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EVALUATING LIGHTNING HAZARDS TO BUILDING ENVIRONMENTS USING EXPLICIT NUMERICAL SOLUTIONS OF MAXWELL'S EQUATIONS *

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ABSTRACT

Lightning hazards to buildings and their internal environments can be described in terms of electric and magnetic fields (and their time derivatives) and the resulting direct and induced electrical currents which are found in and around critical locations of the building during a lightning strike. The space and time distributions of such fields and currents follow solutions of Maxwell's Equations providing that appropriate initial and boundary conditions can be supplied in the regions of interest and that a method of solution can be applied.

Building environments can be electromagnetically complex, because they consist of a variety of inhomogeneous materials (e.g., concrete with rebar) which may be either conducting or partially conducting. In addition, the structures usually have metallic penetrations such as electrical cables or plumbing, as well as a lightning protection system including an earth ground of some type.

The objective of this paper is to describe the lightning hazards to such structures using advanced formulations of Maxwell's Equations. The method described is the Three Dimensional Finite Difference Time Domain Solution. It can be used to solve for the lightning interaction with such structures in three dimensions and include a considerable amount of detail. Special techniques have been developed for including wires, plumbing and rebar into the model.

Some buildings have provisions for "lightning protection" in the form of air terminals connected to a ground counterpoise system. It is shown that fields and currents within these structures can be significantly high during a lightning strike. Time lapse video presentations have been made showing the electric and magnetic field distributions on selected cross-sections of the buildings during a simulated lightning strike.

1.0 INTRODUCTION

Lightning hazards to building environments can be described in terms of electric and magnetic fields (and their time derivatives) and the resulting direct and induced electrical currents which are found in and around critical locations of the facility during a lightning strike.

The space and time distributions of such fields and currents follow solutions of Maxwells Equations providing that appropriate initial and boundary conditions can be supplied in the regions of interest and that a method of solution can be applied.

This paper describes the results of a numerical computer model which applies Maxwells Equations to describe a specified lightning attachment to a specific building or facility. The result shows how electromagnetic fields and currents are distributed in space and time in and near the facility during a simulated lightning strike. Time lapse video presentations have been made showing these distributions on selected cross-sections of the buildings.

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Examples are given; 1. For an earth covered storage igloo with iron rebar re-enforced concrete walls, and 2. For a rectangular building with cinder-block walls and a metal roof. Both structures have provisions for "lightning protection" in the form of air terminals connected to a ground counterpoise system. It will be shown that fields and currents within these structures can be significantly high during a lightning strike.

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 [1] with further discussion by Collier and Perala [2].

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 1, composed of the vector components of E and H. 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 [1].

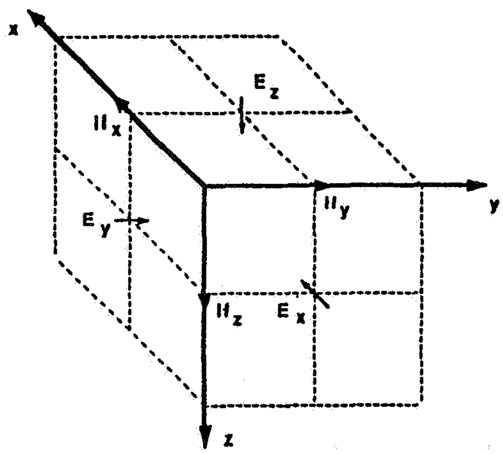

Figure 1 Staggered Spatial Grid

MAXWELL'S EQUATIONS

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

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

$$\nabla \cdot E = \frac{\rho}{\varepsilon} \qquad (3)$$

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

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:

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

$$\frac{\partial I_w}{\partial z} = - C_w \frac{\partial V_w}{\partial t} - G_w V_w \tag{6}$$

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

$$L_w = \frac{\mu o}{2\pi} \ell n \left(\frac{\Delta y}{2a}\right) \tag{7}$$

$$C_w = \frac{2\pi a \varepsilon E_r(a)}{V_w} = \frac{2\pi\varepsilon}{\ell n\left(\frac{\Delta y}{2a}\right)} \tag{8}$$

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

$$G_w \equiv \frac{\sigma}{e} C_w \tag{9}$$

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 (7)) 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 [2].

3.0 THE LIGHTNING STROKE CURRENT WAVEFORM AND INJECTION

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, I(t), is given as a function of time by

$$I(t) = 1.1 \times 10^5 \sin^2\left(\frac{\pi t}{10^{-6}}\right) \quad A$$

$$0 \leq t \leq .5 \times 10^{-6} s \tag{10}$$

$$I(t) = 1.1 \times 10^5 \sin^2\left(\frac{t - .5 \times 10^{-6}}{5 \times 10^{-5}}\right) \quad A$$

$$.5 \times 10^{-6} < t$$

which has a peak current of 110 kA occurring at .5 μs. 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). A number of different parameters are studied: lightning stroke attachment location, soil electrical conductivity, structure wall rebar composition, and power box attachment at the walls and ceiling. These parameters are varied in order to provide environments based upon the range of situations which could be encountered.

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.

4.0 LIGHTNING STRIKE MODELS

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 2 and, (2) a rectangular constructed building with a metal roof as shown in Figure 3.

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 4.

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:

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.

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.

5. Time lapse video presentations showing the magnitudes of the electric and magnetic fields on specific plane cross-sections of the buildings.

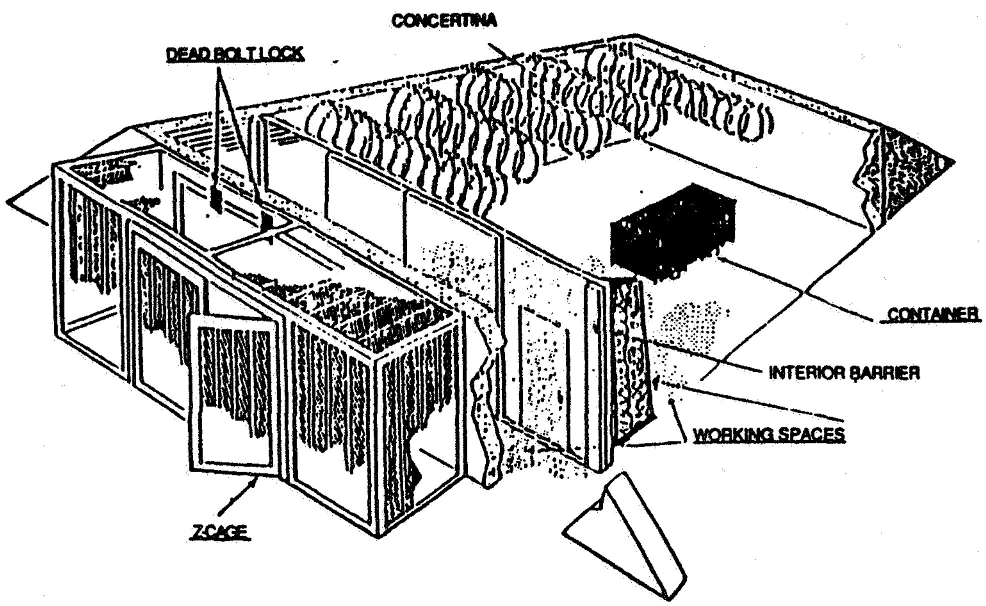

Figure 2 Earth Covered Storage Igloo -- Lightning Strike Model

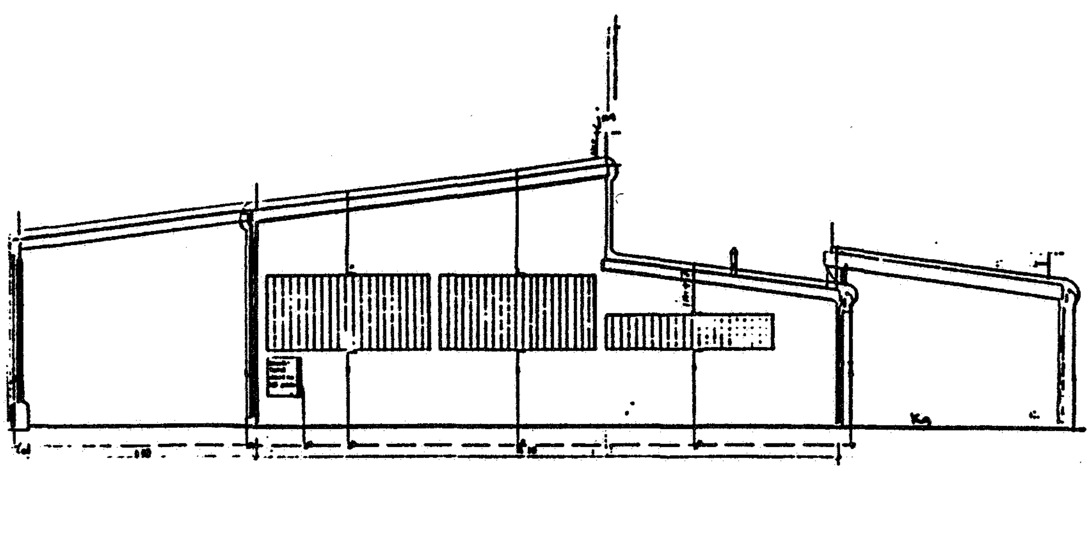

Figure 3 Building - Right Side View With Window Screens and Lightning Protection System

Figure 5 shows a contour plot of the vertical mid-plane longitudinal cross-section of the igloo corresponding to the schematic in Figure 4. 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 μsec 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 6 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.

The window mesh, a wire grid covering the building windows, is being charged (note E-field vectors pointing away from the mesh) and appears to focus the electric field into the interior of the building. The field levels are very high within the building approaching 1 Megavolt/meter (contours are labeled as powers of 10 of the electric field magnitude).

In this case, Figure 6, the lightning protection system is not connected to the metal roof. At .462 μ seconds the top of the roof is positively charged and the bottom of the roof is negatively charged.

Figure 7 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.

Figure 8 shows time dependent plots, corresponding to Figure 7, of the lightning injection current (given by equations (12)), the electric field and wire voltage in the middle of the window screen, and the voltage between the hoist hook and the floor rebar. This is a case showing that connecting the lightning protection system to the building structure can enhance the hazard inside the building.

5.0 TIME LAPSE VIDEO PRESENTATIONS

The video tape shows computer calculated electric and magnetic fields on two different vertical plane cross-sections of the igloo (see Figure 4). The presentation begins with a view of the right-hand side of a transverse cross-section and ends with a views of the longitudinal vertical mid-cross-section (see Figures 4 and 5) and a plane offset from the mid-cross-section.

The data shown is calculated by a Cray II computer using a finite difference form of Maxwell's Equations. The resulting data pertinent to the video display is taken from the Cray II computer results and displayed on an IBM PC compatible EGA screen. These EGA screens have twice the resolution of the VHS video tapes.

The graphic frames are displayed at a rate of about 3 frames per second. Each frame occurs in simulated real time in 50 nanosecond intervals. There are then 20 frames per 1 microsecond simulated real time showing the time development of the electric and magnetic fields for each typical computer run. The time is shown in the upper left-hand corner of the screen.

The electric and magnetic field magnitudes are shown at each finite difference cell on the plane. The colored dots represent the field magnitude ranges at each cell. Vectors centered on the dots also exist at each cell showing the direction of the field projection onto the plane. The scale of values are shown in the video tape. There are approximately 1 million finite difference cells in the entire problem space.

The peak magnitude of the lightning current is 110 KA and the rise time is .2 microseconds. The lightning attaches to the igloo on the rear lightning protection air terminal near the vent chimney of the igloo.

The charge collecting on the rebar may be noted by observing electric field vectors pointing away from the ceiling and back wall in both directions.

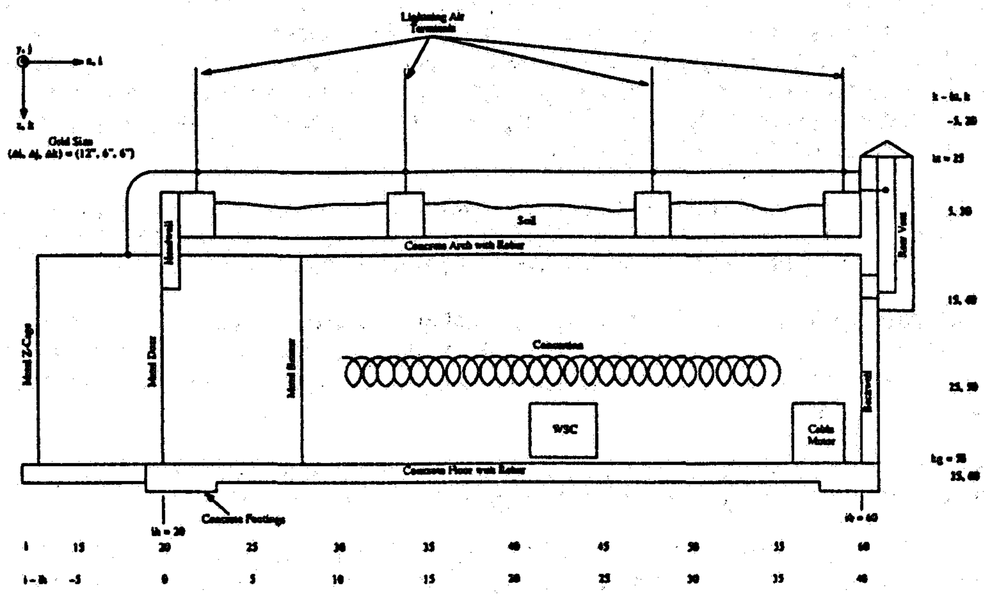

Figure 4 Igloo Vertical Cross-Section at j = jm = 75

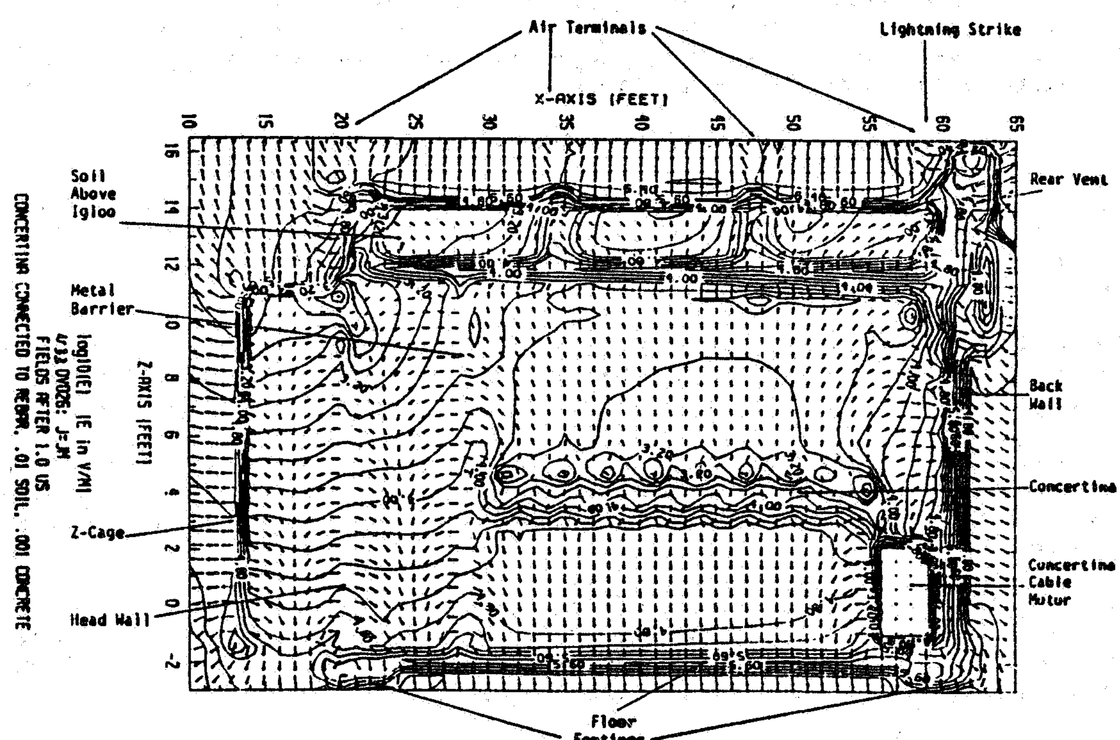

Figure 5 Electric Field Vector and Magnitude Contour Plot for Vertical Mid-Cross-Section of Igloo

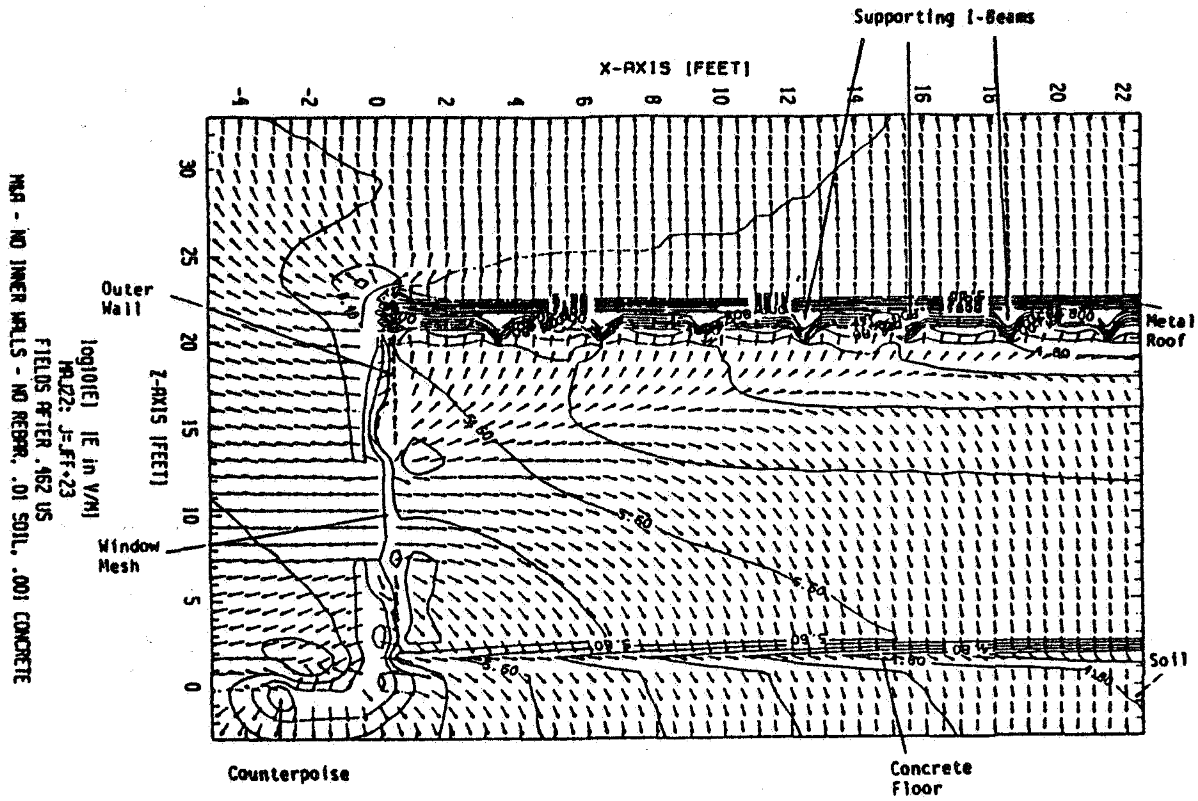

Figure 6 Electric Field Vector and Magnitude Contour Plot for a Vertical Plane Passing Through the Window Mesh of the Building

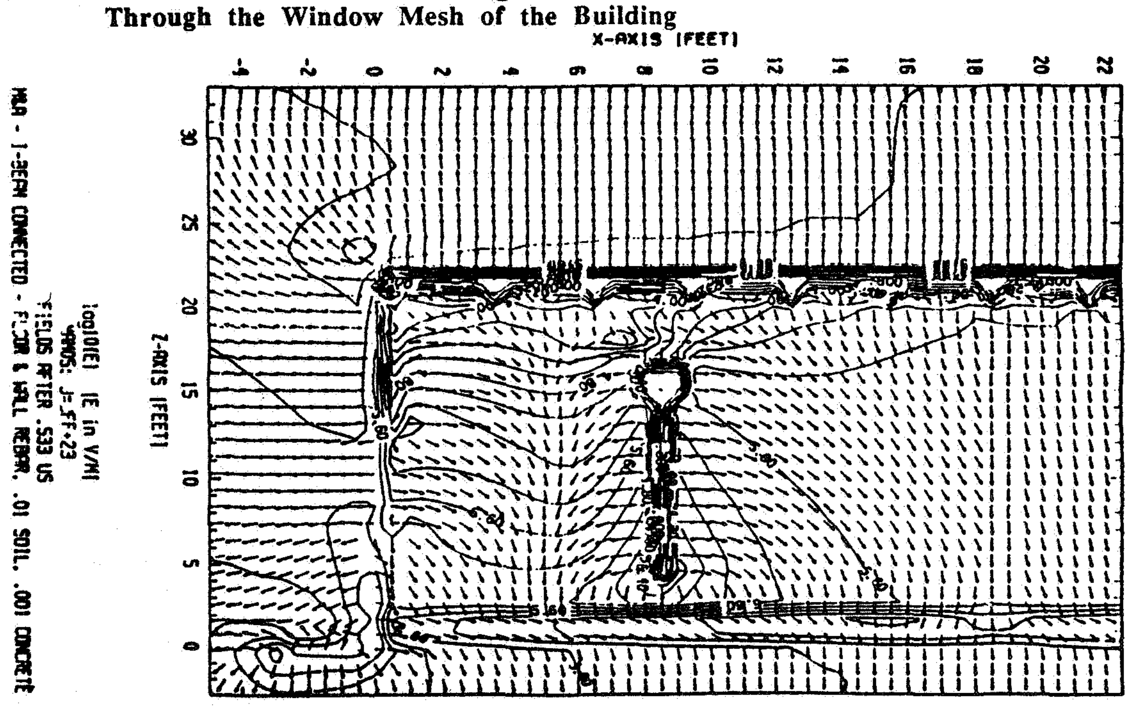

Figure 7 Electric Field Vector and Magnitude Plot for Building Showing the Effect of an Internal I-Beam and Metal Cable Hoist

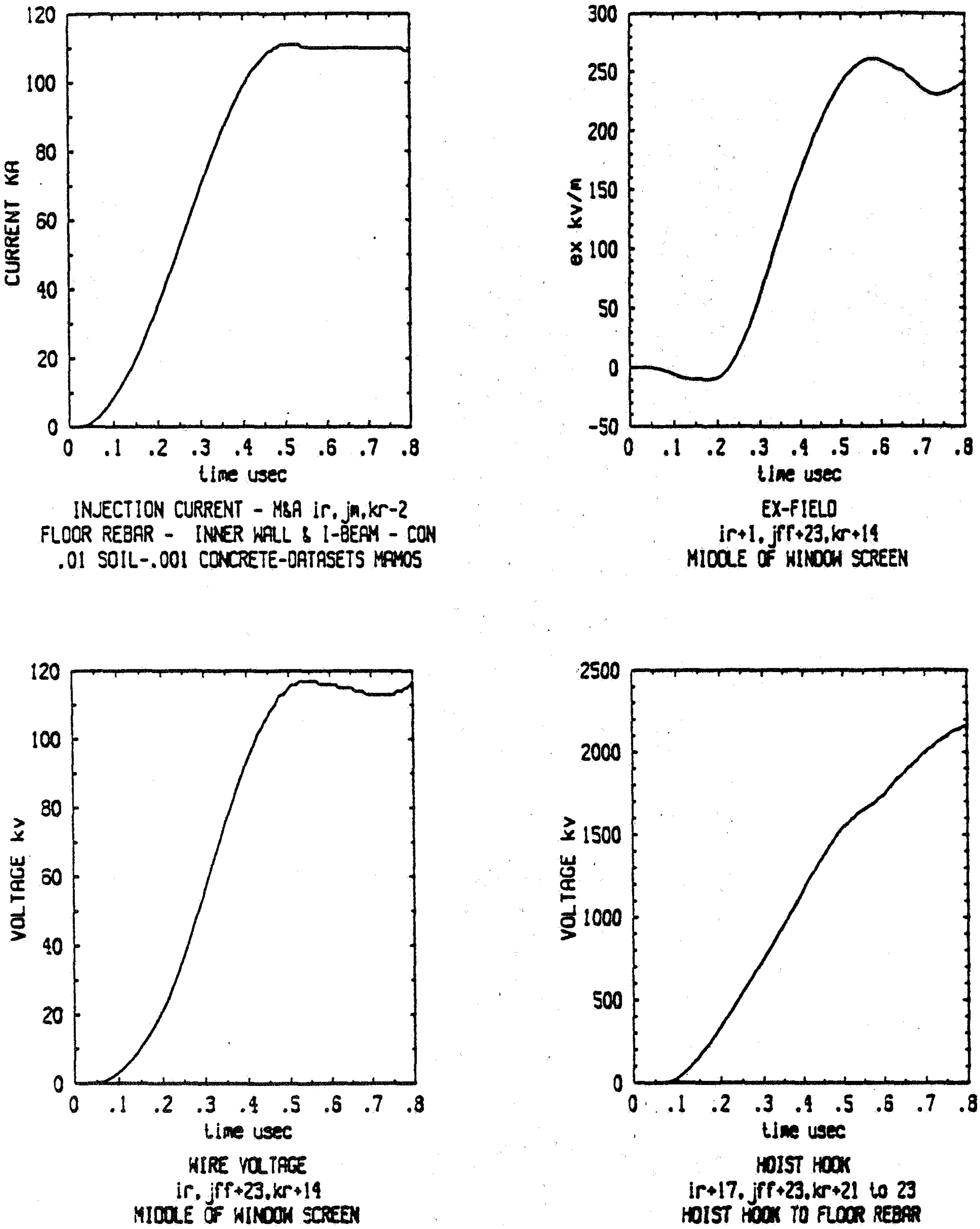

Figure 8 Time Dependent Plots of Building Fields and Lightning Injection Current

It is noted that the largest fields are near the floor and are on the order of 100 Kvolts/meter at 1 μsec. This is due primarily to capacitive coupling of charge on the rebar which, again, is enhanced by electrical contact between the lightning protection system and the igloo metal structure.

6.0 CONCLUSIONS

A numerical computer model of Maxwell's Equations has been applied to buildings typical of munitions storage and handling structures to calculate potential hazards due to lightning strikes. It is seen that detailed electromagnetic field profiles and currents may be calculated which estimate in a realistic manner the hazardous areas in and around the facility. A time lapse video representation has been produced which shows the electric and magnetic field magnitudes on plane cross-sections of the building during a simulated lightning strike.

7.0 REFERENCES

1. Merewether, D.E., and R. Fisher, "Finite Difference Solution of Maxwell's Equations for EMP Applications," Electro Magnetic Applications, Inc. Report, EMA-79-R-4, Final Revision, 1/15/82.

2. Collier, Richard S. and Rodney A. Perala, "Evaluation of Lightning Hazards to Munition Storage Handling, and Maintenance Facilities with the use of Advanced Methods for Solutions of Maxwell's Equations," presented at the Twenty-Fourth DoD Explosives Safety Seminar, Adam's Mark Hotel, St. Louis, Missouri, 28 - 30 August 1990.