

EVALUATION OF LIGHTNING PROTECTION SYSTEMS FOR EXPLOSIVES*

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ABSTRACT

The unpredictable nature of lightning requires that lightning protection systems (LPS) be described in statistical terms such as the "expected efficiency of protection" or the "probability of failure". This implies, as has been observed, that lightning channels occasionally penetrate what has been considered to be a "zone of protection" provided by the LPS. This lightning penetration exposes assets, such as explosives and related fusing and test electronics, to possible direct effects of being part of the lightning current path. Depending on the current amplitude, these direct effects can cause malfunction, upset, or catastrophic damage to these assets and perhaps to personnel and structures in the immediate vicinity.

Even in cases where the LPS has not "failed" there are indirect effects caused by inductive and capacitive coupling which transfers electromagnetic energy to the interior of the "zone of protection" in the proximity of down conductors and other elements connected to the LPS. These conductors and elements can carry the bulk of the lightning current or temporarily store a significant amount of charge from the strike. These indirect effects can also cause malfunction, upset or damage to assets depending on the vulnerability of the asset to electric and magnetic fields and currents. Vulnerability depends on operational configurations, such as, 1. stored in an underground igloo in closed metal containers or 2. exposed in a maintenance building connected to electronic test equipment. Some military and industrial LPS specifications require the LPS to be bonded to other metal objects and to other electrical grounding systems. In some geometrical configurations, this additional bonding can enhance (rather than reduce) the possibility of direct and/or indirect coupling to assets.

A computer model solving the three dimensional Maxwell's Equations for various LPS environments and corroborated by data from triggered lightning tests is used to show that there are areas within the "zone of protection" which are safer than other areas. These calculations are used to establish statistical "safe zones" within the "zone of protection" which are determined by building geometry, the geometrical layout of the LPS, the bonding of the LPS to other metal objects and electrical grounds, the earthing configuration of the LPS, and the vulnerability of the asset in its presumed operational configuration. A quantitatively-based assessment method for LPS evaluation (TESLA) is suggested, which relates survivability to asset strength and the stress from the lightning environment which penetrates typical LPS's.

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1.0 INTRODUCTION

1.1 Background

The purpose of this section is to orient the reader to the different aspects of lightning protection (LP). These aspects include:

1. Types of LP Systems (LPS)
2. Earth Ground Systems
3. Bonding
4. Direct Effects vs. Indirect Effects
5. Statistical Effects and Protection Philosophy

1.2 Types of Lightning Protection Systems

There are three basic types of LPS:

1. Integral Systems (Figure 1.1)
2. Mast Systems (Figure 1.2)
3. Mast plus Catenary Systems (Figure 1.3)

The integral system consists of three parts: the air terminals, the down conductors, and the earth ground system. The air terminals are spaced in a manner which gives protection over the entire facility as shown in Figures 1.1 and 1.7.

The mast system consists of a mast located some distance away from the facility, but close enough to it to provide a protection zone enclosing the facility. The protection zones are defined by either the cone of protection concept or the Horvath rolling sphere method [7], based on the statistical concept of "striking distance" as shown in Figure 1.2 and 1.3. Typical protection zones are shown in Figures 1.2 through 1.7. The mast plus catenary systems provide additional protection coverage from cables attached to one or more masts.

The Faraday Cage Shield (which can be used for additional protection) refers to the asset being protected inside a completely closed metal container, theoretically impervious to electric charges and electric fields. In practice, the containers are never completely closed, having seams, access ports, insulated electrical feedthroughs, or apertures of various kinds allowing energy to penetrate to the interior of the container. Other examples of partial Faraday shielding include screened rooms and networks of iron rebar in re-enforced concrete enclosures. Partial Faraday shielding can reduce the effects of lightning. The screen or aperture size determines the frequency of protection at distances far from the screen or aperture. Low frequency penetration and capacitive effects occur near the screen surface or location of the aperture.

1.3 Earth Ground Systems

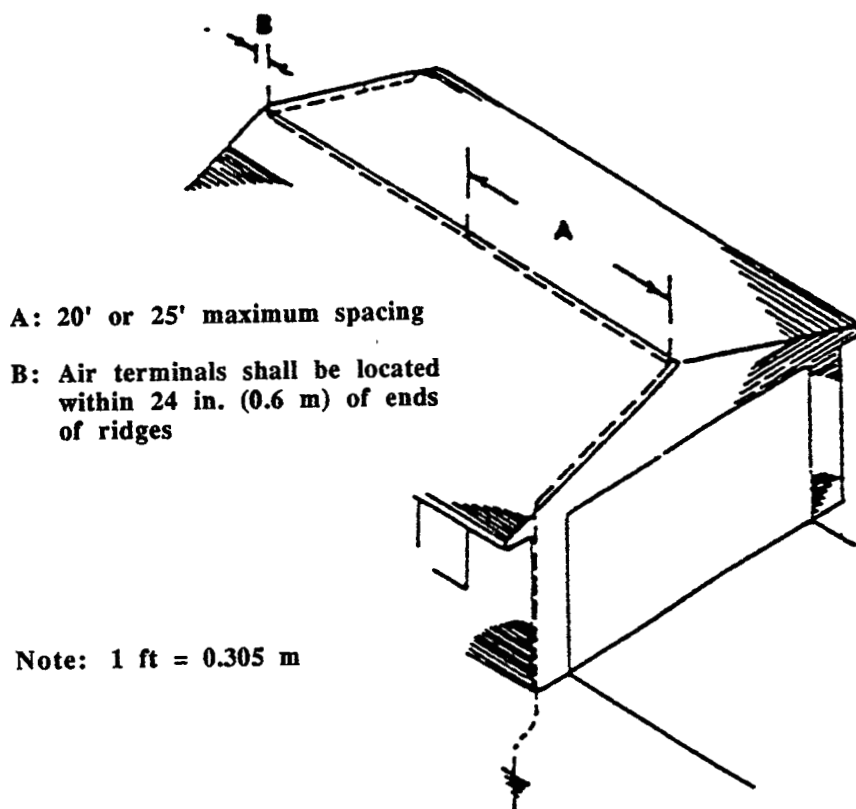
The earth ground system may consist of a ground rod (Figure 1.8) or a counterpoise system (Figure 1.9). The resistance to earth is a function of the rod's length and diameter, and the earth's resistivity. Military requirements usually specify a maximum resistance of 10 Ω to 25 Ω . Multiground rod systems arranged on a counterpoise can be used to achieve low resistance. Formulas exist for computing the DC resistance of various types of ground rod systems (for example, MIL HANDBOOK 419). There have been no clear specifications given for the inductance

or the high frequency impedance of earth ground systems which can affect peak voltages during a strike.

A facility frequently has more than one ground system. Inside the facility, there may be a signal ground (technical ground), a facility ground, and an ordnance ground. Separate earth ground systems may also exist, including a facility earth ground and perhaps a LPS ground. Some military and industrial specifications require that all of these ground systems be connected to each other at one point as shown in Figures 1.8 and 1.10.

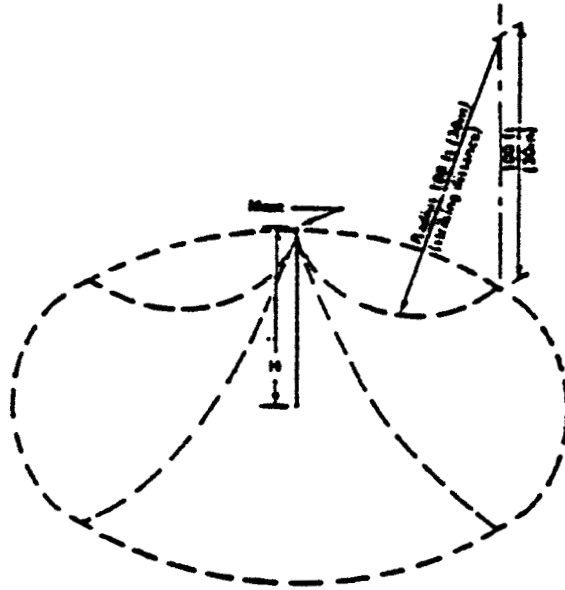
1.4 Bonding

Lightning protection requirements specify conditions under which large metallic objects inside a facility be connected (bonded) to each other and to the earth ground system. The rationale behind this is to prevent arcing between metallic objects, which could create a fire hazard. However, this practice also allows the lightning environment to penetrate into the facility interior.



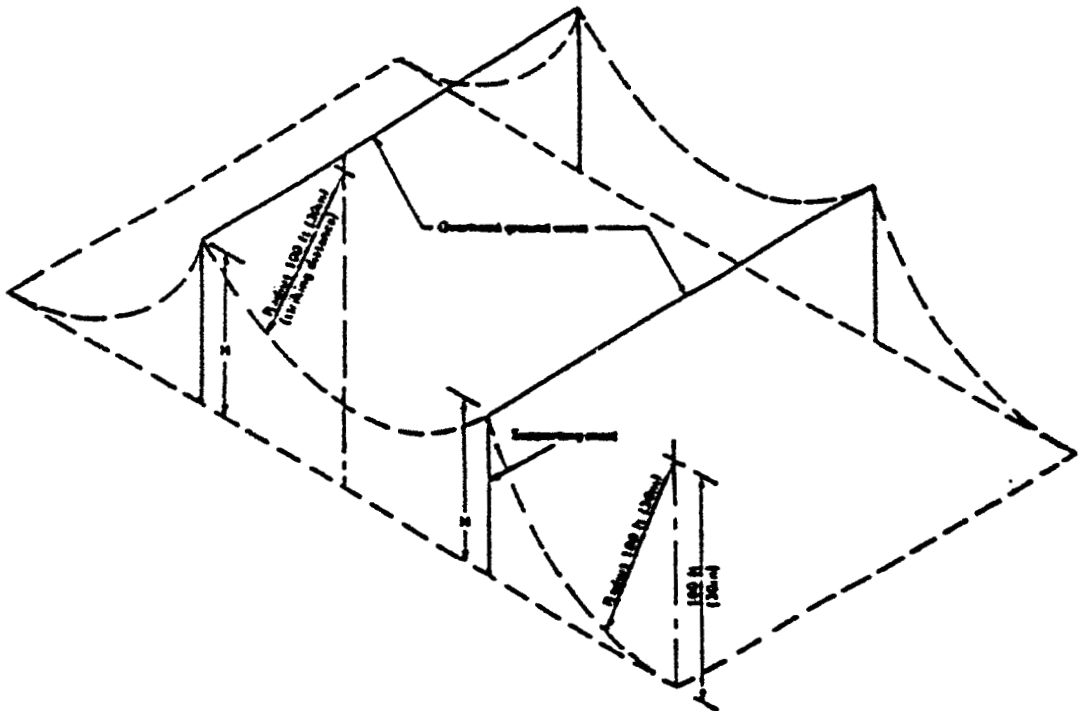
Air Terminals on Peaked Roof (NFPA 78)

Figure 1.1 Integral Lightning Protection System



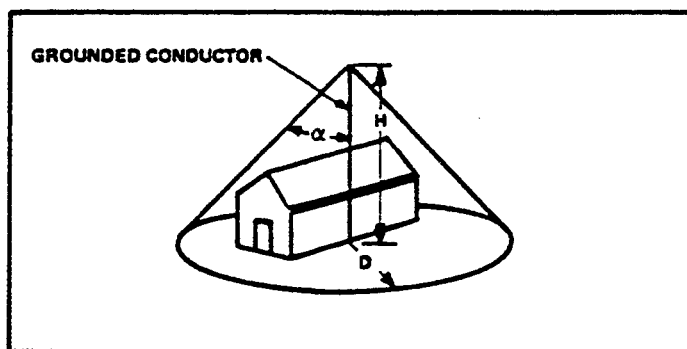
Zone of Protection for Mast (NFPA 78)

Figure 1.2 Mast Type

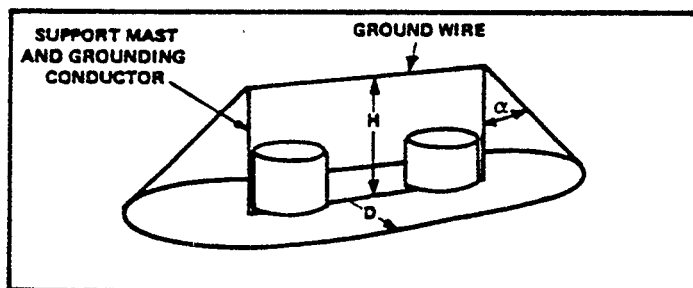


Zone of Protection for Mast Plus Catenary (NFPA 78)

Figure 1.3 Mast Plus Catenary

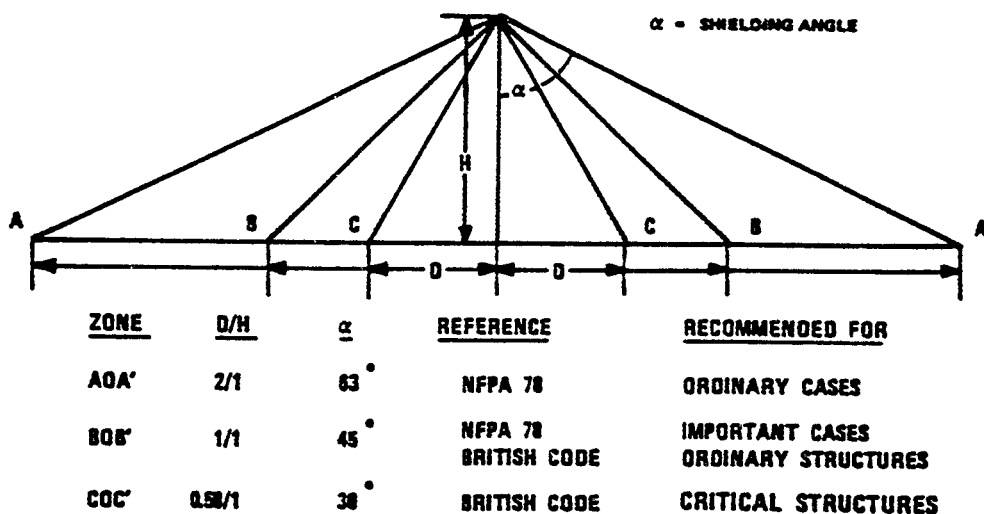


(a) CONE OF PROTECTION PROVIDED BY A VERTICAL GROUNDING CONDUCTOR OF HEIGHT H.



(b) ZONE OF PROTECTION PROVIDED BY A HORIZONTAL AERIAL GROUND WIRE AT HEIGHT H.

Zones of Protection Established by a Vertical Mast and a Horizontal Wire (MIL HDBK 419A)



Some Commonly Used Lightning Shielding Angles (MIL HDBK 419A)

Figure 1.4 Zones of Protection

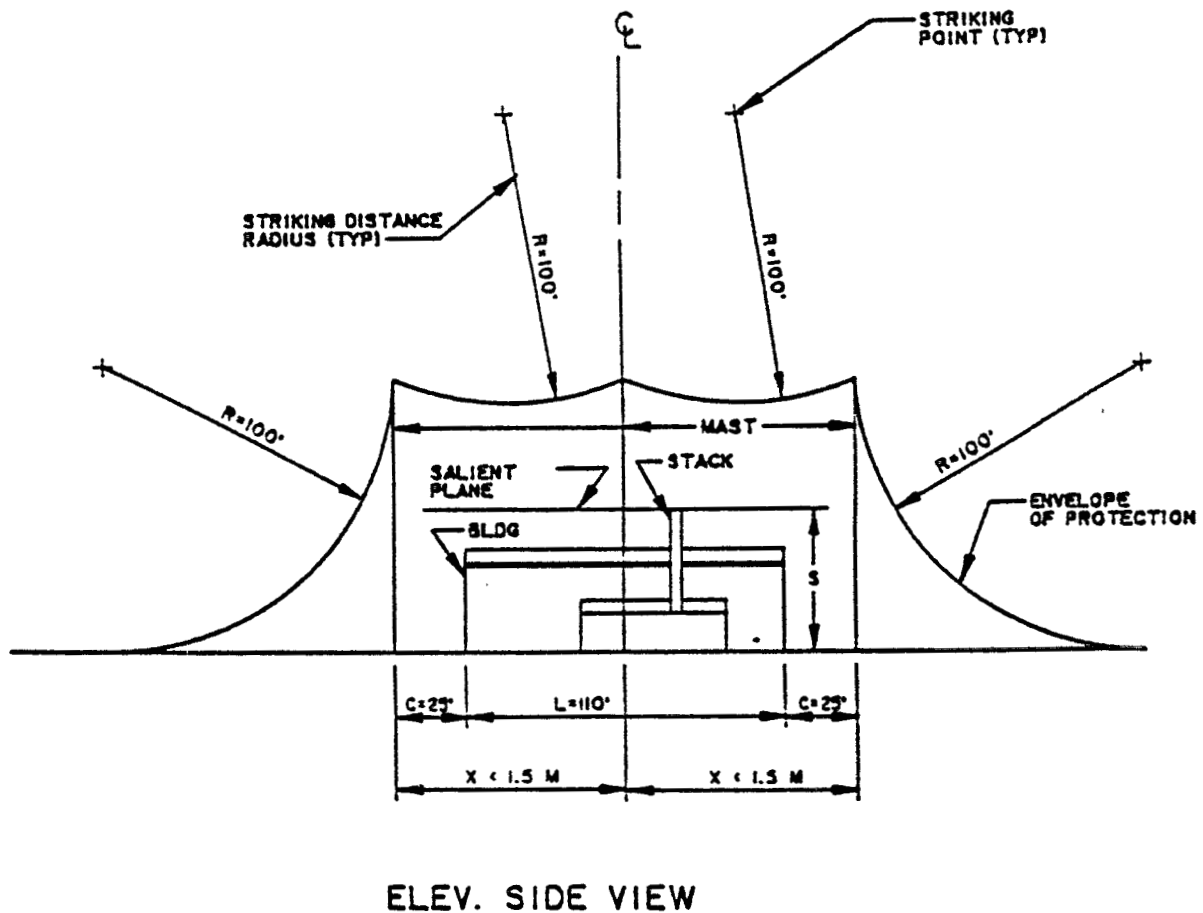


Figure 1.5 Primary Lightning Protection Design for Ordnance Handling Facilities (MIL-HDBK 1004/6)

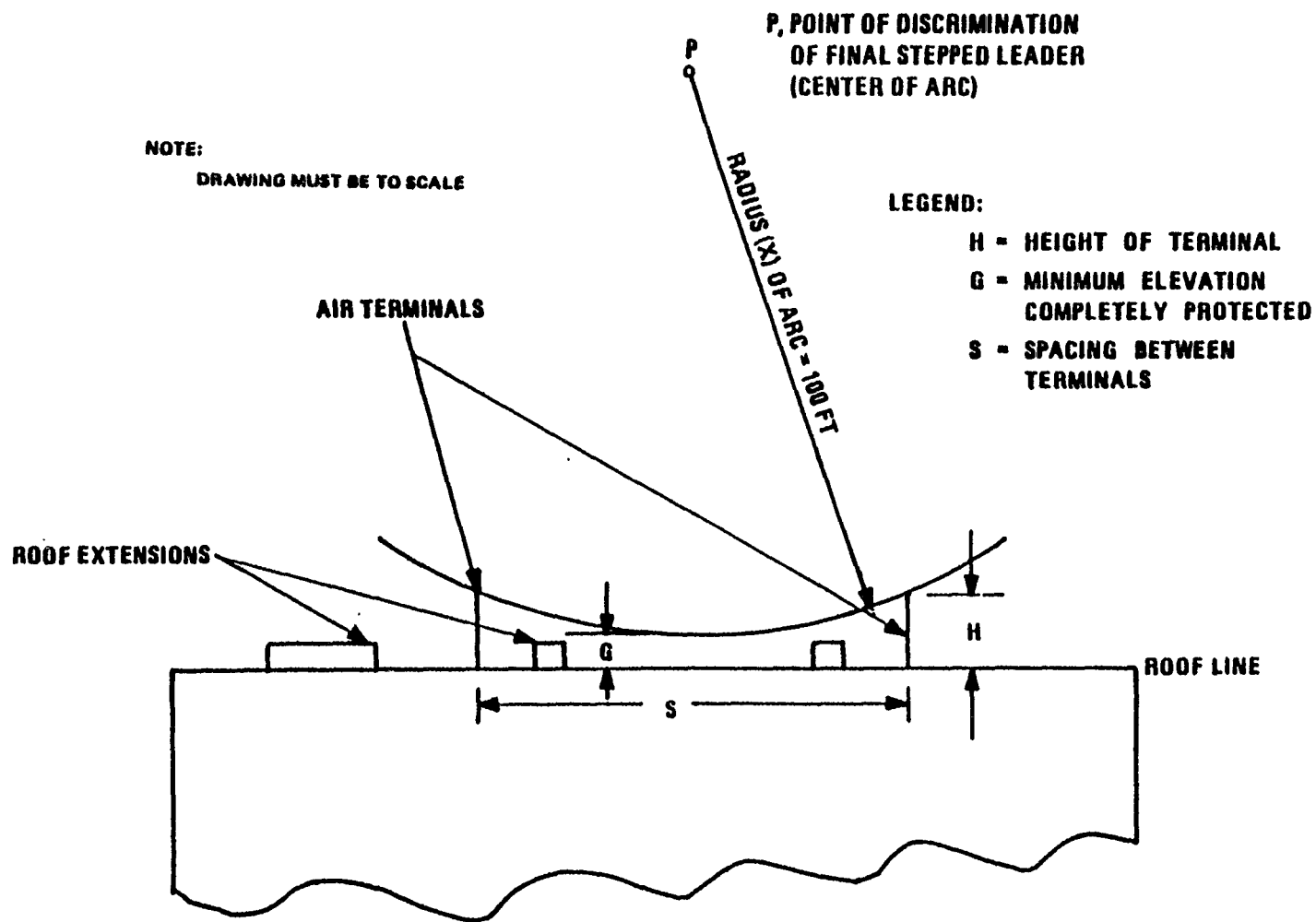
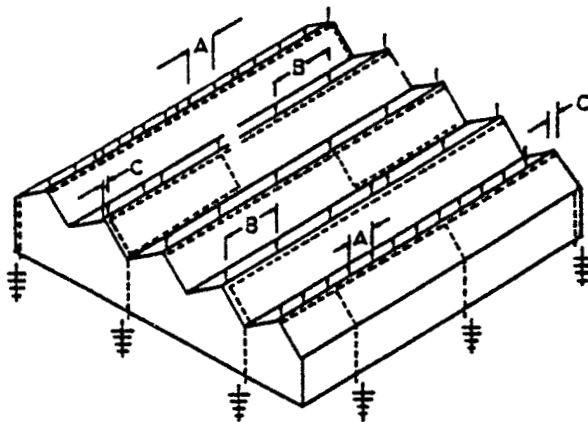


Figure 1.6 Illustration of Method for Determining the Protection of Flat Surfaces as Provided by Air Terminals (1-4) (MIL HDBK 419A)



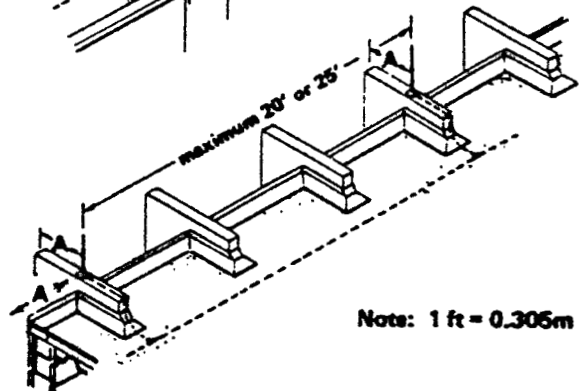
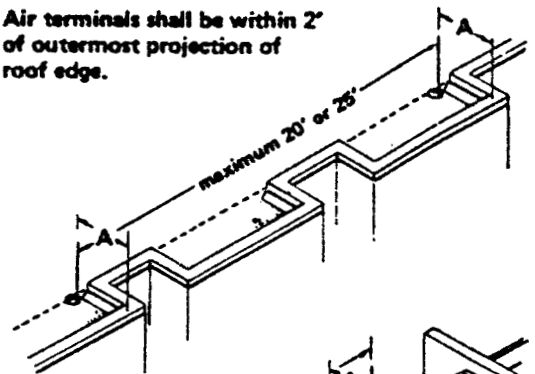
Maximum spacings:

A: 20 ft (6 m) or 25 ft (7.6 m)

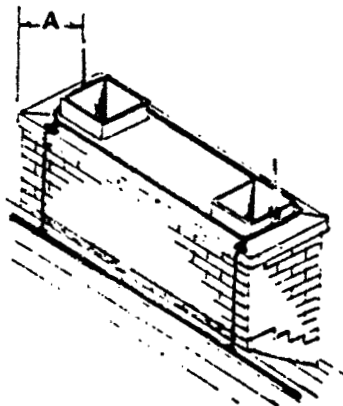
B: 50 ft (15 m)

C: 2 ft (610 mm)

A: Air terminals shall be within 2' of outermost projection of roof edge.



Note: 1 ft = 0.305m



A: 2' (0.6 m) maximum

Figure 1.7 Locations of Air Terminals (NFPA 78)

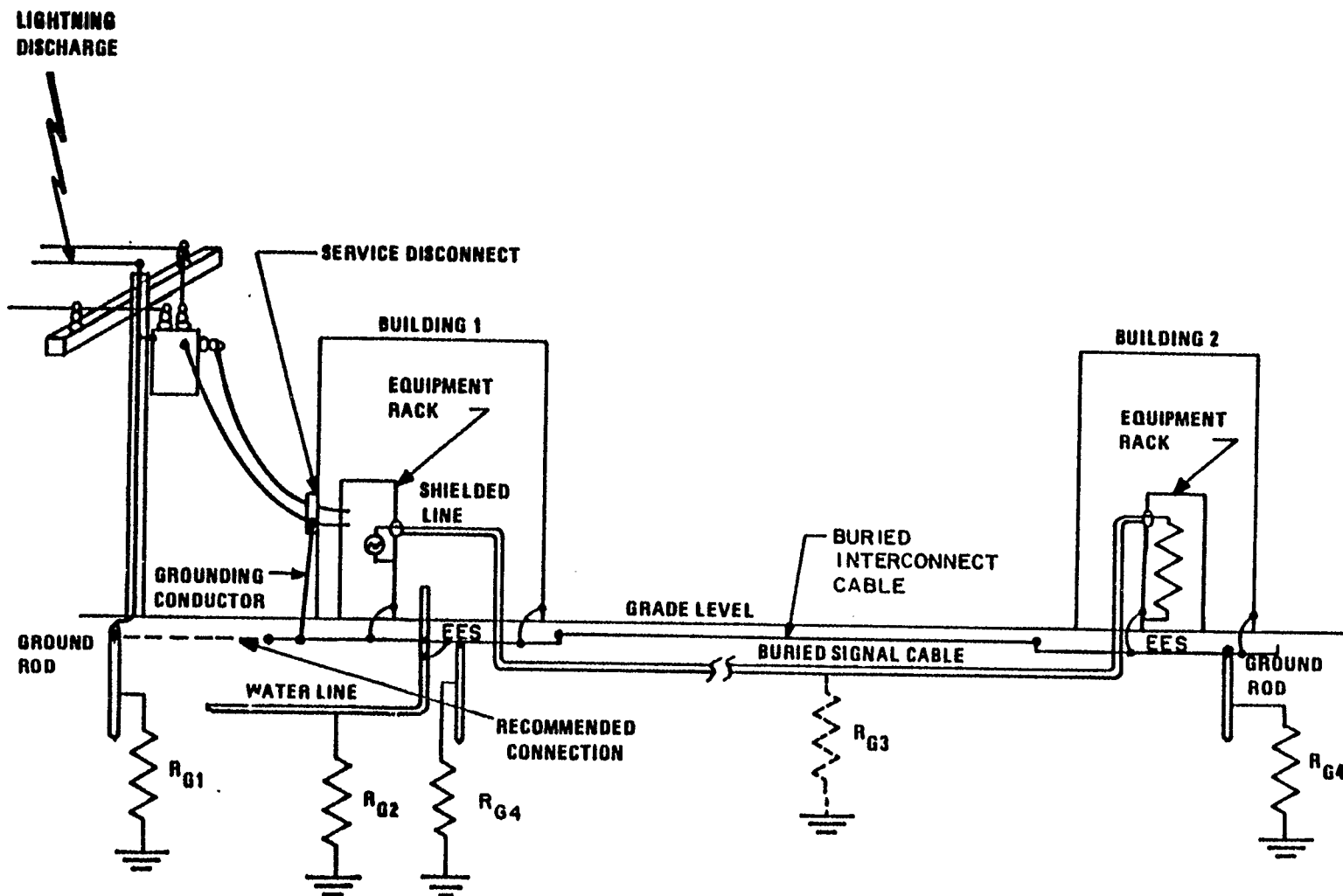


Figure 1.8 Coupling of Lightning Energy Through an Interconnected Facility (MIL HDBK 419A)

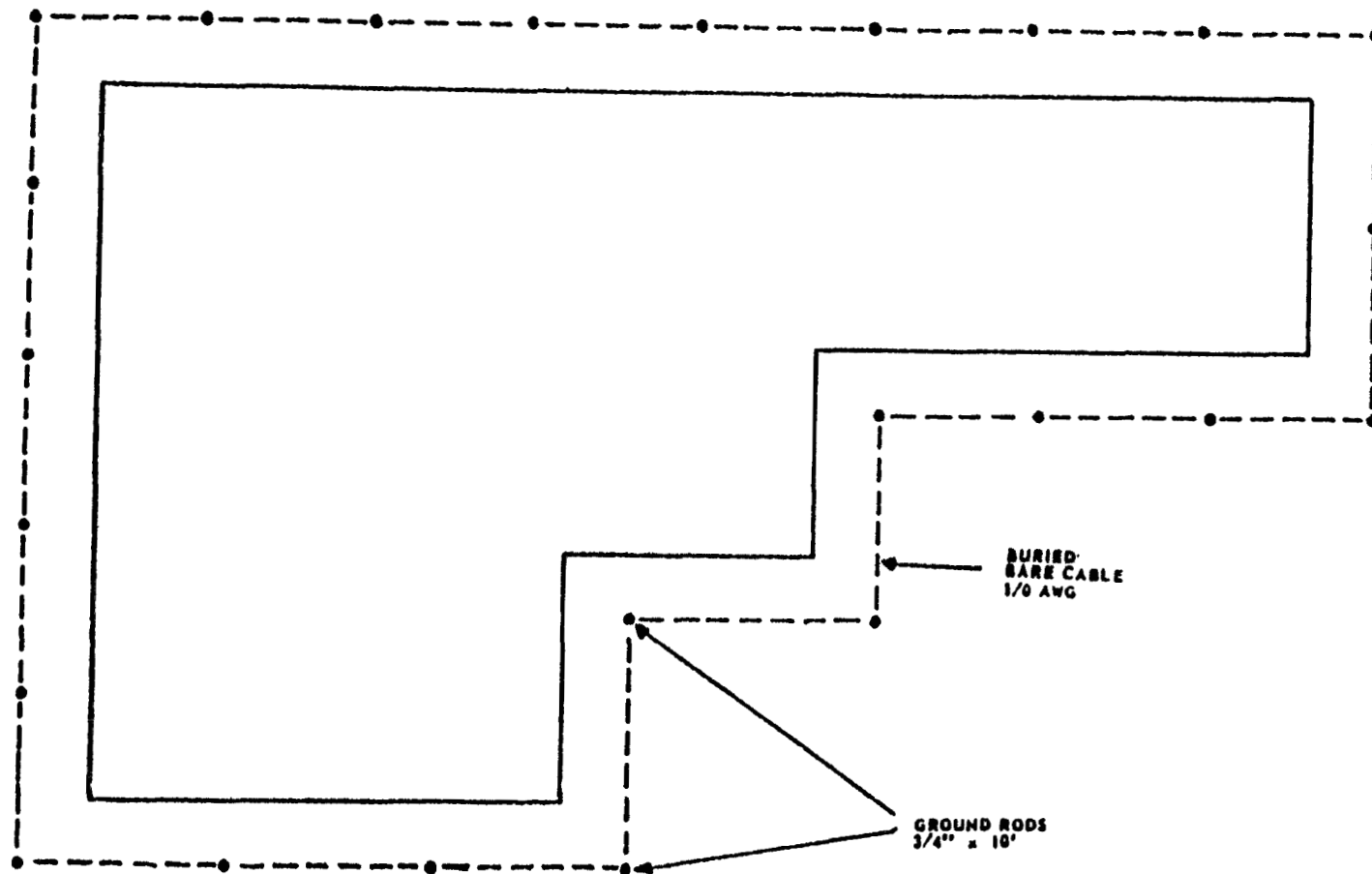


Figure 1.9 Electrode Configuration for Irregular Shaped Facility (MIL HDBK 419A)

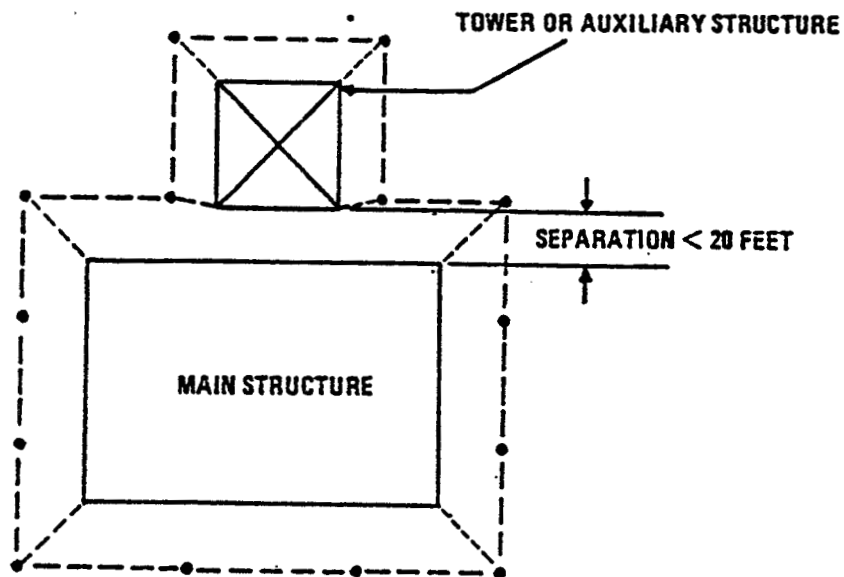


Figure 1-8. Electrode Configuration for Adjacent Structures

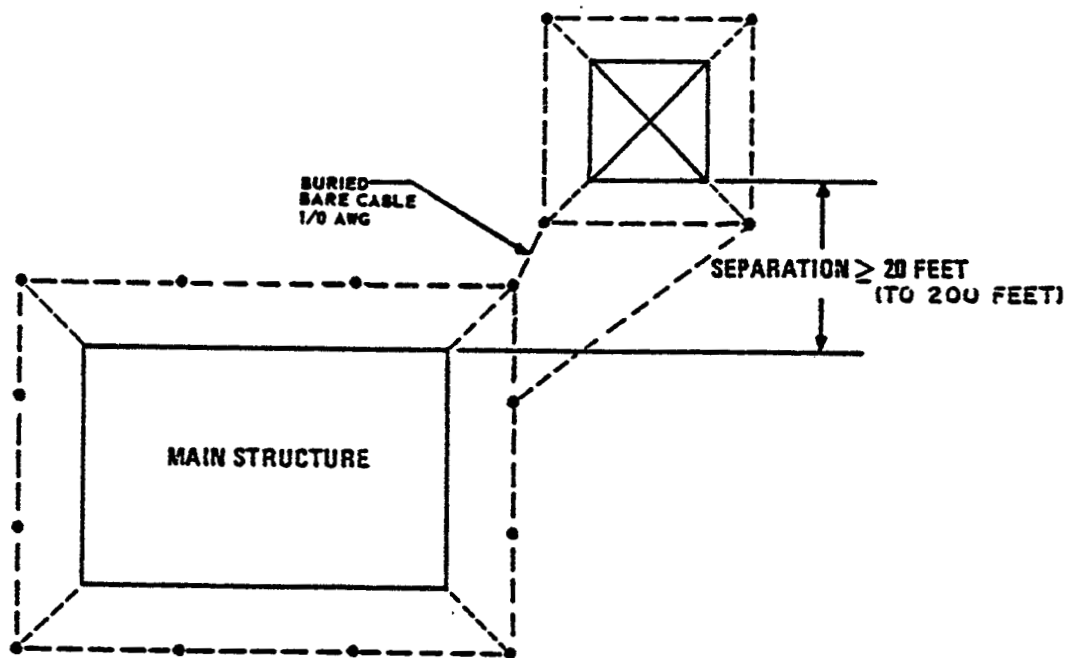


Figure 1.10 Electrode Configuration for Closely Spaced Structures (MIL HDBK-419A)

Some specifications require that external conductors, such as nearby railroad tracks and fences, also be connected to the ground system. The rationale for this may be that this will prevent arcing, and also that it will create a lower impedance earth ground system. It should be noted that this practice will also increase the lightning capture area of the facility.

1.5 Direct Effects vs. Indirect Effects

There are two primary phenomenon which couple energy from the lightning strike to assets and other objects:

1. Direct Coupling, where the object in question provides a path for all or part of the electrical current in the lightning strike,
2. Indirect Coupling, where the object is coupled electromagnetically, through electric and magnetic fields caused by charge and current and the temporal change of these quantities in the lightning stroke. (Temporal changes in electric and magnetic fields are sometimes referred to as E-Dot and B-Dot, respectively).

Induced currents from indirect coupling can cause damage at significant distances from primary conductors carrying the bulk of the lightning current. Because of electromagnetic induced effects, it is not proper to consider lightning energy to be confined to the air terminals, down conductors, and earth grounding systems.

Both direct and induced currents can cause damage by heating and burning. Direct and induced arcing can ignite fuels, explosives, and flammable materials. Mechanical damage can be caused by melting, by projectiles (e.g., wood, concrete) which have been spalled from structural elements, and by mechanical whipping of wires and cables. Indirect currents and fields can cause physiological damage to personnel.

1.6 Statistical Effects and Protection Philosophy

Lightning is, by nature, unpredictable. This unpredictability includes the location and frequency of strikes, the strike amplitude, risetime to peak amplitude, the number of strokes in each strike, and the intermediate current state preceding the lower amplitude continuing current of each stroke.

Statistical formulas and isoceraunic maps (giving the local frequency of thunderstorms and/or lightning strikes per unit area) are useful in determining the likelihood of a strike in any given area. Experimental evidence gives statistical distributions of strike amplitude, risetime, intermediate and continuing currents. Much more precise data is available from lightning locator systems. Local anomalies exist for various local varieties in terrain, for example, mountain peaks or the edge of a bluff.

Lightning Protection Systems can be designed from a consideration of what is "likely to happen" given a "normal" strike, or by considering what "could happen" in a "worst case" scenario. Worst case scenarios are often described in terms of 1% likelihood; that is, something "worse" than a "worst case" is expected to happen in less than 1% of the cases. Lightning protection systems can be described in statistical terms such as "the expected efficiency of protection" or "the probability of failure". This implies, as has been observed, that lightning channels occasionally

penetrate what has been considered to be a "zone of protection" provided by the LPS. These statistical probabilities are often analyzed in terms of Horvath's "Rolling Sphere" Model [7].

For something as serious as explosives and related electronic circuitry, the "normal" lightning protection specifications are considered inadequate. (For example see MIL-HDBK 419A Vol. 1 p.3-13). It remains to determine what is an "adequate" specification of LPS for explosives and related assets. Even in cases where the LPS has not "failed", indirect effects can cause damage if the assets are not properly placed within the system.

Presently, most design specifications in present manuals are independent of asset vulnerability considerations and usually do not consider "safe zones" for particular assets. The balance of this paper will address primarily a calculation method based on explicit numerical solutions of Maxwell's Equations which are capable of defining the safe zones for a given lightning attachment to an LPS or to a structure location point in the event that the LPS has "failed". These calculation methods have been validated well within an order of magnitude from triggered lightning experiments on an underground storage igloo [1, 2].

2.0 DESCRIPTION OF THE NUMERICAL MODELS

The numerical model of the structure and surrounding environment is based upon a finite difference time domain solution of Maxwell's equations. The solution technique is explicit and accurate to second order in the time and spatial increments, which in these models correspond to the three dimensional Cartesian coordinate increments as obtained by Merewether and Fisher [3] with further discussions by Collier, McKenna, and Perala [4,5].

A problem space containing the facility and surrounding environment is divided into rectangular cells. Each cell has a staggered spatial grid, as shown in Figure 2.1, composed of the vector components of E and H (the electric and magnetic fields, respectively). There are approximately one million cells in the lightning strike problem spaces discussed in this paper. The cell dimensions Δx , Δy and Δz are 12"x6"x6" for the igloo and 6"x12"x12" for the building. The field components in each cell are calculated numerically via the finite difference form of Maxwell's Equations [3].

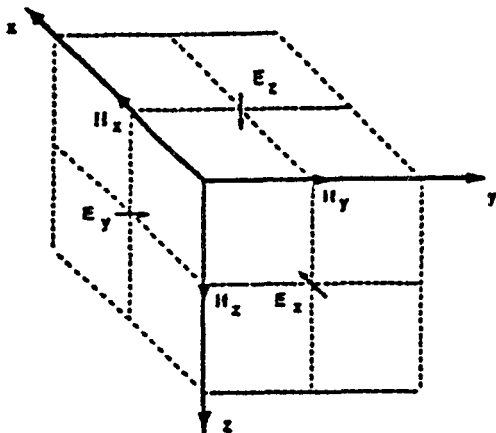


Figure 2.1 Staggered Spatial Grid

MAXWELL'S EQUATIONS

$$\mu \frac{\partial H}{\partial t} + \nabla \times E = M \quad (1)$$

$$\epsilon \frac{\partial E}{\partial t} + \sigma E - \nabla \times H = -J \quad (2)$$

$$\nabla \cdot E = \frac{\rho}{\epsilon} \quad (3)$$

$$\nabla \cdot H = 0 \quad (4)$$

In addition to the appropriate boundary and initial conditions, the material properties at each cell location must be specified. This consists of the magnetic permeability, μ , in equation (1); the conductivity, σ , in equation (2) and the dielectric constant, ϵ , in equations (2) and (3). If the material is homogeneous within the cell (for example, volumes of air, soil, concrete, etc.) then the appropriate values of μ , σ , and ϵ are included in the time advance equations for the cell in question.

If the material properties are inhomogeneous in each cell (detailed structure, etc.) then a decision must be made on how to represent the properties in each cell. In some cases average properties are sufficient and in other cases they are not. Special considerations are available for treating apertures in metal walls and also for pipes and thin wires (radii much smaller than cell dimensions) which may run throughout the problem space. These pipes and wires can be carriers of high current.

The buildings and facilities of interest usually have a great deal of "thin wire" situations in the form of signal and power lines, rebar in reinforced concrete, pipes, plumbing, metal poles, the lightning protection air terminals, down conductors, counterpoise, etc.

The thin wires and rods are implemented in a self consistent fashion by making use of the telegrapher's transmission line equations. The telegrapher's equations (5), (6) are a one dimensional solution of Maxwell's in terms of currents, I_w , and voltages, V_w , on the wires, which are required to have diameters less than cell size (spatial increment). The per unit length inductances and capacitances are defined (7), (8) with respect to the cell size and the wire diameter, $2a$.

The One Dimensional Transmission Line Equations are:

$$\frac{\partial V_w}{\partial z} = -L_w \frac{\partial I_w(k)}{\partial t} - I_w R_w + \bar{E}z(i_w, j_w, k) \quad (5)$$

$$\frac{\partial I_w}{\partial z} = -C_w \frac{\partial V_w}{\partial t} - G_w V_w \quad (6)$$

where L_w and C_w is the in-cell inductance and capacitance of the wire per unit length.

$$L_w = \frac{\mu_0}{2\pi} \ln \left(\frac{\Delta y}{2a} \right) \quad (7)$$

$$C_w = \frac{2\pi a \epsilon E_r(a)}{V_w} = \frac{2\pi \epsilon}{\ln \left(\frac{\Delta y}{2a} \right)} \quad (8)$$

G_w is the in-cell conductance from the wire to the surrounding conductive medium

$$G_w \equiv \frac{\sigma}{\epsilon} C_w \quad (9)$$

The wire resistance per unit length, R_w , is obtained by considering the surface conduction of the metal in question using the skin depth obtained for a frequency of 1 MHz. The resistance for pipes, wire, iron rebar, etc., is normally on the order of 10^{-3} Ohms/meter. In practice, the major results at early time seem to be relatively insensitive to variations of the resistance.

In the computer code, the wires and pipes are embedded into the staggered grid and are driven by the electric field component (see Equation (5)) calculated by the three dimensional solution of Maxwell's equations. In order to maintain electrical charge conservation, this wire current must also be injected back into the driving electric field component as a source current via Maxwell's Equation (2). At the interconnections, which are voltage nodes, Kirchoff's law is invoked. At locations where the wires are situated in the soil or concrete, the wires are in electrical contact with the soil or concrete with in-cell conductance given by G_w in equation (9). This is also true of the facility ground wire which is in contact with the soil.

Complex networks of thin wires (e.g., concertina or metal rebar mesh embedded in conducting concrete) are included in the model by a vectorized extension of the transmission line formalism. Vectorized average wire currents coincide with the electric field vectors in each cell and a corresponding average inductance and resistance is associated with each wire current vector. Six component tensors exist at the cell corners (nodes) describing the equivalent transmission line voltages, wire capacitance, and conductance to the embedding medium. A 36 component connectivity tensor exists at each node describing the ways that wires are connected at the nodes.

At the boundaries of the problem space, some termination condition must be applied to both the counterpoise extensions and the power and signal lines and metal pipes entering the problem space. The boundary condition is applied at current nodes and is the equivalent of the Mur boundary condition applied to the magnetic fields [4].

The problem is initiated by imposing a pre-determined lightning wave form from the top edge of the problem space to a specific point on the structure. In a typical computational case described below, the lightning current waveform is characteristic of a 1% stroke of negative lightning. The lightning current appears without propagation delays in a line of vertical electric fields (E_z) from the top of the computational volume to the attach point. The lightning current is injected into the electric fields by dividing the current by the cell area whose normal is parallel to the vertical direction. This becomes the source current density, J , in Maxwell's equation (2).

The computer model contains features of interest such as, soil, concrete, rebar, counterpoise, etc., which are included in the computer model in a modular form. These separate features may be included or excluded from the model by calling subroutines specific to the features desired. The computations are performed on a CRAY II computer. Typical run times are 1 hour of computer time for each microsecond of real time for problem spaces which, in the cases described here, contain approximately one million cells as shown in Figure 2.1.

3.0 CALCULATION OF SAFE ZONES

The analysis of the preceding sections has been applied to two structures: (1) an earth covered storage igloo with iron rebar reinforced concrete walls as shown in Figure 3.1 and, (2) a rectangular constructed building with a metal roof as shown in Figure 3.2.

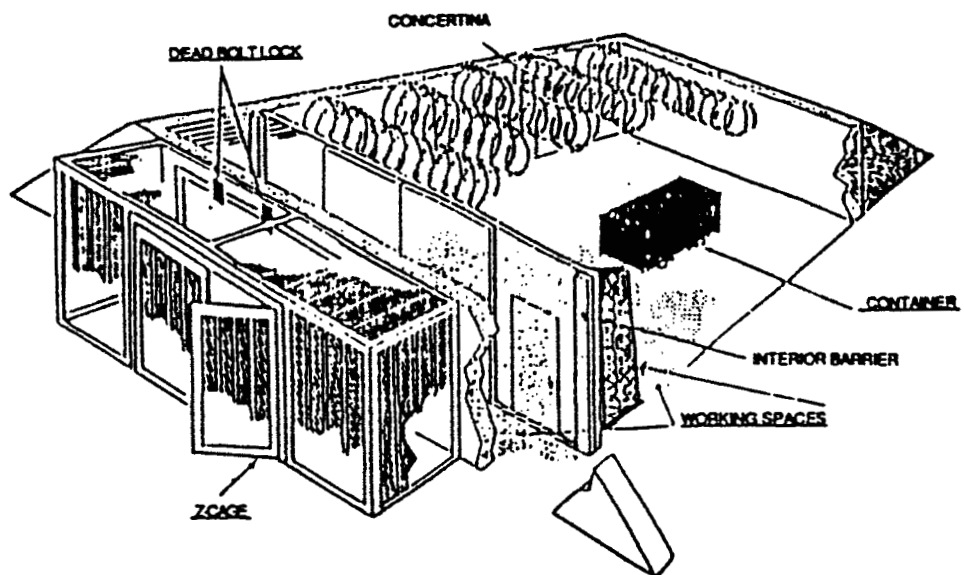


Figure 3.1 Earth Covered Storage Igloo -- Lightning Strike Model

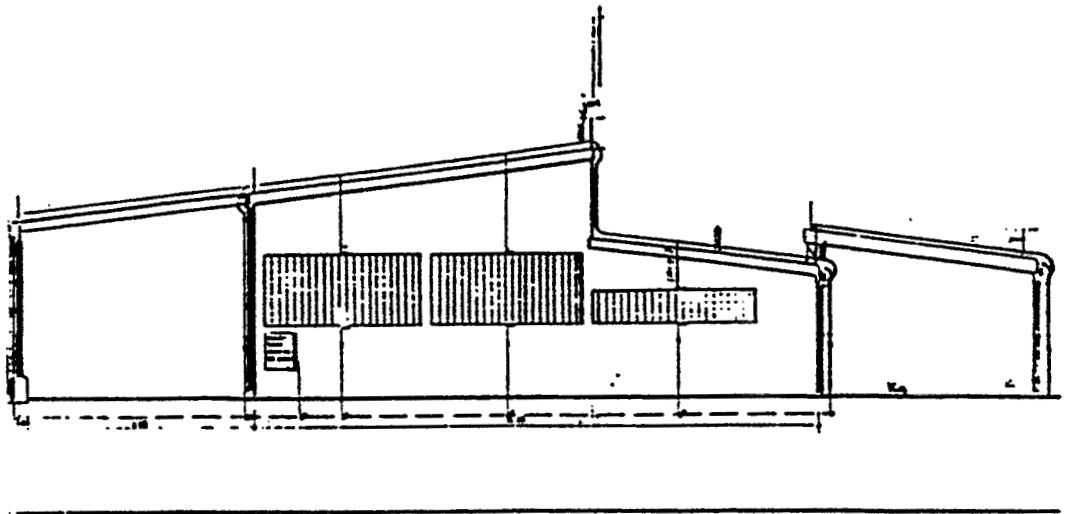


Figure 3.2 Building - Right Side View With Window Screens and Lightning Protection System

The igloo interior is completely surrounded with either metal or iron rebar which forms a "leaky" electromagnetic shield for the interior. A schematic drawing of the igloo vertical mid-cross-section is shown in Figure 3.3.

The building is made of concrete block outer walls with no rebar, a metal roof, and concrete with rebar floor and inner walls with rebar. Thus the building cannot be considered as having a contiguous shielding effect.

For both models the numerical computer output from a simulated lightning strike may be categorized as follows for the establishment of safe zones:

1. Contour Plots - These are "snapshots in time" of the electric and magnetic field structures on a plane cross-section of the building at some time after the initiation of the strike. These contour plots outline areas of constant field magnitude and are used to establish the boundaries of the safe zones for various levels of asset vulnerability. Areas for B-Dot, E-Dot, and total energy are established in the same manner.
2. Time Dependent Plots - these are time dependent graphs of electric and magnetic fields at selected points in the problem space. Currents and voltages on thin wires and rods also have time dependent plots at selected points.
3. Current Arrays - These are spreadsheet tabulations of wire currents in specific areas of the building.
4. Field Maxima - These are computer searches at selected times to find the maximum electric and magnetic fields and the maximum time derivative of the magnetic field within a specified boundary inside the building. This output can be used to check field maxima within safe zones or conversely can identify areas of high threat.
5. Time lapse video presentations showing the magnitudes of the electric and magnetic fields on specific plane cross-sections of the buildings are used for visual development of safe zones [5].

Figure 3.4 shows a contour plot of the vertical mid-plane longitudinal cross-section of the igloo corresponding to the schematic in Figure 3.3. The electric field pattern outlines some of the prominent features of the igloo, i.e., the z-cage, soil berm over the igloo, headwall, backwall, etc. The vectors show the projection of the electric field vector at each cell onto the mid-plane at a time 1 μ sec after the initiation of the strike. The length of the vector is proportional to the logarithm of the electric field. The contour lines show lines of equal electric field magnitude labeled as powers of 10 of the field magnitude in volts per meter. For example, the line labeled 4.0 represents field magnitudes of 10,000 volts/meter.

Figure 3.5 shows a contour plot on a vertical x-z plane of the building cutting through wire mesh on the window nearest the strike. The view is as if looking from the back of the building. The field patterns show essential geometrical features of the model, i.e., roof, supporting I-beams, outer wall, etc.

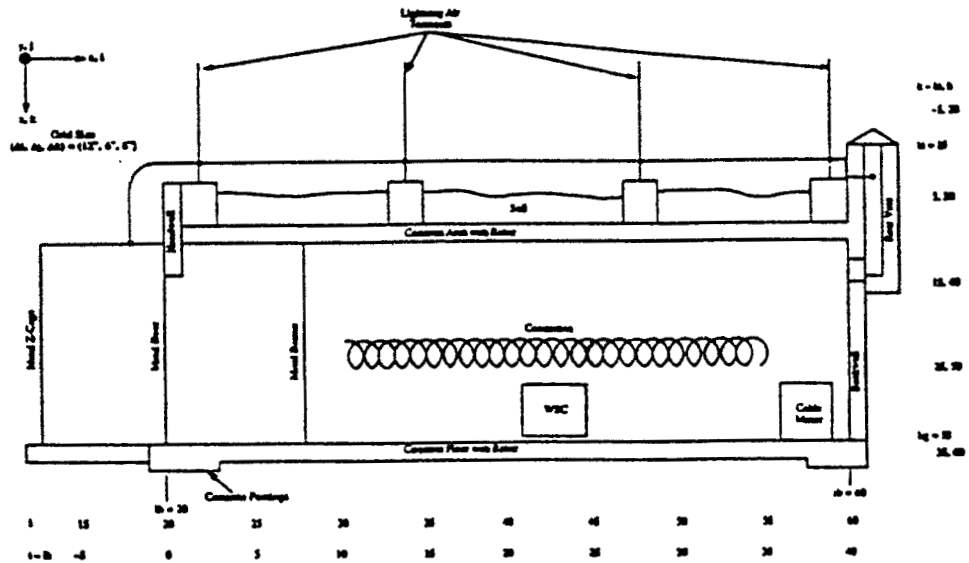


Figure 3.3 Igloo Vertical Cross-Section at $j = j_m = 75$

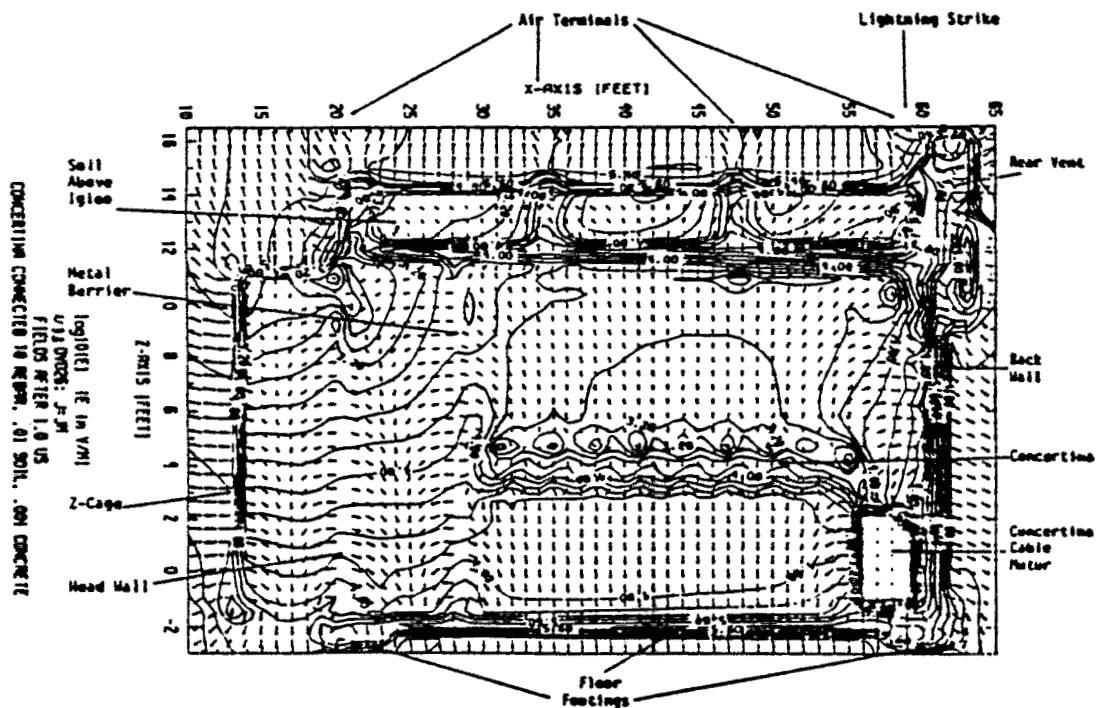


Figure 3.4 Electric Field Vector and Magnitude Contour Plot for Vertical Mid-Cross-Section of Igloo

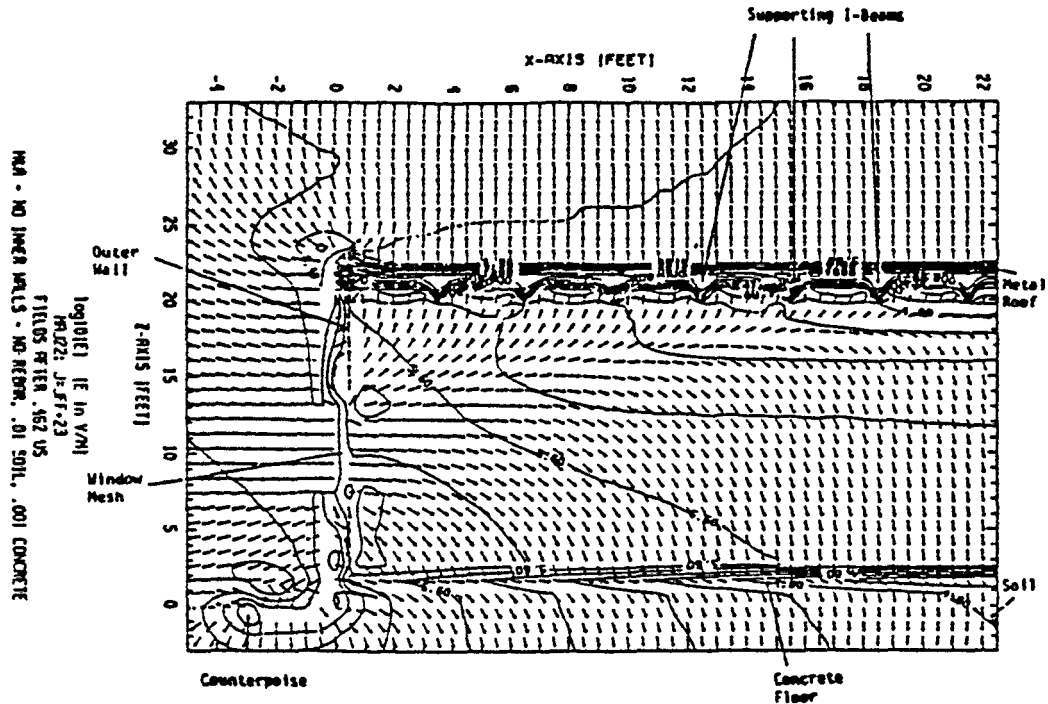


Figure 3.5 Electric Field Vector and Magnitude Contour Plot for a Vertical Plane Passing Through the Window Mesh of the Building .426 μ sec After Attachment

Figure 3.6 shows the effect of adding an I-beam (perpendicular to the contour plane) with a hanging metal cable hoist. The field at the bottom of the hoist is on the order of a few megavolts/meter and represents a potential for arcing between the hoist and the floor rebar (or any other piece of grounded equipment). In this case the lightning protection system is in contact with the metal roof which is also in contact with the I-beam.

4.0 TESLA ASSESSMENT METHOD

The Expert System for Lightning Assessment TESLA procedure for a full/detailed assessment is outlined here for a complicated electronic system; the process was planned to include possible experimental tests and measurements as well as possible extensive calculations [6].

Figure 4.1 shows a block diagram of the work flow for the proposed assessment. The basic activity is a calculation of a margin, that is, a ratio of strength to stress. The stress is compared to strength for interfaces such as electrical lines (e.g., power, telephone) for surges, such as occurs through equipment case seams (for field penetration). These calculations may be performed at various locations throughout the facility to establish safe zones for particular classes of assets.

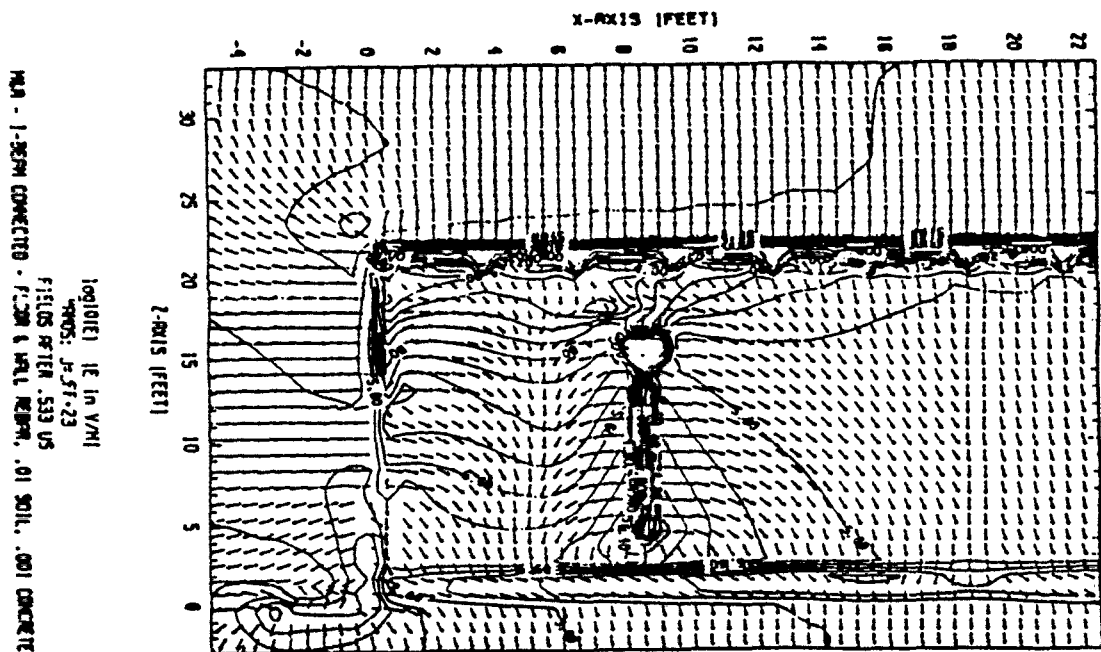


Figure 3.6 Electric Field Vector and Magnitude Plot for Building Showing the Effect of an Internal I-Beam and Metal Cable Hoist

As shown in Figure 4.1, there are nine tasks [6]. Preliminary tasks of planning the assessment and gathering data on the systems and facilities are included in Tasks 1.0 (Preliminary Evaluation), 2.0 (Assessment Plan), and 3.0 (Testing and Data Gathering). The central tasks are 4.0 (Determine Stresses), 5.0 (Determine Susceptibilities) and 6.0 (Calculate Margins/Uncertainties). The approach also includes a review of the final data and possible iteration of the margin calculations, and a final report. These are Tasks 7.0(a) and 7.0(b) (Review, Evaluation), 8.0 (Revise Plans), and 9.0 (Prepare Report).

5.0 CONCLUSIONS

A numerical computer model of Maxwell's Equations V3DFD and a computer based assessment method TESLA have been described for evaluating LPS design and lightning threats to specific facilities. It is seen that detailed electromagnetic field profiles and currents may be calculated and evaluated to determine in a realistic manner safe zones for assets in and around the facility for given lightning attachment points. Further work needs to be done in establishing the probability of location of the attachment points on the LPS and also for probable attachment points on the facility in the event of "failure" of the LPS.

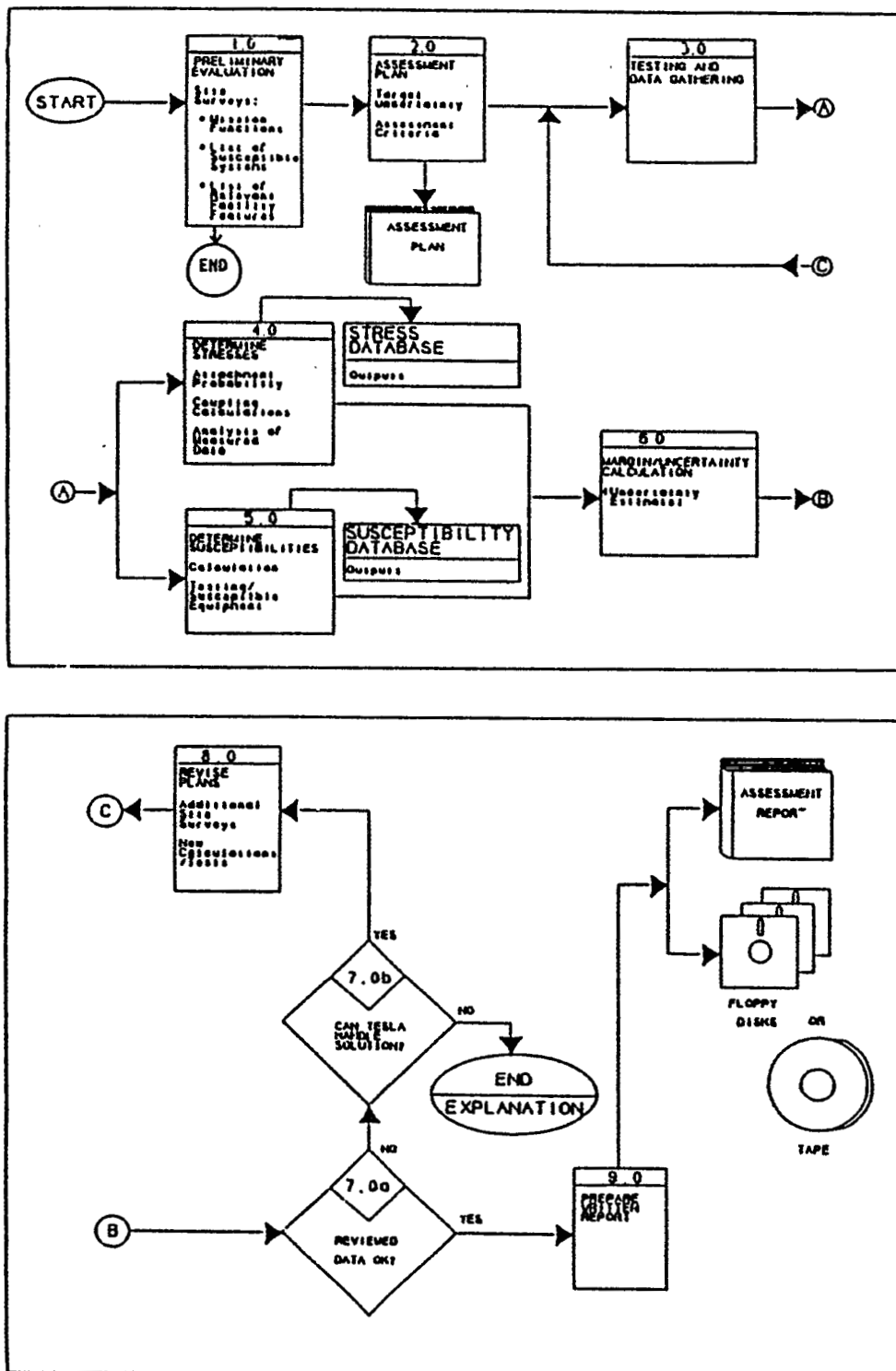


Figure 4.1 The Final Assessment Methodology for a Detailed Assessment by TESLA

6.0 REFERENCES

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