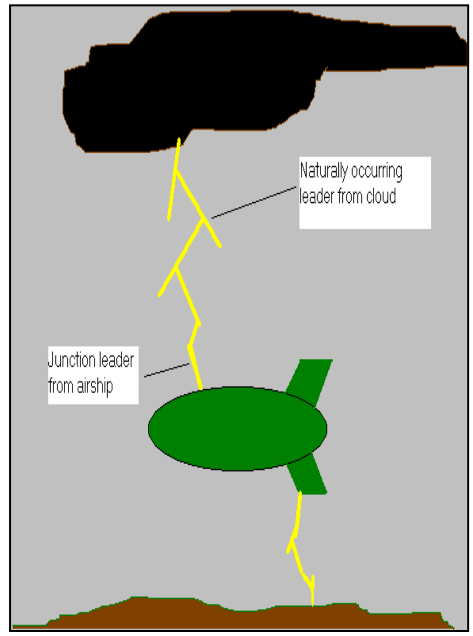



Figure 1 Typical Lightning Strike Scenario

Another possibility is a strike which is "triggered" by entry of the airship into a strong electric field associated with a thunderstorm or other electrified region. In this event the lightning leaders originate at the airship and propagate away from it in the directions of the positive and negative charge regions. This results in the same possible lightning strike scenarios as far as the airship is concerned, although experience of transport aircraft indicates that an airship - triggered strike is more likely to occur in non – thunderstorm conditions, when lightning strike conditions are least expected. This is because many types of clouds can contain electric charges. Under natural conditions the charge in non – thunderstorm clouds may not be accompanied by electric fields strong enough to produce naturally occurring lightning flashes; however if an air vehicle enters such a region the electrically conductive boundaries of the vehicle intensify the field sufficiently so that lightning leaders originate, in generally opposite directions, and propagate in the direction of opposite polarity electric charges; either within the cloud region, or between cloud and earth charge regions.

**Lightning Strike Zones.** The certifying authorities have recognized that not all of the lightning flash currents will enter or exit from the same location on an aircraft, because of the aircraft geometry and flight envelope, and have defined lightning strike zones [5] that can be applied to establish which components of the lightning environment are applicable to each surface and structure. Some lightning currents may "sweep" alongside and reattach to a surface at multiple locations during the flash lifetime so these surfaces receive not all of the lightning flash currents. These lightning strike zone definitions are also applicable to an airship.

Three different situations, shown in Figure 2, have to be considered for location of the lightning strike zones of the airship. Some of these zones depend on what the airship is doing at the time that lightning may occur, as illustrated in Figure 2 for an airship intended to lift heavy loads. In the in flight condition lightning enters the airship at some location on the upper surface and exits from some other position on the lower surface, or a keel, or empennage location. The airship is thus zoned according to the procedures applied for aircraft zoning. But during load exchange procedures (LEP) or while moored, the upper surfaces of the airship are in Zone 1B and probably all of the lightning current is conducted to earth via the load cables or the mast, an there may be no other exit point. The lightning protection designer must consider each of these possibilities.

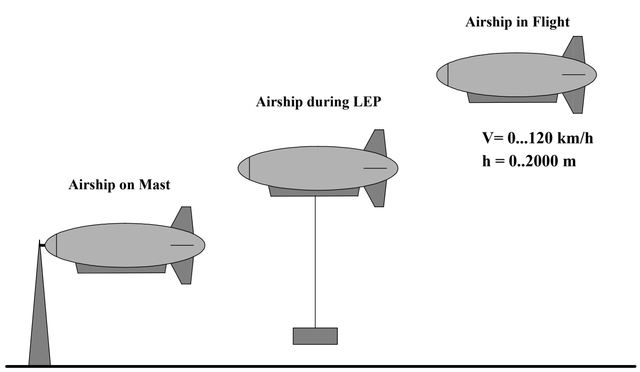



Figure 2. Airship Zoning Situations

The airship designer must consider three possibilities:

- Airship during the load exchange process (LEP)
- Airship at the mast
- Airship in flight

When the airship is in flight the airship speed has to be taken into consideration in determining possible lightning leader and channel sweeping distances, in accordance with the guidelines of [5]. Application of the zone location guidelines in [5] yields the zone locations for all exposure situations. The consequence is that the upper envelope and outer empennage surfaces and the keel lower surfaces are generally located in Zone 1B, the lightning strike zone which has to experience the highest requirements consisting of the fast and slow electric fields and all flash current components defined in [4]. Some other surfaces of the empennage and keels are in zones 2A or 2B. All of the fixed structures are exposed to zone 3 conducted currents. The currents applicable in Zones 1B, 2B, and 3 are shown in Figure 3. These are the currents that an airship should be designed to safely tolerate.

| Lightning Zone | Voltage Waveforms | Current Waveforms |
|---|---|---|
| 1B | A, B, D | A, B, C, D, H |
| 2B | A | B, C, D, H |
| 3 | - | A, B, C, D, H |

Figure 3. Survey of the Lightning Environment Waveforms

With respect to protection against the indirect effects the lightning Multiple Stroke and Multiple Burst environments are also considered. These are also defined in [1] and are applicable for assessment of lightning indirect effects on airship electronic systems.

## PROTECTION DESIGN APPROACH

A major part of any large airship lightning protection design is focused on protection of the envelope which contains the lifting gas. Smaller airships and some tethered aerostats have successfully been protected by a single catenary wire suspended some distance above the envelope; however a large airship makes this approach insufficient. Lighting leaders may approach and enter the helium volume at places other than the catenary wire, so additional lightning conductors will be necessary and a design task is to place these conductors so that they will prevent envelope punctures or other damage associated with internal or external surface flashovers.

**Helium Ionization.** It is known that helium ionizes at lower electrical potentials (electric field strengths) than does air. High voltage tests to evaluate helium breakdown and lightning leader field effects on 2 m and 4 m long, 1 m diameter helium filled cylinders of candidate envelope materials have been carried out at Lightning Technologies, Inc. (LTI) at Pittsfield, Massachusetts, USA, as part of the CL-160 design project. Additional tests to cloud ambient electric field and lightning leader effects on cylinder and larger helium filled envelope material shapes were also carried out at the Labore fur Hochspannung, at Brandenburg Technical University (BTU), Cottbus, Germany.

Typical arrangements for study of helium breakdown characteristics are shown in Figure 4. Helium was flowed into a cylinder fabricated of typical envelope material and from this cylinder into the smaller, transparent cylinder where breakdown voltages could be precisely measured. Tests were conducted on 1 m rod-rod gaps and 11 cm needle electrode gaps. The arrangement for the 1 m gap tests, and subsequent tests of breakdowns inside the helium filled envelope cylinder is shown on Figure 3 and a typical breakdown within the 1 m helium filled cylinder Is shown in Figure 4.

**Rod Gap Enclosure and Cylinder at LTI**

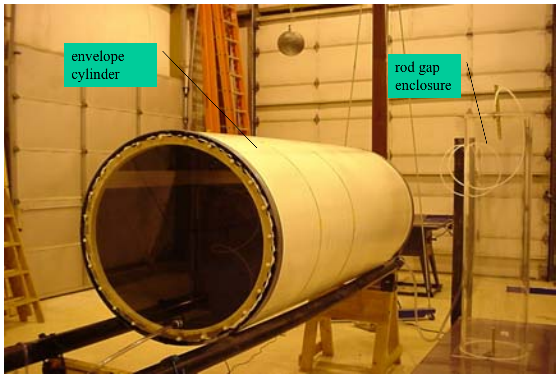



Figure 4. Arrangements for Helium Tests

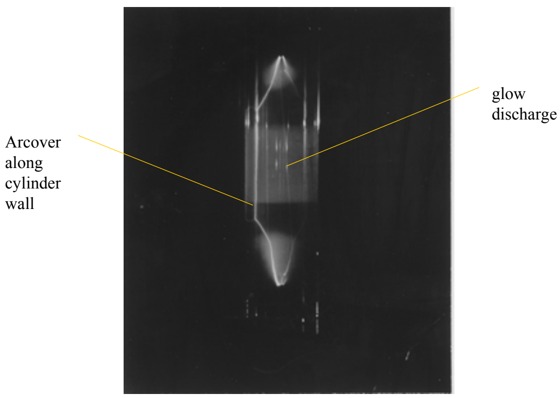



Figure 5. Helium Breakdown in Cylinder

Prior tests with air in the cylinder yielded a critical flashover voltage (CFO) for the 1 m rod-rod gap of 600 kV which is in accord with prior published data. The CFO is the applied voltage that results flashover of the gap 50% of the time.

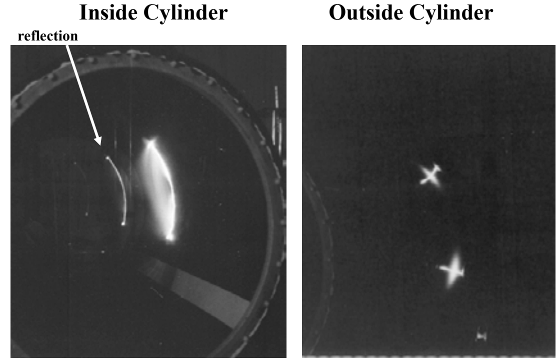
Tests of the same gap within a 99%+ purity helium environment showed partial breakdowns of the same 1m rod - rod gap beginning at 230 kV (approx) into glow (i.e. "cold" streamer formation) at 60% of this voltage and ionization of the Helium into a luminous conducting condition whose volume resistivity averaged about 70 ohm-meters. The luminous condition is visible in the 30 cm diameter transparent plastic cylinder of Figure 4. When the gap was significantly overvoltaged, complete sparkovers occurred, usually along part of the inner surface of the plastic cylinder.

Tests were also conducted with helium concentrations of 86%, 95%, 98%. The concentration percentages are calculated from volumes of He flowed through the cylinder, and are therefore not precise. At 86%, breakdown occurs at 270kV/m on the rise of the 1.2 x 50 us voltage waveform which was set to reach the air breakdown voltage of 600+kV. At 99% the He breaks down at the crest (peak) of a 190kV impulse voltage.

The helium breakdown process appears to begin in the classical fashion with short concentrated streamers at each electrode and a uniform glow (cold) discharge across the gap that is most apparent at the higher He concentrations. At slightly higher generator voltage settings, the gap is bridged with a "hot" arc. Similar tests were made at BTU with an 11 cm needle gap with lightning impulse and DC voltages applied and these results showed nearly the same 1:3 relationship of breakdown voltages with air as had been recorded from the 1 m rod-rod gap tests.

These test results indicate that in the presence of strong electric fields, flashovers would be more likely to occur inside rather than outside of a helium filled envelope. Results of typical tests with two spheres spaced apart on the exterior surface of the envelope cylinder are shown in Figure 6. When the field is applied between closely spaced electrodes breakdown remains in the air along the exterior surface. When the electrodes were spaced further apart, the cylinder is punctured and breakdown occurs inside. In most circumstances the arcs cling to the interior surface of the envelope, which is an area of concern.

**Inside Cylinder** **Outside Cylinder**




**Test 176.** Spheres 43 cm apart at 228 kV

Figure 6 Electrical Breakdown Inside a Helium Filled Envelope

**Protection Effectiveness and Striking Distance.** The effectiveness of an arrangement of lightning conductors on the exterior surface of an airship depends on the lightning leader striking distance. Striking distance is the distance between the last pause position of an approaching natural lightning leader and the object from which a junction leader originates that this leader connects with. Striking distance depends on the amount of charge in the leader, as does the resulting first stroke (i.e. leader discharge) current. The more charge in the leader, the greater the striking distance and the higher the stroke current Empirical relationships between striking distance and stroke current have been developed over the years, mostly to explain lightning effects on electric power transmission lines. One such relationship is shown in Figure 7.

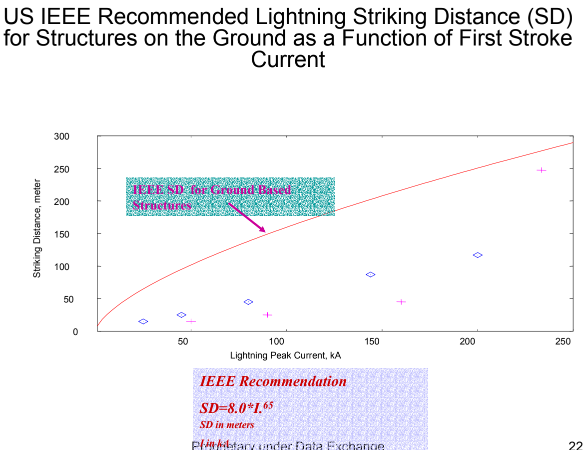



Figure 7 Relationship Between Striking Distance and First Stroke Current

The shorter the striking distance, the greater is the likelihood that lightning leaders will pass by designated lightning terminals or conductors and attach to an unprotected area before inducing a junction leader from a designated lightning conductor. Protection designs based on striking distances 25 m and above have proven satisfactory for critical structures such as oil and gas storage facilities. Only low intensity currents are associated with smaller striking distances. The CL-160 protection design was based upon an a striking distance of 25 m.

## SCALE MODEL TESTS TO DETERMINE PROTECTION DESIGNS

Cylinders with transparent ends offer useful opportunities for evaluation of lightning protection configurations. A 1 m diameter cylinder represents a 1/60 scale model of a 60 m diameter airship envelope, such as the CL-160. Such an arrangement is shown in Figure 8. By placing conductors in a circumferential pattern instead of longitudinally on the cylinder scaled conductor spacings of up to 1/10 could be tested on this cylinder. The cylinder arrangement has the added advantage of allowing the transparent ends to be easily removed so that cylinders could be reassembled with multiple envelope materials, for evaluation of their lightning puncture and internal flashover characteristics. Static electrical charges could also be applied to these cylinders for evaluation of pin-hole formation possibilities, and of the effectiveness of electrically conductive additives in preventing pinhole formation.


Figure 8 Typical Arrangement of Conductors on 1/60 Scale Model Test Article

Three tests of the cylinder of Figure 8 to evaluate the effectiveness of the conductor arrangement in response to leaders approaching from 50 m, 25, m and 12.5 m striking distances are shown in Figure 9. The results show that leaders from 50 m and 25 m striking distances will attach to the protection conductors, but the strike that approached from a 12.5 m striking distance punctured the envelope and flashed along the upper inside surface and punctured the envelope again at one of the protection conductors. The 12.5 m striking distance is considered unrealistically short, so this test series was considered successful.

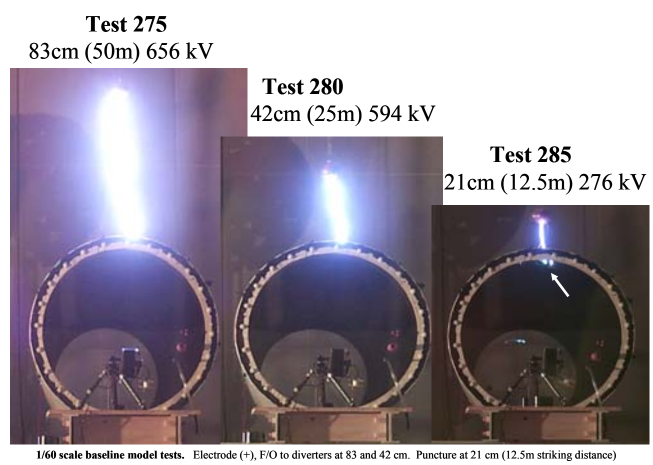



Figure 9 Cylinder 1/60 Model Tests with Leaders at 50m, 25m and 12.5m

Larger models of airships can also be tested, with other features like empennage and propulsion system mocked up so that the influence of these items on lightning attachment can be evaluated. A 1/25 scale model of the CL-160 is shown in Figure 10.

Figure 10 1/25 Scale Model of CL-160

Items that are intended to be installed inside the airship envelope can be mocked up and installed in the model so that their influence on lightning strike behaviour and puncture of the envelope can be evaluated. These include:

- Load cables inside the envelope
- Instruments inside the envelope
- Electrical cables
- Gas management devices

An example of one test that resulted in puncture of the 1/25 scale model envelope is shown in Figure 11. The test allowed the role of envelope materials, load cable configuration and protection design configuration to be evaluated.

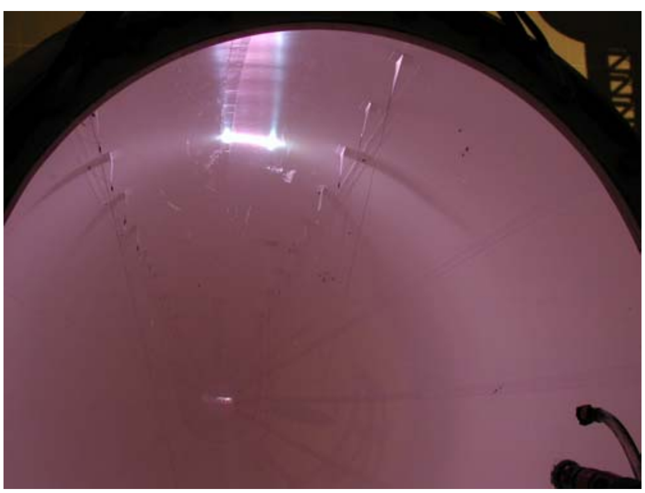


Figure 11 An example of puncture and Internal flashover

## NUMERICAL SIMULATION

BACKGROUND Numerical simulation plays a significant role in the lightning verification of the airship for at least two reasons. First, the vehicle is much too large to perform full scale vehicle testing. Second, by the time such testing could ever be done, it would be too late. It is necessary to understand and solve the lightning issues during the design process, long before the vehicle is assembled.

Numerical simulation is used in close partnership with the testing described earlier in this paper. Both approaches have limitations and advantages, and together they form a complementary capability allowing the creation of protection designs with a high degree of confidence.

NUMERICAL METHODS – Several simulation packages are used in the airship design:

EMA3D – This is a 3D time domain finite difference application produced by Electro Magnetic Applications, Inc. It is used to model the airship in 3D. This package can directly import vehicle geometry directly from several CAD systems such as CATIA, for example, or via IGES or STEP files.

Method of Moments (MOM) – This is a research package developed by EMA used to obtain detailed information about the static electric field structure in the vicinity of various lightning conductors on the airship. This is useful because EMA3D can realistically model the entire airship with a cell size on the order of 1 m, given the existing capability of single processor workstations. However, in order to more fully understand the envelope protection issues, especially those with regard to helium already discussed, it is necessary to evaluate the field structure on a micro-scale, on the order of millimeters. This capability also allows for accurate inclusion of the envelope material properties in the simulation.

MHARNESS – This is a time domain finite difference application produced by Electro Magnetic Applications, Inc. It is a solution of the multiple conductor transmission line equations, and is used to model complex wire harnesses on the airship. It can account for various shielding layers, connector design, harness layout, and bonding issues.

INTERPRETATION OF EXPERIMENTAL RESULTS – An import application area is the interpretation and understanding of experimental results. As noted earlier the basic envelope protection approach is to apply a grid of conductors along the envelope exterior surface, with the expectation that these strips will intercept any lightning strikes and thereby prevent damage to the envelope.

A major design problem, therefore, is to determine where to apply these strips. Our approach was to perform 1/60th scale model testing of a 4m long helium filled cylinder protected by a grid of metallic strips, as shown in Figure 12.

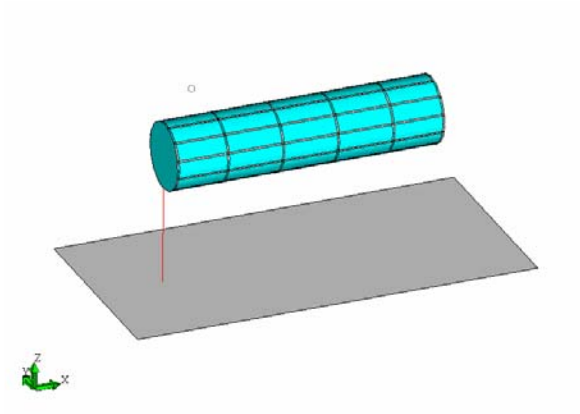


Figure 12 A 4m long helium filled cylinder test configuration

A Marx generator is used to charge a spherical electrode until flashover to the test object occurs. The electrode is placed at distances of .425m and .21m from the cylinder, corresponding to full scale striking distances of 25m and 12.5m, respectively.

Figure 13 shows the computed fields on a vertical plane cut through the sphere and cylinder for the longer distance. The maximum field in the helium is about 150kV/m, not enough to ionize the helium. When the shorter striking distance is used, the field increases to more than 200kV/m, which is enough to ionize the helium and puncture the envelope material. The analysis therefore allows us to develop criteria for LPS performance related to the fundamental concept of helium ionization potential.

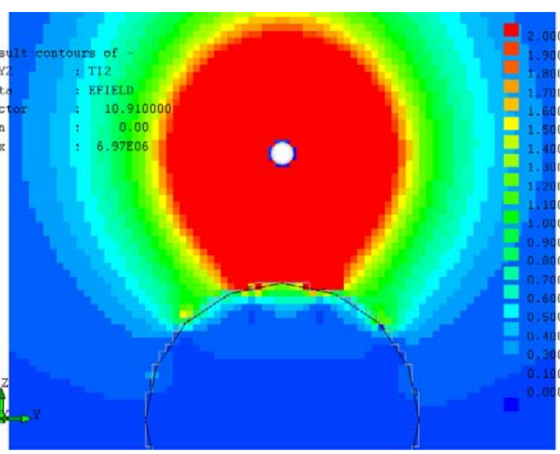



Figure 13 Computed electric fields in a slice through the electrode and cylinder of Figure X.1

Numerical analysis can also be used to evaluate the effects of the test facility on the test results. Figure 14 shows a 1/25th scale model test in a high voltage laboratory. There are several factors which could influence the test results, including the presence of the floor and walls, and the nearby presence of the Marx generator. Numerical simulation is used to compute the fields in the helium for both the test configuration and for the airship in flight, in order to determine any facility effects. The figure also shows a plot of the ratio of these fields in a slice though the airship, and indeed shows that the facility effects are not significant.

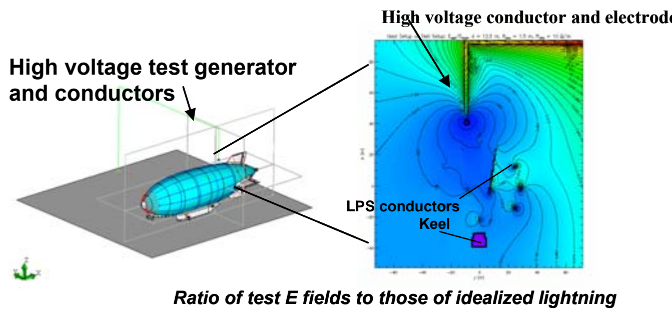



Figure 14 Example of evaluation of faculty effects on 1/25th scale model testing

DESIGN EVALUATION - Analysis can also be used to evaluate the effects of structural design options on lightning protection. An example is shown in Figure X.4, in which the effects of steel load cables inside the envelope would have on LPS performance. The simulation shows that the fields inside the helium would be increased by a factor of ~4 over the fields without the cables, implying that the baseline LPS design would need to be modified to reduce these fields to an acceptable level.

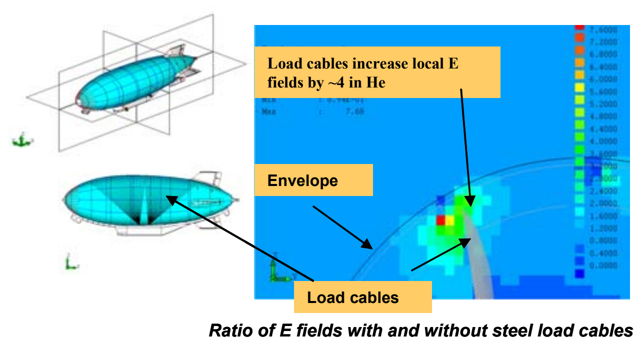



Figure 15 Example of evaluation of the effects of internal steel load cables on LPS performance

LIGHTNING ATTACHMENT SCENARIOS - As noted earlier, the protection design must consider the attachment scenarios associated with airship initiated lightning leaders as well as naturally occurring lightning leaders.

Attachment is a complex process, because the helium properties allow breakdown to occur within the helium volume before breakdown occurs in the air surrounding the envelope. The lightning strike initiation and attachment process, therefore, might begin with initial streamer development within the envelope, and if this occurs, the envelope will be punctured. The lightning protection strips must therefore limit the helium fields to less than breakdown levels so that lightning will first attach to the protection conductors.

In the first case, lightning can be initiated ("triggered") by the presence of the airship in strong static electric fields caused by thunderstorm electrification. The airship structure can locally increase these fields by a significant factor at various airship locations, such that streamers and lightning leaders originate at these locations and eventually propagate to cloud charge regions of sufficient potential to initiate a lightning strike. In this case the objective of the protection conductors is therefore to make sure that these initial streamers originate outside the envelope.

Second, an approaching stepped leader can also induce streamers from the airship, and again the protection strips must ensure that these initial streamers originate outside the envelope.

From a static field point of view, the difference between the two scenarios is that the first one involves numerical solutions for impressed uniform electric fields caused by cloud charges, and the second involves impressed non-uniform fields caused by the approaching leader channel.

Airship Triggered Lightning – For this type of simulation, uniform static electric fields are assumed as the originating lightning environment. These fields are assumed to exist in all three coordinate directions: parallel to the airship axis of travel; horizontal and perpendicular to the axis of travel; and vertical. Simulations are done for each of these orientations.

EMA3D is used to compute the airship interacted fields for each orientation with a 1 m resolution. The incident electric fields are created with a plane wave Huygens' surface. This surface creates an incident time domain step function electric field with a slow rise time. Although the solution is dynamic, it proceeds until a steady state is reached.

A typical result is shown in Figure 16.

Lightning Caused by an Approaching Leader – For this type of simulation, non-uniform static electric fields caused by an approaching leader are assumed as the originating lightning environment. Numerically, it would also be possible to create these fields from a Huygens' surface, but this involves the extra work of creating the appropriate sources on this surface for an approaching leader.

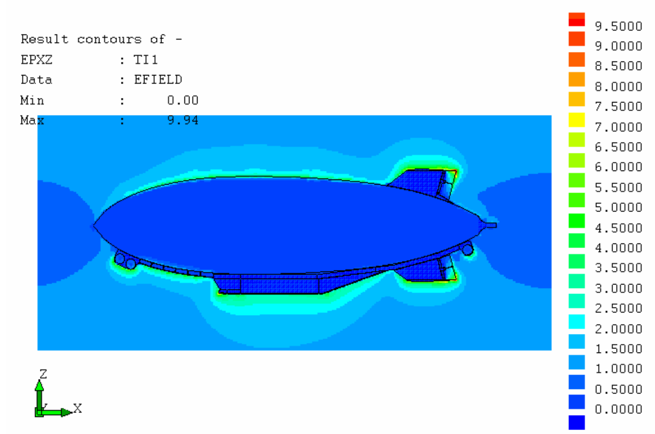



Figure 16 Example of airship field enhancement factors for a vertical uniform incident static electric field for triggered lightning evaluation

Instead, a simpler approach is taken. The fields from a 1 km long leader having a linear charge density of 1 C/km are computed as shown in Figure 17 which also shows an airship shape for illustration purposes. The approach is to replace the linear charge density with an equivalent point charge, such that the incident fields in the vicinity of the likely attach points are the same. This creates some error in the field distribution elsewhere on the airship, but accuracy is really only required in the vicinity of the attach points.

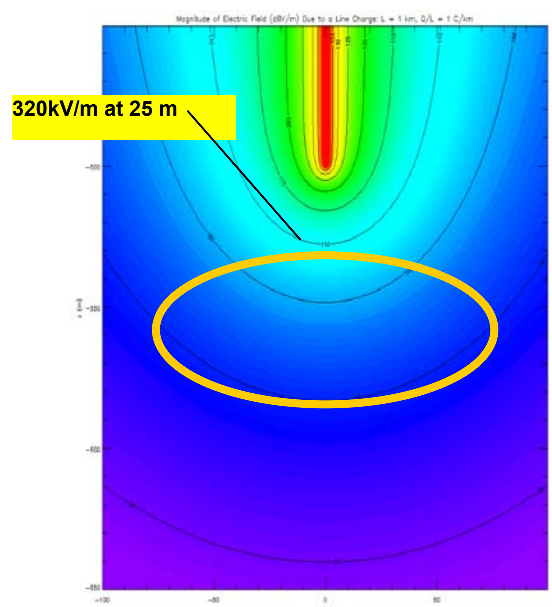



Figure 17 Fields from an Approaching Stepped Leader 1 km long and having 1 C/km linear charge density

This approach also has the advantage that it can be used in the direct simulation of laboratory scale model attachment testing, because a spherical electrode is used as a source there as well.

An example of field distributions on the airship for this case is shown in Figure 18.

Electric Field Microstructure – Once the fields are computed on a 1 m resolution, the fields with much finer resolution can be obtained. The general approach is to obtain the linear electrostatic charge densities on the lightning protection strips from EMA3D. These charge densities are then used as sources for the 2D MOM code, which models the strips as infinitely long, and the fields are computed at any location near the conductor. In addition to the linear charge density, the incident field is also added to the solution. The resolution can be very fine, and cells on the order of 1 mm are used. Figure 19 shows an example.

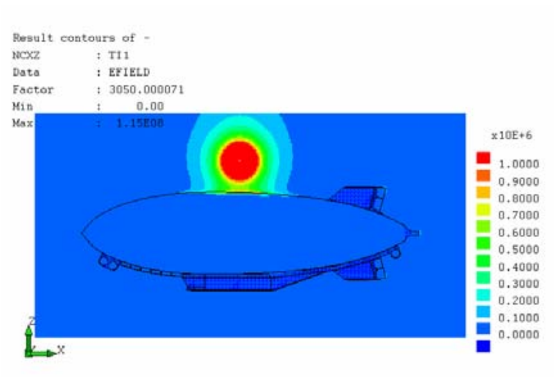



Figure 18 Field Distribution on the airship due a Leader 25m above

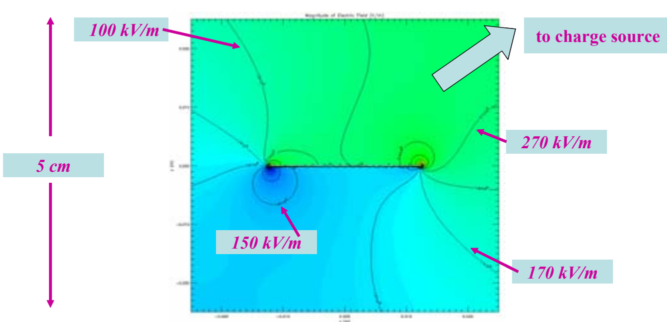



Figure 19 The microstructure of electric fields around a lightning protection strip

## CONCLUSION

Numerical simulation is used closely in combination with testing. Laboratory testing, described earlier in this paper, is used to perform attachment lightning testing on scale model airship protection designs. The same numerical approach described here is also applied to these laboratory test configurations with candidate conductor arrangements included. The result has been a good correlation of laboratory results with the numerical results. This then gives a high level of confidence that the numerical approach can then be used to extend the laboratory scale model results to the full size vehicle in flight.

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