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ASD-TDR-63-370,
Part I

NATURAL INTERFERENCE CONTROL TECHNIQUES

Part I: Lightning Protection of Aerospace Rocket Vehicle Launching Systems

TECHNICAL DOCUMENTARY REPORT ASD-TDR-63-370, Part I
April, 1963

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Electromagnetic Warfare and
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Washington, D. C.

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Lightning & Transients Research Institute
Minneapolis, Minnesota
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NOTICES

FOREWORD

L&T Report No. 407 was prepared by the Lightning and Transients Research Institute under Contract AF 33(657)-10904 sponsored jointly by the Aeronautical Systems Division, U.S. Air Force, and the Navy Department, Bureau of Naval Weapons.

The technical program is administered under the direction of the Electromagnetic Warfare and Communications Laboratory, Aeronautical Systems Division, Mr. H.M. Bartman acting as project chief, Mr. C.R. Austin as task engineer and technical monitor, and coordinated with the Bureau of Naval Weapons through Mr. D.G. Berg.

Participating scientific and engineering staff taking primary part in this report's researches and preparation included: M.M. Newman and J.R. Stahmann.

ABSTRACT

Alternative approaches in lightning protection of diverting a direct lightning strike to some distance away, or shielding sensitive equipment to withstand a direct stroke can be usefully combined for maximum protection. Lightning strokes to diversionary rods or towers still leave intense transient magnetic fields to contend with, as well as possible large ground currents in control cables. Shielding of all conductors and associated "black boxes" of equipment is theoretically possible if resistance of cable sheaths and connector joints can be kept low enough. A possible combination approach in a ground installation is to "invite" nearby strokes to a central high point over a "bird cage" wire assembly surrounding the launching system thus guiding the lightning current symmetrically so that the magnetic fields inside cancel to approach in effectiveness a complete "Faraday cage" with reasonable feasibility as to practicality and cost, for most cases of lightning to ground strokes which are nearly vertical. Slanting strokes or nearby strokes and intense EM waves would require some horizontal interconnecting wires as well. In cases of dry sandy terrain improved additional lightning protection may be necessary even for buried cables as indicated in illustrative test demonstrations.

The degree of external protection necessary can, of course, be minimized by providing less vulnerable internal elements or providing individual component protection as has proved possible on similar problems in aircraft struck by lightning.

TABLE OF CONTENTS

Page No.

LIST OF ILLUSTRATIONS

I. The "Current Shunt" Principle Applied to Lightning Protection and Shielding Systems

For oscillographic lightning current measurements we require an ideal component such as used in textbooks, namely a resistance free of inductance. For example, if we plan to obtain a maximum oscillographic deflection of 50 volts from a peak current of 100,000 amperes, we require a resistance of 0.0005 ohms. Since the inductance of a straight wire is of the order of 0.01 microhenries per centimeter, it is reasonable to expect the inductance of our resistance to be greater than 0.01 microhenries. Now the current rate of rise may be the order of 20,000 amperes per microsecond, thus producing a L (di/dt) voltage across the resistor of at least 200 volts as compared to the 50 volt RI drop we are trying to measure. Clearly a special inductanceless precision resistor is required for measurements of high currents with these steep rates of current rise, and a special shunt resistance system was developed for this purpose.[1] Ideally it consists of a thin cylindrical tube of resistive material such as manganin, as shown schematically in Figure 1. The resistive material must be thin to make the skin effect negligible and must have a low termperature coefficient of resistance. The voltage measuring lead is connected to the center of a plate at the top of the cylinder and runs coaxially through the tube to a coax connector at the bottom. The current to be measured is fed into the top of the cylinder in a uniform and symmetrical fashion. Since the measuring circuit is usually of very high impedance, of the order of megohms, a negligible current flows in the center conductor and the voltage, e, appearing across the output connector is (L-M) (dI/dt) +RI. Also since, with this configuration, (L-M) is zero (perfect mutual coupling), we have succeeded in measuring just the desired RI drop. That is, the inductive drop is cancelled by an equal and opposite voltage induced in the center conductor. An alternative explanation is to conclude that magnetic fields inside the cylinder cancel. A manganin cylinder is shown at the right in Figure 2; and the more commonly used wire shunt, where a cylinder is approximated by a cylindrical grid of manganin wires, is shown at the left.

The principle outlined above has been applied to several lightning protection systems. One of these was a system for protection of personnel in an access shaft, located between the car and the top of an airship, when the top of the airship is struck by lightning.[2] In this case the shielded cables in the shaft were arranged in a cylinder of equally spaced bundles and adequate insulation was provided for the remaining induced and RI voltages. The reduction of induced voltage in a one foot loop as a function of the number of conductors in the cylinder is shown in Figure 3. In Figure 4 a six foot loop is used to represent the situation of a person climbing

1. LTRI Report 133, Front-of-Wave Impulse Measurement Techniques-I, M.M. Newman, conference paper, AIEE summer meeting June 15, 1950.
2. LTRI Report 318, Goodyear Aircraft, March, 1955.

Manuscript released by the authors April 1963 for publication as an ASD Technical Documentary Report.

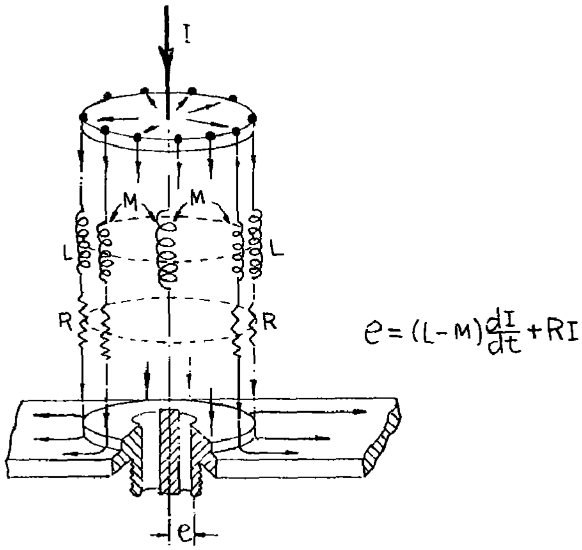


Figure 1. Schematic of current shunt.

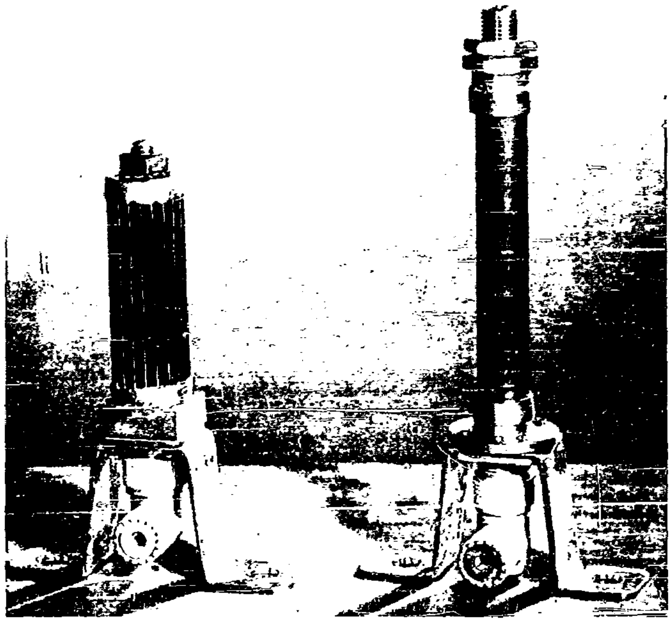


Figure 2. Manganin wire and sheet cylindrical shunts.

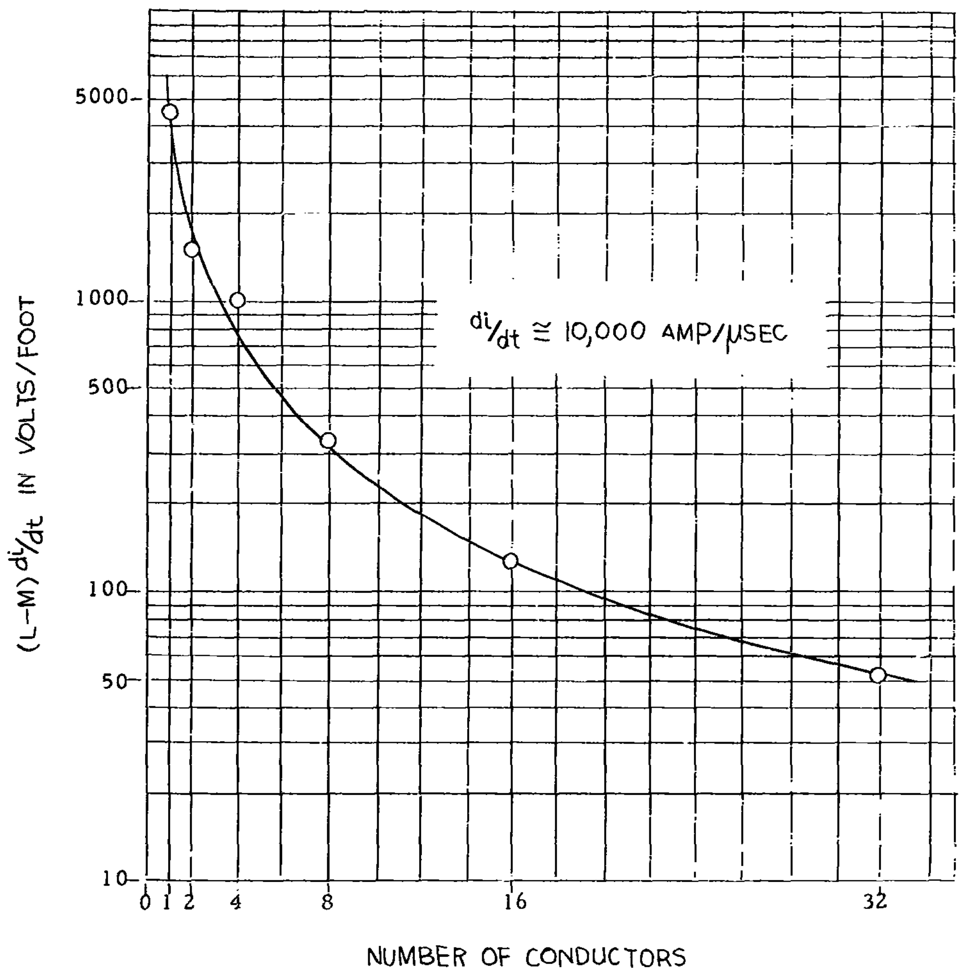
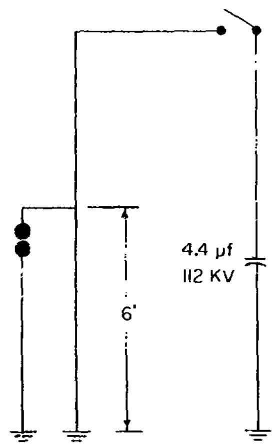


Figure 3. Net voltage induced in loop vs. number of conductors in cylindrical grid.



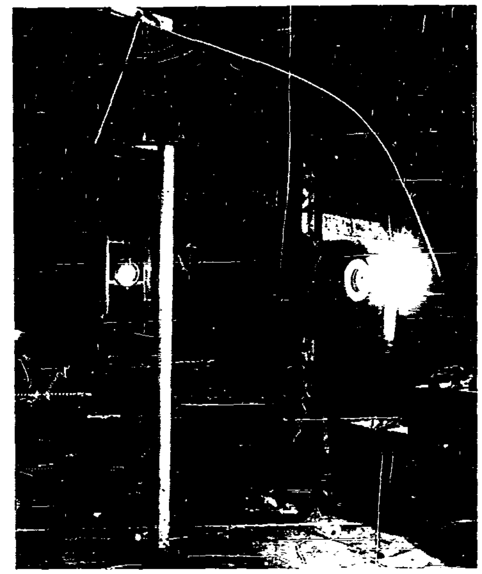
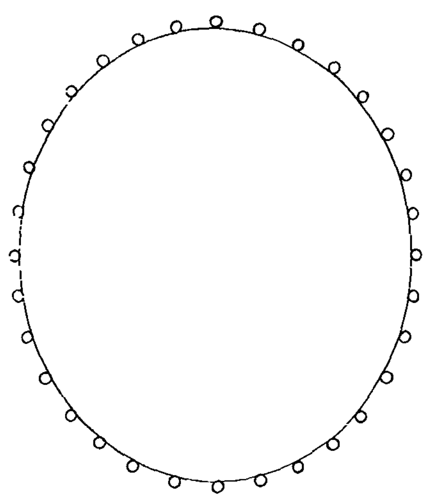
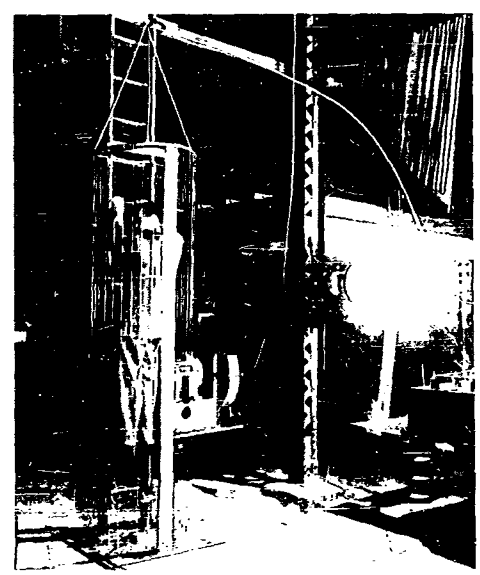


Figure 4. Single wire with spark gap in six foot loop.



Top View - Access Tunnel Grid



$(di/dt)_{max}$ = 12,500 amps/μsec

Figure 5. Final high current test of 32 wire cylindrical grid.

near a single conductor when it is struck by lightning. The spark gap provides a visual indication of the shock received. A grid of 32 conductors was then set up and tested by an LTRI observer, as shown in Figure 5, using a 140 KV capacitor bank which gave an initial rate of rise of 12,500 amperes per microsecond. The observer stood on a ladder with his shoe in contact with a grid wire and a shoulder in contact with a wire connected to the top of the grid. The observer detected no shock.

II. Black Box and Connecting Cable Shielding

When the shunt principle is applied to systems involving the shielding of metal enclosures connected by shielded cables, we realize that the voltage appearing inside the cable can be reduced to at least that caused by the DC resistance of the cable sheaths and connector joints. It can be further reduced by the isolation of the shield so that it is not used as one conductor of the circuit and by the use of double shielding, where practical. Symmetry in current distribution is also important and solid conduit is preferred over braided shielding. Figure 6 shows a cable connector between two "black boxes" when one is struck by lightning. Depending on the conductivity of the ground and possible connections to it, the current divides and part of it charges the stray capacity, C_s, of the trailer box, possible flashing the wheels of the trailer if grounding at the struck enclosure is poor.

Burying the cables in the earth often does not improve the shielding significantly. Even if two grounded copper wires, as shown in Figure 7, are used above the cables for protective shielding, the hoped for shielding may not be realized. In full scale tests[3] of the cable system shown in Figure 8, a vinyl insulated and copper and steel shielded telephone cable with two external shield wires was buried under 4 feet of dry silica sand. Under the sand the simulated lightning contacted all three conductors and divided in inverse proportion to their impedances, most of it being carried by the "protected" cable. A similar result in air is illustrated in Figure 9. The product of the impedance of the shield wires and the high lightning current provides sufficient voltage to arc to the cable even when the lightning first contacts one of the shield wires.

Several types of cable damage are shown in Figure 10. Under sand, gas pressures, probably due to burning vinyl, tended to crush or dent the cable as shown in Figure 10(b). The long duration high charge transfer components of lightning burned a hole through the shields as shown in Figure 10(c) which could possibly result in a cable fault.

III. Rocket Launching System Lightning Protection

A lightning stroke to a tower or diversionary rod placed close to a rocket vehicle still leaves intense transient magnetic fields which can induce currents in nearby conductors as was shown in Figure 4. Large cur-

3. LTRI Report 378, RCA, November, 1960.

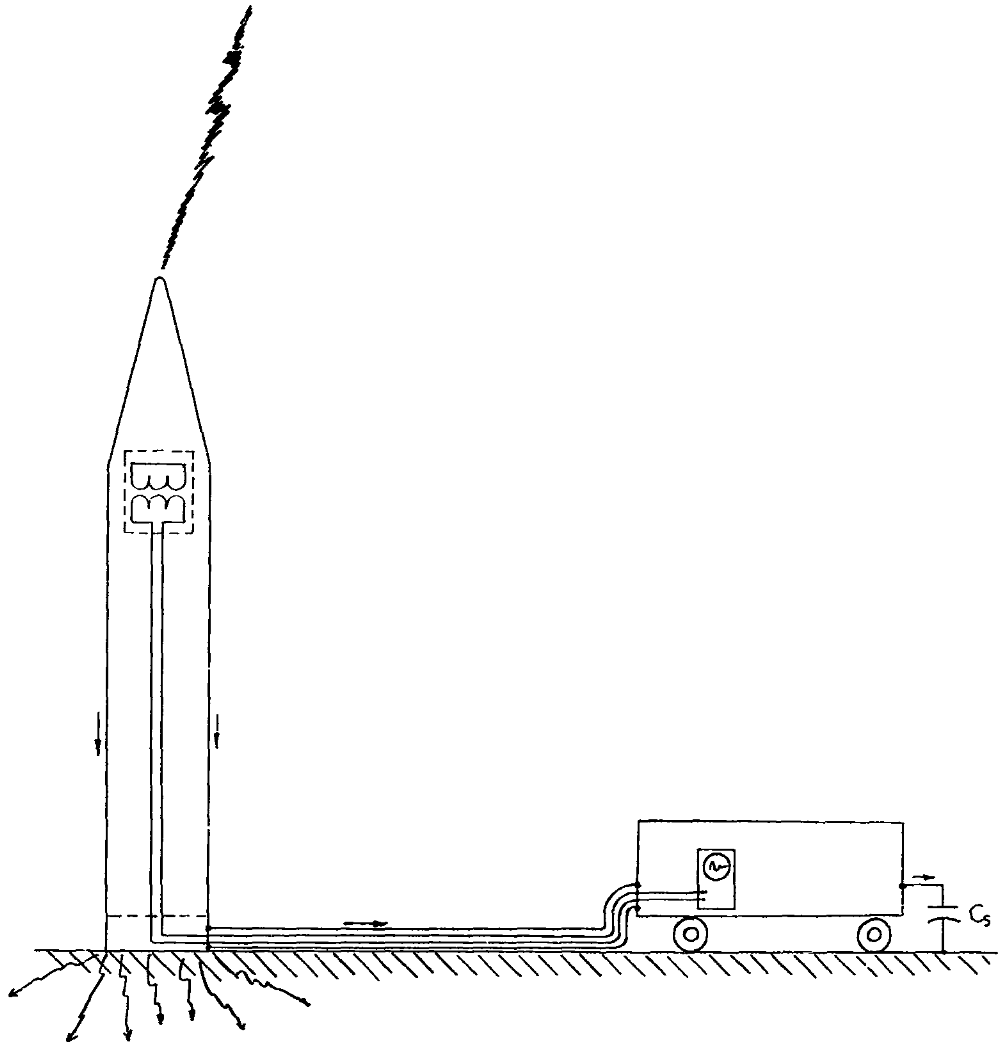


Figure 6. Two shielded enclosures with connecting shielded cable. One enclosure is contacted by a lightning stroke.

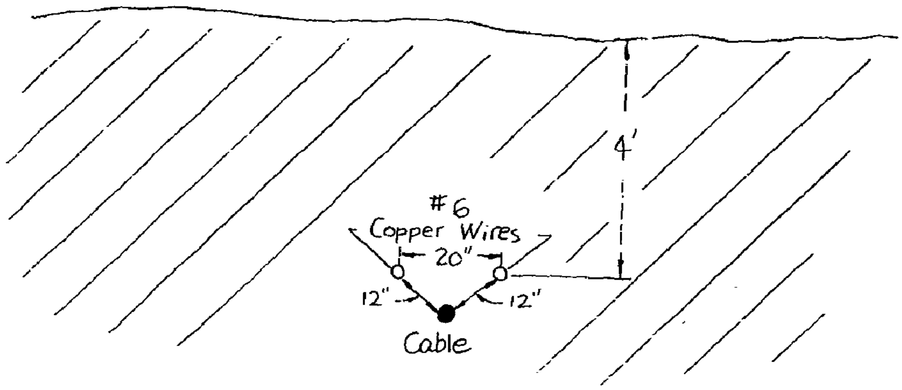


Figure 7. Buried telephone cable with shield wires.

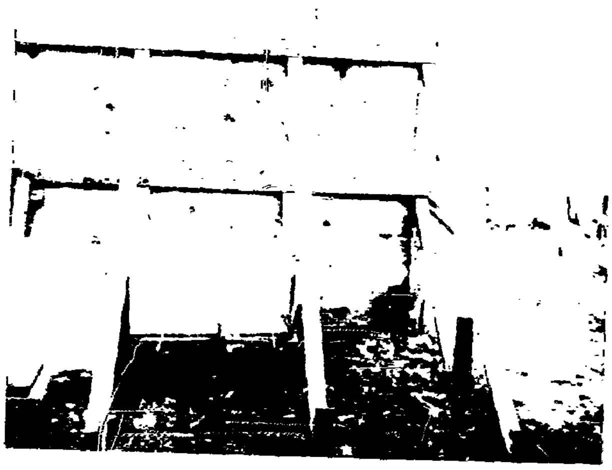


Figure 8. Shield wires and telephone cable buried under 4 feet of dry silica sand for full scale tests.

1827

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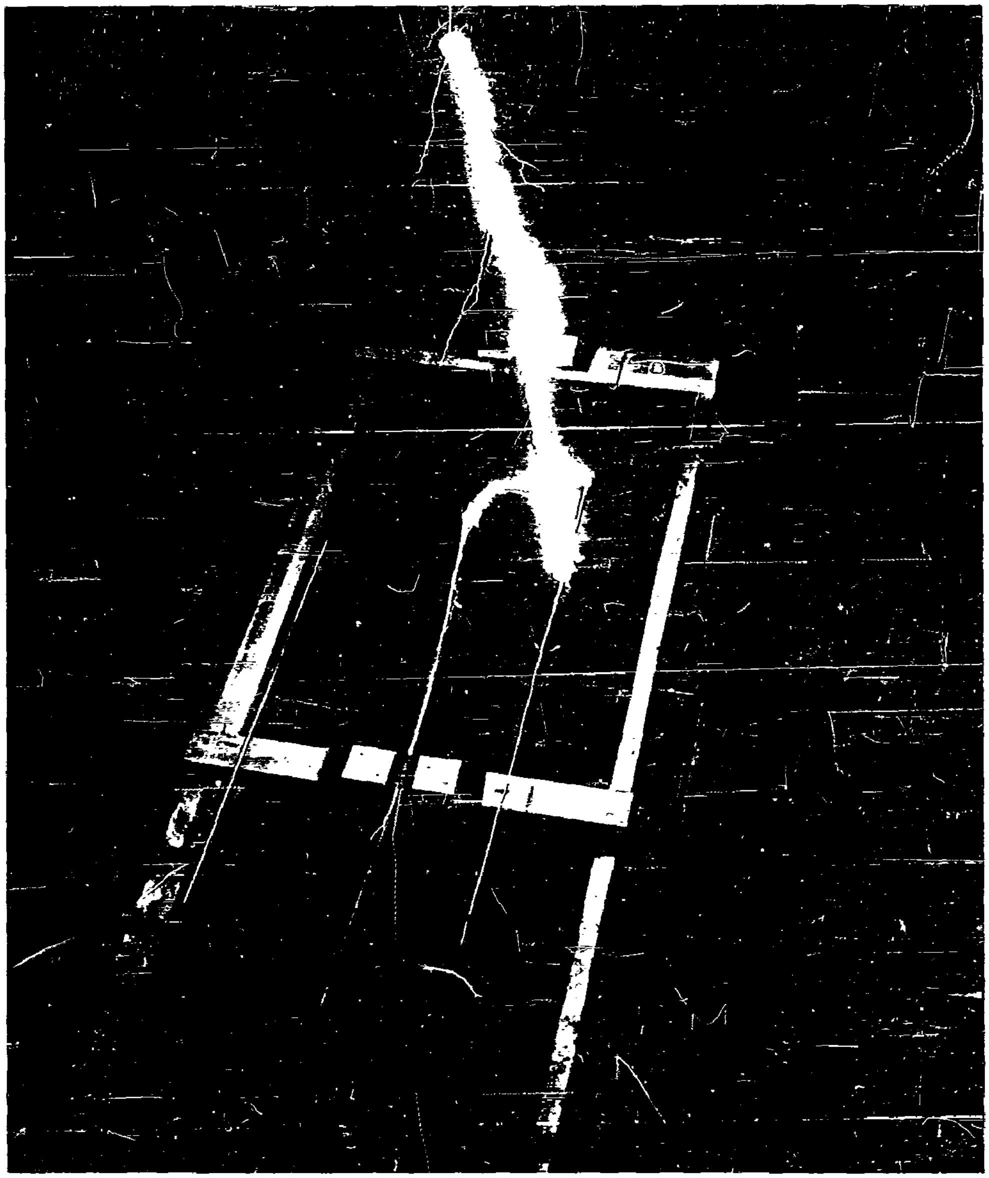
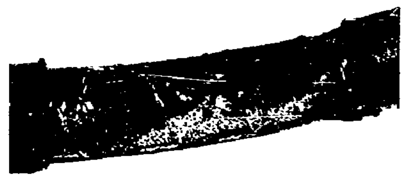


Figure 9. Stroke to shield wire also arcs to telephone cable due to high di/dt of lightning and inductance of wire. When system was buried in dry sand arc went to both shield wires and cable.

(a) Outer jacket rupture due to 50,000 ampere peak current.



(b) Cable crushing action of high current.

(c) Hole through steel and copper due to long duration current under sand.

(d) Hole burned through steel due to long duration current in air.

1829

Figure 10. Cable damage due to high and long duration currents.

rents will also flow in the ground and in connecting control cables. Application of the shunt principle, Figure 5, could be accomplished by inviting the stroke to contact a central high point and providing a grid of wires in a "bird cage" pattern from the central point to ground so as to cover the entire launching system. The lightning current is thus guided symmetrically so that magnetic fields inside the cage cancel, providing a complete electromagnetic "Faraday Cage" for vertical strokes. Conventional diverter, shown in Figure 11(a), may not be symmetrical; has few wires with no horizontal interconnections; and may have equipment external to the wire enclosed region but connected, by means of cables, to equipment inside the region thus leaving strong magnetic field linkages on the cabling. A better system is to use the bird cage pattern, shown in Figure 11(b), which provides a symmetrical screen and encloses all the equipment which is connected by cabling to the missile. Horizontal wire interconnections, which would be needed for angled strokes and incoming EM waves, may be added to the cage. A 250 foot central tower could be made up of 100 foot wooden poles with reasonable feasibility as to practicality and cost. The rocket vehicle would pass through a large opening at the top or some of the wires could be released and removed just prior to launching the missile.

Another rocket launching system requiring consideration of the lightning protection problem is the aircraft launched X-15 type vehicle shown in Figure 12. Since the vehicle is outside the aircraft but connected to it, the shielding at the attachment point must be adequate to prevent malfunctions due to a possible stroke to the airship and vehicle as shown in the figure.

IV. Concluding Discussion

As discussed above, the principle of the current shunt, used for high current measurements, can be applied to lightning protection systems including those of aerospace vehicle launching systems. Since internal fields would be reduced to a minimum by a solid conducting tube, the wire bird cage system is an effort to approximate such a tube by providing symmetrical current paths with horizontal interconnections where feasible. All equipment connected to the protected vehicle should preferably be inside the cage but external cables entering the wire shielded system could enter from below ground centrally at the base.

Direct shielding of all cables and associated "black boxes" illustrated in Figure 6, is also possible. In this case it is important to keep the resistance of cable sheaths and connector joints as low as possible. In addition to possible damage the RI drop in the cable sheath can affect measurement and control circuits in unexpected ways. For example, using RG-58/U shielded cable near a 7500 ampere discharge in a connection similar to that shown in Figure 6 with a good ground at the missile, resulted in the oscillogram shown in Figure 13(a) which was 180° out of phase with the expected

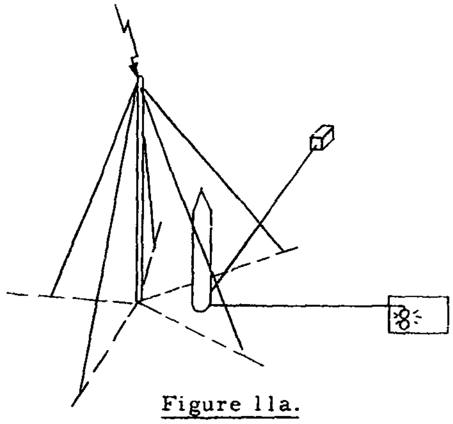


Figure 11a.
Conventional Diverter leaves strong magnetic field linkages on cabling.

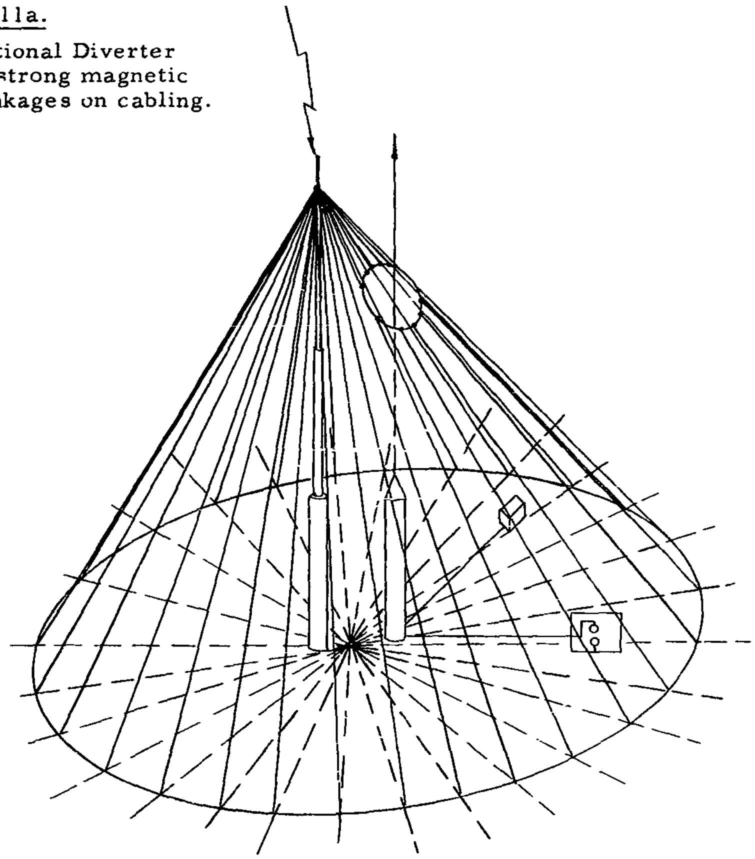


Figure 11b. Symmetrical screen could drop internal field by 100 with reasonable number of wires, for vertical stroke. Horizontal wire interconnections would be needed for angled strokes and incoming EM waves.

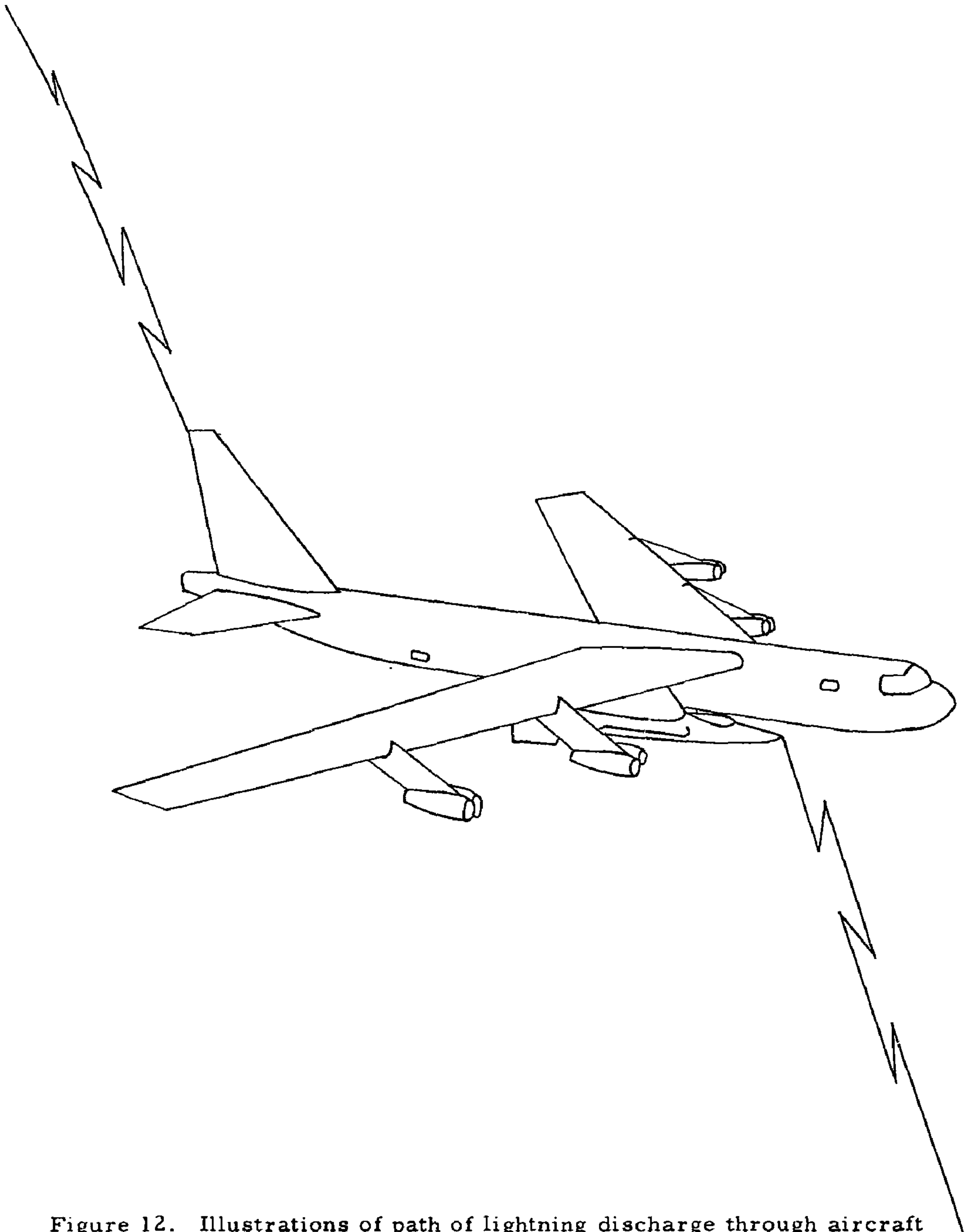


Figure 12. Illustrations of path of lightning discharge through aircraft launched X-15 type vehicle; special care in shielding at the attachment point is required for high rate of rise currents.

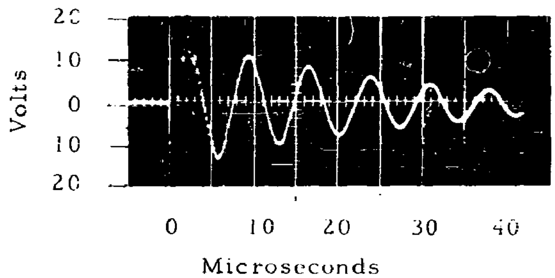


Figure 13(a). Distorted oscillogram obtained when using RG-58/U cable near 7,500 ampere peak discharge.

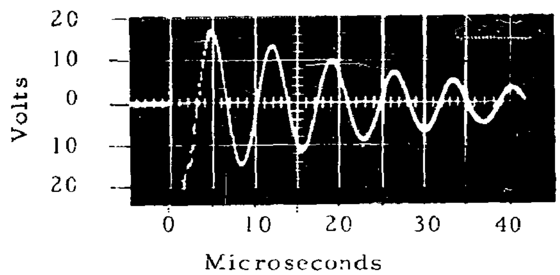


Figure 13(b). Correct oscillogram obtained when RG-58/U cable was double shielded using aluminum conduit over the cable, all other conditions unchanged.

1832

result. Placing the RG-58/U cable inside a solid wall aluminum tube for additional low resistance shielding resulted in the normal expected waveform shown in Figure 13(b). As was illustrated in Figure 9, burying cables in earth of poor conductivity results in little shielding improvement even when shield waves are placed above the cable in some conventional cable installations. Cable damage may be increased by burying the cable.

The external protection required for aerospace vehicle launching systems could, of course, be minimized by providing less vulnerable internal elements or individual component protection in the system as has been done on similar problems in aircraft struck by lightning.

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