R. E. Taylor, Code 523

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Final Report for

LIGHTNING PROTECTION GUIDELINE
FOR
STADAN GROUND EQUIPMENT

Prepared by:

HIGH VOLTAGE LABORATORY
General Electric Company
Pittsfield, Massachusetts

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Written By:

T. J. Blalock — 20 Nov. 67
T. J. Blalock, Development Engineer — Date

Approved By:

E. R. Uhlig — 20 Nov 67
E. R. Uhlig, Manager, Lightning and Transients Technology — Date

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Section 1.0

Introduction

1.0 INTRODUCTION

This report describes an investigation which was made of the lightning protection and grounding system at the National Aeronautics and Space Administration's STADAN Data Acquisition Station near Rosman, North Carolina. The station had experienced severe system interruptions due to lightning prior to this investigation. It was felt that the nature of the problems encountered constituted a threat not only to equipment at the station, but also to the safety of operating personnel. The investigation was initiated for the purpose of providing recommendations as to improvements in the grounding system that would reduce the lightning hazard. These recommendations, and their applicability to other sites of this nature, are described in this report.

1.1 General Description of Rosman STADAN Site

The site under consideration is a tracking station operated by the National Aeronautics and Space Administration for the purpose of tracking and for acquiring telemetry data from unmanned orbiting satellites and space vehicles. The station is one of 13 stations in a world-wide network known as the Space Tracking and Data Acquisition Network (STADAN). The headquarters for STADAN is at the Goddard Space Flight Center in Greenbelt, Maryland.

The site is located in hilly territory near the town of Rosman in the southeastern corner of North Carolina. Two main types of antenna systems are used at the Rosman station:

1. Eighty-five foot steerable "dishes" (2 at Rosman)
2. Satellite Automatic Tracking Antennas (SATAN)
    a. SATAN command yagi arrays (2 at Rosman)
    b. SATAN receive yagi arrays (2 at Rosman)

The auxiliary antenna equipment at Rosman includes several collimation towers, range and range rate tracking facilities, a WWV antenna for the reception of timing signals, and a SATAN system used by the Applications Technology Satellite (ATS) group at the site. The antenna structures and associated buildings are spread over an area of roughly 40 acres. All electric power is generated at the site and there are no ties with public electric utilities in the area. There are ties with the local public telephone system, however. There are four major buildings on the site designated as Operations, Instrumentation, Utility, and Power Generation. The Operations Building houses the personnel and equipment for the major tracking and data acquisitions functions. The Instrumentation Building houses the personnel and equipment of the ATS group. A microwave link is provided between Rosman and Greenbelt, Maryland for the purpose of relaying data to the Goddard Space Flight Center.

Section 2.0

Lightning Strokes to Structures and Earth

2.0 LIGHTNING STROKES TO STRUCTURES AND EARTH

2.1 General

One of the major factors to consider in determining the probability of lightning damage is the number of lightning strokes to earth in a given area and for a given time. Since precise quantitative data do not exist (except at a few specifically-instrumented structures), a secondary measure, the frequency of thunderstorms, is used.

For many years, weather bureau stations have recorded "thunderstorm days" (the number of days per year on which thunder is heard). This index is called the "keraunic level".

It should be noted that the information so collected is of limited value for several reasons. First of all, no distinction is made between cloud-to-cloud discharges and cloud-to-ground strokes. Also, there is no allowance for the duration of a storm. A storm lasting an hour would be counted as heavily as one lasting several hours. Despite these limitations, the keraunic level is broadly useful and can be correlated at least partially with lightning strokes to earth-based objects. The weather bureau has compiled keraunic data on a statistical basis and published a map of the United States which gives isokeraunic areas. Figure 2.1 is an isokeraunic map of the United States. As shown, the incidence of lightning varies throughout the country, being lowest at the Canadian border and West Coast and highest over the Gulf Coast of Florida.

2.2 Stroke Frequency at Rosman, North Carolina

Stroke frequency to ground can be estimated by multiplying the keraunic level at the place of interest by a factor. This factor is an empirical number which has been determined by analysis of data concerning lightning strokes to power transmission lines. This factor varies between 0.23 and 0.5 for strokes to ground per square mile. For example, at the Rosman site where the keraunic level is 50, the expected stroke frequency would be from $50 \times 0.23 = 11.5$ to $50 \times 0.5 = 25$ strokes per square mile per year. For such numbers to have significance, the effective area of the site must be established.

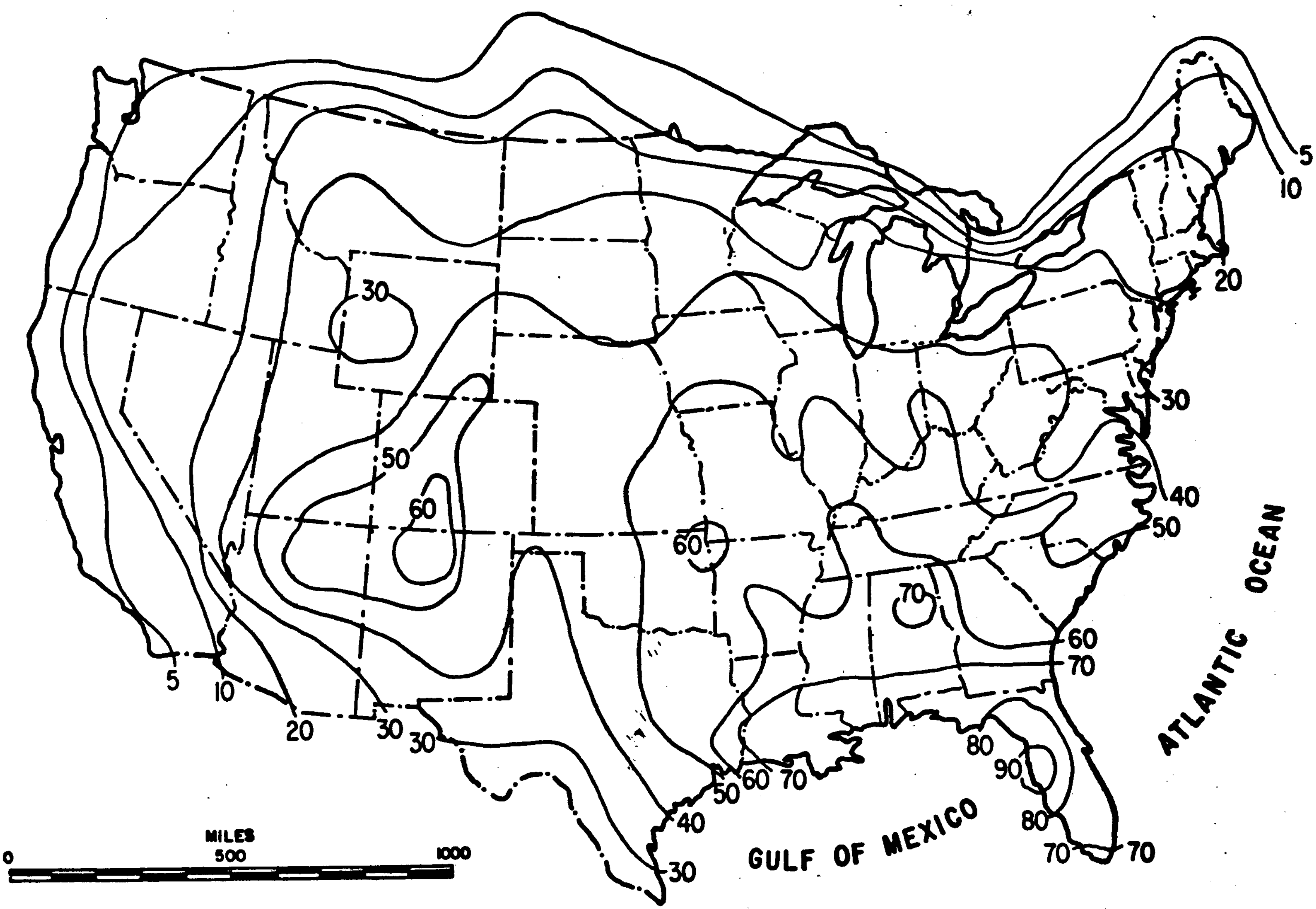


FIGURE 2.1
ISOKERAUNIC MAP
SHOWING
NUMBER OF THUNDERSTORM DAYS PER YEAR

The site effective area must be estimated. This area can be established by drawing a boundary around the site which limits the surface horizontal electric gradient at site facilities to less than 10,000 volts per meter for average current strokes terminating on or outside the hypothetical boundary. The distance the "boundary" must be from site facilities is calculated from Equation A.2 of the Appendix and the average stroke current is determined from Figure A.3 of the Appendix. The earth resistivity must be known or measured. Rosman earth resistivity measurements are shown in Figure 3.2 of this report.

Using a value of 40,000 amperes for an average lightning stroke and a resistivity of 6000 ohm-meters, the "boundary" line at the Rosman site would be 500 feet out from all site facilities. Such a boundary has been drawn around a site plan and is reproduced in Figure 2.2. The area of the odd shape is 0.33 square mile. Using this number and the previously arrived at strokes-per-square-mile numbers, a stroke frequency from 4 to 8 strokes per year to the Rosman facility is calculated. These numbers compare favorably with the number of separate damage-producing storms recorded by site personnel at Rosman.

Tall structures are frequent targets for lightning strokes. The collimation towers at the STADAN sites are the tallest structures and are between 100 and 200 feet high. Statistical data on strokes to tall structures predict that for a keraunic level of 50, a 100-foot high structure would be struck 0.23 times and a 200-foot high structure 0.70 times per year. These stroke rates are directly proportional to keraunic level.

Since these numbers are significantly smaller than the expected 4 to 8 strokes to the general area at Rosman, the lightning problem is not primarily one of strokes to the antenna towers. Design changes and "fixes" to control lightning effects, while including the towers, must be directed at random strokes to ground ultimately contacting some part of the site electric, electronic, data or ground systems.

2.3 Keraunic Levels at Other STADAN Sites

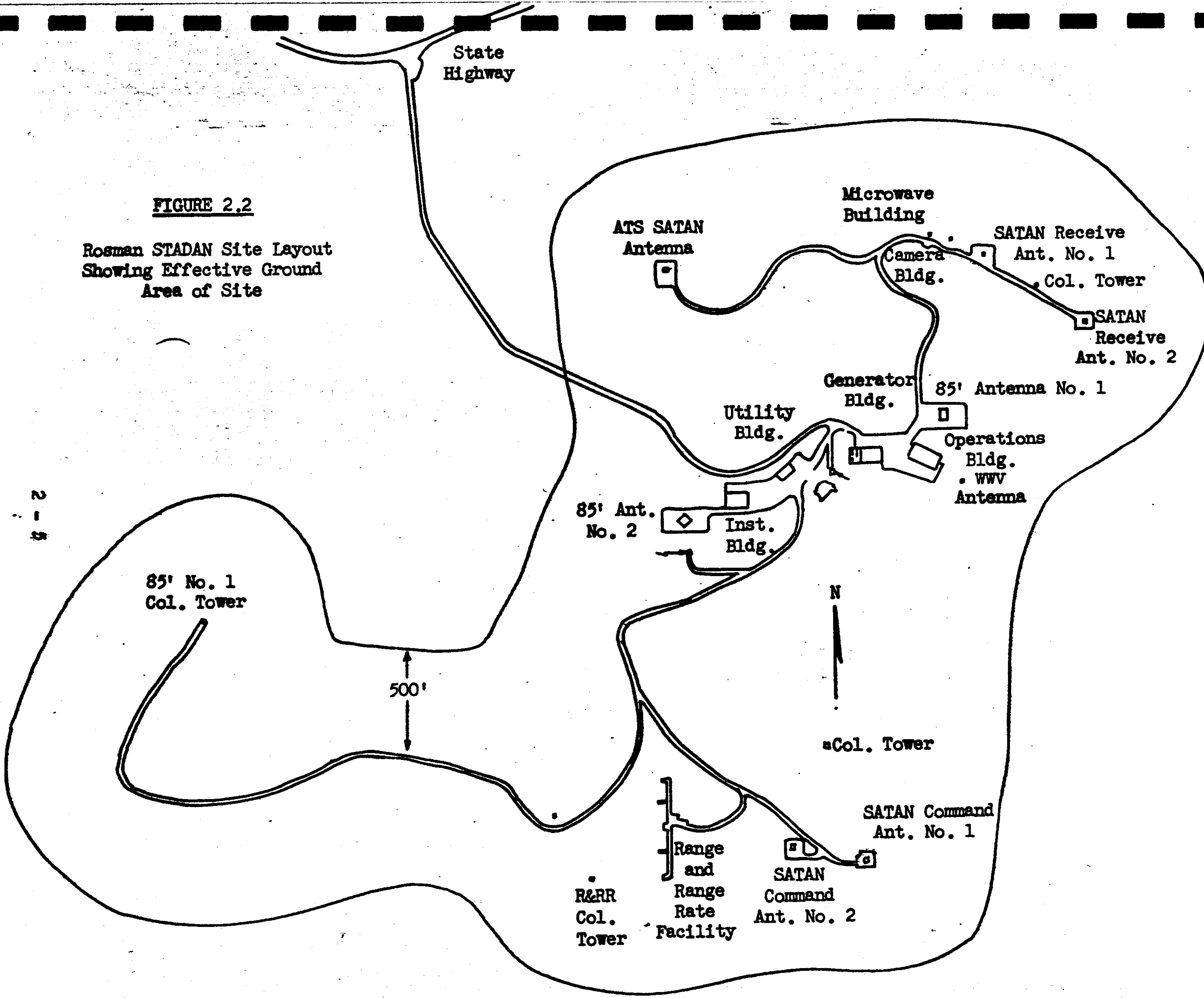
To aid in making stroke frequency calculations at other site locations, the following table has been prepared:

Site Location	Keraunic Level*
Fairbanks, Alaska	10
Carnarvon, Australia	1
Fort Myers, Florida	91
Greenbelt, Maryland	35
Johannesburg, South Africa	74
Kano, Nigeria	82
Kauai, Hawaii	6
Lima, Peru	15
Goldstone, California	5
Newfoundland	5
Orroral, Australia	9
Rosman, North Carolina	50
Santiago, Chile	3
Tananarive, Madagascar	132
Wallops Island, Virginia	40
Winkfield, England	14

* from "World Distribution of Thunderstorm Days", World Meteorological Organization, Geneva, Switzerland

FIGURE 2.2

Rosman STADAN Site Layout
Showing Effective Ground
Area of Site



Section 3.0

Grounding System Analysis

3.0 GROUNDING SYSTEM ANALYSIS

3.1 Description of Rosman Grounding System

Figure 3.1 shows the layout of the grounding system connections between structures at Rosman. This system was designed to provide two distinct grounding systems:

1. a safety ground system to which all metallic structural members and power system grounded conductors are connected.
2. a signal ground system which provides a low noise ground network for signal and electronic power supply common returns.

The conductors for both systems are buried in cable trenches at the site. The safety ground conductors between structures are 500 MCM bare copper cable and the corresponding signal ground conductors are 500 MCM insulated copper cable. Because of high earth resistivity in the area, three ground fields were provided at locations indicated on Figure 3.1. These fields consist of up to 40 driven grounding rods each. These rods are driven in a regular pattern and each rod is salted. Alternate rods in each field are tied together, forming one group for signal ground connections and a second group for safety ground connections. A separate ground conductor for each ground system is run from each structure at the site to a ground field. Also, conductors are run between adjacent fields. The numbers in parentheses along the cable runs shown on Figure 3.1 are the number of conductors for each ground system which is present in that run. All conductors of one system entering a ground field terminate on a connection plate and from this plate conductors radiate to the individual rods in that field belonging to that system. The only intentional connection between the two systems was made at ground field #2 as shown on Figure 3.1. The grounding system conductors are run in trenches along with the power, signal, and control cables which run between structures. Since the safety ground conductors are uninsulated, care was taken to separate the individual conductors in each trench by a specified minimum distance. At each structure, two ground connection plates are provided; one for safety ground connections is bonded to the metallic members of the structure and the other for signal ground connections is insulated from the structure.

3.2 Ground Resistance and Earth Resistivity

Resistivity measurements were made at the site with the aid of a Biddle four-terminal "megger". Figure 3.2 shows the variation in resistivity with depth beneath the surface. These results were calculated from measurements made near the ATS SATAN antenna installation. There were no buried cables or counterpoises in the immediate vicinity, so it is believed that the results are fairly accurate.

It can be seen that over a range of depth from 12.5 to 50 feet, the resistivity increases fairly linearly with depth. This indicates that lightning current injected into the earth would tend to stay fairly close to the surface, thereby creating more of an opportunity for the current to find its way into the grounded conductors of buried cables in the vicinity. It is not known how the resistivity would vary at depths less than 12.5 feet. This variation would be more dependent on surface conditions, especially the amount of moisture present. Also, it is not known whether these resistivities are representative of the Rosman site in general or whether there would be large variations in different locations.

Also shown in Figure 3.2 are the results of similar resistivity measurements made by NASA personnel at a STADAN site on the island of Madagascar. Not only are these resistivity values generally lower than those for Rosman, but the resistivity values tend to decrease with increasing depth, whereas at Rosman the resistivity increased with increasing depth, as was discussed above. Therefore, it would be expected that the Madagascar site should experience much less trouble during lightning activity than the Rosman site. According to failure reports to date, this apparently is the case.

3.3 Cable Shields

Some of the buried instrumentation cables which run between structures are shielded. In the case of multiple conductor cables, individual conductors or conductor pairs may be shielded and the entire cable may be enclosed in an outer sheath as well. It was found that these inner and outer shields are treated differently as far as grounding is concerned, the inner shield being bonded to the signal ground system and the outer shield being bonded to the safety ground system in most cases. In addition, the shields are grounded to their respective systems at one end only, the opposite end being left "floating". This practice was also carried out at cable splicing points in long runs, the shields on one spliced end being grounded and the shields on the other spliced end being left open.

3.4 Effectiveness of the Present Grounding System for Lightning Protection

A primary objective of the present grounding system at Rosman is to provide low-noise signal-return paths as well as suitable power system and lightning grounds. In order to achieve this objective, some practices were followed which can lead to problems during lightning-storm activity.

1. The general configuration of the grounding system is bad from a lightning standpoint because of the electrical isolation of the two subsystems (safety ground and signal ground). This leads to the possibility of the generation of severe surge voltages and subsequent sparking activity since, inevitably, physically-close pieces of equipment will be connected to different subsystems in some instances. This sparking is not only injurious to equipment and cabling, but represents a hazard to personnel either directly or due to the possible presence of combustible material in the vicinity of sparking activity.
2. Again, in an effort to maintain high signal-to-noise ratios, certain parts of the grounding system and grounded conductors were not bonded together so that the possibility of having ground loops which could circulate unwanted noise-generating currents would be minimized. For example, signal cable shields were grounded at one end only in many instances. This again leads to the possibility of sparking and, in addition, can cause surge voltages to appear on the circuit conductors within the cables. These surges can destroy electronic components which are connected to these conductors.

Therefore, from strictly a lightning-protection standpoint, the present grounding system could be improved considerably by the use of additional bonding and/or installation of protective devices to limit surge voltages on both circuit and grounding conductors.

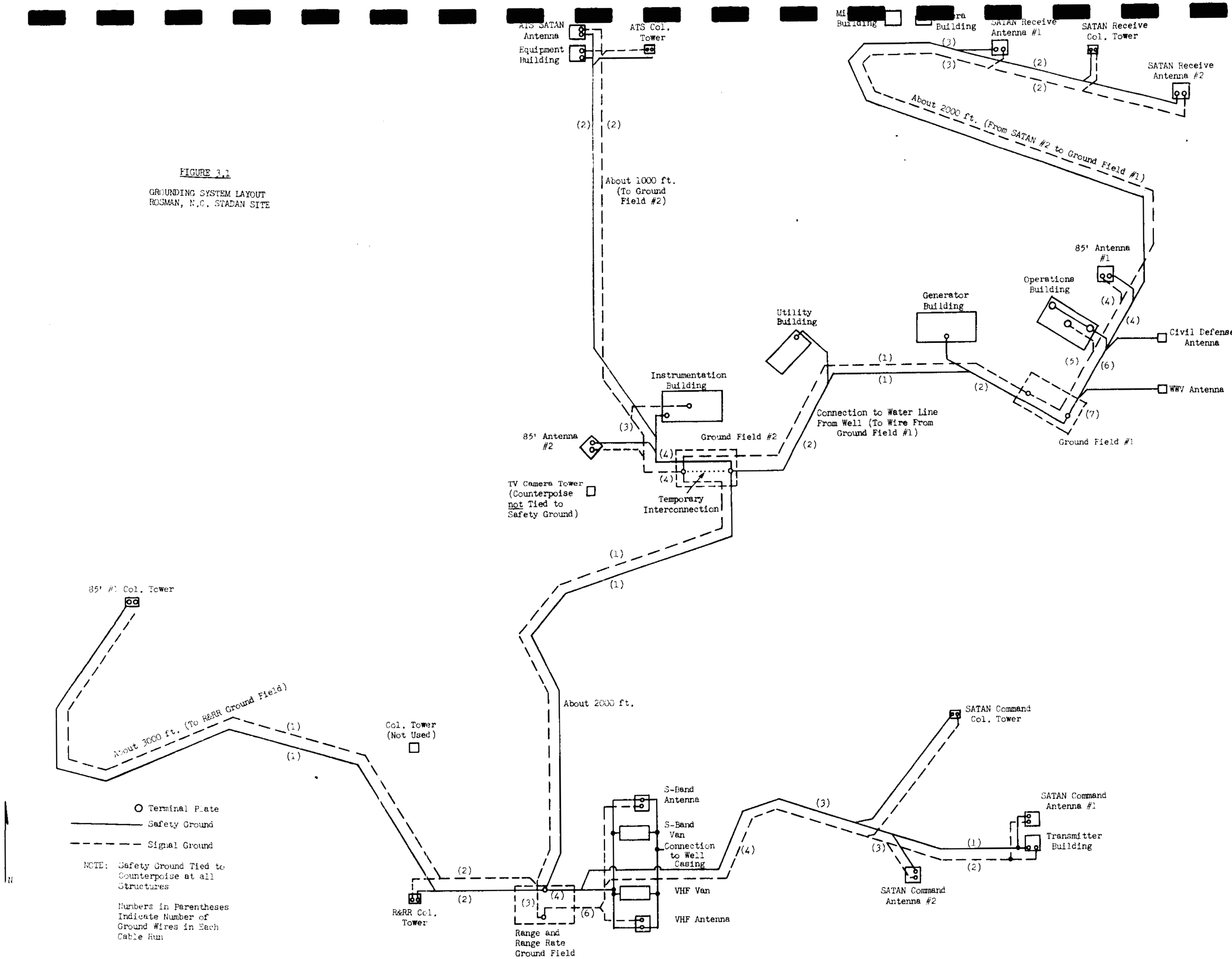


FIGURE 3.1

GROUNDING SYSTEM LAYOUT
ROSMAN, N.C. STADAN SITE

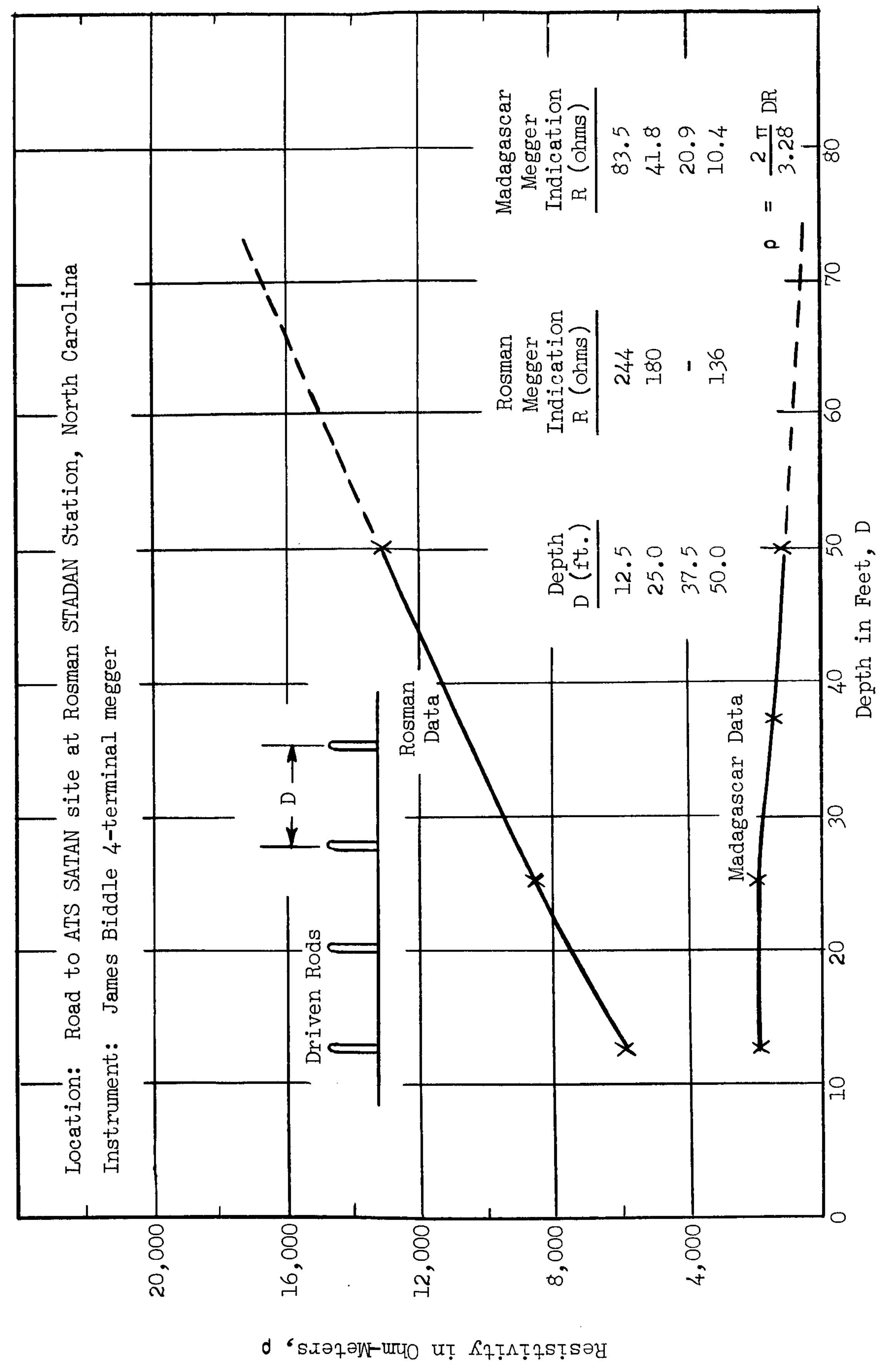


FIGURE 3.2 Ground Resistivity versus Depth

Section 4.0

Lightning Induced Voltages

4.0 LIGHTNING INDUCED VOLTAGES

4.1 General Lightning Induced Voltage Calculations

4.1.1 Magnetically Induced Voltage

A primary means by which voltages are built up under lightning surge conditions in a grounding system such as that at Rosman is magnetic induction. Faraday's Law of Electromagnetic Induction states that:

$$V = - N \frac{d\phi}{dt}$$

This means that if a conductor is bent in the form of a coil with N turns and placed in a changing magnetic field such that an amount of magnetic flux, ϕ, links the coil, a voltage given by V will be induced between the open ends of the coiled conductor. $d\phi/dt$ is the rate of change of the flux linking the coil with respect to time. The minus sign is merely an indication of the polarity of the induced voltage and is of no significance as far as the magnitude is concerned.

For example, consider Figure 4.1 which shows two conductors running in parallel, a situation which is found in the cable trenches at Rosman. The upper conductor is a shielded cable with the outer shield grounded to the safety ground at the right end only. The lower wire is a bare 500 MCM safety ground conductor. Thus, a single loop (N = 1) is formed and a voltage, V, can be induced at Location 2 if the loop is subjected to a changing magnetic field. Such a field would be produced by lightning induced current flowing in the safety ground.

At location 3 some lightning current, I, finds its way into the system. This current will flow, for the most part, into R_{g_2} and through the safety ground to R_{g_1} at location 1. Since the safety ground wire is uninsulated, current will leak to ground along its length and so the current will not be of constant magnitude throughout the length of the safety ground wire. Also a small amount of current will begin to flow in the cable shield until such time as it discovers that there is no path for it to follow at the far end. Since this current would probably be small and would decay to zero in a few microseconds, it was neglected.

The current flowing through the safety ground sets up a magnetic field around this conductor. The amount of flux linking the loop ABCDA is a function of both the rate of change of the flux density and the loop area. The rate of change of flux density, in turn, is proportional to the rate of change of the injected lightning current. Using Equation A.17 from the Appendix:

$$V_{mag} = 61 \times 10^{-9} \times h \times \log_e\left(\frac{r_2}{r_1}\right) \times \frac{dI}{dt} \quad \text{volts}$$

where V_{mag} is the induced potential, V, in volts as shown on Figure 4.1, dI/dt is the rate of change of the current in the circuit in units of amperes/μsec, $\log_e$ is the natural logarithm, and r_1 and r_2 are as defined in the Appendix.

Since the current flowing in the safety ground conductor is not constant along its length, there is no simple number which could be plugged into this equation for dI/dt. The safety ground was treated as a transmission line with a surge impedance of 150 ohms and a total leakage resistance to ground of 14 ohms. The leakage resistance was calculated using Equation A.11 in the Appendix. The ground field resistances, R_{g_1} and R_{g_2} on Figure 4.1, were assumed to be equal to one ohm each. With the aid of a digital computer program, the response of this transmission line to the assumed lightning current wave shape was found. From this the current distribution as a function of distance along the safety ground wire was found. This enabled the induced voltage to be calculated with the aid of Equation A.17 and it was found to be:

$$V_{mag} = 0.7 \text{ volt/amp of lightning current}$$

For example, if I = 1000 amperes:

$$V_{mag} = (0.7)(1000) = 700 \text{ volts}$$

Equation A.17 was the basis for this calculation but, as explained above, the procedure involved was more complicated because of the current leakage from the safety ground wire to earth along its length.

Several points should be mentioned concerning this analysis.

1. This is a simplified illustrative example and should be treated as such. It is believed that the results of these calculations are reasonably correct approximations of conditions which might exist at Rosman. However, not enough information was available concerning actual cable lengths and spacings and soil resistivity to calculate actual voltages to be expected at specified points at Rosman under lightning conditions.
2. For cable runs less than 2,000 feet in length, the induced voltage would be correspondingly less. Also, if the cable in Figure 4.1 ran closer to the safety ground wire, the induced voltage would be less.
3. If R_{g_2} is greater than the assumed value of one ohm, more current would flow in the safety ground wire and the induced voltage would be higher. It is believed that this would be the case at most of the antenna locations at Rosman.
4. If the current which flows in the cable shield for the first few microseconds after lightning current is injected is not negligible, the induced voltage will be slightly less. This is because the flux set up by this current would tend to cancel that set up by the current in the safety ground wire.
5. The leakage resistance of the safety ground wire was calculated by assuming an earth resistivity of 3,000 ohm-meters. This value is an extrapolation of data which were obtained at Rosman. The resistivity could be much greater, in which case the leakage to ground of current flowing in the safety ground wire would be less significant. In the limiting case, when the leakage is zero, the induced voltage is much easier to calculate since the current flowing in the safety ground is constant along its entire length. For this calculation, the surge impedance of the safety ground conductor was assumed to be 150 ohms as before. By the current division principle, the current flowing in the safety ground per ampere of injected current at Point B on Figure 4.1 will be:

$$\frac{1}{150 + 1} = .0066$$

In other words, most of the injected current flows to ground through R_{g_1}. Then, using Equation A.17 (radius of 500 MCM wire equals 0.4 inch or .0333 feet):

$$V'_{mag} = 61 \times 10^{-9} \times h \times \log_e\left(\frac{r_2}{r_1}\right) \times \frac{dI}{dt} =$$

$$61 \times 10^{-9} \times 2000 \times \log_e\left(\frac{2}{.0333}\right) \times \frac{dI}{} = 500 \times \frac{dI}{dt}$$

while still assuming an injected current crest time of 2 μsec:

$$V'_{mag} = 500\left(\frac{.0066}{2}\right) = 500\ (.0333) = 1.75 \text{ volt/amp of injected current}$$

This is 2.5 times the previously calculated value.

6. The time to crest (rise time) of the injected lightning current was assumed to be 2 μs. Some lightning currents crest in times as short as 0.5 μs. For shorter crest times, the magnetic induction effect will be more pronounced (because of a higher dI/dt) and the induced voltage will again be greater.

4.1.2 Ground Resistance Voltage

In Figure 4.1, a lightning current injected into the system at Location 3 will cause a current flow through R_{g_2} as mentioned above. In fact, since R_{g_2} was assumed to be one ohm in this example, most of the injected current will flow through R_{g_2}. The voltage drop across this resistance will appear at Location 2 and will be added to the magnetic voltage at that point.

$$V_{R_{g_2}} = (R_{g_2})(I_{R_{g_2}}) = (1)(1.000 - .007) =$$

0.993 volt/ampere of lightning current

The total voltage appearing at Location 2 is now:

$$V_{tot} = V_{mag} + V_{R_{g_2}} = 0.7 + 0.993 = 1.7 \text{ volts/amp}$$

Again, if I = 1,000 amperes:

$$V_{tot} = 1{,}700 \text{ volts}$$

If R_{g_2} is higher than the assumed value of one ohm, this resistive voltage drop will probably be higher considering that only slightly more current would be diverted through the safety ground.

4.1.3 Current in Cable Shield

The shield of the cable shown in Figure 4.1 acts as an open-ended transmission line. Since the cable is insulated, there is no leakage from the shield to ground. Current will begin to flow in the shield but, upon reaching the open end at Location 2, must drop to zero. The voltage at that point, which is caused by the flow of current, will double. However, this voltage doubling will occur later in time than the magnitude of V_{tot} which was calculated above. Also, this voltage will be small if it is assumed that the current in the shield initially is small (10%) compared to the initial current in the safety ground wire. It is believed that this is a reasonable assumption considering the relative impedances offered to the flow of current by these two conductors. Using this assumption, this voltage component at Location 2 was calculated to be about 0.18 volt. This is small compared to V_{tot} and so can be neglected.

4.2 Analysis of Recorded Failures

1. It has been reported that sparking between rack cabinets in the Operations Room at Rosman occurred during recent lightning activity. Figure 4.2 shows a simplified interconnection between an antenna site, the Operations Building, and a ground field. If lightning current is injected into the system at the antenna site as shown, the current will flow to ground along four parallel paths:

   a. through R_{g_2} directly
   b. along the safety ground to the ground field
   c. along the signal ground to the ground field
   d. along the shield of the single conductor cable to an equipment

rack and then along the signal ground to the ground field. It is this path which will be under consideration.

Although the signal and safety grounds were designed to be isolated systems, it was found during an inspection at the Rosman site that connections between the two systems existed at some SATAN antenna sites. Also, a single-conductor shielded cable such as shown can be bonded to the equipment rack it enters by virtue of a coax connector on a chassis within the rack. It is possible for a rack adjacent to the one under consideration not to have such a single-conductor shielded cable entering it. These conditions have been represented in Figure 4.2. Current will flow through the No. 8 conductor from the right-hand rack to the signal ground radial under the floor of the Operations Room. The current will proceed to the signal ground plate and then to the ground field. The left-hand rack is bonded to the signal ground plate via a noncurrent-carrying path and a loop, ABCDEFA, is formed similar to the loop shown in Figure 4.1. A magnetically-induced voltage can appear between C and D if the cabinets are not bonded. This voltage was calculated to be 2.8 volts per ampere of lightning current for the same current wave shape as was assumed before and for the loop dimensions shown on Figure 4.2. This voltage is the result of the magnetic fluxes set up by two current paths: E to F and F to A. For path E to F, using Equation A.17 (radius of #8 conductor = .065 inch):

$$V_1 = 61 \times 10^{-9} \times h \times \log_e \left(\frac{r_2}{r_1}\right) \times \frac{dI}{dt}$$

$$= 61 \times 10^{-9} (20) \times \log_e \left(\frac{12 \times 20}{.065}\right) \times \frac{dI}{dt}$$

$$= 61 \times 10^{-9} (20) \times \log_e (3700) = 1.0 \frac{dI}{dt}$$

and for path F to A (radius of 4 - 0 conductors = .265 inch):

$$V_2 = 61 \times 10^{-9} \times (2) \times \log_e \left(\frac{12 \times 2}{.265} \right)$$

$$61 \times 10^{-9} \times (2) \times \log_e (90.5) = 5.5 \frac{dI}{dt}$$

Again, assuming an injected current crest time of 2 μsec:

V_1 = 1.0 (1/2) = 0.5 volts/amp of injected current

V_2 = 5.5 (1/2) = 2.75 volts/amp of injected current

Since the fluxes set up by the currents in these two paths are at right angles to each other, these voltages must be combined vectorially:

$$V_{cab} = \sqrt{V_1^2 + V_2^2} = \sqrt{0.5^2 + 2.75^2} = 2.8 \text{ volts/amp}$$

This is the voltage, V, between cabinets shown on Figure 4.2.

If the injected current, I, is 1,000 amps and it is assumed that 10% of this will flow in the cable shield, the voltage between cabinets would be:

$$V_{cab} = 1{,}000 \, (.1)(2.8) = 280 \text{ volts}$$

For a larger injected current, or faster rising currents, this voltage could be much greater. Hence, it is possible to develop a voltage sufficient to cause sparking between adjacent unbonded cabinets.

2. If a cable shield such as shown in Figure 4.1 is raised to some potential above ground by lightning current flowing in the system, the conductors (and shields) inside the cable will also be raised in potential with respect to ground because of the capacitance coupling between these conductors and the outer shield. Since the conductors are in close proximity to the shield, they will be raised to almost as high a voltage as the shield itself. This voltage surge on the conductors can cause failures of electronic components to which they connect. This could apply to the following failures at Rosman which were investigated in some detail:

a. transistors and diodes in the SATAN servo system valve driver cards and op amps.
b. diodes in the SATAN system hydraulic house junction boxes.
c. transistors in the SATAN system dc power supplies.
d. transistors in the SATAN command system reflectometer circuit.
e. synchros in the SATAN command servo system.
f. relay K1 in the SATAN #2 transmitter.
g. meters in the SATAN command circuitry.
h. diodes in the SATAN receiver gimbal control panel and the power control panel.
i. pressure transducer in the SATAN command #2 hydraulic house power supply.

Doubtless, many of the other component failures occurring at the same time were due to this same cause.

If any of these devices failed in such a way as to become short circuits, other devices in the same circuits could then have failed due to abnormal current flow. For example, a shorted semiconductor device across the 28 VDC power supply outputs in the SATAN circuitry could have led to the failure of the fuses and the 2N379 transistors in those supplies. There was no information available concerning the actual conditions of the failed devices at Rosman.

It is interesting to note that failure of tube equipment at Rosman has not been a problem, while failure of transistor equipment has. The surge voltages calculated in the illustrative examples above are of orders of magnitude which would seem to make it possible for transistors to be destroyed while tubes are not. This is because of the inherent ruggedness of tubes in regard to susceptibility to transients and the fact that tubes usually operate at higher voltages than transistors, so that the surge overvoltages represent a smaller percentage of the operating voltage.

Figure 4.3 shows an interconnection diagram incorporating the three major types of trouble spots that have been discussed which could develop at Rosman under lightning conditions. These are indicated by a "V" and are places where abnormal transient voltages could develop. In general, they are:

1. voltages existing between cable conductors and shields and the walls of junction boxes.
2. voltages existing between circuit conductors and rack cabinets.
3. voltages existing between rack cabinets.

These voltages can be injurious to both equipment and personnel and recommendations concerning the possible reduction of these abnormal voltages at Rosman will now be discussed.

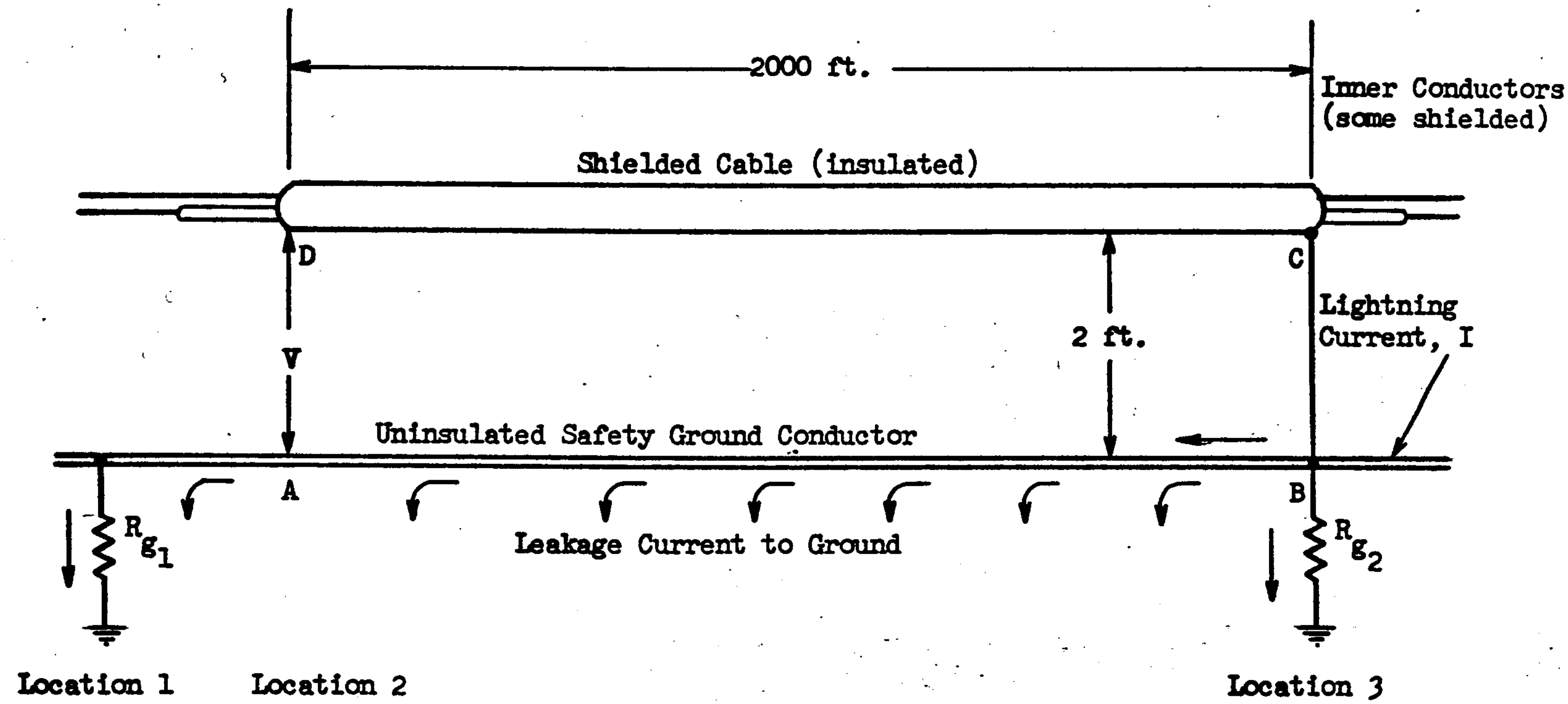

2000 ft.
Inner Conductors
(some shielded)
Shielded Cable (insulated)
D
C
Lightning
Current, I
V
2 ft.
Uninsulated Safety Ground Conductor
A
B
R_{g_1}
Leakage Current to Ground
R_{g_2}
Location 1
Location 2
Location 3

FIGURE 4.1

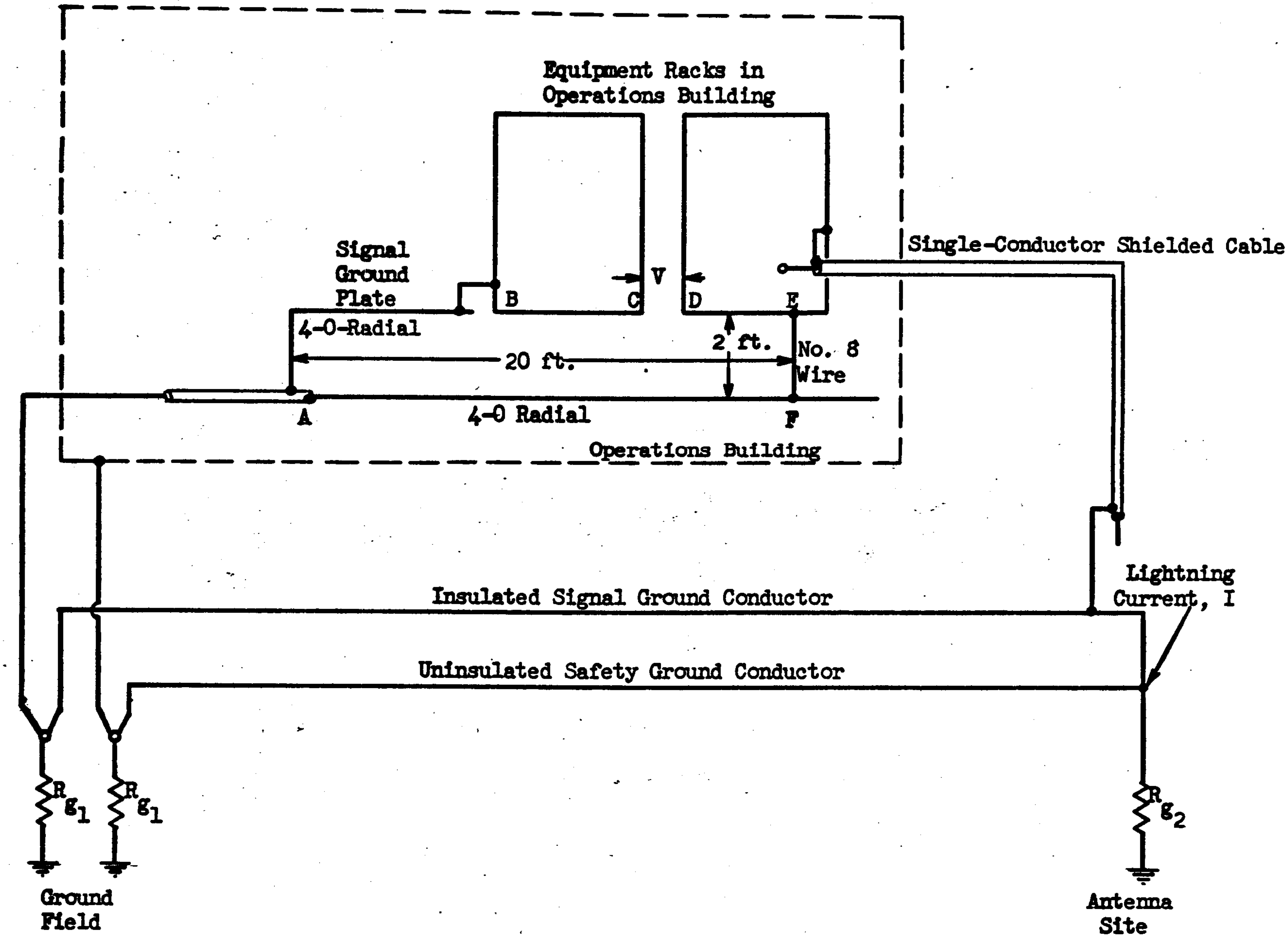

Equipment Racks in
Operations Building
Signal
Ground
Plate
4-0-Radial
B
C
V
D
E
2 ft.
20 ft.
No. 8
Wire
A
4-0 Radial
F
Operations Building
Single-Conductor Shielded Cable
Lightning
Current, I
Insulated Signal Ground Conductor
Uninsulated Safety Ground Conductor
Rg1
Rg1
Rg2
Ground
Field
Antenna
Site

FIGURE 4.2

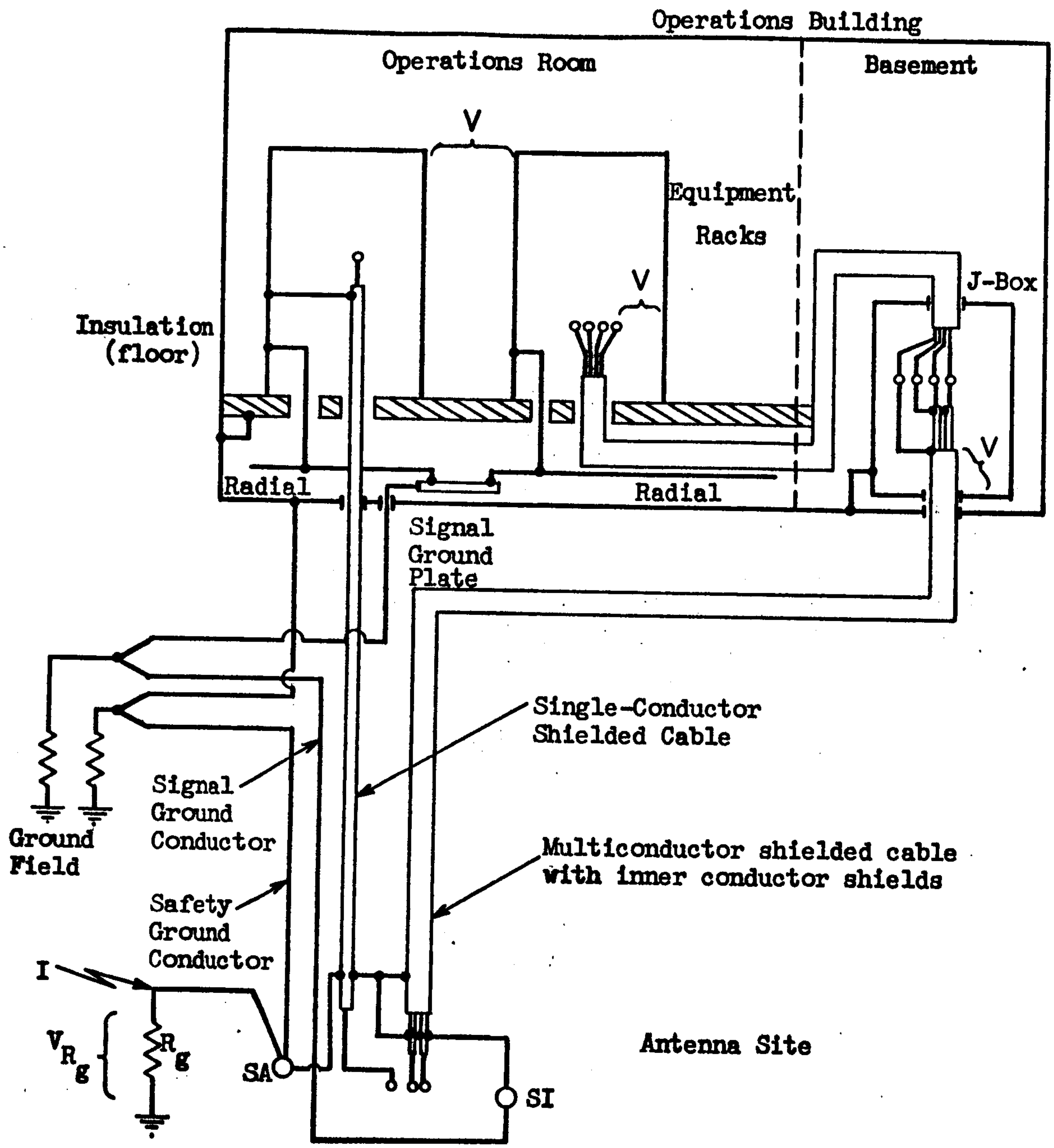

Operations Building
Operations Room
Basement
V
Equipment
Racks
V
J-Box
V
Insulation
(floor)
Radial
Radial
Signal
Ground
Plate
Single-Conductor
Shielded Cable
Signal
Ground
Conductor
Ground
Field
Multiconductor shielded cable
with inner conductor shields
Safety
Ground
Conductor
I
SA
SI
Antenna Site

FIGURE 4.3

Section 5.0

Protective Recommendations

5.0 PROTECTIVE RECOMMENDATIONS

In view of the discussion in Section 4.0 of generated surge voltages under lightning conditions, the following recommendations are made concerning improvement of the grounding schemes at Rosman from the standpoint of personnel and equipment safety.

1. Figures 5.1(a) and 5.1(b) show portions of the circuitry in the SATAN antenna hydraulic house junction box and the test point panel and junction box in the SATAN control console respectively. It has been reported that diodes CR-3 and CR-4 on Figure 5.1(a) failed during recent storm activity. These diodes are connected to a cable run from the SATAN control console in the Operations Building via terminal strips 6TB1 and 8TB1. Protective devices as shown should be installed from the terminals indicated to the power ground in order to clamp the maximum voltage appearing on these circuits during lightning activity to a reasonable value. These devices permit circuit isolation under normal operating conditions, but will provide a direct path to ground for transient overvoltages appearing on the circuits. These devices have been indicated on both figures as General Electric Thyrectors or equivalent devices. For the circuits indicated, Type 6RS21SA2D2 Thyrectors could be used. These are actually ac circuit protectors and, therefore, the possibility of the devices being installed backwards, as would be the case with dc Thyrectors, is eliminated.

   Other terminal strip points (not shown on Figures 5.1(a) and 5.1(b) on which similar protective arrangements might be considered are:

   a. Terminal points which connect the X- and Y-axis synchros at the SATAN antennas to cable runs from the Operations Building. These terminal points would be:

In Hydraulic House Junction Box	In SATAN Test Point Panel and Junction Box
8TB1 - 4	6TB1 - 85
8TB1 - 5	6TB1 - 86
8TB1 - 6	6TB1 - 87
8TB1 - 21	6TB1 - 75
8TB1 - 22	6TB1 - 76
8TB1 - 23	6TB1 - 77
8TB1 - 50	6TB1 - 83
8TB1 - 51	6TB1 - 84
8TB1 - 57	6TB1 - 73
8TB1 - 58	6TB1 - 74
8TB1 - 94	6TB1 - 28
8TB1 - 97	6TB1 - 30

b. Terminal points which connect the pressure transducers in the SATAN antenna hydraulic house power supplies to cable runs from the Operations Building. These terminal points would be:

In Hydraulic House Junction Box	In SATAN Test Point Panel and Junction Box
8TB1 - 61	6TB1 - 59
8TB1 - 92	6TB1 - 19
8TB1 - 99	6TB1 - 12

2. Figure 5.2 shows a typical junction box for single conductor RF coaxial cables (such as the pressurized cables used at Rosman). The shields of these cables should also be clamped to ground by the use of protective devices as indicated. In this case, Type 6RS25SA1D1 Thyrectors are specified. These are high-current ac protective units and would be capable of clamping high values of surge current of either polarity with respect to ground. The connections to the shields may be made on the shields themselves or on the metallic junction fittings in the box with the aid of clamp-type connectors. Again, isolation between shields is maintained during normal operating conditions.

3. Figure 5.3 shows a typical installation of adjacent equipment racks in the Operations Room. Again, protective devices can be installed to limit transient voltages appearing between each cabinet and the metallic building structure (the floor in this illustration, which is bonded to the safety ground). Thus, isolation between the cabinets (signal ground) and the building structure (safety ground) is maintained under normal conditions. During storm activity, voltages appearing between cabinets and building ground will be minimized. Again, Type 6RS25SA1D1 Thyrectors are specified.

Referring to Figure 4.2, this means that Thyrectors should be installed at each rack cabinet from point E to the safety ground. This would largely eliminate the induced voltage around loop ABCDEFA since current would be allowed to flow to the metal floor through the Thyrector. Alternatively, the Thyrectors would be installed from point F to ground, in which case a small induced voltage would appear due to the current flowing in the #8 bonding jumper. This voltage was calculated to be (for the illustrative example of Figure 4.2):

$$V'_{cab} = 0.5 \text{ volt/ampere of lightning current}$$

Again, for an assumed current flow of 100 amperes, only 50 volts would appear between cabinets. Obviously, if Thyrectors were installed from Point A to the safety ground, the loop voltage would be unaffected.

Therefore, the best location for the Thyrectors is as shown on Figure 5.3. However, connecting the Thyrectors to the 4-0 radials at the points of attachment of the #8 jumpers to the racks would probably be acceptable. Figure 4.2 shows a "worst case" condition; that is, the possibility of adjacent racks being on different radials. It is not known whether this situation exists presently at Rosman, but it could arise in the future if changes in equipment are made. Generally, this situation does not exist and so the generated loop voltages as discussed would be much less because of the smaller loop dimensions.

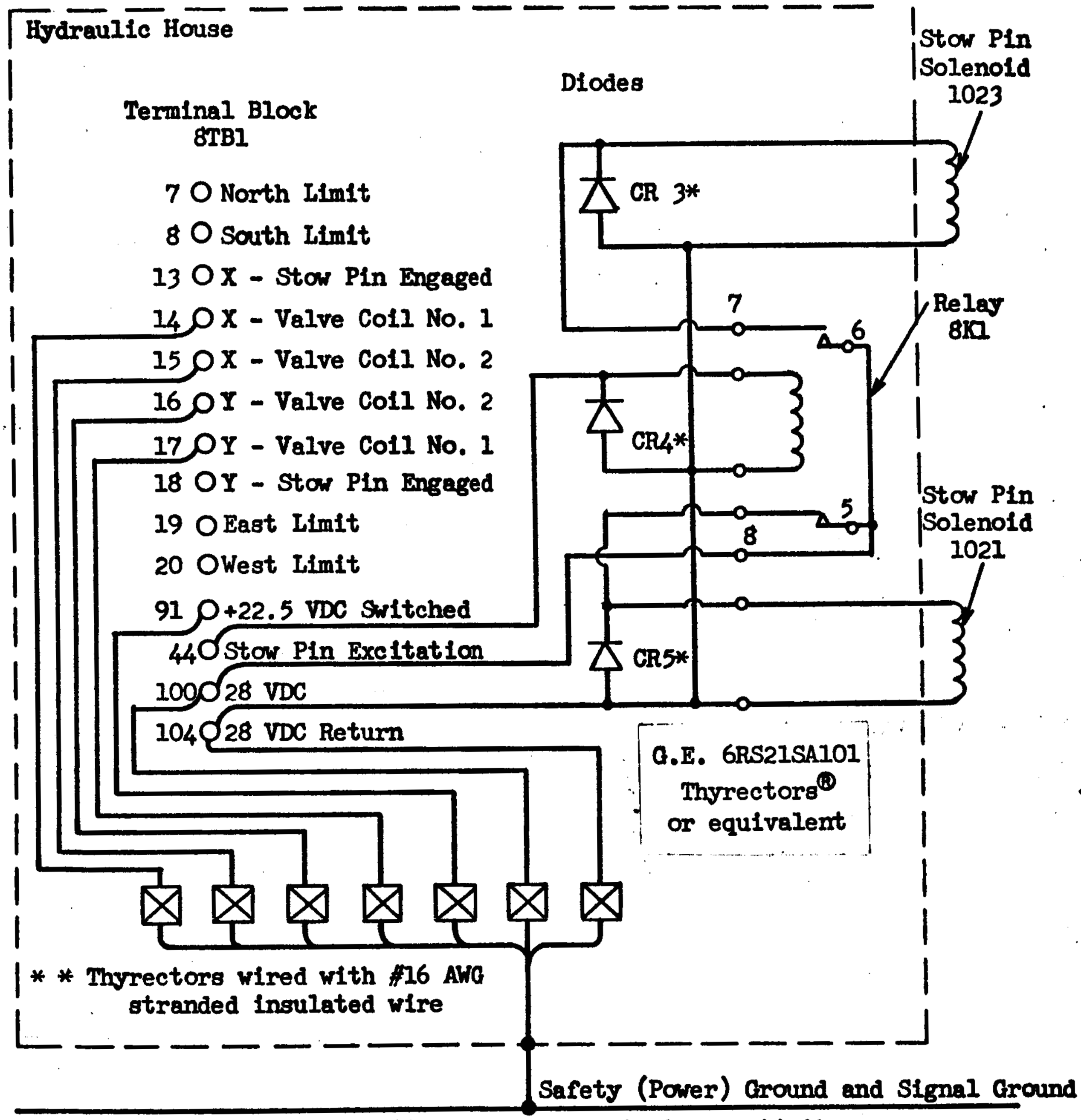
An alternate Thyrector location is also shown on Figure 5.3. If this location is desired, the total lead length between the grounding bus in the cabinet being protected and the terminal of the Thyrector which connects to the 4-0 radial should be kept as short as possible (preferably no longer than the length of the #8 jumpers). Also, the lead length between the Thyrector and the building structure (floor) should not exceed 24 inches.

Since not much information is available on the actual positions of specific racks of equipment at Rosman, it is difficult to determine whether or not each equipment rack need have a Thyrector associated with it or whether Thyrectors on every second or every third cabinet, for example, would be sufficient.

4. Figure 5.4 shows a junction box for multiconductor shielded cables. Generally, these cables at Rosman consist of many twisted pairs, each with its own shield plus an overall cable sheath. This sheath should be bonded to the safety ground along with the metallic junction box, as shown. The ground connection should be carried along with the cable from a basement junction box to the building structure (floor) near the point of entrance of the cable into an equipment rack. If this is done, the grounding scheme applied to the inner shields is not as important. This procedure will tend to eliminate magnetically-induced voltages from appearing at open ends of cable shields as described in Section 4.1.1.

It should be pointed out that these recommendations apply to both SATAN antenna and 85 foot dish antenna installations at Rosman. Only failures in the SATAN equipment were investigated in detail because no information on actual connections for the 85 foot dishes was available. However, it is believed that protection practices which prove adequate for the SATAN systems will be adequate for the dish antenna systems also.

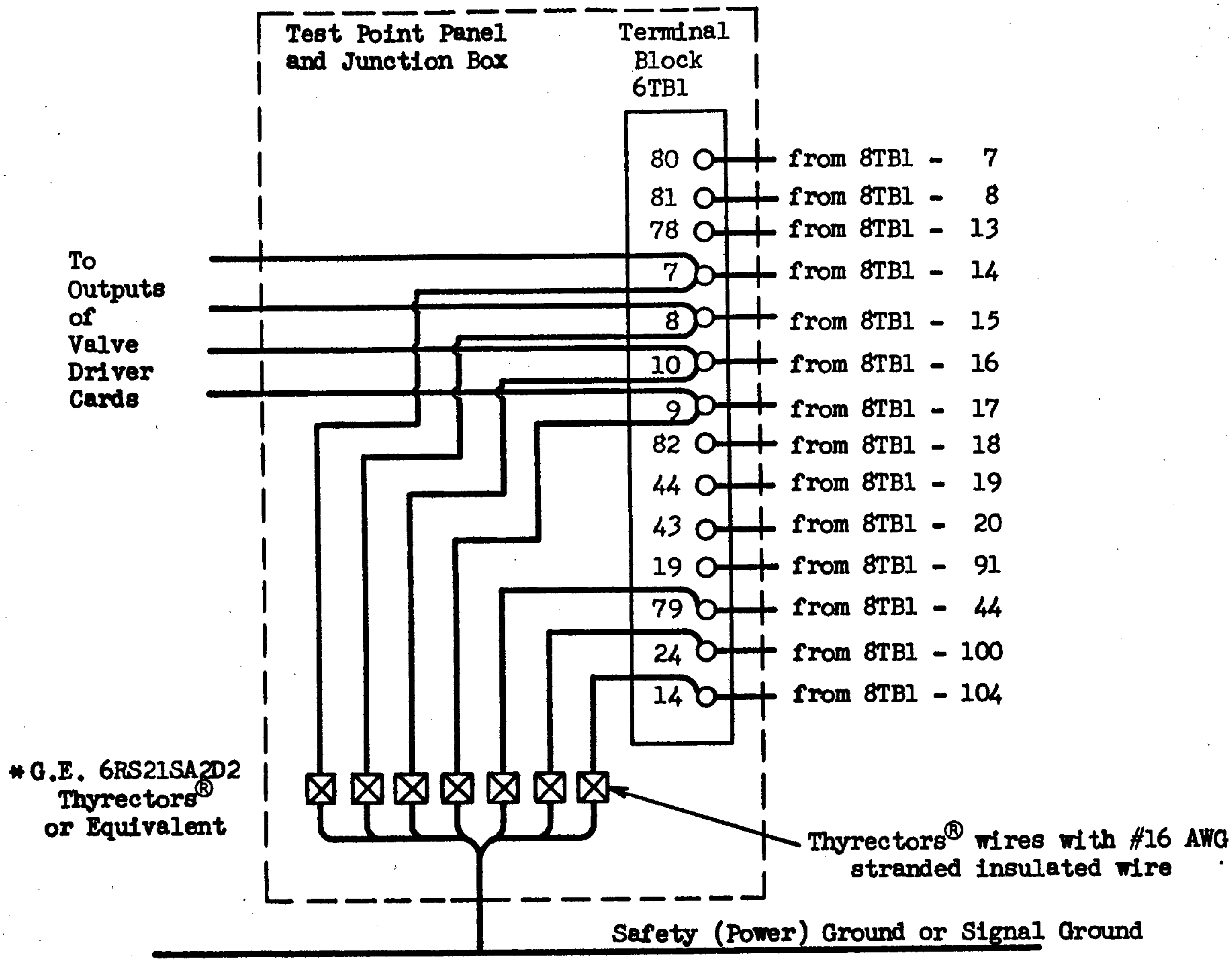
Note: During inspection of Rosman site, it was found that connections between the signal and safety grounds were made at SATAN antenna installations, even though grounding system plans did not call for connections at those locations.



* These components have failed during recent storm activity.

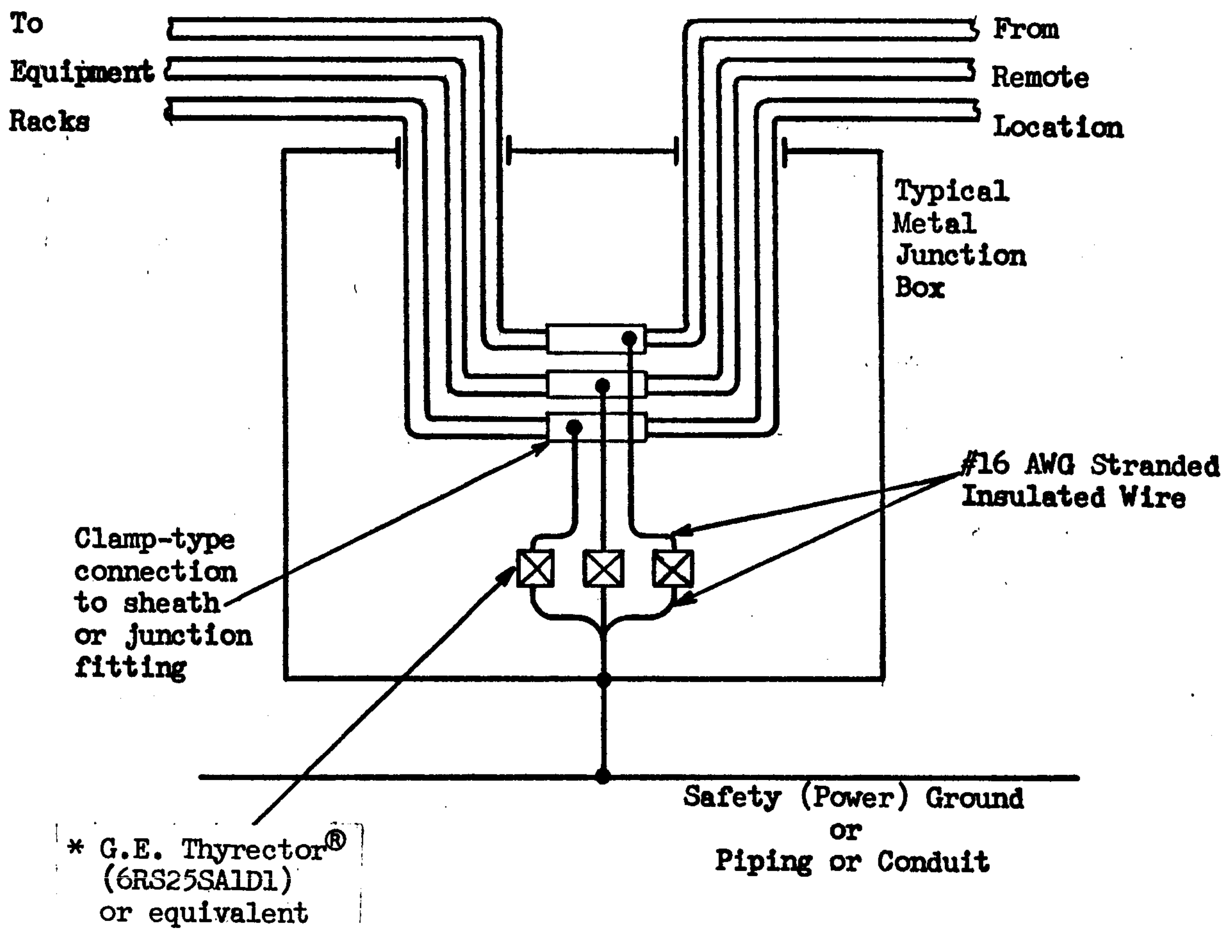
** to be added for lightning protection

FIGURE 5.1(a) Portion of Hydraulic House Junction Box Circuitry



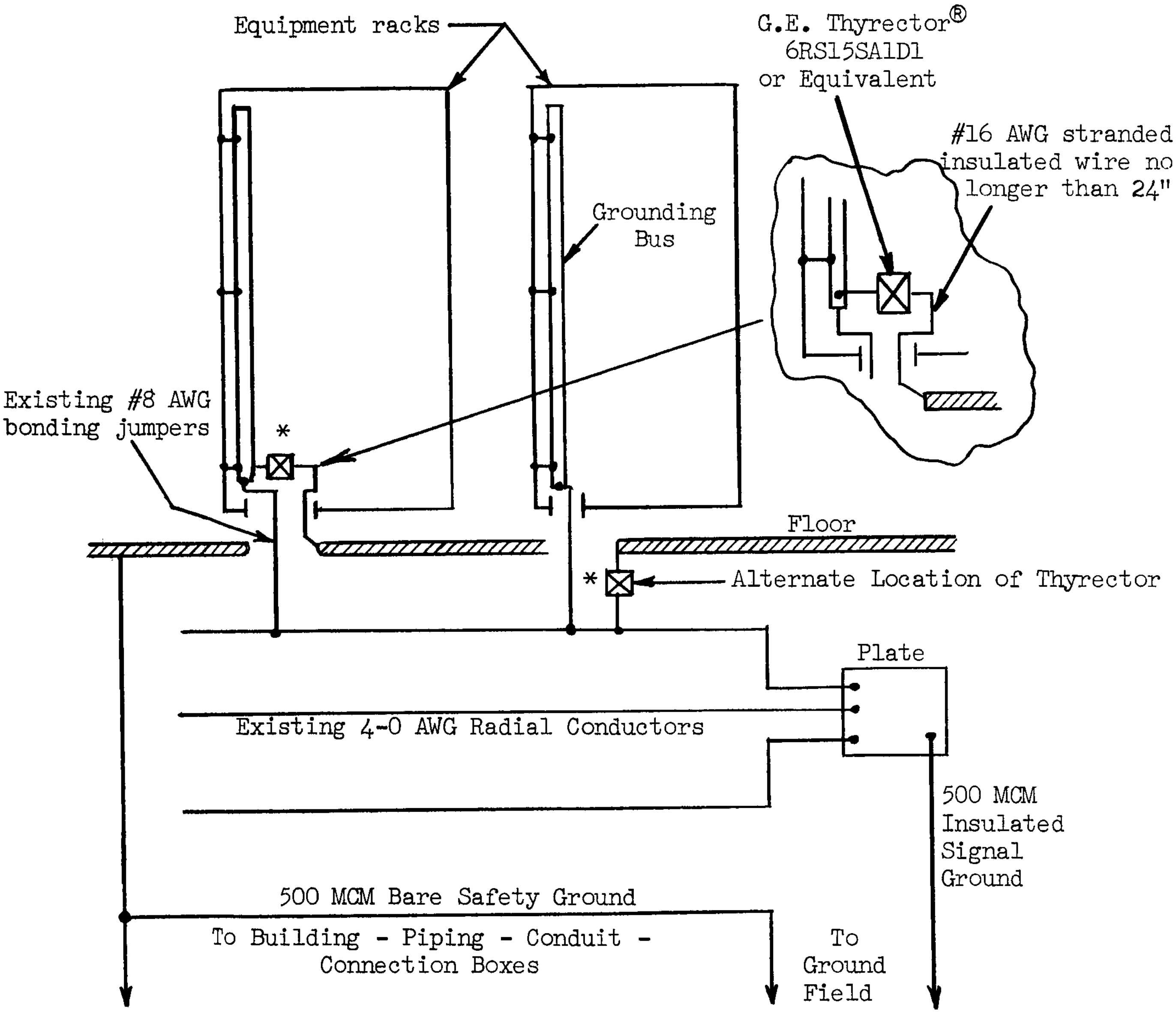
* to be added for lightning protection

FIGURE 5.1(b) - Portion of Test Point Panel and
Junction Box in SATAN Control Console



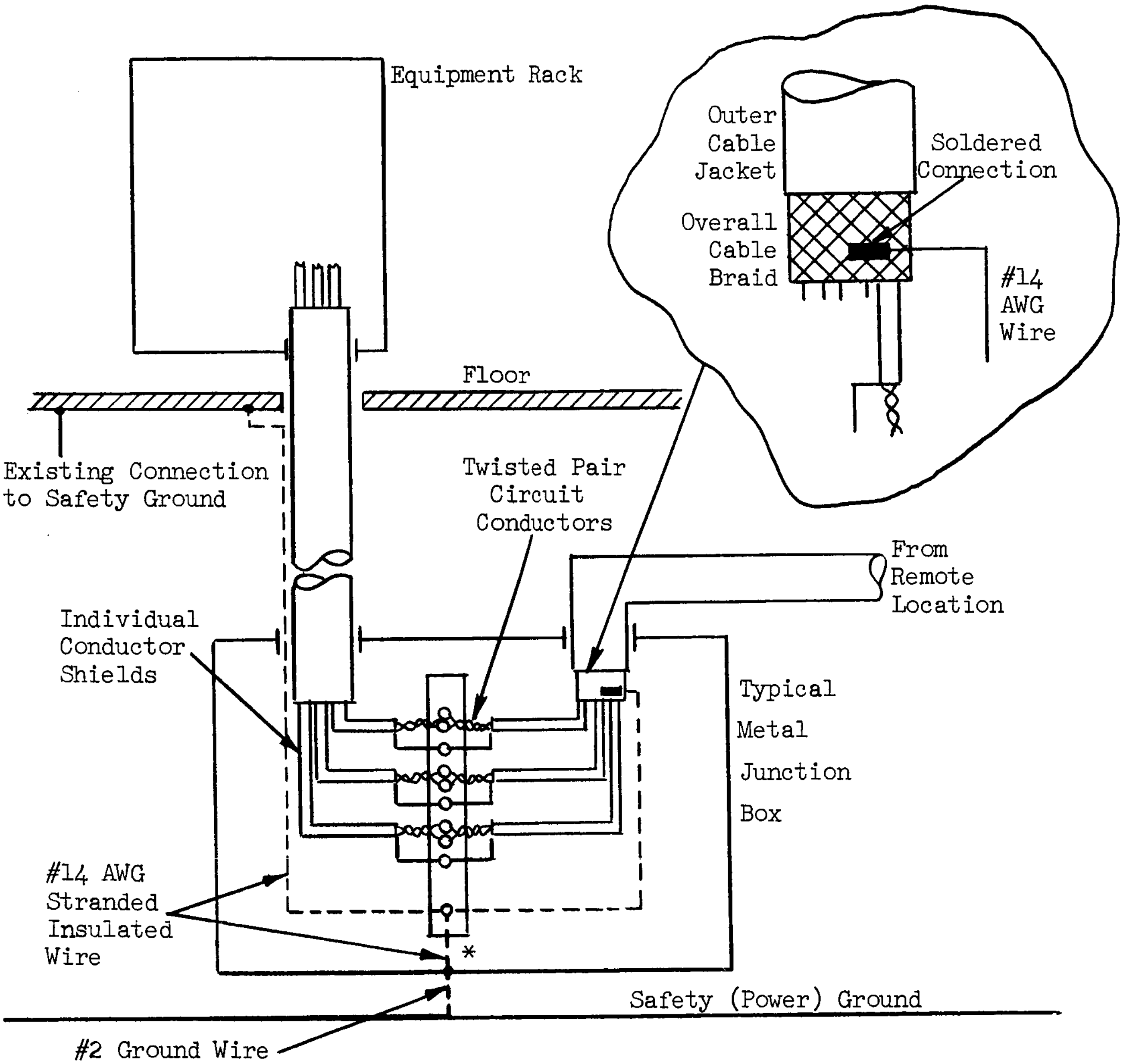
* to be added for lightning protection

FIGURE 5.2 RF Coaxial Cable Shield Protective Device Installation



* to be added for lightning protection

FIGURE 5.3 Equipment Rack Protective Device Installation



- - - to be added for lightning protection

* 6RS25SA1D1 Thyrectors could be used here, but a solid connection is preferable.

FIGURE 5.4 Termination of Shielded Cables from Remote Locations

Section 6.0

Lightning Protective Measures Recommendations

6.0 LIGHTNING PROTECTIVE MEASURES RECOMMENDATIONS

In the preceding sections of this report, the problem existing at Rosman has been described, the damages occurring during lightning activity explained, and specific alterations and additions to the grounding and protective system to minimize the lightning damage situation at Rosman were given. In this section, the factors which must be considered and appropriate recommendations for designing lightning protection in new installations are presented. This section is organized in four parts:

6.1 Protective Grounding

6.2 Signal and Data Transmission Circuits

6.3 Power Circuits

6.4 Equipment Protection

6.1 Protective Grounding

The main considerations for protective grounding at fixed stations are:

1. protection of operators of equipment
2. protection of equipment
3. protection of buildings housing equipment

Some of the grounding recommendations may be in conflict with signal and data transmission circuit grounding practices. Usually, however, these conflicts can be resolved in a manner which is satisfactory to all concerned.

6.1.1 Building Ground

Common grounding of all metal parts in and around a building will provide the best protection for operators and equipment. This includes all metal piping, conduits, structural members, and building outer skins, as well as equipment cabinets, racks, and enclosures.

Such a grounding arrangement should consist of a buried counterpoise around the periphery of buildings with ground rods at the corners and spaced at intervals not exceeding 50 feet for large buildings. Such a counterpoise is illustrated in Figure 6.1, Building Grounding. This arrangement permits separate power and equipment grounding within the building. Should there be a requirement for a completely separate signal or instrumentation ground which is referenced to earth at some point other than the building counterpoise, a protective device must be connected between it and equipment ground at each equipment cabinet, enclosure, or rack where the separate signal ground is used. A protective device such as G.E. Thyrector®, Catalog No. 6RS25SA1D1 should be installed in the manner shown in Figure 5.3.

6.1.2 Building Protection

The protective measures applied to the structural parts of all buildings should follow the recommendations given in

"Code for Protection Against Lightning", NFPA No. 78,
National Fire Protection Association

6.2 Signal and Data Transmission Lines

Signal and data transmission circuits provide paths for lightning currents and voltages to enter sensitive equipment. Circuits totally contained within protected buildings and having no exposure to lightning currents can usually be designed without direct consideration of lightning effects. Circuits which are not totally contained within protected buildings or are connected to or are a part of circuits not within protected buildings must be designed to accomodate lightning effects.

These effects fall into two general categories. The first is mechanical which includes all of the burning and blasting type damage which can occur when a lightning stroke contacts an object. The most direct way of minimizing mechanical damage is to provide a means of intercepting the stroke before it actually contacts a transmission circuit. The interception can be accomplished by enclosing the circuits in metal conduit or providing guard wires such as are used on power transmission lines. For buried data circuits the best protection is provided by two bare guard wires buried three to four feet above and to either side of the cable trench. Above ground data lines must be protected by an overhead guard wire which is grounded at intervals not exceeding 250 feet and is spaced at least eight feet above the data circuit to be protected from direct stroke burning and blasting effects.

The second category of lightning effects includes all of the electrical aspects. This is an immensely complicated situation and it is not wise to generalize on the proper protective measures which should be applied. A complete lightning effects analysis should always be made. This is true because an effective design from a lightning viewpoint must include both the voltage tolerance levels of the equipments and the expected magnitudes of the lightning induced voltages. The following sections present lightning protective measures necessary to obtain minimum induced voltages when common construction practices are utilized. The quality of each of the construction types, from a lightning effects viewpoint, varies quite widely and is given for each construction type.

6.2.1 Metal Conduit Systems

The utilization of rigid steel conduit to form a continuous grounded metal shield around signal and data transmission circuits results in a system which will be as completely free of lightning effects as possible. Such a system usually has no further requirements for supplementary protective devices for the use of shielded cable eliminates special circuit grounding requirements for control of lightning effects.

Lightning voltages on circuits contained within two-inch (electrical trade size) rigid steel conduit will be on the order of 30 volts between conductors and ground and 0.2 volt between conductors for an average lightning stroke directly to a 5,000 foot long conduit-circuit length. Larger conduits and/or short lengths will result in lower voltages. The voltages are proportional to length and inversely proportional to the product of the square of the thickness and cross-sectional area.

The conductor-to-ground voltages are essentially the IR drop along the inside of the conduit; where R is a complex function of the conduit permeability, conductivity, cross section, and the rate-of-change of the lightning current. For the case of two-inch rigid steel conduit and a current pulse shaped like lightning, the effective resistance was measured* to be

* E. R. Uhlig, MAGNETICALLY INDUCED VOLTAGES ON CONDUCTORS WITHIN CONDUITS AND CABLES, OCE NEMP PROGRAM, DEVELOPMENT OF CRITERIA FOR PROTECTION OF NIKE-X POWER PLANT AND FACILITIES ELECTRICAL SYSTEMS AGAINST NUCLEAR ELECTROMAGNETIC PULSE EFFECTS, Military Construction, Office of the Chief of Engineers, Department of the Army, Washington, D. C. 20315, Contract No. DA-49-129-ENG-543

only 1/1000 of the dc resistance.

The voltage between conductors is primarily due to the flux leakage at joints and bends and, hence, varies nearly linearly with length.

Utilization of non-ferromagnetic metal conduit will result in significantly higher voltages even if the non-ferromagnetic metal conduits have a significantly lower dc resistance. For instance, the substitution of two-inch aluminum for two-inch rigid steel results in approximately a 42-fold increase in voltage, even though the dc resistance of the aluminum conduit is only 1/17 that of steel. This seeming inconsistency is due to the large change in permeability between steel and aluminum.

6.2.2 Above Ground Cable Trays with Guard Wires

This type of construction is frequently used in warm regions and it provides the greatest flexibility for adding or subtracting cables. This construction requires the following special bonds and grounds in addition to the guard wires described in Section 6.2.

1. Grounding. The cable trays must be grounded to driven rods at intervals not exceeding 250 feet and to building ground systems at both ends. The ground rods should be 16 feet long. If soil conditions prohibit driving rods, equivalent counterpoises should be installed (see Appendix).
2. Bonding. All trays must be bonded together so as to form a continuous electrical structure.
3. Cables. All signal and data cables should have a continuous overall metal braid or shield (not spiral tape) that is bonded to building ground system at each end.

This construction will not provide the protection that is obtained with steel conduit and some sensitive circuits may require special protective devices. Voltages between conductors will be approximately an order of magnitude larger than with conduit. The conductor-to-ground voltages can be estimated utilizing the techniques given in Section 4.0.

6.2.3 Buried Non-metal Conduits with Guard Wires

This type of construction does not provide the protection that is obtainable with cable trays or conduits. In addition to the guard wires described in Section 6.2, all signal and data cables should have a continuous overall metal braid or shield (not spiral tape) that is bonded to building ground system at each end.

Voltages between conductors will be approximately 100 times larger than with conduit and sensitive circuits connected to long runs will require protective devices. The conductor-to-ground voltages can be estimated utilizing the techniques given in Section 4.0.

6.2.4 Direct Burial with Guard Wires

This type of construction is essentially equivalent to that described in Section 6.2.3 and the restrictions and requirements of that section apply.

6.3 Power Circuits

Power circuit wiring and protection should follow commercial practices. Where sensitive equipment is supplied or where high reliability is desired, the following protective measures should be included.

1. Distribute power on as high a voltage as is economical. Lightning induced voltages are primarily functions of geometry and not system voltage. Therefore, the higher the system voltage, the lower the lightning voltage on a per unit basis. Also, higher voltage systems have the lowest ratio of lightning arrester protection voltage to system operating voltage.
2. Apply lightning arresters at both ends of all exposed (buried or in air) primary distribution circuits.
3. Use station type arresters rather than distribution type.
4. Apply secondary arresters at all distribution panels served by a transformer whose primary is served by a circuit exposed to lightning.

6.4 Surge Protection Devices for Control Circuits, Communications Systems, and Equipment

In general, control circuits and communication systems are operated at voltage levels considerably below those used for electric power work; therefore, the protective devices for these circuits need not handle the very large energies encountered at higher voltage levels. Some of the devices to be described here will handle large surges, but others are somewhat limited in their capabilities.

Protective devices acting as overvoltage suppressors for control circuits and communication systems may be listed under three categories, characterized by their mode of operation:

1. "Crowbar" devices or switches.
2. Voltage clippers and non-linear elements.
3. Linear energy storage elements.

6.4.1 "Crowbar" Devices or Switches

These devices operate by abruptly conducting or breaking down electrically when the voltage across them reaches a specified value. This action can be the result of the breakdown of a dielectric gas between two electrodes, or avalanche or other solid-state phenomena across a semiconductor junction or junctions. In general, devices employing breakdown of a gas can control high energy surges at the expense of rather loose tolerances on their protective voltage levels. Semiconductor devices can provide very tight control over voltage levels, but their thermal capacity to control surge energy is limited.

The breakdown or avalanche may either be directly triggered by the overvoltage so that the device appears as a two-terminal device or be triggered by an auxiliary electrode (gate) in a three-terminal device with the triggering signal supplied by an adjustable voltage sensing circuit.

Many of these devices will continue to conduct after the initial triggering, so that external means must be supplied to interrupt the power current supplied by the steady-state voltage source after the disappearance of a triggering surge. This means that most generally, a serious disturbance is introduced in the system voltage until this power follow current can be interrupted. Some of the devices listed in Table 6.1 incorporate the interrupting means, but this feature is limited to ac applications. For dc

TABLE 6.1

SUMMARY OF CHARACTERISTICS OF LOW VOLTAGE SURGE SUPPRESSORS

Minimum* Breakdown Voltage	Ratio of** Max. to Min. Breakdown Voltage	Peak Amps	Self-Interrupting	Manufacturer and Type
250 to 6000	1.6	2000	No	General Electric Company 730 B
250	2.5	2000	No	AMARK Corp. Cerbesis UA1
800	unknown	3000	No	EG and G Corp. Fenotron
150 to 5000	unknown	unknown	No	Victoreen Inc. VX-96
750 to 50,000	unknown	1000 to 6000	No	Electronic Industries
230 to 800	unknown	unknown	No	Siemens Corp. surge voltage protector
500 to 2600	1.6 or greater	6000	No	Western Electric GA 51574, GA 51724
250 to 400	4	unknown	No	L M Ericsson Corp.
200	7.5	unknown	No	Amperex Corp. Model 0369
70 to 120	4	unknown	No	Neon Bulbs
1000	2.5	10,000	Yes	General Electric Company 9 LA 4C4
1000	4	5000	Yes	Westinghouse Corporation appliance protector
1500 to 5000	6	300	Yes	Dale Corp. LA-9
25 to 500	Zener type	300	Yes	General Electric Company*** Thyrector diodes

* Minimum overvoltage at which the protector will operate. Some manufacturers provide gaps for various voltages.

** Maximum breakdown voltage is defined as the 0.1 microsecond operating voltage.

*** Operating temperature - 70°F to 160°F, meets humidity requirements of MIL-Spec 202.

circuits, a definite voltage interruption is required to stop power follow current.

The initial conduction or breakdown action of these devices is not instantaneous. As in the case of a spark gap, there is a relation between the time to breakdown and the rate at which the voltage is applied with the result that the voltage to initiate conduction increases when the rate of voltage rise is increased. This is shown by the volt-time characteristic of a typical "crowbar" device, as shown in Figure 6.1.

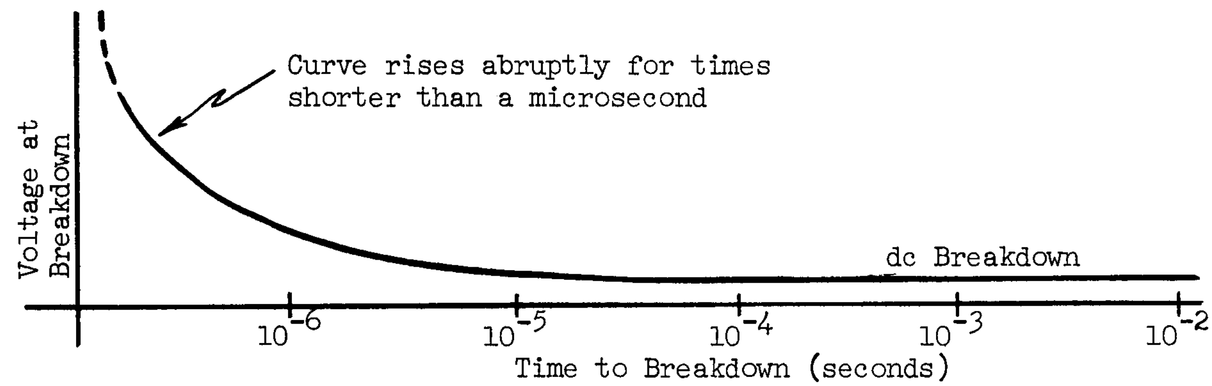


FIGURE 6.1 Volt-Time Characteristic for a "Crowbar" Device

The significance of this volt-time characteristic is that there is a time lag during which the "protective" device has no effect on the overvoltage. With steep-front surges, this can lead to high voltages left unsuppressed for durations of the order of a fraction of a microsecond until the device turns on. In this respect it parallels the volt-time characteristics of the simple spark gap discussed earlier.

Spark gaps, gas tubes, and semiconductor switches have both advantages and disadvantages. Some of these are listed as follows:

<u>Spark Gaps</u>

<u>Advantages</u>

1. Simple and reliable.

2. Easily fabricated.
3. High energy handling capacity.
4. Very low voltage drop (arc drop) during conducting state. When the gap is carrying maximum current, the voltage across the gap is typically 10-20 volts. If more current tries to flow, the arc channel increases in diameter and arc drop stays about the same. (A low arc drop indicates relatively low power absorption during the conducting phase.)
5. Bilateral operation - same characteristics on either polarity.
6. Fast response time - start conducting in less than one microsecond if well designed.
7. Zero power consumption on standby.
8. Wide operating range.
9. Long life expectancy.
10. Low internal capacitance.
11. Require no auxiliary equipment, power supply, or maintenance.
12. Relatively unaffected by radiation.

Disadvantages

1. Relatively high sparkover potential for their low-voltage ratings.
2. Simple gaps will not extinguish follow current. This is a most important point to consider if they are to be used on a power circuit. The arc must be extinguished externally by removing the voltage in some manner. This can be done by interrupting devices (circuit breakers or fuses), or by inserting resistance rapidly into the circuit by an additional element such as Thyrite®, or by gas-blast deionizers. By suitable design, spark gaps can be made self-extinguishing. Such self-extinguishing properties may make use of the magnetic blow-out principle or other means.
3. Spark gaps are seldom available in conveniently-packaged assemblies. They must be designed for each specific application. This situation is being improved.

4. Spark gaps in air are sensitive to variations in atmospheric conditions. Hermetically-sealed gaps do not have this disadvantage.

Gas Tubes

Neon, argon, krypton, zenon, and other gases ionizable at low pressures are often employed as dielectrics in low voltage spark gaps. Such devices can be used as surge suppressors, but their characteristics should be fully understood if they are to be properly applied.

Advantages

1. Low cost.
2. Small size (depending on bulb).
3. Low sparkover voltage - typically 60-100 volts in firing times greater than 2 μsec.
4. Can pass very high currents for short time.
5. Self-healing (usually).

Disadvantages

1. Poor volt-time "turn-up" characteristics.
2. Will continue to conduct if the driving voltage is above 60-100 volts.
3. Possibly more sensitive to radiation than spark gaps in air at atmospheric pressure.
4. Will not absorb large amounts of energy.

Semiconductor Devices used as "crowbars"

These are semiconductors, such as Zener diodes, silicon-controlled rectifiers (SCR's) etc. which conduct abruptly upon avalanche breakdown or upon triggering. Since the impedance of these devices collapses to a very low value when they conduct, it is often necessary to add a series impedance in which surge energy can be dissipated and which, at the same time, limits the magnitude of power-follow current. A non-linear resistor (varistor) such as silicon-carbide (Thyrite®) is very effective for this purpose. This material is used in commercial surge arresters.

Advantages

1. Good surge current ratings, although not as good as spark gaps.
2. Low voltage drop when conducting.
3. Suitable for use on low voltage dc circuits.
4. If properly applied, will interrupt follow current at the first power-follow current zero following initiation of conduction.

Disadvantages

1. Low thermal capacity to dissipate surge energy.
2. Must be triggered by an auxiliary circuit.
3. Will not interrupt follow current on dc circuits.
4. Limited in rate of build-up of current or rate of build-up of voltage which can be tolerated.
5. Expensive.
6. Not bilateral. For protection on both polarities, two rectifiers and additional circuitry must be used. Bilateral devices are available. These are effectively two series SCR's back-to-back.

Descriptions of several types of commercial "crowbar" devices are as follows:

Mark I Engineering Semiconductor Protector (SCP)

This is a semiconductor "crowbar" device which turns on in a very short time. The specification calls for turn-on in less than 0.5 µs; one device tested showed turn-on times of 30 to 50 nanoseconds. The device could be set to exercise tight control over a dc voltage, although surges might rise to an excessively high voltage before the device turns on. In a previous study, a 30 volt SCP device started conducting on surges of 50 volts, but a surge rising at 40,000 volts per microsecond developed 1600 volts across the device before it turned on.

The basic device clears the circuit by blowing a fuse after it has been tripped by a surge. The manufacturer's specifications sheet indicates that a self-resetting model, and models to provide overcurrent protection, are available.

The specification sheet does not discuss the effects of an overvoltage surge of opposite polarity. For protection against surges of either polarity two devices might have to be used.

Dressen-Barnes Overvoltage Load Protector (OVLP)

This is another semiconductor "crowbar" device. It too shows a rapid turn-on time. It provides tight control over a dc voltage, but surges can build up to a high voltage before the device turns on. In this respect it is similar to the Mark I device. In the study mentioned above, the OVLP reached somewhat higher voltages than the SCP before it turned on.

T. I. Klixon Semiconductor Protector

This device combines a mechanical circuit breaker with a semiconductor "crowbar" device. It turns on slower than either the SCP or OVLP and allows even higher surge voltages to appear before it breaks down. Offsetting these disadvantages is its ability to interrupt follow current or overcurrents by means of its mechanical circuit breaker.

The device is polarized, with no comment from the manufacturer as to its performance with reverse polarity surges.

Dickson Series 1100, 1200, and 1300 Solid State Circuit Breakers

These devices are primarily designed for overcurrent protection, but can be used for overvoltage protection. They consist of a semiconductor series element and a semiconductor shunt element, the latter being primarily a sensing device. They provide overvoltage protection by sensing either the overvoltage directly or the overcurrent caused by the overvoltage. When the overvoltage is sensed, the series circuit breaker opens, disconnecting the load from the incoming surge.

It will be noticed that this approach to overvoltage protection differs from the semiconductor "crowbar" devices. A point of concern is the overvoltage that could be tolerated with the series switch open without the danger of "punch-through" of the open switch. An auxiliary protector might have to be used to limit surge voltages so that "punch-through" could not occur.

6.4.2 Voltage Clippers and Non-linear Elements

Voltage clippers, as suggested by the name, limit rise of the circuit voltage above a specified threshold, generally by lowering their impedance in the same proportions that the voltage rises, with the result that the corresponding current causes about the same or a very slightly increased drop through the surge voltage source impedance.

Their effectiveness depends upon the ratio of their impedance under overvoltage conditions and the source impedance. The characteristic of these devices is best revealed through a plot of current versus voltage, which exhibits either a knee or a curvature as shown in the following sketch in contrast with a linear resistor which would be represented by the straight line on this figure. Voltage clippers utilizing non-linear elements draw a small leakage current under steady-state voltage that may be applied to the device. When an increasing amount of surge current flows through the device, the voltage across the device and the shunt-connected system to be protected rises slowly, as shown by the characteristic curve. It is apparent, however, that the voltage under surge conditions will, although limited, increase a significant percentage above the steady-state level.

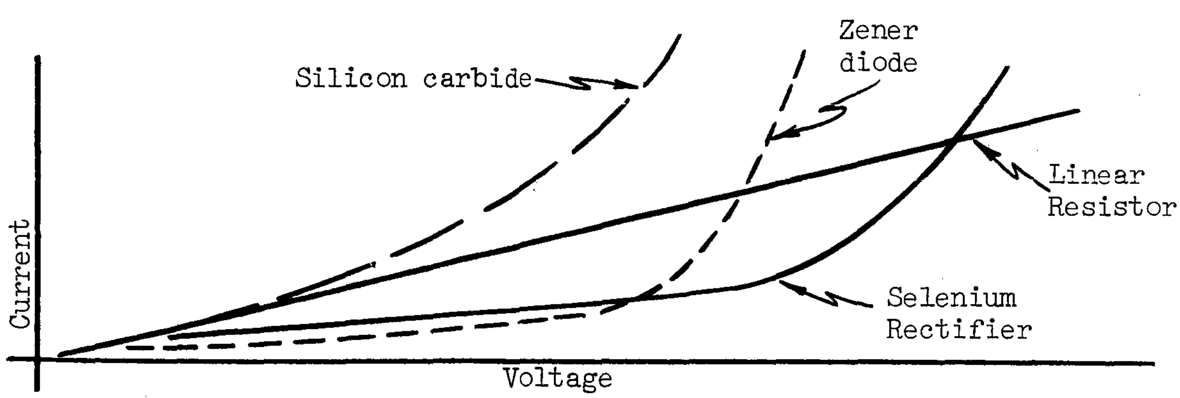


FIGURE 6.2 Performance Characteristics of Clippers and Linear Resistors

Since clippers actually convert the surge energy within themselves into heat, their capacity is directly related to their capability of storing or rapidly dissipating thermal energy. On the other hand, as soon as the surge current decays and vanishes, they recover their normal impedance so that a minimum of disturbance is introduced after the surge; their presence in the circuit is not significant under steady-state conditions.

Typical devices in this category include zener diodes, selenium rectifiers (G.E. Thyrector), and silicon carbide.

6.4.2 Linear Energy Storage Elements

Protective devices in this category consist of capacitors and ordinary resistors which may be used individually or in combination across the equipment.

Capacitors suppress overvoltage surges by temporarily storing surge energy which is gradually dissipated through the impedance of the equipment shunted by the capacitors; also the inherent distributed capacitance of long cables feeding equipment can cause a progressive reduction of wave front steepness of surges reaching the equipment.

Linear resistors are often employed across highly inductive dc circuits. These dissipate the stored energy of inductive elements.

Combinations of capacitors and resistors across equipment are also feasible. Energy in surges is momentarily stored in the capacitors, but dissipated at a predetermined decay rate dictated by the resistor. Such combinations are sometimes used to prevent excessive voltages at open switches accompanying surge reflection.

6.5 Safety of Personnel

The importance of personnel safety cannot be overemphasized. All operating and maintenance personnel, regardless of assignment, should be given instructions as to proper and safe actions during electrical storms. The following lists precautions which should be taken.

1. Maintenance or repair work on electric circuits should not be permitted during electric storm activity. If such work is mandatory,

all wires should be temporarily grounded at the point of repairs and the workmen should wear approved insulated gloves.

2. Personnel must be prohibited from working on towers and antenna structures during electric storm activity.
3. Personnel should seek and stay in areas protected from lightning during electric storm activity. Examples of such areas are protected buildings, metal buildings, and hard top automobiles. In the event of an emergency, shelter could be obtained under large dish antennas.

It is recommended that some means of monitoring electric field strength to establish the existence of dangerous electric storm conditions be obtained. There are several suppliers of this kind of equipment. The B. K. Sweeney Co. of Denver, Colorado is a supplier of complete warning systems.

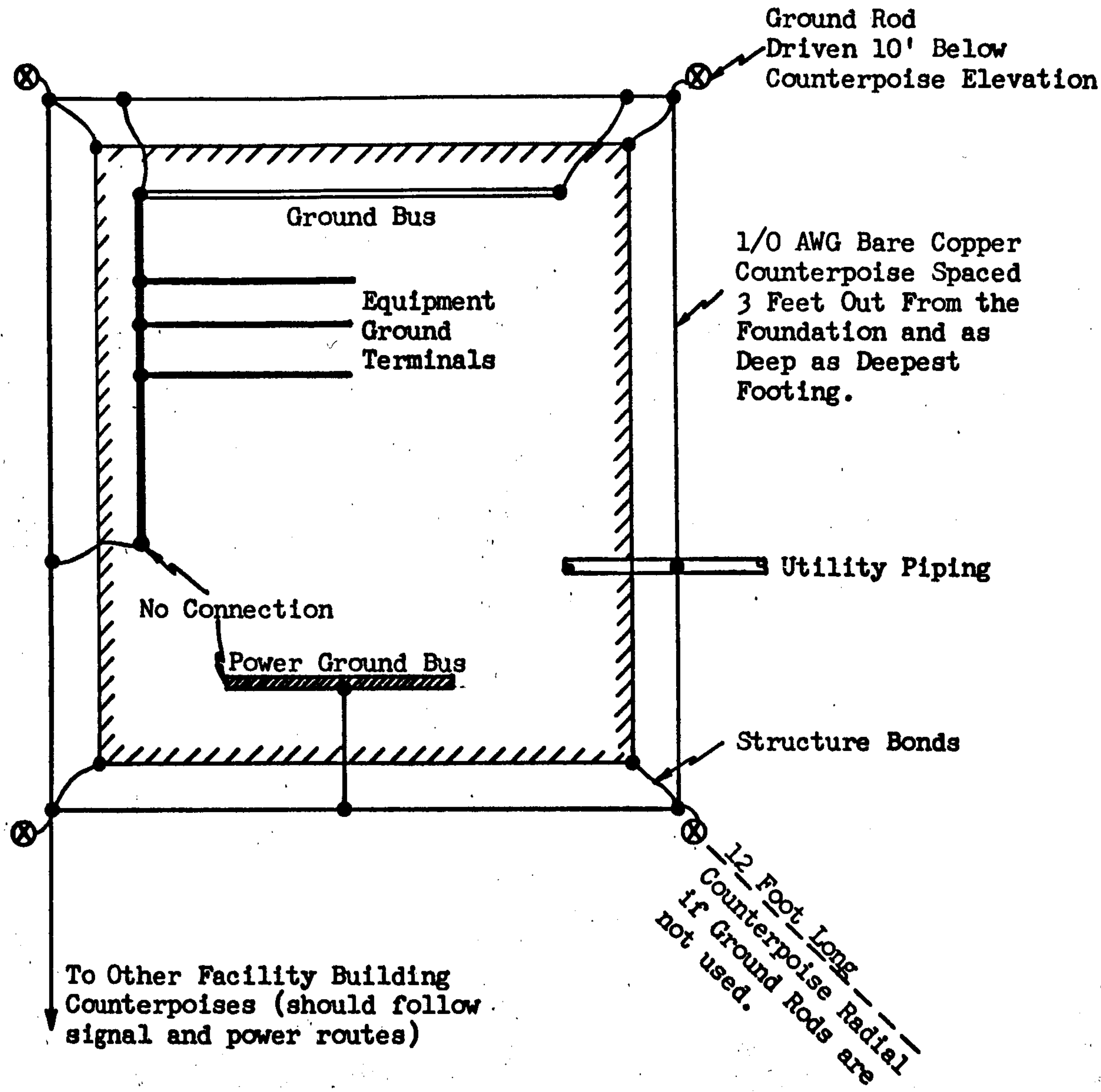


FIGURE 6.3 Building Grounding

Appendix

Background Material

APPENDIX A

BACKGROUND MATERIAL

A.1 Lightning Phenomena

A lightning discharge consists of a rapid discharge of electricity. The current in the stroke generally rises swiftly to peak values of from 1000 to 100,000 amperes in times ranging from 1 to 10 microseconds. Some investigations have indicated that an average current amplitude would be around 15,000 amperes. More recent investigations have indicated, however, that an average current in low country may be considerably higher, on the order of 40,000 amperes. The current generally decreases to one half value in approximately 50 microseconds. A typical time history of a stroke terminating on a very tall structure is shown in Figure A.1. This stroke terminated on the Empire State Building and is representative of many strokes to that building.

Analysis of Figure A.1 shows the stroke begins in the upper left-hand corner with zero time and zero current. Elapsed time runs from left to right across the figure, continuing from one trace to the next. As can be seen, the stroke current reaches a negative 250 amperes in 0.04 second and continues at that value until 0.2515 second has elapsed. Then a negative current peak of 15,000 amperes occurs. After several hundred microseconds, the stroke current falls again to 250 amperes. At 0.2618 second, a current pulse of 4000 amperes occurs. The phenomenon of a continuing low-amplitude current interspersed with high-amplitude pulses continues for the duration of the stroke. In this case the stroke continued for 0.47 second and had four distinct current peaks. The ampere-time area of the stroke, measured in coulombs, largely determines the burning or thermal power. This particular stroke discharged 84 coulombs, of which 60 coulombs were discharged by the continuing current before the first current peak. It is obvious from the figure that most of the coulombs discharged by the stroke are discharged by the continuous current and not the current peaks. Strokes to ground, or much shorter structures, are not likely to exhibit the continuing low-amplitude current prior to the first current peak; consequently, these

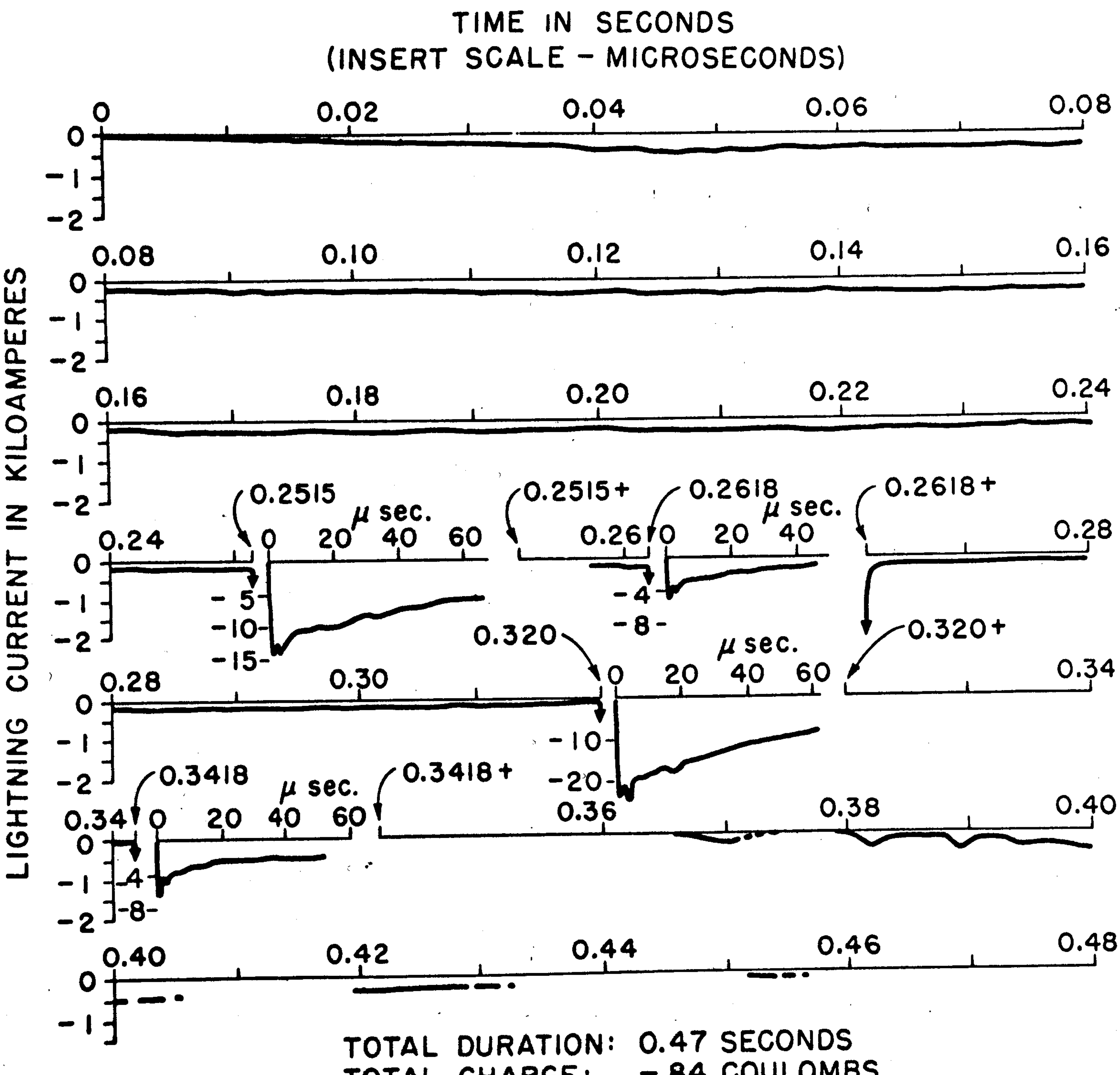


FIGURE A.1 Current Peaks of Multiple Stroke (current peaks and continuing currents of a typical stroke to the Empire State Building) strokes normally have a lower coulomb content. The time duration of a multiple-pulsed stroke may be as long as a second and a half. The time required for a single discharge varies widely, but 100 microseconds is not an unreasonable average. Most data indicates that the duration of the average stroke is about 0.1 second.

The gamut of measured characteristics of lightning strokes is necessary for determining both damage possibilities and protective measures.

a. Figure A.2 is a statistical histogram that shows the average front, or time to crest, for a lightning stroke. This is an important parameter for determining the voltage induced on electrical circuits. The best of several sources of data (see References 1, 2, and 3) is given. One to two microseconds is the predominant time.

b. Figure A.3 gives the distribution of current amplitudes that can be expected. The median is approximately 40,000 amperes.

c. Figure A.4 is the effective rate of rise of lightning-stroke current peaks, with an average of 10,000 to 15,000 amperes per microsecond. This illustration shows that paragraphs "a" and "b" can not be directly compared on a composite basis. The tendency is for front time to become longer as current amplitude increases.

d. Figure A.5 gives a measure of the charge in coulombs, a significant factor in determining the thermal action of the lightning stroke. As mentioned, this occurs largely in the long-duration portion of the stroke.

The importance of the preceding data can be expressed in practical applications as follows:

a. Current amplitude determines the amplitude of voltage that can be developed across resistances in the path of the current flow ($E_R = IR$).

b. Time to crest in conjunction with the amplitude of the current fixes the rate of rise of the current. This, in turn, affects the voltage developed across inductances such as wires and structural members in the path of the current flow ($E_L = L\ di/dt$). It also

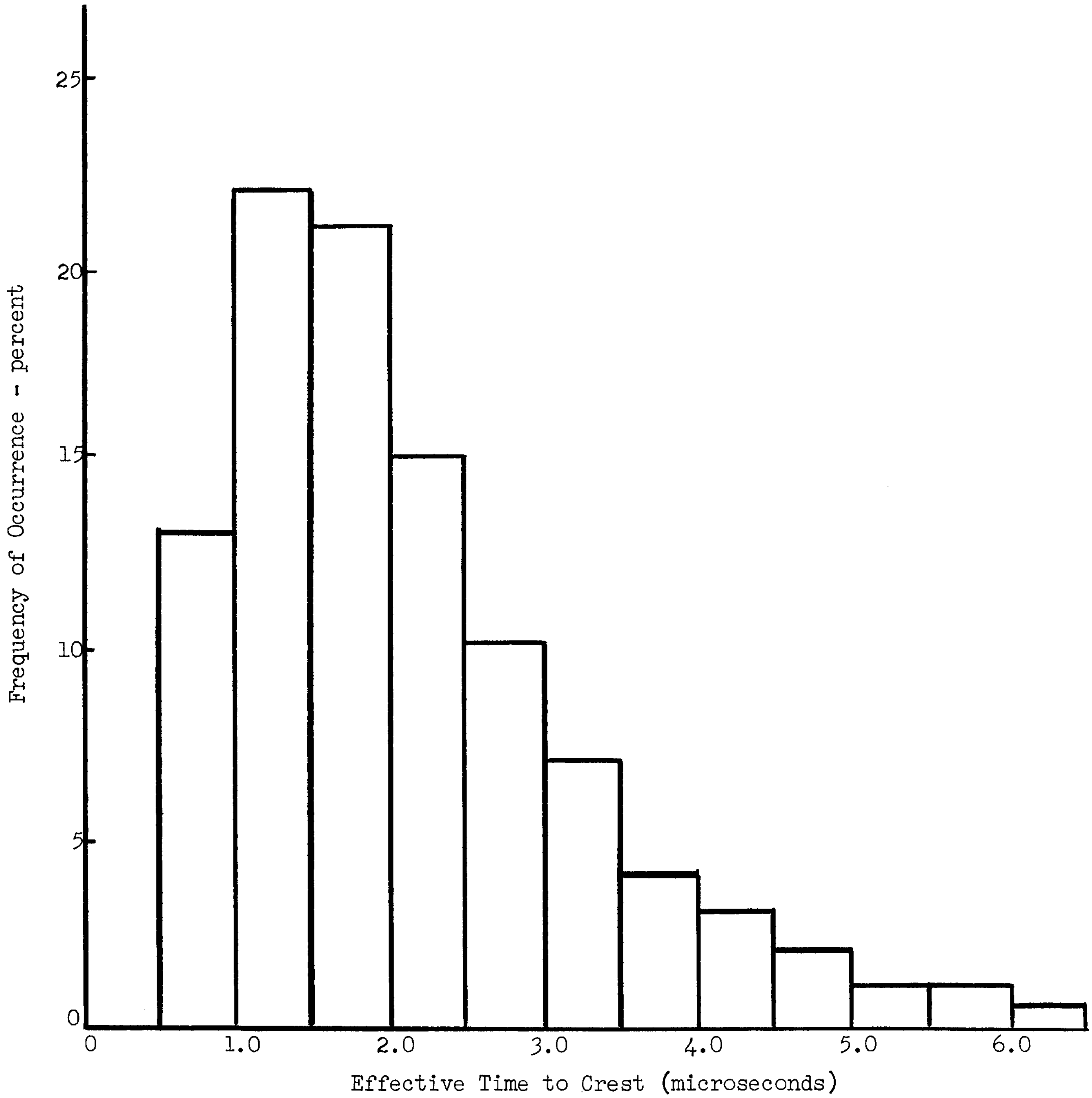


FIGURE A.2 Time to Crest for a Lightning Stroke

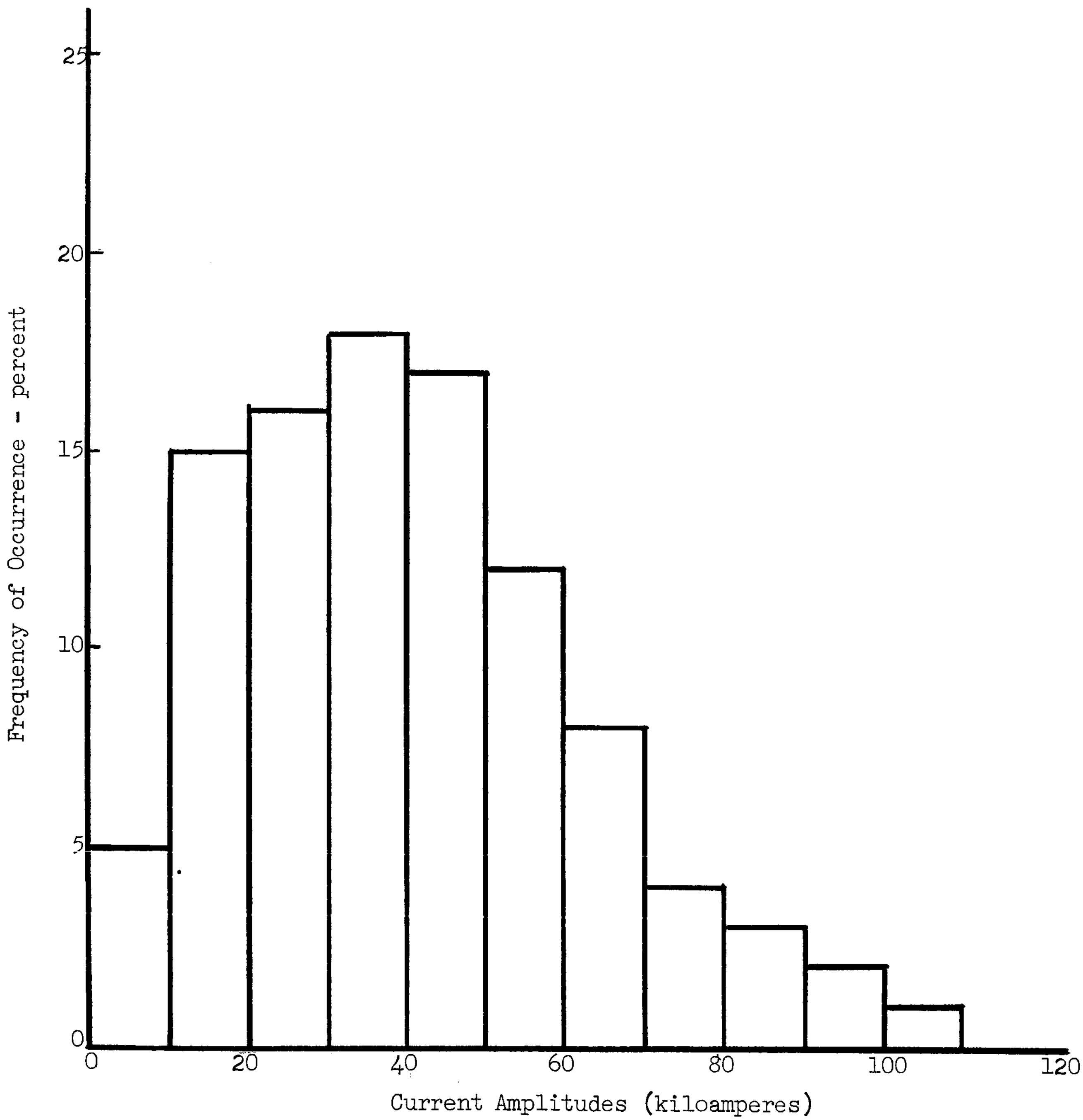


FIGURE A.3 Distribution of Current Amplitudes for a Lightning Stroke

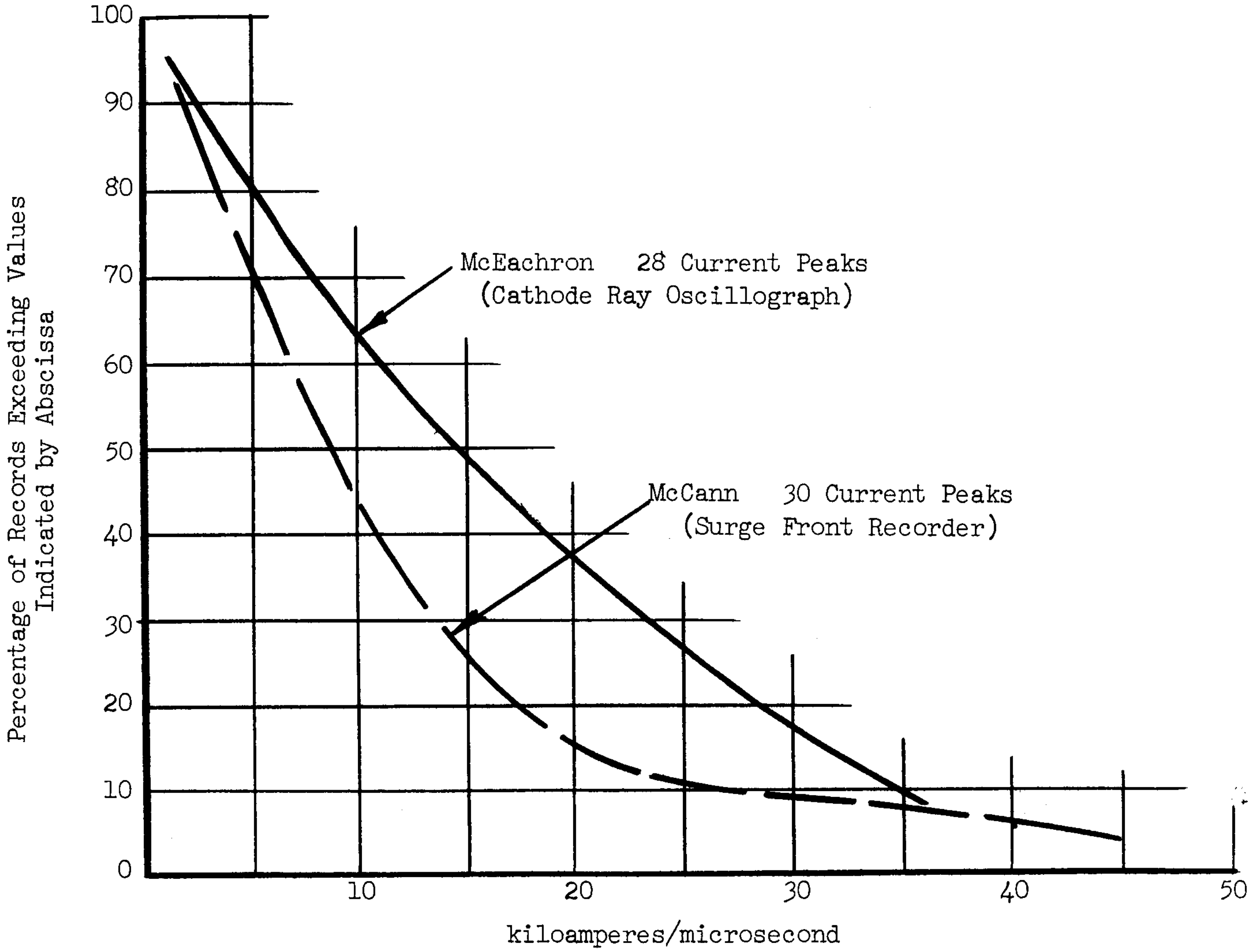


FIGURE A.4 Effective Rate of Rise of Lightning Stroke Current Peaks

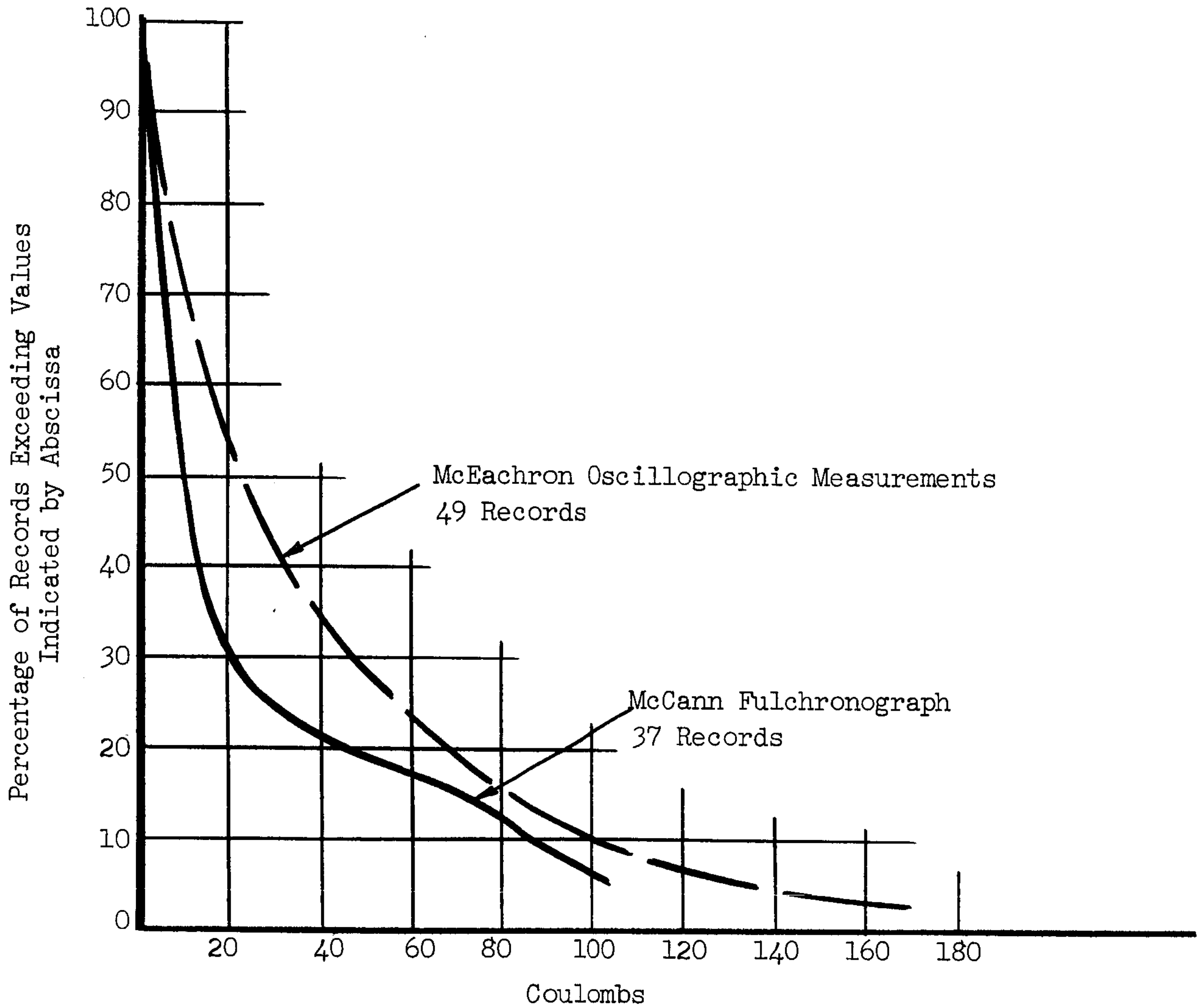


FIGURE A.5 Total Stroke Charges Measured at the Ground Terminal of Lightning Strokes determines the amount of voltage that will be induced in circuit loops in the vicinity of the lightning circuit.

A.2 Grounding, Counterpoises, and Bonding

The requirements of a lightning protective system with respect to grounding, counterpoises, and bonding are based on the following considerations:

a. The lightning current must be conducted into the earth along a controlled path.

b. The current path should be as low a resistance as practical and should be as short as possible to minimize inductance.

c. In areas where electrical equipment is located, a uniform-potential ground plane should be established.

d. In areas frequented by personnel, so-called "touch" and "step" voltages should be prevented. These are the voltages that can exist between two pieces of equipment, which an operator could simultaneously touch or the voltage difference that can exist between the point where a man is standing and equipment he could touch, or simply, the voltage that could exist between a man's feet.

The first step in meeting these requirements is to provide an adequate path to conduct the lightning current into the earth.

A.2.1 Ground Rods

Lightning currents flowing through the resistance of the path between the stroke-termination point and the earth will produce voltage drops that may be dangerous to personnel and equipment. Since these currents can be quite large [40,000 amperes is an average value with a maximum of 180,00 amperes measured recently (see Reference 4)], the resistance of the discharge path must be made as small as possible. For this reason, structures or equipment that may be struck by lightning or which form part of a lightning current discharge path require electrical ground; a connection to earth by a low-resistance circuit. The resistance of this circuit is generally the sum of the resistances of the metallic structure or equipment and its joints and the ground resistance. Usually the ground resistance is the largest component.

To define ground resistance, the underground flow of electric current must be understood. Since this current flows in the earth (a three dimensional body), it loses the simplicity of linear wires by which currents are usually directed. Further, the ground under the surface of the earth is not homogeneous making a rigorous analysis of the distribution of currents very difficult, if not impossible. However, a quantitative analysis of the electric phenomena in the ground is possible if homogeneity is assumed. Such an analysis will allow numerical calculations and permit definite conclusions to be drawn. The literature on ground resistance is extensive and needs little expansion. The purpose of the following paragraphs rather is to provide a capsule introduction to ground resistance (see References 5 & 6).

To provide a better understanding of the phenomena of current flow in the earth, a simple electrode in a homogeneous earth will be considered. The meter-kilogram-second system (MKS) will be used because it yields results in practical electric units.

The simplest electrode is a hemisphere of radius r embedded in the earth as shown in Figure A.6.

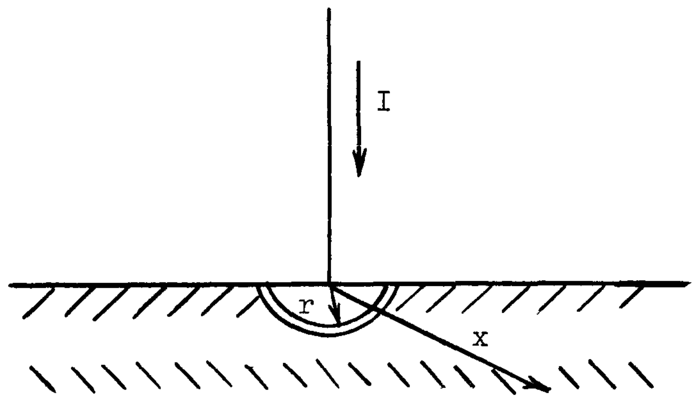


FIGURE A.6 Hemispherical Electrode Embedded in the Earth

If a current, I (in amperes), flows through this electrode spreading out radially in the ground, the current density at a distance of "x" meters from the center of the hemisphere is J,

where

$$J = \frac{I}{2\pi x^2} \text{ amps/meter}^2. \tag{A.1}$$

According to Ohms Law, such a current density produces an electric-field strength (e) in the resistivity ρ (ohms-meters) of the earth,

where

$$e = \rho J = \frac{\rho I}{2\pi x^2} \text{ volts/meter.} \tag{A.2}$$

The voltage, as the line integral of the field strength from the surface of the conducting hemisphere to any distance x is:

$$V = \int_r^x e\,dx = \frac{\rho I}{2\pi}\int_r^x \frac{dx}{x^2} = \frac{\rho I}{2\pi}\left[\frac{1}{r} - \frac{1}{x}\right] \tag{A.3}$$

where

r = radius of the hemisphere.

The total voltage between the hemisphere and a far-distant point with $x \cong \infty$ is

$$V = \frac{\rho I}{2\pi r} \text{ volts.} \tag{A.4}$$

The total resistance experienced by the stream lines of current diverging from the hemisphere is

$$R = \frac{V}{I} = \frac{\rho}{2\pi r} \tag{A.5}$$

As an example, a hemisphere of radius r = 1 meter embedded in soil of resistivity

ρ = 10 ohm-meters will have a ground resistance of

$$R = \frac{10 \text{ ohm meters}}{(2\pi)(1 \text{ meter})} = 1.6 \text{ ohms.}$$

This is the resistance experienced by current flowing through the entire surrounding space. Most of this resistance is encountered in the region immediately around the electrode. As can be shown from Equation A.3, 50% of the total voltage drop resulting from current flowing through this resistance occurs between the electrode and x = 2r; 90% occurs between the electrode and x = 10r. For the example calculated, these distances are two meters and ten meters, respectively. The voltage of a point on the surface of the earth expressed as a percentage of the electrode voltage is shown in Figure A.7.

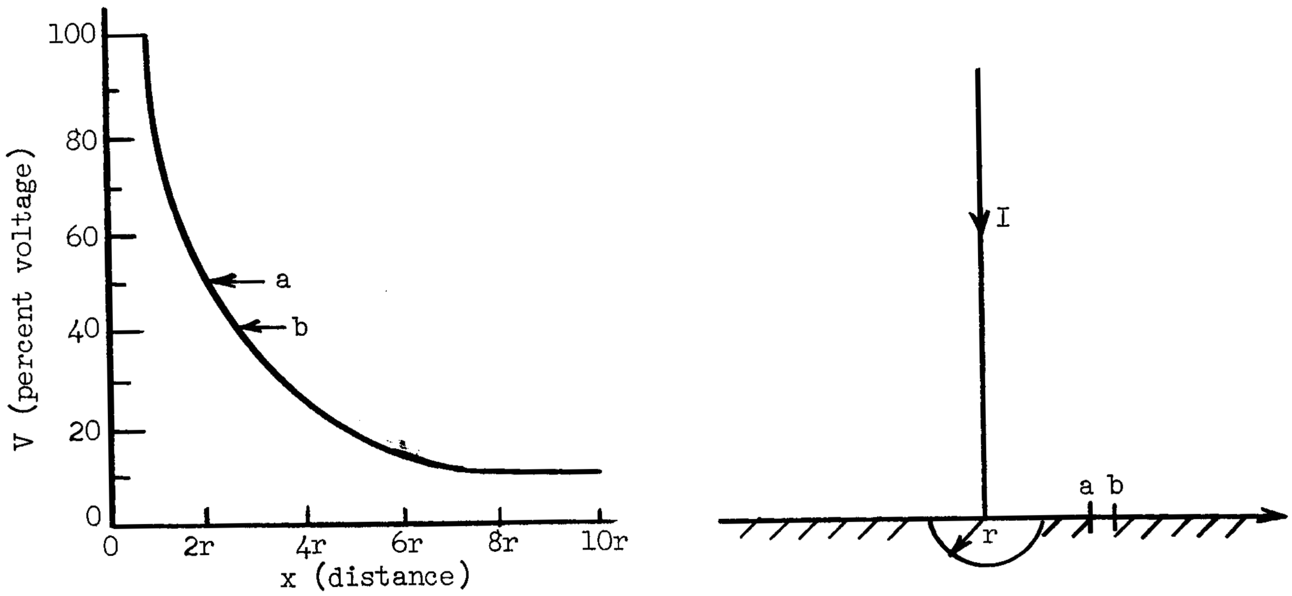


FIGURE A.7 Voltage Gradient for Hemispherical Electrode

A significant voltage can exist between two adjacent points (for example, points a and b) on the surface of the earth near a current-carrying electrode. For instance, an electrode under the following conditions will have 1600 volts between two points that are 2 meters and 2.5 meters from the center of the electrode:

a. Radius of one meter.

b. Resistance of 1.6 ohms.

c. Current of 10,000 amperes.

It is voltages such as these, existing between points on the surface of the earth, that can be harmful to people and electrical equipment.

Thus far, the simple hemispherical electrode has been used to illustrate ground resistance, ground electrode potential, and the voltage gradient (voltage difference) along the surface of the earth near a current-carrying ground electrode. The same phenomena occur with the more commonly used rod electrode having a length much greater than its diameter.

Ground rods usually come in 8- to 12-foot lengths and may be joined by couplings for greater depths. Rod diameters are generally less than one inch. The resistance of a driven ground rod is, from Dwight (see Reference 6),

$$R = \frac{\rho}{2 \pi l} \left[\log_e \left(\frac{4 \ell}{r} \right) - 1 \right], \quad \text{when } \ell \gg r \qquad \text{(A.6)}$$

where:

ρ = ground resistivity, in ohm-meters.

ℓ = length of rod, in meters.

r = radius of rod, in meters.

The diameter of the rod is of minor significance since it affects only the logarithmic term, $4 \ell/r$. However, the length is most important within practical limits. Since resistance does not decrease directly with length, there comes a point where further increase in length is accompanied by only a minor reduction in footing resistance. Table A.1, from Sunde (see Reference 7), shows the variation of resistance with rod length for various rod diameters. The data were obtained from Equation A.6 using a ground resistivity of 100 ohm-meters. Since this information is based on an assumed constant ground resistivity, it is of limited value by itself.

TABLE A.1

GROUND RESISTANCE (in ohms) OF VARIOUS LENGTHS AND DIAMETERS OF GROUND RODS*

Rod Diameter (inches)	For Rod Lengths of						
	1 foot	2 feet	5 feet	10 feet	20 feet	50 feet	100 feet
0.5	225	132	62	35	19.2	8.7	4.7
1	188	113	55	31	17.3	8.0	4.3
2	151	95	47	28.5	15.5	7.2	4.0
4	115	77	40	25	13.6	6.5	3.6
12	69	51	28.5	18.1	10.9	5.4	3.0
24	44	35	21	14.4	9.0	4.6	2.6

* Based on Soil Resistivity = 100 ohm-meters

The practical approach is to determine the ground resistivity of the earth for a variety of soils and moisture content. Table A.2, from Watt (see Reference 8), gives representative values.

TABLE A.2

REPRESENTATIVE VALUES OF EARTH RESISTIVITY

	Material	Approximate Resistivity (ohm-meters)
Soil	good	10 to 10^2
	average	10^2 to 10^3
	poor	10^3 to 10^4
Water	fresh	10^3 to 10^4
	sea	0.2 to 0.25
Sediments	marine sands and shales	1 to 10
	marine sandstones	1 to 10^2
	clay	10 to 10^2
	sandstone (wet)	10^2 to 10^4
	sandstone (dry)	10^4 to 10^7
	limestone	10^4 to 10^8
Igneous Rock	granite	10^3 to 10^9
	basalt	10^5 to 10^9
Metamorphic	slate	10^3 to 10^5
	marble	10^3 to 10^8
	gneiss	10^3 to 10^7
	serpentine	10^3 to 10^7

From the fact that the ground resistance varies directly with the ground resistivity and from the data presented in Tables A.1 and A.2, the ground resistance of any ground rod can be quickly approximated. For instance, a 1/2-inch diameter rod in 10-foot marine sand, such as would exist at Cape Kennedy, would have a resistance of 0.35 to 3.5 ohms. The range is predominantly affected by moisture content.

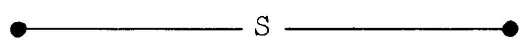
When it is not possible to obtain the desired ground resistance from a single ground rod, several rods may be driven and connected in parallel. If the spacing between rods is large compared to the length of the individual rods, the resistance will be reduced in proportion to the number of rods. If the rods are close together, each rod will be in the intense electrical field of its neighbor.

If the rods are very close together, the overall resistance becomes

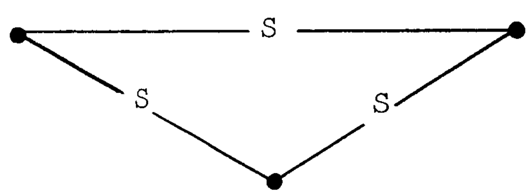
$$r = \frac{\rho}{2 \pi \ell} \log_e \frac{2 \ell}{A} \qquad (A.7)$$

where A represents the radius of an equivalent rod.

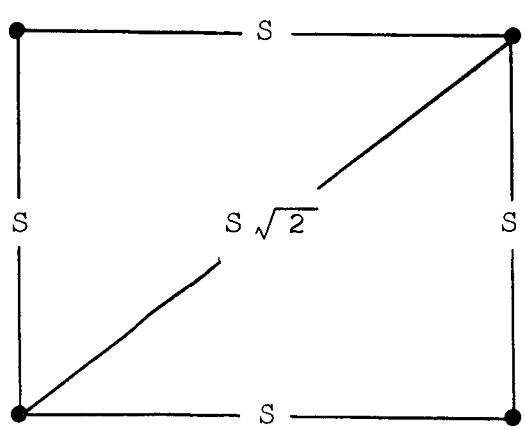
The following expressions show how the equivalent radius depends on rod geometry. In each case "r" denotes the radius of the individual rods.



$$A = \sqrt{rs} \qquad (A.8)$$



$$A = \sqrt[3]{rs^2} \qquad (A.9)$$



$$A = \sqrt[4]{rs^2 \sqrt{2}} \qquad (A.10)$$

If the rods are moderately close to each other, the overall resistance will be more than if the same number of rods were spaced far apart. For instance, using Equation A.7, two 3/4-inch diameter, 10-foot rods, in parallel and spaced one foot apart in a soil resistivity of 10 ohm-meters, will have a resistance of 2.5 ohms. The same two rods spaced 10 feet apart will have a resistance of 1.9 ohms. Lewis (see Reference 9) gives additional information on ground rods in parallel as a function of spacing.

In closing this portion on ground resistance, it is appropriate to include a short discussion on the measurement of ground resistance. The fundamental method of measurement of ground resistance is shown in Figure A.8. Current is circulated between the ground under test and an auxiliary ground. Preferably, this auxiliary ground should be located at a distance that is large compared to the dimensions of the ground under test, since it is not desirable to have interaction of the ground current distributions at the two electrodes. A voltage is then measured between the ground under test and a reference ground is located somewhere between the two current-carrying electrodes. This reference ground should also be so located that it is not in the electric field of either of the current-carrying electrodes. Assuming that the current density is negligible at the reference electrode, the resistance of the ground under test is:

$$R = \frac{V}{I}.$$

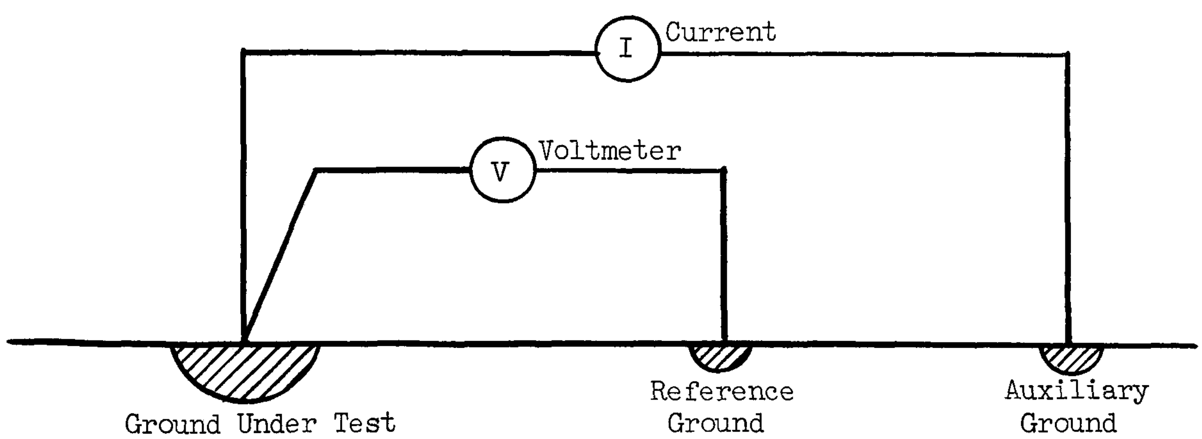


FIGURE A.8 Fundamental Method of Ground Resistance Measurement

The measurement may be made using a voltmeter and ammeter with the current being supplied by a transformer energized from the ac power lines. Alternatively, a bridge may be used for the measurement. Most often, however, ground resistance is measured with self-contained instruments such as the James G. Biddle Company's Megger ground resistance tester.

When measuring the ground resistance of an extensive structure, it may be difficult to place the auxiliary current ground or the reference ground sufficiently far from the ground under test that the electric fields of the electrodes do not interact. Curdts (see Reference 10) has shown substantially that the correct ground resistance is measured if the reference ground is located at a point approximately 60 percent of the distance measured from the ground under test to the auxiliary ground. If the system is large, errors may be encountered resulting from stray currents in the ground from outside power sources. These tend not to affect the measurements when using a self-contained ground tester, since the current frequency of the test set is generally different from the frequency of the interfering currents. Such interfering currents can also be balanced out in the measuring instrument. Duke and Smith (see Reference 11) have described a 60-cycle test set, which contains such balancing circuits, for the measurement of low-impedance grounds.

A.2.2 Counterpoise

A counterpoise is a single bare wire or a network of bare wires buried horizontally. The several functions of the counterpoise are as follows:

a. to reduce the resistance of a ground electrode.
b. to interconnect ground electrodes.
c. to provide a convenient means for grounding equipment and circuits.
d. to reduce voltage gradients on the surface of the earth.
e. to intercept lightning stroke currents which would otherwise terminate on equipment and circuits being protected.

The resistance of a single buried horizontal wire is, from paragraph 3.6 of Sunde (see Reference 7):

$$R = \frac{\rho}{\pi \ell}\left[\log_e\left(\frac{2}{\sqrt{2rd}}\right) - 1\right] \quad \text{when } d \ll \ell \qquad (A.11)$$

where:

ℓ = length of wire, in meters.

r = wire radius, in meters.

d = burial depth, in meters.

Table A.3 shows how this resistance varies with length of wire and burial depth.

TABLE A.3

VARIATION OF RESISTANCE (in ohms) WITH LENGTH OF A HORIZONTAL GROUND WIRE FOR A GROUND AT THE SURFACE AND AT A DEPTH OF 12 INCHES

Burial Depth (inches)	Wire Length						
	10 feet	20 feet	50 feet	100 feet	200 feet	500 feet	1000 feet
0	80	45	19.4	10.4	5.6	2.4	1.29
12	47	27	12.8	7.1	3.9	1.75	0.45
Earth Resistivity = 100 ohm-meters Wire Gauge = No. 10 AWG							

Equation A.11 assumes that the potential is uniform over the entire length of the wire, which could only hold if the wire had perfect conductivity. If the wire is very long, it will not be at the same potential all along its length and Equation A.11 will be in error. However, from a practical viewpoint, the diameters and lengths of counterpoise wire normally used are such that the error, as a result of wire resistance, may be neglected.

Another consideration in determining the effective resistance of the counterpoise is its transient response (impedance with respect to time) when a current surge, such as a lightning stroke, is applied. Initially the effective resistance is quite high, on the order of 150 ohms. This value is defined as the surge impedance of the wire. As the surge propagates along the wire, the resistance decreases as the current spans more and more of the wire and thus makes more effective contact with the earth.

The surge propagates in the earth at roughly one-third the speed of light. As an example, approximately three microseconds would be required for current to span a 1000-foot wire. For a given length of buried wire, the transient resistance will reduce to the steady-state resistance faster if the wire is arranged as several shorter radial wires than if it is laid as one long wire. Figure A.9 from Lewis (see Reference 9) shows how the transient response of buried wires varies for several configurations of wire. In the case of driven ground rods, the final resistance would be obtained quite quickly since the rods would be fairly short. Widely spaced ground rods would not attain their final resistance until a surge current had reached the most distant rod. As a practical matter for the grounding of lightning currents with counterpoise, the first 250 feet of buried conductor are the most effective.

Ground resistance decreases with increasing current, at least until such time as the current heats the soil moisture to the boiling point. The proportional reduction is less for grounds of low resistance than it is for grounds of high resistance. Figure A.10 from Lewis (see Reference 9) shows typical measured values of ground resistance as a function of impulse current.

A.2.3 Bonding (see Reference 12)

Bonding can be defined as providing an electrical connection across mechanical joints metallic structures, the electrical connection of conduits and piping to structural metal, and the interconnection of reinforcing metals in cement structures. The bonding of these joints is necessary for the following reasons:

a. to provide a minimum resistance and direct path for lightning current from the point of stroke termination to the earth.
b. to protect personnel from the shock hazard resulting from equipment internally power-faulted.
c. to prevent the accumulation of static charge that would produce radio interference as well as create a shock hazard and, by periodic sparking, an explosion hazard.

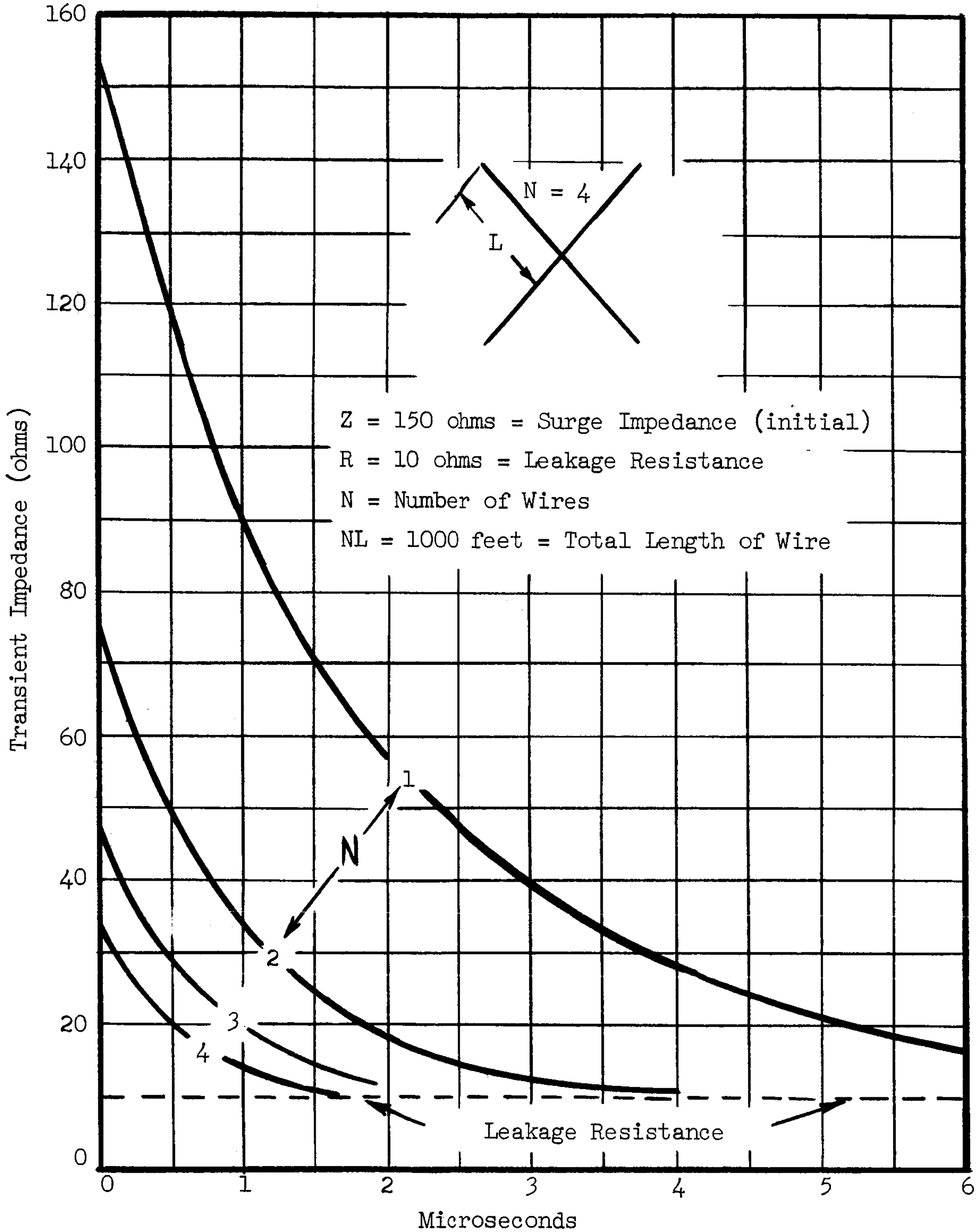


FIGURE A.9 Transient Impedance of 1000 Feet of Counterpoise as a Function of Number of Radial Wires

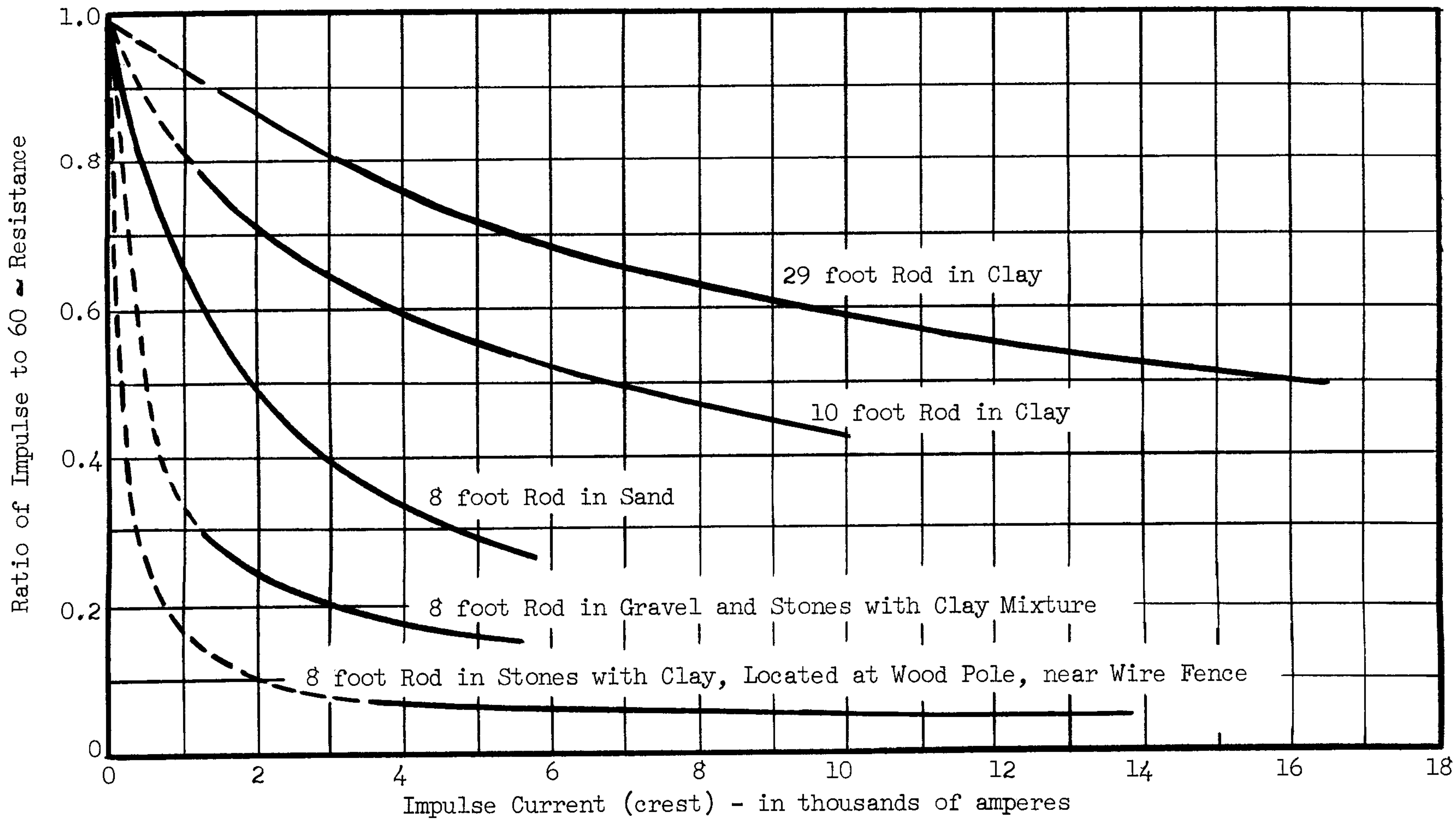


FIGURE A.10 Impulse Current Resistance of Various Ground Rods

A.3 Lightning Induced Voltages

The purpose of the following section is to describe the three principal lightning stroke phenomena that produce voltages on electrical circuits. These are as follows:

a. the voltage induced in circuits that are magnetically coupled to conductors carrying lightning currents.

b. the IR or resistance voltage resulting from lightning current flowing in the structure and ground resistance.

c. the voltage induced in circuits that are capacitively coupled to the lightning stroke.

Lightning voltages in electrical circuits are generally some combination of the three components. For ease in understanding, the components will first be discussed separately.

A.3.1 Inductive Component

The magnetically induced voltage is the most complex and, as previously stated, is the induced voltage in a circuit which is magnetically coupled to a current-carrying conductor. For instance, in Figure A.11, the voltage is magnetically induced in the Loop A by the field produced by the changing current in the Conductor B.

Obviously, for example, B could be a lightning-stroke channel as well as a physical conductor. As another example of induced voltage, consider Figure A.12, where the current path forms part of the voltmeter loop. There is no current flowing through the voltmeter.

This simple circuit is symbolic of lightning current flowing in a wire with a man contacting the wire at two points, a and d. The voltage, E, is related to the rate of change of flux produced by the changing current dI/dt in the loop according to the following equation.

$$E = -N \frac{d\phi}{dt} \qquad (A.12)$$

where:

N = number of turns.

ϕ = flux enclosed by the loop in webers.

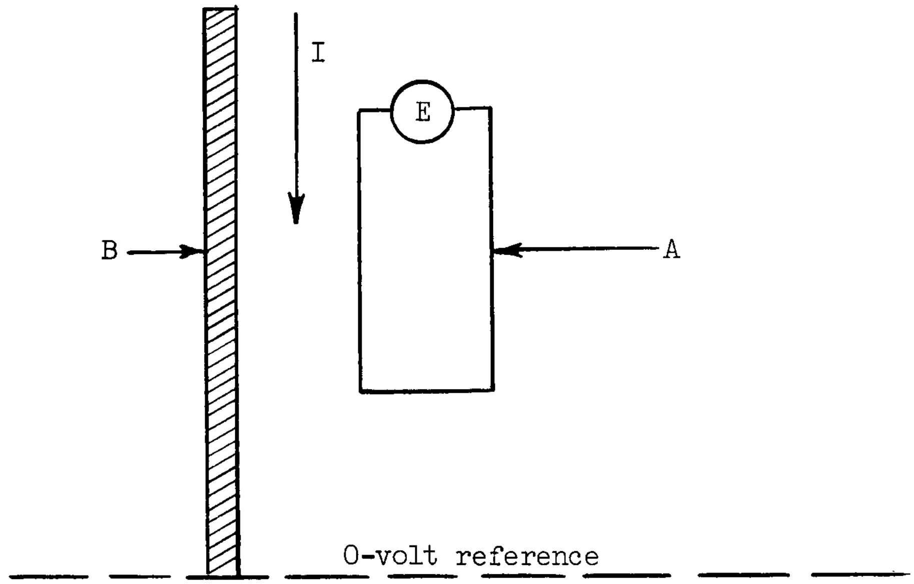


FIGURE A.11 Magnetically Induced Voltage

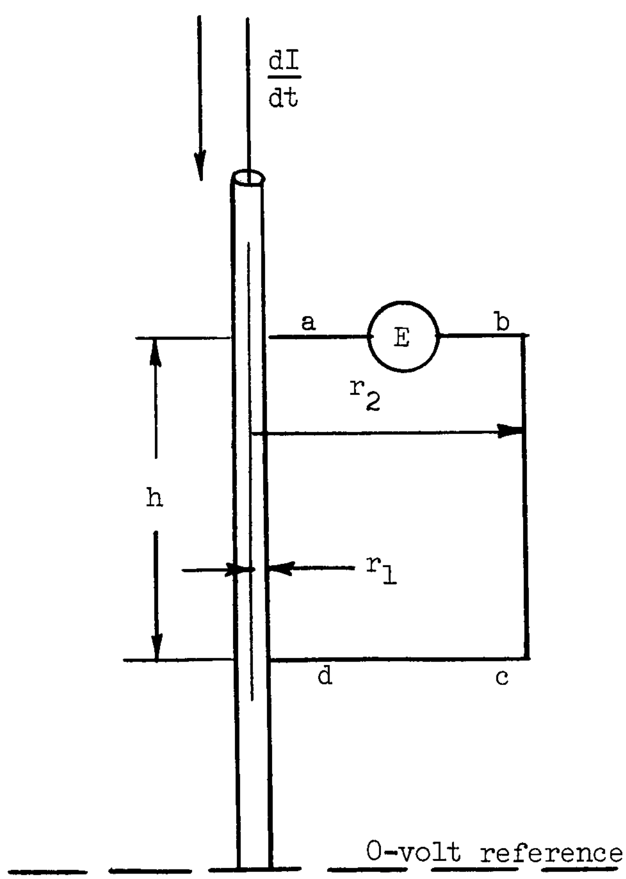


FIGURE A.12 Induced Voltage - Current Path in Voltmeter Loop

To actually determine the voltage, dimensions and rate of change of current must be known. First, the flux density is determined from the relationship

$$\beta = \frac{\mu I}{2 \pi r} \tag{A.13}$$

where:

β = webers/meter^2

μ = $4 \pi \times 10^{-7}$ henries/meter

I = amperes

r = radial distance from conductor in meters.

Next, the flux contained in the loop, abcda, is determined by taking the line integral around the loop.

$$\left.\begin{aligned} \phi &= \oint \beta dr = \frac{h \mu I}{2 \pi} \int_{r_1}^{r_2} \frac{1}{r} dr \\ \phi &= 20 \times 10^{-8} \times I \times h \times \log_e\left(\frac{r_2}{r_1}\right) \end{aligned}\right\} \tag{A.14}$$

$$\frac{d\phi}{dt} = 20 \times 10^{-8} \times h \times \frac{dI}{dt} \times \log_e\left(\frac{r_2}{r_1}\right) \tag{A.15}$$

From Equation A.12 and Equation A.13 for the single-turn loop in Figure A.12.

$$E_{ba} = 200 \times 10^{-9} \times h \times \frac{dI}{dt} \times \log_e\left(\frac{r_2}{r_1}\right) \tag{A.16}$$

where:

h = loop height in meters

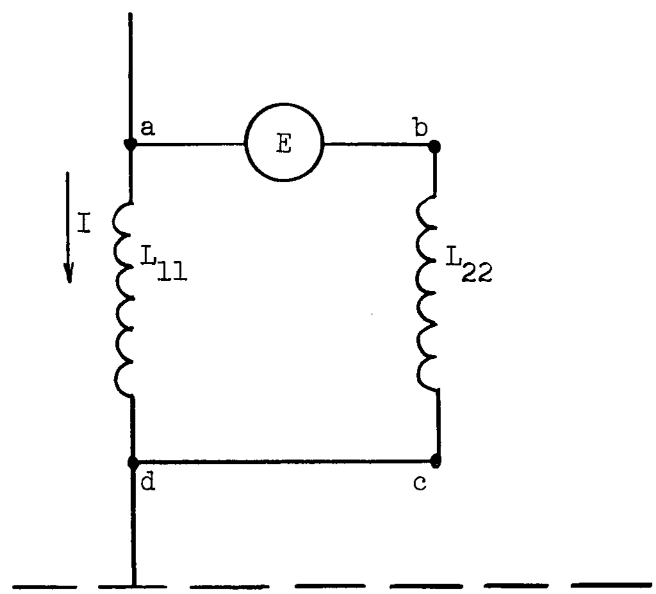
$\frac{dI}{dt}$ = amperes per second

For h in feet,

$$E_{ba} = 61 \times 10^{-9} \times h \times \frac{dI}{dt} \times \log_e\left(\frac{r_2}{r_1}\right) \tag{A.17}$$

This equation expresses the loop voltage in terms of loop dimensions and rate of change of current, which is producing the flux linked by the loop. From the equation it can be seen that the loop voltage is a function of the loop dimensions. For example, if one were attempting to measure the voltage between a and d, the value obtained would be dependent upon the dimensions of the loop, abcda, and not simply the height, a to d. This concept of induced voltage is very important and, therefore, in an attempt to clarify it further the same loop voltage will be described in terms of the familiar lumped inductance. Consider the circuit in Figure A.13.

FIGURE A.13 Voltage in Flux-Linked Loop



where:

I = current amperes

L_{11} = self-inductance of the current-carrying conductor between a and d

L_{22} = self-inductance of meter lead

L_{12} = L_{21} = mutual inductance between L_{11} and L_{22}

Equating the voltages around the loop, abcda, yields:

$$E_{ba} = L_{11}\frac{dI}{dt} - L_{12}\frac{dI}{dt} = (L_{11} - L_{12})\frac{dI}{dt} \qquad (A.18)$$

$$L_{11} = \frac{\phi_1}{I} \tag{A.19}$$

From Equation A.14

$$\phi_1 = \frac{h \mu I}{2 \pi} \int_{r_1}^{R} \frac{1}{r} \, dr \text{ webers} \tag{A.20}$$

where:

h = length of conductor being considered, in meters.

r_1 = radius of conductor, in meters.

R = radius to a distant point where flux density = 0.

Integrating Equation A.20 and combining with Equation A.19 yields

$$L_{11} = \frac{h \mu}{2 \pi} (\log_e R - \log_e r_1) \tag{A.21}$$

Similarly,

$$L_{12} = \frac{\phi_2}{I} \tag{A.22}$$

$$\phi_2 = \frac{h \mu I}{2 \pi} \int_{r_2}^{R} \frac{1}{r} \, dr \tag{A.23}$$

where:

r_2 = radial distance between the center of the current-carrying conductor and the meter lead.

Integrating Equation A.23 and combining with Equation A.22 yields

$$L_{12} = \frac{h \mu}{2 \pi} (\log_e R - \log_e r_2) \tag{A.24}$$

Combining Equations A.18, A.21, and A.24 yields

$$E_{ba} = \frac{h \mu}{2 \pi} (\log_e r_2 - \log_e r_1) \frac{dI}{dt}$$

where:

$\mu = 4 \pi \times 10^{-7}$ henries/meter

$\frac{dI}{dt}$ = rate of change of current in amperes per second

$$E_{ba} = 200 \times 10^{-9} \times h \times \frac{dI}{dt} \times \log_e\left(\frac{r_2}{r_1}\right) \tag{A.25}$$

Equation A.25 is exactly the same as Equation A.16.

So far, a "resistanceless" conductor has been considered. The addition of resistance to the circuit is illustrated in Figure A.14.

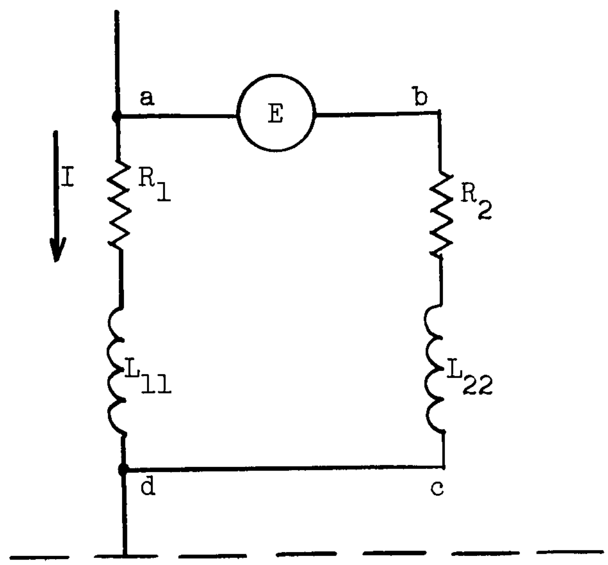


FIGURE A.14 Voltage in Flux-Linked Loop (with resistance)

Equating voltages around the loop, abcda, yields:

$$E_{ba} = RI + (L_{11} - L_{12}) \frac{dI}{dt} \qquad (A.26)$$

where:

$$R = R_1 + R_2$$

Comparing this equation with Equation A.18 shows that in the case of this loop, the total resistance voltage drop simply adds to the net inductive voltage drop.

So far, the illustrations have considered cases where current conductor formed part of the loop. In the more general case, the loop is electrically isolated from the current conductor (see Figure A.15).

$$E_{ba} = (L_{12} - L_{13}) \frac{dI}{dt} \qquad (A.27)$$

This equation has exactly the same form as Equation A.25 and in terms of circuit dimensions instead of inductance,

$$E_{ba} = 200 \times 10^{-9} \times h \times \frac{dI}{dt} \times \log_e \frac{r_2}{r_1} \qquad (A.28)$$

where:

r_2 = radial distance between L_{11} and L_{33}

r_1 = radial distance between L_{11} and L_{22}

h = height in meters of L_{22} and L_{33}

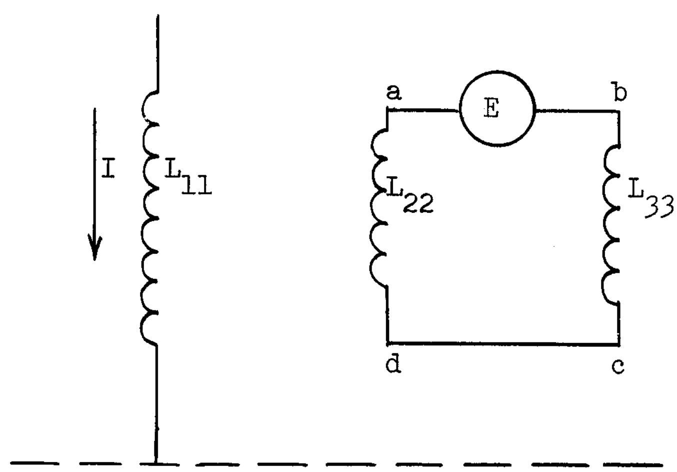


FIGURE A.15 Voltage in Isolated Flux-Linked Loop

Equation A.17 expresses the dimensions in feet instead of meters,

$$E_{ba} = 61 \times 10^{-9} \times h \times \frac{dI}{dt} \times \log_e \frac{r_2}{r_1} \qquad (A.29)$$

As an example of an application of Equation A.29, the loop voltage for various values of loop width $(r_2 - r_1)$ and r_1 were calculated for a dI/dt of 1000 amperes per microsecond. These voltages are plotted on a per foot of loop height basis on Figure A.16. The figure graphically illustrates the

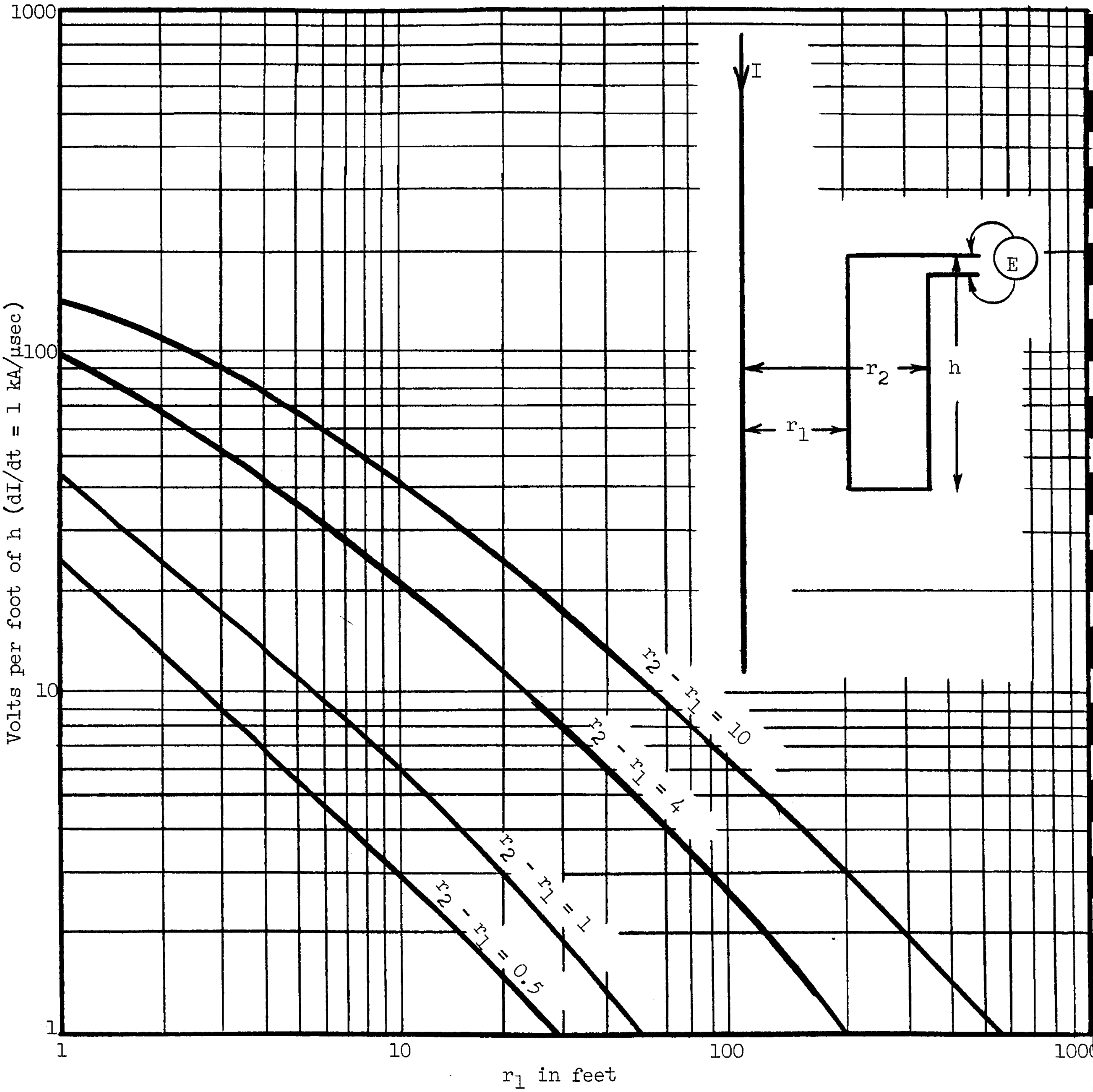


FIGURE A.16 Voltage Induced in a Single-Turn Loop effect of moving the loop with respect to the current conductor and varying the width of the loop, which changes the amount of flux linked. As another example of a voltage induced in a loop near a conductor carrying a changing current, consider Figure A.17.

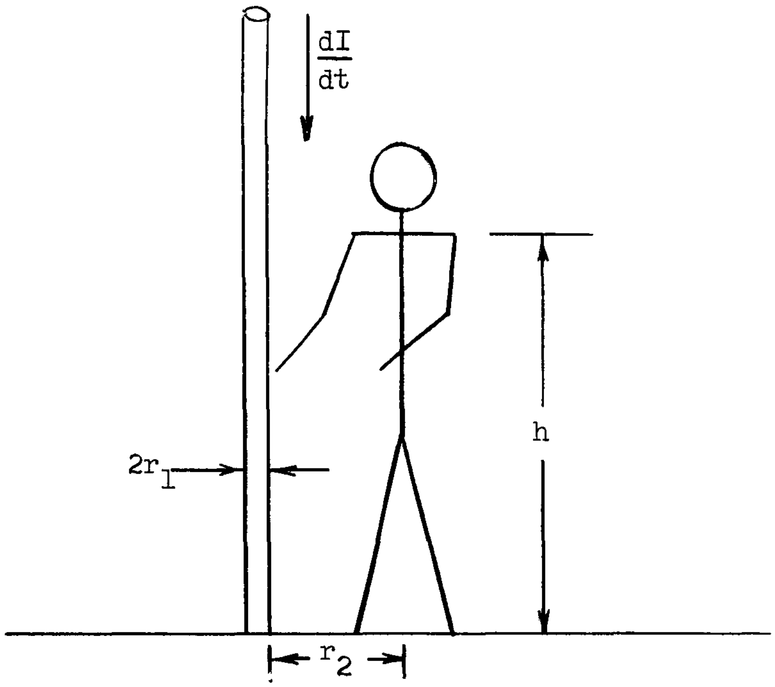


FIGURE A.17 Induced Voltage Where Man Forms the Loop

Here the voltmeter has been replaced by a man and the loop is the path from the man's hand, down his body, across the earth, and up the conductor. If h = 5 feet, r_1 = 0.01 foot, and r_2 = 2 feet, the voltage across the man would be, from Equation A.29,

$$E_{man} = 61 \times 5 \times \log_e \frac{2}{0.01} \times \frac{dI}{dt} \times 10^{-9} \text{ volts.}$$

For a current changing at the rate of 50,000 amperes per microsecond ($dI/dt = 5 \times 10^{10}$ amps/sec):

$$E_{man} = 80{,}000 \text{ volts.}$$

In the foregoing paragraph, it has been illustrated that the voltage magnetically induced depends on the flux linked by the loop and that the flux linked by the loop is determined by loop dimensions.

A.3.2 Resistive Component

The resistance voltage is best described by referring to Figure A.18. The lightning stroke terminates at A and the current, I, flows into the earth through the ground resistance, R_F, producing a resistance voltage, E, between the cable at the bottom of A and the 0-volt reference of the earth. Since there is no electric circuitry between A and the 0-volt reference, the magnitude of E is not important. However, at the other end of the cable, which is shown with the sheath isolated, a voltage E' exists between the sheath and the grounded container B. It is important to recognize that because there is a discontinuity in the sheath and no current flows to ground through R_F', B remains at the 0-volt reference potential and all of the voltage E' is across the discontinuity. The voltage E_1', between the circuit and the container B will be some fraction of E' depending on circuit impedances. If the impedances between the circuits and containers are large, the voltages between the sheath and the conductors within will be small. The purpose of this illustration is to point out an example of resistance voltage resulting from lightning, not how to control such voltages. However, the most direct way to minimize E' and E_1' is to connect the sheath to B and deliberately allow the sheath to carry a portion of the stroke current.

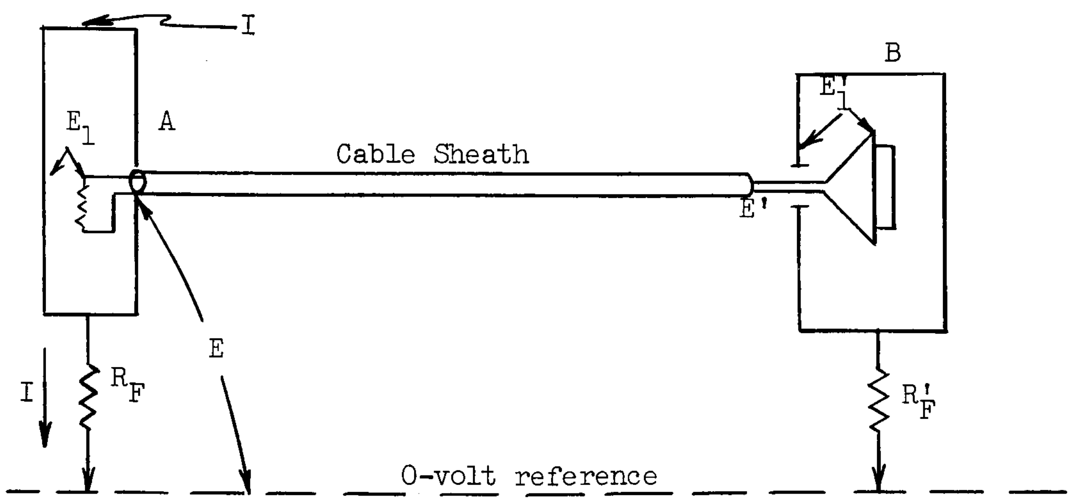


FIGURE A.18 Resistive Component of Induced Voltage Loop

A.3.3 Capacitive Component

The capacitive or electrically induced voltages result from the charge that accumulates on objects capacitively coupled to the lightning stroke and the electrified clouds. As the electric field strength between the developing lightning stroke and ground increases, charge accumulates on all conducting objects in this electric field. This increase in charge occurs slowly enough so that conductors that are grounded through even a high impedance do not change potential appreciably with respect to ground. When the stroke terminates on the ground, the charge on the grounded objects redistributes. The redistribution of charge manifests itself as a current flow through the grounding impedance of the conductors that, in turn, appears as a voltage across that impedance. The voltage between the conducting object and ground can be expressed as

$$E = \frac{Q}{C} e \frac{-t}{RC} \qquad \text{(A.30)}$$

where: (referring to Figure A.19)

Q = charge in coulombs

C = capacitance to ground in farads = $C_1 + C_2 \ . \ . \ . + C_n$

R = resistance to ground in ohms = $R_f \times R_f'/(R_f + R_f')$

t = time elapsed since stroke

Equation A.30 shows that the rate of decay of the electrically induced voltage component is quite large and thus, for any conceivable lightning stroke, the capacitively induced voltage on any well-grounded structure will be very small.

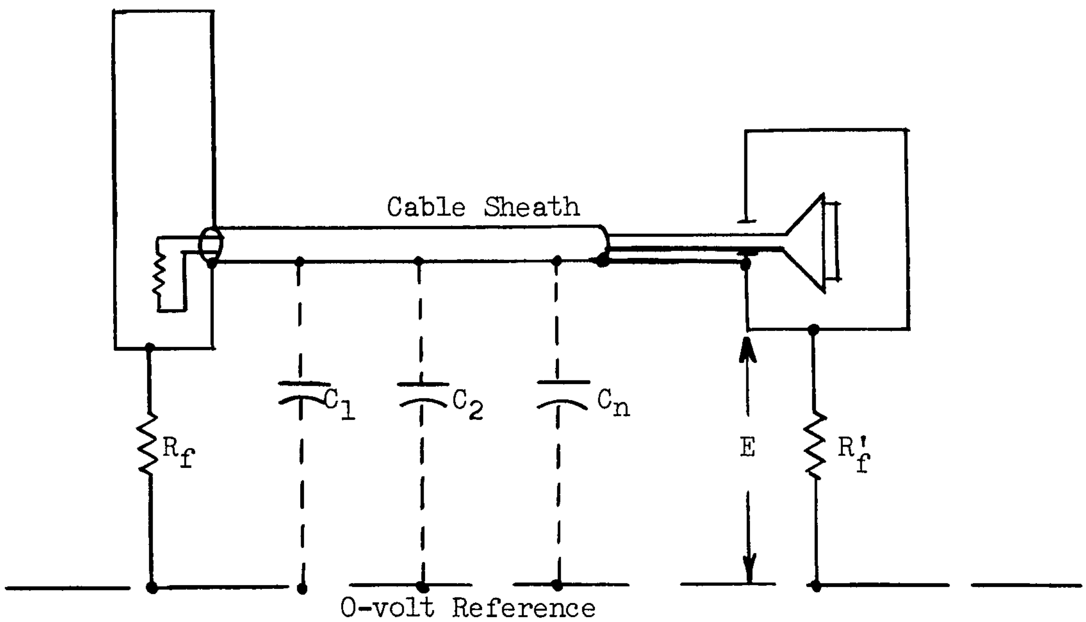


FIGURE A.19 Capacitive Component of Induced Voltage

References

REFERENCES

1. Anderson, J. G., MONTE CARLO CALCULATION OF TRANSMISSION LINE LIGHTNING PERFORMANCE, AIEE Transactions, vol. 80, Part III (Power Apparatus and Systems), pp. 414-420, 1961.

2. Schlomann, R. H., Price, W. S., Johnson, I. B., and Anderson, J. G., 1956 LIGHTNING INVESTIGATION ON THE OVEC 345 kV SYSTEM, AIEE Transactions, vol. 76, Part II (Power Apparatus and Systems), pp. 1447-1459, 1958.

3. Hylten-Cavallius, N. and Stromberg, A., THE AMPLITUDE, TIME TO HALF VALUE, AND STEEPNESS OF LIGHTNING CURRENTS, ASEA Journal, vol. 29, pp. 129-134, 1956.

4. Berger, K., FRONT TIME (RISE TIME) AND CURRENT STEEPNESS OF LIGHTNING STROKES TO THE EARTH, Central Electricity Generating Board, Central Electricity Research Laboratories, Leatherhead. International Conference May 1962. Gas Discharges and the Electricity Supply, Preparing Paper #27.

5. Rudenberg, R., GROUNDING PRINCIPLES AND PRACTICE, PART I: FUNDAMENTAL CONSIDERATIONS ON GROUND CURRENTS, Electrical Engineering, January 1945.

6. Dwight, H. B., CALCULATION OF RESISTANCES TO GROUND, Electrical Engineering, vol. 55, pp. 1319-1328. 1936.

7. Sunde, E. D., EARTH CONDUCTION EFFECTS IN TRANSMISSION SYSTEMS, D. Van Nostrand: New York, 1949.

8. Watt, A. D. et al, SOME ELECTRICAL CHARACTERISTICS OF THE EARTH'S CRUST, Proceedings of the IEEE, vol. 51, 6, pp. 897-910, June 1963.

9. Lewis, W. W., THE PROTECTION OF TRANSMISSION LINES AGAINST LIGHTNING, Chapters 1 and 2, New York, John Wiley, 1950.

10. Curdts, E. B., SOME OF THE FUNDAMENTAL ASPECTS OF GROUND RESISTANCE MEASUREMENTS, AIEE Transactions, vol. 77, Part I (Communications and Electronics), pp. 760-767, 1959.

11. Duke, C. A. and Smith, L. E., THE TECHNIQUE AND INSTRUMENTATION OF LOW IMPEDANCE GROUND MEASUREMENT, AIEE Conference Paper, No. 58-105.

12. MIL-B-5087A, BONDING; ELECTRICAL (FOR AIRCRAFT).