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ENGINEERING DESIGN HANDBOOK

HARDENING WEAPON SYSTEMS AGAINST RF ENERGY

HEADQUARTERS, U.S. ARMY MATERIEL COMMAND

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HEADQUARTERS
UNITED STATES ARMY MATERIEL COMMAND
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Symbol	*Quantity*
A	= ampere
A	= absorption loss; attenuation
Ae	= effective aperture
Aec	= composite effective aperture
Aem	= maximum aperture
AM	= amplitude modulation
Ar	= area
AWG	= American wire gage
a	= semi-major axis of an ellipse
ac	= alternating current
$\bar{a}_r$	= unit radial vector
B	= magnetic flux density
b	= semi-minor axis of an ellipse
C	= conservative loss parameter
C	= coulomb
Cap.	= capacitance
CW	= continuous wave
c	= speed of light
D	= displacement density; directivity
d	= distance
d_e	= electrode spacing
d_h	= distance (height)
d_s	= distance from stroke where dE/dt_{max} is determined
dB	= decibel
dc	= direct current
dE/dt_{max}	= maximum rate of change of electric field
E	= electric field strength
$\bar{E}$	= electric field, vector
E_{max}	= maximum electric field
EED	= electroexplosive device
EMC	= electromagnetic compatibility
EMI	= electromagnetic interference
EMP	= electromagnetic pulse
EMR	= electromagnetic radiation
ERP	= effective radiated power
e	= constant (2.718...), base of natural logarithms
e	= eccentricity
F	= farad
F	= force
°F	= degrees Fahrenheit
FET	= field-effect transistor
FM	= frequency modulation
f	= frequency
f_{MHz}	= frequency in megahertz
ft	= foot
G	= conductance; antenna gain
G_R	= relative conductivity
GHz	= gigahertz
H	= henry
$\bar{H}$	= magnetic field
Hg	= mercury
Hz	= hertz
I	= current
IL	= insertion loss
I_m	= maximum current
I_o	= main stroke current
I_s	= surface current
i	= surface current
in.	= inch
J	= joule
j	= unit imaginary number $\sqrt{-1}$
°K	= degrees Kelvin
kVA	= kilovolt ampere
k	= constant
k_1	= constant (9×10^9)
kA	= kiloampere
kHz	= kilohertz
kV	= kilovolt
kW	= kilowatt
kΩ	= kilohm
L	= inductance
ℓ	= antenna length
ℓn	= natural logarithm
lb	= pound
log	= logarithm to the base ten
MHz	= megahertz
m	= meter
mil	= one thousandth of an inch
mJ	= millijoule
MKS	= meter-kilogram-second

MΩ = megohm
mm = millimeter
MOS = metal-oxide semiconductor
MOSFET = metal-oxide semiconductor field-effect transistor
msec = millisecond
mW = milliwatt
N = newton
n = number
P = power
$P_{\cdot}$ = power arriving (delivered) at input of **RF** supression device
P_s = power that gets through system being protected
P_i = incident power
P_r = reflected power
P_{R1} = received power without shield between transmitter and receiver
P_{R2} = received power inside metallic enclosure
P_T = transmitter power
PD = power density
PD_i = incident power density
PD_s = shielded volume power density
pF = picofarad
Q = charge; quality factor
Q_R = figure of merit
R = resistance; reflection loss
R_A = antenna resistance
R_e = real part
R_g = ground resistance
R_L = load resistance
R_m = mutual resistance
R_R = radiation resistance
R_T = termination resistance
$Re(Z)$ = real part of impedance
RF = radio frequency
RFI = radio frequency interference
r = radial distance; radius
rms = root-mean-square
S_{eff} = shielding effectiveness
SE = total shielding effectiveness
SVD = stray voltage detector
sec = second
T = temperature
TEM = transverse electromagnetic
T_c = transmission coefficient
T_p = transmission loss
TV = television
t = time; thickness of shield
t_r = pulse rise time
V = voltage potential
V = volt
V_{max} = maximum potential
V_r = voltage drop across R_g, the ground resistance
v = velocity; speed
W = power
W = watt
Wb = weber
W_{MT} = power transmitted through a solid metal
W_T = power transmitted through a hole
X = reactance
X_A = antenna reactance
X_s = system reactance
X_T = termination reactance
x = shield thickness
x_d = dielectric thickness
yd = yard
Z = impedance
Z_c = cable impedance
Z_d = small dipole radial wave impedance; input impedance of suppression device
Z_{fu} = impedance of firing unit
$Z_{\bullet}$ = small loop antenna radial wave impedance; impedance of **EED;** impedance associated with a measuring point
Z_o = characteristic impedance or free space impedance (377 Ω)
Z_{pp} = impedance pin-to-pin
Z_{pc} = impedance pins-to-case
Z_s = shield impedance; combined impedance of system being protected
Z_w = wave impedance
Z_w^* = complex conjugate of Z_w

GREEK LETTERS

α = real part of attenuation constant
β = imaginary part (phase constant) of propagation constant
γ = propagation constant of medium
γ_s = function of electrical parameter of a shield
ϵ = permittivity
ϵ_o = free space (air) permittivity
ϵ_s = surrounding medium permittivity
κ = relative dielectric constant

λ = wavelength
θ = plane angle
π = pi (3.14159...)
ρ = resistivity
ρ_p = power reflection coefficient
σ = conductivity
τ = time from leading edge of field to time of interest; transmission coefficient
μ = permeability; micro
μA = microampere
μ_o = free space (air) permeability
μ_R = relative permeability
μsec = microsecond
μW = microwatt
Ω = ohm
ω = angular source frequency ($2\pi f$)
---° = degree (plane angle)
°C = degrees Centigrade

PREFACE

The Engineering Design Handbook Series of the Army Materiel Command is a coordinated series of handbooks containing basic information and fundamental data useful in the design and development of Army materiel and systems. The handbooks are authoritative reference books of practical information and quantitative facts helpful in the design and development of Army materiel. The purpose of this particular handbook is to take the wealth of information accumulated by the Army over a period of years on the subject of hardening weapon systems against RF energy and to make this information available to the designer. Much of the data in this handbook is in chart or table form for rapid retrieval. Also, references are given that specify where these data were obtained.

Although this handbook was prepared for the designer of weapon systems it should also be of benefit to those engaged in designing test programs for determining the hardening of weapon systems. Chapter 5 presents the latest programming concepts that the Army is now using.

This handbook was prepared by the The Franklin Institute, Philadelphia, Pa., for the Engineering Handbook Office of Duke University, prime contractor to the Army Materiel Command, with Mr. Roy Wood as the principal author. Technical guidance and coordination were provided by a committee with representatives from Picatinny Arsenal, The U.S. Army Electronics Command, Redstone Arsenal, Harry Diamond Laboratories, and White Sands Missile Range. Members of this committee were Mr. Daniel Carella, Chairman, Mr. Edward Ramos, Mr. Francis Wilhelm, and Mr. D. Roger Wight.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The Army Materiel Command policy is to release these Engineering Design Handbooks to other DOD activities and their contractors and other Government agencies in accordance with current Army Regulation 70-31, dated 9 September 1966. It will be noted that the majority of these Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

a. Activities within AMC, DOD agencies, and Government agencies other than DOD having need for the Handbooks should direct their request on an official form to:

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ATTN: AMXLE-ATD
Chambersburg, Pennsylvania 17201

b. Contractors and universities must forward their requests to:

National Technical Information Service
Department of Commerce
Springfield, Virginia 22151

(Requests for classified docunients must be sent, with appropriate "Need to Know" justification, to Letterkenny Army Depot.)

Comments and suggestions on this Handbook are welcome and should be addressed to:

Commanding General
US Army Materiel Command
ATTN: AMCRD-TV
Washington, DC 20315

CHAPTER 1

INTRODUCTION

1-1 PURPOSE AND SCOPE

The components used for control, timing, sensing, initiation, and other functions in most of the modem weapon systems are electrical in nature. Power to operate the systems is supplied from electric sources, and the explosive components which are used to perform a multitude of functions are electroexplosive devices **(EED's)**; i.e., they are electrically initiated. While many advantages have been gained by the use of these systems, **EED's** are susceptible to malfunction and degradation as a result of spurious electric signals if the systems and components are not properly protected.

The combined natural and man-made environment which can serve as a source of these spurious signals is at an all-time high and is still increasing. **As** a result, the engineer designing a weapon system must not only consider the effects of such natural phenomena as lightning and electrostatic charge, but also man-made electric sources such as unwanted circuit transients and radio frequency energy originating from communication equipment, radars, transmitters associated with weapon systems, and nuclear explosions.

It must be kept in mind that the technology is continually increasing the number and power of energy sources, and weapon systems are using more components which may result in more critical hazardous conditions. The engineer responsible for the RF hardening of a system must be continually on guard–from the design stage, through construction and finally deployment–to be certain that he is aware of all facets which affect his system and its probable environment so that proper application of the basic hardening concepts may be assured at all stages of development. It is the purpose of this text to supply the necessary basic concepts.

The electrical portions of modem weapon systems–from very small, compact modules to systems with long, complex runs of wires and cables–are subject to the effects of the natural and man-made electrical environment in which the system must operate or will experience during storage and transportation. Furthermore, structural members and other components not specifically part of the electrical system can become part of the system with respect to extracting energy from an incident RF field or providing a path for electrostatic discharge.

System effects produced by these electrical environments can vary from partial failures of components resulting in changes in their characteristics so that they no longer function properly at their design levels, to complete dudding of components resulting in a failure to operate under any conditions. In the case of the **EED** it is possible to have premature initiation, frequently resulting in cataclysmic failure of the system. Furthermore, failures may be produced by spurious signals appearing in portions of the components not considered part of the normal electrical path. For example, a hot wire **EED** specifically designed to be initiated by the dissipation of electrical energy in its bridgewire may be prematurely initiated by a spurious electrical signal appearing between the bridgewire pins and the case of the device.

The electrical environments discussed in this handbook will include the natural environments of lightning and static electricity, and the man-made environment of RF energy. The text will not consider the electromagnetic pulse (EMP) environment of nuclear weapons (see par. **2-4)**.

In summary, the scope of the handbook will encompass:

a. **A** description of the environmental electrical energy sources and the mechanisms by which these sources may be coupled into weapon systems, and the resultant effects of such coupling on systems and components

b. Design techniques and practices required to minimize the effects of these sources, including concepts to be incorporated in the original system design and concepts which can be used in systems already designed and constructed

c. Test methods, equipment, and analytical techniques for determining the possible susceptibility of systems and the effectiveness of a corrective or preventive technique

d. Specific component information pertinent to the overall problem

e. Army or other military facilities available for the required testing

f. Discussion of pertinent Military Specifications.

1-2 EFFECTS OF RADIO FREQUENCY ENERGY

Radio frequency energy, once it has been coupled into a weapon system, can behave in a variety of ways. In general, components susceptible to damage by electric energy fail or are degraded by one of two effects: (1) the component can be subjected to generalized overheating due to too much power dissipation in the unit, or (2) rupture or extreme localized heating can be caused by electric breakdown in the component. The first effect is characterized normally by low voltages and high currents, and the second effect by high voltages and low currents at least before the breakdown. Either effect can result in dudding of the component or complete destruction depending on the magnitude and form of the spurious signal and the sensitivity of the component. In the case of electroexplosive devices premature initiation can result.

Unfortunately, a typical radio frequency (RF) signal can produce both effects in different parts of the same component, depending upon the complex electrical impedance the signal **"looks"** into. Furthermore, RF is frequently delivered in a manner not usually occurring with dc; for example, many radars deliver their RF energy in short, repetitive pulses. These repetiti'. pulses have the capability of producing extremely large instantaneous RF voltages that place large electric stresses in different parts of the components. In addition, since the pulses are repetitive, their effects can be cumulative resulting in thermal stacking, progressive breakdown, and other complex damage mechanisms.

Thermal stacking refers to the condition that exists when a region of a component heated by one pulse of a series of pulses is unable to lose all of its heat before the next pulse arrives. As a result each successive pulse raises (stacks) the temperature of the region to a higher value than that produced by the preceding pulse. Therefore, while a single pulse may not be sufficient to damage a component, a repetitive series of pulses may raise the temperature sufficiently to cause degradation or destruction of the component.

In addition to these destructive effects on components, the designer must also consider RF problems which are usually lumped under the heading of radio frequency interference or electromagnetic interference phenomena (RFI/EMI). These signals which may be of a magnitude much lower than the component destroying magnitude are coupled into the weapon system by the same coupling mechanisms and can produce misinformation from telemetering systems, faulty switching, and faulty transmitting.

As an example of the variable effects which can be produced by an RF signal, depending on the impedance into which it is operating, consider a typical case that occurs for many EED's for signals in the region of 1.5 MHz. Such RF energy arriving on the bridgewire leads of the EED would, in general, proceed to heat the bridgewire in much the same manner as a dc signal. The voltage would tend to be low, the RF current reasonably large, and the RF power required to initiate the EED would be quite comparable to the dc power required for initiation. If the incident energy arrived between the pins and the case of the EED, a quite different situation would prevail. Typical pins-to-case impedances at this frequency have a small resistive part and a large reactive part. As a result, rather small incident RF powers can produce large RF voltages across the impedance (resistive and reactive parts) resulting in possible electric breakdown between the pins and the case. As an example, a typical value of pins-to-case impedance Z at 1.5 MHz is

$$Z = 500 - j10000 \ \Omega \tag{1-1}$$

The conductance G for this impedance would be

$$G = 5 \ \mu\text{mhos}$$

If an RF power P of 500 mW was applied to this impedance, the voltage V appearing across the impedance would be given by

$$V = \sqrt{\frac{P}{G}} = 316 \ \text{V} \tag{1-2}$$

a value sufficient to initiate many EED's.

In summary, damage to components due to RF energy occurs in the same manner as it does when the energy is supplied from a dc pulse. However, determining the actual levels which would produce damage is frequently very difficult. Measurement of RF current or voltage is often of little value unless the impedance is known at the same point. Determination of the impedance at the exact point of interest is usually very difficult particularly at high frequencies. As a result, it is frequently necessary to use an empirical approach to establish the sensitivity of a component to RF energy. As a general rule, however, those failure modes that exist for dc also exist for RF; furthermore, all modes, normal and otherwise, must be considered.

In tnis handbook the part of the electromagnetic spectrum which is normally considered when discussing the interaction of RF energy and weapon systems lies between 10 kHz and 40 GHz. Here RF energy is produced by AM, FM, and TV transmitters; mobile transmitters; communication gear; radars; diathermy equipment, RF heaters, and other sources. In short, the present environment is produced by many different types of RF sources. Furthermore, modern weapon systems frequently have their own family of RF emitters associated with them and these are in close proximity to the system. The number and power of such sources are increasing, and it is imperative that present and future weapon systems be hardened against the environment they create.

1-3 EFFECTS OF STATIC ELECTRICITY

While this text is primarily concerned with hardening weapon systems and their associated components against RF, the problem of hardening against electrostatic hazards is so closely related that it is convenient to include some discussion of this problem, also. The electrostatic hazard can be characterized as primarily a high voltage, low current breakdown phenomenon; and while frequency components can be assigned to the electrostatic discharge pulse, the breakdown is more closely related to the capacitor discharge pulse than to normal RF sources. However, the electrostatic discharge damages components in the same modes as RF energy and is particularly equivalent to high frequency radar pulses in terms of damage. The controlling circuit parameter is the dc resistance, however, rather than the complex impedance as in the case of RF. Many of the techniques for hardening a system against RF are directly applicable to static electricity.

Electric charges are transferred whenever two masses contact, particularly when the masses are nonconductors. Multiple contact, such as created by rubbing or particle impact on a surface, can greatly increase this charge transfer. Furthermore, a charged body need only approach a second body to cause a redistribution of the charge in the second body. If some path, such as a momentary ground connection, is provided to remove or add charge to the second body, a residual charge will remain on the second body. Examples of these charge mechanisms are easy to find in modern weapon systems. A projectile passing through rain or dust, a plastic cover removed suddenly from a weapon, or the mere presence of a highly charged thunderhead all can provide common methods of producing a charge buildup in components of a weapon system. Any contact or rupture of insulation between a charged body and an EED or circuit component will result in an electric discharge through the component, which may have disastrous results. One fatal accident was traced to EED ignition caused by the electrostatic discharge created during the removal of a plastic shroud from a missile (see par. 2-2.3(c) for the mechanics of this phenomenon).

1-4 EFFECTS OF LIGHTNING

Lightning is a specialized case of an RF source of very high magnitudes. The magnitudes are so great as to make most hardening techniques almost useless when a direct strike on the system occurs. However, a properly shielded and grounded weapon system could survive a direct strike. Fortunately, direct strikes are extremely rare and therefore are not of main concern. Near strikes, however, are a frequent reality. In a near strike the lightning stroke generates an RF signal in a limited frequency range and it is of reasonably predictable duration. This RF signal can be treated in the same manner as that from any other RF source and will damage components in the same manner.

Due to the enormous energies involved, two other mechanisms must be considered when dealing with the problem of hardening systems against lightning:

(1) In the lightning stroke process, enormous charge displacements occur in clouds or bodies on the ground. These charge displacements are rearranged rapidly, causing sizable charge movements in the electrical ground. This large scale movement of charge in and around a weapon system can cause large dc currents to flow in the system circuits and produce considerable damage.

(2) The stroke itself carries a huge current which will in turn produce a strong magnetic field around the conductive path formed by the stroke. The action of such strong magnetic fields penetrates the usual electromagnetic shielding, hence, these fields when coupled through the shielding cause heavy current flow in the system components.

1-5 THE COUPLING OF UNDESIRED ENERGY INTO A WEAPON SYSTEM

Up to this point the discussion has centered on the types of sources that make up the **RF** environment to which a modem weapon system may be subjected and has indicated how the emission from these sources produces damage to the components of a system. To recapitulate briefly, any voltage or current beyond the normal capacity of a component will, of course, damage the component. In addition, the designer must also be concerned with failure in parts of the components other than those parts where he would expect the normal signal to travel since (1) these other parts are frequently more sensitive than the normal circuit, and (2) it is generally the nature of the spurious signals to attack in all possible failure modes. The manner in which the energy from these sources is coupled into the weapon system will now be discussed.

A modem weapon system consists of an assortment of electrical devices such as power sources, control units, telemetering links, computers, and other units all interconnected by an assortment of cables. The cabling systems contain a large number of wires of considerable lengths and are frequently interrupted with terminal boxes, switches, junctions, and other devices which result in very complex wiring systems. However, in the final analysis, and to the extent that the wiring runs are unshielded, these complex wiring systems break down into a series of smaller loops and shorted parallel wiring runs that differ very little from the dipole, loop, and rhombic antennas that one constructs for the express purpose of extracting **RF** energy from an incident field. The efficiency of any of these undesired antennas in extracting **RF** energy from an incident field and transmitting this energy to any of the components in the system is a function of its orientation in the field, the impedance it represents, and its transmission characteristics. These, in turn, are all functions of frequency. The efficiency of the antenna system is also affected by other objects in the vicinity, and by the impedance of the field in the vicinity of this antenna system. In the case of electrostatic energy similar coupling circuits exist, but they may be more subtle.

By now it should be apparent that a precise analysis of any given system with respect to **RF,** electrostatic, or lightning hazards can be a very difficult and expensive undertaking for all but the simplest systems. The best method to employ is to understand the extent of the **RF** hazard problem and include in the original design of the ordnance system the proper procedures to harden the system against the expected hazard environment to which it may be subjected. The text which follows provides information to aid the designer in properly evaluating and solving this problem.

CHAPTER 2

SOURCES OF RADIO FREQUENCY ENERGY, STATIC ELECTRICITY, AND LIGHTNING

2-1 RADIO FREQUENCY SOURCES

2-1.1 INTRODUCTION

Many of the modern weapon systems employed by the Army are mobile. This presents a problem since the systems will be subjected to a varying environment that can only be accommodated by an "across-the-board" design against the worst cases likely to be encountered. For fixed installations the protection may be custom-built for the environment encountered at that location but this protection applies only to the particular system configuration at this site and to the specialized assemblies that are used here. Other parts of the system–i.e., those destined for mobile service, although used in the fixed system and perhaps developed under the fixed system concept–should be designed for the usually more rigorous mobile environment. In instances where the fixed environment is expected to exceed the mobile environment, it may be wiser to adhere to the mobile environment for the parts destined for mobile service and employ greater RF protection at the fixed site.

To determine the usual local RF environment of a system, it is necessary to consider the emission from the following three sources:

(1) Civilian RF sources

(2) Military RF sources

(3) Its own RF sources.

2-1.1.1 Civilian RF Sources

The number of communication systems in most civilized countries has increased rapidly during the past few years. TV, **FM,** AM, mobile, and many other types of communication equipments are spread throughout the country. The number of sources in a given area generally depends upon the population. Near big cities the sources are numerous while in sparsely populated areas the number of sources is fewer. These sources of RF energy must be considered both when a weapon system is in transit or **is** being installed at a site. Normally the sources occupy the spectrum from kilohertz to giga, hertz and may have power outputs of megawatts. It is impossible to list all of the civilian RF sources in this handbook; however, Table 2-1 lists, by frequency, the types of systems in use and the maximum power allowed by the Federal Communication Commission for emitters located in the United States (Ref. 1). From Table 2-1 it can be seen that an emitter at almost any frequency in this part of the spectrum might be encountered by the system.

There are two power classifications contained in Table 2-1: (1) power output of the transmitter, and (2) power output of the transmitter multiplied by the gain of the antenna (Effective Radiated Power).

Table 2-1 lists bands of frequencies rather than specific ones and specifies the maximum power and not necessarily what is being used by a given station. The international stations located in foreign countries usually adhere to the limits set forth in the table; however, local stations can vary. Since the weapon system designer usually must assume that his system is to operate in any part of the world, he is forced to design the system to perform under all expected environments.

2-1.1.2 Military RF Sources

The most hazardous environments probably occur in the vicinity of military installations because the number and type of equipment being used vary from day to day and a high density of emitters can usually be found. Table 2-2 (Ref. 1) lists commonly used RF sources at a typical military installation. This is not a complete listing because classified equipments are omitted.

TABLE 2-1

POWERS VS FREQUENCY FOR NONGOVERNMENT RF SOURCES[1]*

Frequency, MHz	Service	Power, W	Frequency, MHz	Service	Power, W
0.010 - 0.014	Radiodetermination	1,200	8.476 - 8.815	Marine	140,000
0.014 - 0.070	International Fixed Public	50,000	8.815 - 9.500	International Fixed Public	50,000
0.070 - 0.130	Radiodetermination	300,000	9.500 - 9.775	International Broadcast	500,000
0.130 - 0.160	Marine	80,000	9.775 - 11.700	International Fixed Public	50,000
0.160 - 0.200	International Fixed	50,000	11.700 - 11.975	International Broadcast	500,000
0.200 - 0.415	Radiodetermination	1,200	11.975 - 12.714	Marine	8,000
0.415 - 0.510	Marine	40,000	12.714 - 13.200	Marine	140,000
0.510 - 0.535	Government		13.200 - 15.100	International Fixed Public	50,000
0.535 - 1.605	Commercial AM	50,000	15.100 - 15.450	International Broadcast	500,000
1.605 - 1.750	International Fixed Public	50,000	15.450 - 16.460	International Fixed Public	50,000
1.750 - 1.800	Land Mobile	10,000	16.460 - 16.952	Marine	8,000
1.800 - 2.000	Radiodetermination	1,200	16.952 - 17.360	Marine	140,000
2.000 - 2.107	Marine	8,000	17.360 - 17.700	International Fixed Public	50,000
2.107 - 2.850	International Fixed Public	50,000	17.700 - 17.900	International Broadcast	500,000
2.850 - 3.155	Aeronautical	400	17.900 - 21.000	International Fixed Public	50,000
3.155 - 3.400	International Fixed Public	50,000	21.000 - 21.450	Amateur	1,000
3.400 - 3.500	Aeronautical	400	21.450 - 21.750	International Broadcast	500,000
3.500 - 4.000	Amateur	1,000	21.750 - 22.400	International Fixed Public	50,000
4.000 - 4.063	International Fixed Public	50,000	22.400 - 22.720	Marine	54,000
4.063 - 4.238	Marine	8,000	22.720 - 24.990	International Fixed Public	50,000
4.238 - 4.438	Marine	140,000	24.990 - 26.950	Land Mobile	500
4.438 - 5.450	International Fixed Public	50,000	26.950 - 26.960	International Fixed Public	50,000
5.450 - 5.730	Aeronautical	400	26.960 - 29.800	Amateur	1,000
5.730 - 5.950	International Fixed Public	50,000	29.800 - 30.000	International Fixed Public	50,000
5.950 - 6.200	International Broadcast	500,000	30.000 - 32.00	Land Mobile	500
6.200 - 6.525	Marine	140,000	32.00 - 33.00	Government	
6.525 - 7.000	Aeronautical	50	33.00 - 34.00	Land Mobile	500
7.000 - 7.300	Amateur	1,000	34.00 - 35.00	Government	
7.300 - 8.195	International Fixed Public	50,000	35.00 - 36.00	Land Mobile	
8.195 - 8.476	Marine	8,000	36.00 - 37.00	Government	

* Superscript numbers refer to References at the end of each chapter.

TABLE 2-1

POWERS VS FREQUENCY FOR NONGOVERNMENT RF SOURCES' (Cont.)

Frequency, MHz	Service	Power, W
37.00 - 38.00	Land Mobile	500
38.00 - 39.00	Government	
39.00 - 40.00	Land Mobile	500
40.00 - 42.00	Government	
42.00 - 50.00	Land Mobile	500
50.00 - 54.00	Amateur	1,000
54.00 - 72.00	Commercial Television	100,000*
72.00 - 74.60	Fixed	500
74.60 - 76.00	Radiodetermination	2,000
76.00 - 108.00	Commercial, TV, FM	100,000*
108.00 - 117.975	Radiodetermination	2,000
117.975 - 114.00	Aeronautical	50
114.00 - 148.00	Amateur	1,000
148.00 - 161.575	Land Mobile	600
161.575 - 161.625	Marine	1,000
161.625 - 174.00	Land Mobile	600
174. - 216.	Commercial	316,000
216. - 225.	Amateur	1,000
225. - 250	Radiodetermination	2,000
250. - 420.	Government	
420. - 450.	Amateur	1,000
450. - 470.	Land Mobile	600
470. - 890.	Commercial Television	5,000,000*
890. - 960.	Fixed	30
960. - 1,215.	Aeronautical	50
1,215. - 1,300.	Amateur	1,000
1,300. - 1,535.	Aeronautical	
1,535. - 1,850.	Government	
1,850. - 2,200.	Fixed	18
2,200. - 2,300.	Government	
2,300. - 2,500.	Amateur	1,000
2,450. - 2,700.	Fixed	12
2,700. - 3,300.	Radiodetermination	
3,300. - 3,500.	Amateur	1,000
3,500. - 3,700.	Government	
3,700. - 4,200	Fixed	100
4,200. - 5,650.	Government	
5,650. - 5,925.	Amateur	1,000
5,925. - 6,425.	Fixed	100
6,425. - 6,575.	Land Mobile	100
6,575. - 6,875.	Fixed	7
6,875. - 7,125.	Land Mobile	100
7,125. - 10,000.	Government	
10,000. - 10,500.	Amateur	1,000
10,500. - 10,550.	Public Safety	40
10,550. - 10,680.	Land Mobile	5
10,680. - 12,200.	Land Mobile & Fixed	
12,200. - 13,250.	Fixed	5
13,250. - 19,400.	Government	
19,400. - 19,700.	Land Mobile & Fixed	5
19,700. - 21,000.	Government	
21,000. - 22,000.	Amateur	1,000
22,000. - 27,525.	Government	
27,525. - 31,300.	Fixed	5
31,300. - 38,600.	Government	
38,600. - 40,000.	Land Mobile & Fixed	5
All Above 40,000.	Amateur	1,000

*Effective Radiated Power

TABLE 2-2

RF SOURCES AT A TYPICAL MILITARY INSTALLATION'

Emitter	Frequency, MHz	Input Power, W	Antenna Gain G, dB	ERP*, W
FRT-24	1.8-26	1,000	8	6310
FRC-6	1.8-26	1,000	2	1590
TCS	1.8-26	40	2	63
FRT-15	1.8-26	3,000	2	5770
TCB	1.8-26	400	2	630
TDQ	100-150	25	2	3980
GRT-3	225-390	100	10	1000
GRC-27	225-390	100	10	1000
TED	225-390	50	10	500
AN/GMD-2	225-390	30	10	300
FRW-2	400-500	10,000	15	316 × 103
AN/ARSR-1	1,300	4,000	34	10×10^6
MPS-19	2,600-3,400	200	33	400 × 103
SCR-584	2,700-2,900	300	35	948 × 103
AN/FPS-6A	2,700-2,900	4,500	39	35.7 × 103
VERLORT	2,800	150	28	94.5 × 103
AN-APS-20C	2,800	400	34	1000 × 103
M-33	3,000	1,300	39	10.3×10^6
AN/FPS-68	5,400-5,700	275	40	2.75×10^6
AN/SPS-5	5,400-5,700	285	28	180 × 103
AN/MPS-26	5,400-5,700	80	38	480×10^3
AN/FPS-16	5,500	1,707	44	43×10^7
AN/CPS-9	9,063	1,300	30	1.3×10^6

*ERP = Effective Radiated Power

ERP = Input power x Antenna gain

(Located in back of manual.)

Fig. 2-1. Frequency Spectrum[3]

2-1.1.3 Weapon System RF Sources

Most Army weapon systems are associated with some form of communication and surveillance equipments. These equipments will normally be the closest RF sources to the system; therefore, it is important that the designer consider the frequencies and power outputs of these equipments so that he may ensure that his system design will be adequate to protect the weapon system against damage or interference at these frequencies.

All military systems that contain electronic equipment must have an RFI/EMI specification. The designer should consult these specifications first to determine the magnitude and the frequencies involved.

2-1.2 ENVIRONMENT

The designer of a weapon system does not have control over the environments that his system will encounter in its use. This includes the physical environment that produces effects as corrosion, shock, heat, etc. It also includes the electrical environment which produces energy in the form of radio frequencies,* static electricity, electromagnetic pulses, and lightning discharges. The information presented in the paragraphs which follow will give the designer of the weapon system some insight into the needs and purposes of the information given on design criteria.

As was pointed out previously, an Army weapon system must be able to operate in any part of the world under all kinds of environmental conditions. Fig. 2-1 indicates the possible types of sources in the frequency spectrum that a system may be exposed to and must be protected against (Ref. **3**). The energy that is radiated over this spectrum can create two problems in a weapon system: (1) the energy can be great enough to damage the components or subsystems, or (2) the RF stimulus may interfere with the operation of the system even without damaging components or subsystems. The second condition is referred to as radio frequency interference or electromagnetic interference (RFI/EMI) and is usually with field intensities lower than those which can cause permanent damage to the system.

* One excellent source of information for the weapon system designer seeking to discover the environment (both military and civilian) he may expect in various localities is the Electromagnetic Compatibility Analysis Center located at Annapolis, Maryland (Ref. **2**). This center is a joint-service Department of Defense facility, established to provide rapid analysis of' electromagnetic compatibility projects of the military departments.

The ideal situation would be to have a chart or a graph that would reveal the expected field intensities a particular weapon system would encounter. The electromagnetic environment that an individual weapon system is required to survive is usually specified in the Qualitative Materiel Requirements (QMR) and Technical Characteristics (TC) for weapon systems requirements.

In Chapter **3,** Fig. **3-3** shows the various field intensities that are encountered when RFI/EMI specifications are given. From this information it can be seen that the maximum field intensity specified is 10 V/m. For hardening, the field intensities to be protected against may be as high as several hundred volts per meter.

2-1.2.1 Calculation of RF Environment

a. General. In order to determine the **RF** environment at a given location in a weapon system it is necessary to know the power density or field strength of every signal impinging on that point in the system.

For a directive antenna, the maximum effective radiated power occurs in the center of the beam and is equal to the product of the transmitter power P_T and the antenna gain G.

b. Power Density. The power density PD at a distance of d meters from a single radiator is

$$\mathrm{PD} = \frac{P_T G}{4\pi d^2}, \mathrm{W/m^2} \tag{2-1}$$

The total power density is simply the sum of the individual contributions.

c. Field Strength. The field strength contributed by each transmitter can be obtained by recalling that PD $= E^2/Z$ and that the impedance of free space is 120π ohms; therefore,

$$E^2 = \frac{120\pi\, P_T G}{4\pi d^2},$$

or (2-2)

$$E = \frac{5.5(P_T G)^{1/2}}{d}, \mathrm{V/m}$$

A conservative estimate of the total field strength of n radiators is:

$$E = (E_1^2 + E_1^2 + \ldots + E_n^2)^{1/2} \tag{2-3}$$

2-1.2.2 Radiating Sources (Antennas)

Radio frequency energy that is radiated into space generates electromagnetic waves. These waves are composed of an electric field $\bar{E}$ and a magnetic field H where both $\bar{E}$ and H are vector quantities (the bar over the letter designates a vector quantity) in that both have direction and magnitude at any point in space. They are perpendicular to each other and to the direction of propagation when located a distance from the source; this is commonly referred to as TEM mode of propagation. The distinction between the fields at a large distance from the radiating source and those near the source is important. Fig. 2-2 illustrates how the region around an antenna is specified. The area outside the circle is called the far field or Fraunhofer region and the area inside the circle is referred to as the near field or Fresnel region. Eqs. 2-1, 2-2, and 2-3 are valid only when applied to measurements made in the far field. Calculation of the field intensity in the near field is very complicated and is seldom attempted. The approximate distance from the antenna to the boundary between the near and far field can be calculated from Eq. 2-4 (Ref. 4)

$$d = \frac{2\ell^2}{\lambda} \qquad (2\text{-}4)$$

where

d = distance from antenna to boundary, m
ℓ = length of antenna, m
λ = wavelength, m

A source that emits radio frequency energy can be considered an antenna regardless of whether it is an intentional antenna or not. The difference usually is that a circuit that is not designed as an antenna will not be very efficient and, accordingly, a poor emitter.

In order to have a method of comparing one radiator to another, the concept of an isotropic antenna was created. In very simple terms an isotropic radiator is an antenna that is a point source that radiates in a spherical pattern. If at a given distance from the point source and with a given input power: (1) a certain power density were measured, and if (2) another antenna were put in place of the isotropic source and the same amount of power applied to it, and (3) the power density at the same point from the source were measured; the ratio of these power densities would be defined as the gain over an isotropic source and would be given in dB of gain.

It would be impossible to make a meaningful list of antenna types since there are so many types in use. The most useful piece of information about an antenna that the weapon system user can obtain is its field pattern. Fig. 2-3 illustrates the two extremes of patterns.

The dipole antenna, with its doughnut-shaped pattern, has the least gain while the parabolic reflector, with its pencil-shaped beam, has the highest gain. In between these two types there are many others. Using Eqs. 2-1, 2-2 and 2-3, the power density and field intensity can be readily calculated if the antenna gain is known.

2-2 STATIC ELECTRICITY

2-2.1 INTRODUCTION

The present understanding of the nature of matter shows it contains equal amounts of and negative

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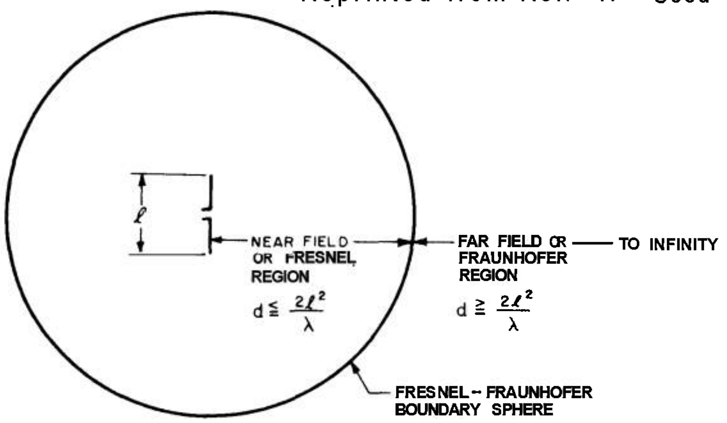


Fig. 2-2. Relationship of Near Field and Far Field

charges, and under ordinary conditions a body thus composed is neutral. There are many ways, however, that the balance between the charges can be distributed to produce an imbalance or a charged body. A rubber rod will become negatively charged when rubbed with fur (Ref. 5). Measurements show that the fur assumes a charge that is exactly equal and opposite to that on the rod. This experiment indicates that a static charge can be generated by the transfer of charged particles from one body to another body.

The generation of a static electric charge on a body by rubbing is called the *triboelectric effect*. Table 2-3 shows an arrangement of nonconductors in what is called a triboelectric series. A substance selected from the series and rubbed with one below it will acquire a positive charge. A conducting material also will assume a positive charge when rubbed since it will give up electrons readily. The conductor must be insulated, however, to prevent other electrons from flowing into it and thus neutralizing the charge.

TABLE 2-3

TRIBOELECTRIC SERIES

(1) Glass	(5) Amber
(2) Wool	(6) Sealing wax
(3) Cat's fur	(7) Sulfur
(4) Silk	

Objects may also be charged by electrostatic induction, i.e., transfer of charge without the objects coming in contact with each other. An example of how this can occur is shown in Fig. 2-4. (A) shows two bodies, one charged and one uncharged, separated by a large distance so that they do not influence each other. In (B) the two bodies are brought into close proximity to each other. Since like charges repel and unlike charges attract, the distribution of the charges on the uncharged object will be altered as shown. Now, if the negative end of the neutral body is grounded (C), electrons will flow into the ground to neutralize the negative charge. Removing the ground connection and separating the two bodies (D), the object that was previously neutral will now be charged positively.

2-2.2 DEFINITIONS

To help the designer avoid designs that are susceptible to static electricity, it is important that the concept of static charges be understood. One way of achieving this is to start by defining certain basic concepts.

(a) *Static Electricity*

In the strict sense of the word, static electricity means electricity that is standing still. It is used to distinguish the effects produced by electrically charged bodies from those produced by heat, chemical action, and magnetic forces which are the results of *dynamic electricity*. In this handbook, the main concern is with static electricity that is the source of a sudden discharge that can activate or damage a circuit.

(b) *Coulomb's Law* (Ref. 6)

The force of attraction or repulsion between two point charges, acting in the direction of a line connecting the charges, is directly proportional to the product of the charges and inversely to the square of the distance between them. The magnitude is given by

$$\bar{F} = k_1 \left(\frac{Q_1 Q_2}{d^2} \right), \text{ N} \tag{2-5}$$

where

$\bar{F}$ = force, N
Q_1 and Q_2 = charge, C
d = distance between charges, m
$k_1 = 9 \times 10^9$ for air, m/F
1 newton = 0.224 lb force

(c) *Quantity of Charge*

The unit of charge is the coulomb C which is equivalent to *the point charge which repels an equal charge of the same sign with a force of k_1 newtons when the charges are one meter apart in a vacuum.* The value of k_1 in air may, for most practical purposes, be taken as:

$$k_1 = 9 \times 10^9 \text{ m/F}$$

This definition of a quantity of charge is used when the derivation of the electric field and potential equations is being developed in a logical sequence. The practical unit of quantity of electricity, or charge, is the coulomb: it is the charge delivered by a current of one ampere flowing for one second.

(d) *Electric Field*

An electric field is said to exist at a point if a force of electrical origin is exerted on a charged body placed at the point. The field intensity is a vector quantity $\bar{E}$ having both direction and magnitude in terms of force per unit charge.

$$\bar{E} = \frac{\bar{F}}{Q}, \text{ N/C} \tag{2-6}$$

In practical applications, electric fields are usually produced by charges distributed over a surface rather

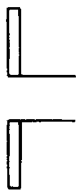
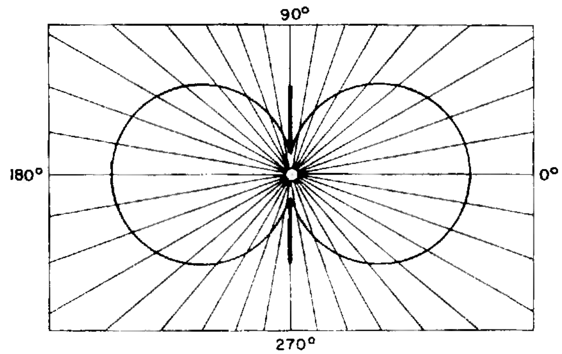
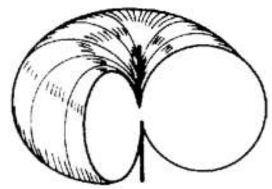
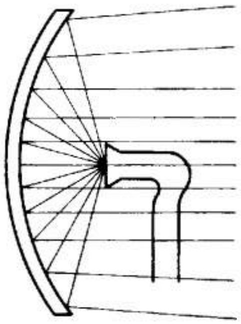
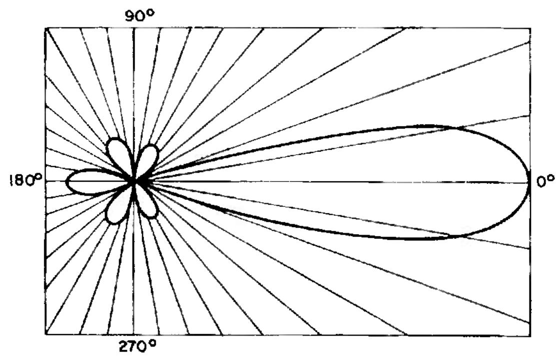
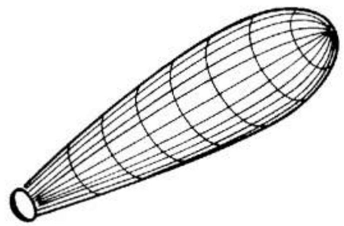
TYPE OF ANTENNA	RADIATION PATTERN		GAIN
	Vertical	Perspective	
Half-Wave Dipole 			1.64
Parabolic Reflector 			20 dB to 50 dB

Fig. 2-3. Antenna Patterns

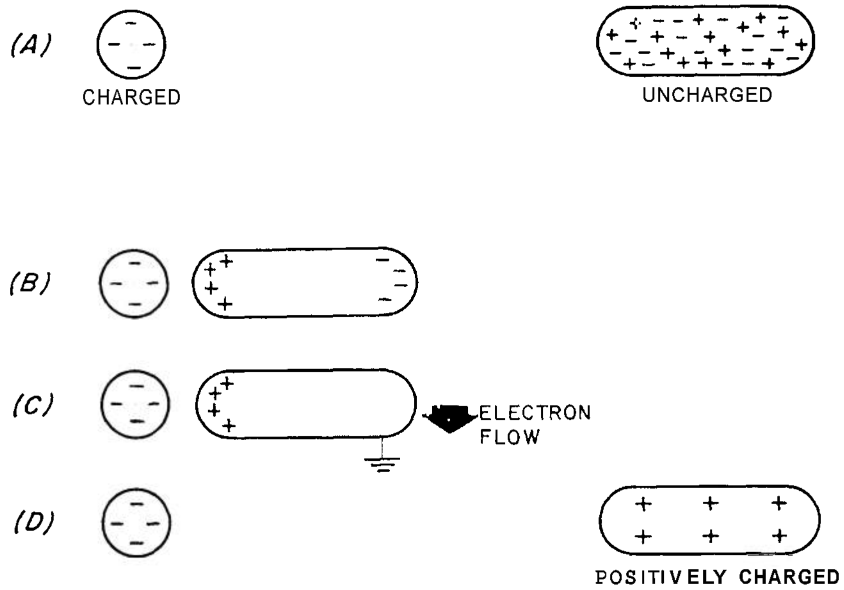


Fig. 2-4. Charging by Induction

than a point source; hence, the vector sum of the charge is used to express the electric field.

$$\bar{E} = k_1 \int \bar{a}_r \frac{dQ}{d^2} \text{, a vector sum, N/C} \quad (2\text{-}7)$$

where

d = distance between the point of interest and charge, m

$\bar{a}_r$ = unit vector in the direction of the field

Expressing E in newtons per coulomb is rather awkward; therefore, it is customary to convert to a more practical set of units (Ref. 7). The units that are consistent with the **MKS** system expresses E in volts per meter.

(e) *Potential*

The potential at a point in an electrostatic field is one volt if the ratio of potential energy of a charge at the point to the magnitude of the charge is one joule per coulomb. For distributed charges,

$$V = k_1 \int \frac{dQ}{d} \text{, V} \quad (2\text{-}8)$$

(f) *Maximum Potential*

If the charge on an insulated body were able to build up indefinitely, then the potential would have no upper limit. Fortunately, this is not true. The maximum charge that can be retained by a conductor in air is limited by the fact that the air itself becomes conductive at an electric intensity of about 3×10^6 V/m. The maximum potential that a metallic spherical body in air can achieve is (Ref. 8)

$$V_{max} = rE_{max}\text{, V} \quad (2\text{-}9)$$

where

V_{max} = maximum potential, V

E_{max} = maximum electric field, V/m

r = radius of the sphere, m

2-2.3 THE GENERATION OF STATIC ELECTRICITY

There are many ways to develop a static charge. If these mechanisms are understood, the designer is better equipped to avoid designs which are susceptible to hazards of static charges.

(a) *Friction*

The generation of static electricity by friction (triboelectricity) is probably the most commonly known method. In par. **2-2.1** an elementary example was given of a rubber rod that was rubbed with a piece of fur where both the rod and the fur exhibited equal and opposite charges as a result of rubbing the two together. This principle can be applied on a large scale; as an example, take the case of a vehicle that is hauling a missile system and is equipped with rubber tires. As the vehicle moves over the ground a charge is built up by the rubber tires and deposited on the vehicle. If there is no leakage path to ground, a charge will accumulate until an arc to ground occurs.

Typical of the potentials that can accumulate on a rubber-tired vehicle are those shown in Fig. 2-5 (Ref. 9). The charges are generated by each part of the tread as it leaves the road surface, with a consequent steady build-up in charge. Since it is not possible to completely prevent the static charges due to the friction between tire and surface, the solution is to dissipate the charge. One method is to use rubber tires that are impregnated with a conducting material. This is practical since a resistance of several megohms will bleed off a static charge. A second method is to ground the vehicle. This normally can be done only when the vehicle is stationary. The use of a chain or conductive cloth strap hanging from the vehicle to ground has not proved to be very effective and presently is not employed.

Another example of static build-up occurs on an aircraft flying in a rain storm. The charge that accumulates on the aircraft in this case is the result of two mechanisms: (1) rain rubbing against the metal surfaces and displacing electrons, and (2) the initial charge on the raindrops being transferred to the aircraft surface. Of course, it is not possible to ground the aircraft while it is in flight, therefore, static dissipators are used to prevent large voltages from building up. Static dissipators (Fig. 2-6) are sharp pointed devices that ionize the air around them so that the charge will leak off into the air (Ref. 10). The method by which these devices work is discussed in par. 2-2.4(b).

An Army weapon system that has a severe static electricity problem is the helicopter. The large rotating blades of the rotor make an ideal generator of static electricity. Potentials of up to 1×10^6 V have been measured on helicopters in flight. The energy associated with this potential is about 1 mJ and its discharge may be of sufficient magnitude to ignite fuel or ammunition, cause radio frequency interference, or shock the cargo handler thereby leading to more serious consequences. Any mechanical damage to the helicopter from the static discharge, however, would be insignificant.

The charging rate of helicopters is normally in the range of 40 to 120 μA per second as the rotor of the helicopter rotates in the air. As the charge on the helicopter increases a point will be reached where a corona discharge occurs from one of the sharp surfaces on the helicopter into the air. The energy that emanates from the helicopter as a result of this is usually in discrete bursts rather than a continuous function; hence, radiated interference to radio and navigation equipment occurs. A continuous discharge, or equilibrium, is established when the corona current equals the charging current.

The energy level selected as being nonhazardous to fuel, squibs, and ground personnel for a helicopter is 1 mJ which respresents approximately 1,700 **V.** In order to reduce the potential on the helicopter to this level, it is necessary to use discharge devices. These discharge devices are rated as one of two types: (1) passive, and (2) forceful.

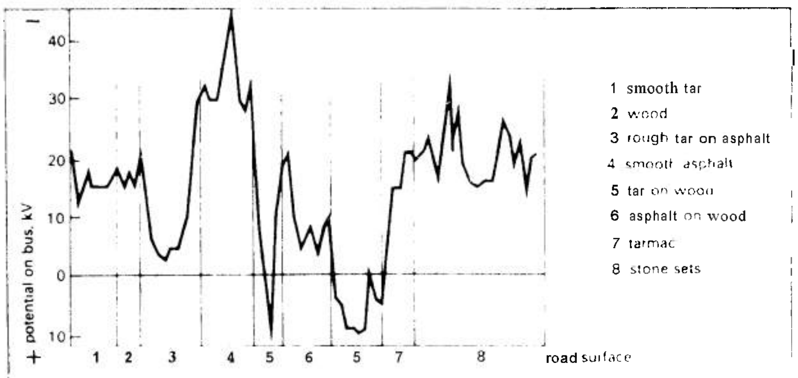


Fig. 2-5. Potential Accumulation on Vehicles With Rubber Tires

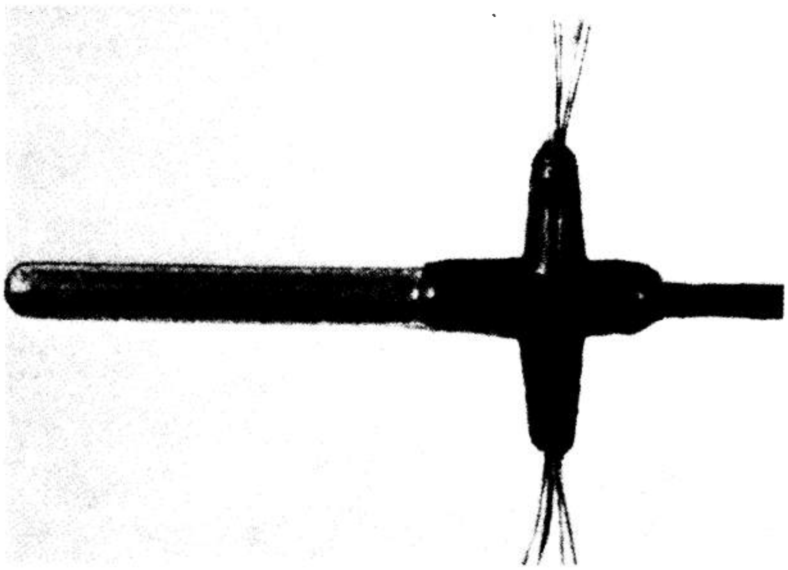


Fig. 2-6. Static Dissipatot Used on Aircraft

The passive type of discharger has been discussed in the example of static build-up on aircraft in a rain storm and an illustration of a typical unit of this type is given in Fig. 2-6. Fig. 2-7 shows the static electricity on helicopters and B-707 jet aircraft. From this figure it can be seen that the most effective type of passive discharger lowers the voltage to about 7,000 V which exceeds the level desired.

Corona discharge occurs when the potential at a point ionizes the air around it, thereby allowing the charge on the body to leak into the air. One of the techniques used for a forced or active discharge device is to lower the potential needed to ionize the air around the discharge element. A device now in use places a voltage source between the sharp point of the discharge element and the helicopter skin. This creates a voltage gradient which ionizes the air and permits dissipation of the charge at a low charge level. A peculiar environment where a static charge can readily be generated is the desert environment where the humidity is low and the frictional action of the blowing sand generates a large charge (Ref. 12). Grounding, of course, is desired to prevent the charge from accumulating; however, the dry sandy soil is a poor conductor. This means that ground rods should be driven deeply and the soil soaked with water to obtain good grounds.

(b) *Induction*

The generation of static charge by induction is not as commonly known as the friction method. The mechanism of charging by induction has been discussed in par. 2-2.1 and portrayed in Fig. 2-4. The basic difference between these two methods is that the friction method requires physical contact and the induction method does not. A better understanding of the induction method follows if one recognizes the existence of a static electric force field around a charged body, similar to a magnetic electric field, comprised of lines of force wherein lines of similar polarity repel each other and lines of unlike polarity attract.

When a charged body is brought close to a neutral body, the neutral body is subjected to the electric field of the charged body. If the charged body carries a negative charge, it is carrying an excess of free electrons and the force field of that charge will repel the free electrons in the neutral body forcing them away from the charge. The formerly neutral body is now charged positively nearest the "charging" body and. negatively in the portion furthest from the "charging 'body".The *net* charge on the charged body is still zero and if this body is removed from the influence of the static field the charge on this body will redistribute itself and the body will return to a state of neutral (zero) charge.

An example of how electrostatic induction can affect a weapon is described as follows. Consider a missile in an open area during the passage of a charged cloud. Assume, for the moment, that the missile is insulated from ground by the rubber treads of the launcher. Under these conditions the missile would still be electrically neutral; however, the charges will be redistributed as shown in Fig. 2-8. Now, consider what happens if the launcher supporting the missile is grounded. The excess

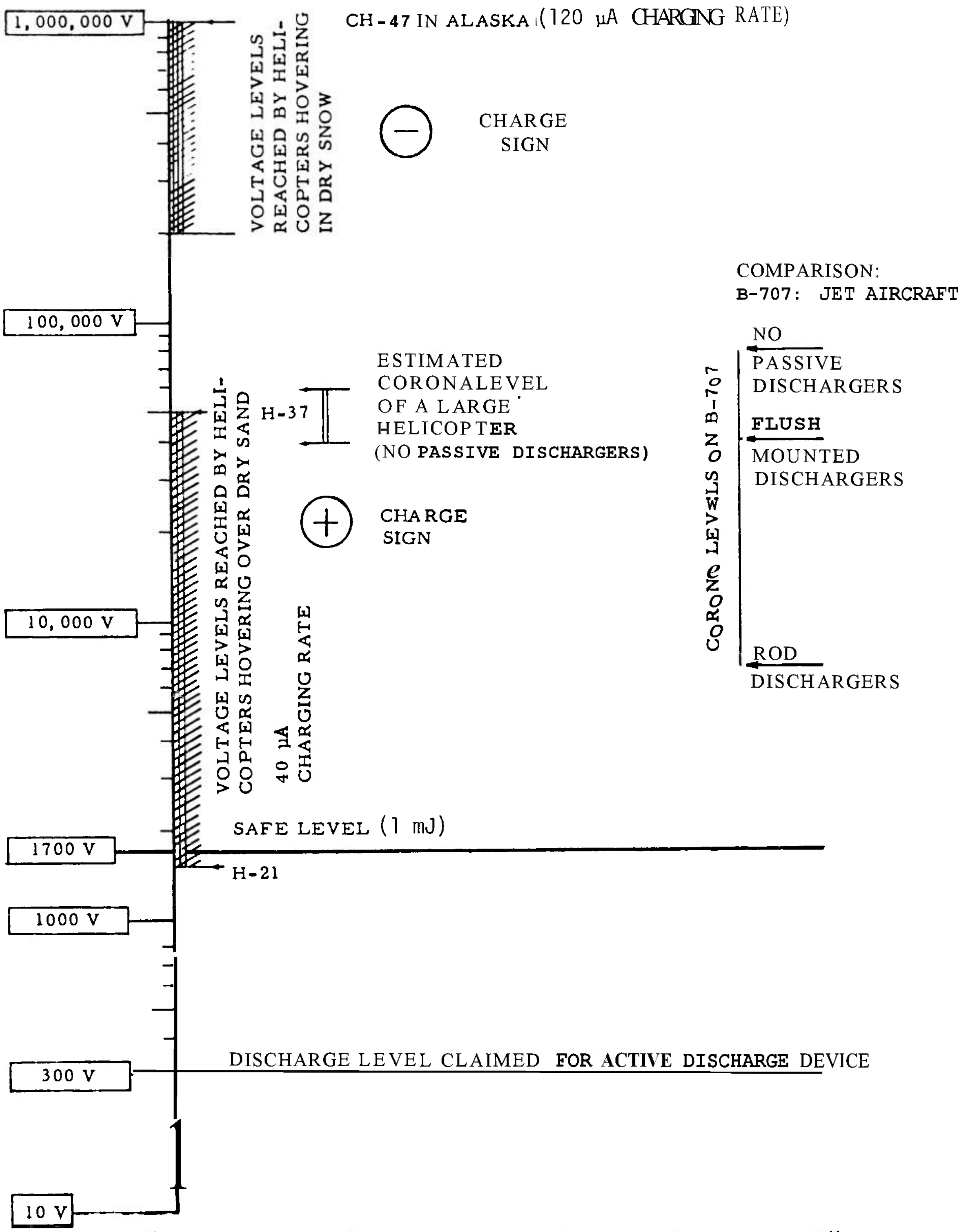


Fig. 2-7. Accumulation of Static Electricity by Helicopters and B-707 Jet Aircraft[11]

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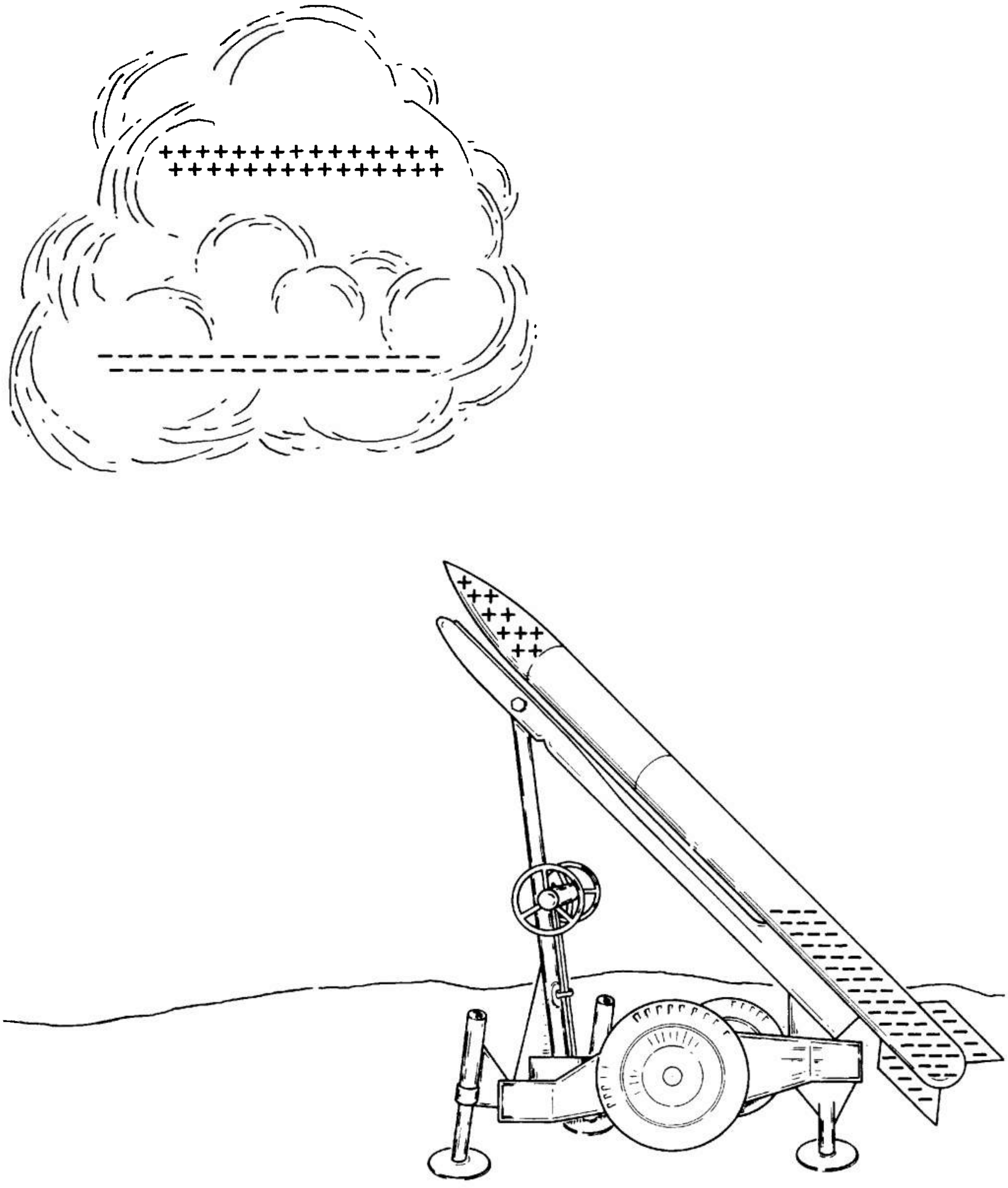

Fig. 2-8. Example of an Induced Charge on an Ungrounded System

electrons will flow into the ground and leave the missile with a positive charge. When the cloud passes, the electrons from the ground will flow back into the missile and neutralize the charge. However, if the ground is removed when the charged cloud is still overhead, the positive charge will remain on the missile even after the cloud has passed because there is no convenient path by which the electrons may return to ground.

Personnel can also induce charges in proportion to the charges that have accumulated on their bodies, but a charge on a human being usually is not sufficient to be of consequence except in certain circumstances where the charge is transferred directly by the skin. An exception to firing by induction occurs in the case of extremely sensitive explosive devices such as conductive mix or carbon bridge detonators (Ref. 13).

(c) *Capacitance and Contact Potential*

If two metal parts of a system are separated from each other by an insulating material, a capacitance will exist between them. Any static charge that builds up on the system will charge this capacitor. Normally the voltages encountered in this situation are not of concern; however, there is a condition whereby the initial voltage can be increased appreciably.

Referring to Eq. 2-10 (Ref. 14),

$$V = \frac{Q}{Cap.} \qquad (2\text{-}10)$$

where

V = voltage, V
Q = charge, C
$Cap.$ = capacitance, F

it can be seen that the voltage across a capacitor is directly proportional to the stored charge and inversely proportional to the capacitance. Now, if the two metal parts are pulled apart, the capacitance will decrease while the stored charge remains constant. The voltage across the metal parts will vary inversely with the change in capacitance. An example of this is as follows.

If the initial charge on the capacitor is 1×10^{-3} C and the capacitance is 1×10^{-6} F, then the voltage would be 1×10^{3} V. Now, consider the situation when the plates are suddenly pulled apart, decreasing the capacitance to 1×10^{-12} **F.** Since the charge does not change, the voltage would have to increase to 1×10^{9} V to balance the equation. In actual practice this high potential is not achieved because the air between the plates ionizes and breaks down allowing an arc to form, and thereby redistributes the charge.

This effect actually occurs whenever a missile is released from its launch pad and also when stage separation takes place. The arcs that occur do not cause any physical damage but they do generate **RF** noises. Proper shielding of the system will prevent this noise from interfering with normal operations.

The same type of voltage generation can occur when two dissimilar metals are in contact and then pulled apart. The different work functions of the two metals will generate a small voltage and when they are pulled apart a small charge will be on each plate. **As** the distance increases, the voltage will rise.

There are two simplified equations for determining the approximate value of the capacitance between two objects: one for a sphere and the other for two metal plates separated by a dielectric.

(1) For a sphere:

$$Cap. = 1.1 \times 10^{-15}\, r,\ \mathbf{F} \qquad (2\text{-}11)$$

where

r = radius of the sphere, m

(2) For flat metal plates:

$$Cap. = 8.85\, \kappa \left(\frac{Ar}{x_d}\right) 10^{-12}\ ,\ \mathbf{F} \qquad (2\text{-}12)$$

where

κ = relative dielectric constant of insulating material
Ar = area of plates, m^2
x_d = thickness of dielectric, m

2-2.4 DESIGN CONSIDERATIONS

The electric field around some simple charge distributions is shown in Table 2-4 (Ref. 15). The entry that is of most importance to the designer is the third one which shows the charge distribution on the surface of a conductive sphere. Although a weapon system rarely ever would be a perfect sphere, the information obtained by using the spherical configuration is considered a good approximation.

A very important piece of design information is contained in Table 2-4. Note that when the ***conductive*** sphere is charged, the charge appears on the outer surface while on the inside of the sphere the field intensity is zero. This, however, should not be interpreted to mean that the voltage inside the sphere is equal to zero. This is not true. To illustrate this point, consider Fig. 2-9, which shows a charged conductive sphere. The plot directly below the sphere is that of the field intensity, while the one below that is the voltage or potential of the sphere. From these two plots, it can be seen that even though the field intensity inside the conductive sphere is ***zero,*** the voltage, referred to ground, is the same on both inside and outside surfaces of the sphere.

TABLE 2-4
ELECTRIC FIELDS AROUND SIMPLE CHARGE DISTRIBUTIONS

Charge Distribution Responsible for the Electric Field	Arbitrary Point in the Electric Field	Magnitude of the Electric Intensity at this Point
(1) Single point charge Q	Distance d from Q	$E = k_1\left[\frac{Q}{d^2}\right]$
(2) Single point charges, $Q_1, Q_2, \ldots$	Distance d_1 from Q_1, d_2, from $Q_2, \ldots$	$E = k_1\left(\frac{Q_1}{d_1^2} + \frac{Q_2}{d_2^2} + \ldots\right)$ (vector sum)
(3) Charge Q uniformly distributed on the surface of a conducting sphere of radius r	(a) Outside, $d > r$ (b) Inside, $d < r$	(a) $E = k_1\left[\frac{Q}{d^2}\right]$ (b) $E = 0$
(4) Two equally and oppositely charged conducting plates with charge per unit area $\bar{D}$	Any point between plates	$E = \frac{D}{\epsilon_o}$

ϵ_o = permittivity of free space
D = charge density

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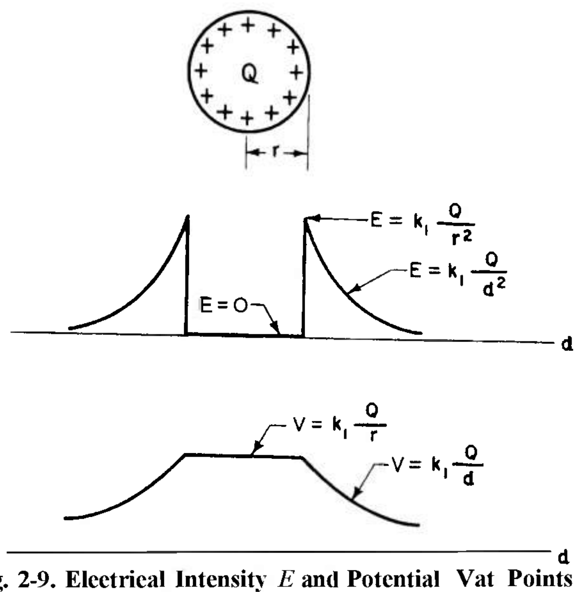


Fig. 2-9. Electrical Intensity E and Potential V at Points Inside and Outside a Charged Spherical Conductor

If the continuous metal skin of a missile is considered as the sphere, then any equipment located inside the missile would not be affected by the static field. Also, since the voltage inside the missile is uniform, the fact that a high voltage from missile to ground exists does not affect the equipment inside the missile. However, if one of the components inside the missile has a return path to ground then there will exist a voltage between that component and ground.

(a) *Effect of Shielding*

Two concepts for protecting the circuits of the weapon system from static electricity are indicated: (1) if the skin of the missile is an unbroken metal surface then the components inside will have protection from an external electrostatic field because no voltage can be induced into them, and (2) if the missile skin is maintained at ground potential there will be very little chance of a charge build-up on the outside of the missile. An exception is shown in Fig. 2-10 where an induced charge can exist on the missile even though the missile is grounded.

(b) *Effect of Shape*

The shape of the missile will influence the amount of charge accumulated on it. The maximum potential that a conductor can exhibit in air is about 3×10^6 V/m because the air itself becomes conductive at this intensity. The formula for the maximum potential to which a sphere can be raised is shown in Eq. 2-9. For example, if a sphere with a 3-m radius is used, then by Eq. 2-9 the maximum voltage that it could attain would be 9×10^6 V. Fortunately, the missiles associated with most weapon systems are not spheres but are more nearly cylindrical in shape with protrusions such as control fins, antennas, vents, etc. The static charge tends to concentrate at the smallest radius on the object. In the case of a missile it could be at the edge of a fin of the missile guidance control system. As an example, suppose the radius of curvature of a control fin is 1 cm, then by Eq. 2-9, the maximum voltage that could be built up on the missile would be 3×10^4 V.

The principle of the smallest radius discharging the static charge is exactly the present system used in aircraft to prevent an electrostatic charge from accumulating during flight. To lower the static potential, several needle-like rods are mounted on the trailing edge of the wing with points having radii of millimeters, this discharges the voltage on the surface of the aircraft to potential of the order of thousands of volts rather than hundreds of thousands of volts. A typical static dissipator is shown in Fig. 2-6. Note the fine wires used to bleed off the charge.

The assumption made in the previous discussion is that the metal skin of the missile is unbroken. If it is assembled from sections that are insulated from each other, the possibility of an unequal charge build-up between sections exists. This can lead to arcing between sections.

(c) *Effect of Separation*

An interesting situation occurs where a static charge can generate a large instantaneous voltage. Consider a missile with a plastic protective cover over it and the cover has some charge. Assume that there is a charge of 100 V on the cover and the cover is removed. The charge on the plastic is referenced to the metal skin of the missile; therefore, the plastic is actually the dielectric of a giant capacitor. The voltage on this capacitor is governed by Eq. 2-10 so that when the cover is pulled away, the capacitance will decrease; however, the charge Q must be conserved according to the principle of the conservation of charge. If the capacitance goes down and Q remains the same, then the voltage must rise correspondingly, to conserve charge. For a plastic cover about 1 mm thick removed 1 m from the missile surface, the voltage would rise by a factor of 1000 or from 100 V to 100,000 V. If the cover were pulled away entirely, the voltage tries to rise to infinity and an arc will occur between the plastic material and the missile skin.

(d) *Effect on Explosive Components*

The sensitivity of electroexplosive devices to static electricity is important since the premature initiation of one of these elements may cause weapon system detonation, and thereby destruction and possible loss of life. It has been demonstrated that sensitive explosive devices can be fired from the electrostatic charge developed by personnel in handling missile components as well as from radiated fields of the weapon system. When selecting the explosive component such as an EED, it is imperative that the designer take into account the possibility of initiation by static electricity.

In par. 4-2 there is a discussion of components used in weapon systems, one of which is the electroexplosive device (EED). The suggestion is made that the designer select EED's from those which have been tested for sensitivity to static electricity. There are several methods employed by the manufacturer of EED's to protect them from static electricity. One method is to place sharp points on the lead wires where they enter the base of the EED to permit any static charge to discharge between these points. A second method is to place a thick insulator between the explosive mix of the EED outer case. The dielectric breakdown voltage of the

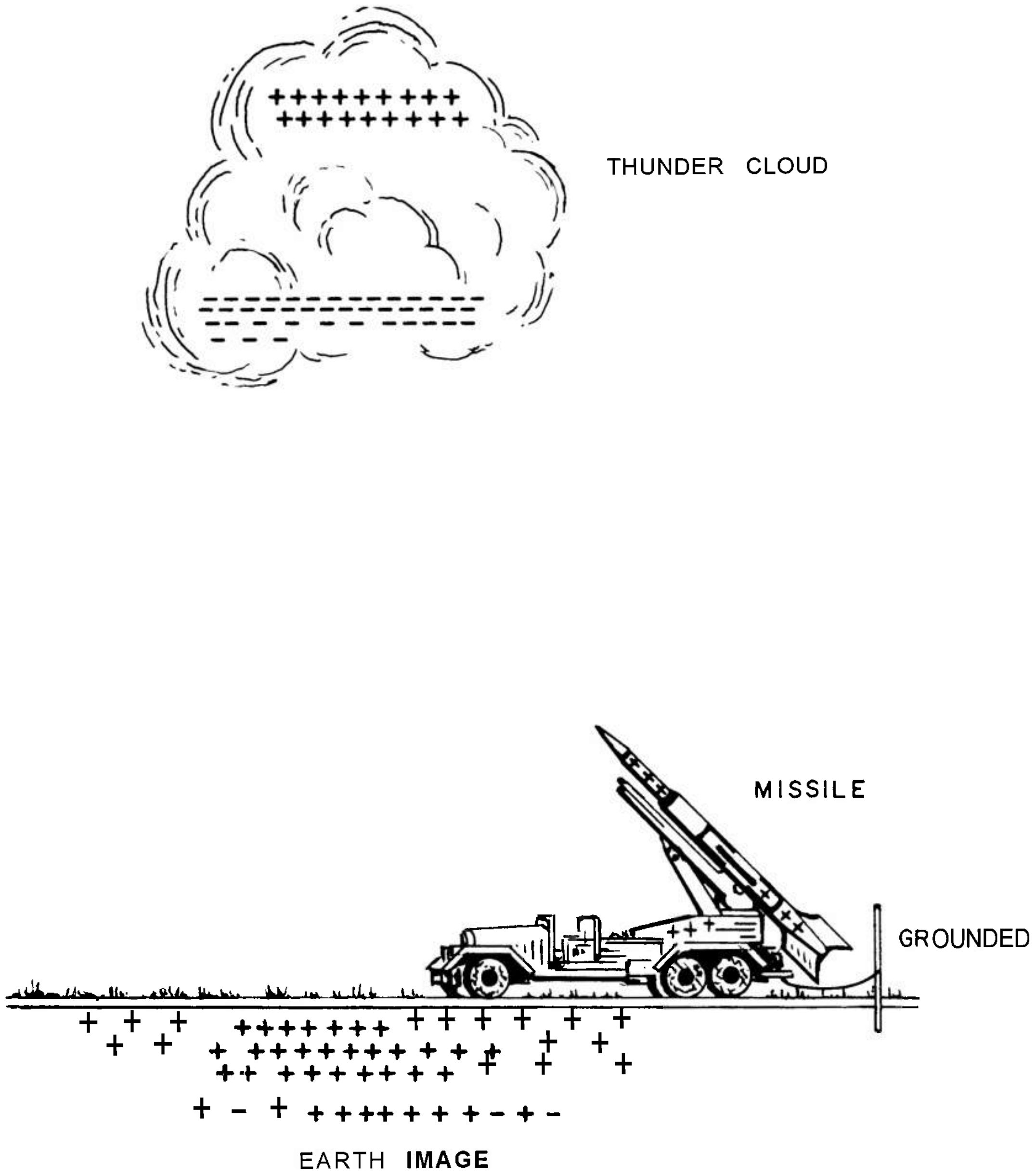


Fig. 2-10. The Static Charge Distribution from Overhead Thunder Cloud on a Missile and Carrier

insulator material should be rated sufficiently high so that the static charge cannot break down the insulator material and arc through the explosive mix. It is not uncommon for an EED of this type to have the ability to withstand 25,000 V from pins-to-case without firing.

A third method employed is to make the plug of the EED conductive so that a static charge cannot accumulate. This, however, presents a problem since some Military Specifications call for the EED to be able to withstand 500 V from pins-to-case from a source capable of delivering high current. At a potential of 500 V, the plugs tend to break down.

Another method for protection from static charge suggested by both the Air Force (Ref. 17) and the Navy (Ref. 18) (not involving the EED directly) is to require that both leads entering the EED have 100,000-ohm resistors between them and ground. The purpose of these two resistors is to bleed off any charge that tends to accumulate between pins-to-case before sufficient voltage can be reached to fire the device.

If this latter approach is used, it should be employed without interrupting the outer shield of the EED circuit. Fig. 2-11 illustrates how the installation of two bleeder resistors may be used in the output side of a safing and arming device.

(e) ***Effect on Solid State Circuits***

Solid state circuits such as those consisting of transistors and diodes are very vulnerable to static electricity. These devices are extremely voltage sensitive and are usually limited to low voltage capability. The potentials associated with static electricity are usually high (even though the amount of power available is small) and are sufficiently large to damage transistors and diodes.

One common electrostatic problem encountered with transistor-type components occurs in packaging. Transistors and diodes are normally shipped in plastic bags or cartons. Unless the leads have been tied together prior to packaging, tearing the bag open and pulling out the component will generate a static charge, as discussed in par. 4-3. The charge developed by this operation may be sufficient to bum out the junction of the transistor. Any weapon system circuit that uses solid state devices should be shielded completely so that no charge can be induced into that circuit.

There is no MIL-STD for static electricity tests on EED's; however, MIL-1-23659, ***Initiators, Electric, Design and Evaluation of*** (Ref. 16), does give the following static requirement:

"3.3.3.2.3 The initiator shall not fire from a 500 micromicrofarad capacitor charged to 25,000 volts when tested as specified in 4.1.4.1."

"4.1.4.1 To determine if the initiator meets the requirements of 3.3.3.2.3, twelve initiators shall be subjected to the following tests. A 500 micromicrofarad ±5% capacitor charged to 25,000 ±500 volts and a 5000 ohm ±5% resistor shall be connected in series between pairs of pins or leads in all combinations and between the shorted pins or leads (all pins or leads shorted to each other external to the initiator) and the case. Each series connection shall constitute a separate test."

2-3 LIGHTNING

Weapon system components face hazards from five distinct lightning phenomena:

(1) The electrostatic field that exists prior to a lightning stroke

(2) The dynamic electric field that occurs during the leader and main strokes

(3) The dynamic magnetic field that emanates from the main stroke

(4) The electric field that is set up in the earth as a result of the main stroke current

(5) The direct conduction of current from the main stroke.

Lightning discharges are the result of a build-up of static electrical energy in cloud centers. Here the charge is believed to be generated by the breakup of raindrops. Clouds are sometimes positively charged but most frequently they are negatively charged, i.e., their charge appears to be negative with respect to the earth (Ref. 19). The effect, even when the cloud is merely overhead, is one of creating a high intensity electric field at the surface of the earth. Fig. 2-10 shows instantaneous distribution of charge near a grounded missile and its carrier (or launcher) as a storm cloud passes over the site.

As the charge on the cloud accumulates, the potential of the cloud center increases until the electric field reaches its breakdown point. At this time, discharges occur either from one cloud center to another or from the cloud-to-earth. Fig. 2-12 demonstrates the time sequence of these events that are the dynamics of the lightning phenomena. The formation of the stepped leader, the first return streamer, and then dart leaders and subsequent return strokes (which are repeated) are shown. The time values shown are approximate; there is considerable debate over the time duration and velocity of propagation of the stroke. More is said later concerning the stroke velocity in par. 2-3.5.

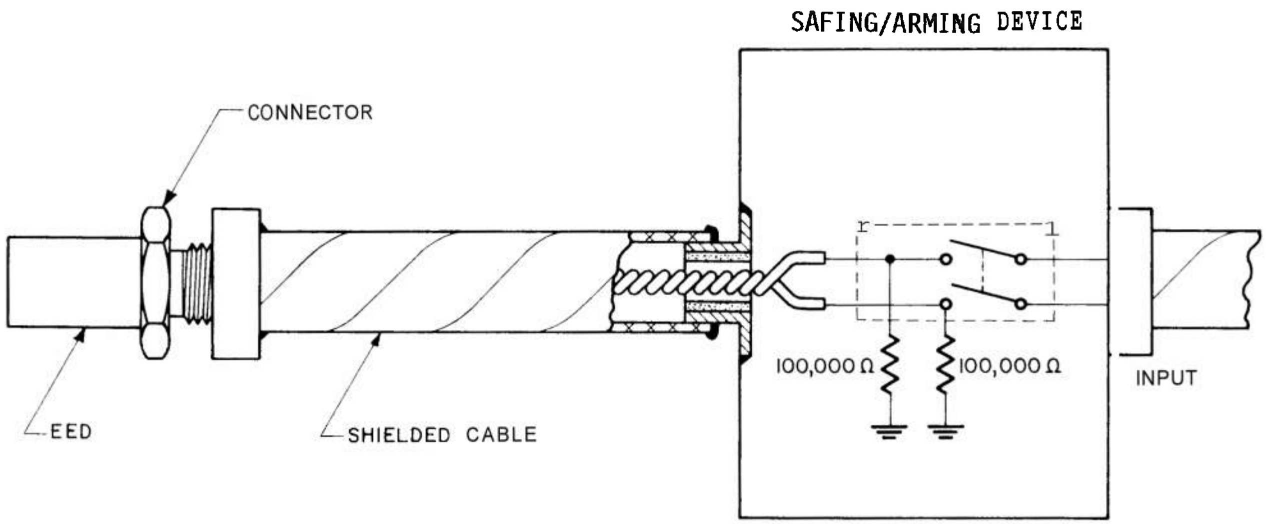
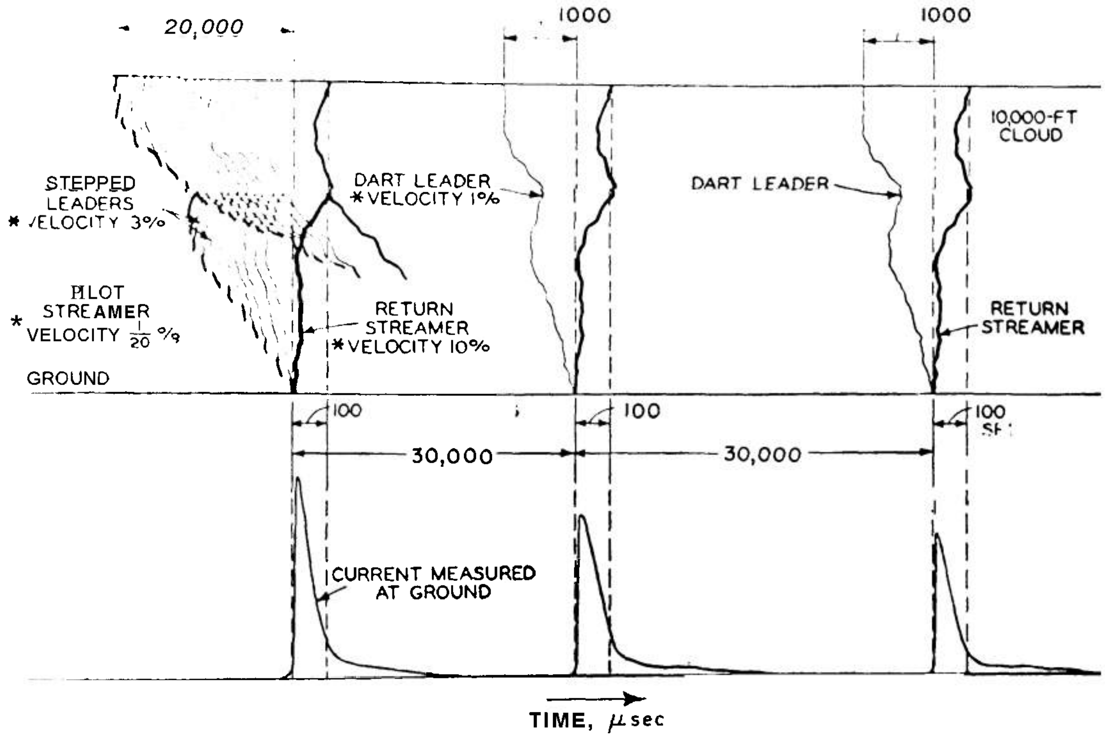


Fig. 2-11. Installation of Static Electricity Bleed Resistors



*IN REFERENCE TO THE VELOCITY OF LIGHT

Fig. 2-12. Sequential Phenomena in the Formulation of Lightning Discharge

In flight, practically the same hazards exist for missiles as those which occur at the launch site. Direct strikes and induced effects from both electric and magnetic fields exist as hazards. The main difference in the hazards in the two cases is that the exposure time for high-flying missiles and aircraft is reduced while flying through the storm area that usually extends from ground level to altitudes of 40,000 ft. Strikes of lightning recorded on jet aircraft show a reduced incidence of occurrence over propeller-driven aircraft. This difference is attributed to the much higher altitude at which jet aircraft operate. Another difference between missiles and aircraft in flight and those on the ground is that no in-flight ground gradients exist.

Experimental evaluation of the effects of lightning on aircraft has been undertaken with models and under full scale conditions with lightning-simulating surge generators and more recently with natural lightning (Ref. 20). Results have shown that abrupt changes in the electric field occur inside an aircraft for strokes that pass within 500 yd of the aircraft.

When in flight, most lightning hazard dangers are the result of cloud-to-earth discharges. Cloud-to-cloud discharges do not contain the return stroke component characteristic of cloud-to-earth discharges. The current maximum for cloud-to-cloud discharge is, therefore, approximately three orders of magnitude less than that of the cloud-to-earth discharge. Furthermore, the time rate of change of both the magnetic and electric fields is considerably less with the result that the induced effects are also reduced.

One question that must be answered is: How often do thunderstorms occur? The answer varies with geographical location and the time of the year. Isokeraunic maps have been developed that show the number of thunderstorm days per year that can be expected in certain areas (Ref. 21). Fig. 2-13 is a sample of such a map for the world. Notice that central Africa has an incidence of 80 thunderstorm days per year and that North Africa, in the arid regions, has an incidence of 5 or less. It is important to remember to consider how often a weapon system will be confronted with lightning storms. In installations that are located only in polar regions, for example, there would be little reason to provide lightning protection while, generally, tropical areas have a high thunderstorm incidence and protection is required. If a system is to be used in all climates, then protection should be considered for the most severe environment.

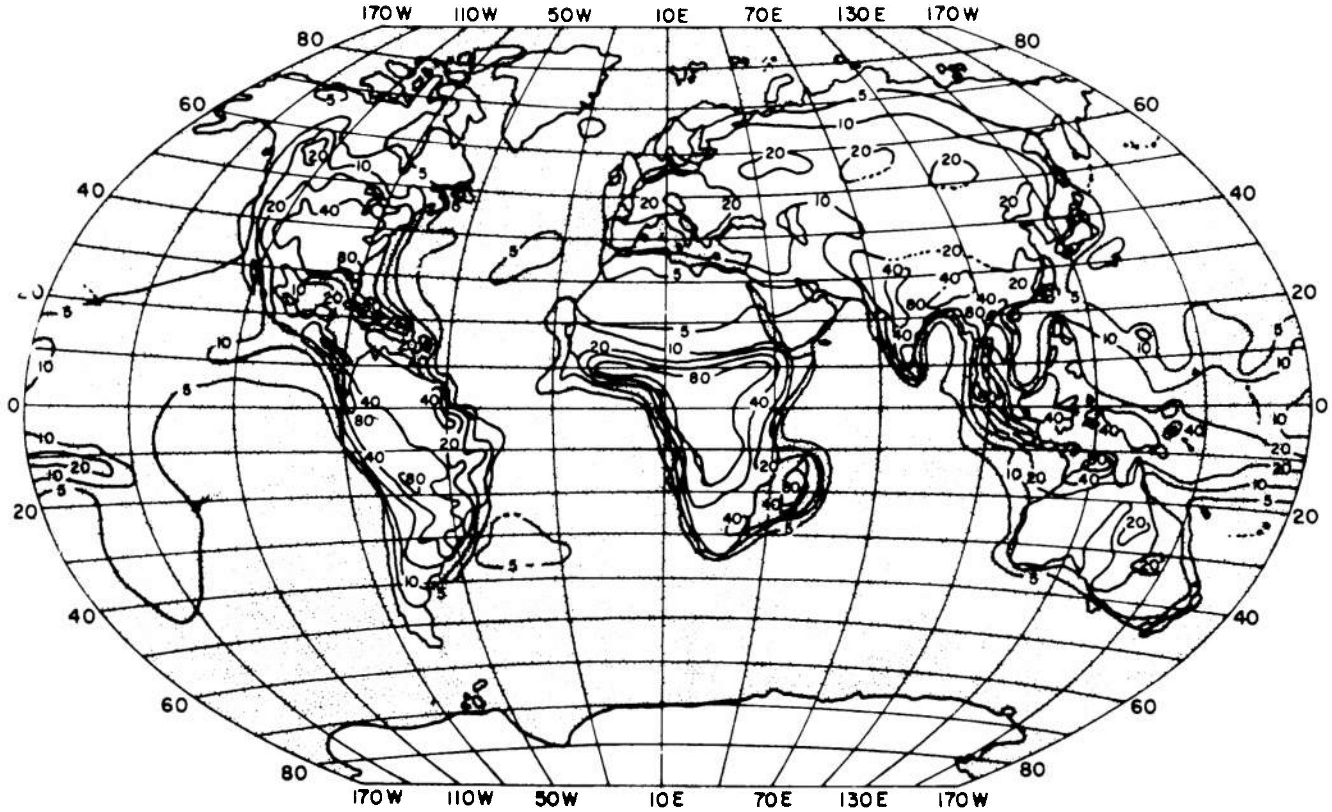


Fig. 2-13. Average Annual Number of Days With Thunderstorms (World)[21]

2-3.1 COMPONENTS OF A LIGHTNING DISCHARGE

The cloud-to-ground discharge begins with a pilot streamer that propagates earthward at about 0.15 m/μsec (Ref. 22). This is followed by a leader that is a series of short stepped strokes. Repeated starts are made but the cloud is unable to supply charge into the leader rapidly enough to sustain the discharge to earth or between clouds. Eventually the charge catches up with the current requirements and the stepped leader reaches the earth.

When the stepped leader reaches the earth, the negative charge on the cloud is effectively brought closer to the earth with the result that the potential gradient, or electric field, is increased. The currents involved in the stepped leader are normally less than 200 A and the velocity of the charge front is relatively small, being only about 10 m/μsec. At this time, the charge formerly on the cloud is suspended in a column from the cloud to the earth, and the head of the positively charged column then propagates from the earth upward toward the cloud to neutralize this negative cloud charge. This neutralizing process results in the main stroke that proceeds with a velocity of about 180 m/μsec and with currents on the order of from 1,000 to 200,000 A.

There is little radiation from the stepped leader compared to that from the main stroke; the reason is that the change of field from the main stroke is approximately three orders of magnitude less in time than that from the leader. The radiated field is proportional to the time rate of change of the electric field. The relative time of the leader and main strokes may be compared in Figs. 2-12 and 2-14. More is said concerning the discharge process in par. 2-3.5.

Repeats of these phenomena are common. The stepped leader is generally replaced by a "dart" leader that re-establishes the path from earth-to-cloud for all strokes other than the first in a series.

2-3.2 CURRENT AND CHARGE

The magnitude of current, initial charge, and charge height varies widely from discharge to discharge. This factor alone probably accounts for much confusion in the theoretical and experimental treatment of lightning data.

The current that is contained in the main stroke can cover a considerable range of values. While there is much information in the literature concerning the magnitude of this current, most of the experimental information that is available is attributed to Norinder (Refs. 23, 24). Through painstaking measurements taken over a long period of time, enough signatures of lightning discharges were obtained to permit some valuable statistical deductions. These data are summarized and compressed into the waveform shown in Fig. 2-15. This waveform can be considered representative of a typical lightning discharge; although the smooth representation of this stroke is not, of course, typical of those obtained in practice.

The following quantitative information concerning lightning strokes was summarized from data secured by several investigators through measurements of strikes to transmission towers and indicates orders of magnitude (Ref. 21).

(1) Median number of components (discharges) in a stroke	2
(2) Median time interval between components	0.02 sec
(3) Median crest current	16,000 A
(4) Maximum crest current	220,000 A
(5) Median rate of rise of current	10,000 A/μsec
(6) Median time for current to drop to half of its crest value	43 μsec
(7) Median total charge in stroke	30 *C*
(8) Maximum total charge in stroke	164 *C*

2-3.3 FREQUENCY SPECTRUM

A lightning discharge has associated with it radiation in the form of light and sound, and radiation in the form of electromagnetic, electrostatic, and induction fields. It is the electrical radiation in which the system designer is most interested. A generalized current waveform from which radiation results is plotted in Fig. 2-15. Both the main component of the discharge and the so-called "superimposed variations" (Refs. 23, 24) contribute to the total radiation spectrum characteristic of lightning discharge.

Norinder (Ref. 23) has observed variations that have a random occurrence; however, the changes that do occur appear to have frequency components that are much higher than those of the total waveform without the variations. This may account for high frequency radiation components that have been observed.

There is no standard lightning discharge spectrum. Differences have been observed in lightning spectra in various locatities of the world and even with simultaneous observation of the same discharge from different locations.

Average spectral data from a number of these observers are shown in the composite source spectra of

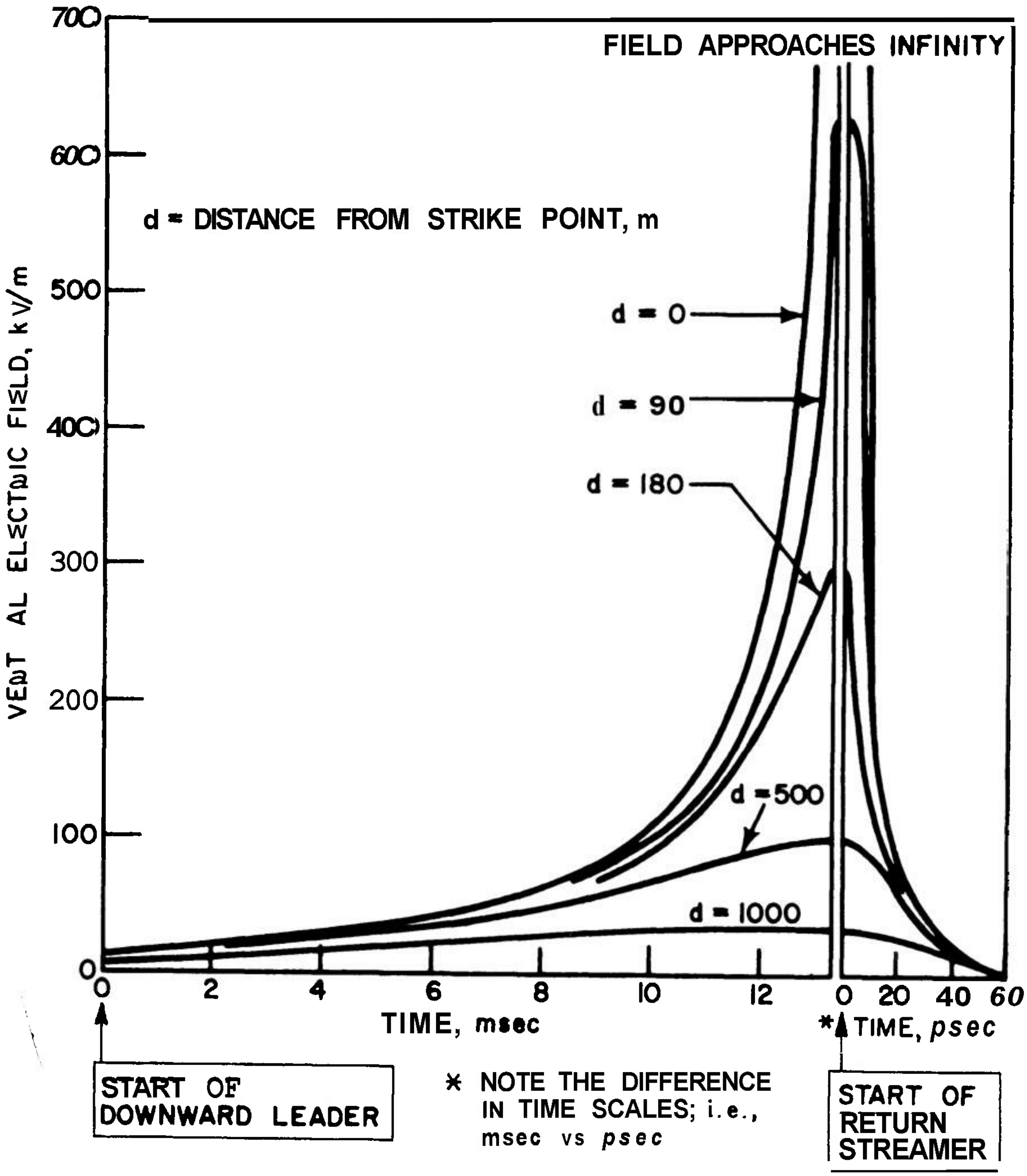


Fig. 2-14. Electric Field of a Lightning Stroke Resulting from the Leader and Main Stroke

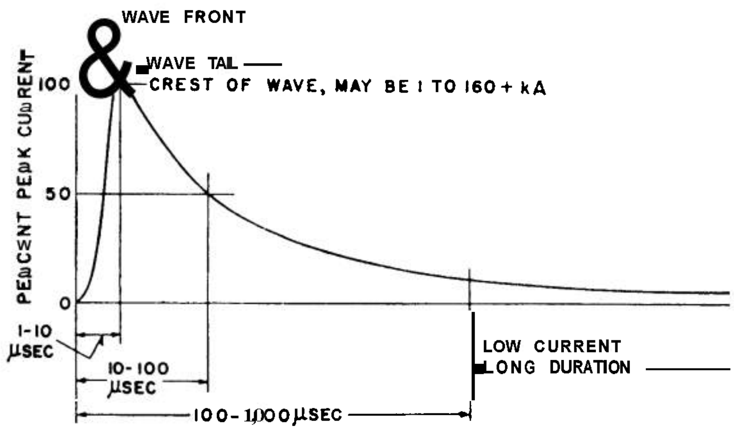


Fig. 2-15. Generalized Wave Shape of Lightning-stroke Current

Fig. 2-16 (Ref. 25). In this figure, the response at 7 kHz is taken as 100 and the response at other frequencies is normalized on this basis.

These average data, that have been compiled by Croom, represent the work of Norinder resulting from observations of current waveforms of close discharges, of Florman observing close discharges, of Croom observing distant discharges, of Taylor and Jean observing groundwaves from close discharges, from Bruce and Golde observing current surges in transmission lines, from Hepbum observing slow tails, and from Hill who made theoretical studies. The results are therefore an agglomerate of information.

2-3.4 STATIC ELECTRIC FIELDS

The magnitude of the fair-weather static electric field is on the order of 100 V/m at the surface of the earth and about 2 V/m at an altitude of 10,000 m. This picture changes considerably during the passage of thunder clouds. Estimates have been made of the gradient of the electric field at ground level just prior to a stroke from a charge center in a cloud (Ref. 22).

Conditions of the cloud centers are quite varied. Heights can vary from a minimum of less than 150 m to over 10,000 m. The average cloud height is 2,000 m. Charges that produce a single discharge vary from 1 to

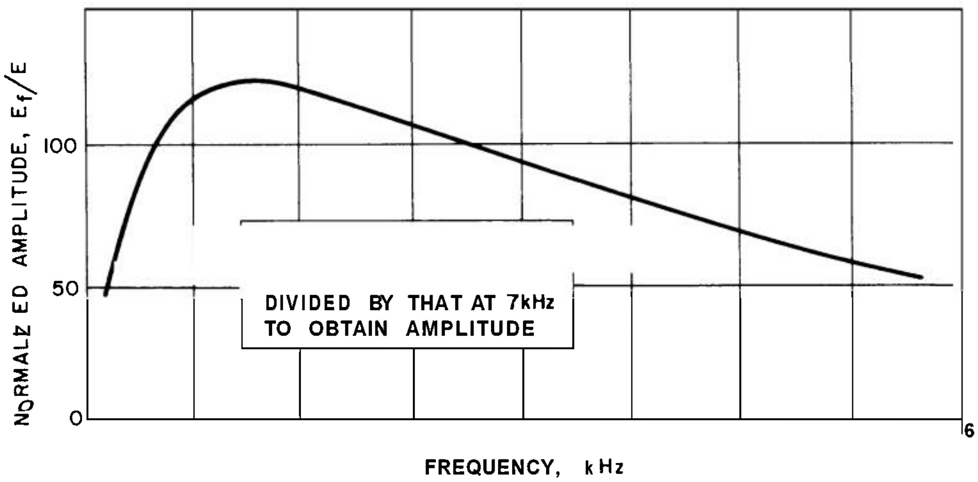


Fig. 2-16. Normalized Average Amplitudes from a Number of Observations as a Source Spectrum for Lightning Discharges

35 C and the average charge is 6.66 C. The voltage breakdown of air is 3,000 kV/m at 25°C and 760 mm Hg (Ref. 27). As the pressure decreases (as at higher altitudes), the voltage gradient required for breakdown decreases. Increased temperature also reduces the voltage gradient required for breakdown in air. This information gives a design working point for protection from static electric fields in the vicinity of a storm. The voltage gradient cannot exceed the value limited by the breakdown potential gradient for air. The value of electric field resulting from the average values of charge and height is shown in Fig. 2-17.

2-3.5 DYNAMIC ELECTRIC FIELDS

The reactions between bodies and dynamic electric fields are not easily analyzed in the general case. Each situation results in a new set of equations from boundary values that are set up by the situation.

Rusck (Ref. 28) has made two general statements in the form of theorems that apply to transmission lines for electric power:

(1) The voltage induced by a lightning discharge is directly dependent on the time derivative of the inducing field.

(2) The voltages induced by a lightning discharge are directly proportional to the height of the line; and for the same line length, are independent of the line design provided that the line is either insulated from earth or directly shorted to it.

For transmission lines the maximum potential V_{max} induced in line at a point d meters from a stroke of current I_o amperes and for a line d_h meters above the earth is

$$V_{max} = \frac{Z_o I_o d_h}{4\pi d_y}\left[1 + \frac{1}{\sqrt{2}}\left(\frac{v}{c}\right)\frac{1}{\sqrt{1-\frac{1}{2}\left(\frac{v}{c}\right)^2}}\right] \quad (2\text{-}13)$$

where

$$Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 377\ \Omega \quad (2\text{-}14)$$

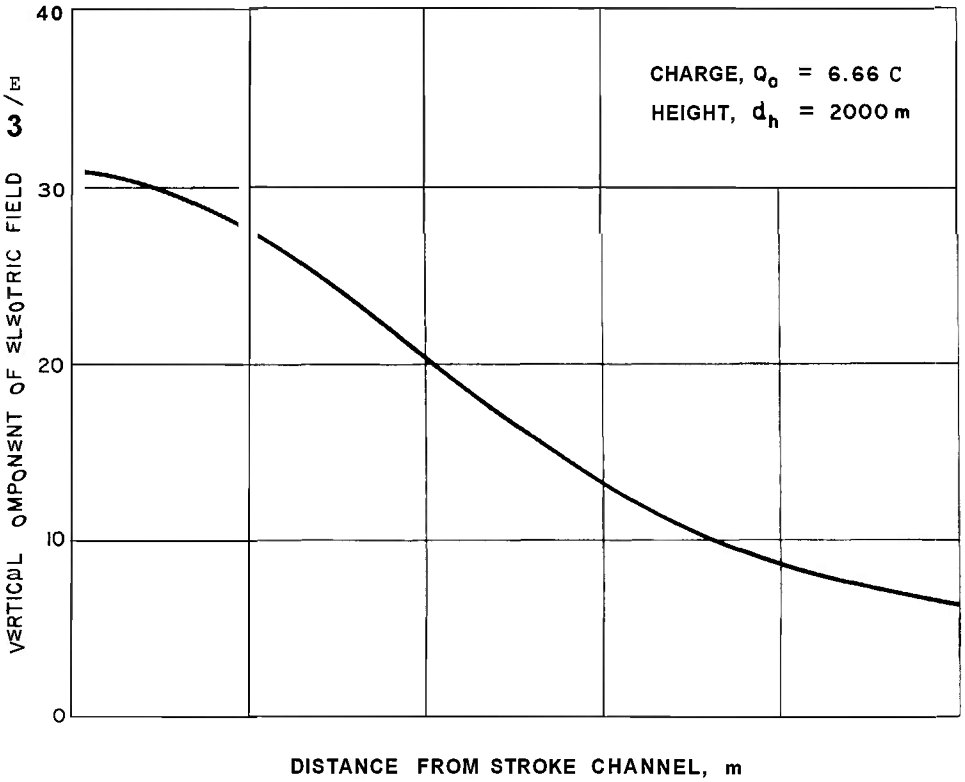


Fig. 2-17. Static Electric Field Preceding a Thunderstorm

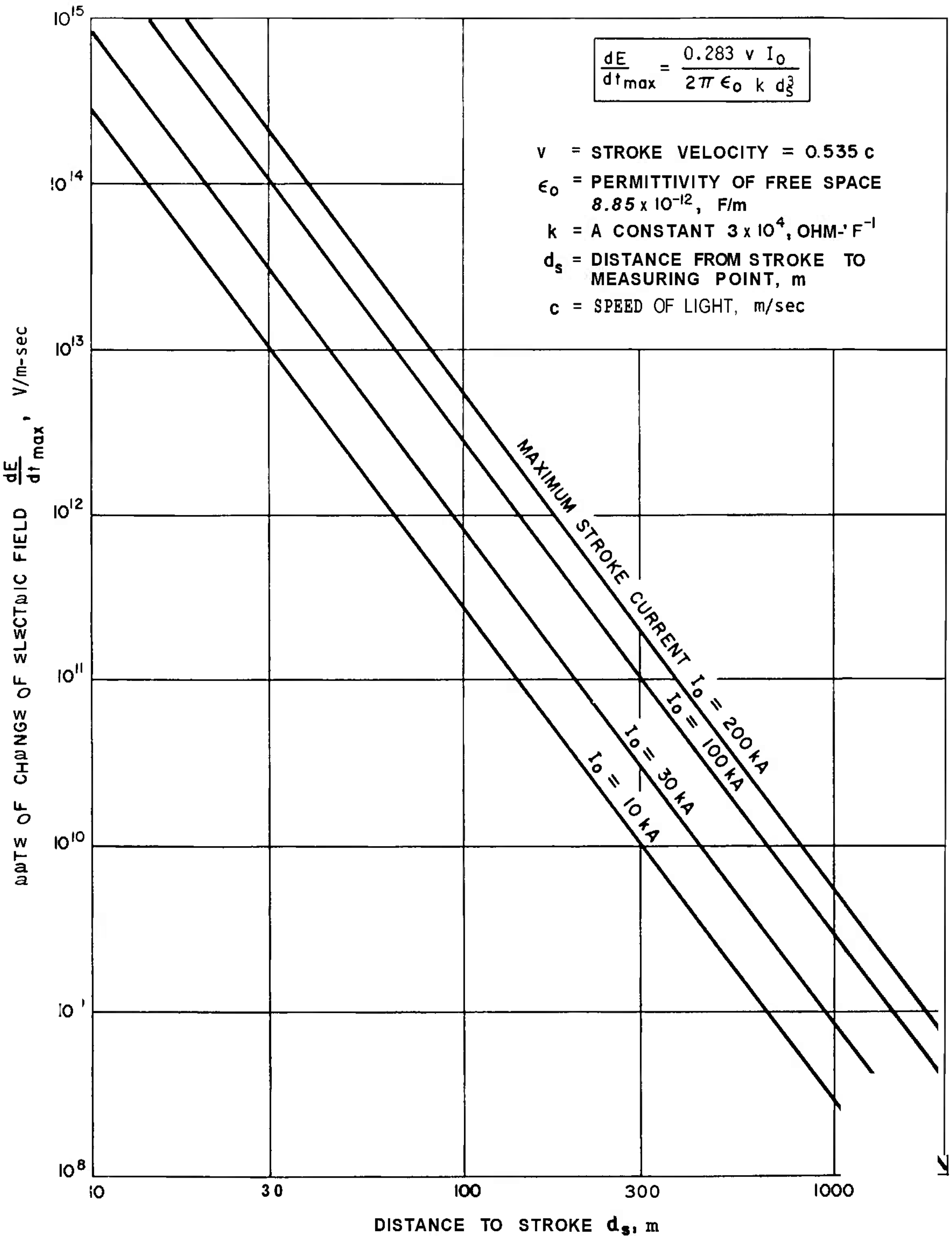


Fig. 2-18. Maximum Rate of Change of the Electric Field in the Vicinity of a Lightning Stroke

μ_o = permeability of free space, 1.257 X 10^{-6} H/m
ϵ_o = permittivity of free space, 8.85 X 10^{-12} F/m
v = return stroke speed, m/sec
c = speed of light, 3 X 10^8 m/sec

The ratio of the speed of the return stroke to that of light is given by

$$\frac{v}{c} = \frac{1}{\sqrt{1 + \frac{500,000}{I_o}}} \quad (2\text{-}15)$$

For a maximum stroke current of 200,000 A the value of v/c is 0.535, i.e., the lightning stroke speed is slightly greater than 1/2 the speed of light.

Under these conditions, Eq. 2-13 reduces to

$$122\left[\frac{Z_o I_o d_h}{d_y}\right] \quad (2\text{-}16)$$

As an example, assume that two horizontal wire lines are located one directly over the other at heights d_y of 9 and 10 m, respectively. Eq. 2-16 may be reduced to

$$V_{max_1} - V_{max_2} = 0.1122\ Z_o I_o\left[\frac{d_{h1}}{d_y} - \frac{d_{h2}}{d_y}\right] \quad (2\text{-}17)$$

If it is assumed that the distance from the stroke to the wires d_y equals 100 m and that the stroke current is 200,000 A, then the difference in potential is

$$\Delta V = (0.1122)(377)(200,000)\left(\frac{1}{100}\right) = 84,600 \text{ V} \quad (2\text{-}18)$$

Therefore, the instantaneous maximum potential difference between the two transmission lines is 84,600 V.

In isolated conducting bodies a charge redistribution inside the body occurs when the electric field surrounding the conductor changes. The current flow is caused by a redistribution of the surface charges. The current flows in the same direction as the field and it is proportional to the rate of change of the field.

For an ellipsoid of revolution the current is given by:

$$I_s = \left[\frac{2\pi a^2 \epsilon_s e^3}{\ln\left[\frac{1+e}{1-e}\right] - 2e}\right]\frac{dE}{dt_{max}} \quad (2\text{-}19)$$

where

I_s = surface current, A
ϵ_s = permittivity of the surrounding medium (8.85 X 10^{-12} F/m for free space)
E = electric field, V/m
t = time, sec
e = eccentricity of the ellipse = $\sqrt{\frac{a^2 - b^2}{a^2}}$
a = semi-major axis of the ellipse, m
b = semi-minor axis of the ellipse, m

For long thin ellipses that approach the configuration of a wire, the current approaches zero because of the effect of the natural logarithmic term in the denominator of Eq. 2-19 that approaches infinity.

For a sphere, the a and b dimensions are equal and Eq. 2-19 reduces to

$$I_s = 3\pi a^2 \epsilon_s \frac{dE}{dt_{max}} \quad (2\text{-}20)$$

Estimates of the dE/dt values are needed in order to arrive at the surface current. Durfee (Ref. 26) estimated the maximum value of the rate of change of the electric field in the vicinity of a lightning stroke by the use of the following empirically determined equation.

$$\frac{dE}{dt_{max}} = \frac{0.283\, vI_o}{2\pi\epsilon_o k d_s^3} \quad (2\text{-}21)$$

where

dE/dt_{max} = maximum rate of change of the electric field, V/m/sec
v = stroke velocity, m/sec
I_o = maximum stroke current, A
ϵ_o = permittivity of free space, 8.85 X 10^{-12} F/m
k = constant, 3 X 10^4 ohm" F^{-1}
d_s = distance from the stroke at which dE/dt_{max} is determined, m

This equation has been solved for a number of currents I_o that are characteristic of lightning strokes. The rate of change of the electric field is indicated as a function of the distance from the stroke for currents of 10, 30, 100, and 200 kA in Fig. 2-18. If the worst case situation is of interest, then the 200 kA line–which represents the worst case situation–is the one of most interest.

To obtain a better insight to the situation, Eq. 2-19 was solved for a number of ellipsoids of revolution, all with a diameter of 2 m at the center and with lengths from spherical to lengths six times the diameter.

To do this, first the eccentricities were determined for each of the ellipses considered as follows:

Ellipse Dimensions

Semi-major Dimensions a, meters	Semi-minor Dimensions b, meters	Eccentricity e
1	1	0.000
2	1	0.866
3	1	0.942
4	1	0.967
5	1	0.979
6	1	0.985

Next, the current was determined for each of these shapes from **Eq. 2-19,** using the value of dE/dt_{max} for **200** kA from Fig. **2-18.** The induced currents are plotted in Fig. **2-19** for the ellipsoid revolution indicated. These data have significance for objects that are insulated from ground, e.g., for missiles in flight. Surface currents of the magnitude indicated in this analysis can, particularly under circumstances where sections of missiles are poorly bonded electrically, result in **(1)** large voltage drops between missile sections, **(2)** current to flow through circuits inside the shell of the missile, and (3) energy may be coupled into circuits containing sensitive devices. This area of hardening is not fully understood at this time; however, efforts are being made to develop suitable criteria for evaluation of these phenomena.

Fig. **2-14** shows the distribution of the electric field with respect to time (Ref. **22).** These data allow for estimation of dE/dt and may be useful in estimating surface currents. The left side of this figure shows the electric field that is generated as the dart leader descends and finally contacts the earth. The magnitude of the field is shown as a function of time for five distances from the point at which the stroke channel contacts the earth. The right side of this same figure shows the collapse of this field as the main stroke progresses to neutralize the charge in the path of the dart leader. While the build-up of the electric field of the stroke is of the order of **13** msec the collapse of the field is much faster, on the order of 40 μsec.

2-3.6 MAGNETIC FIELDS FROM LIGHTNING DISCHARGES

Just as the lightning discharge generates an electric field ***E,*** it also generates a magnetic field B that follows outward from the main stroke much like the waves due to a stone thrown into a pond. The magnetic field is parallel to the surface of the earth and perpendicular to a radius from the point of strike outward for an assumed vertical stroke.

The magnetic field is transient in nature. Investigators do not agree as to the magnitude of the field or its shape.

Rusck (Ref. **28)** has derived a mathematical description of the magnetic field, or at least the leading edge of this field in terms of the characteristic impedance Z_o ohms; the speed of light c (3 X 10^8 m/sec); the distance from the stroke r, meters; and the maximum stroke current I_o, amperes. If the stroke current is assumed to be a step function, then the maximum value of magnetic flux density B is given by:

$$B_{max} = \frac{Z_o I_o}{2\pi c r}, \ \mathrm{Wb/m^2} \qquad (2\text{-}22)$$

The Z_o used in this expression again has the value 377 ohms (see **Eq. 2-14)**

$$Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 377 \ \Omega$$

Eq. 2-22 will apply at distances up to 1,500 m from the stroke. At ground level the magnetic field will rise at a more rapid rate than at distances beyond **1,500** m. The rise times of the magnetic field are shorter close to the strike point than they are at great distances, hence, induced voltages in close-by systems are higher than remote systems. The maximum values of magnetic flux density as a function of distance are shown in Fig. **2-20.**

Where the distance becomes large with respect to the transit time of the stroke front, it is possible to predict the value of the magnetic flux density B from the following relation:

$$B = \frac{Z_o I_o v\tau}{2\pi c^2 r t_r}, \text{ Wb/m}^2 \tag{2-23}$$

where

v = speed of the stroke current, m/sec

τ = time from the arrival of the leading edge of the field to the time of interest, psec

t_r = rise time of the pulse, psec

When τ is greater than t_r the value of τ/t_r is allowed to become unity for the purpose of this analysis. The value of B by Eq. 2-23 is less by a factor of v/c than it was in Eq. 2-22.

Fig. 2-21 illustrates a lightning discharge, the magnetic field generated, and the individual voltage in a loop antenna coupled to the magnetic field. The voltage in the loop is produced by the relationship that is given in the figure. The wave shape of the magnetic field is shown nearly triangular; thus the equation for the potential can be easily solved by multiplying the area Ar of the loop by the rate of change of the flux density. Further, if it is assumed that the angle θ between the plane of the coil and the flux direction is 90°, the sine of this angle is unity and the entire potential is then the product of the rate of change of flux density and the area of the loop. The flux density B and the induced voltage V are shown in Fig. 2-21 as a function of time.

Estimates of the induced voltage due to the rise of the pulse may be made by the following steps:

(1) Determine the maximum current and the rise time.

(2) Obtain the maximum flux from Fig. 2-20 for the distance of interest.

(3) Compute the rate of change of flux for the time of interest.

(4) Multiply this time rate of change by the loop area.

A similar procedure can be used to determine the reduced voltage occurring with the fall of the current.

2-3.7 THE GROUND GRADIENT FROM A LIGHTNING STROKE

The leaders which precede the main or return stroke of a lightning discharge involve relatively small currents, on the order of hundreds of amperes. The main stroke, on the other hand, can generate currents in excess of 200,000 **A.** This current flows through the earth upward into the channel of the main stroke. When it flows in a uniformly resistive earth, the current produces equipotentials in cbncentric circles about the point of the strike. The direction of the electric field, therefore, is radial about the strike point. If we assume that the earth is uniformly resistive, then the equipotentials will look like the concentric circles shown in Fig. 2-22. An expression for the magnitude of the electric field in the earth's surface is given by Rusck (Ref. 28).

$$E_R = \frac{2I_o}{\pi y}\sqrt{\frac{\rho Z_o}{12\pi c\, T}} \tag{2-24}$$

The electric field that can be expected as a function of the distance from the strike point for a 100 kA return stroke current is plotted for three different values of soil resistivity. The values of soil resistivity shown–1; 10,-000; and 1,000,000 ohm-meter–represent the extreme values; most soils have resistivities of less than 10,000 ohm-meter. Since the radial field is directly proportional to the lightning stroke current, the value of the electric field can be adjusted by multiplying the ordinate of this curve by the ratio of the observed, or desired, stroke current to 100 kA to obtain better estimates of the field.

2-3.8 EFFECTS OF MAIN STROKE ON CIRCUIT COMPONENTS

The most common type of lightning damage in telephone and power equipment results from a direct lightning stroke. The direct stroke may (1) cause short circuits in cables due to softening of the insulation, or open circuits as the result of fusing of the conductors, (2) destroy the junctions of transitors, and (3) function EED's.

2-3.8.1 Cables

Fig. 2-23 shows the failures that were produced in telephone cables as the result of lightning current surges through the cable (Ref. 21). The time notation used in this figure is a common one. The first number is the time to crest and the second is the time to trail off to one-half of the crest current. A 10 X 150 psec surge would be one with a 10 psec time to crest and 150 psec for a drop to one-half of the crest value of current. Fusing conditions for common telephone wires are shown in Fig. 2-24.

Aerial cables with a shield or sheath may puncture under the action of a direct lightning strike. In addition to a puncture at the point of strike, more punctures from the sheath to the internal conductors may occur. The potential from the sheath to the core is dependent

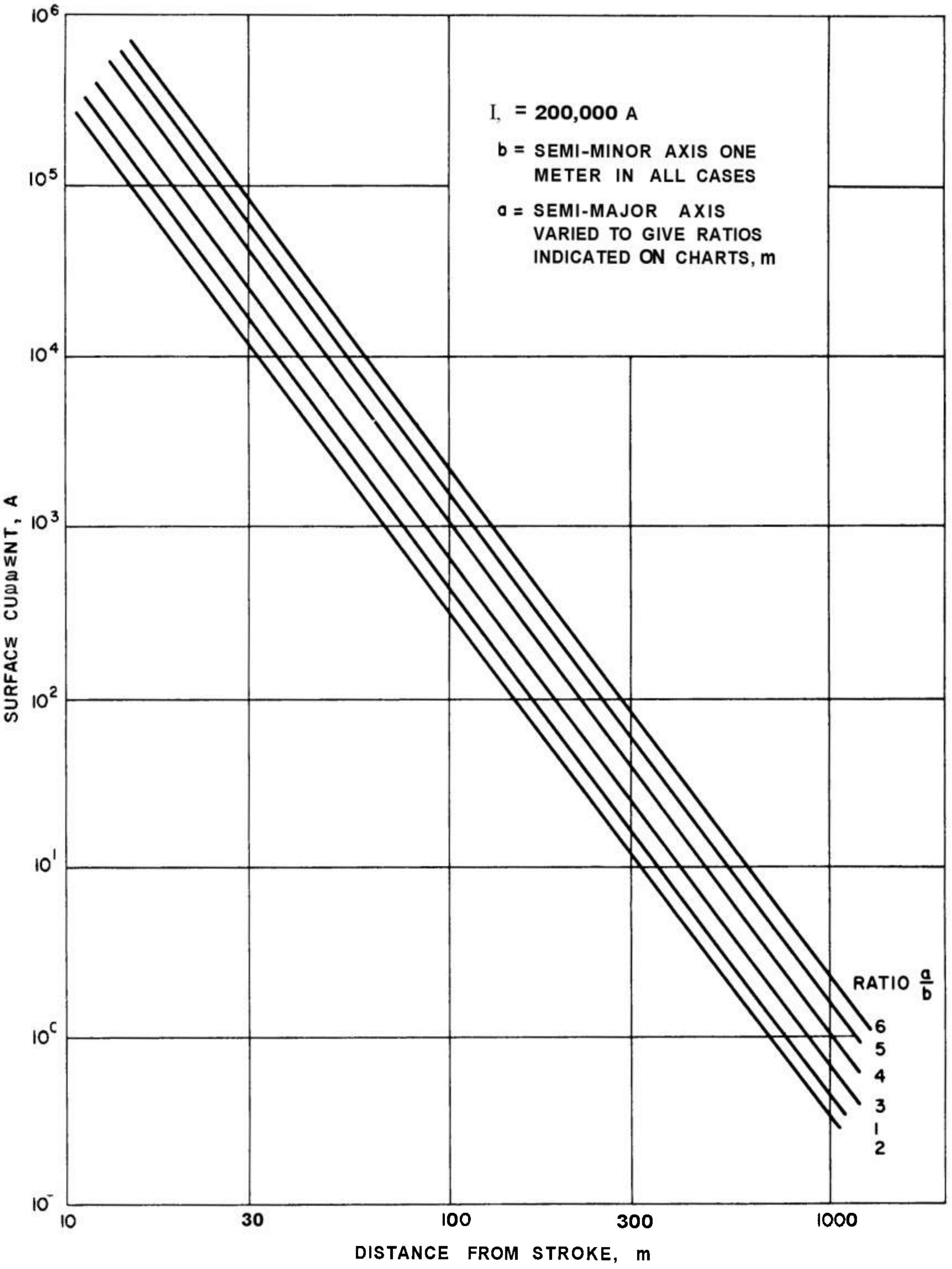


Fig. 2-19. Surface Currents Induced on Conductive Ellipsoids of Revolution by Nearby Lightning Strokes

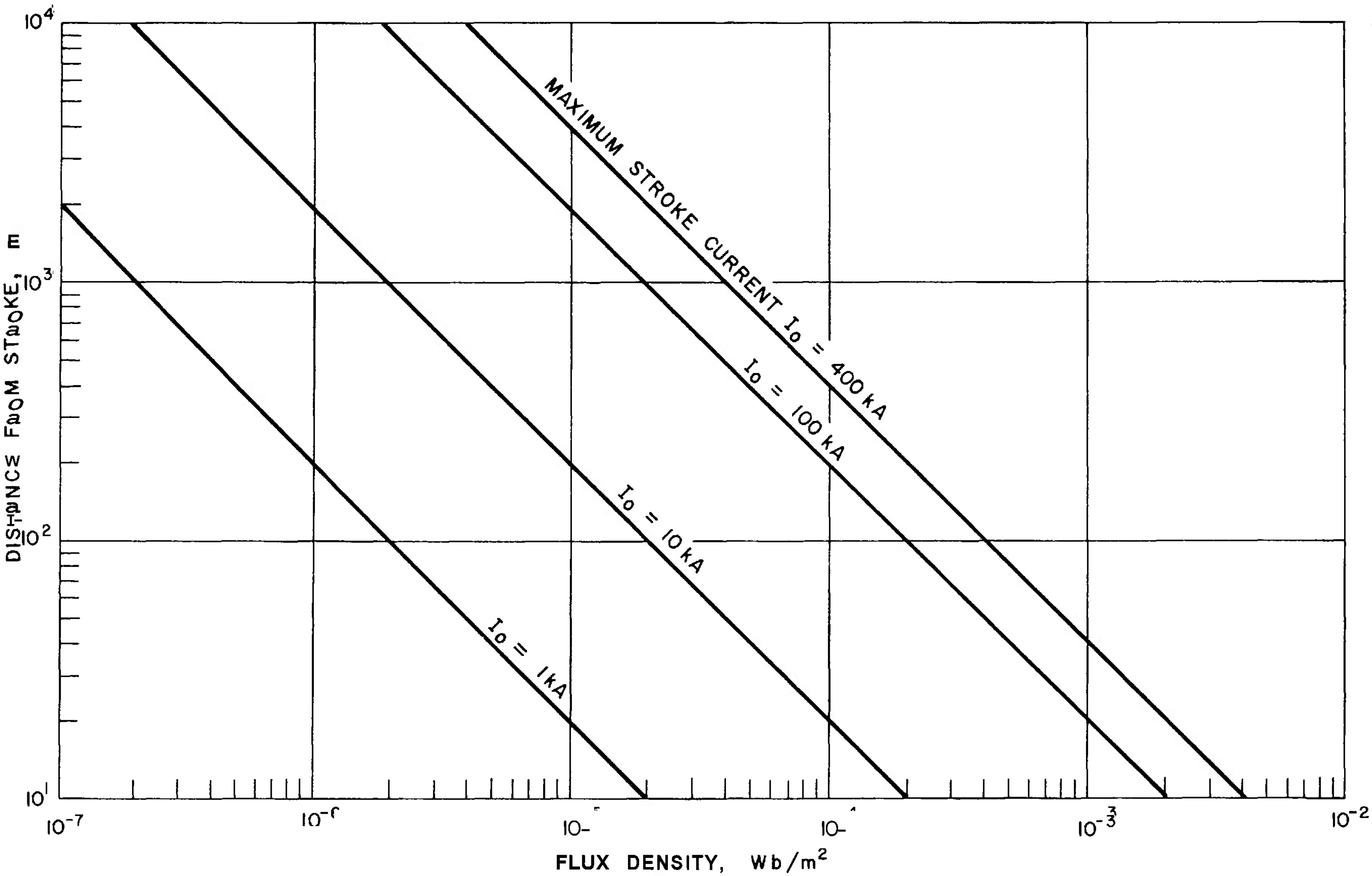
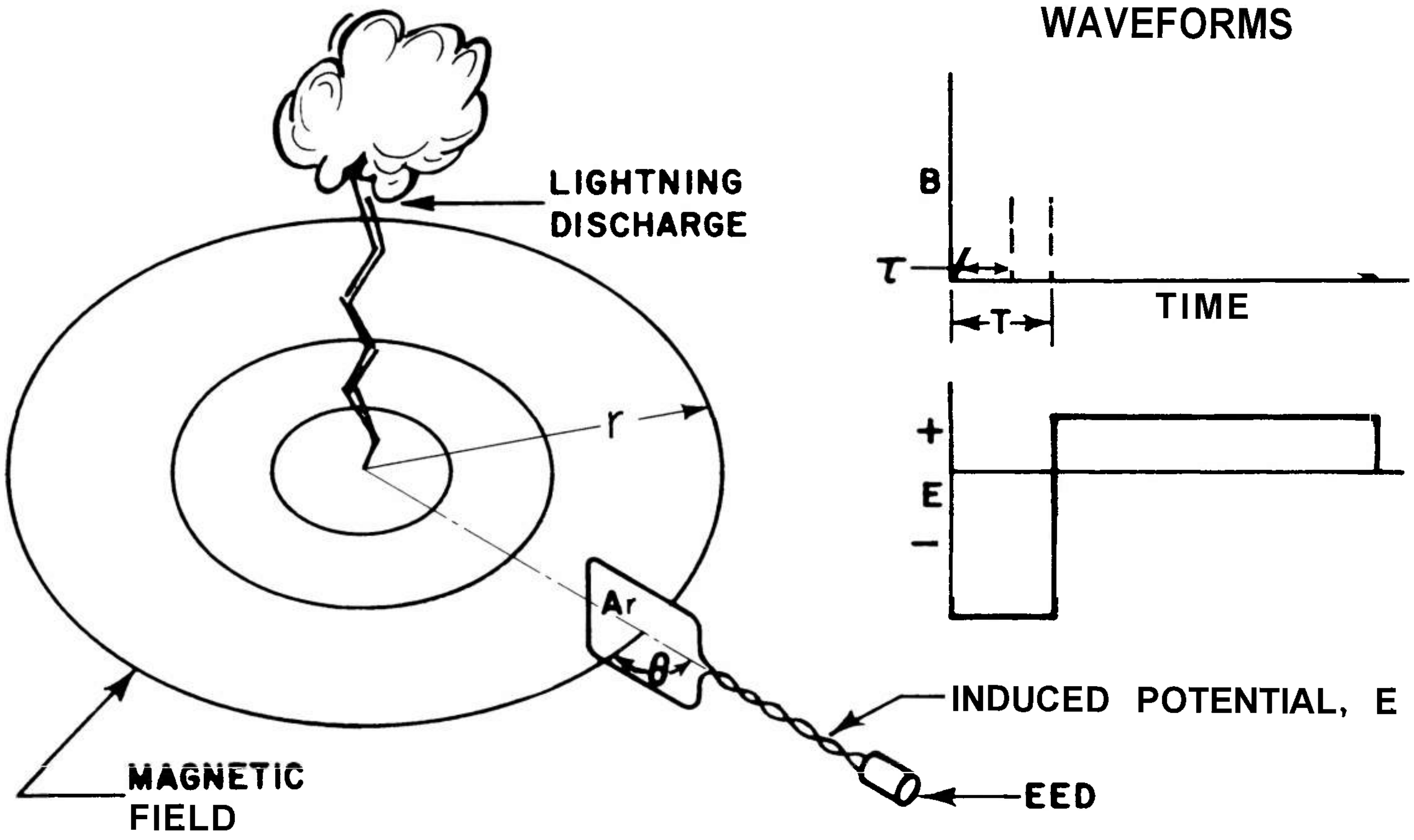


Fig. 2-20. Maximum Magnetic Flux Density from Main Stroke of Lightning



$$B = \frac{Z_0 I_0 v \tau}{2\pi c^2 r t_r}$$

$$E = \frac{-d\left[\int_S \bar{B} \cdot d\bar{S}\right]}{dt} = \frac{-dB}{dt} Ar \sin\theta$$

Fig. 2-21. Potential Induced in a Loop as a Result of the Magnetic Field from a Lightning Discharge

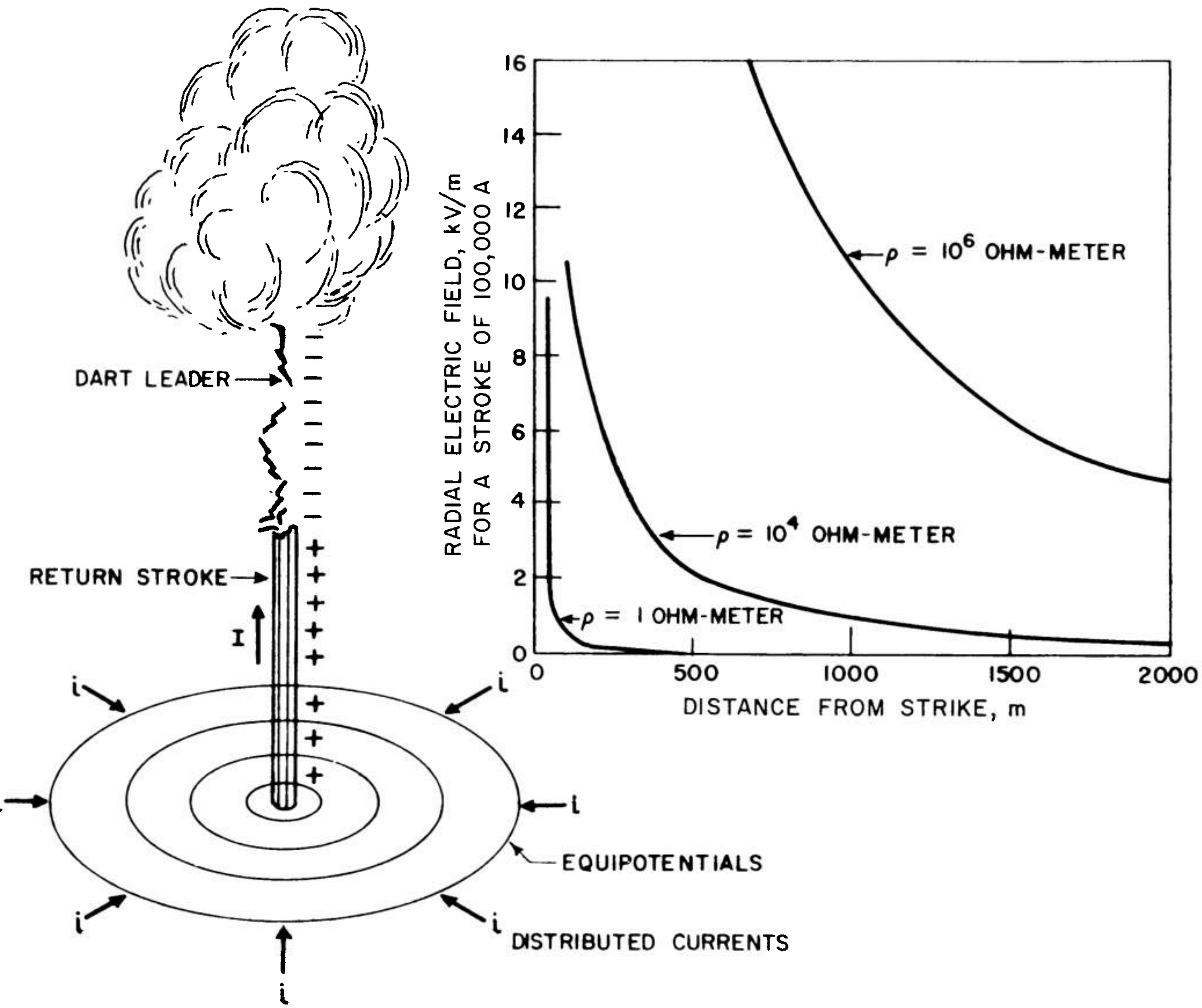
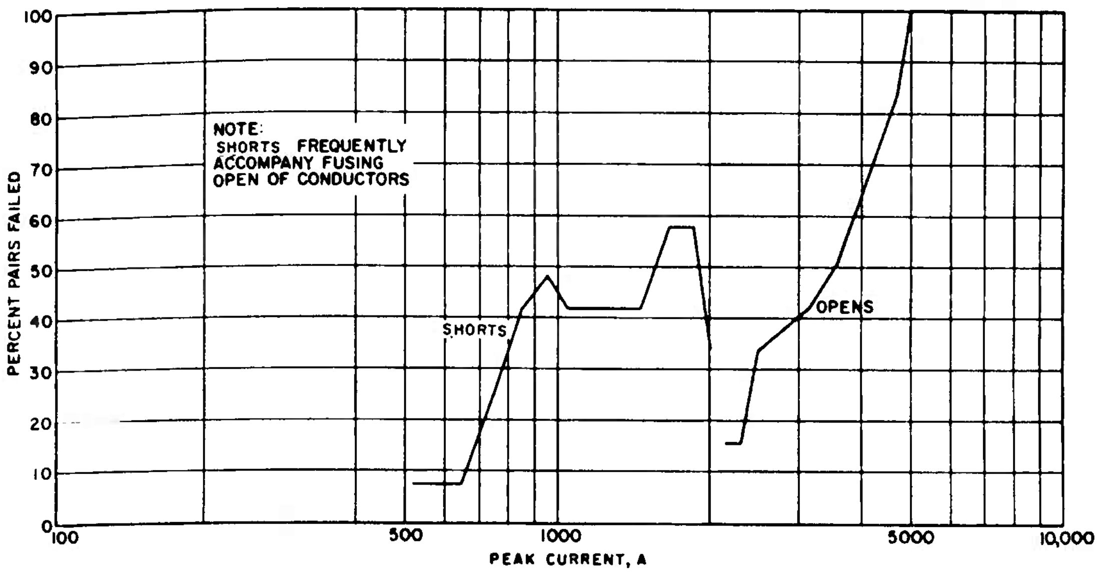
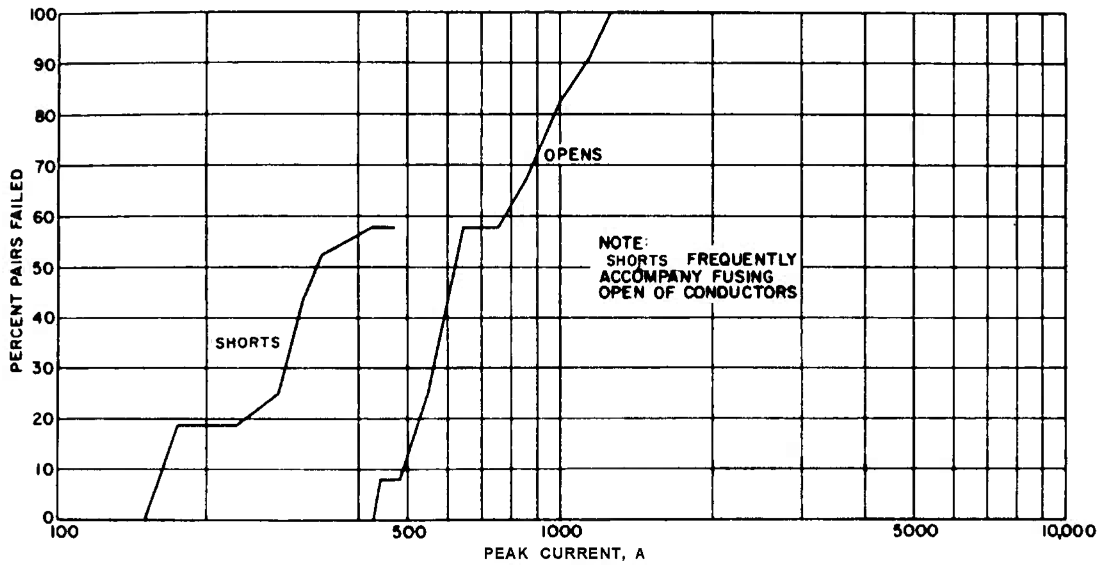


Fig. 2-22. Radial Electric Field in the Earth Surrounding a Lightning Stroke



(A) 10 x 150 psec Surge



(B) 20 x 450 μsec Surge

Fig. 2-23. Surge Current Magnitudes Producing Permanent Faults in Telephone Cable

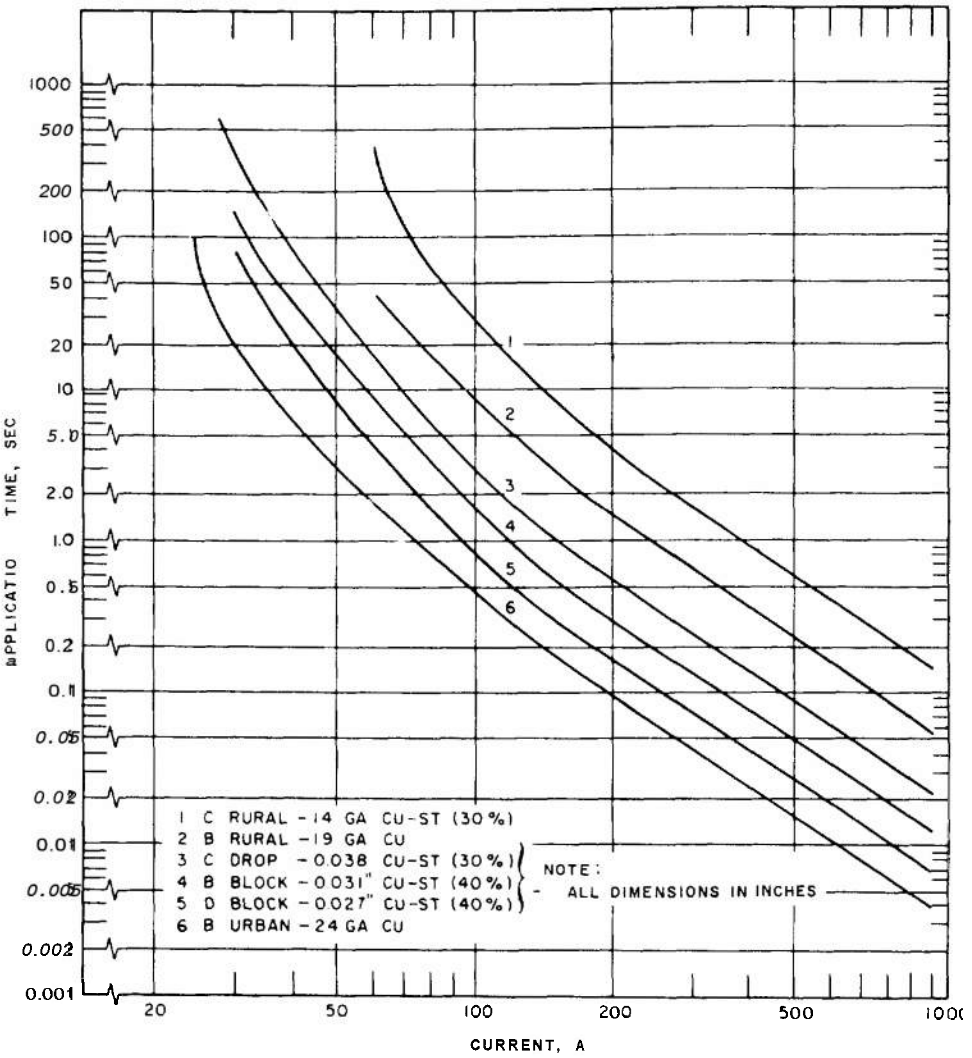


Fig. 2-24. Fusing Characteristics of Wire Used in Telephone Distribution[2']

upon the current and the resistance of the sheath. As the current passes through the sheath, the potential between the sheath and the core increases with distance from the strike point until the ability of the insulation to hold off the potential is exceeded. At this time and point in the cable another puncture occurs.

Even buried cables are not immune to the effects of a lightning strike. The resistivity of the soil surrounding the buried cable has significant distribution influence on the hazard to the cable. Ground currents and the departure of current from the cable will all be affected by the resistivity of the soil. High-resistivity soils are the worst case for buried cables because of the higher potential gradients produced (see par. 2-3.7 and Fig. 2-22), and strokes will arc a greater distance to cables that are buried in high-resistivity soils. Estimates have been made of the lightning stroke currents needed to produce a core-to-sheath potential difference of 2 kV; these are shown in Fig. 2-25 for different values of earth resistivity.

It may appear at first glance that the solution to cable puncture is the use of a heavy insulation around the sheathed cable; however, it does not appear practical to approach the problem in this manner. The first stroke usually punctures this insulation for all reasonable insulation thicknesses and subsequent strokes follow the same path.

Voltages have been measured on telephone aerial equipment subject to the action of lightning strikes and

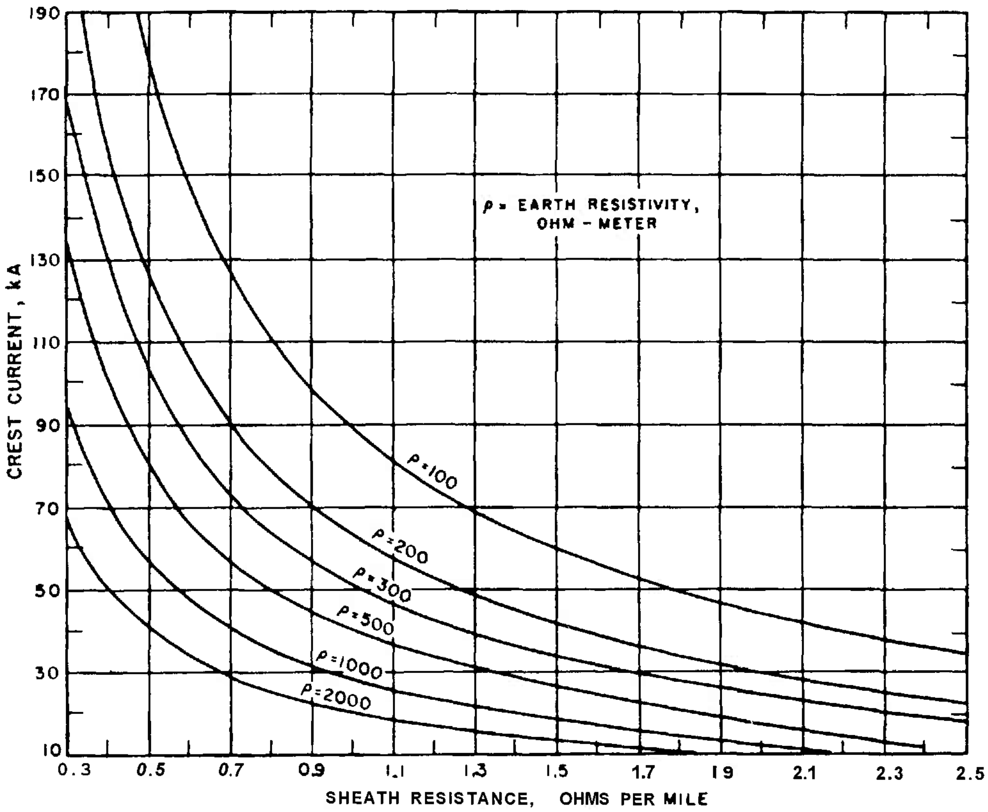


Fig. 2-25. Estimated Lightning Stroke Current Required to Produce Core-to-sheath Voltage of 2 kV

nearby strikes (Ref. 21). The study is summarized as follows:

(1) Voltages may be generated in cables as the result of the inactivity of protectors until a peak voltage of 600 V is reached at the terminals of the line.

(2) The incidence of voltages exceeding 40 V peak may, on the average, exceed 15 per thunderstorm day.

(3) The maximum conditions that will be met in service, as far as wave shape is concerned, is a 10 X 600 μsec pulse.

It must be noted that these conditions apply to lines that were provided with gap protectors. This kind of protection–i.e., circuits provided with gap protectors–will be discussed more fully later.

2-3.8.2 Solid State Components

With voltages of up to 600 V peak induced in the circuits and with a waveform described by a 10 X 600 μsec pulse, some components will be affected partially while others will be destroyed unless steps (beyond high-tension arrestors and low-voltage gaps) are taken toward their protection. One of the components most seriously affected by this high voltage pulse is the solid state component. Very short periods over which excessive voltages are applied are known to destroy the junctions of transistors. A wide variety of solid state devices are available for different types of applications and the potential or waveform which a device can survive is dependent upon its own set of specifications. For this reason it is not possible to specify a general limiting value of voltage or waveshape which will protect all solid state components. It would be well to examine the components being considered for application to military systems in light of the voltages that can be applied from lightning-created surges and in terms of the available protection for these devices.

Field-effect transistors (FET's) of the metal-oxide semiconductor (MOS) type are particularly prone to damage from the effects of high voltages such as those that might be derived from static discharge. The mere act of inserting and removing MOSFET's in styrofoam blocks for storage and shipping purposes has resulted in destruction of the transistor from the static charge generated.

The sensitivity of MOSFET devices to static electricity has been recognized by the electronics industry, hence, special storage and shipping precautions are taken. Precautions include the use of conductive foam for packaging, and bundling of leads and shorting them together by means of wire clips. During wiring, the installer is grounded and a wire clip is employed to shunt sensitive portions of the device. The clip is removed only after installation is complete.

2-3.8.3 Electroexplosive Devices (EED's)

Electroexplosive devices have been found to be sensitive to static electricity. In some cases the devices are excitable in what is known as the pins-to-case mode. The pins-to-case mode is explained as follows. Most common electroexplosive devices have a wire bridge of relatively high-resistivity metal imbedded in a primary explosive material. Leads are attached to this wire bridge and brought out to two lead wires. The entire explosive assembly is contained inside a metal case; the firing leads attached to the wire bridge exit through a plug at one end; and the other end is closed. Static electricity that is stored on some object or on the human body may be applied to the leads during handling, causing a current to flow through the explosive material to the case and ignite the explosive material. Hence, pins-to-case mode means application of a voltage form the pins or leads to the case.

One of the sources of static electricity is the electric field from a lightning storm. This electric field exists either in the form of a static field around a cloud or in dynamic form during discharge of a cloud as has been pointed out earlier. Firings have been noted on EED's with voltages on the order of 2,000 V applied pins-to-case from a 500 pF capacitor, and potentials applied from current-limited direct current sources of 500 V have resulted in firing of some devices. These two bits of experimentally determined data establish the sensitive range for EED's. In the case of electroexplosive devices a serious hazard exists in that they could be explosively coupled to extremely large amounts of explosive or propellant with results approaching major disaster proportions unless adequate precautions are taken to prevent their inadvertent initiation.

2-3.9 DETERMINING SUSCEPTIBILITY

The assessment of damage that can occur to missile components becomes obvious in some instances. For example, if we know the potential difference (and time) that a certain device can withstand without damage, then the effects of the magnetic field from a lightning stroke can be determined as a possible source of damage to this component. The procedures for computing the magnitude of the voltage induced in a loop antenna were demonstrated earlier in this chapter. All that needs to be done is to determine the induced voltage in terms of the physical constants of the circuit and to compare the induced waveform with the one (maximum) that the component can withstand.

The worst case conditions that the component can withstand may not always be readily available, and the exact conditions of the circuit which contribute to electrical energy delivery to the EED may not be known; however, limits may usually be placed on circuit conditions that will determine that the device is either safe or unsafe or that further analysis is necessary.

The effects of electric fields are more difficult to describe because of distortions of the field that occur in producing voltages across circuit components. Each situation involves computations that are long and difficult. Prior to the discharge of the main stroke and leaders, objects in the vicinity of a cloud are charged by the electric field from the cloud. The charges in the cloud migrate to the area of the cloud that are of opposite polarity to the charge at the base of the cloud. Grounded metal objects projecting above the surface of the earth charge most easily because they have a direct path to earth which is the source of charge. Other objects that are insulated from ground may be charged by leakage around or through insulators due to corona (Ref. 29).

A lightning discharge–in the vicinity of the system of which the charged components are a part–results in rapid collapse of the field, which is accompanied by redistribution of the charges. While much work has been performed on power transmission lines and on telephone communications systems, little or no work has been cited on the effects of nearby strikes on systems such as missiles, electronic computers, etc.; however, experiments are currently being conducted to determine some of these effects by actually stimulating lightning discharges from charge-laden clouds (Ref. 30).

The dynamic electric field, a field changing with respect to time, can induce voltages in circuit components. These fields add to the voltage from the static field. The main differences between the dynamic fields and the static fields are that currents induced by dynamic fields can flow in insulators (displacement currents) as well as in conductors. Since these dynamic fields may be in some cases of lightning be strong enough to cause sparking between small bodies at distances over one-half mile from the strike point, they too must be considered hazardous to components. This is particularly true where components are of high impedance; e.g., the pins-to-case modes of electroexplosive devices, field-effect transistors, and other solid state components.

Another approach to the vulnerability of circuit components can be made using the worst case analysis that is described in more detail in par. 4-1. The frequency, power, and bandwidth characteristics of the lightning spectrum can be considered as transmitting sources. With this method of analysis, the aperture of the antenna formed by the circuit leads can be determined and the ambient power density calculated in order to arrive at the power applied to the components. This will be particularly useful at greater distances from the lightning stroke, i.e., at distances of a mile or more.

Direct strokes cause high conduction currents, and even relatively small resistances that carry the stroke current experience large voltage drops. A 150,000 A stroke current will cause a 150,000 V voltage to appear across a resistance of one ohm. This magnitude of resistance is normally considered to be reasonable for the resistance of a good ground connection (Ref. 31).

One of the problems of a direct lightning stroke on a missile is shown in Fig. 2-26 where an electric squib is used as an igniter to initiate the propellant grain in the rocket shown. A twisted-pair of leads connects the squib to a control point or blockhouse. If lightning strikes the missile body, the stroke current flows through the missile body toward earth and a voltage V_r appears between the missile body and earth because of the current I_o flowing through the resistance R_g between the missile shell and earth. Initially no current flows through the twisted leads of the squib because of the high pins-to-case resistance. But as the potential difference increases, eventually a pins-to-case spark (as shown in the upper right equivalent circuit illustration) occurs with the result that this leg of the circuit conducts. The ability of electroexplosive devices to withstand the magnitude of potentials that are obtained from direct lightning strikes is in question. Testing of these components is usually restricted to the human circuit static electricity discharge consisting of a 500 pF capacitor charged to about 25,000 V or less.

2-3.10 METHODS OF PROTECTION

Protection from lightning is generally considered to be either protection from the main stroke through the use of lightning rods, i.e., prevention of a strike to a spot, or protection with lightning arresters of circuits that must be exposed to lightning. Arresters prevent damage after the strike.

Lightning rods provide protection by diverting the strike point to the rod and its associated equipment. A low-resistance path from the lightning rod to ground is provided by conductors of heavy current capacity that allow most of the energy in the stroke to be dissipated in the earth rather than in the wiring of the lightning protected system (Ref. 32).

There is a time delay in the operation of lightning protectors and arresters. They operate after the lightning stroke has struck a particular circuit where they provide a shunt path to earth, bypassing heavy currents around expensive or critical portions of the circuit that would otherwise be damaged. Protection by the use of arresters requires that the arrester operate before enough energy has entered the protected system to damage it.

Arresters must have characteristics that are compatible with the devices being protected. It is important to keep the kilovolt-crest-voltage-vs-time for the arrester below that of any component being protected. The general type of curve that is used to compare these characteristics is shown by the specific example of Fig. 2-27.

Semiconductor devices, silicon diodes, and similar solid state devices are used for limiting voltage levels to safe values. Nonlinear resistors that change resistance rapidly with applied voltage are used in low-voltage circuits for protection.

Most current-limiting devices are thermally operated. Fuses, circuit breakers, and other similar thermal devices provide protection by current interruption.

In most weapon installations the major concern is with protection of low-voltage circuits rather than high-voltage power transmission lines. Some missile sites will have power supplied from commercial high-voltage lines, but it is probable that independent operation of the site will be required from self-contained power generators; consequently, lightning protection of this power system will be the exclusive responsibility of the designer. Protection of most of the power supply circuits will be through the use of low-voltage protectors and breakers.

2-3.10.1 Overhead Wires

Overhead protection by masts and wires has received a great deal of attention in the literature (Refs. 19, 32). Formulas for protective arrangements appear in many references on this subject. One of the most simple protection criteria that has been advanced is the one-to-one cone (Ref. 33). Protection is afforded to equipment inside an imaginary cone that is formed with the apex of the cone at the peak of a vertical metal mast and with the base radius equal to the mast height as is illustrated

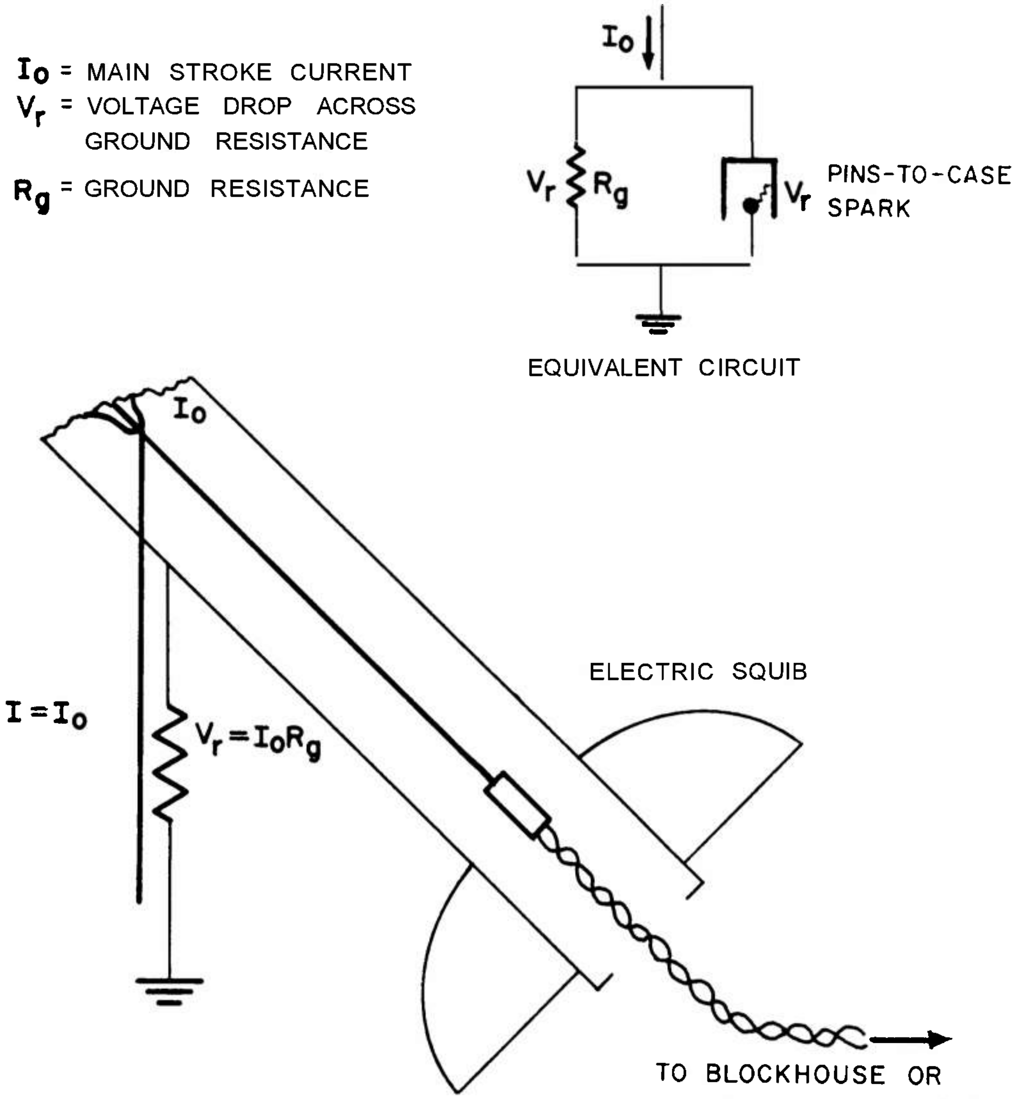


Fig. 2-26. Pins-to-case Voltage Applied to Rocket Igniter Squibs by Direct Lightning Stroke

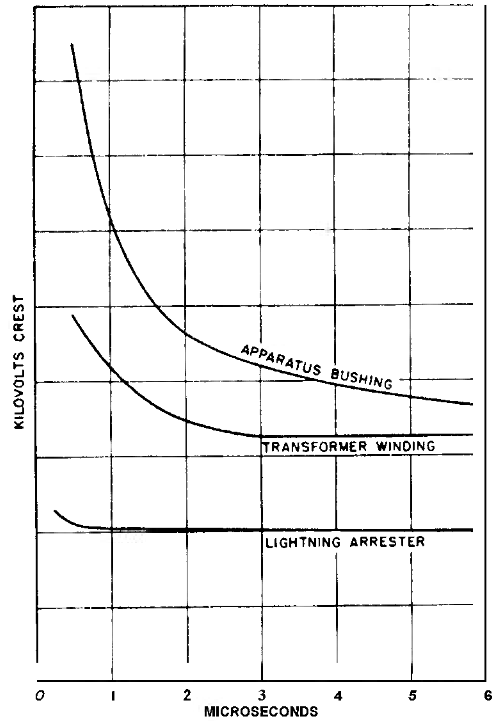


Fig. 2-27. Desired Operating Characteristics of Lightning Arrester for Protection of Bushing and Winding"

in Fig. 2-28(A). Objects included within this cone of protection have chances of being struck on the order of one in one thousand, compared to the likelihood of strikes on the protective mast. For the protection cone, there is still much debate over the proper ratio of radius to mast height to use. In the United States a ratio of 2 to 1 is most generally used for ordinary structures and a 1 to 1 ratio is used for so called "danger" structures. The United Kingdom requires a 1 to 1 ratio for ordinary structures and 0.58 to 1 ratio for "danger" structures. The criteria used to determine the protection afforded by mast structures have been derived from actual experience with such objects as high church spires and from model studies. Both of these criteria are subject to argument.

Overhead wires offer protection of the same type afforded by masts in that they provide a bypass for the stroke current through a low resistance path to earth. Overhead-wire protection is applicable to long structures over which the ground wire can be strung. The protection afforded is the same geometrically as the single mast illustrated in Fig. 2-28(A). Instead of a cone of protection, the protected region takes the form of an inverted trough. The configuration of this trough is illustrated in Fig. 2-28(B).

2-3.10.2 Natural Air Gaps

There are established patterns for house wiring that may well serve as a guide. A study of rural wiring has shown that secondary circuits longer than 500 ft are likely to be struck by lightning or more likely will pick up surges as a result of induction (Ref. **34**). It is also possible to pick up surge voltages through the primary of the transformer if the transformer is connected to a high voltage power line. Some protection is afforded house wiring because of the arcing of appliances and wiring that have natural air gaps in switches and junction boxes (Ref. 31). These usually arc across at less than 6,000 V before puncture of the insulation can occur and, as a result, some form of natural protection is in effect. For this reason most homes need no special lightning protection. But in the case of missile sites it would be well not to rely on the protection that is inherent in the form of air gaps that normally are formed in circuits and components.

2-3.10.3 Protector Gap Devices

Telephone companies are experienced in the protection of low-voltage circuits. Devices have been developed and used for the limitation and equalization of voltages (Ref. 21).

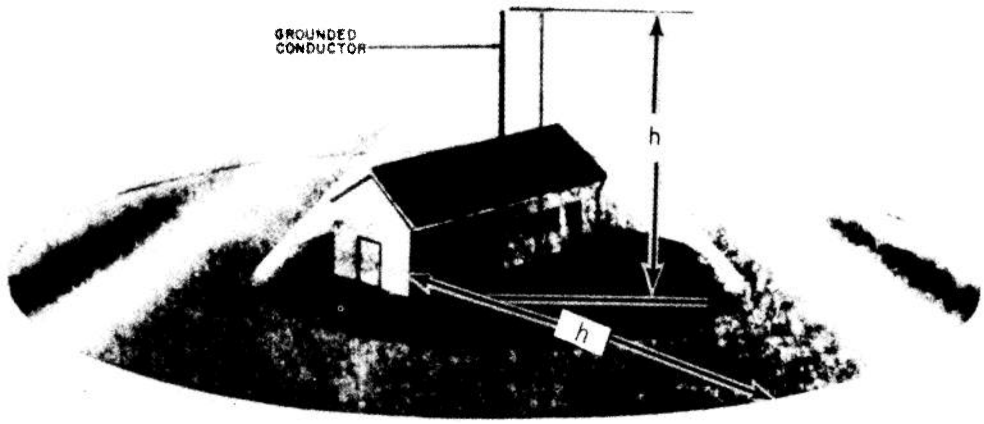
Protectors have been developed that operate over an air gap when a predetermined potential is reached.

Protector tubes are enclosed gaps housed in an insulated tubing. The gaps are normally closely coupled to high-voltage lines by means of a spark gap in order to prevent long-term effects such as leakage currents through the insulation and damage to insulation by corona.

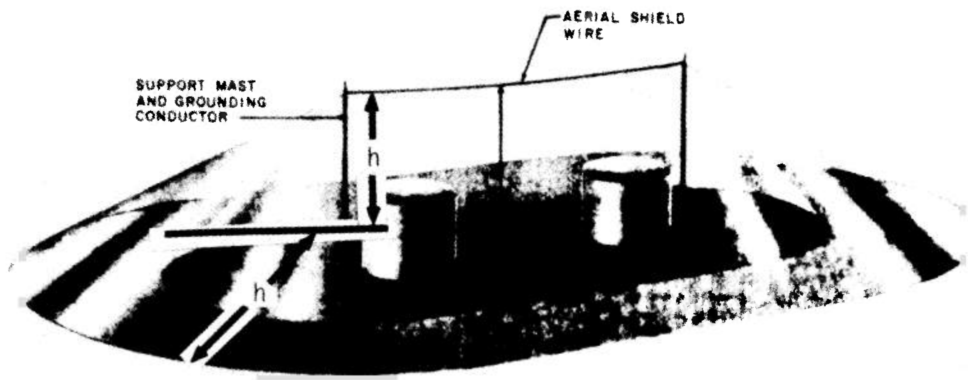
Similarly, there are gas tube protectors that contain a gap enclosed in an envelope along with an inert gas at less than atmospheric pressure.

2-3.10.3.1 Carbon Block

To illustrate the action of an overvoltage protector that is commonly used, the carbon block protector that has a long history of use by telephone companies is shown in Fig. 2-29. Connections are made to the carbon insert from the circuit being protected and from the carbon block to ground. If a voltage of approximately 600 V or more is applied to the circuit connected to the carbon insert, then the air gap between the base of the insert and the carbon block breaks down and conduction is maintained through the carbon block to ground as long as the overvoltage persists.



(A) Cone of Protection Provided by Vertical Grounded Conductor



(B) Zone of Protection Provided by a Grounded Aerial Shield Wire

Fig. 2-28. One-to-one and Two-to-one Protection Zones for Vertical Masts and Overhead Wires

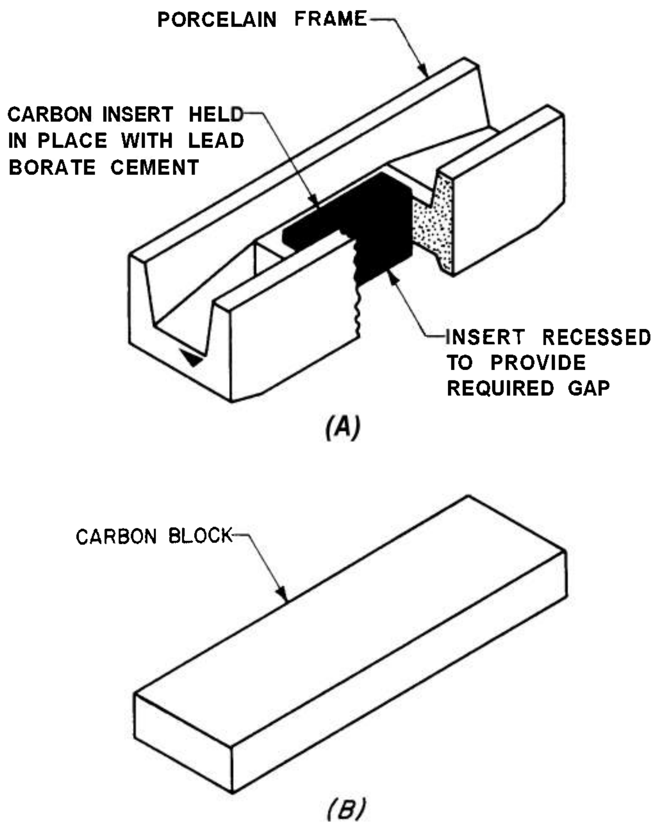


Fig. 2-29. Protector Block Commonly Used by Telephone Companies for Surge Protection

Such protectors are often used in conjunction with fuses, the fuse being located between the incoming line and the protector. In this type of service, the carbon block protector may function many times without being materially affected by fault currents.

Protectors have inherent characteristics that may make selection of one type or another advantageous in a given application.

One of the most important characteristics is operating time at a given voltage. Carbon block protectors function at a lower voltage with a smaller gap, but gaps below 2.8 mils create short life and quick, permanent shorting of the protector. The surge characteristics of the carbon block protector are such that a higher voltage is required for breakdown of the gap than for dc. With 2.8 mil gaps, the surge voltage breakdown is nearly twice the dc breakdown for application rates of 10,000 V/μsec. As the voltage rise rate is reduced to 500 V/μsec, the surge breakdown voltage approaches the dc breakdown voltage.

Generally carbon block protectors are rated according to (1) the magnitude of the discharge current they can pass without damage, (2) volume resistivity of the electrode, (3) impedance of the mount, and (4) voltage drop of the arc. In general, voltages are less than 600 V. Even for current discharges as high as 6000 A, the voltage across the protector is not likely to exceed the 600 V.

2-3.10.3.2 Gas Tube

Gas tube protectors generally have much longer ionization times than the carbon block protectors. The result is that voltages tend to exceed the dc rate value, exposing the protected component to potentials four to five times the dc rating. Gas tube protectors are generally of higher cost and larger size than their carbon block counterpart.

One advantage of the gas tube protector is the large gap spacing that is possible. This feature virtually eliminates the chance of a permanent short circuit. The relatively low operating potential of the gas tube is a distinct advantage where the rate of potential application is slow.

2-3.10.4 Arresters

Arresters differ from protectors in that they contain two distinct elements: (1) a gap to sense that a certain potential has been exceeded, and (2) a means of disconnecting the arrester by interrupting the ensuing follow-up current which is due to the voltages on the protected power line.

Low-voltage arresters are available with very narrow gaps. These function as follows. When an overvoltage on the line occurs, the arrester short-circuits causing a large overload on the line which blows the fuse or circuit breaker. The arrester then must be replaced. These are rated for about 175 V and can be obtained with single poles, or with two poles for three-wire circuits.

Low-voltage circuits do not usually have the follow-up currents normally associated with transmission lines used for high voltages, and for this reason the protection of low-voltage systems is somewhat simplified. Follow-up currents are the result of an arc being sustained after the passage of lightning-induced spark-overs by the high voltage of a high-tension line.

Two general types of arresters are the valve type and expulsion type. These differ mainly in their means of preventing the flow of steady state follow-up current. Arresters are used on circuits that have appreciable steady state potentials where a gap alone would continue to provide a current path after attenuation of the surge. Secondary arresters, the type of most interest in low-voltage circuits for communication purposes, are usually of the valve type and employ a nonlinear resistance element. The resistance of the element drops rapidly when potentials exceed the normal operating line potential.

These arresters are rated in terms of maximum rms voltage to ground at which the follow-up current will be interrupted. The impulse spark-over potential may be five to nine times greater than the normal rating. The spark-over potential is determined by a 1.5 X 40 psec test waveform.

Two standard types of "Secondary Type Arresters" are available and so classified by the American National Standards Institute. They may be obtained from any one of several American manufacturers. Characteristics are:

(1) Two-element devices designed for use on 120/240 V, three-wire circuits. Rated at 175 V rms. Impulse spark-over voltages 1400 to 1700 V peak, and discharge voltages at discharge currents of 1500 A crest of about 1800 V peak. At 10,000 A crest, discharge voltage is about **2300** V peak.

(2) Two- and three-element devices, rate at about 650 V rms for application to either three phase delta circuits having one corner grounded (two element) or regular three phase application (three element). Spark-over voltage is about 2800 V peak and the discharge voltage is about 2600 V peak for a crest current of 1500 A; 4000 **V** at 10,000 A.

These secondary arresters will protect adequately the usual equipment operated on branch circuits. Unusual equipment of a delicate nature may require additional protection in the form of a carbon block protector fitted with a series, nonlinear element such as that shown in Fig. 2-30. This arrangement provides for protection at a lower voltage with prevention of excessive permanent shorting by the series inductances between the secondary arrester and the branch protector.

A conduit or metal tube enclosure for the wiring between the secondary arrester and branch protector results in a higher surge impedance than for wiring not so enclosed. If at least 20 ft of enclosed wiring exists, then operation of the secondary arrester is assured before excessive current is passed through the branch circuit protector. Occasionally the branch (circuit protector will permanently short under very high surge currents, resulting in operation of the branch fuse or circuit breaker unless subsidiary disconnect devices such as those in Fig. 2-30(1) are used. Practice dictates the use of an alarm system in the breaker to indicate that protection is lost.

2-3.10.5 Semiconductor Devices

Zener diodes can be used in solid state circuits to harden them against transients that may arise from lightning and similar disturbances.

Zener diodes are good voltage-limiting devices for low-voltage circuits. Inserted, like any gap device, between the circuit to be protected and ground, the diodes refuse to conduct in the reverse direction until a certain potential is reached. When this "zener" potential is reached, an avalanche breakdown occurs that allows conduction in the reverse direction. Zener voltages of available diodes range from less than 3 V io over 200 **V.** At potentials less than zener value, the diode has a very high resistance and may in most cases be considered an open circuit. The breakdown occurs nanoseconds after application of an overvoltage. most purposes the response time is so fast that the transient response and dc testing may be used to determine transient response. In this respect, as well as in its lower voltage range of operation, the solid state device is distinctly superior to either the gap or gas tube protectors.

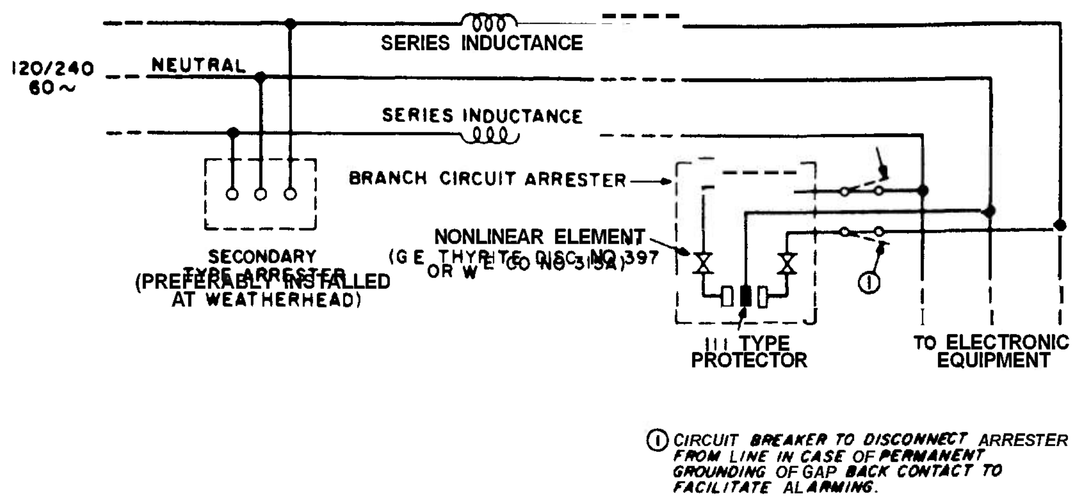


Fig. 2-30. Arrangement to Provide Low-voltage Branch Circuit Protection

The power dissipation capabilities of zener diodes cover a wide range, and precautions in their use are required. Western Electric has developed and used silicon zener diodes for protection for some time and has published data on a number of these devices (Table 2-5). Advances in zener diodes have been made at a very rapid rate and by now cover an even greater range of power dissipation and current capacity than those described in Table 2-5. Motorola, for example, claims power ratings of 20 kW for periods up to 0.1 msec for a Motorola MPZ5 transient suppressor (Ref. 35).

To use zener diodes effectively requires considerable knowledge of circuits, but basically the designer can provide circuit protection by specifying the minimum potential required for forward conduction (on the order of 1 V), and zener voltage for each diode that limits and regulates the reverse voltage. A diode connected directly across a circuit will, therefore, limit voltage to the minimum forward potential in one direction and the zener potential in the other direction. At potentials lower than these it will act as a relatively high impedance; however, the loading effect of the diode must be noted for the specific circuit in question. It should be observed that the capacitance of zener diodes decreases appreciably with the increase in magnitude of reverse voltage prior to breakdown. The voirage-current characteristics of the device are usually published by the manufacturer.

Power ratings of zener diodes need to be carefully considered too. These depend primarily upon the junction temperature of the diode. Junction temperature is influenced by the ambient temperature, the applied power, the duty cycle and the thermal time constant. These ratings are also given by the manufacturer.

For protection from the effects of lightning discharges, it is, of course, assumed that protection in the form of arresters and protectors is in effect before zener diodes can be expected to perform their protective function. If this kind of protection is offered, crest potentials as high as 600 V in a waveshape 10 X 600 psec may be expected. It will normally be necessary to limit power supplied to diode-protected devices by the use of series impedances, working with these assumed conditions. The effect of these series impedances must be considered in assessing the primary functions of the individual electronic system.

2-3.10.6 Fuses

Fuses are commonly used for circuit protection and are thoroughly discussed in a number of publications. They are usually metallic strips that heat, melt, and interrupt current flow before damage can occur in the protected circuit. They normally are not considered fast enough to provide protection from lightning surges; therefore, their use is not recommended for lightning protection.

2-3.10.7 Grounding

Grounding offers excellent protection from lightning as well as being useful for a number of other purposes, namely: interference suppression, improved performance of communication equipment, and personnel safety from shock hazards.

TABLE 2-5

INVERSE SURGE CURRENT-CARRYING ABILITY OF SILICON PROTECTION DIODES[21]

Type of Diode	W. E. Co. Code	*Dia of Junct., in	**Die Size	Average Breakdown Voltage, volts	Waveshape of Surge	Withstand Currents (Crest Amperes)		
						minimum	median	maximum
Alloy	420A	0.025		6.0	1-1/2 x 40	80.0	90	100
Alloy	420A	0.025		6.0	10 x 600	10.0	12	24
Alloy	F-51686	0.025		9.5	1-1/2 x 40	11.0	17	55
Alloy	F-51686	0.025		9.5	10 x 600	5.0	9	11
Alloy	420E	0.025		17.5	1-1/2 x 40	16.0	28	32
Alloy	420E	0.025		17.5	10 x 600	4.0	7	8
Alloy	420H	0.025		59.0	1-1/2 x 40	3.0	4	5
Alloy	420H	0.025		59.0	10 x 600	1.0	1	1.25
Diffused	†		0.045	8.0	10 x 600	10.0		
Diffused	†		0.125	17.0	1-1/2 x 40	170.		
Diffused	†		0.125	17.0	10 x 600	35.0	40	50
Diffused	†		0.045	38.0	1-1/2 x 40	20.0	22	24
Diffused	†		0.045	38.0	10 x 600	3.5	3.5	4
Diffused	F-51699		0.125	66.0	1-1/2 x 40	45.0	50	65
Diffused	F-51699		0.125	66.0	10 x 600	8.0	9	10
Diffused	1N670		0.045	72.0	10 x 600	1.5	1.6	2.0

Notes: * = Diameter of the effective circular junction of alloy types.

** = Side Dimension of the square wafer used in diffused types, in. Approximately entire wafer area is effective junction.

† = Experimental Units

It is important that all electrical equipment at any site be bonded to a common ground through a low resistance to avoid the establishment of large potential differences between any two objects. The result is that of voltage divider exposed to a constant current source. Unless the bonding resistance is very low, there are apt to be high potential differences between objects during a lightning strike to a point in the system. It was pointed out previously that because of the very high currents involved in lightning discharges, even what may be considered low resistance may cause high potential differences.

Earth itself is normally not a good conductor and connection to it becomes a considerable problem in some instances. The actual connection to earth is an important matter because lightning currents are returned to earth via this connection. It is usually necessary to make the contact area of this connection relatively large to make an effective connection through earth's relatively high resistivity.

Design formulas for various earth connections are shown in Table 2-6. The most generally used procedure involves a grid system in which long grounding rods (10, 15, or 20 ft) are driven into the earth at intervals along the structure being protected. A heavy cable is attached to the tip of the grounding rods, usually by a thermite type of reaction that bonds the rod to the cable. The tips of the grounding rods are usually located in a trench below the floor leve! of the building being protected and extension straps are welded to the rods or cables and brought through the building floor or wall Tor attachment to equipment and electrical machinery.

It will be noted that each of the equations for the resistance to earth in Table 2-6 contains the resistivity of the earth in the area of the installation. Usually, this information must be obtained by measuring; a method is illustrated in Fig. 2-31. Direct current is applied to the terminals A and Band the resultant potential drop is measured across a and b. These measurements make possible the determination of a mutual resistance $R_.$ When the electrodes are equally spaced and in a straight line, the resistivity may be expressed as:

$$\rho = 1.92\ R_m d_e \qquad (2\text{-}25)$$

where

ρ = resistivity, R-m
d_e = spacing of the electrodes, ft*
R_m = mutual resistance, R

* The spacing is expressed in feet because of the common difficulty experienced in obtaining tapes and chains that are cali brated in meters. The constant accounts for the change in units.

It is possible to estimate this resistivity from the condition of the soil that is being encountered in the area. Table 2-7 shows some of the values of resistivity that can be expected for various types of soils.

While combinations of the configurations shown in Table 2-6 may be used in the design of a grounding system, these are not directly additive. The net resistance of a grounding grid system will be somewhat less than the sum of the individual resistances of the connected system.

For radio frequency grounds, where the length of the lead to the ground rod is an appreciable portion of a wavelength, the ground impedance may appear considerably higher than the dc or low-frequency ac resistance of the grounding system. This increase in impedance is due to standing waves that may be generated on the conductors leading to the ground rod. Conversely, for short duration pulses, the ground impedance may appear smaller than that indicated by dc or low frequency ac measurements. This low impedance is due to a capacitive effect in the grounding system that results in displacement currents in the earth in addition to the conductive currents. The requirement for reduced impedance appears to be increased current as well as a short time duration. Reductions to 10 percent of the resistance measured at 60 Hz have been experienced.

The resistance of a grounding system can be checked using the same procedure outlined earlier, but with terminals a and A of Fig. 2-3 l connected to the system being measured, and band B spaced outward from the connection point. The resistance of the grid system to earth will be indicated by the value of R, obtained in this manner. The resistance of the grid system to earth is read directly on the instrument being used.

A number of factors influence the resistance of grounding grids to earth. Probably the most important is moisture in the earth–the greater the moisture, the lower the resistance. Seasonal changes affect the moisture content of the soil; hence, changes in the resistance of the grounding systems are observable. Grounding systems have been aided by salting of the area, thereby reducing the resistance of the system to earth.

No standard value of resistance to earth is available. Some authorities claim that building and structure grounds should have a resistance between 5 and 15 Ω (Ref. 31). In missile sites it would seem more reasonable to require a resistance of 1 Ω or less from the grid system to earth. Connections to the common grid system should differ no more than 0.1 Ω from one connection to another.

To illustrate what happens with an improperly connected ground system, consider the connections that

TABLE 2-6

FORMULAS FOR CALCULATION OF RESISTANCE TO GROUND[31]

	GEOMETRY	FORMULA*
	Hemisphere with radius a.	$R = \frac{\rho}{2\pi a}$
O	One ground rod with length L, radius a.	$R = \frac{\rho}{2\pi L}\left(\ln \frac{4L}{a} - 1\right)$
O O	Two ground rods with length L, spacing S.	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} - 1\right) + \frac{\rho}{4\pi S}\left(1 - \frac{L^2}{3S^2} + \frac{2L^4}{5S^4}\right)$
OO	Two ground rods with length L, spacing S.	$R = \frac{\rho}{4\pi L}\left(\ln \right. \quad 16L^2 \quad 512L^4$
—	Buried horizontal wire with length $2L$, depth $S/2$.	$R = \frac{\rho}{4\pi L}\left(\ln \frac{4L}{a} + \ln \frac{4L}{S} - 2 + \frac{S}{2L} - \frac{S^2}{16L^2} + \frac{S^4}{512L^4}\right)$
L	Right-angle turn of wire with length of arm L, depth $S/2$.	$R = \frac{\rho}{4\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{S} - 0.2373 + 0.2146 \frac{S}{L} + 0.1035 \frac{S^2}{L^2} - 0.0424 \frac{S^4}{L^4}\right)$
A	Three-point star length of arm L, depth $S/2$.	$R = \frac{\rho}{6\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{S} + 1071 - 0.209 \frac{S}{L} + 0.238 \frac{S^3}{L^3} - 0054 \frac{S^4}{L^4}\right)$
+	Four-point star length of arm L, depth $S/2$.	$R = \frac{\rho}{\ldots L_z}\left(\ln \frac{2L}{a} + \ln \frac{2L}{S} + 2.912 - 1.071 \frac{S}{L} + 0.645 \frac{S^2}{L3} - 0.145 \frac{S^4}{L^4}\right)$
✳	Six-point star length of arm L, depth $S/2$.	$R = \frac{\rho}{12\pi L}\left(\ln \frac{2L}{a} + \ln \frac{2L}{S} + 6.851 - 3.128 \frac{S}{L} + 1.758 \frac{S^2}{L^3}\right.$

*Approximate formulas including effects of images. Dimensions must be in centimeterE to give resistance in ohms.
In this table, ρ is resistivity of the surrounding soil, in ohm-cm.

Reprinted from Ref. 31. Used by permission.

TABLE 2-6

FORMULAS FOR CALCULATION OF RESISTANCE TO GROUND[31] (Cont.)

	GEOMETRY	FORMULA*
	Eight-point star length of arm L, depth $S/2$.	$R = \frac{\rho}{16\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{S} + 10.98 - 5.51\frac{S}{L} + 3.28\frac{S^3}{L^3} - 1.17\frac{S^4}{L^4}\right)$
O	Ring of wire with diameter of ring D, diameter of wire d, and depth $S/2$.	$R = \frac{\rho}{2\pi^2 D}\left(\ln\frac{8D}{d} + \ln\frac{4D}{S}\right)$
—	Buried horizontal strip with length 2L, section a by b, depth S/2, $b = a/8$.	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \ln\frac{4L}{S} - 1 + \frac{S}{2L} - \frac{S^2}{16L^2} + \frac{S^4}{512L^4}\right)$
	Buried horizontal round plate with radius a, depth $S/2$.	$R = \frac{\rho}{9a} + \frac{\rho}{4\pi S}\left(1 - \frac{7a^2}{12S^2} + \frac{33a^4}{40S^4}\ldots\right)$
	Buried vertical round plate with radius a, depth $S/2$.	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} \ln\frac{4L}{S} - 1 + \frac{S}{2L} - \frac{S^2}{16L^2} + \frac{S^4}{512L^4}\right)$

*Approximate formulas including effects of images. Dimensions must be in centimeters to give resistance in ohms.

In this table, ρ is resistivity of the surrounding soil, in ohm-cm.

are shown in Fig. 2-32. Here two ground rods have been placed in the earth, and connections have been made to an electroexplosive device. Rod 1 is connected to the case and rod 2 to the shorted leads. A lightning stroke of 100,000 A occurs at a distance $r_o = 500$ m from rod 2. Assuming the distance between rod 1 and rod 2 is 10 m and that the earth resistivity is 10^4 Ω-m we may compute the electric field in the earth or read the value from the graph of Fig. 2-22. The value of the field at rod 2 is approximately 2 kV/m. This value will not change appreciably in the 10 m from rod 1 to rod 2, and the shunting effect of the two rods and the EED load is assumed to be negligible. Under these circumstances the potential between the rods will be 2 kV/m × 10 m or 20 kV. Had both of the rods been connected together by means of a large cable, the effects of the ground gradient would have been very small.

While this example may seem obscure, incidences that simplify to this condition have actually happened in practice. In field situations, a single ground rod, in particular, is at times used for a weapon case ground and a second rod is used at a firing location some distance from the weapon. This situation is nearly identical to the simplified example.

2-4 ELECTROMAGNETIC PULSE (EMP)

In the event of a nuclear explosion, equipment must be safeguarded against the effects of the nuclear explosion environment. In addition to the phenomena of air

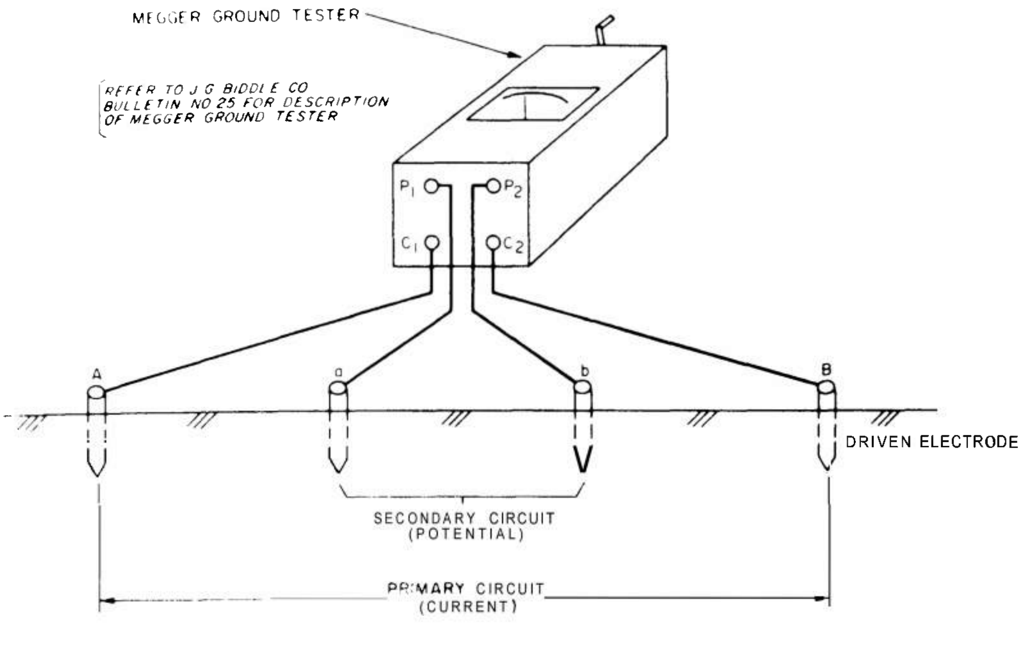


Fig. 2-31. Megger Ground Tester

TABLE 2-7

RANGE OF RESISTIVITY VALUES FORSEVERALTYPES OF SOILS

Physical Composition	Resistivity, Ω-m
Sea Water**	1-2
Marsh	2-3
Clay	3-160
Clay mixed with sand and gravel	10-1,350
Chalk	60-400
Shale	100-500
Sand	90-800
Sand and gravel	300-5,000
Rock (normal crystalline)	500-10,000

**Often used as a reference

blast, ground shock wave, thermal radiation, and nuclear radiation there also is an electromagnetic pulse of energy referred to as EMP. Critical electronic systems can be temporarily or permanently disabled by the electromagnetic pulse. Both the detailed frequency spectrum and the magnitude of EMP environments are classified information; however, if the design practices set forth in this handbook are followed for protection against RF energy, static electricity, and lightning; protection from EMP will be provided.

For the designer who must take into account nuclear weapons effects there are six handbooks: Engineering Design Handbooks AMCP 706-335 through-338 ***Design Engineers' Nuclear Effects Manual (DENEM),*** (SRD), a very comprehensive series of documents on nuclear weapons effects that addresses the practical problems of weapon system design; and two DASA handbooks of a more generalized, theoretical nature–***DASA EMP (Electromagnetic Pulse)*** Handbook DASA 2114-1 and classified supplement 2114-2, and ***DASA TREE (Transient Radiation Effects on Electronics)*** Handbook DASA 1420 and classified supplement 1420-1.

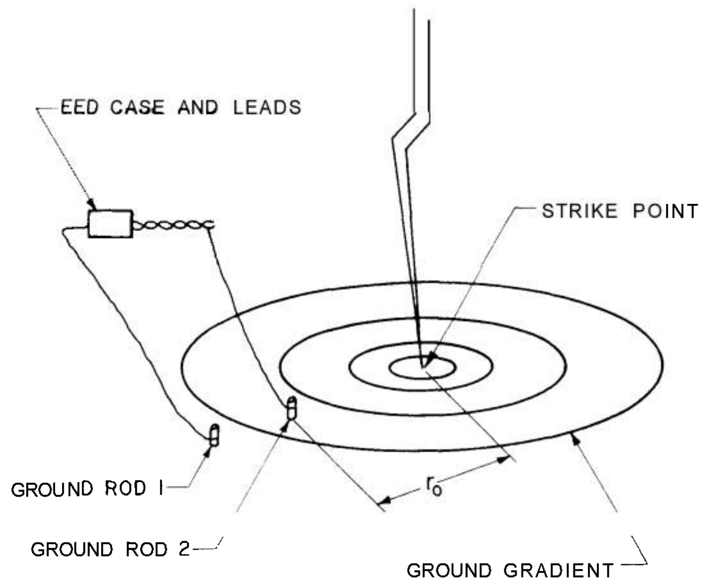


Fig. 2-32. Earth Radial Field Producing Pins-to-case Hazard as a Result of Improper Grounding Procedures

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CHAPTER 3

CONCEPTS FOR HARDENING WEAPON SYSTEMS AGAINST RF ENERGY, LIGHTNING, AND STATIC ELECTRICITY

3-1 GENERAL

The weapon system designer can correctly apply the general concepts for hardening against Electromagnetic Radiation (EMR) only if he understands the basis of the concepts. A lack of such understanding leads to the blind application of approximations in circumstances where they are not valid. The use of approximations in weapon system EMR hardening is, however, unavoidable; therefore, the designer must be aware of the areas of uncertainty.

Information on RF susceptibility and static electricity sensitivity of certain common weapon system components (particularly in guidance, telemetry equipment, fuzes, and electroexplosive devices) has accumulated to a point where the designers can and should consider susceptibility data in selecting these components but, in general, little is known about the susceptibility of the bulk of typical weapon system components. As a result, RF protection is usually a "hardening" rather than a component selection task; most components are selected for characteristics other than their RF invulnerability.

RF hardening of a weapon system simply consists of decoupling the weapon components from the external electromagnetic environment. The electromagnetic environment criteria for the individual weapon system are described in the weapon system's Qualitative Materiel Requirements (QMR) and Technical Characteristics (TC).

In classical electromagnetic theory the two methods of reducing to zero the electromagnetic field components due to a single source, measured at some given point in space, are: (1) enclose either the receiving point or the radiating source inside a perfect electric or magnetic conductor, or (2) remove the source of radiation *to* an infinite distance. Both methods are used for protection against EMR; however, reducing the electromagnetic field *to* zero is not possible with practical methods. Generally, some level other than zero must be specified so that individual components of the weapon system can endure without impairing mission or safety objectives.

In general, the high frequency response of typical weapon system components under operating conditions is not well known. For example, the response of typical integrated circuit logic, high gain servo loops, individual transistors, diodes, etc., to high frequency stimuli applied in various ways to the components or subsystems is, in many cases, completely undefined. The amount of hardening or decoupling necessary to ensure that the weapon system will survive in the specified external electromagnetic environment is, therefore, not known. In practice the weapon system is hardened until the amount of coupling seems so low that the probability of malfunction is low.

The general problem of predicting the amount of hardening necessary can be illustrated by considering a weapon system immersed in a known multisource electrical environment. If the physical environment and the weapon system itself were completely specified, then we could predict the stimuli delivered to any component-due to the external environment–by solving an electromagnetic boundary problem.

The classical boundary value problem can be stated as follows: *Given the location, shape, size, and electrical parameters of every object in space, find the electric and magnetic fields everywhere in space for all times due to an electromagnetic source current that is completely described in terms of its spatial and time dependence.*

Patently, it is not that easy. Exact solution of such problems, even with relatively simple geometric shapes for both boundaries and sources, is extremely difficult. Progress is being made by computer approximation to solutions (Ref. 1), but even here the boundaries are relatively simple geometrically. The *exact* solution of the boundary value problem involving the components of a modern weapon system and a typical external electromagnetic environment is decidedly beyond economic solution. Further, every change made in either the weapon system or the external electromagnetic environment would require a new solution; and each new solution would be on the same order of complexity as the previous one. This, plus the fact that the external electromagnetic environment will probably be an unknown due to differing sources and external bodies, indicates that there is no hope for an exact solution to the general problem, even in greatly simplified cases.

The electromagnetic current source mentioned in the statement of the general boundary value problem is, in essence, any source and in consequence assumes different aspects in different problems. For instance, in one problem the source may be a known electrical current at some place in space; in another problem it may be equated with a known electromagnetic field in some portion of space. In this latter case, the source can be treated equivalently by considering related electrical and magnetic surface currents over the volume in which the electromagnetic field is known. The magnetic surface currents cannot, it is presently believed, exist but are convenient to assume for analytical purposes. This concept of the source as a known electromagnetic field in space is the one usually used in hardening evaluation. The electromagnetic field in which the weapon system is required to survive is assumed to impinge upon the weapon system. This is equivalent to assuming that this required field is the only significant field that originates far away from the weapon system.

It has been found *experimentally* that the solutions to these problems–for objects that are large enough to be described by bulk or average electrical parameters (permittivity, permeability, and conductivity)–always satisfy the set of partial differential equations proposed by J. *C.* Maxwell; hence, the analytic approach to the general boundary value problem is to seek a solution that satisfies Maxwell's equations and the given conditions.

Historically, the solutions of electromagnetic problems were first obtained at frequencies such that the objects involved were much smaller than the wavelength of the source frequencies. These solutions satisfied what are today called Kirchhoff's Law and are the basis of modern circuit theory. Methods of analysis of electrically long uniform structures evolved from circuit theory and developed into modern transmission line theory. At this point it was recognized that the assumptions of the circuit and transmission line theories were specializations of, or approximations to, Maxwell's equations. The very large body of knowledge, experience, and methods that makes up circuit and transmission line theory is almost universally used in the solution of complex electromagnetic problems. The analyst usually reduces the complicated electromagnetic field problem to a point where circuit or transmission line theory can be applied. The analytic solution of all the technical problems in electrical engineering can be considered as solutions to a general boundary value problem.

Practical methods for solving boundary value problems lean heavily on several approximations. First in importance is the assumption that all matter involved in the problem is such that the electrical and magnetic parameters (permittivity, permeability, and conductivity) of the matter do not depend upon the magnitude or polarity of the electromagnetic fields in the matter. This approximation is often stated more stringently so that the electrical parameters of the matter are also independent of time. This is equivalent to saying that the parameters are constants at any one frequency. This approximation is usually an excellent one for the ranges of electromagnetic fields and materials normally encountered in weapon systems. Materials that are prime examples of elements that are not linear are magnetic materials, rectifying elements (such as semiconductor junctions or point contact diodes), and bolometer elements.

The linearity assumption is usually justified, in most practical problems, since the number of elements exhibiting nonlinear behavior is quite small in relation to the total number of elements in the overall weapon system; hence, the amount of energy "scattered" in a nonlinear element is small and will not seriously change the overall linear behavior of the fields except in regions quite close to the nonlinear elements. For example, when a missile is weakly irradiated by a remote transmitter, there is no reason to expect the electromagnetic fields existing in the volume between a missile's skin and its internal "black boxes" to exhibit any nonlinear behavior due to the presence of conventional electronic circuits containing transistors in the black boxes. In contrast, the effect of an extremely intense nearby magnetic field source on a weapon system containing large quantities of steel, which could be driven into saturation by the high magnetic fields, might very well be nonlinear.

If it is assumed that all materials involved in a weapon system are linear, then the solution of the problem will be a linear solution, making it possible merely to add separate responses due to separate sources to obtain the system's total response to the several sources. The linearity of the problem also allows the use of the many sophisticated transient analysis techniques which would seem to be very valuable. However, the sources (and the conditions of the whole problem in general) are usually so ill defined that Fourier and Laplace transforms in relation to time cannot be used to much advantage.

Other approximations can be used for particular types of matter. Metals are usually assumed to be perfect electrical conductors in their effect on external fields. Air and common dielectrics are assumed to be completely lossless.

Even with these assumptions the complex geometry of a typical weapon system and its environment preclude a simple solution to the practical problem of predicting the amount of RF energy a given system component will pick up. Solutions can be adapted from much simpler geometries, however. The most commonly used method is to separate the overall problem into several simplified sections. As an example, this approach would divide the complex problem of a weapon system hardening prediction into the several sections shown in Fig. 3-1(A), **(B),** and (C). The portion shown in Fig. 3-1(C) is actually an approximation to the more complicated problem shown in Fig. 3-1(D). The validity of a division approach, of course, depends upon the degree to which the sections resemble the actual problem. Often the individual section can be treated by some "worst case" method which yields valuable RF protection information irrespective of the variables that relate one portion of the overall problem to another. Results of this type are among the most definitive obtainable in complicated electromagnetic problems. Varying the physical components that represent the weapon system in each of these individual problems, such that overall field levels are reduced, corresponds to a method of protection of the missile system components.

The example shown in Fig. 3-1 reflects one method of specifying the overall problem and also indirectly illustrates methods used to protect weapon systems.

Fig. 3-1(A) illustrates the simplest operational method of protecting a weapon system, i.e., maintaining large distances between potential sources of RF energy and the weapon system. Fig. 3-1(B) illustrates the concept of shielding by the interposition of a metallic structure between the incident field and the volume of space in which a reduced field is desired. The model antenna (Fig. 3-1(C)), if the component to be protected and its associated circuitry are properly designed, can form a very poor receiving antenna. Another method is to insert an RF suppression device in cascade with the component to be protected, which will lower any expected stimulus to a tolerable level. A general discussion of these three methods follows; a specific discussion of each and their application to weapon system protection is given in Chapter 4, Design 'Techniques.

3-2 SEPARATION

In free space, at distances large in relation to both the physical dimensions of the source and the wavelength of the source frequency, the magnitudes of both the electric and magnetic fields vary inversely with distance, and the power density of the entire electromagnetic field varies inversely with the square of the distance. In actual practice these variations are complicated by the effects of the material (environment. At large distances, departure from the free space variation can be looked upon as due to either reflections or a guiding property of the environment. Guiding is usually considered as a variation due to the shape of the terrain or the presence of a reflecting layer in the ionosphere. At the higher frequencies, such as those used by search radars, departures from inverse square power variation can almost always be attributed to reflections. Departures at the communication frequencies, in contrast, are usually considered as due to guiding properties of the environment.

In actual practice, the designer does not have any control over the separation between the system and the source of EMR; therefore, he must base his calculations on the electromagnetic field in which his weapon system is required to survive. The required survivable field is usually classified information and can be determined by the designer by examination of the weapon system's Qualitative Materiel Requirements and Technical Characteristics.

There is a great amount of similarity between the overall hardening problem (EMC), and the RFI/EMI and personnel hazard problems. The RFI/EMI specifications (see Fig. 3-2) (Ref. 2) require measurements in electromagnetic fields of no more than 10 V/m. A personnel hazard level of 195 V/m (Ref. 3) (100 W/m^2) has been accepted by the military and, for many manned weapon systems, is often appropriate as a design goal for hardening.

3-3 SHIELDING

Shielding as a concept for protection of weapon systems usually refers to the interposition of a metallic

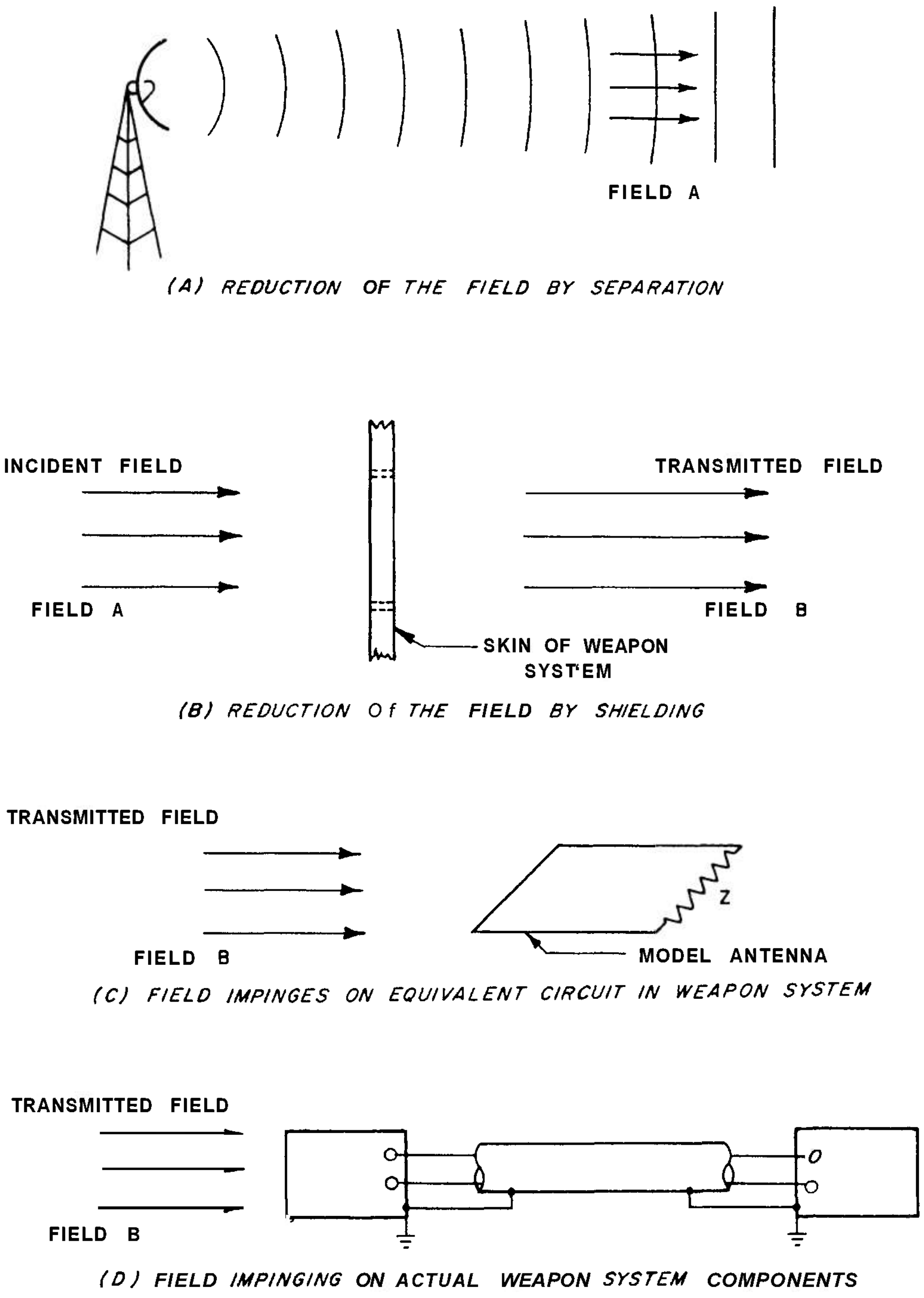


Fig. 3-1. A Common Division of the Overall Problem

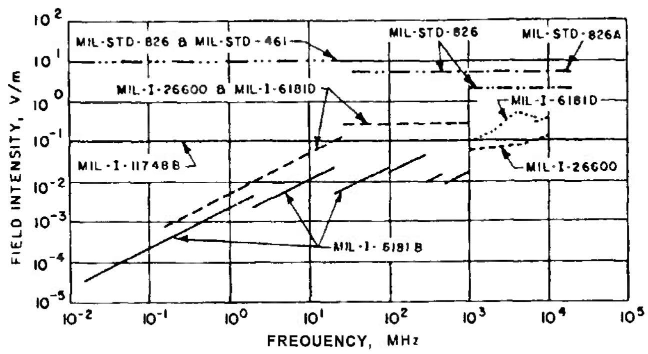


Fig. 3-2. RF Radiated Susceptibility Limits[2]
Reprinted from Electronic Engineer, Chilton Co. July 1968, by permission.

structure between the source of the electromagnetic energy and the items to be protected. For solid metal shields that completely enclose the items to be protected, the protection provided by the shield can be conveniently broken down into a loss due to energy reflected and a loss due to energy absorption.

The division of the total loss into these components becomes rather indistinct for shields that are not solid or do not completely enclose the items to be protected; however, reflection losses can loosely be considered as that energy radiated back toward the source by currents induced in the shielding material. High reflection loss, therefore, requires materials in which currents can easily be induced. Solid metals of high conductivity are ideal for this application but other common shielding materials are often used as compromises–such as metal screens, meshes, and braids. Also, considerable shielding can be obtained purely by the construction of support members and by "black box" housings.

The preferred method of shielding encloses the entire system to be protected inside a seamless metal shield. Fig. 3-3 shows a sketch of the development of such a system. The practical problems of shielding development are mainly concerned with the joints, seams, and connectors necessary in practical implementation of the complete enclosure of the system to be protected.

3-4 ELECTRICAL CIRCUIT CHARACTERISTICS

The electrical and physical characteristics of the electrical circuits which are associated with the items to be protected influence both the amount of energy received by the circuit and its distribution among the various items to be protected. The designer's task is to make the circuit a very inefficient antenna.

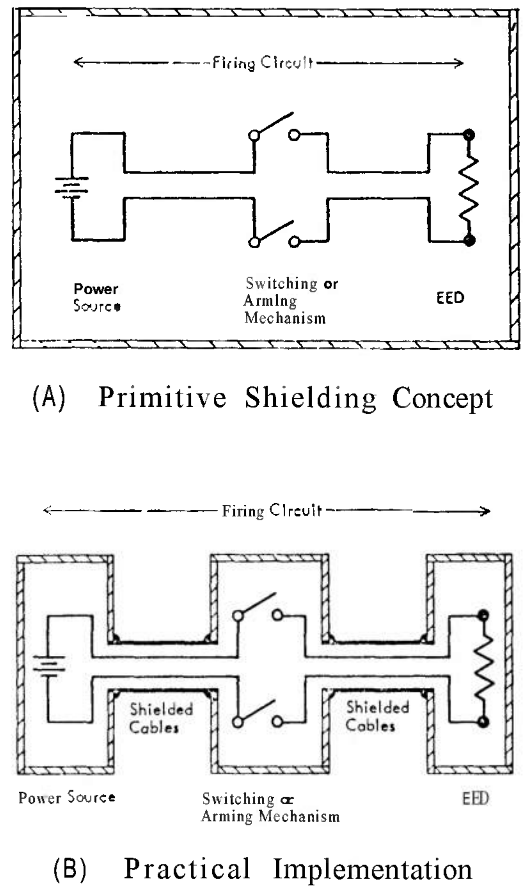


Fig. 3-3. The Conductive Box Concept

Circuits that are composed of unshielded wires can often be treated as linear antennas, and upper limits can be set on the amount of energy that they can extract from a given incident field over large portions of the frequency spectrum. Design concepts can be developed from this treatment such that the maximum energy extracted from the field is minimized. Often techniques of this type result in various electrical and mechanical design guides such as balanced circuits, twisted pair wiring, etc. These protection techniques are dictated by analysis that usually cover only part of the frequency band that may be of concern for weapon system protection; hence, if a wide frequency band is of concern, there can be some confusion as to which techniques should be used.

3-5 DIRECT PROTECTION OF COMPONENTS

Once a system has been designed, modification is usually expensive. In this case, or occasionally as a trade-off in original design, and in cases where it is not possible or feasible to evaluate the effectiveness of other protection techniques, components can be protected by adding special protection devices to the system. These must function over the entire frequency range to which the item it protects will be exposed. Further, it should not interfere with the normal operation of the circuit. The magnitude of protection afforded is difficult to ascertain since the equivalent generator and load impedances at the point at which the protective device is to be inserted almost never are known as a function of frequency. In addition, the device must usually provide protection in both balanced and unbalanced modes of excitation.

As a result of these many unknowns and complexities, several parameters which purportedly describe the protection provided by the protective device cannot be relied upon under actual operating conditions. There are, however, ways of specifying the attenuation of the protective device such that it will, in all situations, have the minimum attenuation specified. A thorough examination of the protective parameters that are quoted for a protective device is recommended before procurement. This is discussed in detail in par. 4-4.

In general, the direct protection of components includes the selection of nonsensitive components. In the case of new design that must utilize highly sensitive components, direct protection using cascaded protective devices should always be considered.

REFERENCES

1. C. L. Frederick et al., ***Digital Computer Program for Determining the Effect of High-Level RF Exposure on Missile Systems,*** Report No, RE-TR-66-10, Vitro Laboratories, Silver Spring, Maryland, May 1966.
2. C. B. Pearlston, "What is Wrong With EMI Specifications", The Electronic Engineer **27,** 66 (1968).
3. MIL-I-6181D, ***Interference Control Requirements, Aircraft Equipment,*** *25* November 1959, p. 14.

CHAPTER 4

DESIGN TECHNIQUES

This chapter covers the principal protection concepts and their applications to practical design problems. The overall protection concepts treated are:

1. Shielding
2. Electrical circuit characteristics
3. Direct protection **of** components

4-1 SHIELDING

4-1.1 SHIELDING EFFECTIVENESS

An ideal shield completely surrounds the volume it protects with a solid metal covering having no openings, joints, or other discontinuities. In general, such a structure is negated by other design requirements. The joints and openings in the metal of the shield are, in almost all cases, the main source of electromagnetic leakage into the shielded volume. The effectiveness of a closed solid metal shield in excluding electromagnetic energy from the interior items depends upon:

1. Conductivity G_R of the metal shield in relation to copper
2. Permeability μ_R of the metal shield in relation to free space
3. Thickness of the shield
4. Geometry of the shield
5. Contents and their position inside the shield
6. Wave impedance of the electromagnetic radiation incident on the shield at every point of the shield
7. Frequency of the incident radiation

The effectiveness of shields that have joints, breaks, holes, penetrations, perforations, or other types of discontinuities depends–in addition to the parameters previously cited–very heavily on the type and dimensions of the discontinuity.

Much effort has been expended in the past to determine by analysis the effectiveness of solid metal shields. Appendix A of this handbook covers some of this work in detail, and gives graphs and nomographs of the results obtained by these techniques. These methods, however, are based on the assumption that the interior of the shielded volume is infinite in extent so that energy entering the volume is never reflected or perturbed. This assumption is of paramount importance in the formulation of the classical shielding effectiveness analyses. It rests on a power ratio to be written as the square of the magnitude of the ratio of two electric or two magnetic field strengths since it allows both field strengths to be theoretically associated with waves of precisely the same impedance. The conservation of power must be the basis of any evaluation of shielding effectiveness and, since the classical methods of evaluating shielding effectiveness provide only field strength information, the assumption of no reflections inside the shielded volume (which is equivalent to assuming that the impedance of the measurement point does not change if it is enclosed in a complete metal shield) is critical to the validity of the shielding effectiveness predicted by these classical methods.

The closed metal shields used in weapon system design, ignoring the very complex equipment usually enclosed by these shields, quite clearly modify the impedance conditions assumed in the classical evaluation. If the assumptions of the classical shielding effectiveness evaluation were satisfied, the shielding effectiveness ratio so derived would relate, in dB, the power density incident on the shield to the power density immediately inside the shield. For weapon system shields, and almost all other practical applications of shielding for that matter, the classical shielding effectiveness does not correctly relate the power densities. Furthermore, the results so obtained may be greater than, equal to, or less than the actual values. In general, the results normally predict a power density inside the shielded volume which is much lower than the actual value.

Since the actual shielding effectiveness of a shield depends heavily upon the geometry of the shield and, more important perhaps, on what the shield contains and its position, it would seem important to determine this dependence. However, this problem is equivalent to determining the impedance looking into the shielding volume (from the inner surface of the shield) at every point on the shield. Considering that the shielded volume will be full of complex metal structures which affect theoretical propagation modes and cavity resonances, this effort is decidedly beyond economic solution either analytically or experimentally.

It is recommended that the shielding designer read Appendix A if he desires to become more familiar with the basic approaches, definitions, and techniques of shielding analysis. He can, however, utilize the information given in this chapter to evaluate the performance of weapon system shields.

Although the impedance looking into the shielded volume is unknown, the effectiveness of the shield can be evaluated in a conservative manner for most practical shielding problems by assuming that the region internal to the shielded volume always presents an impedance equal to the complex conjugate of the shield impedance to every point in the inner surface of the shield. This procedure results in a shielding effectiveness parameter C defined as

$$C = T_p + A - 3 \qquad (4\text{-}1)$$

where

C = ratio of the power density incident on the shield to the maximum power density that can exist, irrespective of the contents or its geometry, immediately inside the shielded volume, dB

T_p = power transmission loss of the power density incident on the shield to the power density in the shield, dB

A = absorption loss; i.e., actual dissipation of energy as heat of the shield and is identical to that from the classical shielding effectiveness calculations, dB

The parameter C is directly applicable only to solid, closed metal shields but has indirect application to perforated or leaky shields. This conservative loss parameter can be counted on to predict a conservative estimate of protection provided by the shield if the absorption factor A is 10 dB or greater.

Another limitation of the parameter C, or for that matter any shielding parameter, is its dependence on the value of relative permeability μ_R. The values of relative permeability for magnetic materials is, in general, not well known above 150 kHz, and the shielding designer is thus without pertinent information for a large part of the frequency range to be considered. A conservative approach is to use published values of permeability and assume that μ_R has the value of one when there is no published value.

Another problem involved with permeability evaluation is that of saturation. The values of the relative permeability of magnetic materials is a function of the magnetic field strength in the material. Normally, only the small signal value of μ_R is quoted in the literature.

If the shield is to be exposed to very high magnetic fields, the incremental value μ_R will instantaneously vary from the small signal value to some much lower value. This results in harmonic generation in the field and, so it is thought, in a lower shielding effectiveness. Very little is presently known about large signal shielding effectiveness of magnetic materials.

4-1.1.1 Loss Mechanisms

The ratio of the power density incident on a shield, that is terminated in the complex conjugate of its own intrinsic impedance, to the power density into the matching impedance can be written as†

$$\frac{PD_i}{PD_s} = \left(1 - \left|\frac{Z_s - Z_w^*}{Z_s - Z_w}\right|^2\right)^{-1} \frac{e^{2\alpha x}}{2} \qquad (4\text{-}2)$$

where

PD_i = incident power density, W/m^2

PD_s = maximum power density into the shielded volume, W/m^2

α = attenuation constant of the shield, mil^{-1}

x = thickness of the shield, mil

Z_s = intrinsic impedance of the shield, Ω

Z_w = incident wave impedance, Ω

Z_w^* = complex conjugate of Z_w, Ω

The vertical lines in the equation denote magnitude of the enclosed complex quantity.

Eq. 4-2 assumes that the absorption loss of the shield is high enough so that the input impedance to the shield

†A list of symbols with a brief definition is presented at the beginning of handbook.

is the intrinsic impedance of the shield and not an impedance dependent on the conjugate impedance terminating the shield.

The exponential term of **Eq. 4-2** is a function of the above shield parameters and can be associated with the power absorption, by heat, of the shield. The remaining term in Eq. 4-2 is a function of the incident wave impedance and the shield's intrinsic impedance. This term can be associated with the transmission or reflection of power at the incident wave/shield interface. We will call this the transmission loss and will associate T_p a dB ratio, with this loss. The factor of 2 in Eq. 4-2 is the result of assuming a complex conjugate rather than an intrinsic impedance termination for the shield.

Parameter C as given in Eq. **4-1** can also be written as ten times the logarithm to the base ten of **Eq.** 4-2. Thus

$$C = A + T_p - 3 = 10 \log \left[\frac{e^{2\alpha x}}{2} \left(1 - \left| \frac{Z_s - Z_w^*}{Z_s + Z_w} \right|^2 \right)^{-1} \right] \quad (4\text{-}3)$$

therefore,

$$A = 10 \log e^{2\alpha w} - 10 \log 2 = -3 \quad (4\text{-}4)$$

and

$$T_p = 10 \log \left(1 - \left| \frac{Z_s - Z_w^*}{Z_s + Z_w} \right|^2 \right)^{-1} \quad (4\text{-}5)$$

Eq. **4-5** can be simplified to

$$T_p = 10 \log \left(\frac{|Z_s + Z_w^*|}{4 Re\{Z_s\} \; Re\{Z_w\}} \right) \quad (4\text{-}6)$$

where

Re $\{Z_s\}$ is read "the real part of Z_s."

The parameter C is a function of the shield's thickness, conductivity, and permeability, as well as of the frequency and incident wave impedance. Parameter C is directly applicable only to closed metal shields. It will predict a conservative estimate of protection provided by the shield if the absorption loss A is **10** dB or greater. The conditions for A to be **10** dB or more reduce to

$$f_{MHz} \; G_R \; x^2 \; \mu_R > 8.95$$

where

x = shield thickness, mil
f_{MHz} = frequency, MHz
G_R = relative conducitivity, mhos
μ_R = permeability of metal shield in relation to free space

For example, a 20-mil copper shield would have 10 dB of absorption loss for all frequencies greater than 22.2 kHz and the parameter C would thus be applicable above this frequency.

It is recommended that the shielding designer provide at least 10 dB absorption loss over the frequency range of interest. Analysis of cases where the 10 dB criterion is not met are possible but are beyond the scope of this handbook.

4-1.1.1.1 Transmission Loss

The shield/source transmission loss T_p is defined as the ratio in dB of the power density incident on the interface to the power density at the interface, assuming that the input impedance of the shield is the same as the shield's characteristic impedance. The calculation of this **loss** is based on the assumption that the shield has 10 dB or more absorption loss *A*.

T_p, as shown in Eq. **4-5,** can be written as

$$T_p = 10 \log \left(1 - |\rho_p|^2 \right)^{-1} \quad (4\text{-}7)$$

where

$$\rho_p = \frac{Z_s - Z_w^*}{Z_s + Z_w} \quad (4\text{-}8)$$

is the power reflection coefficient.

The quantity ρ_p as defined is similar to the normal definition of reflection coefficient as defined **in** transmission line theory. The exception **is** the complex conjugate term Z_w^* which in normal transmission line theory would not be conjugated. The conjugation of this term, however, allows for the consideration of complex incident wave impedances.

Computation of T_p can be simplified by rewriting **Eq.** 4-8 in the form shown in **Eq.** 4-6.

$$T_p = 10 \log \left\{ \frac{|Z_s + Z_w|^2}{4 \mathrm{Re}\{Z_s\} \; Re\{Z_w\}} \right\} \quad (4\text{-}9)$$

The characteristic impedance of a solid metal shield is (from Appendix A)

$$Z_s = (1 + j) \sqrt{\frac{\mu_R \, f_{MHz}}{G_R}} \times 2.61 \times 10^{-4} \quad (4\text{-}10)$$

The wave impedances considered important by the classical evaluation techniques are:

1. Z_o = **377** R, the free space wave impedance

2. Z_r, the radial wave impedance of a small loop antenna when the loop dimensions are much smaller than either the wavelength being radiated or the distance to the point where the impedance is evaluated

3. Z_d, the radial wave impedance of a small dipole when the dipoles' dimensions satisfy the same conditions as those given for the small loop.

At a distance of 1 ft and for frequencies below 100 MHz the expressions for these impedances can be written as

$$Z_r \cong 0.62 \times 10^{-6} f^4_{MHz} + j2.4 f_{MHz} \qquad (4\text{-}11)$$

$$Z_d \cong 0.0153 f^2_{MHz} - j\left(\frac{0.059 \times 10^6}{f_{MHz}}\right) \qquad (4\text{-}12)$$

Table **4-**1 gives T_p for the above three wave impedances and Table **4-2** compares the transmission loss of any shield for frequencies up to 100 MHz.

A study of Table **4-2** shows that T_p for the free space wave impedance is always less than the highly reactive wave impedances of the small dipole and small loop when the latter two wave impedances are evaluated **1** ft from the source and the frequency **is** below 100 MHz. **A** more detailed study of the values of T_p for higher frequencies and other distances from the dipole and loop sources shows that, for practical weapon system protection, use of T_p evaluated with a free space incident wave impedance gives a conservative loss estimate.

Fig. 4-1 plots the calculated values of T_p for a 377 Ω wave impedance as a function of frequency. Note that the ordinate is $T_p + 10 \log\sqrt{\mu_R / G_R}$. To use the figure for a shield characterized by a given value of μ_R and G_R, calculate

$$\zeta = 10 \log\sqrt{\frac{\mu_R}{G_R}} = 5 \log \frac{\mu_R}{G_R} \qquad (4\text{-}13)$$

Now, at the frequency of interest, find where the frequency intersects the curve and read the ordinate value. Then subtract ζ from the ordinate value of **Fig. 4-1.**

TABLE 4-1

T_p FORMULAS

Wave Impedance, ohms	T_p, dB
Free Space Z_o = 377	$55.58 - 10 \log\sqrt{\dfrac{\mu_R f_{MHz}}{G_R}}$
Small Dipole at 12 in $f_{MHz} < 100$	$143.38 - 10 \log\sqrt{\dfrac{\mu_R f_{MHz}}{G_R}} - 10 \log f^4_{MHz}$
Small Loop at 12 in $f_{MHz} < 100$	$99.5 - 10 \log\sqrt{\dfrac{\mu_R f_{MHz}}{G_R}} - 10 \log f^2_{MHz}$

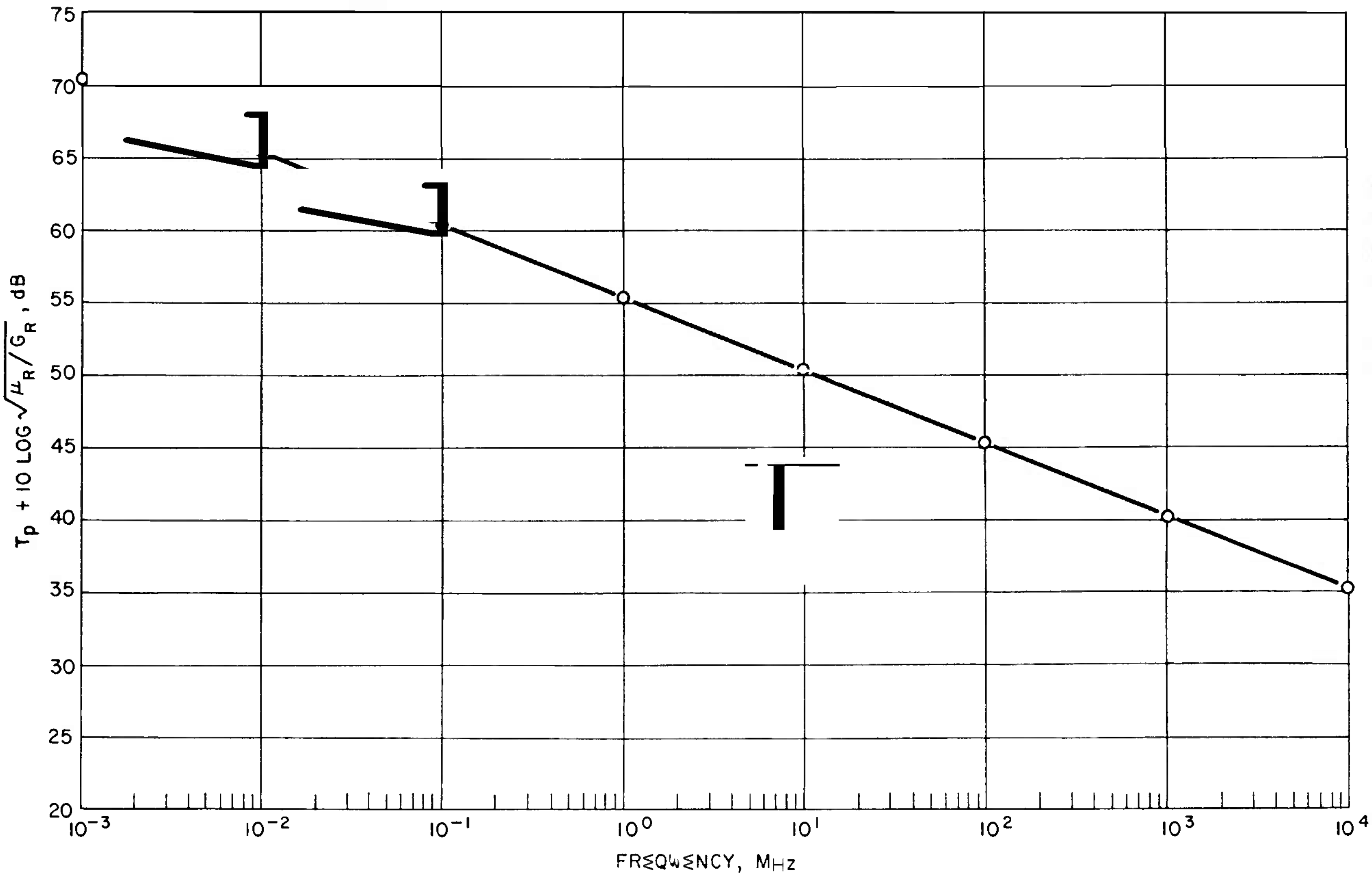


Fig. 4-1. Transmission Loss T_p for a Solid Metal Shield Irradiated by a Wave of 377-ohm Impedance

TABLE 4-2

COMPARISON OF TRANSMISSION LOSS FOR ANY SHIELD FOR THE COMMON WAVE IMPEDANCES

f_{MHz}	$T_p + 5 \log \left[\frac{\mu_R}{G_R} \right]$ in dB		
	$Z_w' = 377$ ohms	$Z_w = Z_d$	$Z_w = Z_\ell$
100	45.48	49.5	53.38
10	50.58	74.5	98.38
1	55.58	99.5	143.38
0.1	60.58	124.5	188.38
0.01	65.58	149.5	233.38
0.001	70.58	174.5	274.38

The result is T_p for the given shield when a free space incident wave impedance has been assumed.

Values of G_R and μ_R for various metals are given in Table 4-3. The μ_R values are quoted at 150 kHz.

4-1.1.1.2 Absorption Loss

The absorption loss A in dB is the ratio of power density into a solid shield to the power density out of the complex conjugate impedance matched shield at the shield's interior surface; thus

$$A = 10 \log e^{2\alpha x} = 3.34 x \sqrt{G_R \, \mu_R \, f_{MHz}} \quad (4\text{-}14)$$

where x is the shield thickness in mils.

Fig. 4-2 plots A for a 1-mil copper shield (i.e., $\mu_R = 1$, $G_R = 1$) as a function of frequency. Any other shield thickness can be evaluated by multiplying the ordinate of Fig. 4-2 by $x_1 \sqrt{\mu_{R_1} G_{R_1}}$, where the subscript 1 refers to the material of the shield in question. Thus for a 20-mil aluminum shield

$$x_{aluminum} = x_1 = 20$$

$$G_{R_{aluminum}} = G_{R_1} = 0.61$$

$$\mu_{R_{aluminum}} = \mu_{R_1} = 1$$

$$\therefore x_1 \sqrt{\mu_{R_1} G_{R_1}} = 15.6$$

The ordinate values of Fig. 4-2 would be multiplied by 15.6 *to* obtain the absorption loss for the 20-mil aluminum shield.

The absorption loss A can also be found easily from the nomograph given in Fig. 4-3. A straightedge should be positioned between the $\mu_R G_R$ product of the shield of interest on the lefthand scale and the frequency of concern on the righthand scale. The intersection of the straightedge and the center scale then gives A, the absorption loss in dB/mil directly.

In general, the solid shields used in weapon system protection will provide absorption losses greater than 10 dB until quite low frequencies are approached. That is, an absorption loss of 10 dB is assured if

$$f_{MHz} \, x^2 \, G_R \, \mu_R \geq 8.95 \quad (4\text{-}15)$$

Table 4-3, in addition to listing the μ_R and G_R values of various metals at 150 kHz, also gives absorption loss A at this frequency in dB/mil. The G_R values are, as far as presently known, applicable for all frequencies below those of visible light.

4-1.1.1.3 Total Loss

The conservative loss parameter as given in Eq. 4-1

$$C = T_p + A - 3$$

TABLE 4-3

ABSORPTION LOSS OF METALS AT 150 kHz

Metal	Relative Conductivity, G_R	Relative Permeability, μ_R	Absorption Loss, dB/mil
Silver	1.05	1	1.32
Copper, annealed	1.00	1	1.29
Copper, hard drawn	0.97	1	1.26
Gold	0.70	1	1.08
Aluminum	0.61	1	1.01
Magnesium	0.38	1	0.79
Zinc	0.29	1	0.70
Brass	0.26	1	0.66
Cadmium	0.23	1	0.62
Nickel	0.20	1	0.58
Phosphor-bronze	0.18	1	0.55
Iron	0.17	1,000	16.9
Tin	0.15	1	0.50
Steel, SAE 1045	0.10	1,000	12.9
Beryllium	0.10	1	0.41
Lead	0.08	1	0.36
Hypernick	0.06	80,000	88.5*
Monel	0.04	1	0.26
Mu-Metal	0.03	80,000	63.2*
Permalloy	0.03	80,000	63.2*
Steel, 18-8 Stainless	0.02	1,000	5.7

*Obtainable only if the incident field does not saturate the metal

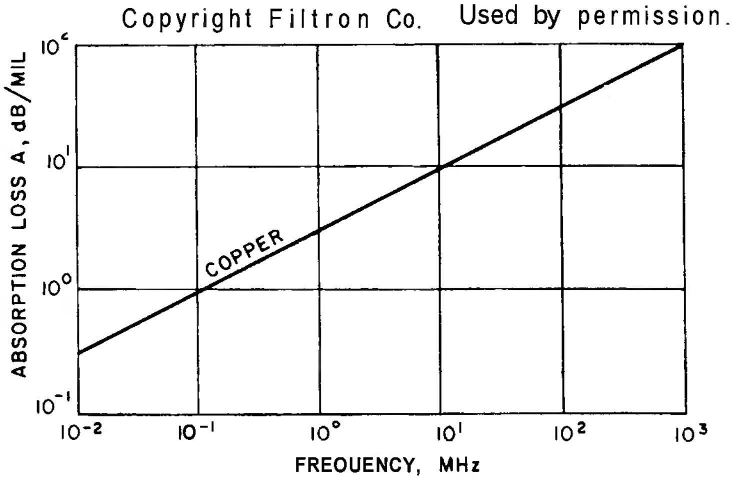


Fig. 4-2. Absorption Loss for Copper vs Frequency

T_p and A are calculated as described in the previous paragraphs. The parameter C can be used in two ways to facilitate the evaluation of weapon systems protection. First, it can compare the effectiveness of arbitrary solid shields against each other; second, it can evaluate the effectiveness of a particular shield in a particular weapon system/electromagnetic environment.

The first usage is straightforward. Plot C for the given environment for both shields and compare the results. The object of the second usage is to actually predict a margin of safety for the components inside the solid shield. The parameter C relates maximum power density immediately inside the shield to the incident power density. If the designer determines C for the chosen shield in the electrical environment the system is required to safely endure, then the total power W that can be transferred to the shielded volume can be easily calculated by multiplying the incident power density W/m^2 times the surface area of the shield m^2 and reducing the product by the amount of dB calculated for the parameter C.

For example, assume that it is desired to evaluate the protection provided by a 20-mil solid copper shield installed on all six sides of a 1-m cube. The electromagnetic environment is specified as 100 W/m^2 and the frequency range of interest is 1 MHz to 10,000 MHz. Further, assume that 1 mW of power at any frequency in the range of interest will not affect any of the components inside the shielded box. Parameter A can be found directly from Fig. 4-2 by multiplying the ordinate by 20. T_p is given directly by Fig. 4-1. By use of Eq. 4-1, C can now be computed for the 20-mil shield. The minimum attenuation occurs in 1 MHz (in this example) where C is approximately 119 dB. The total power that can be coupled through a cube having 1 m^2 faces is, therefore, 100 W reduced by 119 dB. If it is assumed that the field could impinge equally on all sides of the shielded cube, which is unlikely, a total power inside the cube of 600 W reduced by 119 dB is obtained. This is approximately 756 X 10^{-12} W, which is so far below the safe level of 1 mW that there is no reason to worry about the safety of the shielded components. The conclusions from this example should not lull the designer into thinking all shields are as effective. In general, all solid shields are very effective, but very seldom are complete solid shields used in weapon system protection.

For Z_w equal to 377 Ω, the computed total loss has a property that is quite useful in rough calculations: the parameter C, the total loss of any given shield, increases with an increase of frequency whenever the absorption loss A is 10 dB or more.

The evaluation technique described contains the following worst case assumptions:

1. The incident wave impinges equally on all sides of the shield (this is improbable).

2. The impedance just inside the shield (looking into the enclosure) is equal to the shield impedance (very unlikely).

The shielding values as predicted by this method are, without question, conservative.

4-1.1.2 Compromises in Shielding

The previous paragraphs have developed means of computing a conservative shielding effectiveness parameter for solid shields and also for evaluating the maximum amount of power that can be coupled into the completely shielded volume.

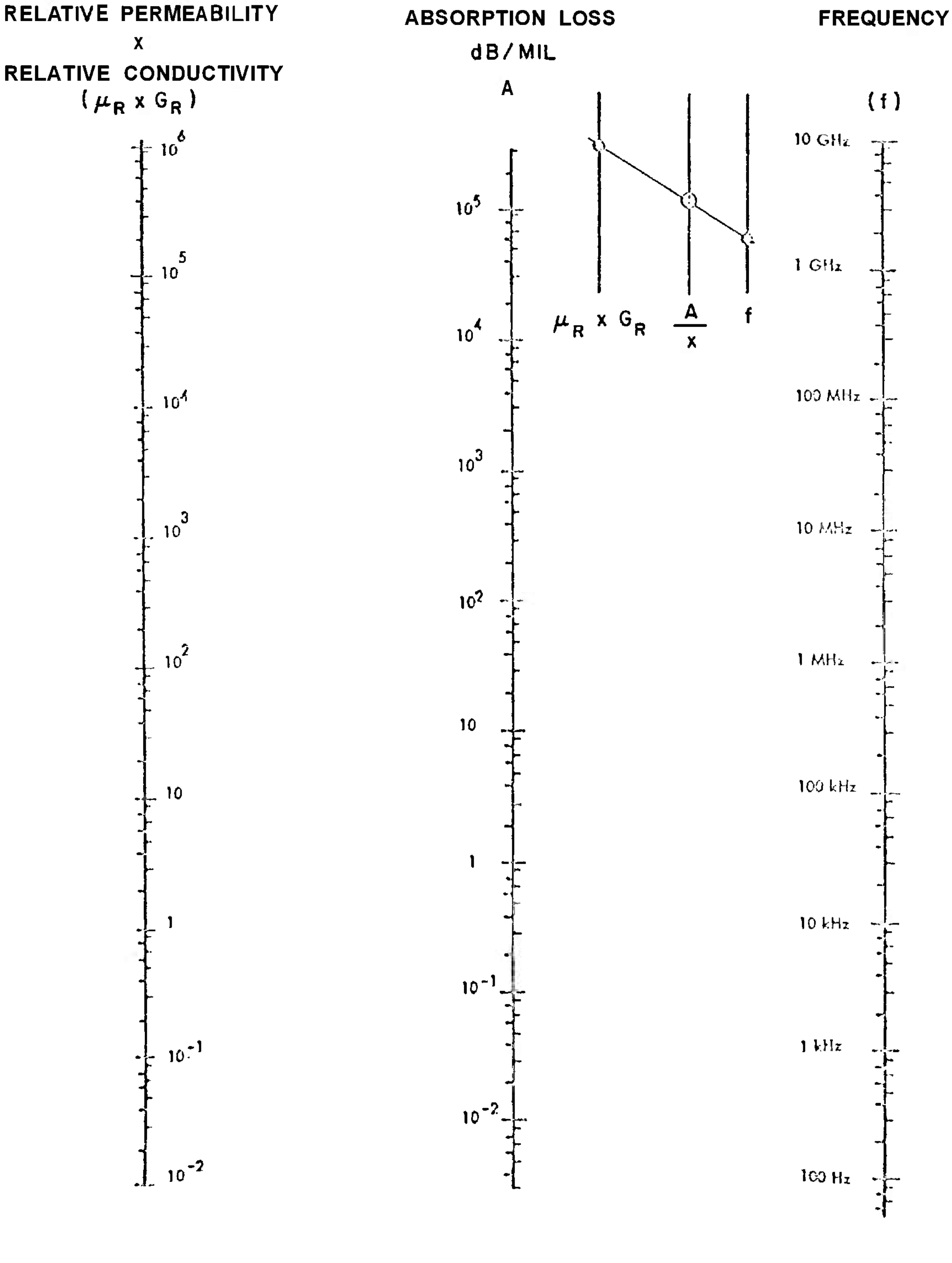


Fig. 4-3. Absorption Loss *A* of Solid Magnetic and Nonmagnetic Materials

A study of these paragraphs, particularly par. 4-1.1.1.3 will show that solid metal shields are extremely effective in reducing the overall level of electromagnetic energy that can be delivered to a component. The metal case of a typical weapon system must, however, have openings and other discontinuities for at least some of the following purposes: to pass power, control and output leads; to allow access for maintenance and servicing; to permit ventilation and environmental sensing; etc. The metal braided shield that often is used as a cover for the cables in a weapon system is itself a collection of small holes to which the previously discussed solid shielding effectiveness calculations do not apply. The evaluation of the leakage through holes, joints, seams, etc., in solid shields is considerably more difficult than evaluation of the protection provided by the solid shield. In general it may be stated that the discontinuities in the solid metal shielding surface are much more important in the evaluation of the leakage than the solid shield itself provided the shield is of reasonable thickness.

The designer's main concern with the shielding in weapon systems is, therefore, to reduce to a minimum the number of holes or gaps in the solid shielding of the missile system components and to reduce the coupling through the holes to an acceptable level. Fig. **4-4** illustrates proper and improper handling of a typical weapon system shielding problem.

In terms of the conservative shielding parameter defined in par. 4-1.1.1, the presence of holes in a solid shield affects both the power reflection term T_p and the attenuation term A. The A term which is associated with the power loss through the metal shield is not applicable to the power loss through the hole. The power reflection loss T_p which depends on the input impedance of the shield will change in the vicinity of the hole since the overall input impedance of the shield will be altered by the hole.

4-1.1.3 Shielding Tests

At present all tests designed to evaluate the performance of a shielding material are based, with the exception of shield-on/shield-off irradiation tests of a complete equipment, on a specified impedance insertion loss determination procedure. The output of a sensing antenna is recorded both before and after the insertion of the shield as the item is irradiated. This procedure is essentially designed to stimulate the conditions of the classical shielding effectiveness formulations and as such would be expected to give data in agreement with that formulation. However, the literature shows that many of the experiments yield data, especially at low frequencies, that cannot be easily explained by the classical formulation.

In any case, the shielding test results recorded in the literature are not applicable to the evaluation of the shielding protection provided by the shield in weapon system usage since the weapon system conditions will not conform to the test conditions.

4-1.1.4 Evaluation of Leakage Through Gaps or Holes in the Shielding

Gaps and holes in a weapon system shield are at present unavoidable. The coupling of electromagnetic energy through these holes or gaps depends on the incident wave impedance, the size and shape of the holes, and the complex contents of the shielded volume. The simplest example is shown in Fig. 4-5 where a rectangular hole exists through a solid metal shield. The hole is excited by an incident wave of impedance Z_w and terminated by an impedance Z_t that represents the unknown impedance that terminates the hole. This impedance is a function of the contents of the shielded volume.

Considerable work has been done on a simpler version of the problem that assumes the shield to be of perfectly conducting material of almost zero thickness and Z_t to be determined by absolutely empty space on the nonexcited side of the perfectly conducting plane. This problem has been treated at length and exact solutions for various shaped holes are available for an assumed transverse electromagnetic (TEM) incident wave. (Reference is par. 2-1.2.2 for a definition of the TEM mode of propagation.) The solutions take the form of expressions for the transmission coefficient of the hole T_c defined as:

$$T_c = \frac{W_T}{Ar\, P_i} \qquad \textbf{(4-16)}$$

where

W_T = power transmitted, W
Ar = area of the hole, m^2
P_i = incident TEM power density, W/m^2

These solutions show that T_c is a maximum, and has values somewhere between 1 and 2, when the dimensions of the hole are comparable to the wavelength of the incident radiation. At higher frequencies T_c approaches one, and at lower frequencies T_c decreases rapidly. For instance, a circular hole has a maximum value of T_c of approximately 1.7 when the perimeter of the hole is approximately 1.5 wavelengths. Experimental results, for holes whose dimensions are larger than or

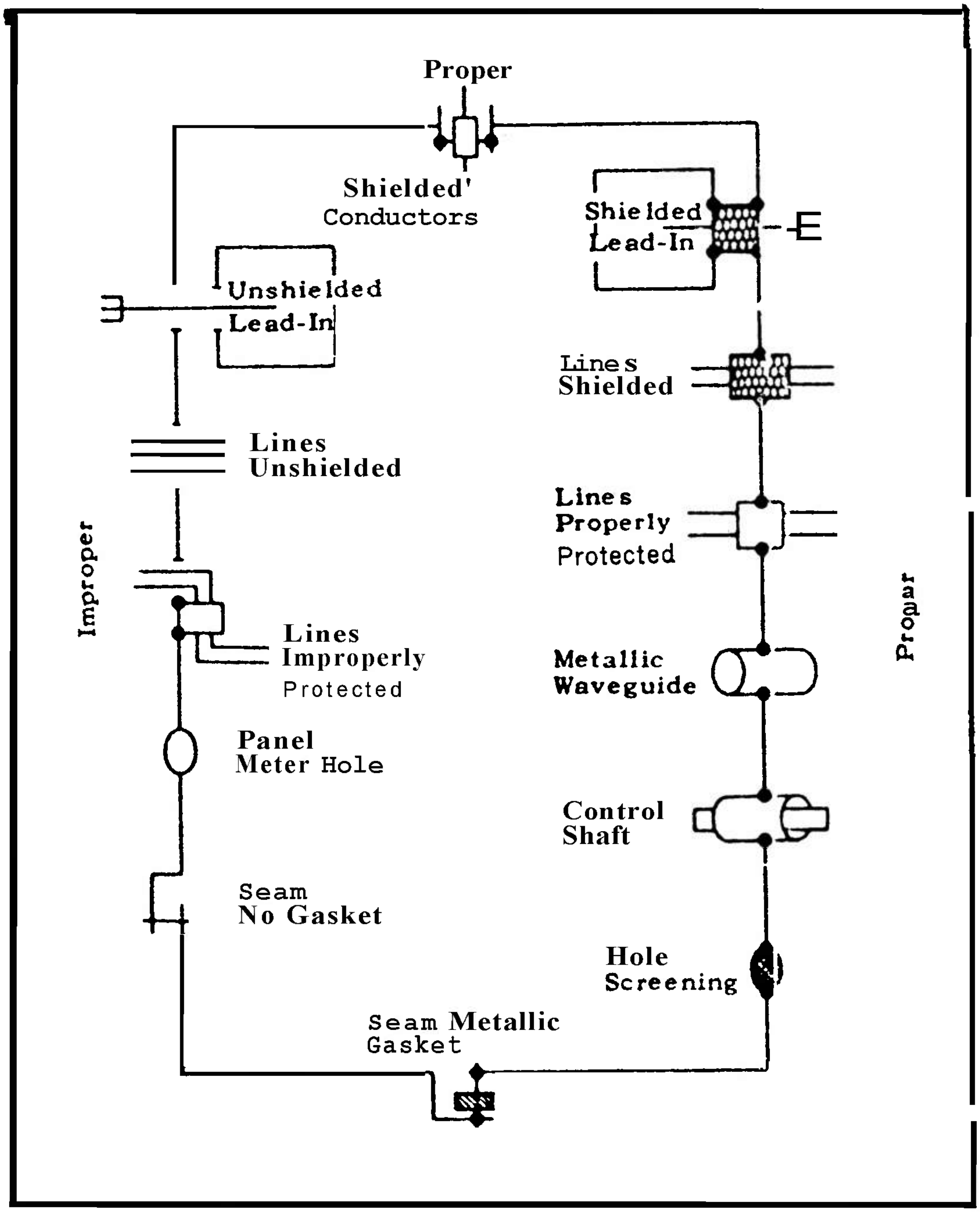


Fig. 4-4. Typical Shielded Compartment Discontinuities

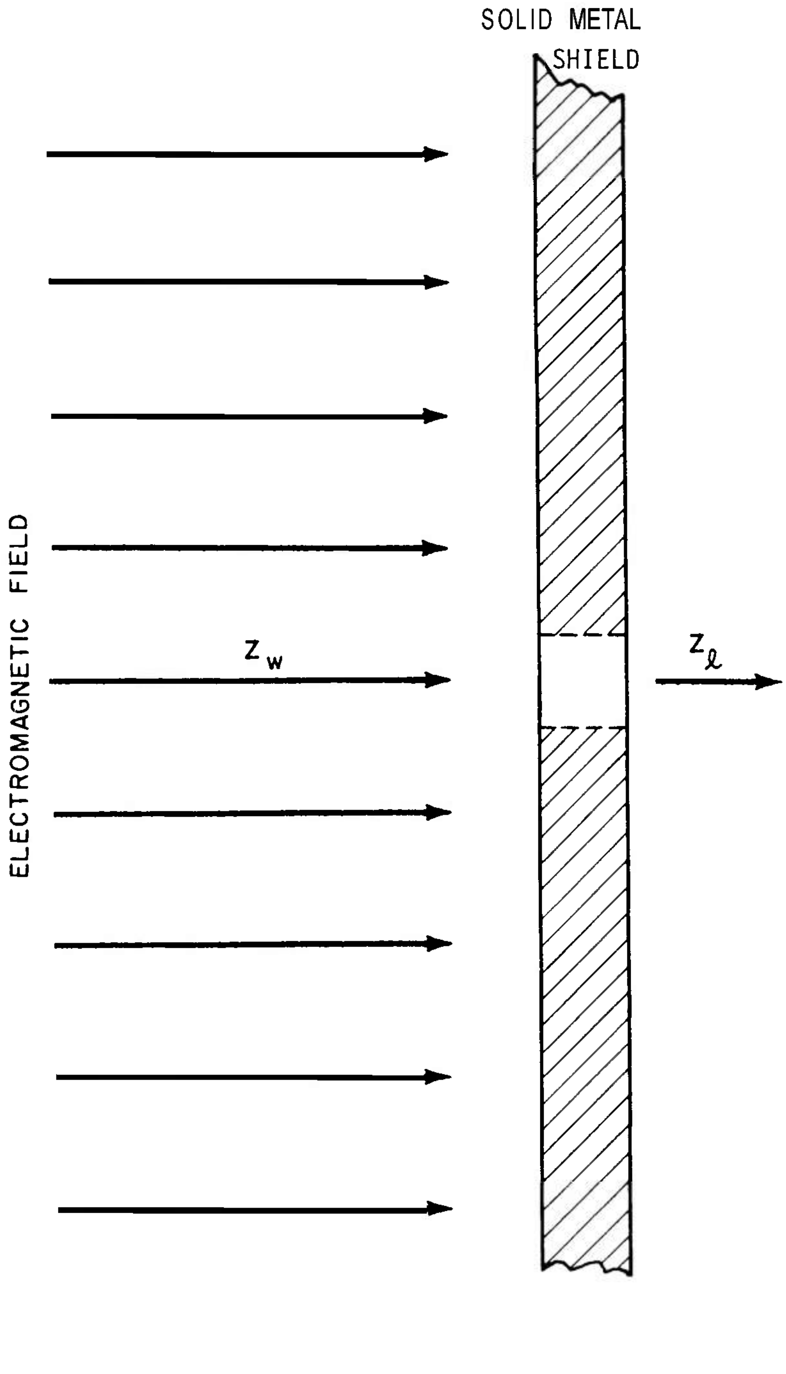


Fig. 4-5. Electromagnetic Field Impinging on a Solid Metal Shield Containing a Rectangular Hole

comparable to the incident wavelength, show good agreement with these solutions.

Limited theoretical work has been done that considers a non TEM-excitation. The results are roughly the same as those previously described. These results are not directly applicable to the weapon system protection problem even if it is assumed that the weapon system shield has infinite conductivity. First, the weapon system shield is of finite thickness and this imposes further restrictions on the solutions. Second, the impedance conditions immediately inside the surface of the weapon system shield will, especially at the lower frequencies, be influenced by the contents within the shield as well as the opposite sides which enclose the shield itself.

As far as it is known there are no available solutions to the hole leakage problem for finite thickness holes even assuming a known hole terminating impedance condition. Various works suggest, however, that the hole's finite thickness will reduce the coupling from that given by the simpler problem, although the coupling still depends upon the hole's terminating conditions. The use of waveguide below cutoff attenuation calculations for coupling through finite length holes is widely used but these calculations do not consider the actual problem of power transfer. In weapon systems usage, the hole terminating impedance conditions cannot be adequately predicted or measured except in exceptional circumstances.

The evaluation of leakage through holes in weapon system shields is thus an engineering estimation process. A procedure that is thought to be conservative, and yet not unduly restricting, is to assume that a perforated shield provides the same transmission loss T_p as a solid shield of the same material and that the holes transmit power to the interior of the shielded volume as

$$T_T = Ar\ P_T \tag{4-17}$$

where

W_T = power transmitted, W
Ar = area of the hole, m^2
P_T = power density at the external interface assuming the shield is solid, W/m^2

This procedure is to be used only for holes whose maximum dimensions are much less than the incident wavelength. As an example, consider a square hole 1 cm (10^{-2} m) on a side through a surface of a cubical copper covered box with 1 m edges. Let the copper covering be fairly thin, say 10 mils, and the box be irradiated by a TEM field of 100 W/m^2 at 10 MHz.

T_p as defined by par. 4-1.1.1.1 gives the dB relation between incident power density and power density at the interface. Fig. 4-1 gives approximately 50 dB for these conditions. The leakage through the hole should then be, symbolically:

$$W_T = P_i\ (\text{down } T_p \text{dB}) \times \text{Area of Hole}$$
$$W_T = 100 \times 10^{-5} \times 10^{-4}$$
$$W_T = 10^{-7}\ \text{W}$$

where W_T is the power coupled through the hole.

The leakage through the solid metal portions of the box can be calculated by using the absorption loss of copper A, given by Fig. 4-3. It is approximately 10 dB per mil of copper at 10 MHz. Therefore, the power coupling through the metal is, symbolically:

$$W_{MT} = \left[(P_i \text{ down } T_p\ dB) \text{ down } A\ dB \right] \cdot \text{Box Area}$$
$$= 100 \times 10^{-5} \times 10^{-10} \times 6 \times 10^{0}$$
$$\cong 6 \times 10^{-13}\ \text{W}$$

where W_{MT} is the power transmitted through the solid metal.

If the dimensions of the hole are comparable to the incident wavelength the hole may be conservatively assumed to couple as

$$W_T = P_i A. \tag{4-18}$$

For instance, in the previous example assume the frequency is changed to 10 GHz where the wavelength is 3 cm, then the power transmitted into the interior of the box is estimated at

$$W_T = 100 \times 10^{-4} = 10\ \text{mW}$$

and the power through the solid metal is negligible.

Holes in shields should be kept as small as possible. If a braided shield is used as part of an outer RF protection shield, the holes should be as few and as small as possible. Shields braided from metal ribbon achieve this objective much better than shields braided from round wire, therefore ribbon braided shields are preferred.

4-1.2 SHIELDING MATERIALS

4-1.2.1 Electrical and Physical Properties

The total protection provided by an RF shield for reasonable shield thickness, is degraded by the gaps, seams, and holes in the shield, as has been stated. In consequence the choice of a metal for shield use should be determined by its ability to eliminate leakage at joints over the life span of the weapon system.

Where corrosion, for example, may affect seams, etc. (see par. **4-1.3.4)**; extreme care must be exercised. The electrical parameters of most commonly available metals provide adequate solid shield protection. In some special applications where the shield must perform unusually well or be very thin, it may be necessary to consider high permeability and/or high conductivity metals. The range of conductivities and permeabilities of common metals is given in Table **4-3.**

Absorption loss A (in dB) varies directly as the square root of the relative permeability, relative conductivity product. At any one frequency, the transmission loss

$$T_p = \text{Constant} + 10\left(\frac{1}{2}\right) \log \left(\frac{G_R}{\mu_R}\right), \text{ dB.} \qquad (4\text{-}19)$$

Therefore, an increase of relative conductivity G_R by a factor of **100** increases A by a factor of 10 and increases T_p by 10 dB. An increase of relative permeability μ_R by a factor of **100** also increases A by a factor of 10 but decreases T_p by **10** dB.

At times conductive epoxies and pastes, carbon loaded rubbers, and other similar conductive materials are utilized as shielding materials. The dc conductivity of these materials is often the only electrical parameter known. The amount of shielding protection provided by these materials is problematical and–in addition–strain, pressure, and decomposition are likely to degrade the shielding performance of such materials. Unless extensive tests are performed to determine conductivity as a function of frequency and shielding degradation as a function of time, the use of such materials should be confined to emergency measures.

4-1.2.2 Closing Metal Shields

Closure of gaps and seams in shielding requires the application of good electrical bonding techniques. Electrical bonding can be defined as the process of mechanically connecting certain metal parts so that they will make a low-resistance electrical contact (see par. **4-1.3.8).** Good bonding is required to ensure that a system is electrically stable and relatively free from the hazards of lightning, static discharge, and electrical shock as well as to assist in the suppression of RF interference. Usually, the dc resistance of electrical bonds should be in the order of 0.0025 ohm.

Holes in the shielding that must pass unshielded power or control leads create a special problem. These unshielded leads, external to the shielded volume, can couple very large amounts of power into the shielded volume in comparison to the amount of power that directly penetrates the shield. Such leads as these must be decoupled with RF suppression devices to ensure adequate RF protection to the components within the shielded volume. Par. **4-4** describes applicable RF suppression devices.

4-1.2.2.1 Gaps and Seams

Gaps resulting from improperly bonded seams can lead to considerable RF leakage.

Bonds which result in gaps and degrade the shield's effectiveness are most commonly produced by poor spot welds or poorly spaced fasteners such as screws or rivets. See Fig. **4-39(D)** for an illustration of gaps resulting from a poor spot weld.

4-1.2.2.2 Construction of Seams

Several configurations for seams between two metallic members within a weapon system are shown in Fig. **4-6** (see also par. **4-1.3.8.1).** The preferred seam is a continuous weld around the periphery of the mating surfaces. The type of weld (other than spot welding) is not critical, provided the weld is continuous. In all cases, a continuous weld is desired since spot welding leaves gaps or slits. Table **4-4** summarizes, in order of preference, techniques for implementing permanent or semipermanent seams.

4-1.2.2.3 Overlapping Seams

An acceptable alternative technique is the overlap seam shown in Fig. **4-6(D).** In an overlap seam, all nonconductive materials must be removed from the mating surfaces before the surfaces are crimped, and the crimping must be performed under sufficient pressure to ensure positive contact between all mating surfaces.

4-1.2.2.4 RF Impedance

Regardless of the type of seam used, the RF impedance of the seam must not differ appreciably from that of the materials being joined. If the RF impedance of the seam is relatively high, RF voltages can develop across the seam from skin currents, permitting RF energy to enter the shielded enclosure. It is sometimes necessary to use continuous welding of seams to ensure shielding effectiveness.

4-1.2.2.5 Recommendations

Seams that are properly bonded will provide a low impedance to RF current flowing across the seam. Wherever possible, mating surfaces of metallic members within a weapon system should be bonded together

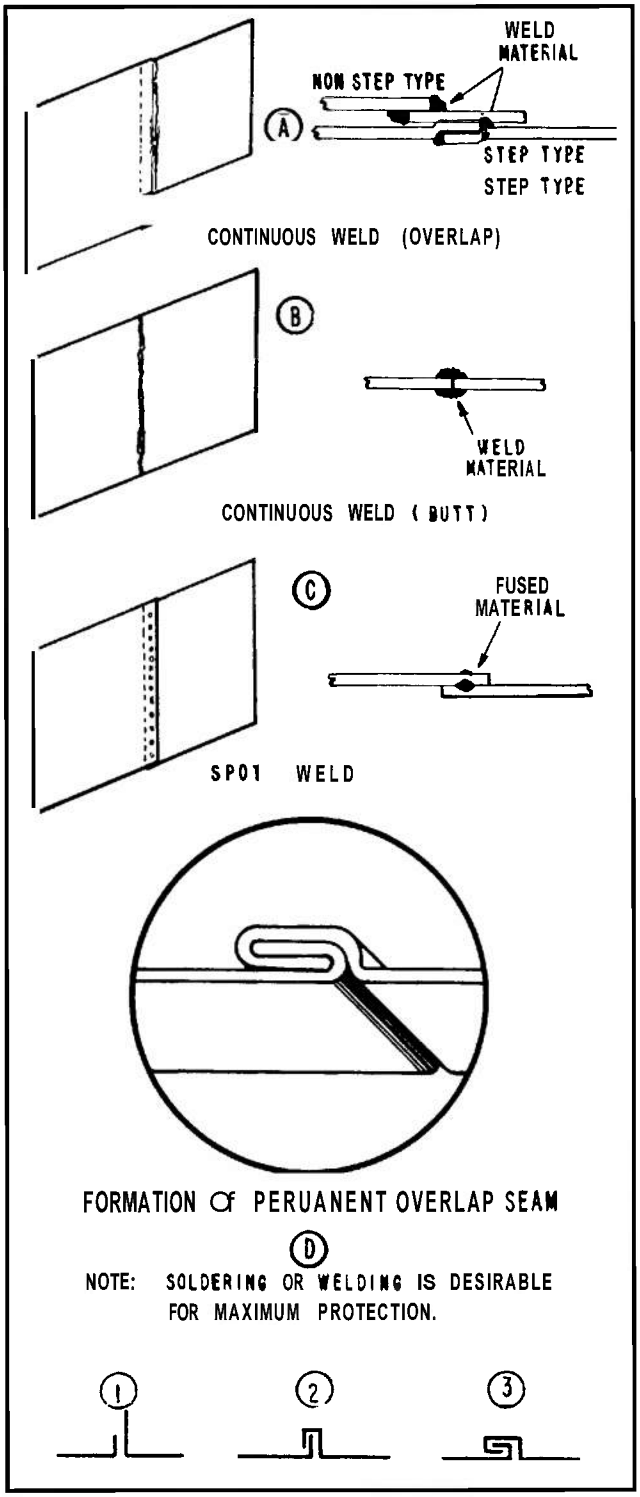


Fig. 4-6. Panel Seam Configurations

TABLE 4-4

PREFERENCE	TYPE OF SEAM	REMARKS
1	Continuous weld	Best RF seam
2	Spot weld	Space weld joints less than 2 in. apart
3	Crimp seam	Use strong and lasting crimping pressure; pressure is maintained by spot welding

by welding, brazing, sweating, swaging, or metal-forming. To assure adequate and properly implemented bonding techniques, observe the following recommendations:

a. All mating surfaces must be cleaned before bonding.

b. All protective coatings having a conductivity less than that of the metals being bonded must be removed from the contact areas of the two mating surfaces before the bond connection is made. (The conductivity of coatings, such as anodizing materials, should be verified with the manufacturer whenever it is questionable.)

c. When protective coatings are necessary, design them so that they can be easily removed from mating surfaces. Since the mating of bare metal to bare metal is essential for a satisfactory bond, a conflict may arise between the bonding and finish specifications. It is preferable to remove the finish where compromising of the bonding effectiveness would occur.

d. Generally, protective metal platings such as cadmium, tin, or silver need not be removed. Coatings having poor conductivity destroy the effectiveness of a bond to produce a low impedance RF path.

e. Mating surfaces should be bonded immediately to avoid oxidation after protective coatings are removed.

f. The nonreplaceable portion of a bonded joint that must be formed by dissimilar metals should be a metal lower in the electromotive force series than its mate (see Table 4-10). When two dissimilar metals must be bonded, select metals that are close to one another in the electromotive force series.

g. Bolted sections may be used for temporary bonds. However, bolted sections could be bonded to ensure consistent contact pressure over an extended period of time. Shield material must be rigid enough to prevent buckling between contact points.

h. When bolts or rivets are used to make a bond, they should be applied first at the middle of the seam and then progressively applied toward the ends of the seam to prevent the mating surfaces from buckling. The protection provided by the joint seems to depend on the number of fasteners per linear inch, the pressure of the contacting surface, and the cleanliness of the two mating surfaces.

i. When pressure bonds are made, the surfaces must be clean and dry before mating and then held together under pressure to minimize the growth of oxidation due to moisture entering the joint because the joint may not be 100% moisture-tight. The periphery of the exposed joint should then be sealed with a suitable protective compound and, whenever possible, one that is highly conductive to RF currents.

4-1.3 APPLICATIONS

The protection of a weapon system from RF energy requires construction of an adequate shield, reducing coupling through the necessary openings in the shield, and design of internal circuitry to reduce coupling to sensitive components. The use of the RF suppression devices on any unshielded leads entering the shielded volume is also an important part of providing adequate RF protection. RF suppression devices are discussed in par. 4-4. This paragraph presents some of the techniques necessary to reduce coupling through the holes in the shield and also points out the problems associated with special applications.

4-1.3.1 External Structures

In many weapon systems the external metal case of the system can be utilized as an effective RF shield.

If the external skin of the weapon system is nonmetallic, then shielding protection must be provided by the equipment cases, containers, or specially designed protective structures which are used when the equipment is assembled, inspected, or serviced. The problems in design and construction of these shields are similar. Additional shielding from RF exposure is required even if the weapon system skin does provide a shield for itself because–in the servicing, inspection, and assembly operations–shielding is negated by breach of the external skin resulting from opening access doors, removing sections of the weapon for inspection, etc. The locations at which these assembly, maintenance, and inspection operations are performed must be carefully investigated by the designer to provide adequate RF protection there. If operational requirements dictate that the weapon system skin must be breached occasionally in RF active areas, the designer should require that the outer metallic skin still be constructed with RF protection in mind. The cost is usually minor and the advantages from an RF protection viewpoint are obvious.

4-1.3.2 Shipping Containers

Shipping containers carrying a weapon system or its components are an important part of the hardening against the effects of RF energy, lightning, and static electricity. These environments are particularly hazardous to electroexplosive devices (EED's) and to solid state devices which are found in most modern weapon systems (Ref 1). If the systems are to arrive at the launching site in operating condition (or even arrive there), then precautions are necessary to the process of packaging.

Some of the factors that may influence a package are shown in Fig. 4-7. While most of these factors are of little interest with respect to hardening against electrical phenomena, the figure does illustrate the magnitude of the packaging problem.

Part of the problem in packaging is to determine the level of excitation that will affect the subsequent performance of the system being packaged. It is known, for example, that shock, vibration, and heat experienced in normal shipping are of little consequence to the subsequent performance of EED's and solid state circuits. The shock levels are seldom greater than 10 times gravity (Ref. 2) and the temperatures that are encountered in shipping are seldom greater than 150°F. Both of these conditions are readily met by devices currently in use by the military, and portions of the **MIL-STD** tests through which these components must pass should screen out those that are not capable of withstanding this environment.

The electrical environment, on the other hand, can be a definite hazard unless specific steps are taken in shipping to allow for this environment. One reason that the electrical environment tends to be difficult to protect against is that it is undefined, as is discussed in par. 2-1, throughout the journey of the package.

One source of electrical problems associated with components is the unpackaging of EED's or the handling of MOSFET's (metal-oxide semiconductor field-effect transistors). Some of the packages used are constructed in such a way that withdrawal of the devices causes frictional static electricity to be generated. EED's have actually exploded during the withdrawal process and personnel have been injured (Ref. 3).

Packages that tend to generate static electricity are to be avoided. These are generally of the plastic film type. Some of them are difficult to recognize because the film of plastic is deposited on the inside of a metal foil bag. The plastic materials are convenient for packaging because they form a good moisture barrier and are easily heat welded.

To overcome this problem, a number of plastic manufacturers are using an antistatic plastic film. These appear to offer some protection against the effects of static, limiting, to some extent, the ability of the plastic film to generate static electricity. The status on these materials is still generally vague in respect to their use with EED's.

A more positive approach to the prevention of the effects of static is to wrap the devices in metal foil, followed if necessary by enclosure in a plastic envelope, although this procedure needs to be carried out with precautions. Unwrapping of this kind of a package must be carried out with the operator grounded and with disposal of the plastic bags from the work area prior to unwrapping the foil. Operations on foil-wrapped EED's must be carried out on a conducting grounded surface.

Shipping containers for components that may be influenced by electric energy should be made of metal rather than wood. Present interstate shipping regulations for explosive devices, however, call for wooden boxes (Ref. 4). In some instances the wooden box requirement is supplemented by having metal containers inside the wooden box. Thus the shipping requirements are met and the system and EED are enclosed in what amounts to a Faraday shield.

Radio frequency energy is effectively limited by the use of a complete Faraday shield. The classical field reduction afforded by copper and iron shields for reflection and absorption effects are shown in Fig. 4-8

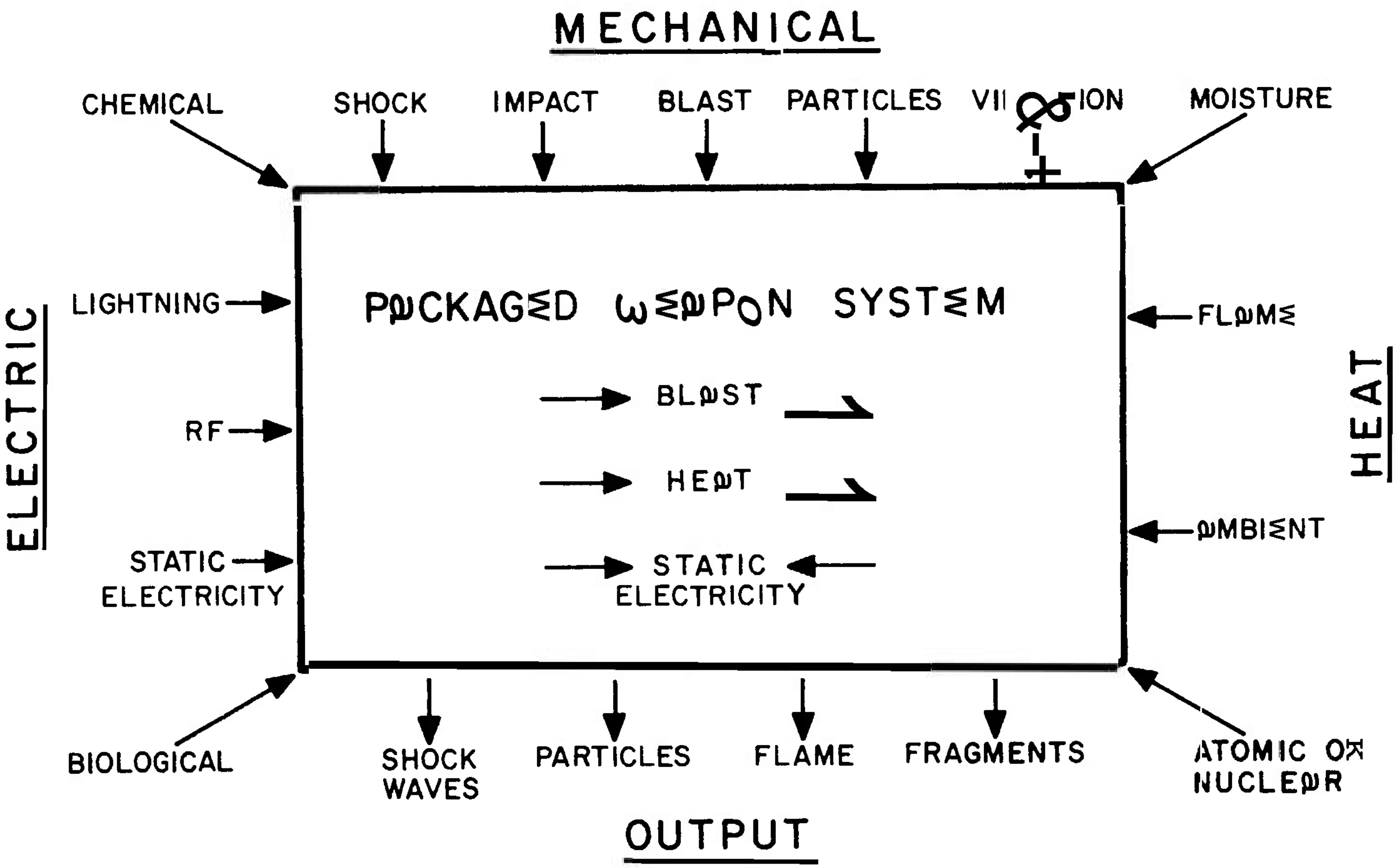


Fig. 4-7. Some of the Factors To Be Considered in Weapon System Packaging

(Ref. 5). In general, there is a relatively large loss associated with copper and iron containers. Reflection losses account for most of the elimination of energy at the lower frequencies. The reflection losses for the magnetic field increase with increasing frequency until a frequency of about 100 MHz is reached and then tend to level or to decrease slightly. The absorption loss behavior of iron and copper are different as shown by curves *A* and B in Fig. 4-8. Copper appears to be superior to iron for high reflection losses, but the reverse is true for absorption losses (up to 1 GHz). Thus it appears from this viewpoint that a copper-flashed iron would provide the ideal material for a shielded shipping container. Par. 4-1 discusses shielding in detail and should be consulted for a full understanding of applicable design equations.

energy from the environment both contribute materially to the amount of attenuation that is actually required for a given environment. Even in the absence of a Faraday shield for a container, it is well to follow several generally accepted practices in the use of EED's and sensitive solid state components:

a. It is generally accepted that the input leads to the EED should be short circuited.

b. If these leads are wires of any appreciable length, they should be twisted together. The reason for twisting is that induced currents in individual twists of the wire will tend to be out of phase with one another and the net result will be in cancellation of the induced electromotive forces of the individual loops.

on.

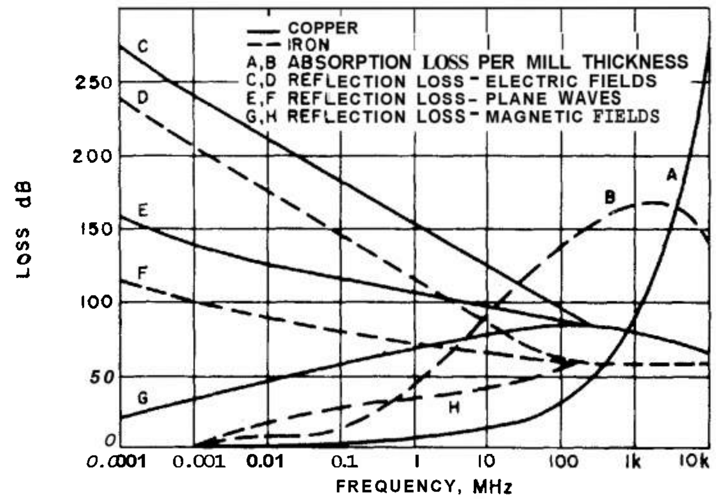


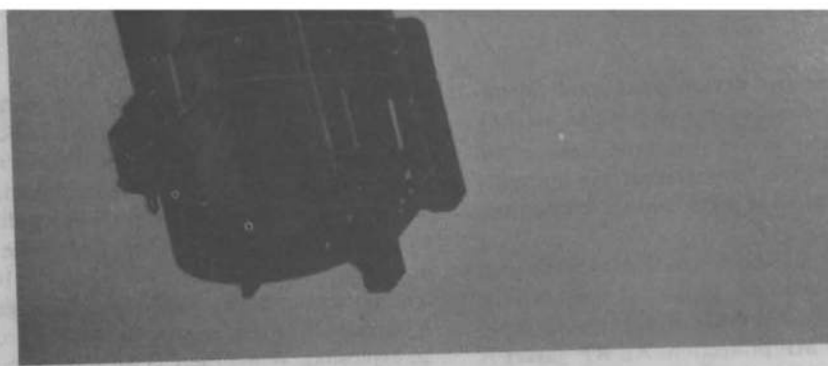
Fig. 4-8. Relative Shielding Effectiveness of Iron and Copper

Containers for sensitive devices need good electromagnetic seals at the closure junction (see par. 4-1.3.6). Tight fitting junctions assure that little leakage will occur past the joint. Gasket materials are currently manufactured that provide good contact under pressure.

Fig. 4-9 illustrates a shipping container that is used in transporting the warhead section of the LANCE weapon system. The case is made of soft steel to aid in low frequency and EMP protection. An RF gasket is used between the sections to ensure a good **RF** seal at the mating edges.

The sensitivity of the device contained in the package and the efficiency with which exposed leads can extract

There is one other shipping and storage problem peculiar to EED's. If one device in a package of many devices fires, then it is important that the remainder of the devices do not fire or, at a minimum, do not fire within a very short time interval. The additive effect of all of the devices firing in a very short time could result in severe damage to external systems. It is for this reason that dunnage is required in packages of EED's. A barrier effect is necessary to prevent propagation of an explosion. While there is little specific information on the means of designing an effective type of barrier, there is considerable information that has been obtained experimentally on the effect of various barrier materials on specific explosives. For high explosives,



on the means of designing an effective type of barrier, there is considerable information that has been obtained experimentally on the effect of various barrier materials on specific explosives. For high explosives,

The sensitivity of the device is retained in the package and the efficiency with which exposed leads can extract the most efficient barrier appears to be wood. Sawdust is in wide usage as a dunnage material. The requirement is that the high velocity particles and flash are absorbed and the shock wave is attenuated. Table **4-5** illustrates the gap distance for several materials and for several explosive types.

Little has been said about the packaging of low explosive devices or pyrotechnics. These generally create a higher heat output with the temperature of the reaction being maintained for a longer period of time. It would appear that additional barrier requirements for this type of a reaction would include thermal insulation and the use of a barrier material that would not burn or support combustion.

4-1.3.3 Test Equipment and Ground Support Equipment

Any test equipment or ground support equipment to be used with a weapon system in a potentially high electromagnetic environment should be designed to at least as high a level of RF protection as the weapon system itself.

In general, weapon system shields should be removed and common test equipment employed only in RF quiet areas. Special test equipment and ground support equipment should be equipped with completely shielded test and monitor cables. All unused jacks and plugs should be supplied with shielding caps. Permanent installations should use metal conduit for cable runs wherever possible.

4.1.3.4 Packaging of Components

The high density of electrical and electronic equipment in modern systems makes it difficult at times to place sensitive circuits or components away from interfering sources (Ref. 7). There are, however, certain precautions that should be observed when packaging equipment into a system. Assume for the moment that the system is protected against the external environment by proper shielding and the concern is now with its own internal environment. The major problem is then with transients which couple between circuits due to their close proximity. The examples which follow and which actually have occurred illustrate situations that should be avoided.

Fig. 4-10 shows a missile that has the sensitive guidance computer mounted on a metal bulkhead, while in the reverse side of the bulkhead is the firing unit for the EED's (stage separation, spin, etc.). When the firing unit was activated, the transient from this unit was coupled into the guidance computer and saturated it. The solution to this problem was to move the firing unit away from the guidance system.

The same firing unit also presented another transient coupling problem. In many systems where long runs of cables are involved, it is common practice to bind them in harnesses and then place them in metal conduits as was done in this system. The transient current for firing the EED peaked 2,000 A. The firing leads were shielded, twisted pair–yet the field from this transient coupled energy into adjacent shielded leads such that a two-volt spike appeared at the end of the cable and interfered with the operation of control circuits.

4-1.3.5 Cable Assemblies

Shield discontinuities in weapon systems should be avoided as much as possible to reduce the amount of **RF** leakage. Examples of areas where discontinuities

TABLE 4-5

SENSITIVITY FOR VARIOUS SPACER MATERIALS (WAX GAP TEST)[6]

Spacer Material	Average Penetration, in.			
	Tetryl	Comp. B	HBX	Pentolite
Air	5.04	1.21	G.93	
Wood (oak)	1.39	1.04	0.93	
Copper	1.69	1.17	0.86	
Polystyrene	1.85	1.43	1.19	1.90
Acrawax B	1.89	1.46	1.28	2.08
Aluminum	1.90	1.51	1.33	2.05
Stanolind Wax	2.07	1.50	1.28	2.06

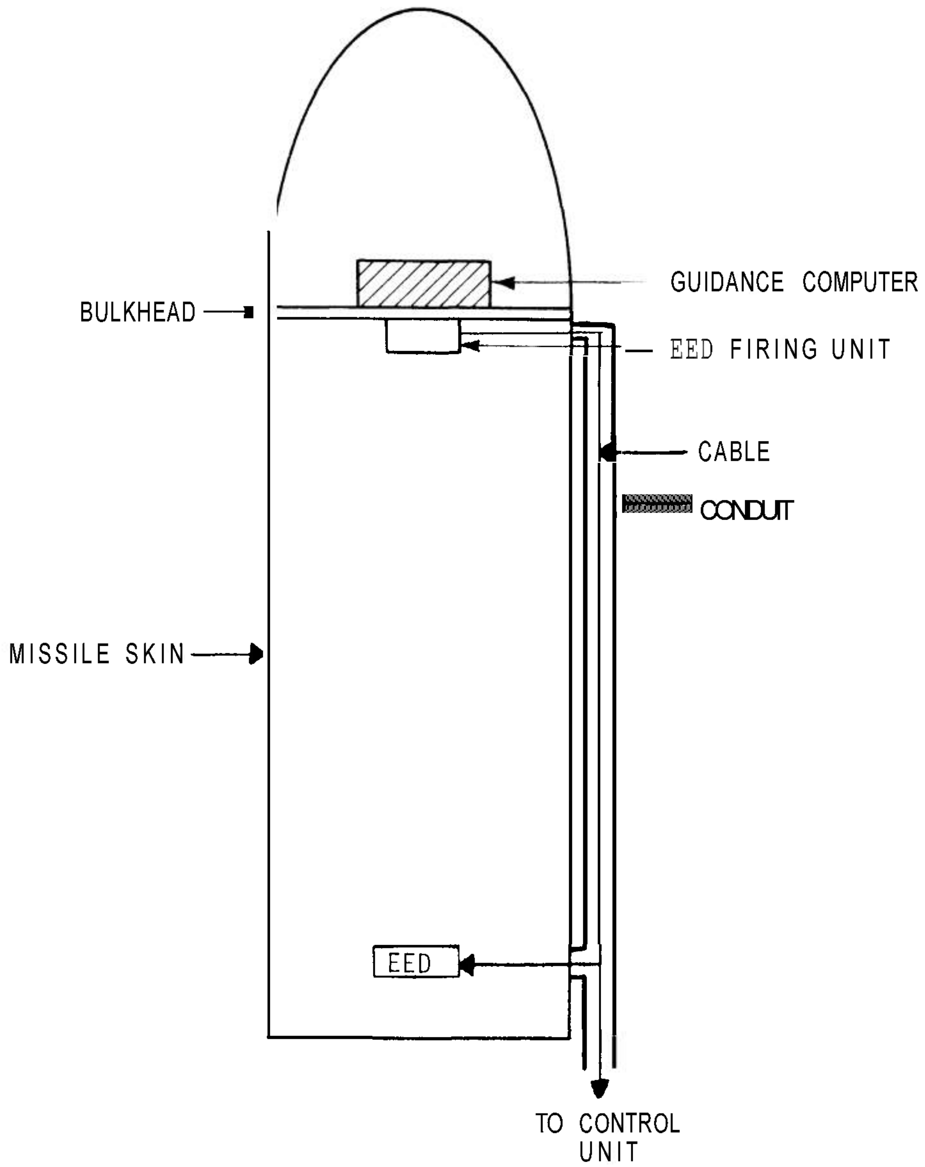


Fig. 4-10. A Missile Showing the Improper Location of Sensitive Components

can be eliminated by proper design practices are shield termination of cable assemblies, construction seams, and connectors. Some shield discontinuities are seemingly unavoidable, e.g., the points where conductors branch off. Where these occur, there are techniques that will ensure that the shielding effectiveness of the cable will not be reduced.

4-1.3.5.1 Cable Shielding

There are several methods for shielding cables. These include: (1) braid, (2) flexible conduit, (3) rigid conduit, and (4) spirally wound shields of high permeability materials.

Braid, which constitutes woven or perforated material, is used for cable shielding in applications where the shield cannot be made of solid material. Advantages are ease of handling in cable makeup and lightness in weight. However, it must be remembered that for radiated fields the shielding effectiveness of woven or braided materials decreases with increasing frequency and the shielding effectiveness increases with the density of the weave.

Conduit, either solid or flexible, may also be used to shield weapon system cables and wiring from the RF environment. The shielding effectiveness of solid conduit is the same, for RF purposes, as that of a solid sheet of the same thickness and material. Linked armor or flexible conduit may provide effective shielding at lower frequencies, but at higher frequencies the openings between individual links can take on slot-antenna characteristics, seriously degrading the shielding effectiveness. If linked armor conduit is required, all internal wiring should be individually shielded. Degradation of shielding conduit is usually not because of insufficient shielding properties of the conduit material but rather the result of discontinuities in the cable. These discontinuities usually result from splicing or improper termination of the shield.

Protection against RF energy, static electricity, and lightning is not the only shielding problem. Solenoids, or other devices associated with high inrush currents or incorporating switching devices that normally develop high-amplitude transients, can also prove a source of difficulty particularly where spacing between components is small. For protection against this type of energy, shielding materials with high permeability are desirable. These materials cannot be drawn into tubing because they lose their shielding properties when cold worked; therefore, an adequate shield is often developed by wrapping a continuous layer of annealed metal tape around the cable.

A typical application may involve shielding a cable of approximately 0.5 in. diameter, which has to be flexible in the final assembly. Annealed Mu-metal tape 0.001 in. thick and 0.25 in. wide wrapped in two layers would provide a suitable solution to this problem. The first layer can be spaced approximately 0.125 in. between convolutions, with the second layer overlapping the first layer to cover the gap between turns. The assembly should be covered with a protective rubber coating so that it may be flexed without losing its shielding effectiveness. A form of shielded cable using four counterspiral-wound bands of foil, Netic, Co-netic or their equivalent* is also recommended. This construction is shown in Fig. 4-11. The strips can be from 0.25 in. to 1 in. wide. To minimize leakage between gaps, it is necessary to wind the material so as to permit spiral positioning along the length of the cable, with each following layer consisting of another spiral in the opposite direction. Successive layers of the tape, wound in this manner, ensure a minimum of gaps while permitting flexibility.

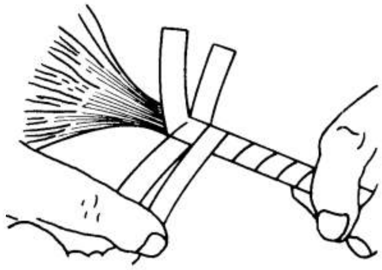


Fig. 4-11. Shielding by Using Bands of Foil

Such spiral-wound shielded cables are commercially available. A design engineer who needs a shield of this nature can procure the tape in foil form and, for evaluation purposes, fabricate a prototype shield for his own cables. A total of four wraps, or multiples of four, may be necessary for cables carrying appreciable current to prevent leakage due to magnetic saturation. For conductors carrying currents greater than two amperes, the first two layers should be Netic S3-6 foil or its equivalent; the remaining layers should be Co-netic AA foil or its equivalent. Netic and Co-netic foils and their equivalents are available from 0.002 to 0.007 in. in thickness and in various widths. After wrapping, the cable can be potted or encapsulated to prevent unraveling of the foil. Zipper tubing, as shown in Fig. 4-12, can also be used as an efficient means of mechanically holding the foil wraps in place. Zipper tubing is not recommended for cable shielding by itself. For additional

* Netic, Co-netic, Mu-metal, Unimag 80, Hi-Mu 80, and Hypernom are trade names of some materials which are used for shielding.

information on cables in general refer to AMCP **706-**125, Engineering Design Handbook, *Electrical Wire* ***and Cable.***

Fig. 4-12. Zipper Tubing

4-1.3.5.2 **Types of Shielded Cables**

The principal types of shielded cables that are available include shielded single wire, shielded multiconductor, shielded twisted pair, and coaxial. Cables are also available in both single and multiple shields in many different forms and with a variety of physical characteristics. Proper selection and application of appropriate cables for particular design requirements are necessary for the prevention of pickup of external energy. Table **4-6** presents a relative comparison of the four types of shields.

4-1.3.5.2.1 Shielding Effectiveness

If one were to refer to manufacturer's catalog of coaxial cable, he would discover that there is no reference made to shielding effectiveness. This is not an oversight but is the standard practice of the cable manufacturers. If the designer were to consult an electronics catalog, such as the ***Electronic Engineers Master,*** he will find that the fifteen cable companies who list their shielded cable specifications do not mention shielding effectiveness.

There are several reasons for not including these data in the manufacturers specification. First, there is no MIL-SPEC on shielding effectiveness; therefore, there is no way to report information that is compatible with one cable versus another. Second, the way in which the cable is used–i.e., its loading–affects its characteristics, e.g., MIL-C-7078B calls for the ratio of metal to open space in a shield to be 85-90 percent when in its normal position. When the cable is bent, however, the ratio changes depending on the radius of the bend. Also, the ratio can be altered when the shield is fastened to the back shell of a connector; e.g., a cable with a shield having an inner diameter of 0.375 in. If the shell diameter is larger, the cable will be spread, thereby lowering the metal to open space ratio. Third, the impedance of the cable's termination will also affect its shielding effectiveness.

4-1.3.5.2.2 Cable Capacitance

The designer should be aware that in addition to the increase in size and weight that shielding produces, the

TABLE 4-6
COMPARISON OF SHIELDED CABLES

	Copper Braid	Foil	Solid Conduit	Flexible Conduit
Shield Effectiveness (audio frequency)	Good	Exc.	Exc.	Good
Shield Effectiveness (radio frequency)	Good	Exc.	Exc.	Poor
Normal % of Coverage	60-95%	100%	100%	90-97%
Fatigue Life	Good	Fair	Poor	Fair
Tensile Strength	Exc.	Poor	Exc.	Fair

capacitance per foot also increases. This shunt capacitance of the cable can be important in some circuits and has to be considered. Fig. 4-13 shows the effect that shielding has on capacitance of various wires.

4-1.3.5.2.3 Current Rating

The current rating of the conductors used in cables is specified in MIL-B-5087B, *Bonding, Electrical, and Lightning Protection for Aerospace Systems.* A listing of specified current-carrying-capacity of conductors is reproduced in this handbook as Table 6-5.

4-1.3.5.3 Cable Specifications

In order to aid the designer in selecting the type of cable required and to ensure that the manufacturer delivers a qualified product, several cable specifications are available. The following five specifications are the most pertinent:

1. MIL-C-17D, *Cables, Radio Frequency, Coaxial, Dual Coaxial, Twin Conductor, and Twin Lead.*
2. MIL-C-7078B, *Cables, Electric, Aerospace Vehicle, General Specifications for.*
3. MIL-C-27500, *Cables, Electrical, Shielded and Unshielded, Aircraft and Missile.*
4. MIL-C-55021A, *Cables, Twisted Pair and Triples, Internal Hookup, General Specifications for.*
5. QQ-B-575a, *Braid, Wire, (Copper, Tin Coated, Tubular).*

4-1.3.5.4 Branches and Terminations

4-1.3.5.4.1 Branches

In many instances it is necessary to branch-out some of the conductors located inside a shielded cable. The junction so formed is usually referred to as a *Y*- or a T-type. It is very important that the integrity of the shield be maintained at this point, otherwise, the shielding effectiveness of the complete assembly can be seriously impaired. Fig. 4-14 illustrates a T-type junction that ensures the maintenance of shielding integrity. A solid metal sleeve is used as the junction between the shields and is soldered 360 deg to ensure minimum leakage.

Under no circumstance should a wire be brought out through a hole in the shield. This includes a shielded wire within the main shield. Soldering the two shields together at the point of penetration is not a satisfactory solution.

4-1.3.5.4.2 Terminations

The most common method of terminating a shielded cable is with a connector. When considering the shielding effectiveness of a cable assembly, the connector must be included since the various parts represent discontinuities in the shield. Even though there is mechanical contact with the cable shield through the outer ring of the mating connector, an adequate RF connection is not assured. Poor contact at these interfaces can be considered as gaps in the cable assembly. To ensure that the quality of the connectors used by the military services meet a minimum standard, the letters MS that prefix a connector part number are used to indicate an approved connector under the current Military Specification, MIL-C-5015.

One of the methods used to ensure a superior RF proof connector is to place spring contacts inside one portion of the connector (see Fig. 4-15) so that positive contact is made along the circumference of the mating

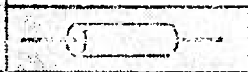
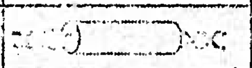
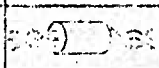
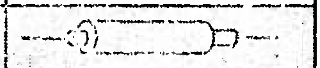
CAPACITANCE IN PICOFARAD PER FOOT												
TYPE	ONE WIRE SHIELDED				TWO WIRE SHIELDED				THREE WIRE SHIELDED		ONE WIRE DOUBLE SHIELDED	
CONFIGURATION												
WIRE SIZE	16	18	20	22	16	18	20	22	20	22	22	22
CONDUCTOR TO SHIELD pF/ft	89	91	74	98	68	65	64	62.5	60	52	98	340
					(EITHER CONDUCTOR TO SHIELD)				(ANY CONDUCTOR TO SHIELD)		(CONDUCTOR TO INNER SHIELD)	(INNER SHIELD TO OUTER SHIELD)
CONDUCTOR TO CONDUCTOR pF/ft					42	39.5	38	36.5	36	30		
NOTE: DATA FOR USE IN CALCULATING THE EFFECTS OF CAPACITANCE IN SUBSYSTEMS WIRING.												

Fig. 4-13. Capacitance of Various Shielded Wires*

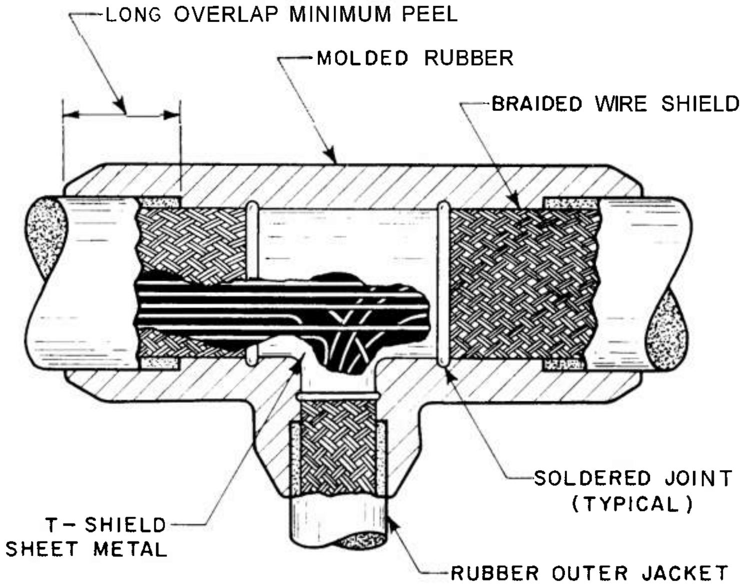


Fig. 4-14. T-junction

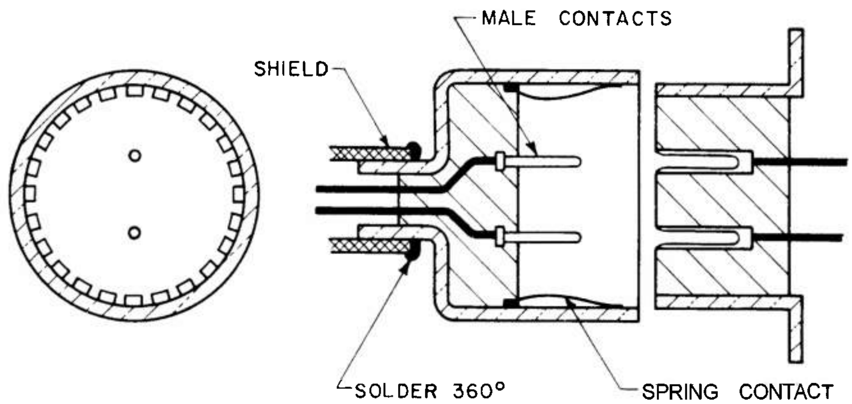


Fig. 4-15. RF-proof Connector

parts. These contacts are extended so that the shell of the connector mates before the pins make contact on assembly of the connector and breaks after the pins on disassembly. A connector which meets these requirements is available under MIL-C-27599 and is the preferred type to be used in RF-proof designs.

Fig. 4-16 illustrates the type of connector that should be used when a shielded cable assembly contains individual shielded wires. The practice of pigtailing these shields and connecting them to one of the pins is not recommended. The individual shields should be connected to coaxial pins specifically adapted for this purpose. MS32-101, shown in Fig. 4-17, is an example of a connector that has twelve contacts, two of which are made to handle shielded wires.

When considering the interconnection of subsystems, it is not always desirable to use connectors in the cabling between them. In this situation, it is necessary to find some other method of terminating the cable without affecting its RF integrity. The practice of inserting the shielded cable through a hole in the metal case of the terminating subsystem should be avoided. Even if the shield is soldered at this point, the practice is not acceptable. The technique illustrated in Fig. 4-18 is one method that can be used without affecting the shielding effectiveness.

4-1.3.5.4.3 Connector Specifications

In order to aid the designer in selecting the type of connector required and to ensure that the manufacturer delivers a qualified product, several connector specifications are available. The following six specifications are the most pertinent:

1. MIL-C-5015D, *Connectors, Electric, "AN" Type.*
2. MIL-C-26482D, *Connectors, Electric, Circular, Miniature, Quick Disconnect, Environment Resisting.*
3. MIL-C-26500C (USAF), *Connectors, General Purpose, Electrical, Miniature, circular, Environment Resisting, Established Reliability.*
4. MIL-C-27599, *Connector, Electrical, Miniature, Quick Disconnect (for Weapon Systems) Established Reliability.*

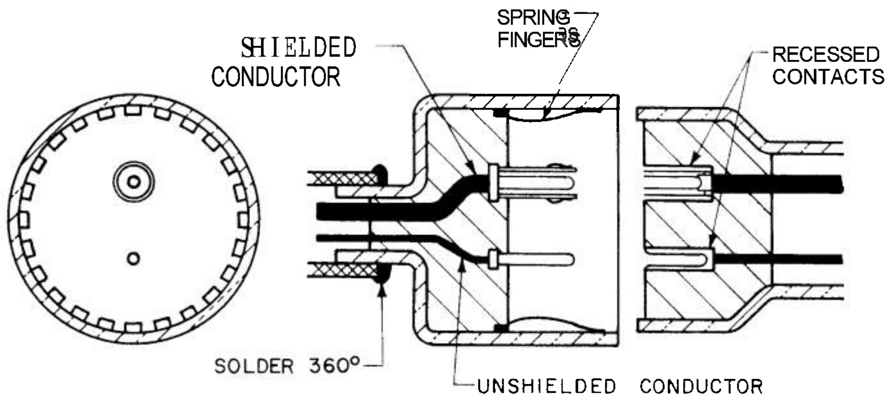


Fig. 4-16. Connector for Shield Within a Shield

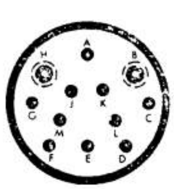


Fig. 4-17. Typical Connector for Handling Shielded and Unshielded Wires

5. MIL-C-38300A (USAF), *Connectors, Electrical, Circular, Multicontact, High Environment, Quantitative Reliability, General Requirements for.*
6. MIL-C-39012A, *Connectors, Coaxial, Radio Frequency, General Specifications for.*

4-1.3.6 Access Doors and Lids

Breaks in the outer metal skin of a weapon system can result in RF susceptibility problems. Breaks should be held to an absolute minimum compatible with other overall requirements on the system. If a break or joint

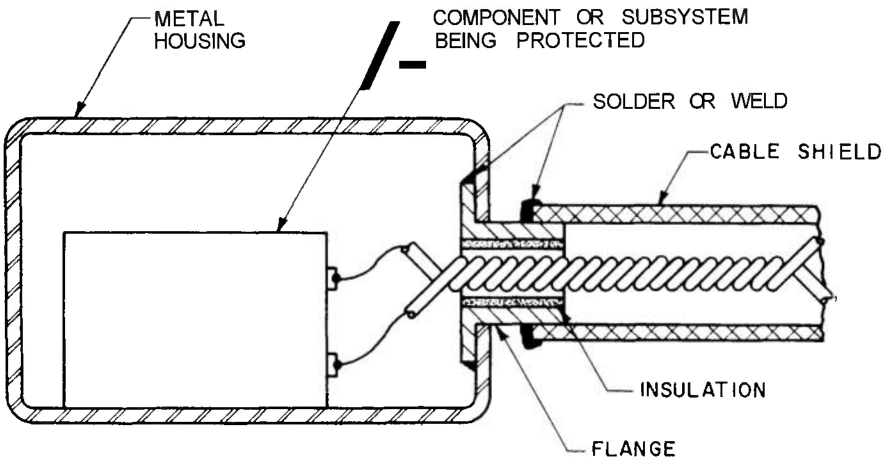


Fig. 4-18. Method of Terminating Shielded Cable Without a Connector

is unavoidable, then the type of closure or joining used is extremely important to the weapon system's overall susceptibility.

Often the weapon system designer must provide access to the electronic equipment located inside the system. The equipment itself also requires the use of doors or lids to facilitate servicing. In terms of RF effects, these access doors and lids represent breaks in the metal shield, and thus affect the susceptibility of the weapon system to radio frequency energy, static electricity, and lightning.

Wherever a junction appears between two surfaces, whether it be a door or a joint, special care must be exercised to prevent it from leaking RF. This is true whether the object is to confine RF within an enclosure or to prevent extraneous interference from entering an enclosure. A great deal of research has gone into this problem by persons concerned with radio frequency or electromagnetic (RFI/EMI) interference, where RFI/EMI is defined as *any radiofrequency or electromagnetic signal that causes an undesirable response in the system under consideration.* Since most of the data available are obtained from RFI/EMI studies, it is convenient to discuss the problem from a RFI/EMI standpoint. The designer should remember, however, that the **RF** field densities his weapon system must be hardened against are usually several orders of magnitude higher than those that generate RFI/EMI.

The definitions of terms specifying shielding effectiveness in RFI/EMI terminology are compatible with simple measurement techniques and relate variables associated with a particular set of measurement conditions. There is little justification for assuming that the results apply to the actual protection provided a weapon system in its tactical environment except for conditions that are very close to those in which the measurements were made.

There are two basic elements to the problem: electrical and mechanical.

4-1.3.6.1 Electrical Aspects

Three items are commonly used when rating RFI/EMI shielding ability: (1) attenuation A, (2) insertion loss IL, and (3) total shielding effectiveness SE where

$$SE = A + IL \qquad (4\text{-}20)$$

4-1.3.6.1.1 Attenuation

Attenuation is defined as the ability of a material to reduce the transfer of RF energy when the material is inserted in the path of the energy transmission. If P_T is a constant transmitted power from a transmitter, then P_R, is the received power without any shield in the path between transmitter and receiver. P_{R2} is the power at the receiver located inside a metallic enclosure where no RF gasket or other means of shielding is used. The decrease in signal strength due to the material, expressed in decibels, is the theoretical attenuation of the material (Ref. 9).

$$A = 10 \log \left[\frac{P_{R1}}{P_{R2}} \right] \qquad (4\text{-}21)$$

4-1.3.6.1.2 Insertion Loss

Insertion loss is that loss of radio frequency leakage due to the insertion of shielding material. This loss can be determined in the following manner. A constant level signal source is placed in an enclosure and the opening in the enclosure is gasketed with shielding material which is inserted under the pressure recommended by the manufacturer. The value of the received signal is observed at the receiver. The shielding material is then removed and a variable attenuator, located between the receiving antenna and the receiver, is adjusted until the receiver's output coincides with the readings obtained with the shielding material in place. The value of this attenuation, expressed in dB, is the insertion loss.

4-1.3.6.1.3 Total Shielding Effectiveness

Total shielding effectiveness (Ref. 10) is the decrease in RF leakage, due to the combination of enclosure and gasketing, expressed in decibels.

These definitions are specialized meanings of the terms as applied to shielding discussion. Reference is made to par. 4-3.5 for a theoretical discussion.

4-1.3.6.2 Mechanical Aspects

If a gasket material is selected properly and is applied properly, electrical requirements will usually be satisfied; but it must be noted that there are three basic design parameters involved in the mechanics of the gasketing problem (Ref. 11). These are: average pressure in the gasket, gasket height, and total joint unevenness.

Fig. 4-19 shows the change in insertion loss due to change in pressure on the gasket. The value of 20 psi is an average value (after many tests with various materials) at which additional pressure does not produce much additional insertion loss (Ref. 9). The type of joint being gasketed also affects the gasket height computations, because RFI/EMI gaskets take a degree of compression set. Joints are classified in three categories:

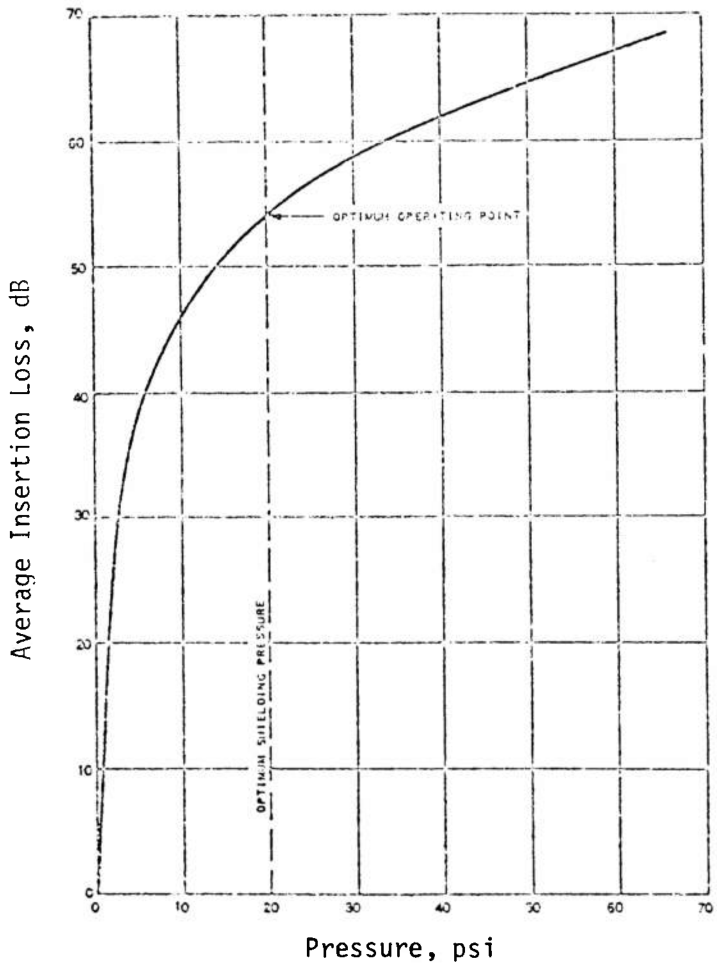


Fig. 4-19. Insertion Loss vs Pressure for Resilient Metal Gasket

(1) ***Permanently closed joints.*** In this situation compression set is of no concern. If the joint is opened for maintenance, a new gasket should be used for resealing.

(2) ***Reclosable fixed-position joints.*** When mating surfaces always match, as with hinged doors, compression set creates a constant, reduced "uncompressed" height. This makes it possible to recycle gaskets continuously if sufficient thickness is built into the original gasket.

(3) ***Interchangeable joints.*** Symmetrical coverplates, for example, rarely are replaced in the exact position of previous closure. Thus a point of minimum compression may coincide with a point of maximum gasket compression set. This type of joint requires the greatest thickness of gasket when originally installed to reduce the amount of compression set. Interchangeable joints should be avoided in RF-proof designs.

The third design parameter, total joint unevenness, is important because it is used for the determination of the gasket height. Fig. **4-20** shows how the total joint unevenness A d_h is determined. A simple rule of thumb determines the minimum gasket height for the three categories:

Category (1) Gasket height equals **2** X A d_h
Category **(2)** Gasket height equals **3** X A d_h
Category (3) Gasket height equals **4** X A d_h

Another rule of thumb that applies specifically to fluid gaskets can also be applied to conductive gaskets: the greater the compressibility, the greater the sealability. This principle is illustrated in Fig. **4-21** which depicts a simulated joint and three gaskets. Fig. 4-21(A) is the joint to be closed. Gasket 1 is one half the height of 2 and 3, and is very resilient; gasket **3** has the same resiliency as 1; and gasket **2** is harder than 1. For simplicity, assume gaskets 1 and **3** have twice the resiliency of **2.** They compress **50** percent under the force $\bar{F}$ applied to the joint, while **2** compresses only to **75** percent of original height. Fig. **4-21(B)** shows gasket 1 compressed to 50 percent at the point of maximum

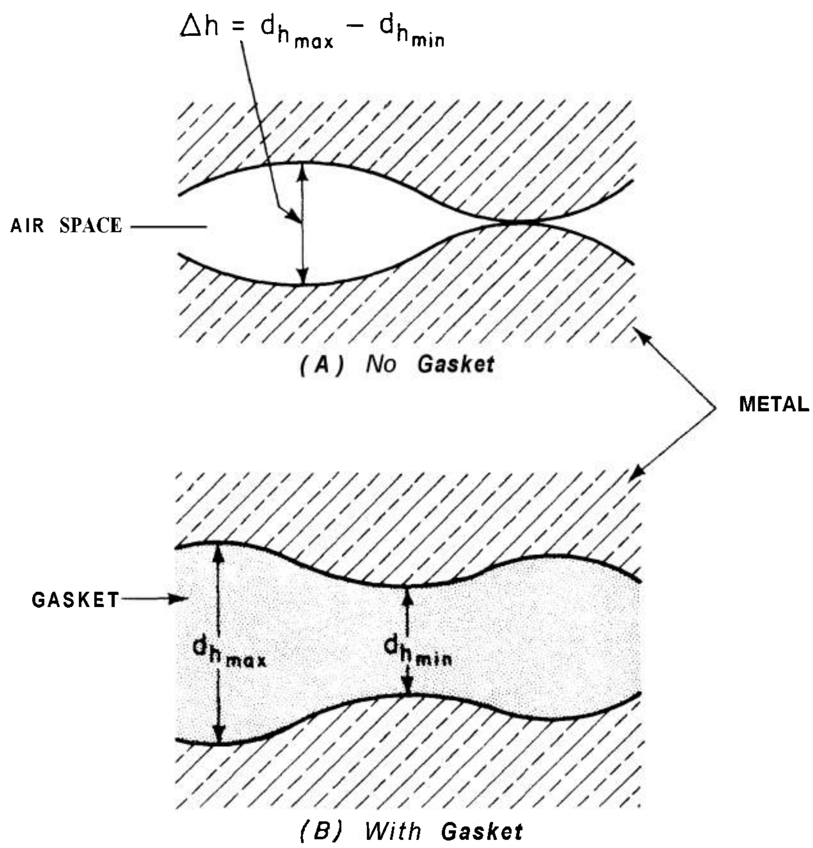


Fig. **4-20.** Typical Mechanical Characteristics **of** a Resilient Metallic Gasket compression and is not sufficient to seal the joint fully. Gasket 2 is then inserted (Fig. **4-21(C)**) but, because it compresses only **25** percent under the same force, its greater height does not result in greater sealability. In Fig. **4-21(D)** gasket **3** is compressed 50 percent, the same percentage as **1**, since they are equally resilient. Because **3** is twice as thick as gasket 1, the same percentage of compression results in twice the actual compression, which is enough to effect the seal. Fig. **4-21(D)** illustrates the basic axiom of gasket design; the gasket must be compressible and thick enough to conform to the irregularities of both surfaces under the applied force.

4-1.3.6.3 Material Selection

The classical shielding effectiveness equations for solid metal shields indicate that shielding performance depends on the permeability and the conductivity of the metal used as a shield. The same type of behavior can be expected, in a general way, from gasket material. The common procedure for selection of a gasket material is to select a material that would perform adequately as a solid shield in the frequency range and field conditions being considered. For example, if a gasket is to perform adequately in high magnetic fields at low frequencies, a material having a high permeability is usually selected.

The absorption loss (attenuation) of various materials at **150** kHz is given in Table **4-3.** Study of this table shows that Mu-metal and Rermalloy, whose permeabil ity is approximately **80,000,** offer the highest attenuation at low frequencies to both magnetic and electric fields. These. theoretical attenuations cannot be obtained if the material is driven into magnetic saturation; however, in gasket material selection this fact is usually ignored. In selecting a gasket material, the several major points to consider are:

a. Material should be compatible with mating surface.

b. Material should be corrosion resistant.

c. Matetial should be ferrous if intended for attenuating low frequencies.

d. Material should have good physical properties.

e. Material should have the highest possible conductivity compatible with its use.

The relative properties of three widely used knitted wire mesh materials are shown in Table **4-7.**

Various materials have been used to combine resiliency and conductivity. Some of the more common materials are tabulated in Table **4-8** with their chief advantages and chief limitations.

There is available to the designer various manufacturers' handbooks and catalogues which illustrate the form and type of gasketing material the manufacturers can supply along with specific information as to mechanical, electrical, and corrosion properties of the gasket materials. The list includes the following:

a. Primec Corporation, Los Angeles, California: "electroknit" mesh, strips and gaskets, monel, aluminum, and silver plated brass.

b. Technical Wire Products, Inc., Cranford, New Jersey: strip matting, formed gaskets, shielding tape, fluid and shielding gaskets, felts, monel, aluminum, silver plated brass (Ref. **12).**

c. Magnetic Metals Company, Camden, New Jersey: tubing, tape, and foil. Nickel iron alloys, silicon iron alloys, low carbon steel, copper.

d. Metex Corp., Edison, New Jersey: metallic sheath, honeycomb panels, feltex material, mesh strip, knitted wire. Aluminum, monel, silver-plated brass.

4-1.3.6.4 RF Gasket Design

When it is necessary to join several parts of a complete shield, the first consideration should be to minimize the number of joints. The next most important requirement is that a continuous metal to metal contact be maintained along the joints. To achieve this, the two surfaces in contact should be free of oxides, grease, dirt, and warping. If bolts or screws are used, a sufficient number are required to ensure high pressure at contact points furthest away from the bolts or screws (see par. **4-1.3.8.1.2).**

Lack of stiffness of mating members produces distortion of mating surfaces, which results in bulging and insufficient pressure for maintaining good electrical contact. The design of these joints can be facilitated by the use of conductive gaskets. Such gaskets include textile gaskets and knitted wire mesh which are available in many different materials such as copper, monel, silver-plated brass, aluminum, and beryllium copper (see par. **4-1.3.6.3** for company listings). These gaskets can be combined with or imbedded in rubber or plastic to serve as water-, air-, and oil-seals as well as impenetrable interference shields. Examples of typical mounting methods are shown in Fig. **4-22,** and various available configurations of gaskets are shown in Fig. **4-23.**

Another type of gasket frequently used (Fig. **4-24**) is fingerstock. This is a multiple joint spring-loaded contact with serrated fingers, which is a very efficient method of obtaining continuity. The serration gives enough spring pressure at the points of contact for electrical continuity. Materials used for fingerstock include beryllium copper, phosphor bronze, sheet metal,

TABLE 4-7

PROPERTIES OF TYPICAL GASKET MATERIALS"

Gasket Material	Corrosion Resistance	Compatibility With Aluminum or Magnesium	Conductivity Intrinsic	Conductivity Contact	Conductivity In Presence of Corrosion	Resistance To Set	Tensile Strength	Surface Hardness
Monel	1	2	3	2	1	2	1	1
Silver-Plated Brass	2	3	2	1	2	1	2	2
Aluminum	3	1	1	3	3	3	3	3

where 1 is the most desirable material
2 is a compromise
3 is the least desirable material

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TABLE 4-8

CHARACTERISTICS OF CONDUCTIVE GASKETING MATERIALS

Material	Chief Advantages	Chief Limitations
Compressed knitted wire	Most resilient all-metal gasket (low flange pressure required). Most points of contact. Available in variety of thicknesses and resiliencies.	Not available in sheet form (Certain intricate shapes difficult to make). Must be 0.040 in. or thicker.
Aluminum screen impregnated with neoprene	Combines fluid and conductive seal. Thinnest gasket. Can be cut to intricate shapes.	Very low resiliency (high flange pressure required).
Soft metals	Cheapest in small sizes.	Cold flows, low resiliency.
Metal over rubber	Takes advantage of the resiliency of rubber.	Foil cracks or shifts position. Generally low insertion loss yielding poor RF properties.
Conductive rubber	Combines fluid and conductive seal.	Practically no insertion loss, giving very poor RF properties.
Contact fingers	Best suited for sliding contact.	Easily damaged. Few points of contact.

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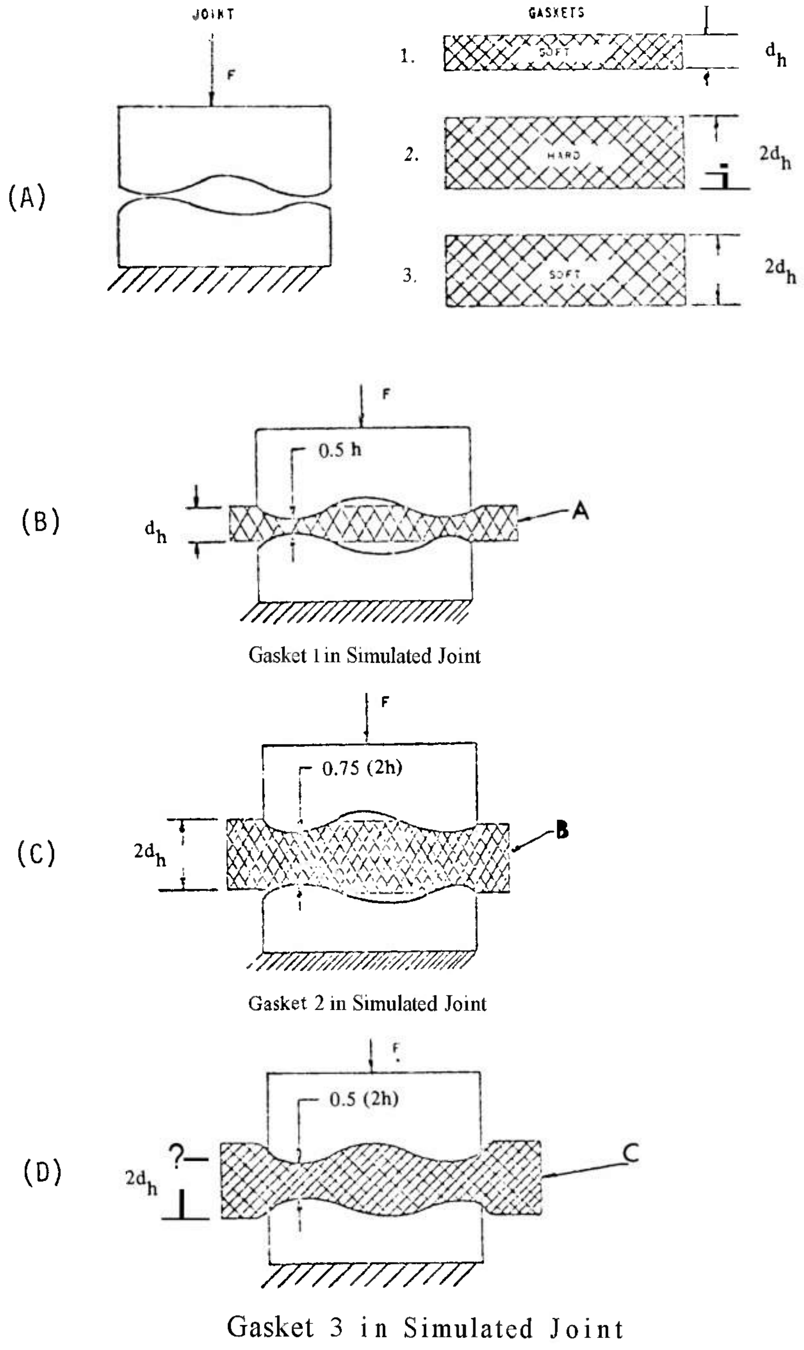


Fig. 4-21. Gasket Compressibility vs Sealability[13]

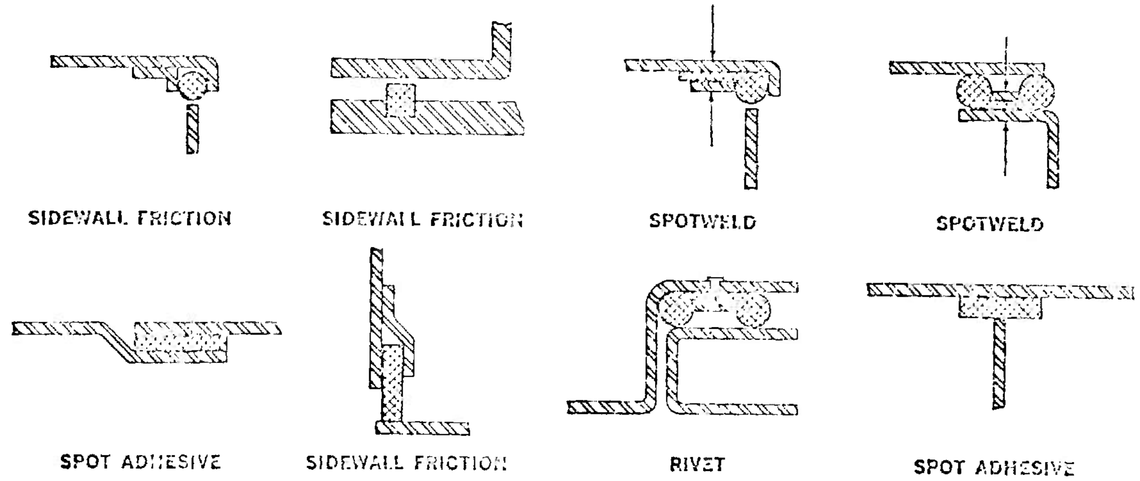


Fig. 4-22. Typical Mounting Methods[15]

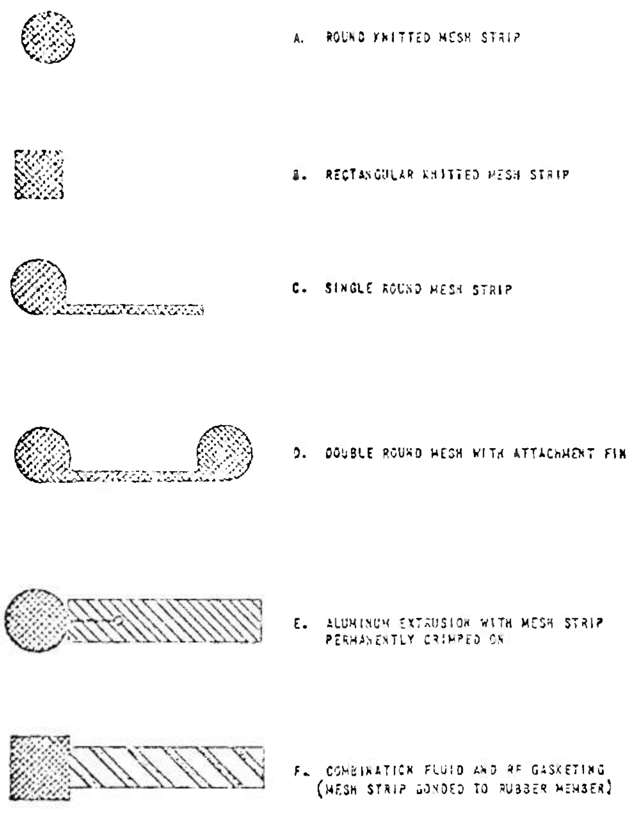


Fig. 4-23. Various Gasket Configurations

and tempered aluminum. The case of the component should be made of the same material to prevent corrosion. Use of fingerstock permits simplified design of enclosures. There is little or no shearing load placed on fasteners and the fingerstock has high dynamic range, long life, and multiple lines of wiping contact.

A typical example of a weapon system in which RF gaskets are used is shown in Fig. 4-25. This figure shows the ballistic case of the LANCE warhead section, Gaskets are used between Sections A, **B,** C, and D. Gaskets are also required at the maintenance door and the parameter insertion door. Fig. 4-26 is a photograph of the XM205 Adaption Kit Subassembly. In this assembly, gaskets are used at the bolted flange and also under each component that is attached to the bulkhead. Two other features that are employed are the use of a sealed input shaft similar to Fig. 4-27 and every bolt is backed up internally by metal cups that are soldered to the back plate of the door flange to the shield in back of the bolts. Fig. 4-28 is a sketch of the feature.

4-1.3.7 Holes and Openings

The weapon system designer could ignore any RF effect if he could place the various components of his system in a metal enclosure, seal it, and never have to disturb it during its useful life. Unfortunately, this is not possible; every opening (doors, shaft holes, ventilation holes, etc.) must be considered as a possible point of entry for radio frequency energy.

The number and size of openings in an equipment enclosure should be kept to a minimum. For example, when holes are provided in the bottom of an enclosure for draining of condensed moisture, only a few holes, no more than 0.25 in. in diameter, are usually sufficient. Leakage of electromagnetic energy through these holes is usually negligible. Large openings require waveguide devices or screens to deny entry of RF energy.

4-1.3.7.1 Waveguide-below-cutoff Devices

Maximum hole dimensions permitted vary according to frequency. Electromagnetically, a small aperture is one which is smaller in its largest dimension than the shortest wavelength of concern. An aperture approaching or exceeding a wavelength in size should be covered by a fine copper mesh screen. Alternatively, a series of small unscreened apertures may be used instead of a large single hole; or waveguide attenuators may be used to shield large apertures. The waveguide attenuator is also of considerable value when shafts must pass through an enclosure. When an insulated control shaft passes through a waveguide attenuator, the control function can be accomplished with small **RF** leakage. Fig. 4-29 is an illustration of how a circular waveguide can shield a hole in a weapon housing.

The coupling through small holes has been considered in par. 4-1.1.2. The actual value of **RF** protection provided by a waveguide-below-cutoff device depends upon the impedance conditions at the inside interface of the hole, and the impedance of the wave incident on the RF illuminated end of the hole as well as the depth (or length) of the hole. The best estimates of the protection provided indicate that the longer the hole, in relation to its longest transverse dimension, the more protection provided. This estimate is based on the impedance behavior of any mode of propagation that can exist in the hole. Essentially the estimate is that the greater the length to longest transverse dimension ratio, the more unlikely it will be that the impedance conditions existing at the interior interface of the hole will cause appreciabie coupling through the hole.

An acceptable method of shielding apertures for meters or other panel-mounted readout devices is illustrated in Fig. 4-30. Exhaust nozzles also should be shielded. A method that is easy to apply is to cover the nozzle with metal foil; the exhaust blast will simply tear off the foil from the nozzle.

Where the use of waveguide materials is impractical or otherwise undesirable, as in the case of large ventilating holes, substantial reduction of electromagnetic energy can be obtained by covering the aperture with a wire mesh screen. Fig. 4-31 shows an acceptable method of mounting a wire screen over an aperture. A similar method can be used in installing rectangular and circular waveguide materials.

An equipment enclosure that requires inlet and/or outlet apertures for ventilation or pressurization should be designed with a screen or a series of honeycomb tube ducts (designed to act as waveguide-below-cutoff devices) placed over the apertures. Although louvered openings are generally used for cooling-air circulation, they are extremely poor RF shields because of their long narrow gaps. In descending order of protection properties, the following materials should be used: honeycomb-type ventilation panels, perforated metal sheet, woven metal mesh, and knitted metal mesh. If perforated metal sheet is used, a single or double layer of copper or brass screen of No. 16 or 22 gage wire, having openings no greater than 1/16 by 1/16 in., is recommended as a backing (Ref. 13).

The RF protection provided by a mesh is thought to be considerably less than that afforded by a solid metal plate. The principal shielding action of a mesh is due

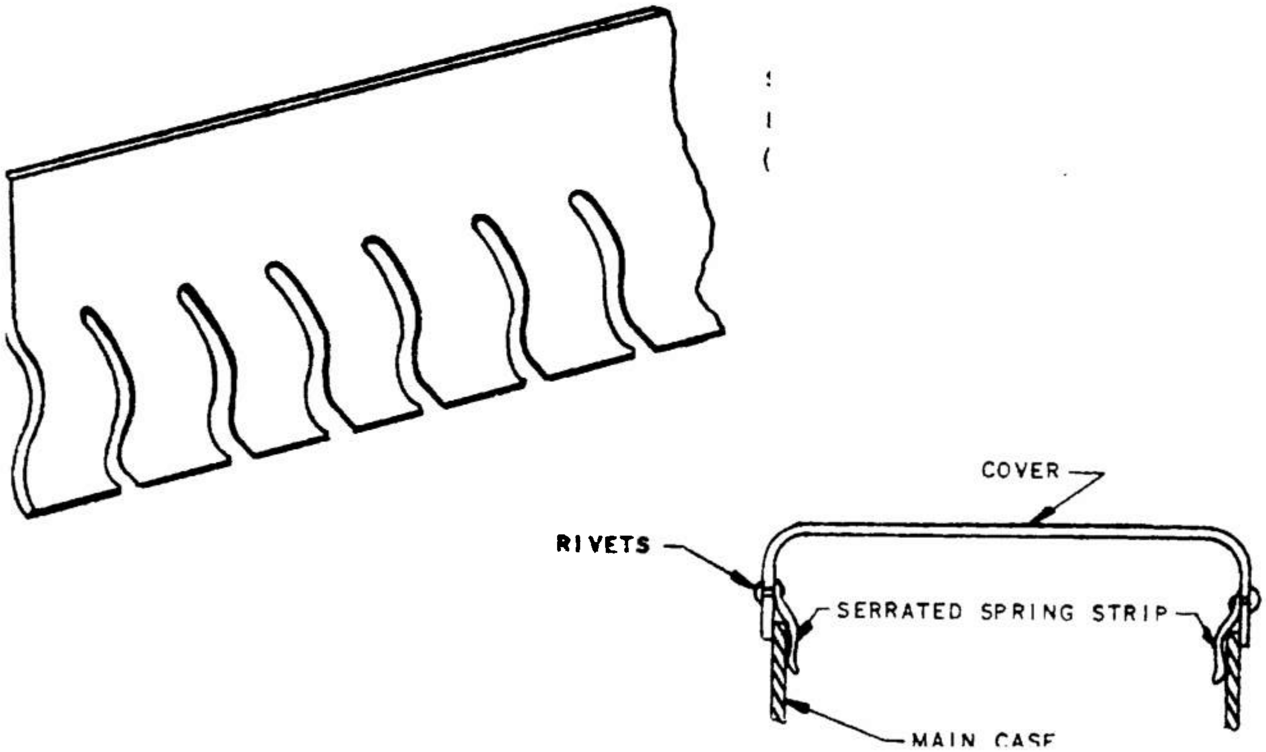


Fig. 4-24. Fingerstock

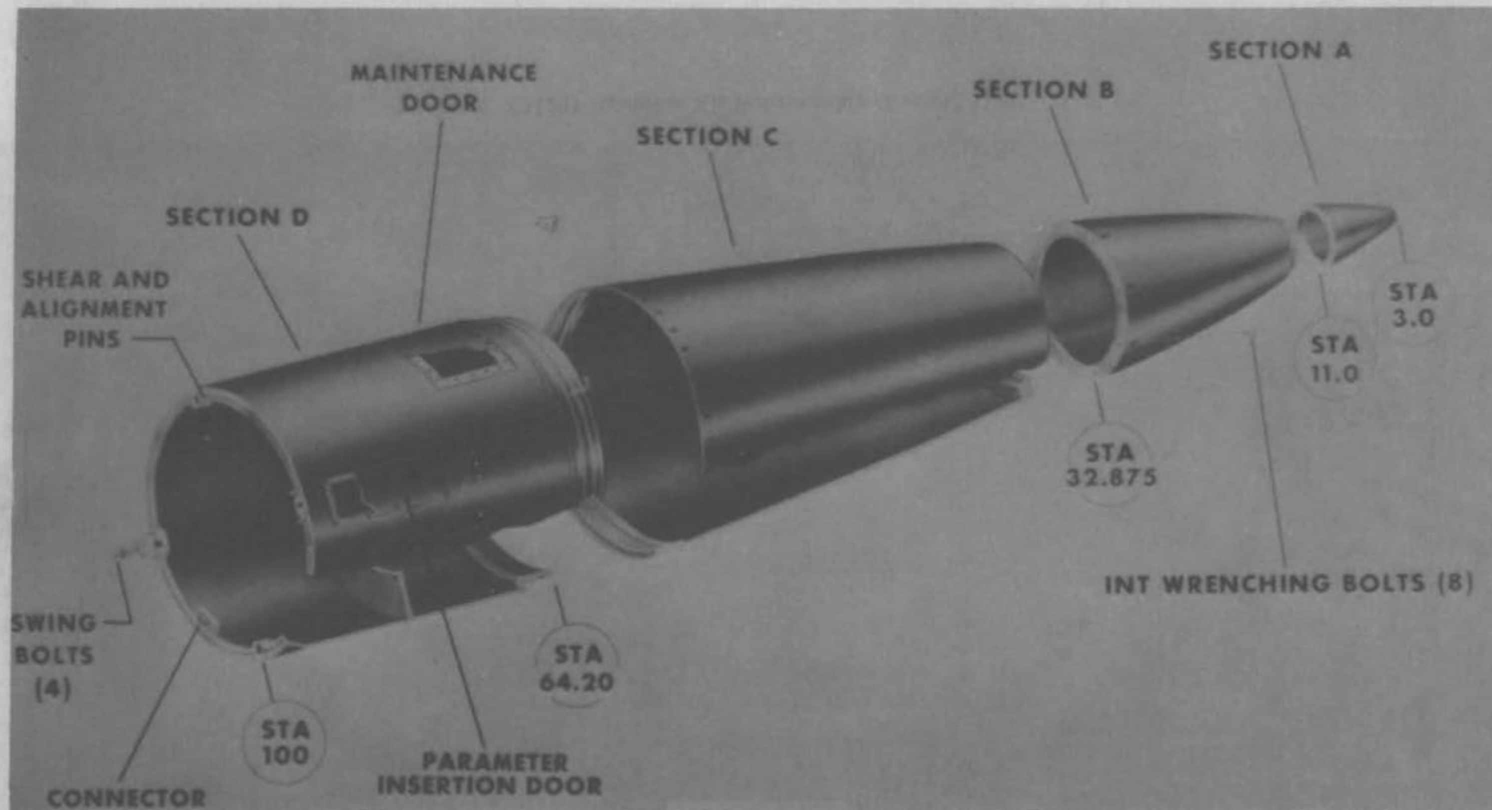


Fig. 4-25. Ballistic Case for LANCE Warhead Section

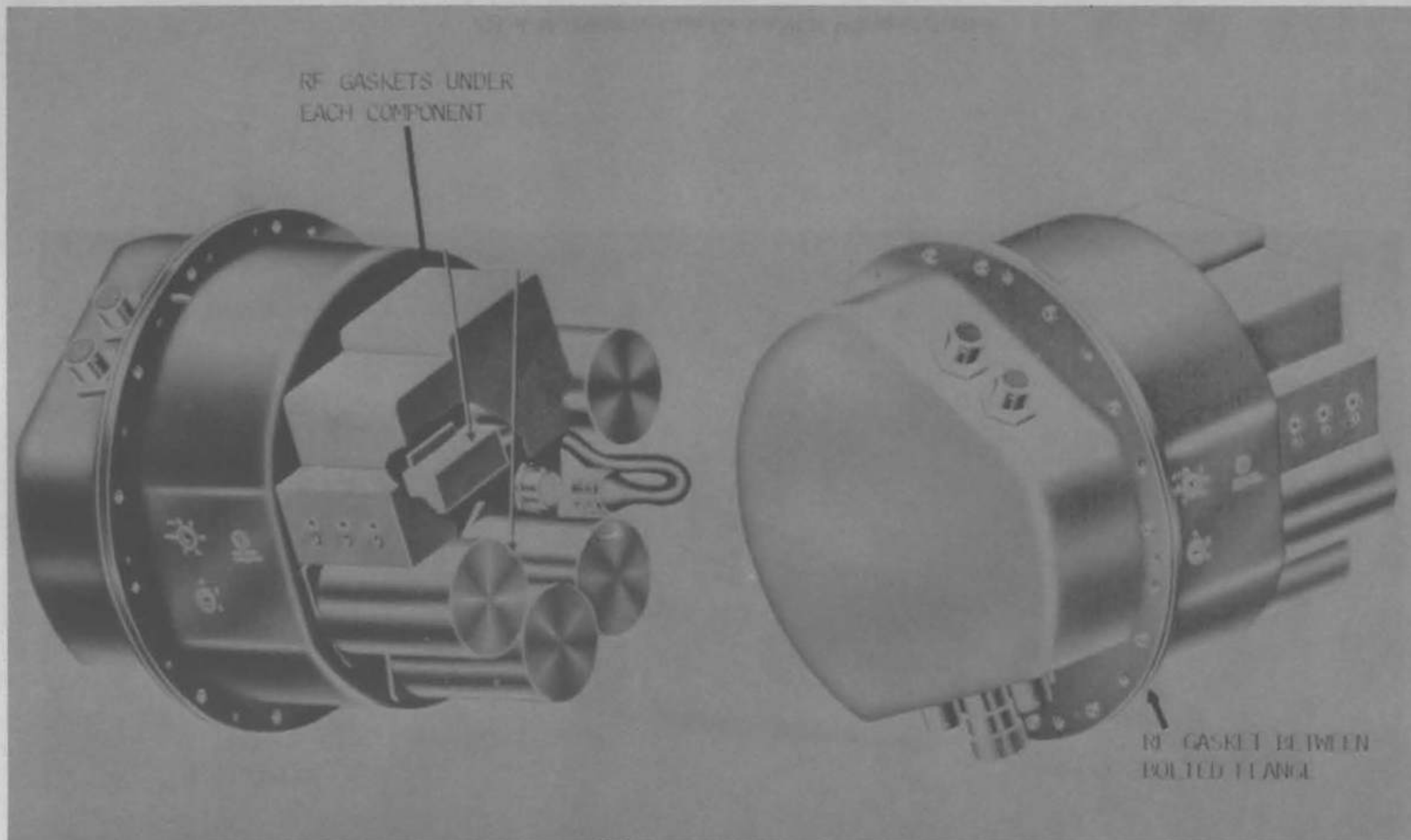


Fig. 4-26. XM205 Adaption Kit Subassembly (Control Unit)

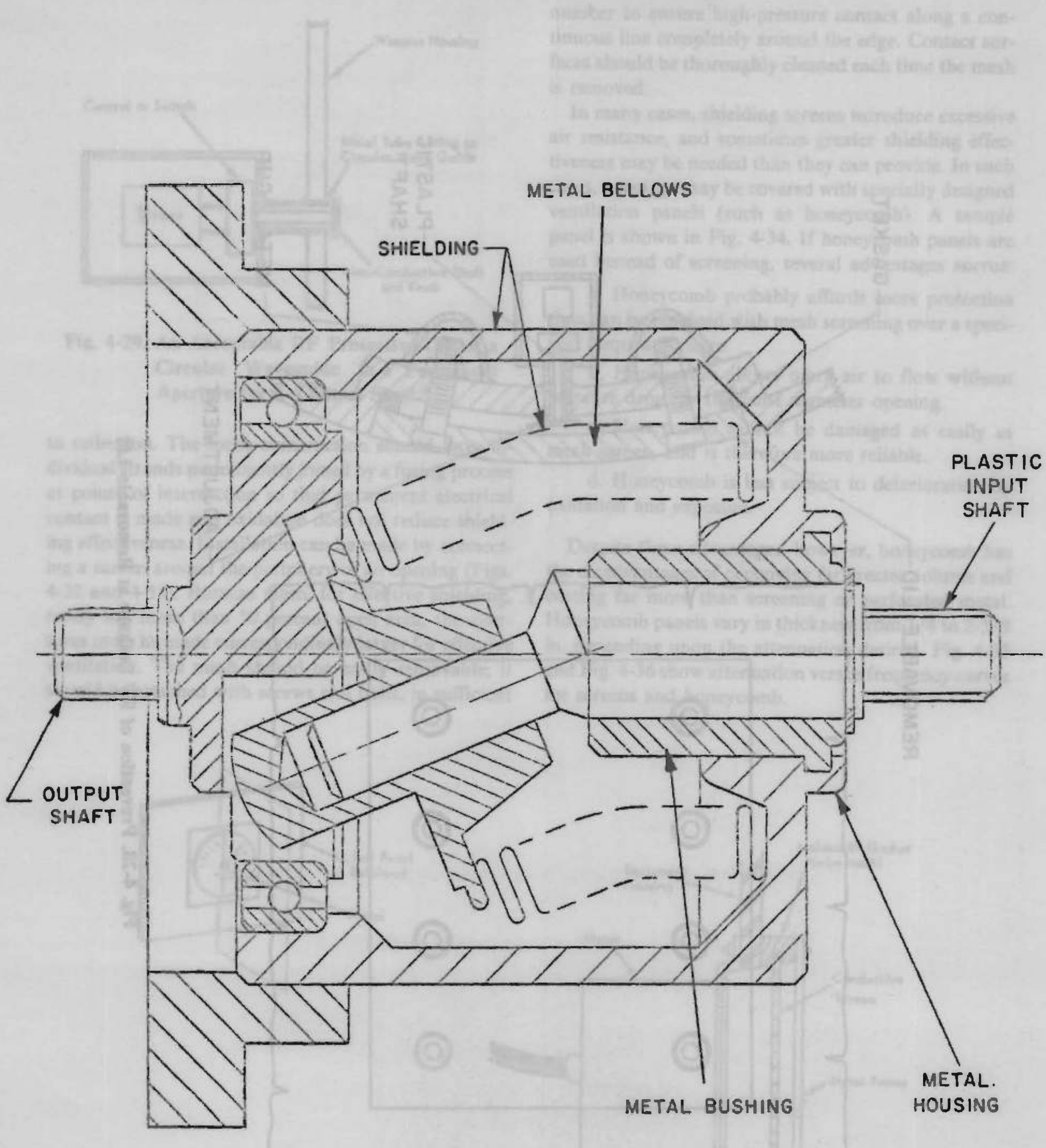


Fig. 4-27. Sealed Input Shaft Mechanism

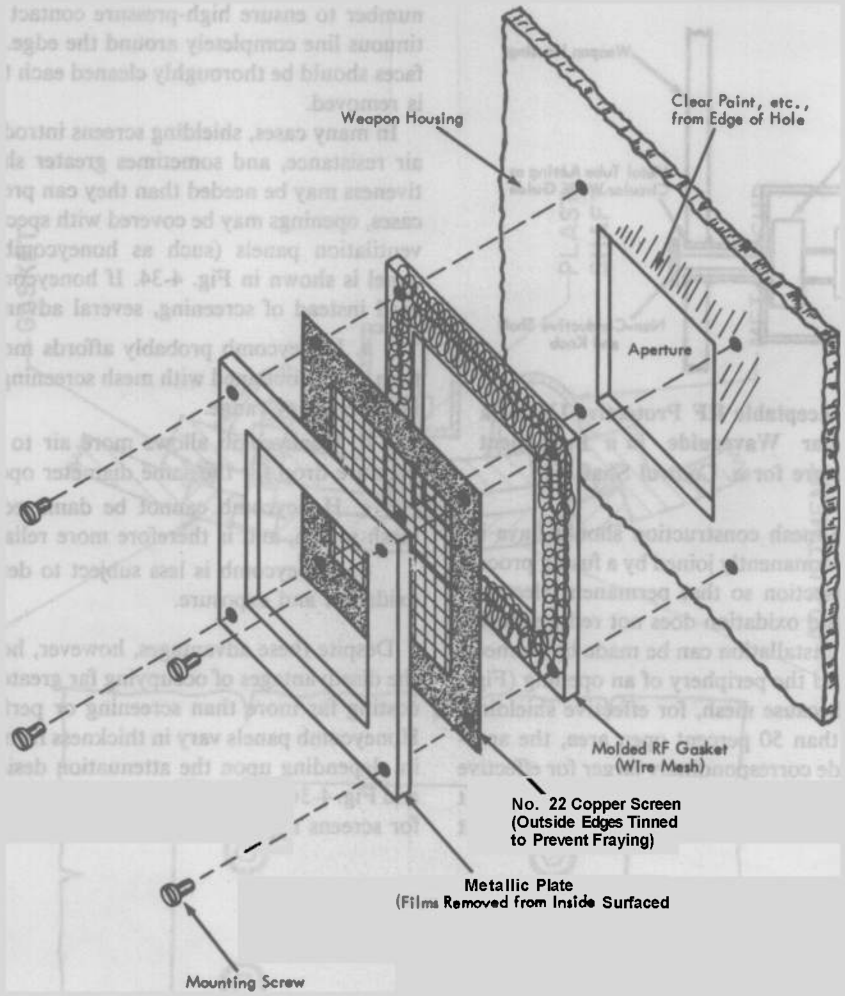


Fig. 4-31. Method of Mounting Wire Screen Over a Large Aperture

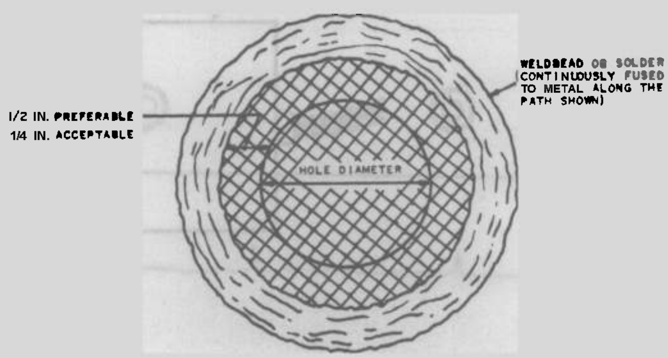


Fig. 4-32. Typical Welded Screen Installation Over a Ventilation Aperture[13]

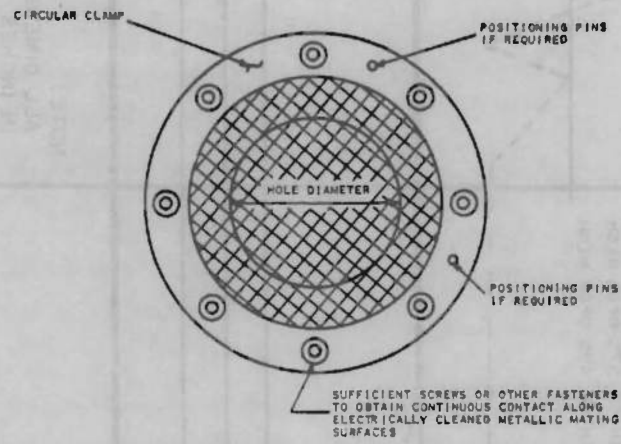


Fig. 4-33. Typical Bolted Screen Installation Over a Ventilation Aperture[13]

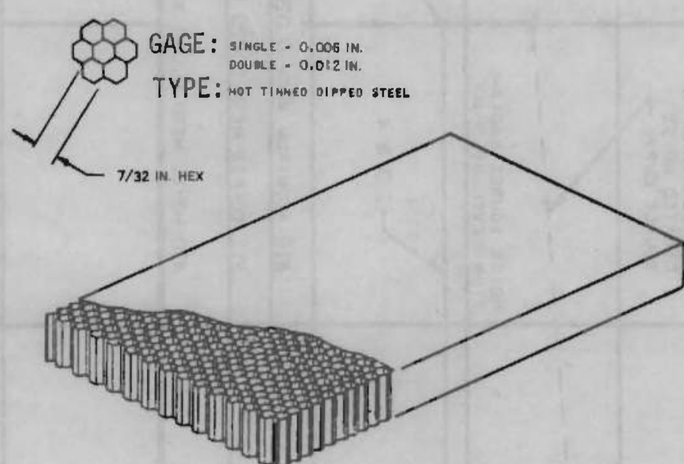


Fig. 4-34. Honeycomb-type Ventilation Panel

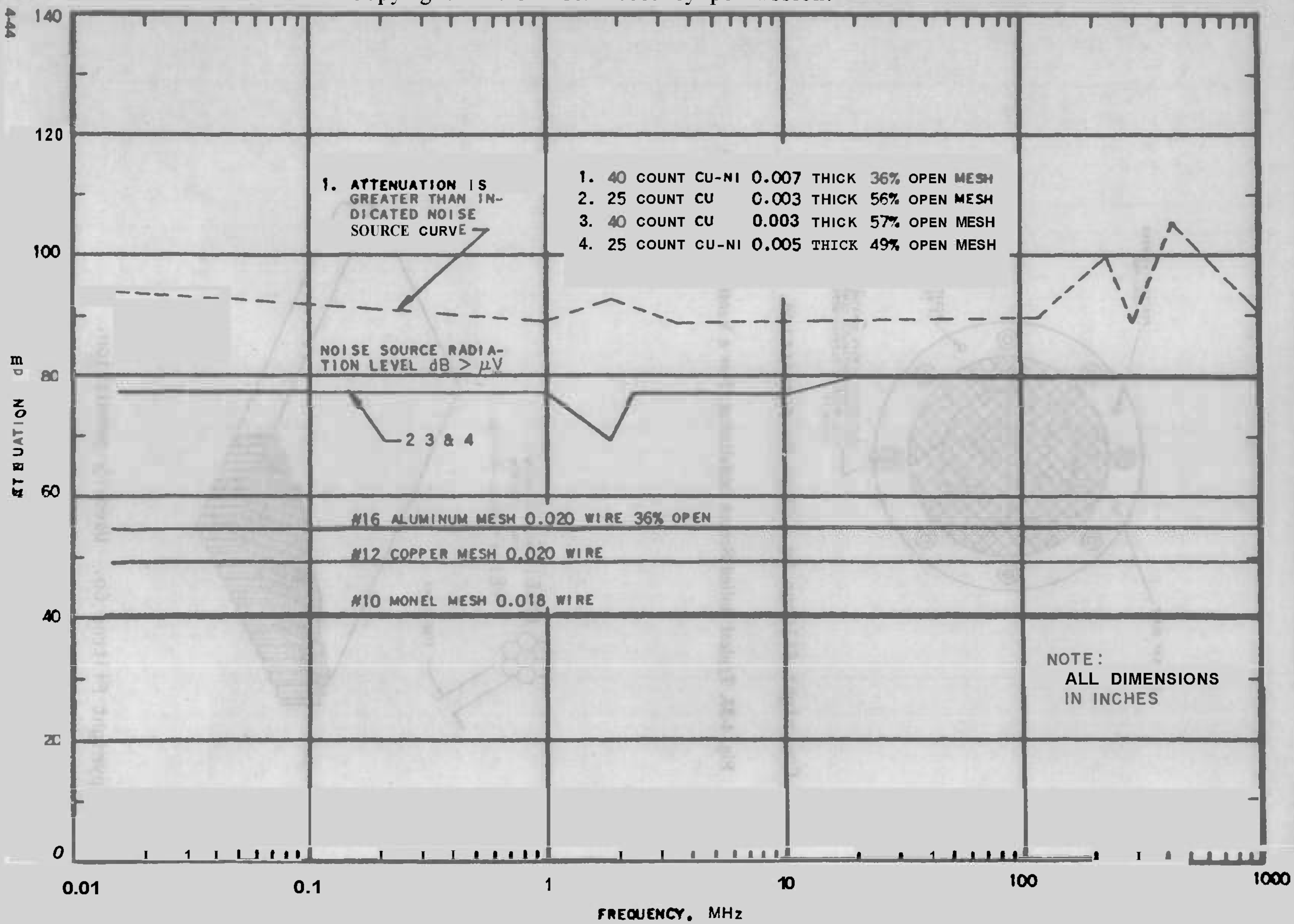


Fig. 4-35. Attenuation vs Frequency Curves for Various Screens

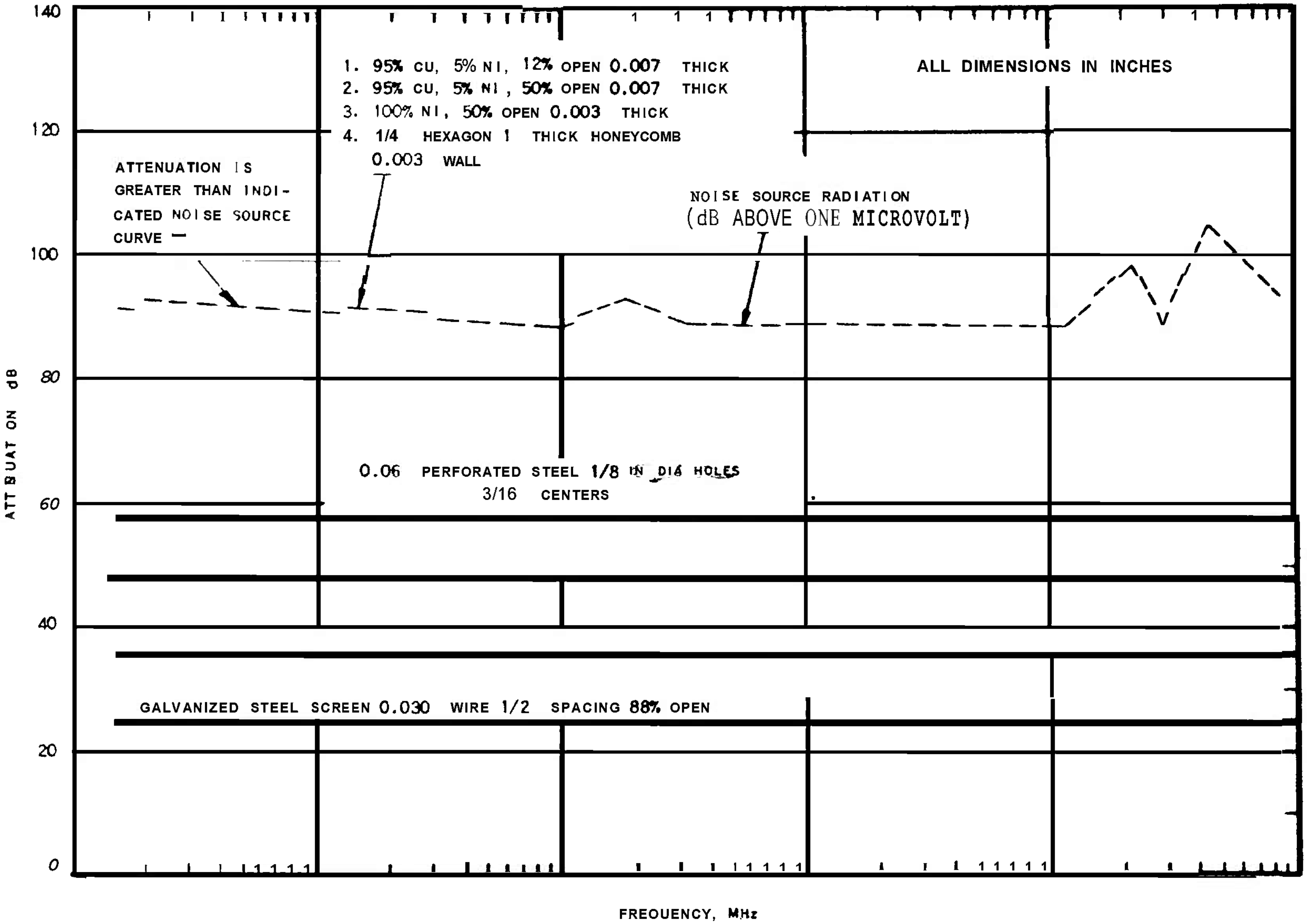


Fig. 4-36. Attenuation vs Frequency Curves for Various Screens and Honeycomb

4-1.3.7.2 Shielding Effectiveness

The action of the waveguide operating below cutoff (when it is used at a wavelength greater than its cutoff wavelength) is represented in Fig. 4-37 for a rectangular waveguide and in Fig. 4-38 for a circular waveguide, both for a d_d / d_d ratio of 1 where d_d is depth of waveguide (inches) and d_c is inside diameter of waveguide (inches) for a circular waveguide and the largest inside cross-sectional dimension (inches) for a rectangular waveguide. *To compute the correct attenuation for a particular design, the value of decibels obtained from these curves must be multiplied by the d_d / d_c ratio for* that design. The frequency range through which any particular size opening can be used is illustrated in Figs. **4-37** and **4-38.**

Screened openings usually must be large to permit sufficient air to flow. If frequencies above 1,000 MHz are to be attenuated to a high degree, ventilation openings must be designed as waveguide attenuators operating below cutoff at their lowest propagating frequency. In this way, shielding effectiveness of over 100 dB can be obtained at frequencies of 10,000 MHz: a 1/4 in. diameter tube, 1 in. in depth, would afford 120 dB of shielding effectiveness at 10,000 MHz: a 1/2 in. diameter tube, 2-1/4 in. in depth, would afford 100 dB at 10,000 MHz. Openings 1 in. or more would have little or no attenuation at 10,000 MHz. To obtain an opening of sufficient size to admit the required volume of ventilating air, tubes should be placed side by side until sufficient air flow is obtained.

4-1.3.8 Bonding to Metallic Structures

Electrical bonding is the process of mechanically connecting certain metal parts so that they will make a good low resistance electrical contact. Adequate bonding is necessary to ensure that a system is electrically stable and protected from the hazards of radio frequency energy, lightning discharges, and static electricity. This differs from grounding which refers to the establishment of an electrical conductive path between the circuit to some reference point. The reference point can be earth, the equipment enclosure, or the vehicle's structure.

In order to obtain the necessary electrical conductivity between various units or between units and the main structure of a system, weapon system designers use various methods which can be included under the general heading of electrical bonding. These bonds must remain electrically stable since they are instrumental in protecting the system from lightning, static electricity, and radio frequency energy. Most weapon systems are constructed with the assumption that the frame and metal skin are electrically continuous as specified by par. **3.3.6.3** in MIL-B-5087: *"Vehicle skin shall be so designed that a uniform low impedance skin is produced through inherent **RF** bonding during construction. RF bonding must be accomplished between all structural components comprising the vehicle."*

Unfortunately, the specification does not indicate what constitutes an acceptable bond. There is, however, a reference made to a maximum dc resistance of 2.5 milliohms from an enclosure to its grounding point. This value is sometimes used as a criterion for panel-to-panel and panel-to-frame acceptance.

4-1.3.8.1 Classification of Bonds

MIL-B-5087B classifies bonds according to their applications. A listing is given in Table **6-4.** An alternate method is to list them by type of bond.

4-1.3.8.1.1 Permanent Electrical Bonds

The permanent electrical bond is the most desirable form of bond from an electrical viewpoint. The interface between the mating metals is cleaned until it is electrically conductive, and then made permanent and moisture proof by welding, brazing, sweating, or other metal flow processes other than soldering. Soldering can be used to fill in the resulting seam, but it is not used as part of the bond strength. Conductive epoxy adhesives are also used in certain applications. The impedance across a permanent joint **is** primarily resistive in nature and can be held at least an order of magnitude lower across a wider frequency range than a jumper or strap. **Also** movement and corrosion between the two permanently joined surfaces are virtually eliminated.

Fig. **4-39** illustrates three types of welds in common use. To obtain the maximum electrical benefit, the weld should be continuous. As an example, if a lid is being permanently welded on an enclosure, the enclosure's shielding effectiveness will be enhanced if the lid is welded continuously around the periphery rather than being tacked only at the corners.

The least desirable weld for a seam **is** a spot weld. Fig. **4-39(D)** shows an exaggerated view of two sheets of metal spot welded together. Note that the area between the welds has a tendency to buckle, thereby making poor electrical contact between the welds. The buckled area will also be susceptible to corrosion unless the seam is covered with a protective coating. The thinner the metals being welded, the more pronounced this buckling effect.

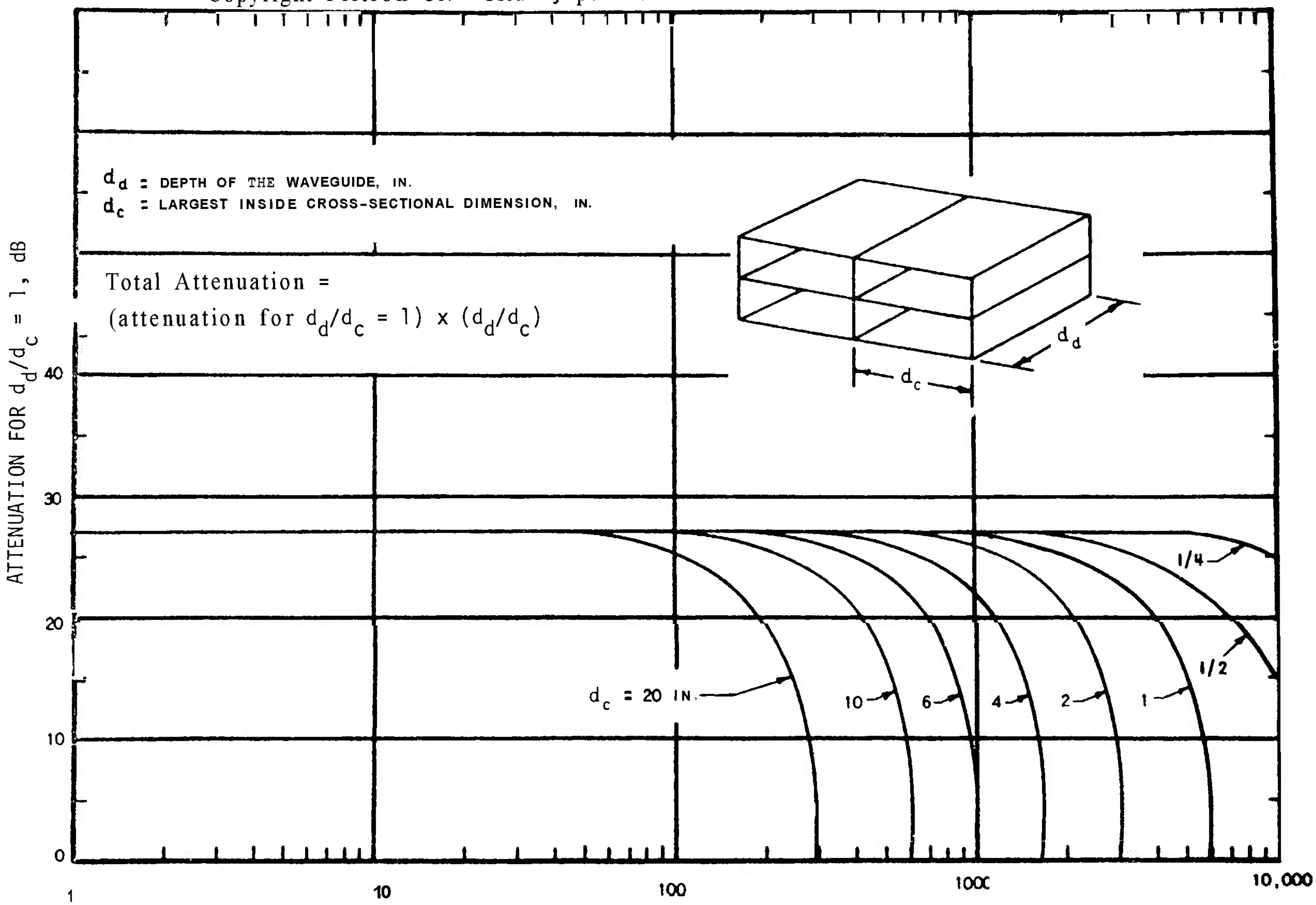


Fig. 4-37. Attenuation–Rectangular Wavegide

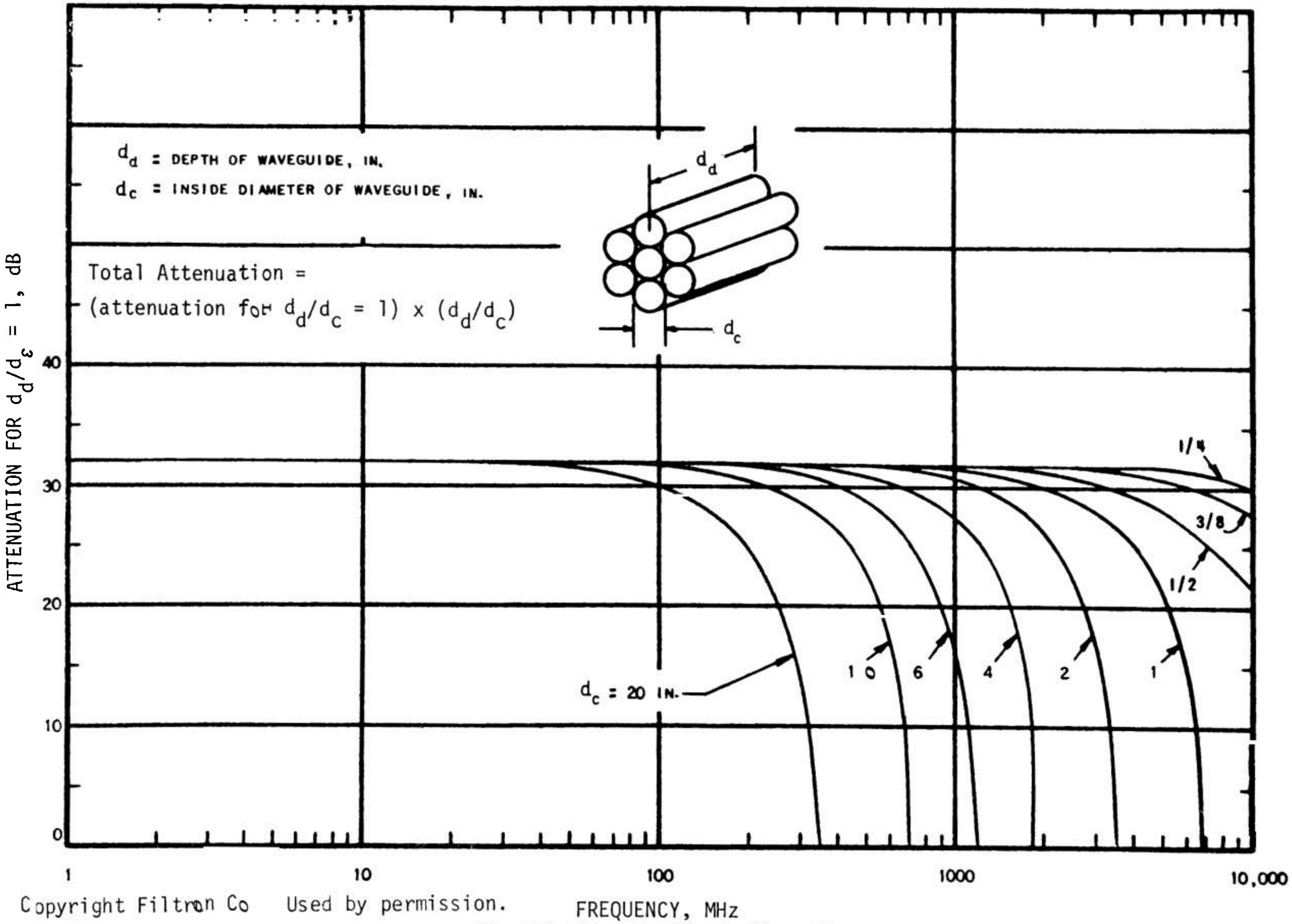


Fig. 4-38. Attenuation–Circular Waveguide

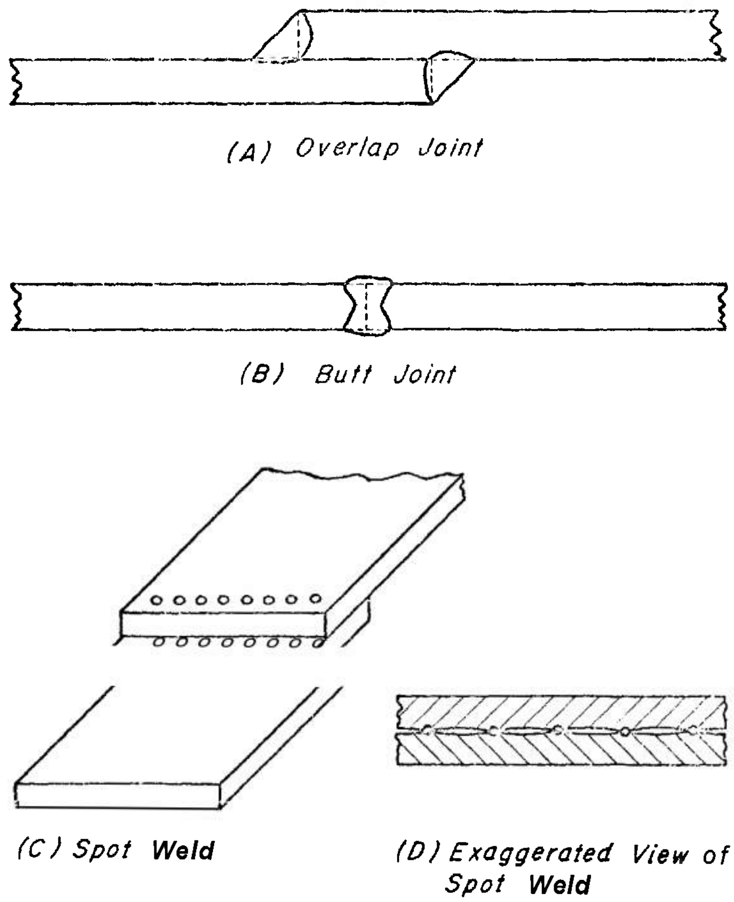


Fig. 4-39. Different Types of Welded Joints

4-1.3.8.1.2 Semipermanent Electrical Bonds

a. *Direct Bonds*

This classification includes metal joints or interfaces formed by swaging, metal-to-metal joints held together by thread-locking devices, riveted joints, tie-rods, structural wires under heavy tension, and pinned fittings driven tight and not subject to wear. It is good practice to protect such joints from moisture and its resulting corrosion since they tend to experience separation between the surfaces similar to that encountered with spot welding.

When bolts, screws, rivets, or spot welds are used to fabricate a bond, the shielding effectiveness is influenced by the spacing between the joints as illustrated in Fig. **4-40** (Ref. 3). The shielding effectiveness presented is that measured by RFI/EMI specified methods and does not represent the RF protection provided in weapon system usage. Measurements of this type provide the only data normally available.

An acceptable bonding technique using bolts is shown in Fig. **4-41** In this semipermanent installation, the mating surfaces are soldered together. Once again it should be mentioned that the purpose of the solder is to lower the joint impedance and should not be considered as parr of the bond strength. This is considered as a semipermanent bond since the solder can be easily removed with a hot iron.

The assembly in Fig. 4-41(A) shows a locknut as the mate to the bolt which is typical when soft metals; e.g., aluminum, are used. For harder metals, a regular nut plus a lock washer can be used (Fig. 4-41(B)).

b. ***Indirect*** *Bonds*

There are situations where it is not possible to directly bond a piece of equipment to the main structure.

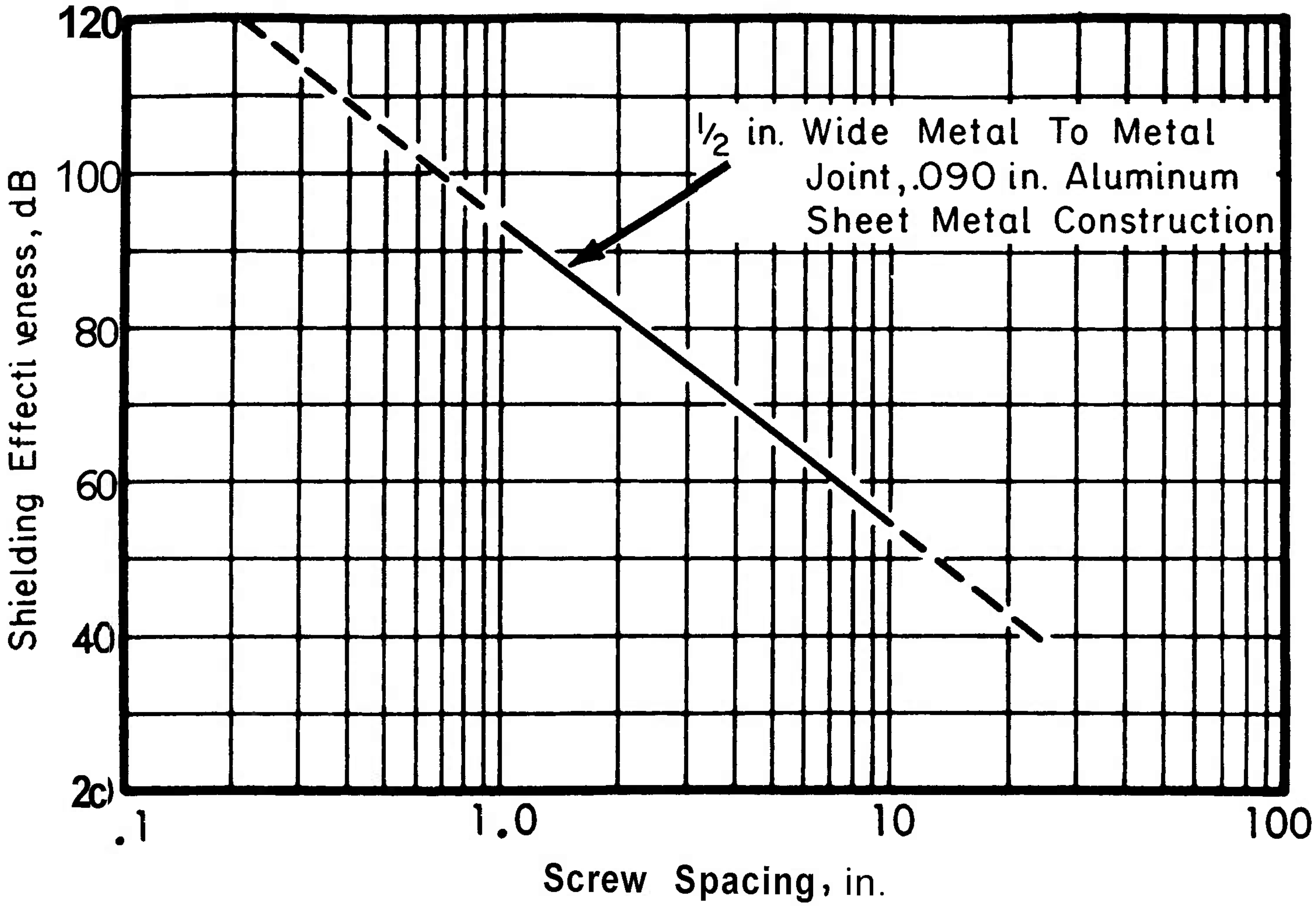
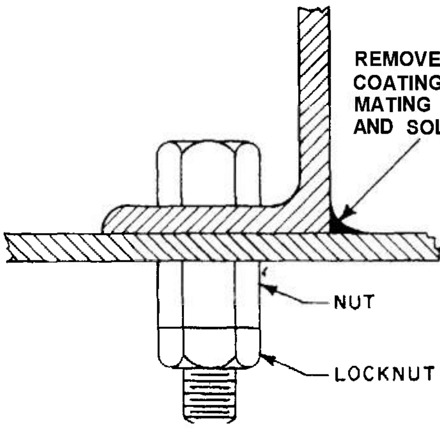
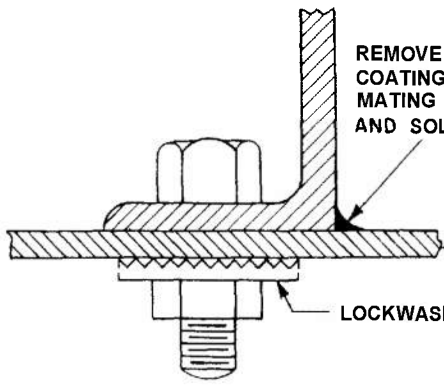


Fig. 4-40. Influence of Screw Spacing



(A) LOCKNUT FOR SOFT MATERIAL



(B) LOCKWASHER FOR HARD MATERIAL

Fig. 4-41. Use of Nut and Bolt for Bonding

Under these circumstances, it is common practice to use a bond strap or a jumper. MS25083 is used by the military services as a guide in constructing jumper assemblies. Fig. 4-42 shows a page from this MIL-STD in which a diagram of the construction of a strap is given plus a table that presents information as to the type of strap, terminal size, wire size, resistance, and tensile strength.

A few simple rules should be observed when bonding components to the main system. Two such procedures are illustrated in Figs. 4-43 and 4-44. Both of these figures imply that the bond should be made directly to the basic structure rather than to any adjacent component, and that the strap should be unbroken.

A chassis that is insulated from ground will have a certain stray capacitance between it and the ground. When a ground strap is placed between the two, the capacitance is effectively short circuited if the strap has a resistance of only a few milliohms. However, when radio frequencies are considered, the length of the strap becomes important because of its inherent inductance. For this reason, bonding straps are usually considered effective when their length is one sixteenth or less of the wavelength of the frequency being grounded.

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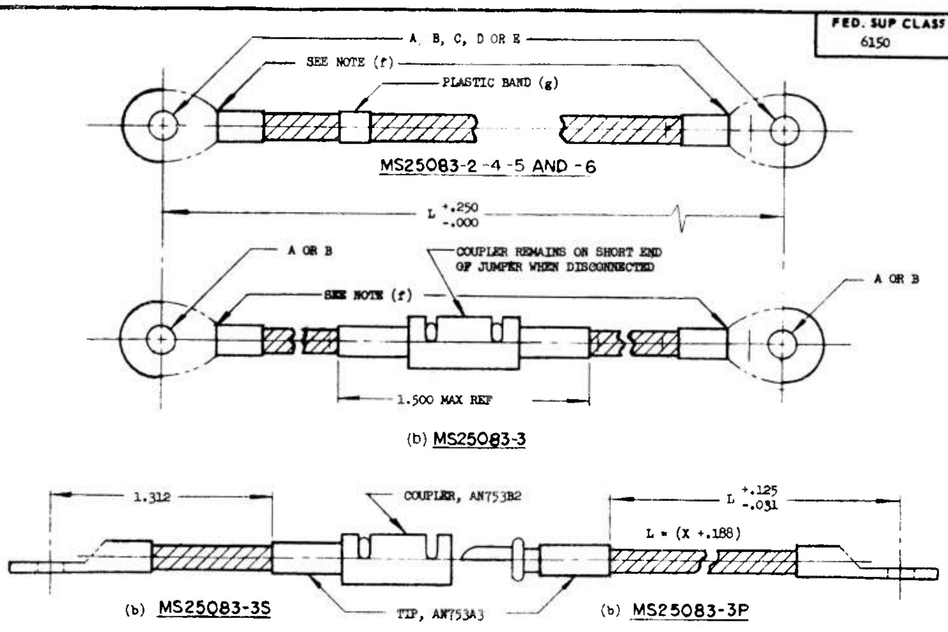


TABLE IV

	DASH NO.	TYPE	TERMINAL STUD SIZE (OPTIONAL)	PLASTIC BAND COLOR	COPPER WIRE SIZE	TERM. TO TERM. RESISTANCE* OHMS - MAX Initial	TERM. TO TERM. RESISTANCE* OHMS - MAX After Test	TENSILE STRENGTH lb. Min.
	-2	Bonding	A,B,C,D,E	-	12	.00016 L +.00024	.00016 x L +.00034	110
(b)	-3	Quick Disconnect	-	-	12	.00016 x L +.00085	.00016 x L +.00120	
(b)	-3S	Short End of -3	A,B	-	12	-	-	
(b)	-3P	Long End of -3	A,B	-	12	-	-	
	-4	Current Return	D,E	-	8	.00006 x L +.00013	.00006 x L +.00016	225
	-5	Bonding (Lightning)	A,B,C,D,E	Yellow	12	.00016 x L +.00024	.00016 x L +.00034	110
	-6	Current Return (Lightning)	D, E	Yellow	8	.00006 x L +.00013	.00006 x L +.00016	225

* L in inches

TABLE V

STUD HOLE DESIGNATION	STUD SIZE	(F) TERMINAL (REF) MS25036	MS20659 (e)
A	NO. 4 OR NO.6	-111	
B	NO. 8 OR NO.10	-112	
C	1/4	-157	
D	5/16	(c)-113 (d) -117	(c)-106 (d)-108
E	3/8	(c)-114 (d) -118	(c)-128 (d)-129

(b) MS25083-3, -3S AND -3F INACTIVE FOR AIR FORCE AIRBORNE APPLICATIONS AFTER 9 DECEMBER 1963.
(c) APPLICABLE FOR MS25083-2.
(d) APPLICABLE FOR MS25083-4.
(e) MS20659 OPTIONAL TO MS25036 AS SHOWN.
(f) RESISTANCE READINGS SHALL BE TAKEN BETWEEN INTERSECTION OF TERMINAL BARRELS AND TONGUES.
(g) PLASTIC BANDS SHALL CONFORM TO IMMERSION TESTS OF MILT-7928.

User activities:

Review activities: Navy - AS, Army - EL, USAF - 11

This military standard is approved by the Department of Defense and is mandatory on all activities. Selection for all new engineering and design applications and for repetitive use shall be made from this document.

APPROVED 30 Jun 54 REVISED (F) FOR CHANGES SEE SHEET 3.

P.A. Navy - AS Other Cust Army - EL USAF - 11	TITLE JUMPER ASSEMBLY, ELECTRIC, BONDING AND CURRENT RETURN	MILITARY STANDARD MS25083
PROCUREMENT SPECIFICATION NONE	SUPERSEDES: AN749, AN751, AN752 AND SPECIFICATION AN-J-1	SHEET 3 OF

DD FORM 672-1 (Coordinated) PREVIOUS EDITIONS OF THIS FORM ARE OBSOLETE.

Fig. 4-42. Military Standard for Bonding Strap

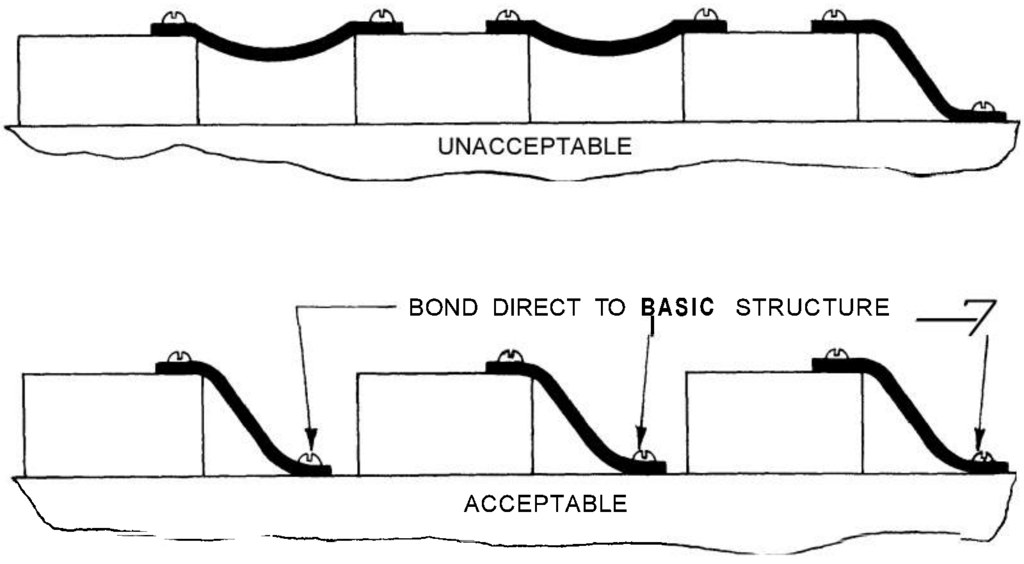


Fig. 4-43. Bonding Techniques (Direct vs Indirect)

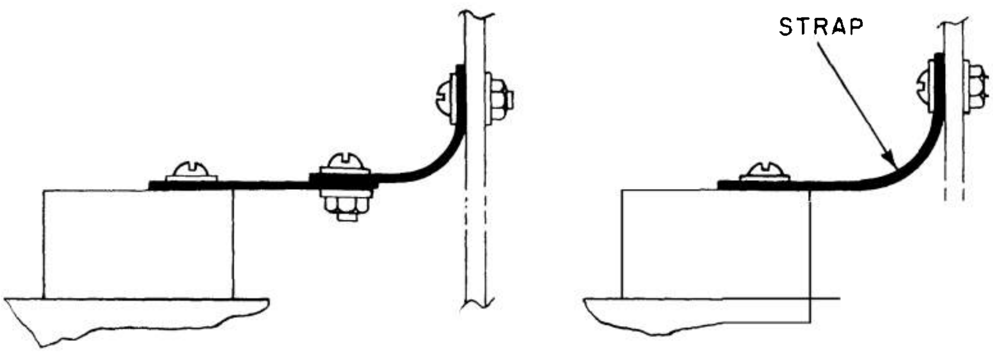
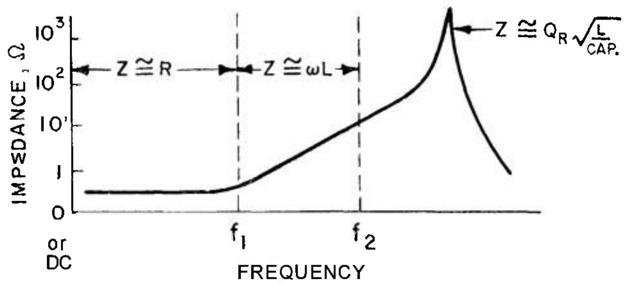


Fig. 4-44. Bonding Techniques (Solid Strap)

Examination of the literature on bonding reveals that the impedance of a jumper varies with frequency as shown in Fig. **4-45.** Three distinct frequency ranges can be discerned in this figure. From 0 to f_1 the impedance is primarily resistive, being composed of the jumper resistance and contact resistance at the terminals. From f_1 to f_2, the inductive reactance of the jumper predominates. Above f_2 parallel resonance with the stray capacitance occurs with the jumper being considered as a one turn coil. The obvious conclusion drawn from these data is that the bonding strap should be as short as possible. There are, however, other factors that must be considered such as shown in Fig. **4-46** where a strap length is required which will not restrain the shock mounted unit.

4-1.3.8.2 Dissimilar Metals

In the process of bonding, dissimilar metals come into contact. Direct contact of dissimilar metals in the presence of moisture results in corrosion which will impair the effectiveness of the electrical bond and also physically weaken the bond. The procedure to follow when this occurs is discussed in par. **4-**1.3.9, Corrosion.



Z = IMPEDANCE OF STRAP, Ω

R = RESISTANCE OF STRAP, Ω

L = INDUCTANCE OF STRAP, H

CAP. = STRAY CAPACITANCE TO GROUND, F

$\omega = 2\pi f$

f = FREQUENCY, Hz

Q_R = FIGURE OF MERIT $\left(\frac{X_L}{R}\right)$

Fig. 4-45. Impedance of a Bonding Strap

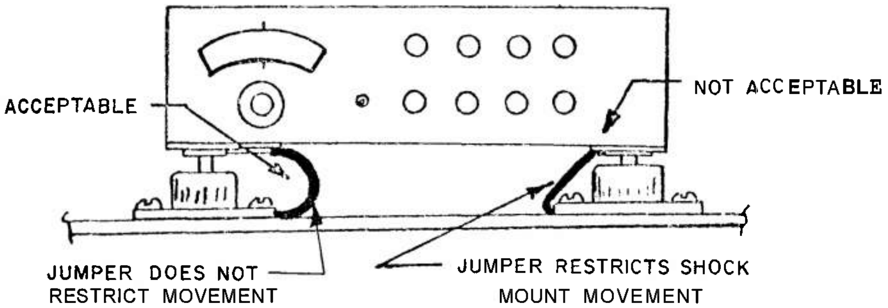


Fig. 4-46. Improper Bonding Jumper Installation Showing Restriction of Equipment Movement

4-1.3.8.3 Metallic Structures

It is common practice to consider a system such as a missile to have an outer skin and a structure that are electrically continuous. This is not always true. This problem arises when anti-corrosion materials are used at the junction of panels. Anti-corrosive coatings are usually not electrically conductive; therefore, it is possible for the panel to be electrically insulated from the main frame. Or, if it is not insulated completely, the panel makes contact only at a few points. This is one reason why the Army does not recommend that the metal structure of a system be used as the current return for electrical circuits. A separate conductor should be used for this purpose.

The designer also should recognize that bonding to some of the new alloys will present a problem from an electrical standpoint; the high resistivity titanium alloy is an example. The resistivity of annealed copper is approximately 1.7 μohm-cm; for certain titanium alloys used in missiles it is about 200 μohm-cm. This represents an approximate decrease in conductivity by a factor of 100 which can seriously affect the grounding and bonding of a system.

4-1.3.9 Corrosion

In almost every application involving metals in the design of components of a weapon system, the designer is faced with the problem that some form of corrosion is possible. Corrosion of metallic surfaces presents a hazard to a weapon system in that it can affect the integrity of electrical joints. It is, therefore, of prime importance that consideration be given to some appropriate means of protection from corrosion. In order to do this, the designer must know the operational requirements of the design, the environmental conditions that the item will encounter in service, the materials that are available, and the protective measures that can be employed (Ref. 17).

For each design problem, it is difficult to achieve a solution that meets all requirements. It becomes necessary to balance the corrosion resistant qualities of a particular metal against the cost, workability, mechanical properties, fabricability, availability, and electrical properties. In cases where alternate materials are being considered, it may become necessary to conduct simulated service tests to determine suitability of the material. There is much information available in published form which can be used to aid the designer. The Bibliography at the end of the handbook will aid in this regard.

4-1.3.9.1 Corrosion Processes

Corrosion is a process involving the transformation of elemental metals to compounds of the metals through electrochemical reaction with their environment; thus, an electric current is associated with corrosion. This mechanism of corrosion applies to all metals to a varying degree. There are four factors necessary for corrosion, namely:

(1) Electrolyte (continuous liquid path, usually water in the form of condensate, salt spray, etc.)

(2) Cause (electrolytic action between dissimilar metals)

(3) Electron conductor–(in a structure, usually a metal-to-metal contact; e.g., rivets, bolts, spot welds)

(4) Effect (corrosion caused by galvanic action).

The tendency for a metal to acquire an electric potential when it is immersed in an aqueous solution can be characterized by what is known as the electromotive series of metals (see Table 4-9). The metals with a very great tendency for forming ions in solution (magnesium, aluminum, manganese, zinc) are at the reactive or less noble end of the series, while metals with little tendency to form ions (platinum, gold) are at the noble or unreactive end of the series. Thus, there is a relationship between the susceptibility of a metal to corrode and its position in the series.

The electrode potential of a metal is dependent on the concentration and type of ions in solution which usually are quite different from the arbitrary conditions established for the electromotive series. Metal specimens immersed in solutions containing ions (cations) of that metal only, but of different concentrations, will have a higher potential or tendency to dissolve as the concentration of ions in the solution decreases, and vice versa.

Further, the nonmetallic ions (anions) in solution also will influence the potential of the metal, depending on whether or not the anions will complex with the metal ions and promote dissolution of the metal. For example, tin is more reactive than iron in dilute citric or oxalic acid solutions, owing to the fact that the concentration of tin ions is kept relatively small by the

TABLE 4-9
ELECTROMOTIVE SERIES

	Metal	Standard Electrode Potential V at 25°C, volts EMF[a]
Less Noble (Anodic) ↑	Magnesium	−2,340
	Beryllium	−1.700
	Aluminum	−1,670
	Manganese	−1.050
	Zinc	−0.762
	Chromium	−0,710
	Iron	−0,440
	Cadmium	−0,402
	Cobalt	−0.277
	Nickel	−0.250
	Tin	−0,136
	Lead	−0,126
	Hydrogen	0,000
	Copper	+0,345
	Silver	+0.800
	Mercury	+0.854
	Platinum	+1.200
More Noble (Cathodic) ↓	Gold	+1.420

Note:

[a] These values are obtained when the specific metal is placed in a solution containing one equivalent weight of its ions per liter.

complexing power of the acid. From this it can be seen that reversals of activity of elements in the electromotive series are possible under various situations encountered in practice. Accordingly, Table 4-9 should be used only as a general guide for establishing the relative corrosion behavior of metals in a particular environment.

To account for overall and practical aspects as well as theoretical considerations, another relationship has been devised. It is referred to as galvanic couples, shown in Table 4-10. In this table, members of groups connected by lines are considered as permissible couples. However, this should not be construed as being devoid of galvanic action. Permissible couples represent a low galvanic effect. There are several factors which influence and control galvanic action, namely: the effectiveness of the electric circuit, the ratio of anode and cathode areas, and the polarization of the electrodes.

Galvanic corrosion requires not only a conductive environment but also good electrical contact between the dissimilar metals. If this is not maintained, the galvanic action will subside. Insulating materials–such as nonwicking gasketing, paint and plastic films, and certain inorganic coatings–at the mating surfaces of the dissimilar metals will prevent or reduce the galvanic current and the progress of corrosion. This, of course, brings the designer in direct conflict with his electrical design which requires the best electrical contact possible; therefore, some compromise must be made.

Another deterrent to galvanic corrosion is polarization. This condition can occur either at the anode or cathode and is the result of deposition through electrolytic action. Corrosion products can accumulate at the anode or hydrogen deposited at the cathode. Either tends to reduce the electrochemical action. The designer must be aware of these contributing factors in order to decide their importance in his application. Table 4-1 1 lists the factors which influence corrosion in solution.

4-1.3.9.2 Types of Corrosion

There are a number of types and forms of corrosion which are evidenced by uniform corrosion attack over a surface of the metal or concentrated attack at local or isolated areas. These are usually categorized as uniform corrosion, galvanic or dissimilar metal corrosion, concentration-cell corrosion, stress-corrosion, fretting corrosion, and high temperature corrosion. Other modes of attack which may encompass one or more of the preceding categories are described as pitting, intergranular, erosion, impingement, cavitation, fatigue, filiform, dezincification, graphitization, and biological causes. A brief discussion of each follows:

a. *Uniform Corrosion.* Simplest form of corrosion which can occur in atmosphere, liquids, or in soil. Examples are rusting of iron, tarnishing of silver, and high temperature oxidation of iron or stainless steels.

b. *Galvanic Corrosion.* Previously discussed. Corrosion results from grouping of dissimilar metals in a conductive environment.

c. *Concentration-cell Corrosion.* Caused by nonuniformity of electrolyte or the environment. It is electrochemical in nature and ensues because of differences in ion concentration or of cracks or crevices in the metal surface, which deplete electrolyte components due to reactions in confined places.

d. *Stress Corrosion.* Results from the combined effects of tensile stresses and corrosion. Cold-working, quenching, grinding, or welding may produce internal stresses. The most destructive type of stress is that which is local and nonuniform, and the stressed zones are subject to accelerated corrosion.

e. *Fretting Corrosion.* Term is applied to metal damage caused when two metal surfaces are in contact, under load, and subjected to vibration or relative motion. Corrosion is characterized by surface discoloration, depressions, or pits.

f. *High Temperature Oxidation.* Direct combination of an oxidizing agent (oxygen, sulphur dioxide, carbon dioxide) with a metal at high temperatures.

g. *Pitting.* Common and severe form of localized corrosive attack. Thin metal sheets and plates are especially vulnerable; corrosion may result in perforation and subsequent unserviceability.

h. *Intergranular Corrosion.* Occurs in boundaries between grains or crystals in metals. Nonstabilized stainless steels are particularly vulnerable. At temperatures of 900° to 1500°F, carbon contained in the alloy will combine with chromium to form iron chromium carbide. This results in lowering chromium content and the deprived areas are then susceptible to corrosive attack.

i. *Erosion Corrosion.* Involves acceleration of corrosion by erosive action. Liquid particles impinging on a metal surface wear away protective films, which invites corrosive attack in the exposed areas.

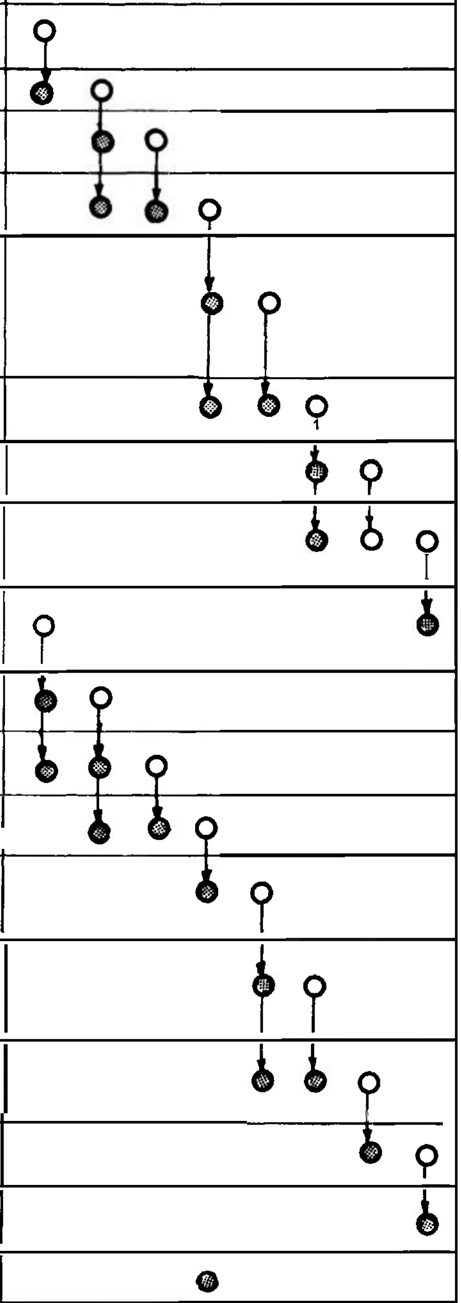
j. *Impingement Corrosion.* A severe form of erosion corrosion. Occurs mostly in turns or ells of tubes, pipes, or impeller surfaces.

k. *Cavitation Corrosion.* The most severe form of erosion corrosion. Occurs as a result of high impact on a metal surface by the liquid environment (e.g., as on an hydraulic impeller blade).

TABLE 4-10

GALVANIC COUPLES[18]

Group	Metallurgical Category	EMF V	Permissible Couples*
1	Gold, solid and plated; gold-platinum alloys; wrought platinum	+0.15	
2	Rhodium; graphite	+0.05	
3	Silver, solid or plated; high silver alloys	0	
4	Nickel, solid or plated; Monel; high nickel-copper alloys; titanium	−0.15	
5	Copper, solid or plated; low brasses or bronzes; silver solder, German silver; high copper-nickel alloys; nickel-chrome alloys; austenitic stainless steels (301, 302, **304,** 309, 316, 321, 347)	−0.20	
6	Commercial yellow brasses and bronzes	−0.25	
7	High brasses and bronzes; naval brass; muntz metal	−0.30	
8	18% chromium type corrosion-resistant steels 440-430, 431, 446, 17-7PH, 17-4PH	−0.35	
9	Chromium, plated; tin, plated; 12% chromium type corrosion-resistant steel, 410, 416, 420	−0.45	
10	Tin-plate, terneplate; tin-lead solders	−0.50	
11	Lead, solid or plated; high lead alloys	−0.55	
12	Aluminum, wrought alloys of the duralumin type, 2014, 2024, 2017	−0.60	
13	Iron, wrought, gray, or malleable; plain carbon and low alloy steels; Armco iron	−0.70	
14	Aluminum, wrought alloys other than duralumin; type 6061, 7075, 5052, 5056, 1100, 3003. Cast alloys of the silicon type 355, 356	−0.75	
15	Aluminum, cast alloys other than silicon type; cadmium, plated and chromated	−0.80	
16	Hot-dip-zinc plate; galvanized steel	−1.05	
17	Zinc wrought; zinc-base die cast alloys; zinc, plated	−1.10	
18	Magnesium and magnesium-base alloys cast or wrought	−1.60	



○ Indicates the most cathodic member of the series, ● an anodic member, and the arrows indicate the anodic direction.

*Refer to Table II, MIL-STD-186, for group amplification of galvanic couples.

TABLE 4-11

FACTORS INFLUENCING CORROSION IN SOLUTION[19]

Characteristics of the Metal
Composition and chemical homogeneity of the metal
Surface properties; inherent protective films
Effective electrode potential of the metal in solution
Overvoltage of hydrogen and oxygen on the metal that must be overcome
Surface conditions; physical homogeneity of the metal
Protective deposits formed as a result of contact with the solution (environment)
Characteristics of the Solution (Environment)
Hydrogen-ion activity in the solution,
Oxygen content of the solution
Presence of oxidizing or reducing agents
Characteristics and distribution of other ions in the solution
Motion of solution in relation to metal
Temperature
Effect on Progress of Corrosion by Product of Corrosion
The oxide may inhibit corrosion by combining with other elements in the solution to form a protective layer on the surface of the metal. Scale formulation on boilers is an example of this.
The formation of oxides may consume the available oxygen where the supply of oxygen is limited. This action would lessen or retard further corrosion.

l. ***Corrosion Fatigue.*** Fatigue failure brought about by a corrosive environment. Endurance limit of metal is lowered as it undergoes stress cycles.

m. ***Filiform Corrosion.*** A thread-like strand which appears under water-permeable coatings and sometimes under electro-deposits.

n. ***Dezincification.*** Occurs with some brasses. Involves loss of zinc, leaving a residue of one or more of the other constituents, primarily copper. If not arrested, the entire metal will be reduced to a weak spongy mass.

o. ***Graphitization.*** Occurs in grey cast iron and is similar to dezincification suffered by some brasses. Requires specific conditions which corrode away the iron leaving a matrix which is mostly graphite.

p. ***Biological.*** Various types of micro-organisms, bacteria, yeasts, and molds influence the electrochemical reactions which cause corrosion. The most common result of this influence is pitting.

The foregoing constitutes a list of the main corrosion hazards that a designer faces. Ways and means of overcoming these hazards are the subject of the next paragraph.

4-1.3.9.3 Methods of Protection

In the design of electronic equipment, the corrosive effect of oxygen, moisture, and airborne corrodents can be minimized by the use of methods such as proper choice of materials, protective coating or encapsulation of components; evacuation and hermetic seals; filtered air, and removal of moisture. Materials which break down or outgas should not be used in devices which are to be evacuated and sealed.

When forced air cooling is used in order to maintain the equipment at temperatures below the maximum permissible operating temperature; precautions should be taken to remove dust, moisture, and contaminants from the air, preferably externally, before the cooling air passes over the electronic components.

The moisture level inside electronic equipment should be maintained below 30% relative humidity at 20°C (Ref. 20), and moisture can be kept out of electronic devices by use of proper housings, gaskets, seals, and enclosures. Various means can be provided to exclude the moisture–such as avoidance of sump areas, pockets or traps, the avoidance of hygroscopic materials, guarded use of desiccants, and maintenance of components at temperatures below the dew point.

In the selection of materials, those that are suitable for the purpose and inherently resistant to corrosion should be used. If dissimilar metals are used in contact or near one another, they should be protected against electrolytic corrosion (refer to Table 4-12 and Table 4-13).

Five problem areas which should be given special attention are surface contamination, intergranular and stress corrosion, hydrogen embrittlement, whisker growth, and silver migration.

Where maximum conductivity is required on items exposed to the atmosphere, metals resistant to oxidation such as gold, rhodium, and platinum should be selected. If other metals are used, then the surface should be protected by suitable noninsulating coatings or by plating it with noble metals.

Preference should be given to those metals and alloys which are resistant to both intergranular and stress corrosion. Fabrication operations such as bending, forming, and shaping should be performed on the metals in the annealed conditions.

Hydrogen embrittlement can result in a delayed fracture in those metals which can pick up hydrogen from acid cleaning or plating. If metals are used which are susceptible to this type of pickup, some methods which can be used to minimize the damage include:

a. Organic coating, vacuum deposition.

b. Low hydrogen embrittlement baths should be used if plating is necessary.

c. Embrittlement relief after plating (baking) (Ref. 21); thermal stress relief and mechanical stress relief should be done before plating.

d. No acid or alkaline cathode cleaning should be used.

Whisker growth on tin, cadmium, or iron can be reduced by using heavy metal coatings, hot-dip tin rather than electro-deposited tin, stress relief after tin plating, and the maintenance of low humidity in the equipment.

Electrolysis and silver migration, which is the movement of metal from one conductor in a circuit to another at a different voltage potential under humid conditions particularly if one metal is silver, can be minimized by:

a. Wide spacing between conductors

b. Organic moisture barrier coatings

c. Careful cleaning away of contaminants

d. Use of gold, platinum, or tin-lead coatings

e. Controlled humidity

f. Use of nonhygroscopic materials.

The most effective means of preventing electrolysis and silver migration, and one which is commonly used, is the application of protective film or coatings. These protective coatings can be described under three main headings: (1) chemical or anodic films, (2) metallic coatings, and (3) organic coatings. Each of the methods are described:

(1) Chemical or Anodic Films:

In chemical or anodic treatment, metals and alloys are coated with suitable solutions of chemicals under controlled conditions to form protective surface coatings. This coating is physically integrated with the underlying metal and serves as a barrier against corrosive attack. Coatings commonly used are oxides, phosphates, chromates, or complex compounds of the substrate metal and the components of the metal, and the components of the treatment solutions. These coatings may be formed on iron and steel, aluminum, magnesium, cadmium, and other metals.

(2) Metallic Coatings:

Metallic coatings should be selected for their suitability for the application involved, with attention to problems of aging, cracking, diffusion, and corrosion. When metallic coatings are applied by electroplating, hydrogen embrittlement should be avoided. There are recommendations (see Table 4-12) for the prevention of corrosion which should be considered and specifications (see Table 4-13) for the coatings themselves.

Metallic coatings are also applied to some metals by the process of hot-dipping. This is largely confined to the coatings of ferrous alloys with metals and alloys of low melting points. Typical hot-dipping coating materials are zinc, and tin and lead alloys including

TABLE 4-12

SELECTION OF METALLIC COATINGS FOR MINIMUM CORROSION[20]

Purpose	Recommended	Not Recommended
Contact with aluminum or magnesium	Cadmium or tin	Chromium, copper, silver, gold
Prepaint coating	Cadmium or tin	Chromium, copper, nickel, gold, silver
Tarnish prevention	Rhodium over silver Gold over silver, copper, or nickel Nickel between copper and silver	
Marine exposure	Heavy gold, 0.00030 in. minimum	
Solderability	Tin, gold, or tin-lead	Nickel, chromium, rhodium
Storage	Gold, rhodium, or reflowed heavy tin	Cadmium, silver, copper
Wear	Chromium, nickel rhodium, or hard gold	Cadmium, tin
Easy etching (for printed circuit board manufacture)	Cadmium, nickel, (in ferric chloride only), indium, tin	Rhodium, sifver, tin-lead, gold

terne metal. Tinned steel, and zinc-coated or galvanized iron and steel articles are the most common hot-dipped products. If corrosion-resistant steels are used, passivation should be done in accordance with QQ-P-35. If steels of the 300 series are used, no further finish is required.

The noble metals (gold, palladium, platinum, and rhodium) and the corrosion-resistant metals (chromium, nickel, tin, tin-lead solder, and titanium) require no finish other than cleaning.

Applications of aluminum, copper, and magnesium require special treatment unless they are used in hermetically sealed units.

Aluminum should be anodized; where this is impossible, chemical film treatment in accordance with MIL-C-5541 may be used. Continued exposure of aluminum at high temperatures may require the use of metallic coatings. These various coatings should be applied after fabrication or machining operations.

Copper and copper alloys may be black oxide treated in accordance with MIL-F-495 or may be plated or painted. If bare copper is required, a tarnish-preventive thin silicone cured resin film may be used.

Magnesium has very poor resistance to corrosion and, therefore, should be anodized. Several coats of alkali-resistant primer with one or more coats of compatible top coat should be applied or it may be given moisture proofing coatings such as epoxy or polyurethane. Furthermore, magnesium used with any other

TABLE 4-13

SPECIFICATIONS FOR METALLIC COATINGS[20]

hletal	Specificatior,
Aluminum, vacuum deposited	MIL-C-23217
Cadmium, electroplated	QQ-P-416
Cadmium, electroplated, low hydrogen content	AMs-2401
Cadmium, vacuum deposited	MIL-C-8837
Chromium, electroplated	QQ-C-320
Copper, electrodeposited	MIL-C-14550
Gold, electrodeposited	MIL-G-45204
Lead, electrodeposited	MIL-L-13808
Lead, hot dip	MIL-L-13762
Nickel, electrodeposited	QQ-N-290
Nickel-cadmium, diffused	AMS-2416
Nickel-phosphorus, electrodeposited	MIL-C-26074
Palladium, electrodeposited	MIL-P-45209
Rhodium, electrodeposited	MIL-R-46085
Silver, electrodeposited	QQ-S-365
Tin, electrodeposited or hot dip	MIL-T-10727
Tin-cadmium, electrodeposited	MIL-P-23408

metal requires extreme precautions to prevent destructive corrosion.

Cladding is a process for covering one metal with another metal to utilize the superior corrosion-resistant properties of the exposed metal. Cladding may be applied by working, co-rolling, pressure welding, spot welding, explosive welding, and diffusion welding. Principal clad composites produced for industrial purposes are high purity aluminum or aluminum alloys on less resistant aluminum alloys; stainless steel on steel; nonferrous metals including copper, brass, lead, nickel, and nickel alloys on steel.

Another method of applying metal coatings is by metallizing or metal spraying. These coatings are porous, but they provide protection from corrosion mainly because of their thickness. They require sealing or impregnation followed by painting. Metals used to spray coat are zinc, cadmium, and aluminum.

(3) Organic Coatings:

Organic coatings are used to protect metal parts, equipment, and structures primarily against atmospheric corrosion. They are applied as liquids and act chiefly as a barrier between the metal to be protected and the environment. As a class, organic coatings include paints, varnishes, enamels, and lacquers. The value of the organic coating depends upon its ability to provide complete and uniform coverage, a good degree of impermeability, good adhesion, cohesion, resistance to mechanical damage, and good chemical inertness.

4-1.3.9.4 Other Problem Areas

In the use of dissimilar metals in intimate contact, the great danger of galvanic corrosion becomes possible. Because of the seriousness of galvanic corrosion, every effort must be made to avoid the use of dissimilar metals, to exclude moisture, and to protect metal surfaces in the contact area. When it is necessary to use dissimilar metals not shown as "permissible" in Table 4-10 as assembled, the measures where they apply in Table 4-14 should be used to prevent corrosion.

If, in the course of the design, methods of forming for mechanical strength or for electrical applications are to be used, consideration must be given for possible corrosion problems and the solutions previously discussed should be used.

These joining methods include adhesive bonding, structural mechanical joints, crimping and wrapped leads, brazing, soldering, welding and electrical bonding. These joining methods are discussed in par. 4-1.3.8, Bonding to Metallic Structures.

4-2 ELECTRICAL CIRCUITRY

Since weapon system shields commonly contain gaps and holes for necessary functions, the shields allow some electromagnetic energy to enter the shielded volume. Good design practice in the physical and electrical construction of the internal circuitry can be

TABLE 4-14

PREVENTION OF DISSIMILAR METAL CORROSION[20]

Preventive Measure	Example
(1) Select metals which form a permissible couple in Table 4-10.	Use nickel, not naval brass, in contact with silver.
(2) Interpose a metal which reduces the potential difference between the two metals.	Tin plate brass to be used next to aluminum.
(3) Design the metal contact *so* the relative area of the cathodic (more noble) metal is the smaller.	Stainless steel screws in aluminum chassis.
(4) Apply corrosion inhibitor such as zinc chromate primer MIL-P-8585 or zinc chromate paste MIL-P-8116.	Use zinc chromate inhibitor when assembling steel screws in aluminum.
(5) Interpose an insulating barrier or nonhygroscopic gasket between dissimilar metals.	In structural joints, interpose tape MIL-T-23142. In components, use organic insulants such as conformal coating MIL-1-46058.
(6) Apply insulating organic coating to surface of each metal.	Coatings such as vinyl zinc chromate primer MIL-P-15930, epoxy primer MIL-P-52192, insulating coating MIL-C-46057, MIL-V-173, MIL-1-46058.
(7) Seal joint area with moisture-proof coating or organic sealant.	In structural joints, sealant such as MIL-S-7124. In components, coatings such as MIL-V-173 or MIL-146058.

ex to reduce coupling to sensitive components. In this area of weapon system protection, RF and electromagnetic compatibility (EMC) practices often overlap or coincide. (See par. 3-2 and Fig. 3-2 for a definition of the EMC and RFI/EMI problems.) In the EMC design of circuitry internal to a shield volume, the sources of interference are considered as the circuits of the weapon system themselves and the problem is to eliminate coupling from circuit to circuit. In the RF protection problem, primary concern is with a source that can be represented as electric and magnetic sheet currents on the interior walls of the overall shield. The power density produced by these currents is likely to be much more intense at gaps and holes in the shield. The problem, then, is to lessen this coupling to the sensitive circuits.

In general, EMC design procedures deal with relatively low frequency circuits, say below a few megahertz. The higher frequency components are usually completely shielded and offer small internal coupling problems.

In contrast, many of the weapon system RF protection problems occur at frequencies above a few megahertz, and the protection techniques that are most effective at these frequencies often conflict with the EMC prescribed techniques.

An obvious requirement on any system circuitry is that it be compatible with itself and perform reliably; therefore, the EMC requirements and techniques should always be utilized when necessary. In many weapon system circuits the application of EMC techniques is not necessary and EMC derived procedures are not appropriate. For example, the EED firing leads in weapon systems are often shielded twisted pair with the shields grounded at the source or firing circuit end of the shielded cable. This shielding technique is standard for elimination of unwanted inductive pickup in instrumentation systems but contributes very little or nothing to the protection of the EED circuit. In this case RF protection of the EED can be greatly enhanced by grounding the EED end of the shield directly (preferably by a 360° contact) to the metal case of the EED.

The RF protection techniques given in this paragraph should be utilized when they do not conflict with the necessary EMC prescribed techniques.

4-2.1 CIRCUIT BALANCE

4-2.1.1 Definition of Balance

Any two wires leading to a sensitive component can be considered balanced, for a particular incident field, if their mechanical placement and electrical characteristics are such that no current will flow in the sensitive component when either or both of the leads are opened (Ref. 22), or, more simply stated, two wires are considered balanced when an external field induces currents that balance (self-cancel) each other. (This definition has meaning only at fairly low frequencies and at dc because at higher frequencies a single wire cannot be treated as a single circuit element.) Also, static electricity charging currents through sensitive components can be reduced by proper balance of sensitive component leads. At higher frequencies any attempt at circuit balance can only succeed by symmetrical placement of identical components throughout the circuit. This will lead to a balanced circuit only for sources or incident fields which are symmetrical in relation to the circuit layout. If no other requirements are imposed on the circuitry, balance is helpful to RF protection but for most systems the actual protection gained cannot be evaluated.

4-2.1.2 Twisted Pair Wiring

The use of twisted pair wiring for sensitive components is recommended for RF protection. At the higher frequencies where the wavelength of the RF leaking through the shield is equal to the distance between two twists (along the twisted pair) the pickup of the twisted pair may be expected to be greater than that for untwisted wires with the same separation. However, twisting keeps the wires close together and certainly helps prevent low frequency inductive coupling to the wires. Keeping the wires close together, thereby reducing the physical size of the potential antenna, is desirable from an RF protection viewpoint. Shielded twisted pair wiring is superior to twisted wire alone (see par. 4-2.3.3).

4-2.1.3 Mechanical Design and Layout

The foremost requirement for mechanical design of circuits is to keep all potential pickup structures as short and as near to a massive ground plane as possible. Ideally all components would be packed as closely as possible on a metal sheet at the center of the shielded volume. Cable and lead length would be kept as short as possible and all cables would be kept close to the ground plane. Obviously, this idea contrasts with most weapon system functions, therefore, the designer's guideline should be "keep it short and close to a metal member if possible".

4-2.1.4 Printed Circuits

Printed circuits, in general, conform to the mechanical and layout requirements given in the previous paragraph (Ref. 23). The designer should try to use the large amounts of plated metal on the boards as a barrier between the external shield and sensitive components. Mount printed circuit boards in pairs with mounted components between the boards, or mount single boards with their components next to metal structural members or other ground planes.

4-2.1.5 Conductor Routing and Lead Dress

All cables and leads should be kept as close to a ground plane and as short as possible. Pigtails, jumper wires, and all other miscellaneous leads should be kept to minimum length. Leads to sensitive components should be bundled as tightly as possible with other leads, the sensitive leads inside the bundle or on the ground plane side of bundle. The object is to get as much metal as possible between the sensitive leads and the exterior shield.

4-2.2 GROUNDING (OTHER THAN FOR ELECTRICAL POWER SYSTEMS)*

Grounding refers to the establishment of an electrical conductive path between the circuit to some reference point. The reference point can be earth, the equipment enclosure, or the weapon system structure itself. Good grounding techniques depend on good bonds. A uniform grounding philosophy is mandatory to avoid conductive coupling, low impedance ground loops, and hazardous operations (Ref. **24**).

As far as **RF** protection of weapon systems is concerned, grounding of weapon system circuits inside the shielded volume is merely another technique that can be applied to reduce coupling to the circuits. The same remarks, in reference to EMC requirements, apply as previously given in par. **4-2.** Use the established EMC techniques to obtain operational reliability; then, apply the grounding procedures which follow to provide RF protection for the sensitive components if these techniques do not compromise the circuit reliability.

4-2.2.1 Single Point Grounds

Single point ground systems are used to eliminate mutual impedance coupling between circuits. As such it is an effective and, for many systems, necessary approach. However, even in the cases where single point grounding **is** necessary for reliable performance it is seldom necessary for every circuit.

Single point grounding should be avoided, if possible, for RF protection of sensitive components. In general, circuits and sensitive components should be grounded as frequently as possible to massive metal members of the system.

4-2.2.2 Chassis Return

The low or ground side of a circuit when completed through the chassis of the equipment itself is termed chassis return. It **is** the prime alternative to wire return systems. Its primary advantage **is** the elimination of the **wires** used to form the returns and its largest disadvantage **is** that is permits mutual coupling between circuits. As such it is seldom used because it conflicts with EMC techniques. At the higher RF frequencies, however, most circuits act as though they were chassis return circuits since the structural members act to provide an alternative and often lower impedance return to the circuit.

From the RF protection standpoint, chassis return eliminates the return wire, a potential source of pickup, and is desirable. This advantage must be contrasted with the inherent disadvantage of a chassis return circuit if the weapon system structure is exposed to lightning or other large transients. It is possible for these transients to force large currents through the structural members thus providing very large voltages and powers to the sensitive components. For this reason chassis return is not recommended.

In summary, chassis return–while an attractive alternate–is not recommended because it permits mutual coupling between circuits and, therefore, is in conflict with accepted EMC hardening techniques. Accordingly, all circuits should be double-ended and balanced.

4-2.2.3 Ground Returns for Sensitive Components

The previous two paragraphs point to the best ground return system for protection of sensitive coniponents that have metal cases. Such circuits should use shielded twisted pair wiring with one of the leads being used as the ground return for the circuit operation. The shield should be 360° tied to the metal case of the sensitive component and grounded to structure as frequently as possible (see Fig. **4-47**). If the sensitive components do not have metal cases or if the components require no appreciable cable run, standard EMC techniques are the best overall compromise.

4-2.2.4 Gable Shield Grounding

The grounding of cable shields used on sensitive components should be directly to the structure, avoiding straps or pigtails. Cable clamps that are mounted

* Single-point grounding of the negative returns of a weapon system will be made at only one point on the weapon system structure.

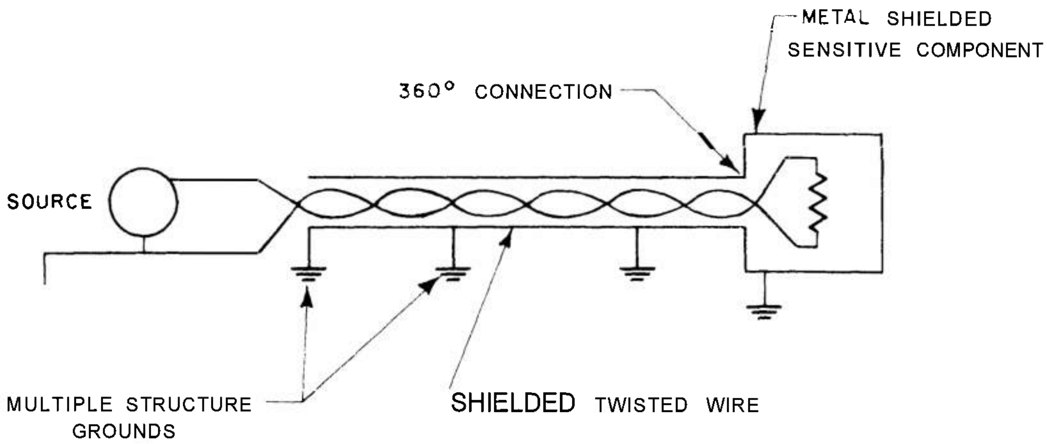


Fig. 4-47. Ground Return System for Metal Shielded Sensitive Component

on the structure should contact the metal braid of the individual cable shields. The shielded cable should be run as closely as possible to metal structural members. If many shielded cables are bundled together, the individual shields should be tied together with the shortest possible method and the resulting group cable clamped to the structure. The ideal configuration is to continuously tie the cable shield to the structure throughout the cable run.

4-2.2.5 Shield Discontinuities

The shielded cables used to protect shielded sensitive components should be 360° connected to the component shield. Use of a short length of wire between the cable shield and the component shield is detrimental to protective measures. The designer should try to make the shield completely continuous. Braided shields on cables should be selected to provide the least open area on the braid surface. Braids of metal ribbon usually provide very small open areas in relation to braids of round wires. Ribbon braid is, therefore, recommended for all braided shielding for RF protection.

4-2.3 Applications

A weapon system has many electrical (or electronic) circuits and subsystems that must be protected for electromagnetic radiation and static electricity. This protection has two objectives: (1) to prevent inadvertent functioning of various parts of the weapon system due to induced energy, and (2) to prevent incapacitation (dudding) of the system due to induced energy. Because of the wide variety of components and subsystems which must be protected, it is not feasible to present the design approach used with each; however, many subsystems have common characteristics that do permit some specific recommendations. Several subsystems and their related problems are discussed in the paragraphs which follow.

4-2.3.1 Fuze Systems

A fuze is a device with explosive components designed to initiate a train of fire or detonation in a item of ammunition by an action such as hydrostatic pressure, electrical energy, chemical action, impact, mechanical time, or a combination of these (Ref. 25). Types of fuzes are distinguished by modifying terms forming part of the item name. (In some cases the explosive components may be simulated, or omitted (Ref. 26).) A certain stimulus is required to trigger the fuze operation. Since it is possible that the trigger stimulus can be encountered in ordinary handling, as during transportation or loading, safety devices are included to ensure that the fuze can be triggered only under the proper circumstances (Ref. 26).

Fuzes are commonly classified by their method of target sensing: impact, time, proximity, and barometric.

4-2.3.1.1 Impact Fuzes

This type of fuze functions on target impact; it finds wide use in projectiles, bombs, rockets, and mortars (Ref. 27). A typical mechanical impact fuze–Fuze M525–is shown in Fig. 4-48. After arming, the firing pin is driven into the detonator and generates sufficient heat to initiate the detonator. The metal housing that completely envelopes the detonator and the absence of electrical wiring makes this type of fuze extremely

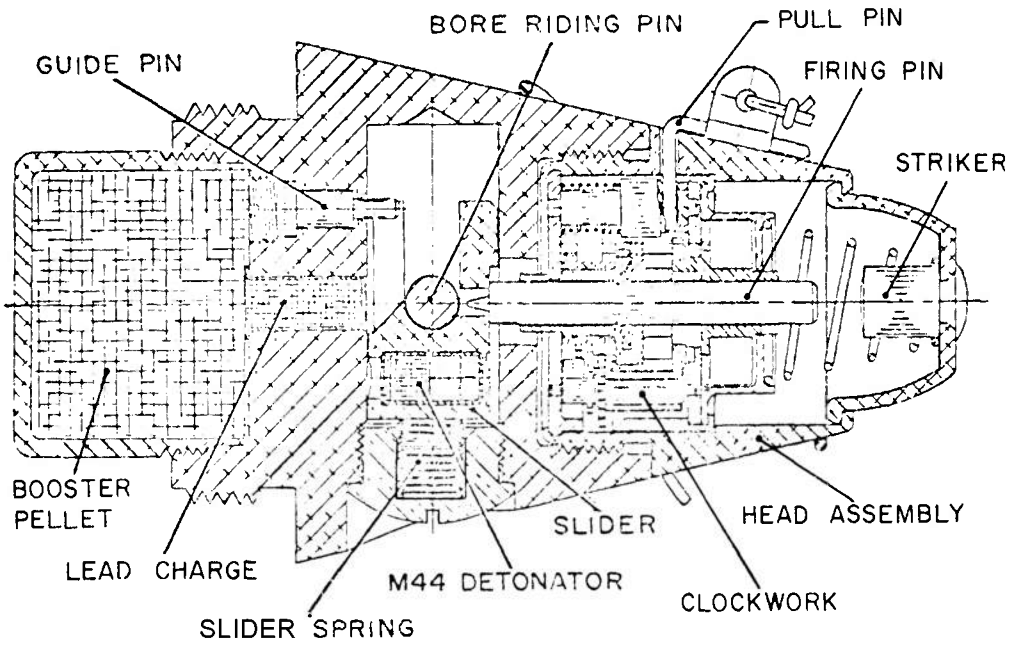


Fig. 4-48. Fuze M525

invulnerable to RF energy, static electricity, and lightning.

Fig. **4-49** illustrates an electric impact fuze which uses a piezoelectric element as the triggering source. The voltage generated by this element, when it is stressed on impact with the target, is used to fire the EED. Even though there is wiring from the piezoelectric element to the EED, the metal case is usually adequate to shield it from most external radiation.

In general, impact fuzes when enclosed in a metal housing are not vulnerable to external electric energy.

4-2.3.1.2 Proximity Fuzes

Proximity fuzes initiate warheads by sensing the presence, distance, and/or direction of a target. They may by of the radio or nonradio type. Radio types generally contain transmitting and receiving circuits to sense the target. Fuzes are available that operate with emitted frequencies from VHF up to the microwaves, and employ both CW and pulsed signals.

In general, the electronic circuits of proximity fuzes are sophisticated and are designed to resist triggering

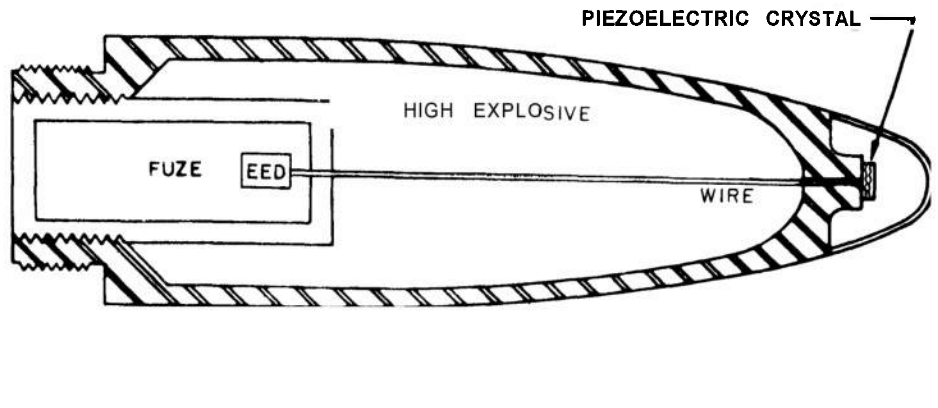


Fig. 4-49. Point-initiating, Base-detonating Fuze Having Piezoelectric Core Element

by extraneous signals. Signals generated by external RF sources, a lightning stroke, or EMP would have to introduce stimuli that are precisely on frequency and applied in the proper sequence (coding) to activate the fuze. If the ambient **RF** field intensity is extremely high, however, a problem may be encountered if the receiving antenna can extract enough energy to damage the input of the receiving circuit thereby rendering the unit inoperative.

As an example of the voltage that can be introduced into the input circuit of a proximity fuze, consider an antenna 1.5 cm (0.015 m) long and 0.5 cm (0.005 m) in diameter projecting from a missile body that is one meter in diameter. This would be representative of an X-band, quarter-wavelength antenna. Assume also that the antenna is terminated with a semiconductor transmit-receive switch having an input resistance of 200 Ω and is capable of withstanding 200 V. Consider the question as to whether the electric fields from lightning discharges could damage the semiconductor switch. A rigorous solution to this problem involves intricate mathematics; however, there is a simplified method of analysis that sacrifices some accuracy at the expense of indicating more potential on the switch than would be encountered in the exact analysis.

This approach involves computation of the surface current in the antenna. In the example being considered, make the following assumptions:

(1) The antenna, including its image in the missile surface, gives an effective antenna length of 3 cm.

(2) The 200-R semiconductor switch resistance is connected in the center of the antenna; i.e., at the base of the actual antenna, and has no appreciable effect on the current induced.

(3) The electric field extends uniformly across the entire length of the antenna.

With these assumptions, Eq. 2-19 can be used to determine the surface current in the antenna by approximating the antenna as an ellipsoid of revolution.

The eccentricity c of the ellipsoid is given by

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} = \sqrt{\frac{(0.015)^2 - (0.0025)^2}{(0.015)^2}} = 0.986 \quad (4\text{-}22)$$

where

a = semi-major axis of the ellipse (0.015 m in this example from assumption (1))

b = semi-minor axis of the ellipse (0.0025 m in this example)

The surface current is calculated by Eq. 2-19.

$$I_s = \left[\frac{2\pi a^2 \epsilon_s e^3}{\ell n\left(\frac{1+e}{1-e} - 2e\right)}\right] \frac{dE}{dt_{max}}$$

$$I_s = \left[\frac{6.28\,(0.015)^2\,(8.85 \times \quad {}^2)\,(0.986)^3}{\ell n \frac{1986}{(0.014} - 1.972)}\right] \frac{dE}{dt_{max}}$$

$$I_s = 2.43 \times 10^{-15} \left(\frac{dE}{dt_{max}}\right)$$

The maximum rate of change of the electric field in the vicinity of a lightning stroke can be determined by Eq. 2-22 and is shown as a function of distance in Fig. 2-18. If the voltage drop across the semiconductor is 200 V, current through the 200 Ω load will be 1 A. Under the conditions of $I_s = 1$ A, the value of dE/dt would have to be 4.12 X 10^{14} V/m-sec. Note from Fig. 2-18, that this magnitude of dE/dt may be obtained at distances of less than 30 m and all current strokes, even with maximum current of 200,000 A.

The proximity fuze circuits which may be susceptible to extraneous **RF** energy, static electricity, and lightning are classified; therefore, they can not be discussed in this handbook. Proximity fuzes are discussed in other handbooks (Refs. 28-32).

4-2.3.1.3 Barometric Fuzes

A barometric fuze is a type of influence fuze which is actuated by sensing the increase of barometric pressure as it descends toward the target area. The barometric fuze is employed on ballistic re-entry vehicles either as a back-up for other types of influence fuzes or as an enabling device for them. The sensing elements in barometric fuzes are similiar to aneroid barometric sensors i.e., they are designed to operate electrical switches by their deflection. The switches are used in various series and parallel arrangements to provide the required reliability.

In general, RF environments have little effect on barometric fuzes because of the metal fuze body which acts as a shield. Connection to the outside atmosphere is solely mechanical through the baroports and plumbing which is terminated in the aneroid sensing elements. Barometric fuzes are interconnected with other components of the fuzing system–such as safing and arming devices, programmers, or another fuze–by cables which, so far as their susceptibility to **RF** is concerned, must be shielded in the manner described in par. 4-1.

4-2.3.2 Interconnected Units

Interconnected units are used extensively in missile safing and arming subsystems. In this type of subsystem, shown in a block diagram form in Fig. 4-50, components are joined by a cable harness and are dependent upon the cable shielding integrity for protection from the effects of RF radiation.

In designing such a system it is important to provide unbroken shielding protection for all circuits which may be associated with the firing unit or the initiators. One method of achieving this is by using junction boxes at all interchange points, and requiring that the shields of the cables be electrically bonded through the connectors to the skin of the junction boxes.

Be forewarned that the practice of fanning cable leads on exposed terminal boards at the interchange points will negate the protection provided by the cable shields. A more detailed discussion of connections and cabling techniques is contained in par. 4-1.3.5.

4-2.3.3 Safing and Arming Devices

Safing and arming (S&A) devices are operated by different forces: (1) missile acceleration, usually subject to integration by a clockwork mechanism, (2) an electrical signal which energizes a solenoid, and (3) application of power to an electric motor which moves an actuator.

S&A devices connect an initiator to its firing circuit only when certain conditions of performance have been met (armed position). They also keep the initiator safe from inadvertent firing or mechanical damage at all other times (safe position). In most S&A devices, inadvertent firing is prevented by interrupting the firing circuit, moving the initiator to an out-of-line and barricaded position, and placing a low-resistance shorting bar across the initiator electrical leads while connecting them to ground. In addition, a low-value resistor is sometimes placed as a load on the input leads of the initiator to absorb any electric energy that may be coupled to the S&A input. This approach is shown in Fig. 4-51 and has the objective of preventing the initiator from firing in the normal or bridgewire mode. All cables and leads terminating the S&A device should be properly shielded and grounded to eliminate RF pick-up.

In addition, S&A devices should be designed to prevent firing by voltage between the initiator pins and case (pins-to-case initiator firings). Fig. 4-52(A) shows a S&A device in the apparent safe position. To arm this circuit, the jumper from *A* to *C* is removed and connected between *C* and *D*, which will then permit the bridgewire of the detonator to be energized by the firing pulse. Note that in the safe position (as shown) a potential can occur between shorted input lead 1 and the detonator case, which could fire an EED that is sensitive in this mode. A much better circuit is that shown in Fig. 4-52(B). This circuit interrupts both firing lines, and short circuits the detonator's input leads and grounds them. With this arrangement it is difficult for the detonator to absorb any RF energy. The low-value resistor across B and *D* (optional) dissipates any stray RF currents that enter the firing cable, and it also prevents a build-up of a static electric charge.

4-2.3.4 Power Sources

The most common power sources used in the delivery portion of a weapon system are batteries and fuel cells. They are usually integrated into systems by means of cables or are contained in a housing as a component part of a package.

There are two areas to note where good design practices will provide protection from improper functioning by RF energy, namely:

(1) *The circuitry required for initiating the power sources.* Common methods of initiation are by electric matches and pyrotechnic igniters. It is important that the proper procedures for shielding, grounding, and elimination of pickup loops be followed throughout the design and construction of the system. Thus, the possibility of inadvertent actuation of the power source will be reduced.

(2) *The output cables from the power source.* The output cables convey power from the power source to timers, programmers, S&A devices, fuzes, firing devices, etc. Since the power leads are usually connected directly into these subsystems, the designer must take care that the power supply's output leads are properly shielded and bonded. A power source that feeds more than one subsystem also may require an RF suppression device to eliminate coupling between subsystems. Figs. 4-53 and 4-54 illustrate good and poor battery design approaches, respectively. In Fig. 4-53, leads to and from the battery are terminated in a connector which maintains the integrity of the shields. Cable shields are bonded to the battery case. In the battery shown in Fig. 4-54, however, both input and output leads are fanned and attached to unshielded terminal posts, and undesirable design which permits RF intrusion even when exposed to fields of fairly low level.

4-2.3.5 Accelerometers and Timers

In operation, accelerometers and mechanical timers are electrically similar to safing and arming devices.

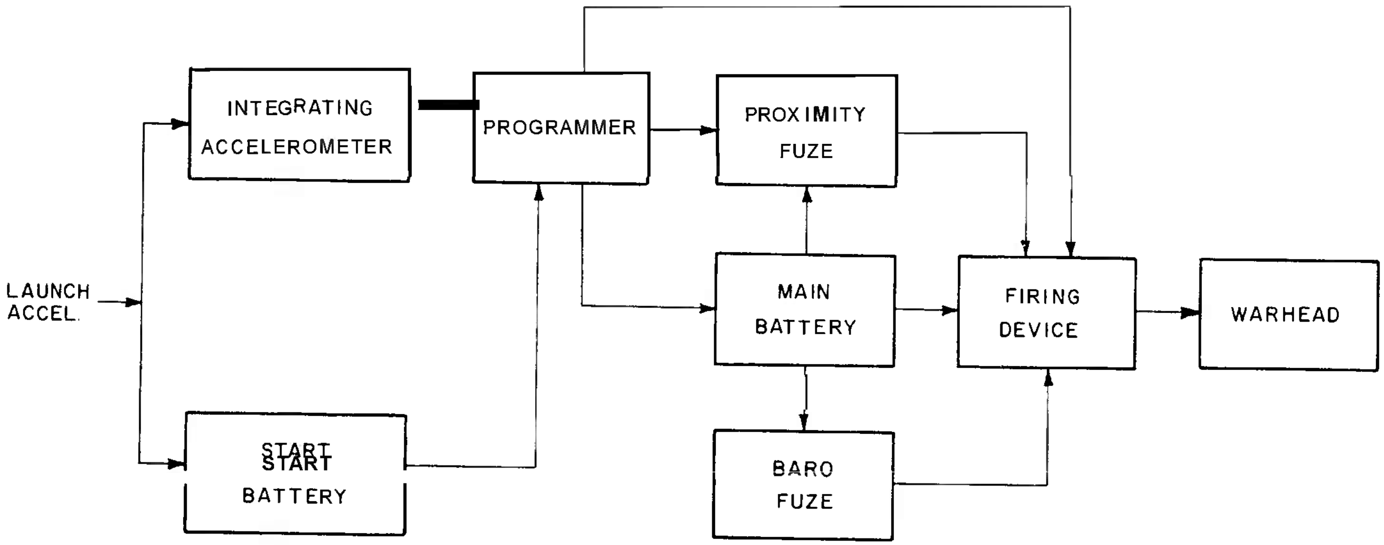
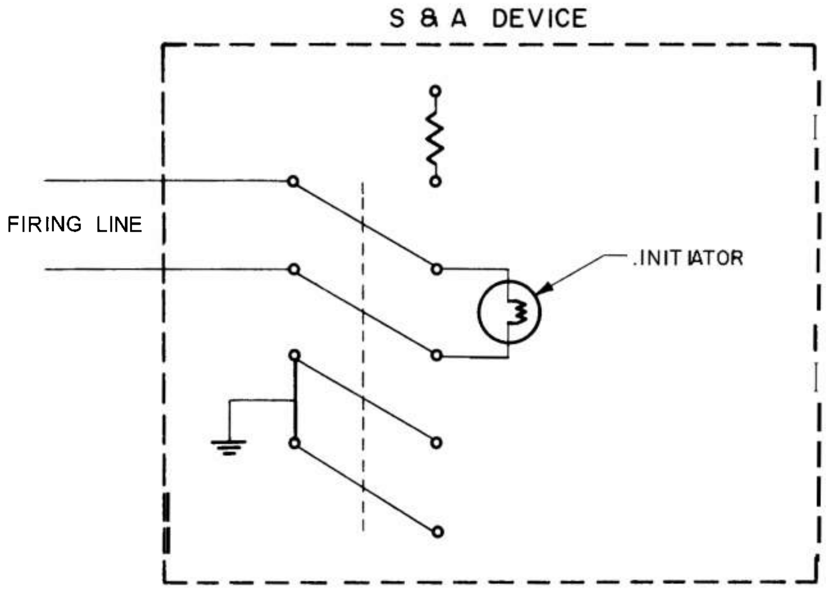
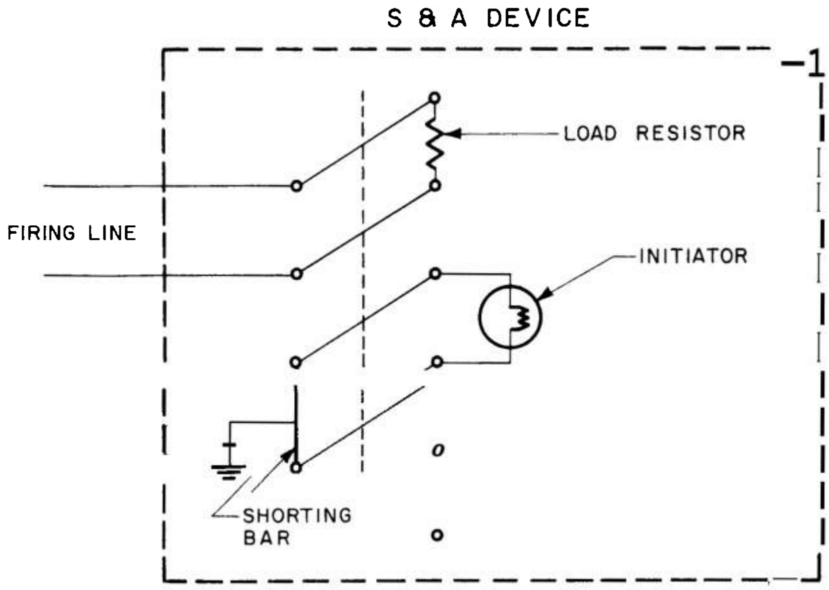


Fig. 4-50. Typical Interconnected Fuzing System

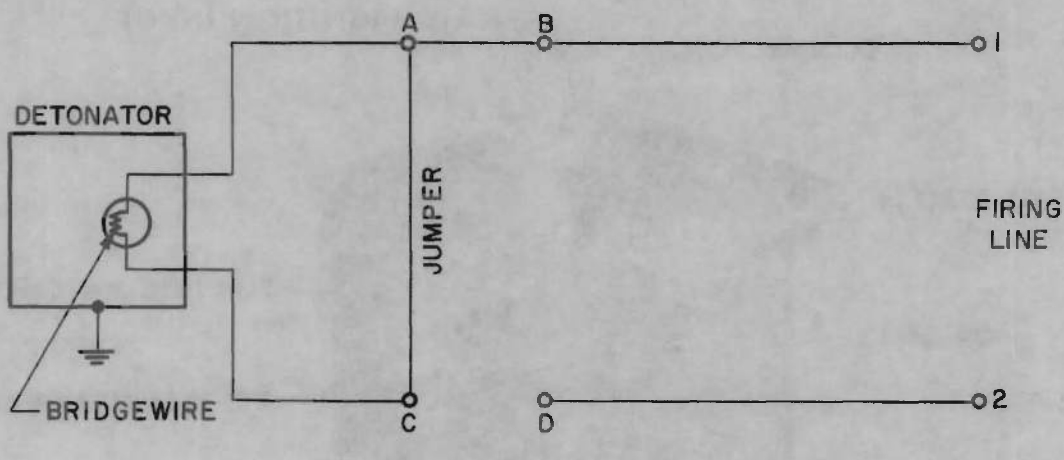


(A) Armed Position

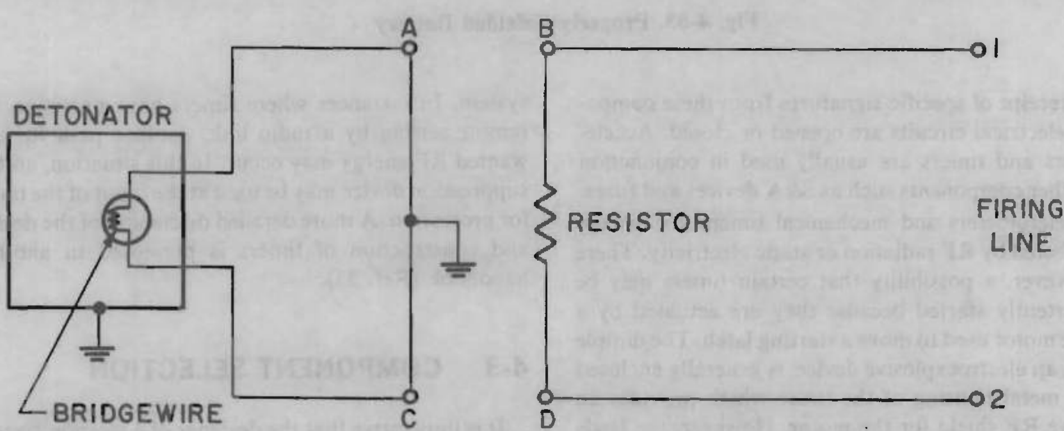


(B) Safe Position

Fig. 4-51. Operation of S&A Device



(A) Poor Design



(B) Proper Design

Fig. 4-52. Elimination of Pins-to-case Mode of Firing EED

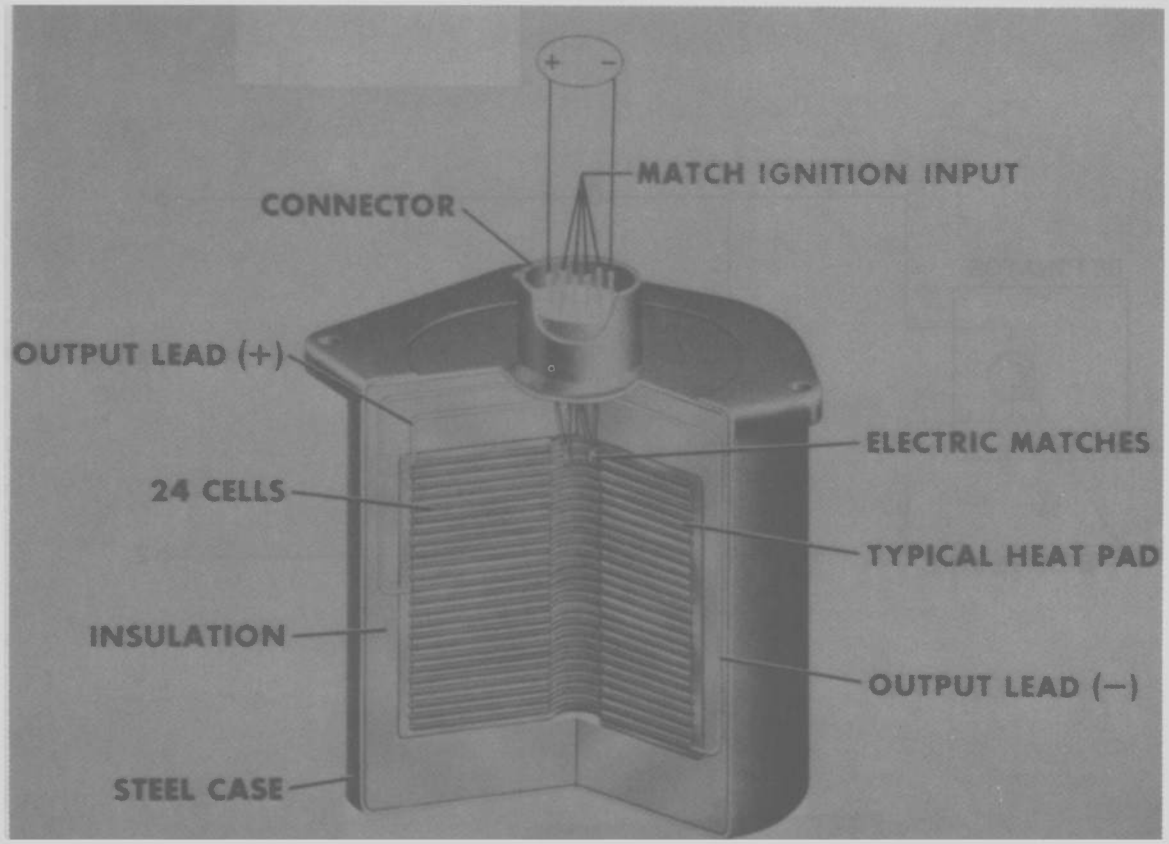


Fig. 4-53. Properly Shielded Battery

Upon receipt of specific signatures from these components, electrical circuits are opened or closed. Accelerometers and timers are usually used in conjunction with other components such as S&A devices and fuzes.

Accelerometers and mechanical timers are usually not affected by RF radiation or static electricity. There is, however, a possibility that certain timers may be inadvertently started because they are actuated by a dimple motor used to move a starting latch. The dimple motor, an electroexplosive device, is generally enclosed in the metal housing of the timer which provides an effective RF shield for the motor. However, the leads to the dimple motor, as well as those to other explosive devices in the system, should be carefully shielded and grounded to prevent RF and static electricity pickup.

Many military systems incorporate electronic timers. The operating elements of these timers are magnetic cores and transistors which are arranged in time base and counting circuits. When these timers are packaged in metal enclosures, the sole remaining mode for entrance of extraneous RF energy is through the cabling system. In instances where timers have provision for remote setting by a radio link, another path for unwanted RF energy may occur. In this situation, an RF suppression device may be used at the input of the timer for protection. A more detailed discussion of the design and construction of timers is presented in another handbook (Ref. 33).

4-3 COMPONENT SELECTION

It is imperative that the designer of a weapon system be fully aware of the hazardous and unreliable conditions that can be created by the existence of RF energy, static electricity, or lightning. If the designer has a complete understanding of the problems and their possible solutions at the beginning of a program, he can incorporate the hardening techniques set forth in this handbook into the initial design. Experience has shown that this is far less expensive than trying to modify an existing system. The purpose of the discussions in the

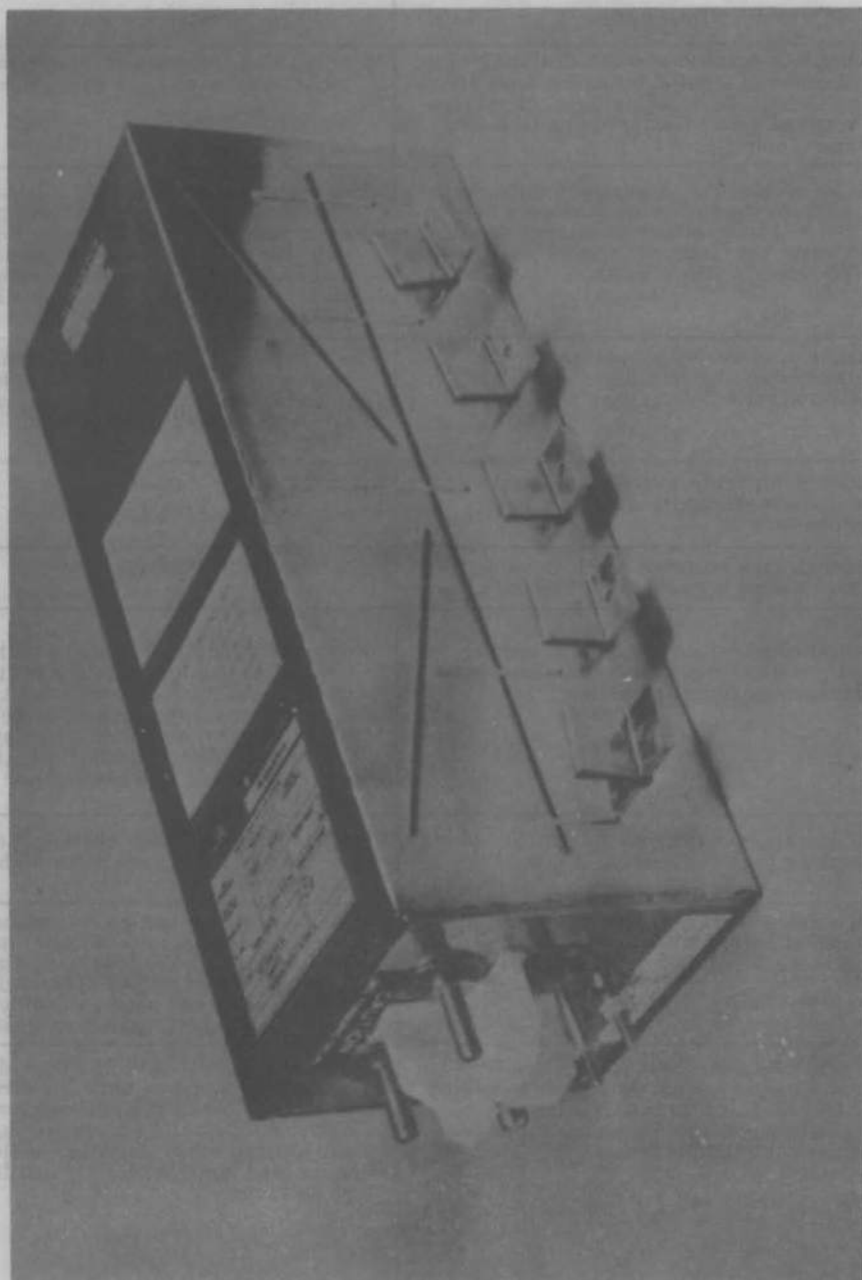


Fig. 4-54. Battery With Open Terminals

TABLE 4-15.

BASIC AEROSPACE ORDNANCE DEVICES

Name	Description	Application
Igniter	A complete ignition system consisting of an initiator and a deflagrating material of a pyrotechnic or propellant type. Produces sustained generation of hot particles, flames, and gas.	For ignition of solid- and liquid-propellant rocket motors and gas generators.
Initiator	Can be divided into 3 groups: squibs, primers, detonators. Squibs produce a hot flash and little brisance; primers produce a brisant hot flash; detonators produce high-velocity shock waves.	Primers and squibs initiate the burning of igniters in pressure cartridges, gas generators, rocket motors, flares, and spotting charges. Detonators provide high-order detonation in high explosives, explosive bolts, Primacord, and other high-explosive systems.
Squib	A flame producer with no brisance, i.e., produces no high explosive effect and is used to ignite deflagrating mixtures.	(See "Initiator" above). For actuation of explosive valves, drogue guns, thrust-reversal and termination systems, shear-pin systems, and pressurization of small volumes.
Primer	Produces higher brisance than a squib and is lower in energy production than a detonator.	(See "Initiator" above)
Detonator	Produces high brisance and high-velocity shock waves almost instantaneously.	(See "Initiator" above)
Pressure Cartridges	Consist of an initiator (squib or primer) and *a* main charge which contains a pressure-producing propellant.	For pressurization of systems with high-energy hot gas for operation of linear and rotary actuators, explosive valves, disconnects, stage-separation devices, thrust-reversal and termination systems, detent and unlatch mechanisms, thrusters, pin pullers, and reefing-line cutters.
Boosters	Produce high-order shock waves to detonate high explosives.	Initiate Primacord, line charges, destructors, MDF, FLSC, and other high explosives.
Explosive Bolts	Fragmenting and nonfragmenting special or standard bolts with an integral or separately installed high explosive charge.	Missile-stage separation, nosecone separation, booster-motor release, rocket-sled release, thrust termination and reversal; jettisoning of special devices, solar panels, and antenna deployment, missile-launcher separation, destruct.
Gas Generators	Hot and cool gas. Essentially small rocket engines consisting of a propellant, an initiator, igniter, and a pressure-regulating nozzle. Produces hot or cool gas at controlled pressure.	Operation of APU, APS, CAD, hydraulic pumps, gyroscopes, turbo blowers; for pressurization of liquid-propellant systems, hydraulic accumulators, and fire extinguishers; inflation of flotation units; and ignition of solid and liquid propellants.

paragraphs which follow is to give some guidelines for the designer in the selection of components that will aid in minimizing the effects of extraneous energy.

The hardening of a weapon system against RF and related effects must be considered from an overall standpoint. After the designer has made the maximum use of the criteria of shielding and wiring layout, the next step is to choose the proper component for the system, which will be resistant to damage or failure produced by these electrical stimuli. Of course, the designer does not have a completely free choice. He must also choose his components to meet all the other requirements of his particular system, but the consideration of RF hardening at this stage can certainly minimize later problems.

Components used in weapon systems can be separated into three general groups: electroexplosive devices, electronic components, and mechanical components. When these components are subjected to intense RF fields, the resulting failure of the component may fall into one of the two categories: (1) a temporary failure occurs during the time the extraneous energy is applied, or (2) the component fails permanently.

Circuits or components that have their normal operating parameters temporarily affected are usually referred to as being susceptible to RFI/EMI. After the RF field is removed, the components regain their normal characteristics.

In this handbook the type of component failure of concern will be of two types: (1) abrupt failure, and (2) deterioration, which is the slow degrading of the component until it no longer passes a certain acceptable limit.

Employing these definitions of failure, components can now be discussed in terms of obtaining maximum hardness to RF energy.

4-3.1 ELECTROEXPLOSIVE DEVICES (EED's)

An EED is activated by the application of an electric stimulus. There are two ways in which EED's may be classified: (1) by their output characteristics, and (2) by their input characteristics. Table 4-15 is a reprint from the *Aerospace Ordnance Handbook* (Ref. 34) which essentially defines EED's according to their output characteristics. In Table 4-16 the EED's are classified according to their electric input characteristics. The use of EED's is justified because of their light weight, small size, high reliability, low energy requirements, and their variety of input and output characteristics. A partial display of available EED's is shown in Fig. 4-55. Their typical constructions are shown in Fig. 4-56. The basic parts of an EED are:

(1) Lead wires or connector
(2) Plug
(3) Bridge
(4) Outer case
(5) Explosive or pyrotechnic charge.

A description of these parts follows:

(1) *Lead Wires or Connector*

Electroexplosive devices are available with a variety of input connections. These include wire leads, multipin connectors, and optical fiber bundles. The photograph in Fig. 4-55 shows a few of the types of EED's used in explosively actuated systems.

The EED pictured in Fig. 4-57 is a recent development that is activated by a laser beam. The absence of electrical wiring (or connector pins) and a bridge should provide immunity to RF fields.

(2) *Plug*

The plug serves two purposes: (a) it mechanically holds the input leads or pins, and (b) it seals the explosive mix from the atmosphere. Normally the plug is made of an insulating material such as glass, Bakelite, or nylon. There are, however, some EED's that use a conductive plug to shunt the bridge. These are normally used in EED's that have high resistance bridges such as carbon bridges and spark gaps (Ref. 35).

There are also some EED's that incorporate RF attenuating materials in the plug so as to reduce their RF susceptibilities. At the present time there are three Army EED's that have been so constructed (Ref. 36): the T20E1 and T24E1 Detonators, and the M6 Blasting Caps. Table 4-21 lists the designations of these items protected in this manner. These three EED's are also less susceptible to static electricity since they have a lower leakage resistance from the pins to the case than their unprotected versions. This low leakage resistance makes it difficult for a charge to build up in a circuit that contains one of these protected EED's.

(3) *Bridge*

The bridge in an EED converts the electrical energy supplied to the EED into another form of energy that can activate the device (Ref. 37). Table 4-16 shows several types of bridges in use which primarily are characterized by the required form of input stimulus sensitivity and expected functioning time. The particular application often governs the choice of EED. For example, an antitank projectile making use of a shaped charge frequently requires functioning times on the order of several microseconds. Also, little space in the projectile is available for a power source, hence, the

TABLE 4-16

TYPES OF EED'S WITH TYPICAL INPUT CHARACTERISTICS

Transducer	dc Resistance, ohms	Sensitivity No-fire	Sensitivity All-fire	*Functioning Time
Hot Wire Bridge				
Standard	0.1 - 10	0.1 A	1.0 A	psec to msec
1 Amp/1 Watt	1.0	1.0	5.0	msec
Exploding Bridge-wire				
gapped	∞	1 μF 800 V	1 μF at 2000 V	μsec
ungapped	0.01 - 0.1	1 μF 800 V	1 μF at 2000 V	
Conductive Mix	$0.01 - 10^6$	0.1 A	10 A	psec
Carbon Bridge	800 - 12,000	10 V	1000 V	less than a μsec
Specials				
Spark gap	∞	150 V	300 V	
Semiconductor	0.05 - 1.0	1.0 A	10 A	msec

*Does not include delay squibs. Reprinted from Ref. 34. Used by permission.

amount of available energy to initiate the bridge is limited. For such an application, a carbon bridge detonator may be used, however, this device is extremely sensitive and is not recommended for RF-hardened designs. On the other hand a launch bolt, used to hold a missile to its launching platform, could use a hot wire-type EED that requires several amperes to fire. This is feasible since the firing current can be obtained from ground equipment which has a high current capacity.

(4) *Outer Case*

The outer case serves several purposes. The first, of course, is to hold the EED together. Second, it protects the device from the effect of moisture and low pressure. With few exceptions the outside case of an EED is made of metal. Usually this case completely encloses the EED except at the base of the plug where the connector pins enter. A metal case has definite advantages when hardening against RF, static electricity, and lightning since the case will act as a shield.

In many applications the metal case is threaded so that the EED can be screwed into the unit it activates. This facilitates the mounting of the EED and also provides a good heat sink as well as continuous shielding.

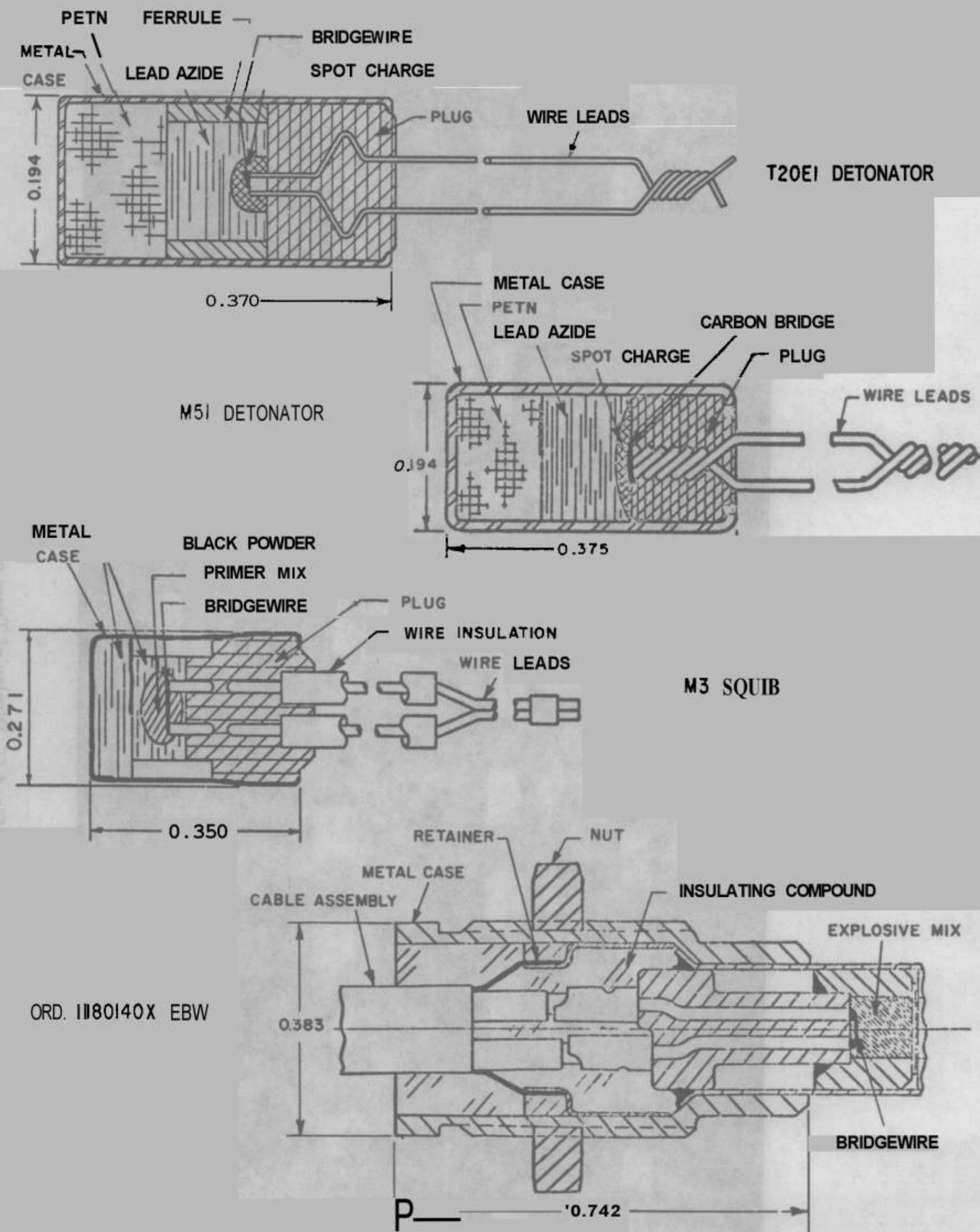
There are some EED's that do not have metal cases. An example is the electric match shown in Fig. 4-58 which is widely used to activate thermal batteries. Since the match does not have an outer metal case, it will depend upon the component to which it is assembled for shielding from RF energy.

(5) *Explosive or Pyrotechnic Charges*

The type of explosive or pyrotechnic charge used in an EED is determined by the purpose of the EED. The more sensitive EED's usually have very sensitive explosives placed adjacent to the bridgewire as shown in Fig. 4-56. The bridge is used to transfer energy to this mix which, when ignited, sets off an intermediate charge which in turn ignites the base charge.

There are also EED's which do not use the sensitive charge adjacent to the bridge. In this type of **EED** the

Fig. 4-55. Display of Types of EED's



ALL DIMENSIONS ARE IN INCHES

Fig. 4-56. Drawings Showing Construction of Typical EED's Used in Army Missiles

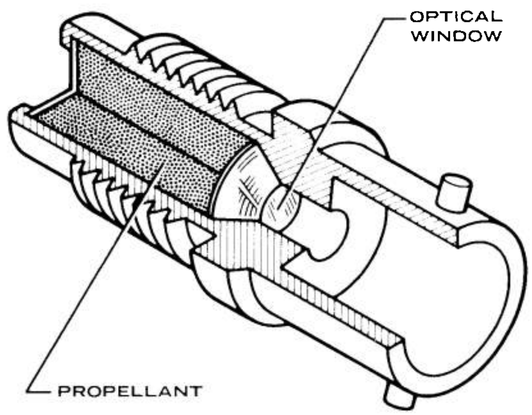


Fig. 4-57. Laser Activated EED

bridge transfers its energy directly into the intermediate mix. A typical example of this type is the exploding bridgewire (Ref. 38). The output of the charge can be made to perform many functions. Some outputs are explosive in nature, some produce a flame, while others may generate a gas.

4-3.1.1 Effects of Extraneous Electric Stimuli on EED's

The normal firing stimulus for an EED is specified by the manufacturer. The stimulus is carefully applied directly to the bridge element and is of a magnitude and shape to produce an initiation with high reliability. *Extraneous electric manifestations such as those produced by RF, lightning, static electricity, transients, or other sources are not so well behaved.* These unwanted stimuli may be picked up in the external circuit and coupled to the EED in such a manner as to produce a reaction in parts of the EED never designed to sustain such stimuli. The modes of excitation include:

a. Pin-to-pin where the stimulus is applied through the bridgewire and corresponds to the normal excitation mode of the EED.

b. Pins-to-case where the stimulus is applied through the explosive between the pins and the outer case.

c. Bridgewire-to-bridgewire. Applicable to EED's with multiple bridges where the stimulus is applied through the explosive charge between the bridgewires.

Extraneous excitations may also produce different functioning characteristics. For example, the stimulus may be of sufficient magnitude to produce an instantaneous initiation such as that produced by the normal firing stimulus. Conversely, it may be of a greatly reduced magnitude which, if applied for a sufficiently long time, may produce initiation by cook-off or thermal stacking, or it could reduce the EED to a dud. To be informed on these phenomena not only aids in the

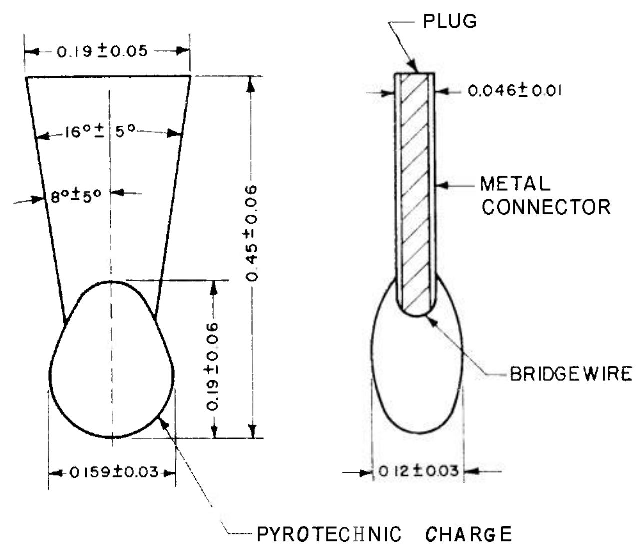


Fig. 4-58. Drawing of Electric Match (Atlas Chemical Industries M-103)

selection of the best components but provides a more thorough understanding of the procedures which must be used in shielding, filtering, and other hardening procedures.

4-3.1.1.1 Modes of Excitation

The bridge element in an EED converts electric energy into some other form of energy to activate the device. If the unwanted energy can cause the bridge to respond in a similar manner, the device may fire. As an example, consider a hot wire-type EED where the mechanism of initiation is the heating of the bridgewire by the electric energy input and heat transfer from the bridgewire to the explosive charge. If the unwanted energy also can cause bridgewire heating, the bridgewire could not differentiate between the intentional stimulus and the unwanted stimulus, and unintended firing could occur.

(1) *Pin-to-pin (Bridgewire Mode)*

Fig. 4-59 shows the firing sensitivity of a typical hotwire EED (Flare Northern 207D squib) excited in the pin-to-pin mode by radio frequency signals (Ref. 39). Fig. **4-59(A)** presents the sensitivity of the 207D squib to continuous wave (**CW**) power while Fig. 4-59(B) presents the sensitivity to pulsed power. The 50% dc firing level (the level at which one half of a group of EED's being tested would be expected to function) for a ten-second constant current pulse is 0.35 **W** and is shown in Fig. 4-59 as a dashed line. The magnitude of power needed to achieve 50% initiation when radio frequency energy is used is also plotted in Fig. 4-59 as a solid line. From these data it can be seen that the magnitude of power to fire this EED with a radio frequency stimulus is always greater than that required for a constant current stimulus.

There are some EED's that do not follow the aforementioned pattern. Fig. 4-60(B) shows the radio frequency sensitivity of an EED that exhibits an unexpected sensitivity to pulsed power from 2700 to 9000 MHz (Ref. 39). Whereas the constant current power for the *50%* firing level is 0.18 W (point *A*), at 2700 MHz, pulsed, it is 0.085 **W** (point *B)*.This is not critical in itself as long as the level does not obtain a value that **is** considered hazardous for the particular application of this squib. Data of this type are not normally available from the manufacturer and the designer will have to refer to the sources listed in par. 4-3.1.4 for guidance.

(2) *Pins-to-case*

RF stimuli or any spurious electric stimuli can be impressed between the outer metal case and the bridge of the EED. This occurrence is schematically illustrated in Fig. 4-61. Though the EED leads are completely shielded, it is possible that the RF energy can be coupled into the system by a component which has unshielded input leads (Ref. 40). A shorting switch, which is used to prevent firing if the trigger circuit is accidentally activated (Fig. 4-61), may be used to place a short across the EED leads. An RF-potential could exist between this shorting switch and ground or between one of the leads and ground if no shorting switch were used. There is, however, no normal pins-to-case firing transducer; in fact, precautions are taken by the manufacturer to reduce to a minimum the chance of a pins-to-case initiation by proper selection of dielectric material, spacing of input leads, and other details. This is done not with consideration for RF protection but for protection from static electricity so that there will be no discharge through the pyrotechnic mix. The mechanism of initiation in the pins-to-case mode is usually either by cook-off (par. 4-3.1.3) due to heating of the plug or by an arc between the pins and the case through the explosive charge.

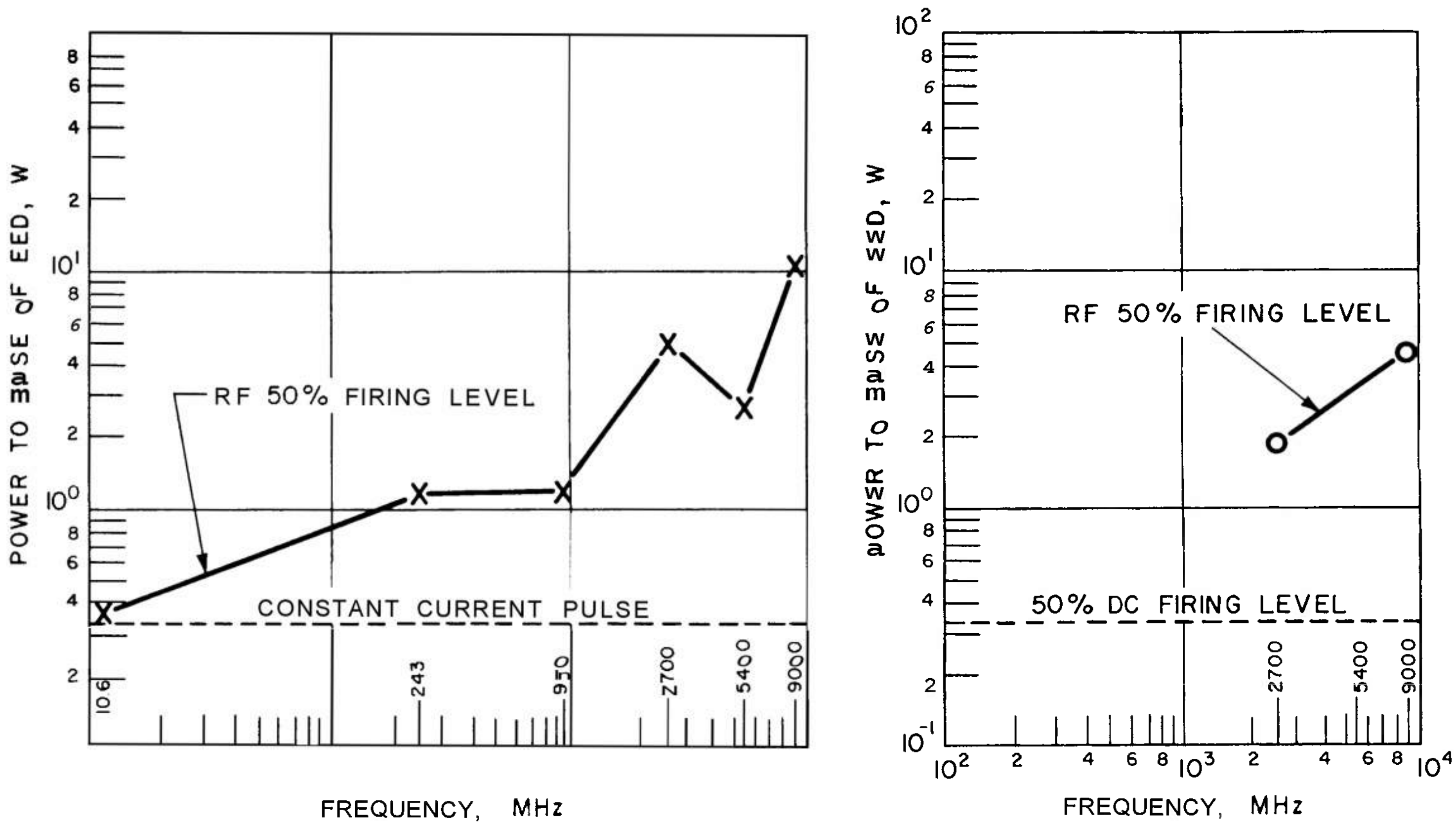
This discussion of pins-to-case sensitivity only applies to balanced type EED's. There are some EED's that have the bridgewire connected between the case and a pin. **An** example of this type is the coaxial EED shown in Fig. 4-62.

(3) Bridgewire-to-bridgewire

Many EED's are constructed with two bridgewires; hence, it is possible that KF or other electric stimuli may be picked up in external circuits and propagated between the twisted pairs, acting as a transmission line, to the bridgewire-to-bridgewire impedance termination (explosive charge between the two bridgewires) as shown in Fig. **4-63.** Functioning in this mode is similar to that for the pins-to-case mode in that the induced current will flow through the explosive charge.

4-3.1.1.2 Dudding and Degrading

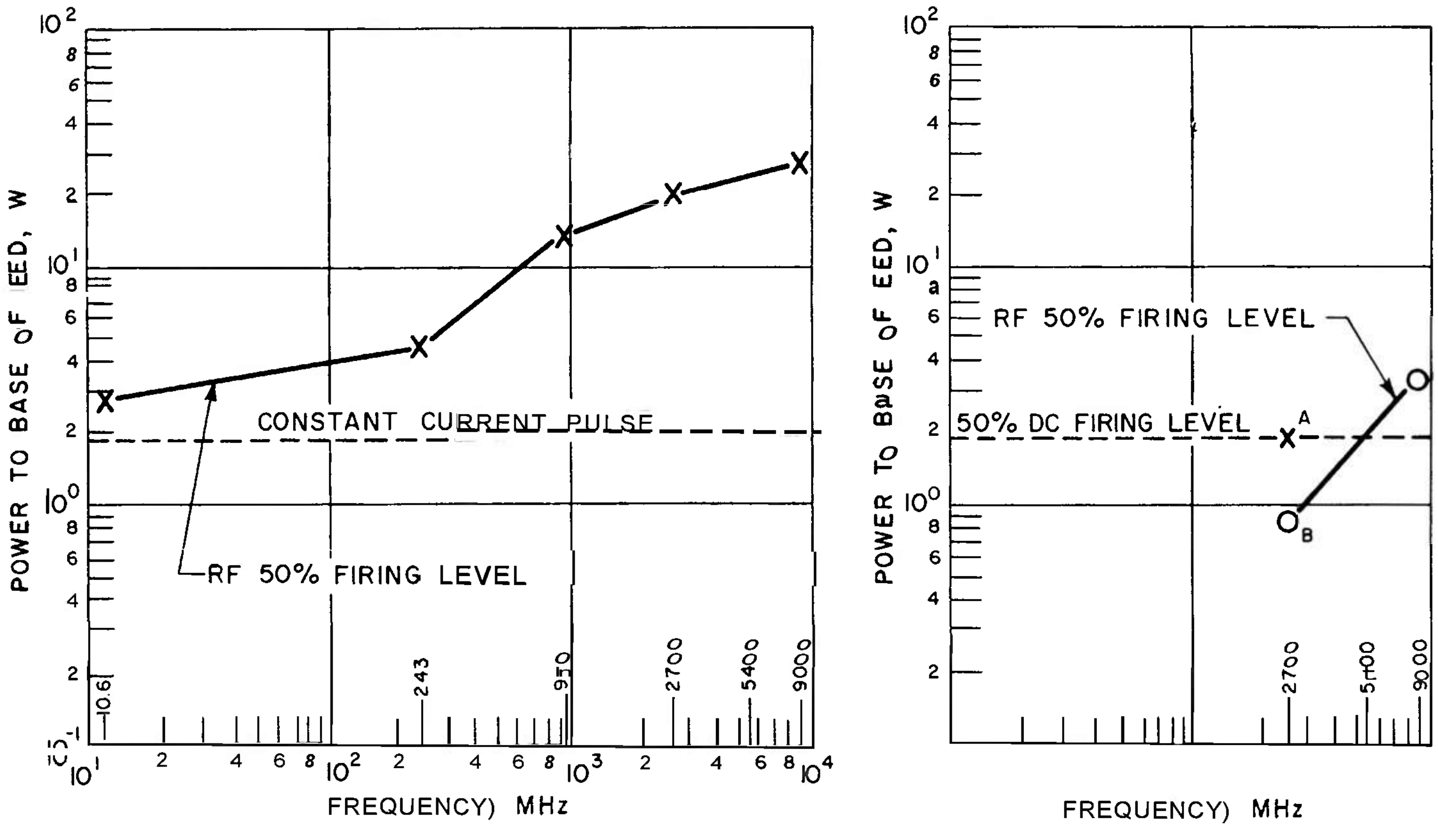
The continual passage of a current less than tne no-fire current through a bridgewire will produce some heating regardless of whether the source is dc or RF. If this heat produces a temperature below that for autoignition, it is possible that the explosive mix adjacent to the bridgewire may slowly decompose. When the normal firing stimulus is then applied, this decomposed mixtures acts as a thermal barrier and prevents ignition. EED's that had telemetering signals flowing through them have dudded when called upon to fire (Ref. **31).** The most susceptible types are those that have lead styphnate adjacent to the bridgewire; therefore, it is not advisable to use this type **EED** when there



(A) CW POWER

(B) PULSED POWER

Fig. 4-59. RF Firing Sensitivity of the Flare Northern 207D Squib (Bridgewire Mode)[6] Average Bridgewire Resistance 0.18 ohm



(A) CWPOWER

(B) PULSED POWER

Fig. 4-60. RF Firing Sensitivity of a Squib to High Frequency Pulsed Power (Bridgewire Mode)[6]
Average Bridgewire Resistance 1.20 ohms

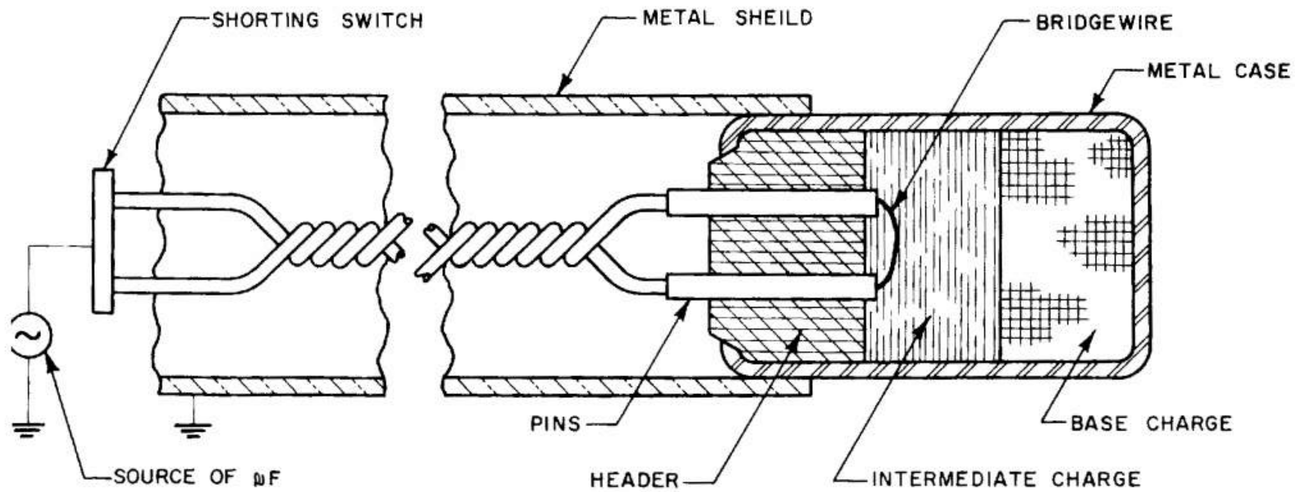


Fig. 4-61. RF Stimulus Applied in the Pins-to-case Mode

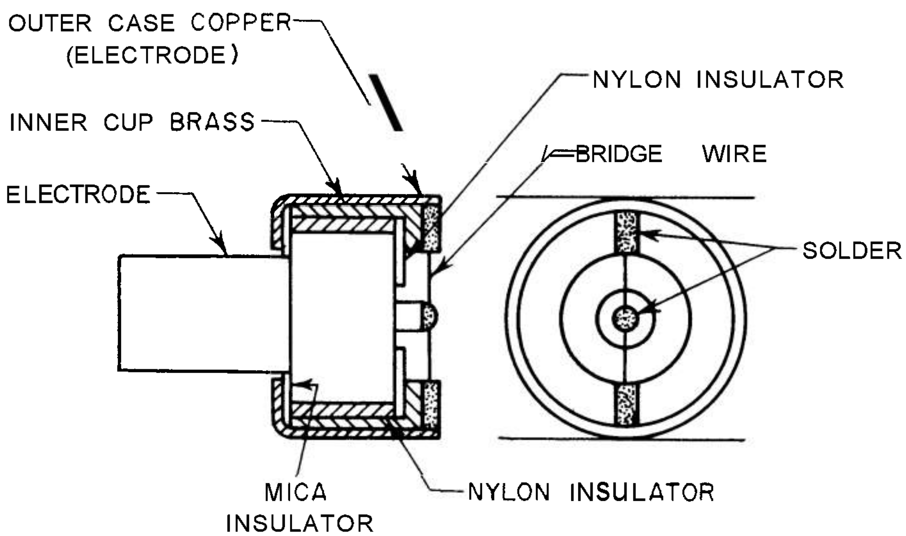


Fig. 4-62. Drawing Showing Construction of Coaxial EED, Mark 7 Mod 0

is the possibility of it being subjected to a continuous electric stimulus.

4-3.1.1.3 Cook-Off

a. *Continuous Wave Power*

If the RF input power does not initiate the EED by bridgewire heating or arcing, there may be enough energy available to raise the temperature of the plug or explosive mix gradually to some critical point where functioning can occur; this occurrence is called ***cook-off:*** An example of this occurs when lead styphnate is used adjacent to a bridgewire. The autoignition temperature for lead styphnate is 350°C. (Autoignition temperatures for other explosive mixes can be found in Refs. 42 and 43.) If the application of energy causes the mix or components in contact with the mix to reach this temperature, ignition will occur. The normal method of minimizing this condition is to provide a heat sink that is larger than the supplying source. Fortunately, in most designs the EED is inserted into a metal body which provides the heat sink. ***When the EED is inserted into any poor thermal conducting material the possibility of cook-off must be considered.*** It should also be noted that this situation can occur in the pins-to-case mode or the bridge-to-bridge mode if a low impedance, conductive path can be established through the mix.

b. *Pulsed Power*

There is a special case of cook-off that occurs when pulsed RF is encountered. Consider the situation shown in Fig. 4-64 where the pulses represent the output of a high-power pulsed radar which heats the bridgewire. The bridgewire temperature will alternatively increase and decrease as the pulses are applied. If, within the interval between pulses, the bridgewire temperature does not fall to its previous value (true if the thermal time constant is larger than the time between pulses), successive pulses will gradually increase the peak temperature of the bridgewire as indicated by the dotted line of Fig. 4-64. If, within the total time of power application, the bridgewire temperature exceeds the threshold temperature required for ignition; the EED may initiate, become desensitized, or its bridgewire may be destroyed without firing.

4-3.1.2 Selecting the EED

When selecting an EED, the designer has several criteria that must be met:

a. Device must perform the function for which it is to be used; i.e., it must have the required output and functioning time. The amount of energy required to fire the device may or may not be of importance. If the power source is limited, then a relatively sensitive device will have to be used.

b. Size, weight, reliability, and cost must be considered. From Fig. 4-55 it is apparent that there are many types of EED's available.

c. Device should not exhibit any unusual sensitivity to RF energy or static electricity.

It would be very convenient for the designer if these data were available from one source. Unfortunately, a

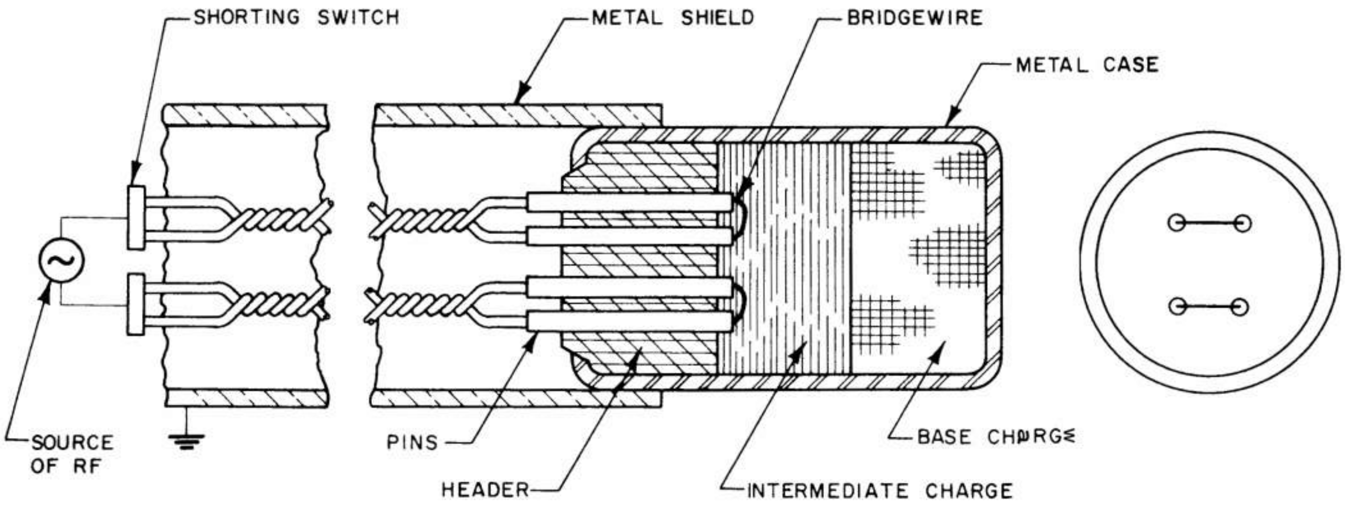


Fig. 4-63. RF Stimulus Applied Bridgewire-to-bridgewire Mode

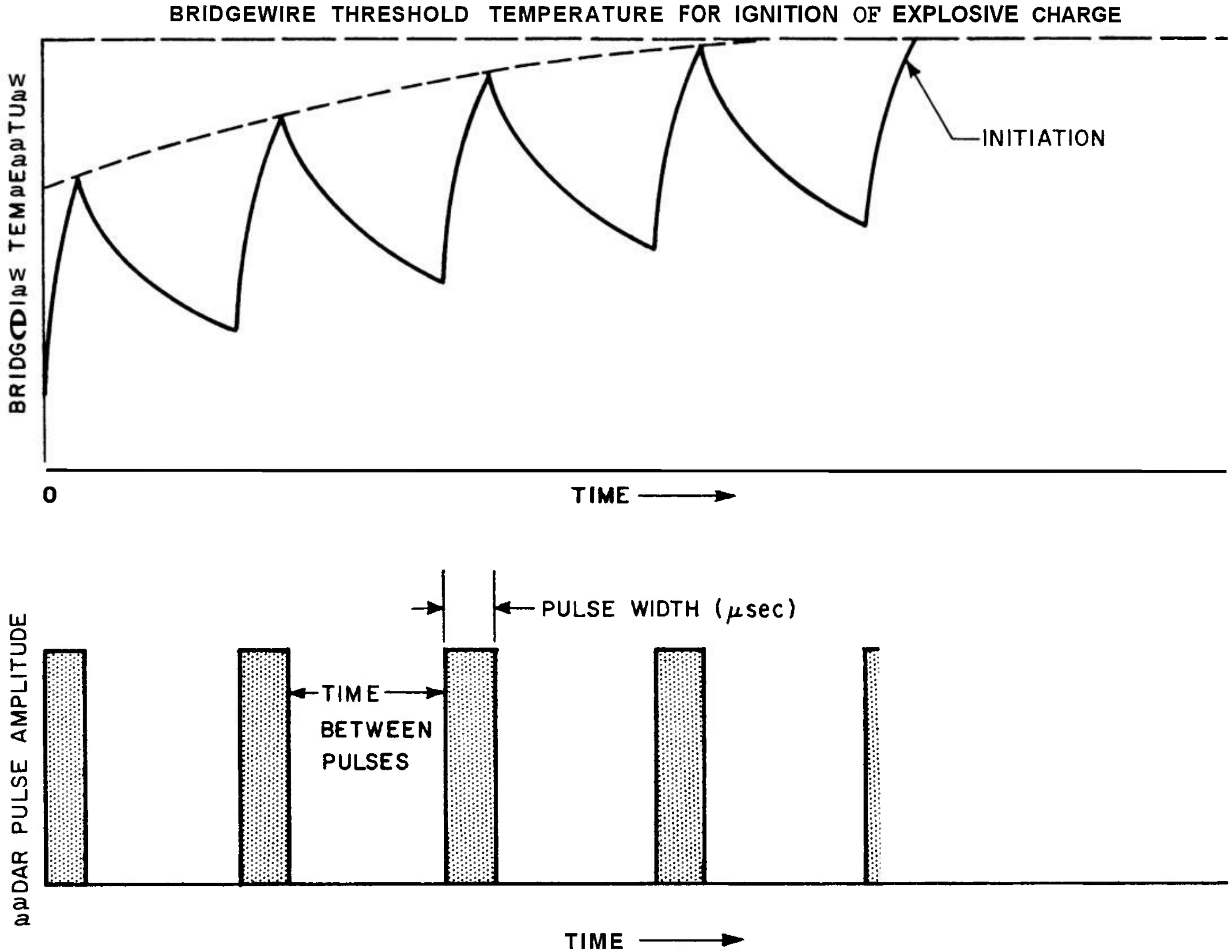


Fig. 4-64. Ignition of Explosive *Charge* by Thermal Stacking of RF Pulse Energy

central information center for EED's does not exist; hence, the designer must seek out the information himself. There are many sources of information available to the designer and several are listed in the paragraphs which follow.

4-3.1.2.1 Library

A good starting point is the library. The librarian is most likely familiar with the standard sources such as the indexes of DDC, NASA, and Clearinghouse. There are also information centers maintained by several Government agencies–DoD has 22, NBS 28, AEC 26, and NASA 8–which the librarian can draw upon. As was mentioned in the previous paragraph, there is no information center exclusively for EED's; therefore, the designer must extract the desired information from these other centers.

4-3.1.2.2 Mission Installations

Mission installations are those Government agencies whose mission calls for research or development on the item of interest. NASA, AEC, Army, Navy, and Air Force all have installations that are responsible for a particular piece of hardware or for research in the area of EED's. The advantage of going to a mission installation is that they (1) have people who can answer a question or who can direct you to a place where the information can be found, (2) have good technical libraries stocked with documents in their field, and (3) publish reports, catalogs, indexes, and other documents of current interest. There are four Army installations that can be listed as good sources of information on EED's:

(1) Harry Diamond Laboratories, Washington, D.C.

(2) Frankford Arsenal, Philadelphia, Pa.

(3) Picatinny Arsenal, Dover, N.J.

(4) Army Missile Command, Redstone Arsenal, Alabama.

Samples of three publications that are typical of those available from mission installations are:

(1) ***Initiators and Initiation Compositions:A Literature Survey,*** by Alfred M. Anzalone, Picatinny Arsenal, Feltman Research Labs, Technical Report 14, September 1960. This literature search resulted in the compilation of almost 1,000 abstracts on initiators and initiating compositions. Included are reports by Picatinny Arsenal, its contractors, OSRD, and other reports distributed to Picatinny. Subject coverage is broad; there are excluded only artillery primers, igniters, and fuzes. Volume I (U) and II (S) contain abstracts, and Volume III (U) is a coordinated index.

(2) ***Explosive Components, Information Pertaining to Fuzes, Volume IV (U),*** by S. Ordierno, Picatinny Arsenal, September 14, 1964 **(S)**. This volume lists physical and performance characteristics of fuze explosive components such as detonators, primers, delays, leads, and boosters.

(3) ***Compilation of Data on Army, Navy, and Commercial Standard Electric Squibs,*** by Robert E. Betts, Redstone Arsenal, Report 3J14N1, January 1956. This compilation of electric squibs is the second revision of these data. Listed are 32 Army, Navy, and selected commercial squibs. The volume is similar in nature to the ***Electric Initiator Handbook*** (Picatinny Arsenal), and lists the specifications and test data on input, and physical and explosive properties.

4-3.1.2.3 Specific Documents

There are some documents available that do compile data on EED's. These are valuable to the designer since they give information on specific EED's. A listing follows:

(1) ***Electric Initiator Handbook (U),*** Picatinny Arsenal, Feltman Research Laboratories, Third Edition, 1963, (C), AD-319 980. The purpose of this handbook is to furnish information on the pertinent characteristics of electric initiators. This includes drawings of the EED's, firing stimuli required, and type of explosive charge used.

(2) ***Power Cartridge Handbook,*** U.S. Naval Weapons Laboratory, NAVWEPS Report No. 7836, Second Edition, **(U)**. This handbook lists cartridges and ignition elements used in naval weapon systems.

(3) ***List of Electroexplosive Devices Tested in Accordance with Eastern Test Range Document AFETRM 127-1,*** The Franklin Institute, August 1968, updated periodically. This document lists EED's that have been evaluated in sufficient depth to permit assessment of RF hazard from dc to 10,000 MHz according to Eastern Test Range Document AFETRM 127-1, 1 November 1966. Table 4-17 gives a listing of the EED's evaluated for their RF characteristics as of January 1969.

(4) ***Electroexplosive Devices Used in Army Weapon Systems,*** by Arthur Davis, Redstone Arsenal, Report RT-TN-64-88. This is a summary of the electrical characteristics of the EED's used in Army missile systems.

4-3.2 SEMICONDUCTORS AND INTEGRATED CIRCUITS

The trend in modern weapon systems is to use semiconductors and integrated circuits rather than vacuum tubes and individual components. There are two types

TABLE 4-17

LIST OF EED'S EVALUATED FOR THEIR RF CHARACTERISTICS

MANUFACTURER	IDENTIFYING NO.	TYPE
Aerojet (Librascope)	P/N 365738 (367676)	Igniter
Aerojet	AG2602	Detonator
Aerojet	AGX 2601	Detonator
Aerojet-Gen.	P/N 1128115-5C	Squib Cartridge
Atlantic Res. (ARC)	NMI-133 MOD 0	Igniter
Atlantic Res.	P/N 3046	Gas Generator
Atlantic Res.	FND 534A	Initiator
Atlantic Res.	MK 12	Initiator
Atlas	1QB221	Squib
Atlas	1QB24	Squib
Atlas	IGN-111	Match
Atlas	M62 (carbon bridge)	Detonator
Atlas	Martin P/N GV896120	Squib
Atlas	RXL 517B	Primer
Bermite	20KS-120	Igniter
Conax	CC-8-56	Valve Detonator
Conax	Martin Co. P/N PD60S0147-003	Pressure Cartridge
Conax	3286-A	Valve Detonator
Conax	JPL P/N1621-005-01	Valve Detonator
Dupont	s-94	Squib
Eimac(Librascope)	Lockheed P/N2339557	EBW* Squib (Polaris A3)
Francis Associates	Martin Co. P/N PD26S0022-005	Explosive Bolt Cartridge

TABLE 4-17

LIST OF EED'S EVALUATED FOR THEIR RF CHARACTERISTICS (Cont.)

MANUFACTURER	IDENTIFYING NO.	TYPE
General Electric	GGC49103PZ	Pressure Cartridge
General Electric	QW 93649, QW 93598	Pressure Cartridge
Hercules	D3A2	Detonator
Hercules	D45A1	Detonator
Hercules	GG-20D3	Gas Generator
Hercules	S6H0	Squib
Hercules	S225D0	Squib
Hercules	SD11C1	Delay Squib
Hercules	SD18C2	Delay Squib
Hercules	SD2A8	Delay Squib
Hercules	SD2B1	Delay Squib
Hercules	SD36B0	Delay Squib
Hercules	SD36B1	Delay Squib
Hercules	SD55A3	Delay Squib
Hercules	SD60A0	Delay Squib
Hercules	SD60A1	Delay Squib
Hercules	SD83A0	Delay Squib
Hi-Shear	PC32-003	Pressure Cartridge
Hi-Shear	PC62-003	Pressure Cartridge
Holex	P/N 4497	Squib
Holex	P/N 5394	Cartridge
Holex	P/N 106382	Initiator
Holex	3184	Squib
Holex	3675A	Match

TABLE 4-17

LIST OF EED'S EVALUATED FOR THEIR RF CHARACTERISTICS (Cont.)

MANUFACTURER	IDENTIFYING NO.	TYPE
Holex	4630	Squib
Holex	5310/5393	Squib
Holex	Philco P/N TRW C106382-1/Holex 5310	Squib
Librascope (link)	DT-154	Detonator
Lockheed	P/N 282339553	Squib
Martin, Orlando	P/N 11180140X-6	EBW* Deton tor
Martin, Orlando	P/N 1183764X-4	EBW* Squib
McCormick-Selph	M56	Squib
McCormick-Selph	M69	Squib
McCormick-Selph	M79	Squib
McCormick-Selph	Lockheed P/N1451809	Separation Bolt Cartridge
McCormick-Selph	Martin Co. P/N 804095-1	Pressure Cartridge
McCormick-Selph	Delta 3rd Stage P/N 808098-1 Rev. A	Initiator
McCormick-Selph	Martin Co. P/N PD60S0147-001	Pressure Cartridge
Olin Mathieson	Bechman & Whitley P/N BW100081	Primer
Pelmec	1138C-02A	Squib
Pyronetics	P/N 3555D	Cartridge
Raymond Engineering	M-62	Carbon Bridge Detonator
Reynolds Rockets	RS-C910	Squib
Rocketdyne	P/N 650717	Igniter
Rocketdyne	P/N 652027	Gas Generator
Space Ordnance Systems	SO1-266-6	Initiator

*EBW - exploding bridgewire

TABLE 4-17

LIST OF EED'S EVALUATED FOR THEIR RF CHARACTERISTICS (Cont.)

MANUFACTURER	IDENTIFYING NO.	TYPE
Space Ordnance Systems	NCASI (Non-conductive Apollo Standard Initiator)	Initiator
Space Ordnance Systems	SEEI (Stray Electrical Energy Indicator)	Initiator
Space Ordnance Systems	SBASI (Single-Bridgewire Apollo Standard Initiator)	Detonator
Special Devices	100640	Squib
Special Devices	Matrix Sciencc No. 003-310	Squib
Talley Industries	Mk 2 MOD 0 (Navy)	Ignition Element (Primer)
Talley Industries	P/N 20565016	Gas Generator
Thiokol	M125 MOD 1	Detonator
Thiokol	P/N 200223-01	Destruct Primer
Unidynamics	Lockheed P/N 1463162	"V" Detonator
Unidynamics	s120	Detonator
Unidynamics	UMC-31-702-3936-1	Detonator
Unidynamics	UMH 1051	Sealed Match
Unidynamics	BuORD No. LD612330	"V" Detonator
Unidynamics	XUD-1094	Detonator
U.S. Flare (ARC)	207A	Squib
U.S. Flare (ARC)	207D	Squib
U.S. Flare (ARC)	706A	Squib
Wurlitzer (ATLAS)	M105	Squib

of integrated circuits in general use. The first is the nonminiature type which employs discrete components; i.e., individual transistors, resistors, capacitors, etc. The second type is called miniaturized or microcircuit and has all of the components on the same substrate. The small size of integrated circuits would seem to signify that their ability to pick up extraneous energy would be minimal when compared to circuits that use vacuum tubes. This is correct; however, the compactness feature is cause for concern in that the circuits may not be able to dissipate as much power or withstand as large a voltage gradient as vacuum tubes.

There are two detrimental things that can happen to a solid state circuit when exposed to a high level RF environment: (1) the unwanted stimulus can cause a false signal in an energized circuit, and (2) the unwanted energy can damage the component. The latter is particularly true in integrated circuits because of their inability to dissipate heat. RFI/EMI design and test techniques are necessary steps in hardening a component to the first effect; however, further hardening techniques may be required when the circuit is built into a weapon system. The second part, which deals with actual damage to the components, is of particular concern for integrated circuits because the small size and dense packing make heat dissipation difficult.

A distinction is made between RFI/EMI and hardening tests because of the difference in the field intensities that are encountered. The maximum field intensity for RFI/EMI tests is 10 V/m while the vulnerability tests for hardening can be in the order of hundreds of volts per meter.

There are several problems which the designer must be cognizant of when dealing with integrated circuits:

a. The small circuit cannot dissipate much heat.

b. The circuit normally operates at low voltages; therefore, the transistors and the capacitors are rated at low voltage.

c. The wiring in a typical system is of the printed circuit variety which is limited in current handling capacity and, because of small spacing, could be susceptible to arcing.

Since integrated circuit components are small and cannot dissipate much heat, the usual way of protecting the sensitive integrated circuits is to use adequate shielding and provide a heat shield.

4-3.3 OTHER ELECTRONIC COMPONENTS

Why do electronic components fail? An over simplified answer is that the stress applied exceeds that which the individual component can withstand. This stress can be mechanical, chemical, or electrical. This handbook deals mainly with the electric stresses expressed in terms of voltage, current, and power. It does not matter whether the system is exposed to an electric field, a magnetic field, or both simultaneously. The induced energy can always be expressed in one or more of the parameters of voltage, current, or power.

The type of stress that causes a component to fail varies according to the nature of the component and is not always a function of just one parameter. A capacitor, for example, may be sensitive to overvoltage and, as in the case of an electrolytic capacitor, also sensitive to reverse voltage. At high frequencies, however, the dielectric of the capacitor may absorb RF energy and dissipate it in the form of heat. The voltage breakdown rating of a capacitor decreases with an increase in temperature; therefore, a combination effect is encountered.

Resistors are normally considered power sensitive since they fail because of overheating, yet it is important to remember that a resistor can fail because of arcing when high voltages are applied. This is an important point to remember when considering a circuit where pulses from a radar are being picked up. In this case the average power may be low but the peak power and, therefore, the peak voltages may be very high.

4-3.4 FAILURE MODE

4-3.4.1 Abrupt Failure

When a device fails abruptly, it exhibits one of two characteristics, i.e., becomes an open circuit or a short circuit. Table 4-18 summarizes the results of a survey on how different electronic components fail. It should be remembered that the definition of abrupt failures is a sudden and complete failure. One of the facts that should be noted in Table 4-18 is that certain components normally fail in a particular manner; however, it is not one hundred percent certain that this will be the case.

4-3.4.2 Deterioration Failure

Abrupt failures are easy to detect. Deterioration is more subtle; it is the slow change of the component's parameters with the application of power over a period of time. The component is said to fail by deterioration when it has exceeded a certain limit. The limit, of course, depends upon the type and the make of the item. Some devices can have a large variation in their parameters without affecting their operations; others cannot.

TABLE 4-18

COMPONENT PART FAILURE MODES FOR ELECTRICAL COMPONENTS[44]

Part Type	Abrupt failure mode, % occurrence	
	Short	Open
CAPACITORS		
Ceramic (general purpose)	95	5
Ceramic (temp. comp.)	80	20
Glass	90	10
Mica (dipped)	90	10
Mica (moulded)	90	10
Paper	80	20
Metallized (paper Mylar)	80	20
Polystyrene	90	10
Teflon	80	20
Mylar	90	10
Tantalum		
Solid	90	10
Wet slug	80	20
Wet foil	75	25
RESISTORS		
Carbon composition	90	10
Carbon film	5	95
Metal film	5	95
Power (wire wound)	5	95
Precision (wire wound)	5	95
Variable (composition)	10	90
Variable (wire wound)	10	90
Variable (metal film)	10	90
Variable (carbon film)	10	90
TRANSISTORS	90	10
DIODES	90	10
TRANSFORMERS	60	40
CHOKES and COILS		
Single layer	5	95
Multi-layer	50	50

4-3.4.3 Reliability

Determining the effects of **RF** energy, static electricity, and lightning on component parameters gets into the realm of reliability engineering and is not within the scope of this handbook; however, in Table 4-19 a list of parameters is presented which reliability engineers measure to ascertain the status of the component.

4-3.5 RECOMMENDATIONS

When considering the components to be used in a circuit, the designer will obviously pick the one that will perform the assigned task. Next, he will insure that these items are qualified under present MIL-SPEC'S. After this, the problem of hardening is considered. If the designer still has a choice of several components, then those that have the highest power dissipation and voltage breakdown capability are desired. In the situation where the choice cannot be made in regards to hardening, the only approach is to adequately protect the components by proper shielding and use of **RF** suppression devices.

4-4 RADIO FREQUENCY SUPPRESSION DEVICES

The various techniques of shielding, circuit layout, and component selection will not always produce a system that is safe from interference or damage by **RF** energy. Because of weight or size restrictions, or the inherent RF sensitivity of particular components, it may be necessary to employ other or additional methods to prevent RF energy from impairing the system. Thus, the term "suppression device" is used in lieu of "attenuator" or "filter" since it is intended to be all encompassing.

The concept of attenuation due to reflection and absorption provided by the shields is presented in par. 4-1. In the paragraphs which follow a slightly different approach to attenuation is presented to help the designer understand the use of radio frequency suppression devices which attenuate the RF energy that has penetrated the shields.

4-4.1 CONCEPT OF ATTENUATION

If P_d is the power arriving at the input of the **RF** suppression device whose impedance **is** Z_d, and P_s **is** the power that actually gets through to the system being protected whose impedance is Z_s; then the degree of protection in dB is

$$dB = 10 \log\left(\frac{P_d}{P_s}\right) \qquad (4\text{-}23)$$

By making the proper substitution for power in terms of voltage and current, dB of attenuation can be expressed in terms of voltage and current ratios:

$$dB = 20 \log\left|\frac{V_d}{V_s}\right| \qquad (4\text{-}24)$$

$$dB = 20 \log\left|\frac{I_d}{I_s}\right| \qquad (4\text{-}25)$$

where the vertical lines indicate magnitudes, i.e., absolute values.

While power ratios are independent of input and output impedance values, voltage and current ratios in Eqs. 4-24 and 4-25 hold true only when the two impedances Z_d and Z_s are equal. In circuits where these impedances differ, voltage and current ratios are expressed by Eqs. 4-26 and 4-27.

$$\left.\begin{aligned} dB &= 10 \log \frac{|V_d|^2\, Re\left[\frac{1}{Z_d}\right]}{|V_s|^2\, Re\left[\frac{1}{Z_s}\right]} \\ dB &= 20 \log \left|\frac{V_d}{V_s}\right| \sqrt{\frac{Re\left[\frac{1}{Z_d}\right]}{Re\left[\frac{1}{Z_s}\right]}} \end{aligned}\right\} \qquad (4\text{-}26)$$

$$\left.\begin{aligned} dB &= 10 \log \frac{|I_d|^2\, Re\left[Z_d\right]}{|I_s|^2\, Re\left[Z_s\right]} \\ dB &= 20 \log \left|\frac{I_d}{I_s}\right| \sqrt{\frac{Re\left[Z_d\right]}{Re\left[Z_s\right]}} \end{aligned}\right\} \qquad (4\text{-}27)$$

where $Re[Z]$ designates that the real part of the impedance **is** to be used, i.e., the numerical values of R from $Z = R \pm jX$. If $Z_d = Z_s$, Eqs. 4-26 and 4-27 reduce to Eqs. 4-24 and 4-25, respectively. It should be noted that attenuation is usually defined only for single frequency excitation of a supposedly linear system. **Also,** computation of transient behavior from a knowledge **of**

TABLE 4-19

TYPICAL INDICATOR PARAMETERS[44]

Part Type	Test Parameters
Tantalum capacitors	1. Leakage current at 25°C 2. Capacitance at 25°C 3. Dissipation factor at 25°C 4. Leakage current at 65°C
Paper Mylar capacitors	1. Insulation resistance at 25°C 2. Capacitance at 25°C 3. Dissipation factor at 25°C 4. Insulation resistance at 85°C
Glass capacitors	1. Capacitance at 25°C 2. Dissipation factor at 25°C 3. Insulation resistance at 25°C
Ceramic capacitors	1. Insulation resistance at 25°C 2. Capacitance at 25°C 3. Power factor at 25°C 4. Insulation resistance at 85°C
Mica button capacitors	1. Insulation resistance at 25°C 2. Capacitance at 25°C 3. "Q" at 25°C 4. Insulation resistance at 85°C
Film resistors	1. Resistance at 25°C 2. Noise at 25°C
Diodes	1. I_R Reverse leakage 2. V_F Forward voltage drop 3. T_{CRV} Thermal coefficient 4. V_Z Zener voltage 5. Z_Z Zener impedance
Transistors	1. h_{FE} Beta 2. I_{CBO} Leakage current (collector to base) 3. P_g Power gain 4. V_{CE} (Sat) Saturation voltage 5. h_{FE1}/h_{FE2} Beta ratio 6. I_{DSS} Leakage current (drain to source) 7. I_{GSS} Leakage current (gate to source) 8. BV_{CEO} Breakdown voltage (collector to emitter) 9. V_P Gate to source pinch-off voltage, at reverse-biased drain

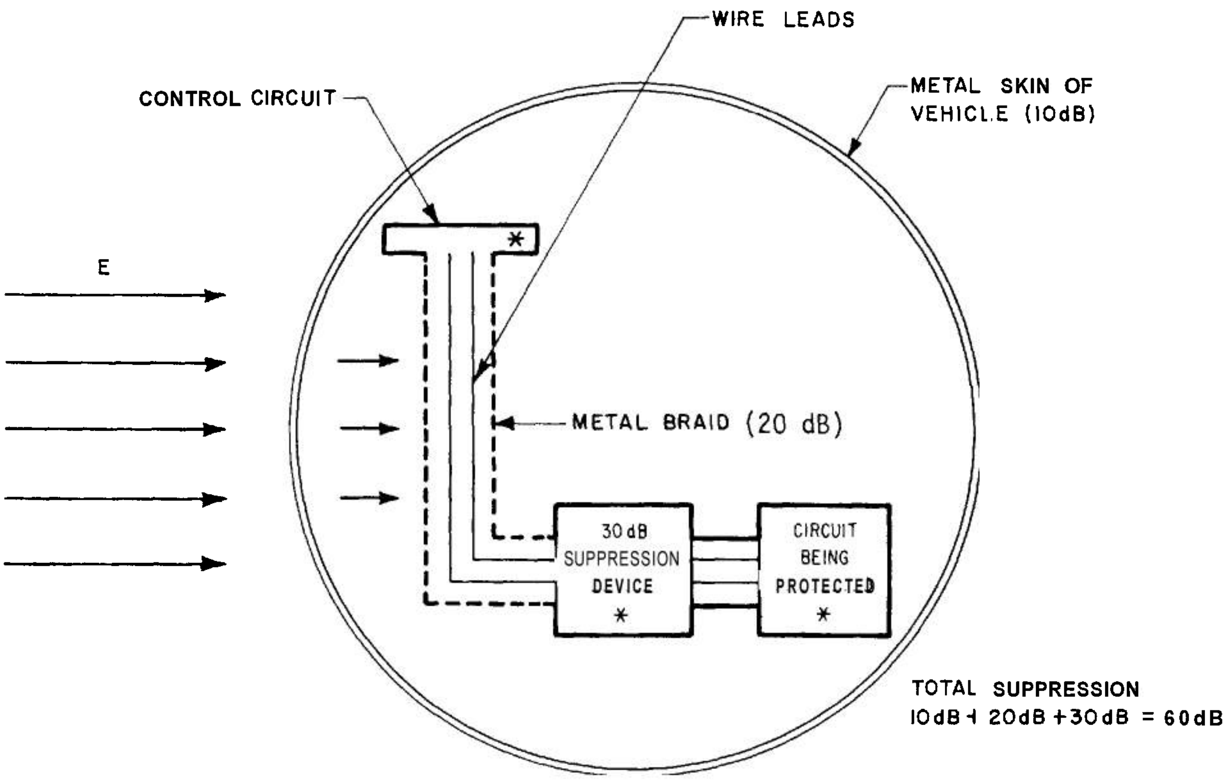
attenuation is, in general, not possible since phase behavior is not included in attenuation data. The discussion which follows assumes single frequency excitation.

The advantage of using the decibel notation arises from its logarithmic character (Ref. 45). This permits enormous ranges of power levels to be expressed without using large, unwieldy numbers, while at the same time permitting small ratios to be conveniently expressed. Thus, 1 dB represents a power ratio of approximately 1.26:1, while 60 dB represents a power ratio of approximately 1,000,000: 1. The logarithmic character of the decibel also makes it possible, in some cases, to express the degree of protection of a complicated circuit as the sum of the attenuation of the different parts of the circuit that are in cascade.

An example is illustrated by the situation shown in Fig. 4-65. Assume that a pair of wires would, if not protected, extract one watt of power from a given field E and deliver it to the input of a circuit. If the wires are covered with a metal braid (the situation if a shielded cable was being used) rated at a minimum of 20 dB, a 30 dB suppression device is placed between the harness and the circuit, and the complete system is placed inside the metal skin of a vehicle that reduces the incident field by at least 10 dB; then the reduction in power delivered to the circuit being protected would be at least 20 dB + 30 dB + 10 dB, or 60 dB. This means that the power delivered to the circuit would be reduced by a factor of at least one million, to 1 μW or less.

These calculations are made with the assumption that the control circuit, suppression device, and circuit being protected are enclosed in solid metal boxes that will afford 60 dB of shielding to each component. If they do not have this amount of attenuation, then the power they pick up will have to be added to the value obtained previously.

Voltage, current, and power ratios expressed in dB are given in Table 4-20.



*For this example it is assumed that the control circuit, the suppression device, and the circuit being protected are enclosed in solid metal shields, each with 60 dB of attenuation.

Fig. 4-65. A Weapon System in an RF Field

TABLE 4-20

DECIBEL-VOLTAGE, CURRENT, AND POWER RATIO

dB	Voltage or Current Ratio	Power Ratio
0	1.000	1.000
1.0	1.122	1.259
2.0	1.259	1.585
3.0	1.413	1.995
4.0	1.585	2.512
5.0	1.778	3.162
6.0	1.995	3.931
7.0	2.239	5.012
8.0	2.512	6.310
9.0	2.818	7.943
10.0	3.162	10.000
10.5	3.350	11.22
11.0	3.548	12.59
11.5	3.758	14.13
12.0	3.981	15.85
12.5	4.217	17.78
13.0	4.467	19.95
13.5	4.732	22.39
14.0	5.012	25.12
14.5	5.309	28.18
15.0	5.623	31.62
16.0	6.310	39.81
17.0	7.073	50.12
18.0	7.943	63.10
19.0	8.913	79.43
20.0	10.000	10^2
25.0	17.8	3.16×10^2
30.0	31.62	10^3
35.0	56.2	3.16×10^3
40.0	100.0	104
45.0	177.8	3.16×10^4
50.0	316.2	105
60.0	1000	10^6
70.0	3162.0	10_7
80.0	10,000	10^8
90.0	31,620	10^9
100.0	100,000	10^{10}

4-4.2 TYPES OF LOSSES

A suppression device affords protection from RF energy in one of three ways: (1) by reflecting the energy, (2) by dissipating the energy, or (3) (most commonly) by a combination of the two.

In practice, a designer working to harden his system against RF energy can safely select suppression devices according to their ability to dissipate RF energy, this being a characteristic solely of the device itself. The designer will not have enough information to compute the RF reflection ability of a device; this reflection depends upon the impedance that the circuits and the components in the system present to the device at each frequency.

4-4.2.1 Reflection Losses

Consider the situation shown in Fig. 4-66(A) which represents a circuit in a weapon system that is picking up RF energy. At the point where the cable connects to the input of the RF suppression device, two impedances are encountered: (1) the input impedance Z_d of the suppression device, and (2) the combined impedance Z_s of the cable and the firing unit. The impedances of the cable and firing unit are shown split in (B) to indicate a balanced system. The generator shown in the firing unit is not a real generator but is inserted to represent the source of RF energy that is being coupled into the system from an external RF field. A simplified unbalanced form of the circuit is shown in (C) for initial reflection loss calculations.

Reflection losses can perhaps be best illustrated by making a simplified assumption. The equation for Z (impedance) can be written as

$$Z = R + jX \tag{4-28}$$

where

R = resistance, the real part of Z
X = reaction, the imaginary part of Z
j = complex number operator $\sqrt{-1}$

Assume that the imaginary part of Z_s and Z_d are equal to zero, then $Z_d = R_d$ and $Z_s = R_s$. The concept of letting the imaginary part be zero and using R is normally stated mathematically as $Re[Z]$ and is used in this form in Eqs. 4-26 and 4-27.

The magnitude of power that can be delivered to the RF suppression device is

$$P_d = P_i - P_r \tag{4-29}$$

where

P_d = power delivered to input of the suppression device
P_i = incident power (power delivered by the theoretical generator)
P_r = reflected power (power reflected from the suppression device and absorbed by Z_s)

For purely resistive components (imaginary part equal to zero) the ratio of power reflected to that incident on the input to the component can be calculated from Eq. 4-30.

$$\frac{P_r}{P_i} = \left|\frac{R_s - R_d}{R_s + R_d}\right|^2 \tag{4-30}$$

Consider the situation where the circuit has an impedance of 1,000 ohms and the suppression device 1 ohm, then, by Eq. 4-30

$$P_r = \left|\frac{1000 - 1}{1000 + 1}\right|^2 P_i$$

$$P_r = 0.996\, P_i$$

or, for a P_i of 100 W, only 0.4 W will be coupled into the suppression device.

An another example, let the circuit impedance be 10 ohms and the input impedance of the suppression device be 1 ohm. Substituting in Eq. 4-30

$$P_r = \left|\frac{10 - 1}{10 + 1}\right|^2 P_i$$

and

$$P_r = 0.67\, P_i$$

or, for a P_i of 100 W, 33 W will be coupled into the suppression device.

From these two examples, it can be seen that the amount of power reflected, for the assumed conditions, is dependent on the ratio of Z_s to Z_d. A reflection effect will also occur between the output of the suppression device and the input to the load, or circuit, being protected by the device (in this example the output is assumed to be matched to the load). The relationship of the impedance ratio to power reflected is plotted in Fig. 4-67 for real source and load impedances. This plot shows, for the simplified conditions assumed, the overall behavior of the power reflection mechanism. The actual case of complex load and generator impedances is considerably more complicated but behaves in the same overall manner; i.e., the larger the disparity between load and equivalent generator impedances, the more power reflected.

If the impedances of the system, suppression device, and load were known at all frequencies, reflection loss could then be used as a valid mehod of providing protection. Unfortunately, these impedances are rarely known over the frequency band of concern; therefore, reflection losses cannot be used with confidence.

It is important that the designer understand the mechanism of reflection since he will encounter this concept when the protection afforded by different types of RF suppression devices is discussed.

4-4.2.2 Dissipation Losses

Energy that is not reflected from the input of the RF suppression device will be coupled into it. Two things can happen to this energy; (1) it can pass through the device and be delivered to the terminating load, or (2) it can be absorbed by the device and released in the form of heat. This latter mechanism is referred to as the dissipation loss; it is a function of the suppression device and the equivalent terminating impedance.

Every suppression device has, at each frequency, a minimum dissipative loss. This minimum dissipation loss of the device is sometimes referred to as the *worst* caseattenuation since this is the minimum ˙.ɔss that the device can exhibit regardless of the input, and/or output impedance value. (Usually, because of circuit mismatches which result in reflection loses, the actual attenuation achieved will be greater than the *worst* case attenuation.)

The simplest way to determine the worst case attenuation of an RF suppression device is to place an impedance matching system between the source and the input of the device, another between the output of the device and its termination, and then adjust the two matching systems until maximum power is delivered to the termination (Ref. 46). The difference between the generator output power and the power delivered to the termination is the actual power dissipated in the RF protection device (assuming negligible losses in either matching system) (Ref. 56). The ratio of the power from the generator to the power delivered to the load under these conditions is a measure of the worst case attenuation of the device and can be expressed in dB by using Eq. 4-23.

The basic technique of matching for worst case attenuation is detailed in MIL-A-3933B (see Table **6-2).** An example of a matching system taken from MIL-A-3933B is shown in Fig. 4-68. This specification is for fixed coaxial and waveguide attenuators; however, the method can be applied to any type of RF suppression devices. It is recommended that the designer use worst case loss in specifying RF suppression devices.

4-4.2.3 Reflection and Dissipation Losses Combined (Insertion Loss)

Placing an RF suppression device between the circuit picking up the energy and the component to be protected will usually result in a reduction of energy transfer by both reflection and dissipation. This combination is referred to as ***insertion*** Zossand is defined for a special case in MIL-STD-220A (see Table 6-1). This definition, as quoted from MIL-STD-220A, is as follows:

> "*3.1* ***Insertion*** *Loss.* At a given frequency, the insertion loss of a feed-through suppresssion capacitor or a filter connected into a given transmission system is defined as the ratio of voltages appearing across the line immediately beyond the point of insertion, before and after insertion. **As** measured herein, insertion loss is represented as the ratio of input voltage required to obtain constant output voltage, with and without the component, in the specified 50-ohm system. This ratio is expressed in decibels (dB) as follows:

$$\text{Insertion loss} = 20 \log \left(\frac{E_1}{E_2} \right) \tag{4-31}$$

where *

E_1 = output voltage of the signal generator with the component in the circuit

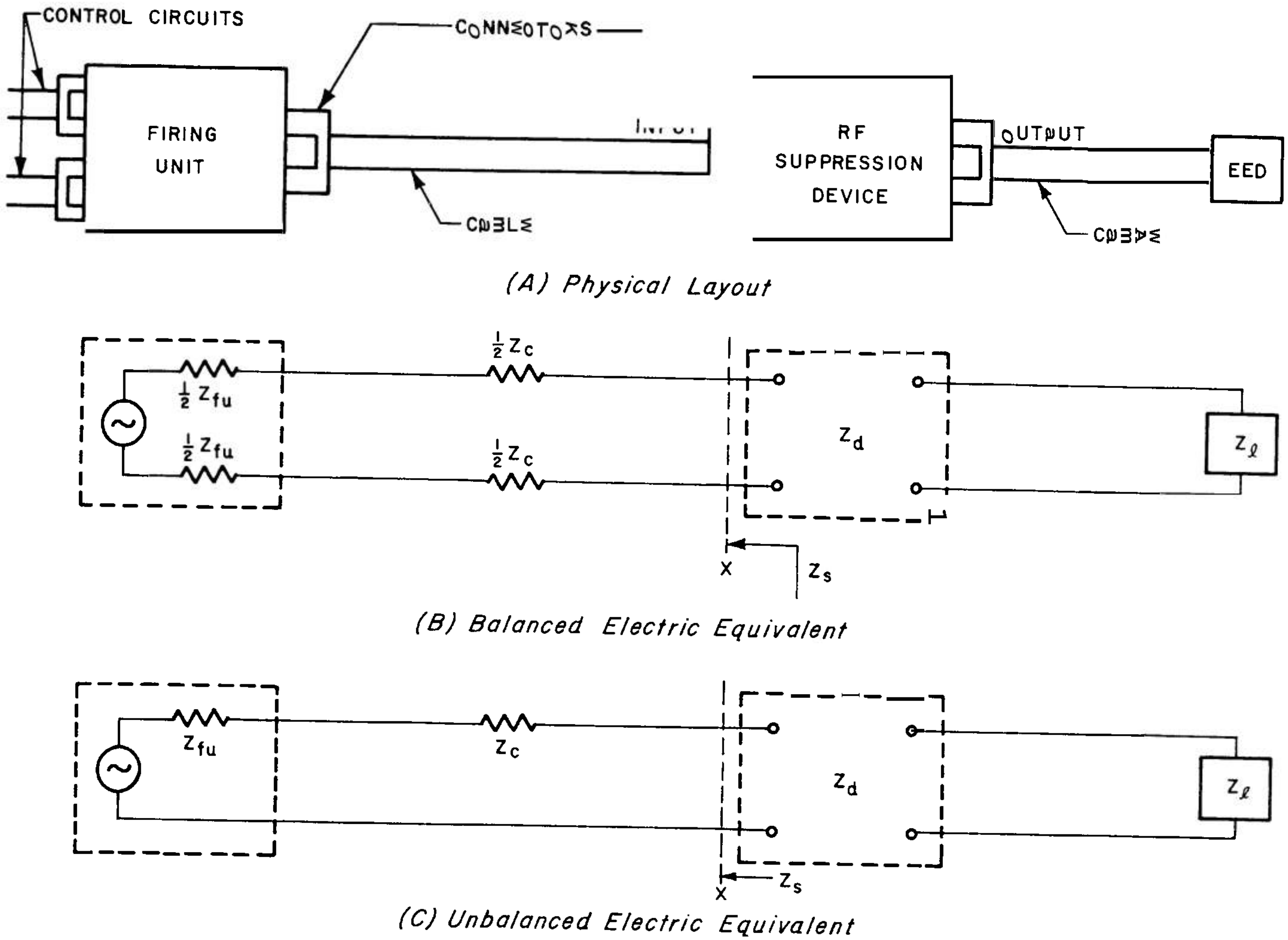
E_2 = output voltage of the signal generator with the component not in the circuit."

Measurements are made using the system shown in Fig. 4-69. Since the voltage readings are always taken across the output of the 10-dB, 50-ohm isolation attenuator, the voltage ratio method of calculating dB is correct.

The limitation of this method of specifying the loss in a device is on the assumption that the input and output impedances that terminate the suppression device are 50 ohms. This, of course, is not always the case.

The insertion loss method of comparing characteristics of various 50-ohm devices is quite convenient when

*The symbol used for voltage in **MIL-STD-220A** is Ewhich differs from the handbook designation of *V*.



<u>WHERE</u>

Z_{fu} = IMPEDANCE OF FIRING UNIT

Z_c = IMPEDANCE OF CABLE

Z_s = IMPEDANCE OF SYSTEM $[Z_s = Z_{fu} + Z_c]$

Z_d = IMPEDANCE OF RF SUPPRESSION DEVICE

Z_ℓ = IMPEDANCE OF EED

$Z_d = Z_s$ FOR THIS EXAMPLE

Fig. 4-66. Weapon System Circuit

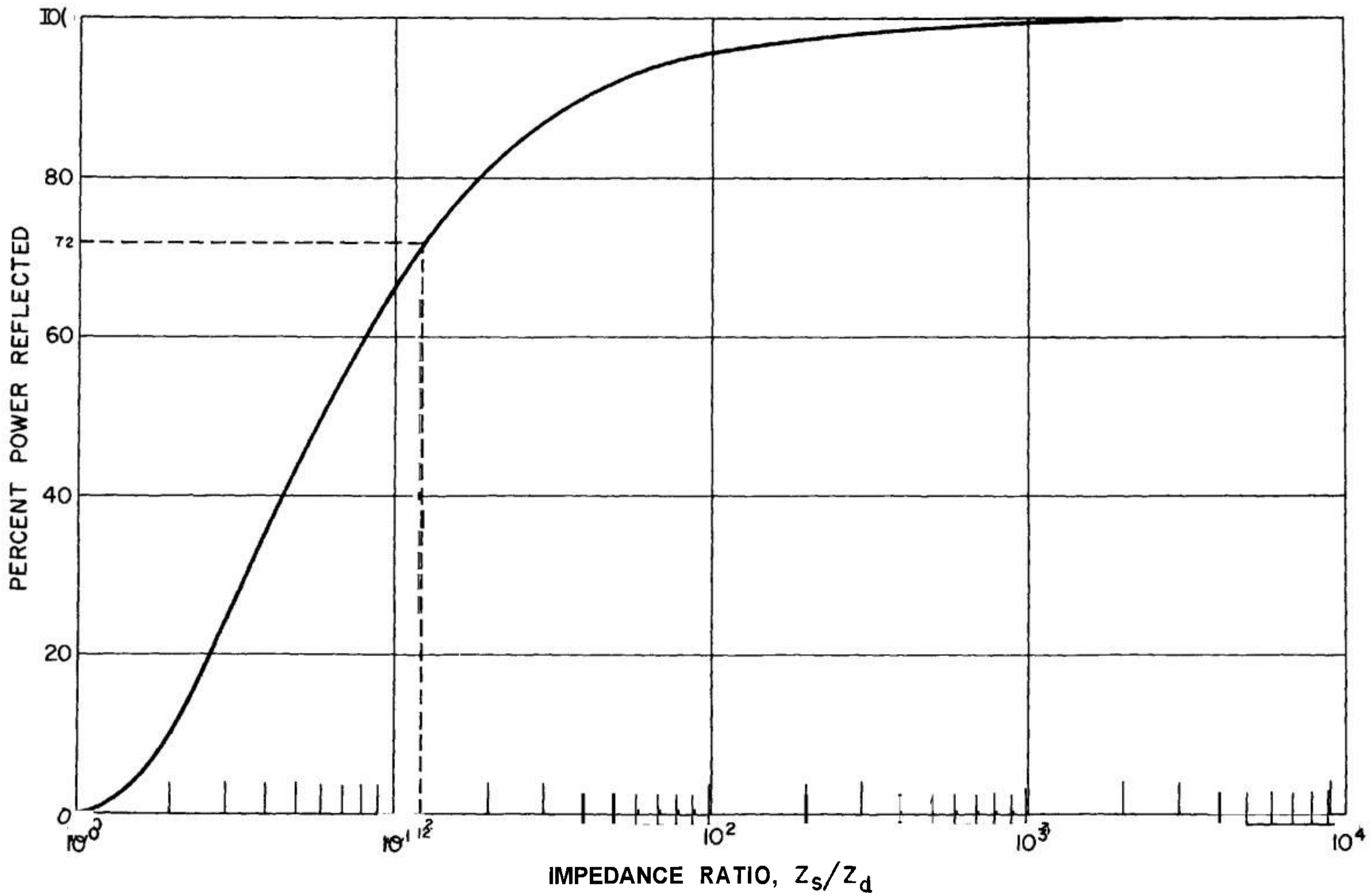


Fig. 4-67. Power Reflected as a Ratio of Impedance

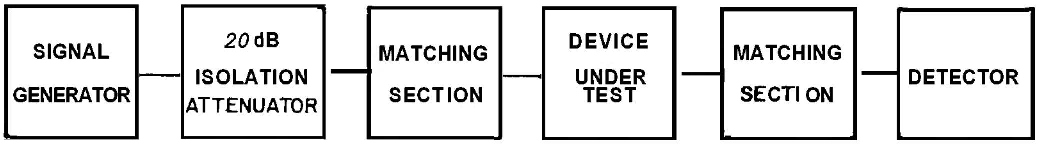
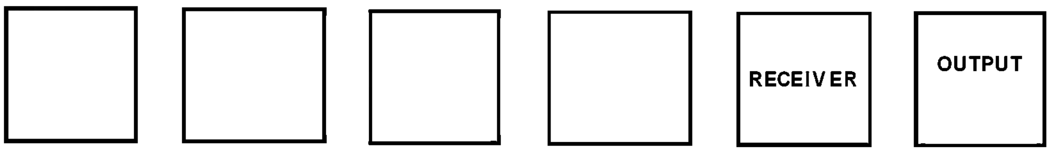


Fig. 4-68. Matching System for Worst Case Attenuation



(a) PLACE A SECTION OF 50 OHM CABLE BETWEEN THE 50 OHM ISOLATION ATTENUATORS.

(b) RECORD VOLTAGE ON OUTPUT METER.

(c) REMOVE 50 OHM CABLE AND REPLACE WITH DEVICE TO BE MEASURED.

(d) RECORD VOLTAGE ON OUTPUT METER.

(e) CALCULATE LOSS BY EQ. 4-31

Fig. 4-69. Insertion Loss Measuring System

all of the system components have 50-ohm characteristic impedances. Commercially available signal generators, coaxial components, meters, loads, etc., have standardized on 50 ohms as the characteristic impedance, where the emphasis is on assembling systems with easily interchangeable components that minimize system losses. The goal of this handbook is to help the designer select the RF suppression devices as lossy as possible to RF energy while passing the desired signals efficiently.

As an example, consider the case of a suppression device which has a real input and output impedance of 600 ohms and a worst case attenuation of 20 dB. If this device were measured according to MIL-STD-220A, it would, according to Eq. 4-32, exhibit 5.5 dB of reflection loss at both the input and output terminals.

$$\text{Reflection Loss} = 10 \log_{10}\left[\frac{1}{1 - P_r}\right]$$

$$\text{Reflection Loss} = 10 \log_{10}\left[\frac{1}{1 - 0.72}\right] \qquad (4\text{-}32)$$

$$\text{Reflection Loss} = 5.5 \text{ dB}$$

The value for P_r is obtained from the curve in Fig. 4-67. The ratio of Z_s/Z_d is 600/50 or 12. Plotting the value 12 on the abscissa, a value of reflected power of approximately 72% is indicated. Eq. 4-32 is in decimals, therefore, 0.72 is used.

If the ratio is less than unity—e.g., 50/600—invert the two numbers and proceed as before. The equation is independent as to which is the generator and which is the device.

The measured insertion loss would be equal to or greater than 31 dB (20 + 5.5 + 5.5), a power ratio of 1,259:1 (5.5 is used twice to account for input reflection and output reflection). Now if this 600-ohm device were placed in a circuit that uses equivalent generator and load impedances of 1,000 ohms (i.e., a set-up like that given by MIL-STD-220A except read 1,000 for 50), the insertion loss could drop as low as 22.6 dB for a power ratio of 182:1. The protection measured by these two insertion loss systems would then differ by a factor of (1259/182) or 8.4 dB (31 - 22.6 = 8.4).

It is recommended that the designer use worst case attenuation for the RF suppression devices that he specifies. Unfortunately, many of the commercial devices available do not give worst case attenuation but specify the insertion loss value obtained using MIL-STD-220A. This leaves the designer with one of two choices if he feels that he must use one of these devices: (1) have the device measured for worst case attenuation, or (2) estimate the worst case attenuation.

Several of the Government agencies have supported programs that have resulted in the measurement of worst case attenuation of RF suppression devices. The designer is referred to Refs. 48, 49, 50, and 52 for further information.

Estimating the worst case loss is very difficult. However, in the following paragraphs, which discuss the various types of devices, some indication as to how to make an estimate is given.

4-4.3 TYPES OF SUPPRESSION DEVICES

One method of classifying RF suppression devices is shown in Fig. 4-70. There is also another classification that should be noted and that is whether the device is a low band-pass, high band-pass, or a band-elimination type.

Low band-pass means that the suppression device will pass all frequencies below a specified value and attenuate those above. High band-pass **is** the opposite. ***All of the RF suppression devices discussed in this paragraph are of the low band-pass type and the only type used for hardening.***

The band-elimination type refers to a device that will attenuate or reject a particular frequency or a band of frequencies and will not attenuate frequencies on either side. These find use in circuits where a narrow range of frequencies is of concern rather than broad band protection.

If the designer finds that the low-pass type is not adequate for some portion of his circuitry because of some overriding, dominant energy at a specific frequency or in a specific frequency band, he may use the band-elimination type to obtain selective attenuation of this specific frequency or frequency band.

4-4.3.1 Broad Band Absorbers

RF suppression devices that achieve attenuation by dissipating the applied energy in a lossy material and releasing it in the form of heat are referred to as broad band absorbers. Two types of lossy materials were developed by the Army: ***carbonyl iron*** and *lossy* ***ferrites.*** The initial objective was to develop a material that could be used in the base of the EED to absorb RF energy and thereby supply RF protection. This objective was achieved and several RF-protected EED's are now available. At the time of publication of this handbook, the RF-protected EED's listed in Table 4-21 are available:

TABLE 4-21

LIST OF EED'S AVAILABLE

RF-protected EED	EED It Replaces
XM8	M6
M78	T24E1
M78E1	T24E1
XM81E1	T20E1

The next step was to use these materials in KF suppression devices which were external to the EED.

4-4.3.1.1 Carbonyl Iron

The first RF-protected EED using the broad band absorbing material was the T24E1 Detonator (Ref. 48), later designated as the M78. In physical dimensions and dc characteristics the original unprotected detonator and its RF-protected version are identical. Table 4-22 indicates the protection afforded the M78 when using a carbonyl iron plug. For frequencies above 500 MHz the protection is good but below 500 MHz it drops off rapidly. When the carbonyl material was developed it was felt that protection was needed mainly at the radar frequencies, accordingly, the values listed in Table 4-22 and plotted in Fig. 4-71 were acceptable.

When it became apparent that protection was needed also at the lower frequencies, other materials were investigated. The carbonyl iron M78 Detonator is still

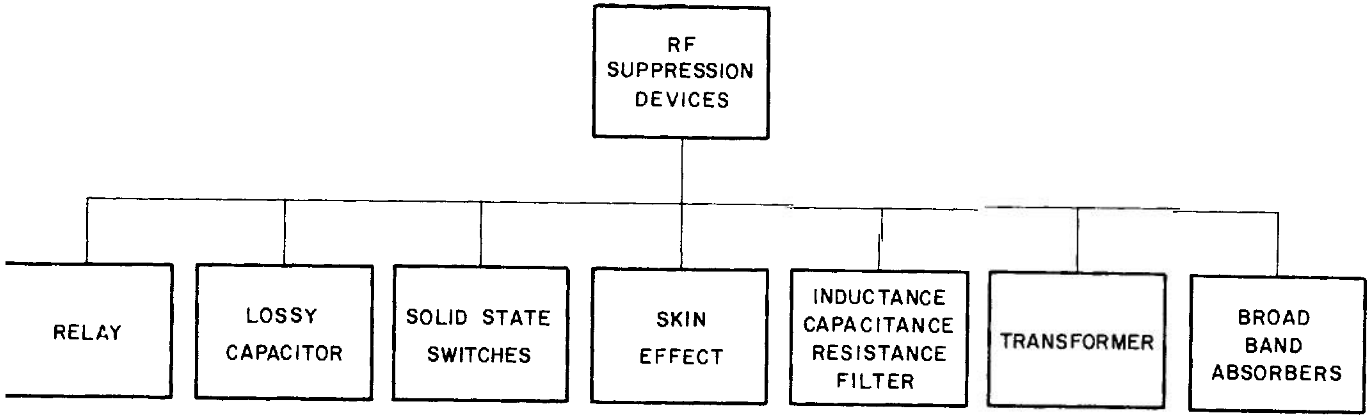


Fig. 4-[illegible] Classification of Protective Devices

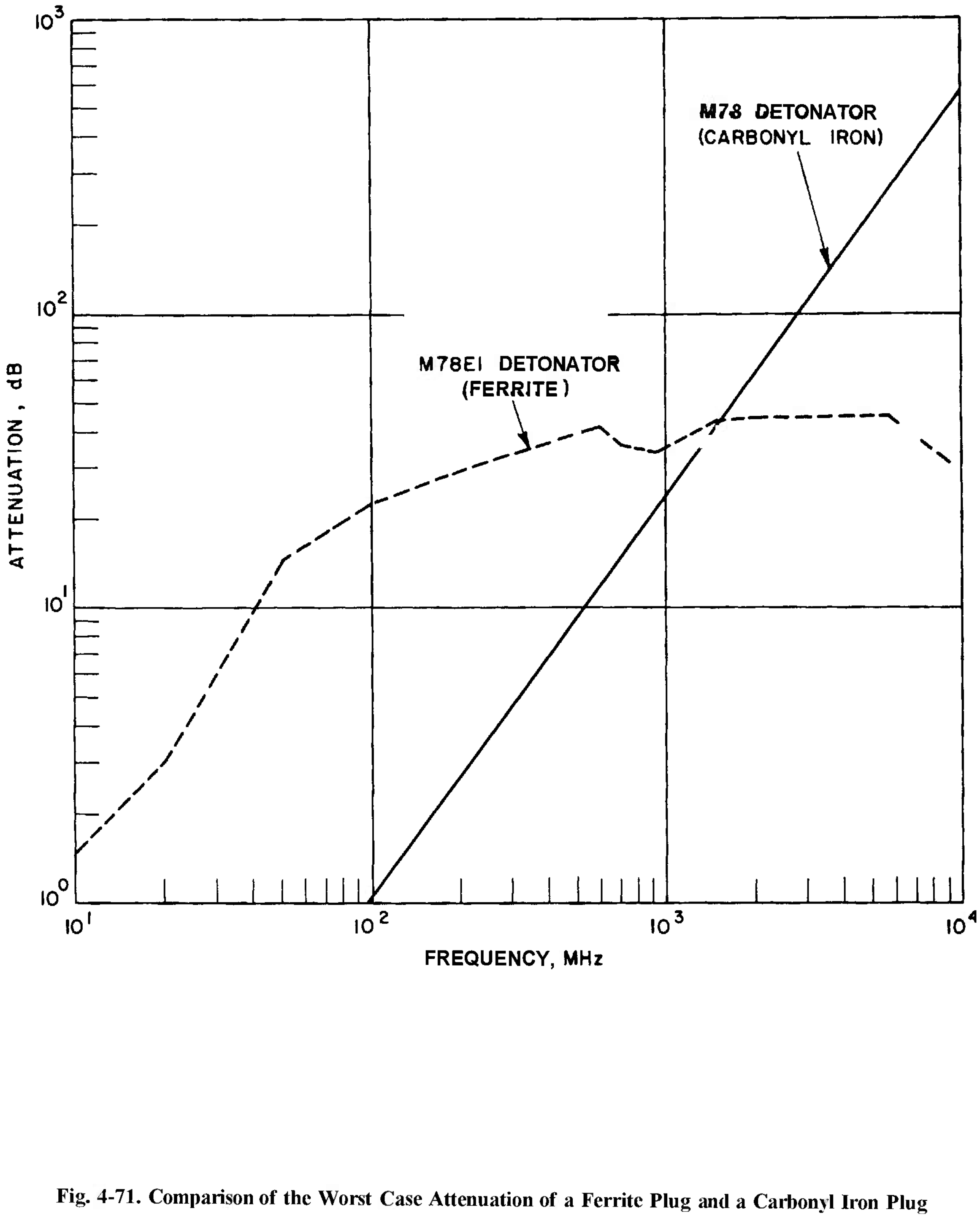


Fig. 4-71. Comparison of the Worst Case Attenuation of a Ferrite Plug and a Carbonyl Iron Plug

Frequency, MHz	dB	Amount of Protection (worst case) Power Ratio
1	0	0
10	>0.1	>1.02
100	1.0	1.26
500	10	10
1,000	25	316
10,000	>100	$>10^{10}$

available but because of its poor low-frequency attenuation and its low voltage breakdown, pins-to-case (24 V dc), it was superseded by the M78E1 Detonator which uses a ferrite plug.

The M78 Detonator with a modification to overcome the low breakdown voltage characteristic is used in the SHERIDAN Weapon System. Fig. 4-72 shows the detonator insulated from a metal sleeve by insulation shrink tubing, the detonator assembly will withstand 500 V, rms, between the two leads and the metal sleeve.

4-4.3.1.2 Ferrites

The search for a broad band absorbing material that attenuates at the lower frequencies as well as the higher frequencies led to the development of the insulated ferrite (Ref. 48). Fig. 4-71 compares the protection afforded the T24E1 Detonator when it has a plug made of ferrite (M78E1) as opposed to one made with carbonyl iron (M78). Note the two major attenuation differences between the two materials. First, the ferrite is superior to the carbonyl iron at low frequencies but drops off at the high frequencies. Second, the iron has a smooth predictable slope (53" on log-log paper) while the ferrite does not. This does not affect the use of the ferrite; it means that whenever it is used in the design of a new EED, several measurements must be made to define its attenuation curve.

The electrical characteristics of the ferrite plug are:

a. Resistance between leads: 50 MR

b. Voltage breakdown: 500 V, rms, 60 Hz

c. Risetime delay: Less than 1 μsec

Fig. 4-73 shows the internal parts of the M78E1 Ferrite Plug. This is taken from Picatinny Arsenal Drawing No. 9230659, 13 Feb. 68.

As more types of protected **EED's** become available, the designer should consider using them in situations where an RF hazard may be indicated.

The insulated ferrite bead as an attenuator is not limited to being used in the base of the EED. In some devices it is possible to build the beads into the housing that contains the EED. A good example of this is the squib switch shown in Fig. 4-74. The amount of attenuation obtainable depends upon the number of beads that can be cascaded.

A more recent development is illustrated in Fig. 4-75 where the ferrite attenuators are shown assembled on the pins of a connector. These connectors are available to meet MIL-C-27599.

4-4.3.1.3 Hybrids

Very few RF suppression devices that use ferrites alone were made because it was determined early in the development that a combination of inductance-capacitance-resistance (LCR) and ferrites produces the maximum loss per unit volume. These combination types are generally referred to as hybrids.

There are two general classes of hybrid suppression devices under development: (1) those that use shunt capacitors in conjunction with the ferrite, and (2) those that use inductors in series with the ferrite. The capacitor hybrids are superior to the inductor hybrids with regard to attenuation; however, they have lower voltage and temperature ratings. This is due to the tantalum capacitors used to obtain the large shunt capacity required while keeping the size and weight to a minimum. An example of capacitor-ferrite hybrid is given in Fig. 4-76. The maximum ratings of this device are 50 V and an upper temperature limit of 80°C. The worst case attenuation of this device is plotted in Fig. 4-77.

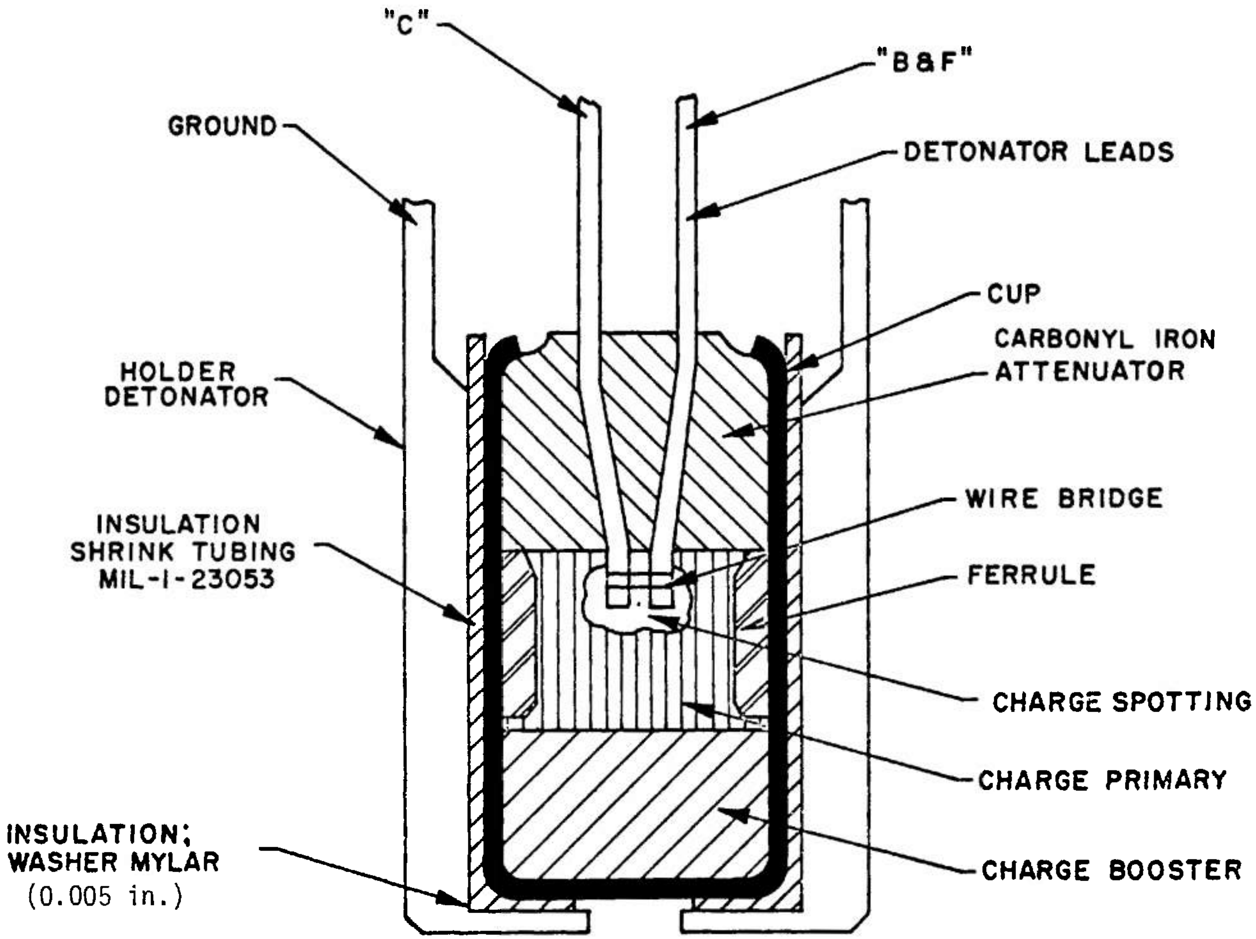


Fig. 4-72. M78 Detonator in Its Holder

A drawing of an inductor-ferrite hybrid is shown in Fig. 4-78; its worst case attenuation curve is plotted in Fig. 4-77. The ratings for this device are 500 V and 180°C. Another version of the inductor-ferrite hybrid is an NASA-Apollo development and is shown in Fig. 4-79 (Ref. 49). It is also rated at 500 V and 180°C. Its worst case attenuation curve is plotted in Fig. 4-80.

At this writing, commercial ferrite-hybrid suppression devices are just appearing on the market. The designer should consider the use of these devices in circuits that need RF protection. Fig. 4-8 1 illustrates the types of ferrite devices that the Army has under development (Ref. 50).

4-4.3.2 Inductance-capacitance-resistance (LCR) Filters

Of all the RF suppression devices available, those consisting of inductors, capacitors, and resistors (commonly referred to as LCR filters) are the most common. Withjust a cursory survey, over forty commerical low-pass filters can be found. Fig. 4-82 shows two typical arrangements used in LCR filters. Classical LC and LCR filter design capitalizes on insertion loss parameters of frequency dependent inductors and capacitors.

The basic technique used with LCR circuits is to block the undesired frequenciesby using a high impedance and then shunt them to ground through a low-impedance path. By selecting the proper combination of capacitors and inductors, this technique can be applied over a limited range of frequencies. Since the impedance of the networks is a function of frequency, there will be certain frequencies where the filter's attenuation will drop appreciably.

An example of the difference that can exist between insertion loss of an LCR filter, as quoted by the manufacturer using **MIL-STD-220A,** and worst case loss can be seen by examination of the curves shown in Fig. 4-83.

At 1 MHz the insertion loss is 57 dB.

At 1 MHz the worst case attenuation is 16 dB.

$$57 \text{ dB} = \text{power ratio of } 5.01 \times 10^5$$
$$16 \text{ dB} = \text{power ratio of } 3.98 \times 10$$
$$\text{ratio} = \frac{5.01 \times 10^5}{3.98 \times 10} = 1.26 \times 10^4$$

The power delivered to the load could be 12,600 times greater than that indicated by the insertion loss rating.

The worst case value of 16 dB was obtained with a matched input and output. This situation is very unlikely to exist in actual practice. On the other hand, the chances of each side being terminated with 50 ohms is also remote; therefore, somejudgment must be made as to the amount of attenuation that can be assumed. From experience, it would appear that one-half the insertion loss value quoted by the manufacturer would be a conservative number to use for the attenuation expected from a LCR suppression device.

4-4.3.3 Lossy Capacitors

In normal use, capacitors that are lossless are desirable. It is possible, however, to go to the other extreme and make the capacitor lossy. Several manufacturers have taken advantage of this characteristic to design capacitors that protect circuits from RF energy by a combination of shunting and absorption losses.

One example of a lossy capacitor is the tantalum feed-through capacitor (Ref. 51). This type takes advantage of the high loss associated with a solid-electrolytic capacitor. A curve showing worst case attenuation of a typical tantalum capacitor is plotted in Fig. 4-84. There are two disadvantages of this type of device: (1) it has a low voltage breakdown rating (about 50 V), and (2) it will not withstand a reverse voltage (it is polarized).

4-4.3.4 Solid State Switching Device

The use of mechanical switching circuits, such as relays, is one of the oldest methods of achieving protection. With the advent of semiconductor electronics, this switching can be achieved with no moving parts. The idea of using this switching method as the basis of an RF suppression device has been investigated; however, no practical devices have yet been developed.

Some of the difficulties encountered are: (1) leakage across the junction when the switch is opened (leakage due to dc resistance and capacitance), (2) low power handling capability, (3) inability to function over a wide range of frequencies, and (4) susceptibility to transients (Ref. 52).

4-4.3.5 Skin Effect Filter

Two types of filters have been designed using skin effect as the loss mechanisms. The first type uses the increase in wire resistance that occurs as the frequency is increased. The RF resistance of the wire will, above some specific frequency, increase as a function of the square root of the frequency. To take advantage of this effect, several feet of copper wire coated with nickel-iron are used.

A second type called **RIG** (Radio Interference Guard) was developed for the Naval Weapons Laboratory (Ref. 16). This RF suppression device operates on the principle of skin-depth penetration. The two major

(Located in back of manual.)

Fig. 4-73. RF Filter and Plug Assembly, M78E1

Fig. 4-75. Connector With Built-in RF Supressors

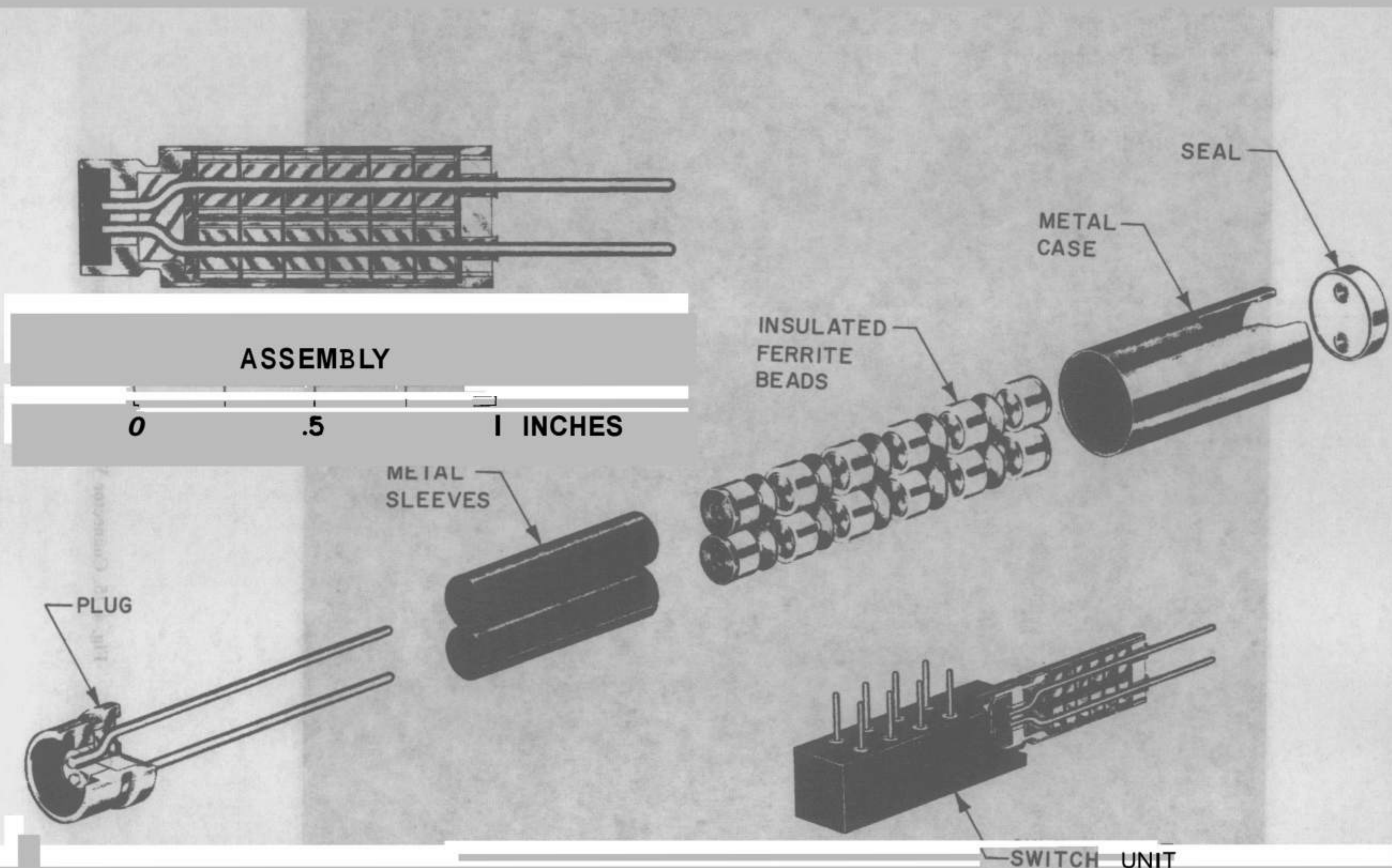
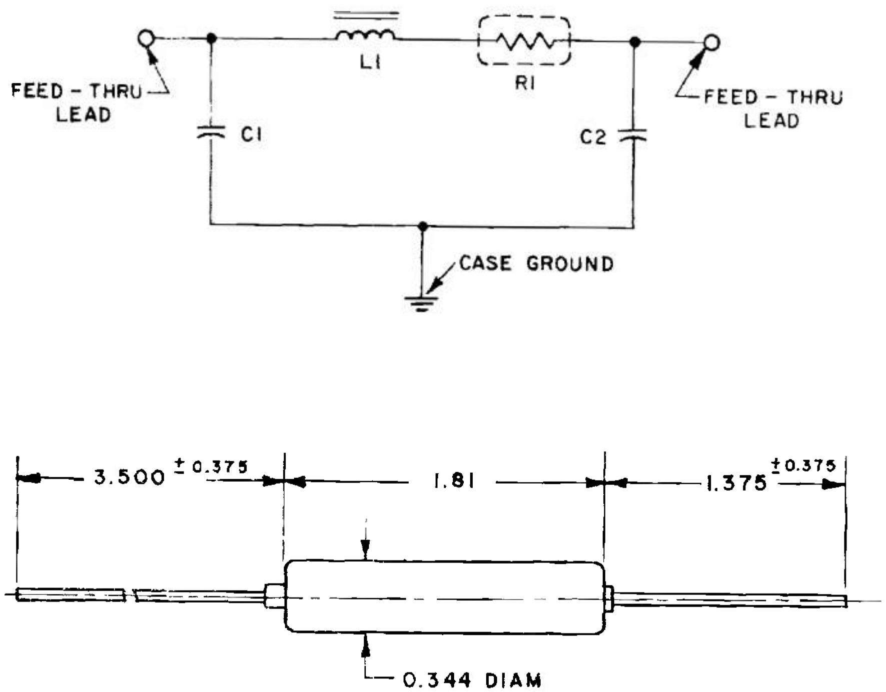


Fig. 4-74. Ferrite Bead Attenuator (Squib Switch)



NOTE

ALL DIMENSIONS IN INCHES

Fig. 4-76. Capacitor-ferrite Hybrid Filter

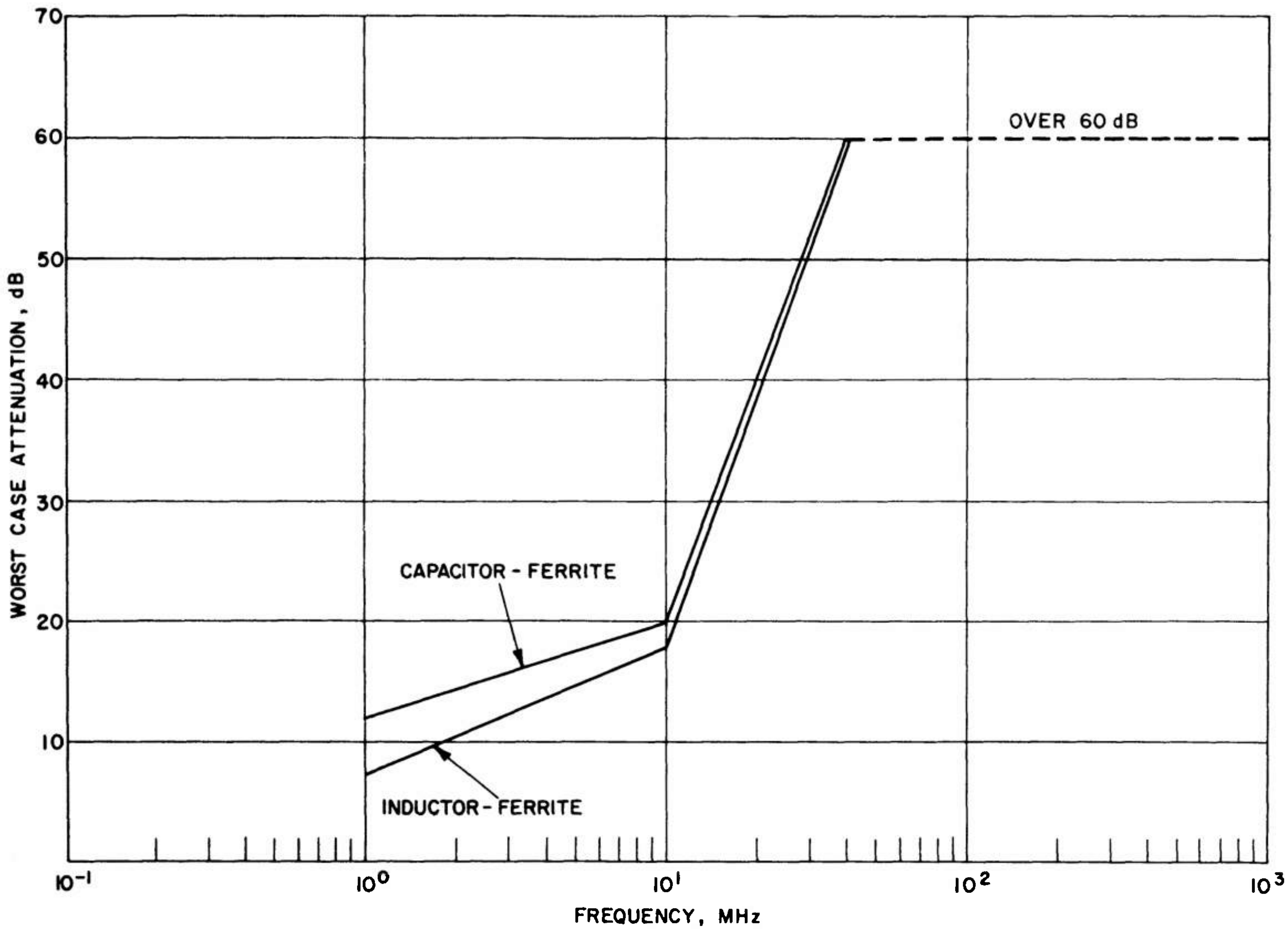


Fig. 4-77. Worst Case Attenuation of Ferrite Hybrids

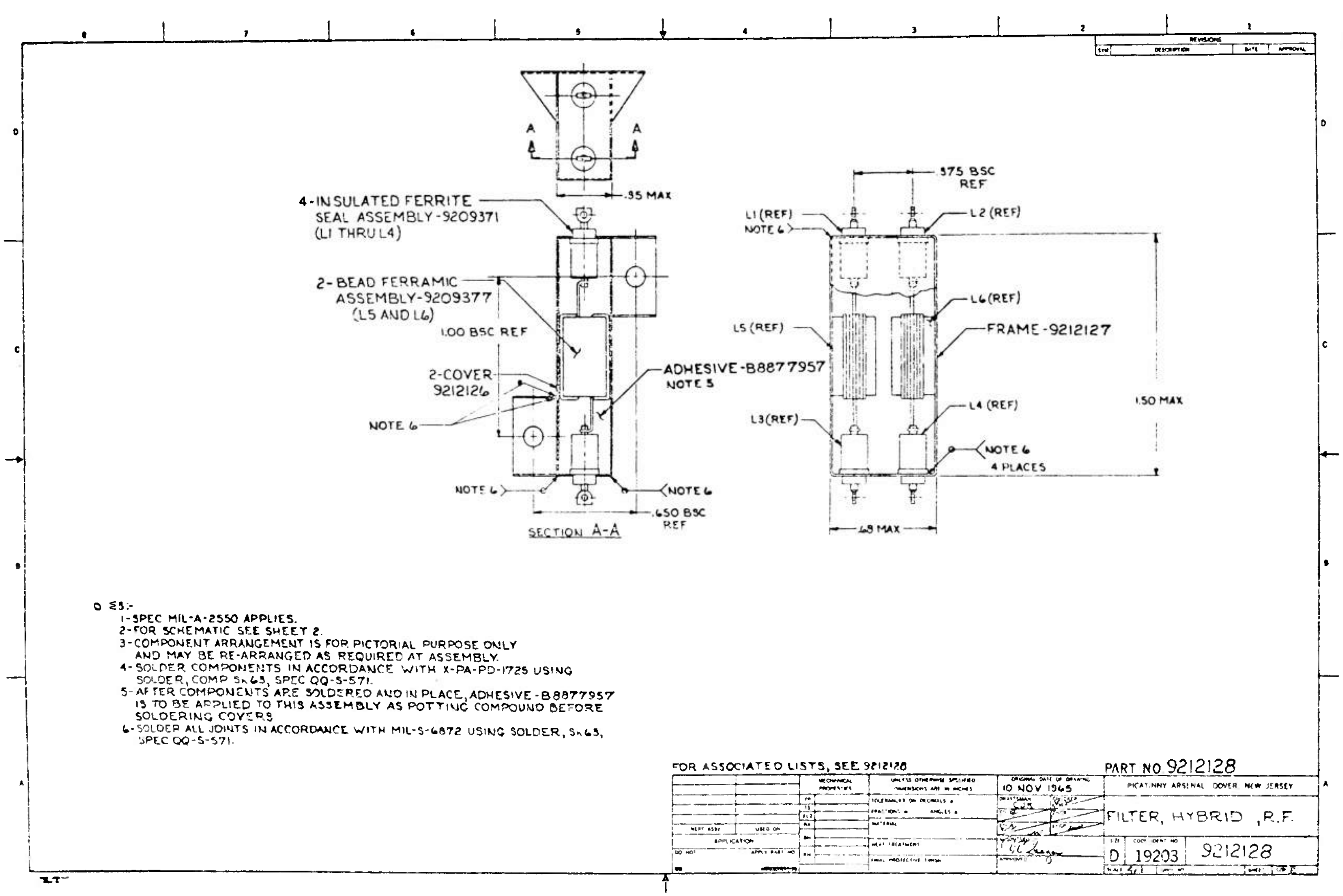


Fig. 4-78. Inductor-ferrite Hybrid

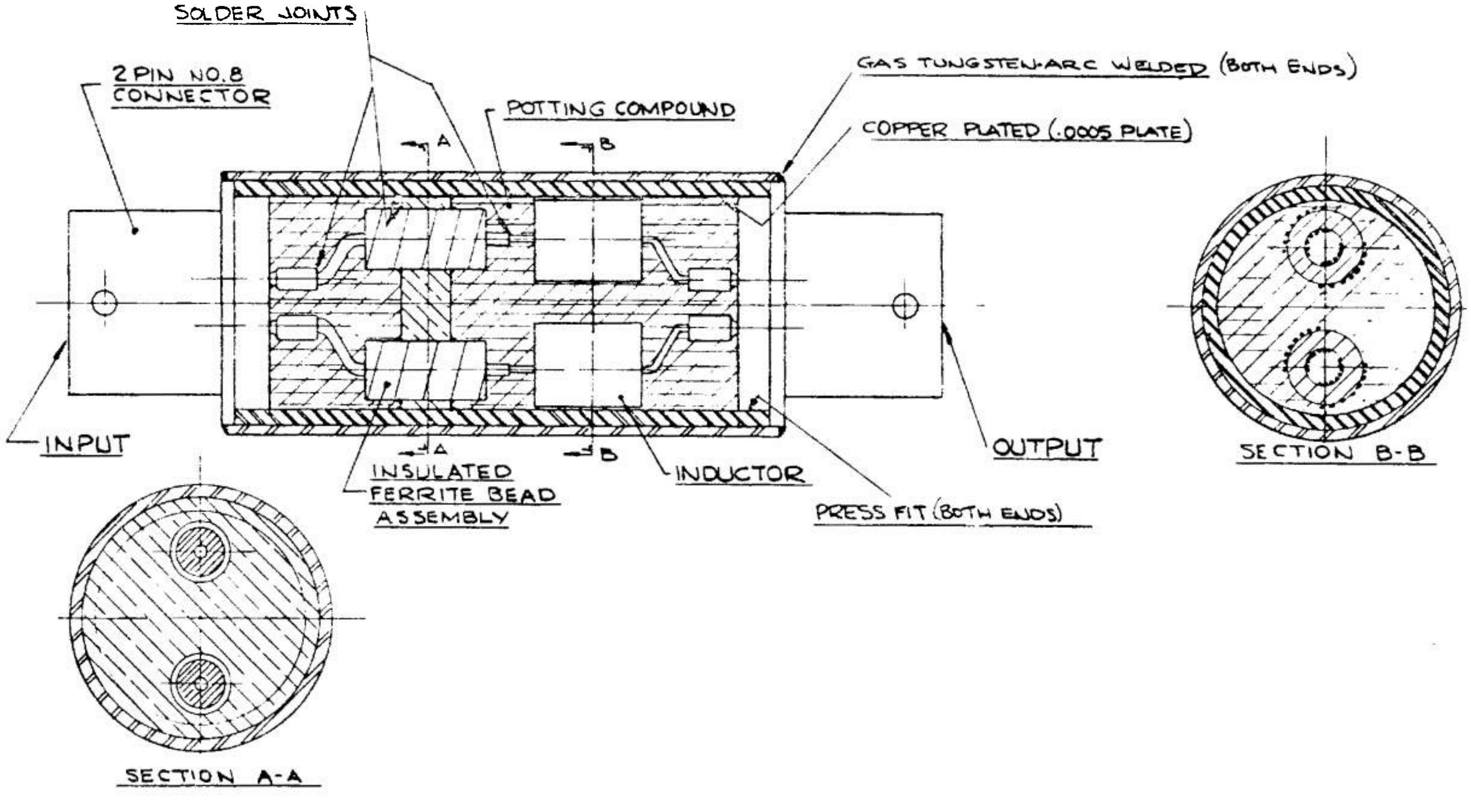


Fig. 4-79. Assembly Drawing of 2-pin Hybrid Filter (NASA)

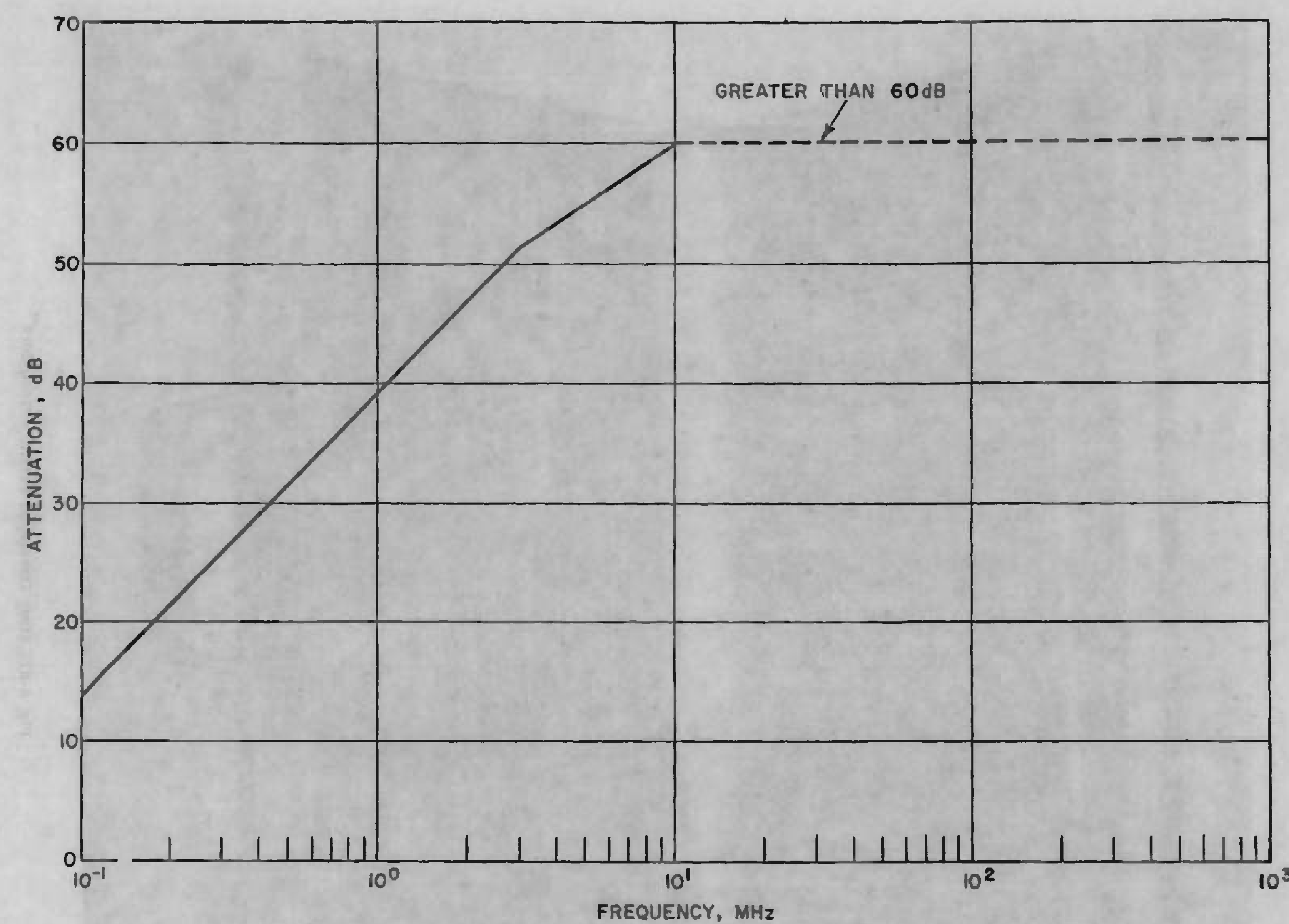


Fig. 4-80. Worst Case Attenuation of Apollo Filter

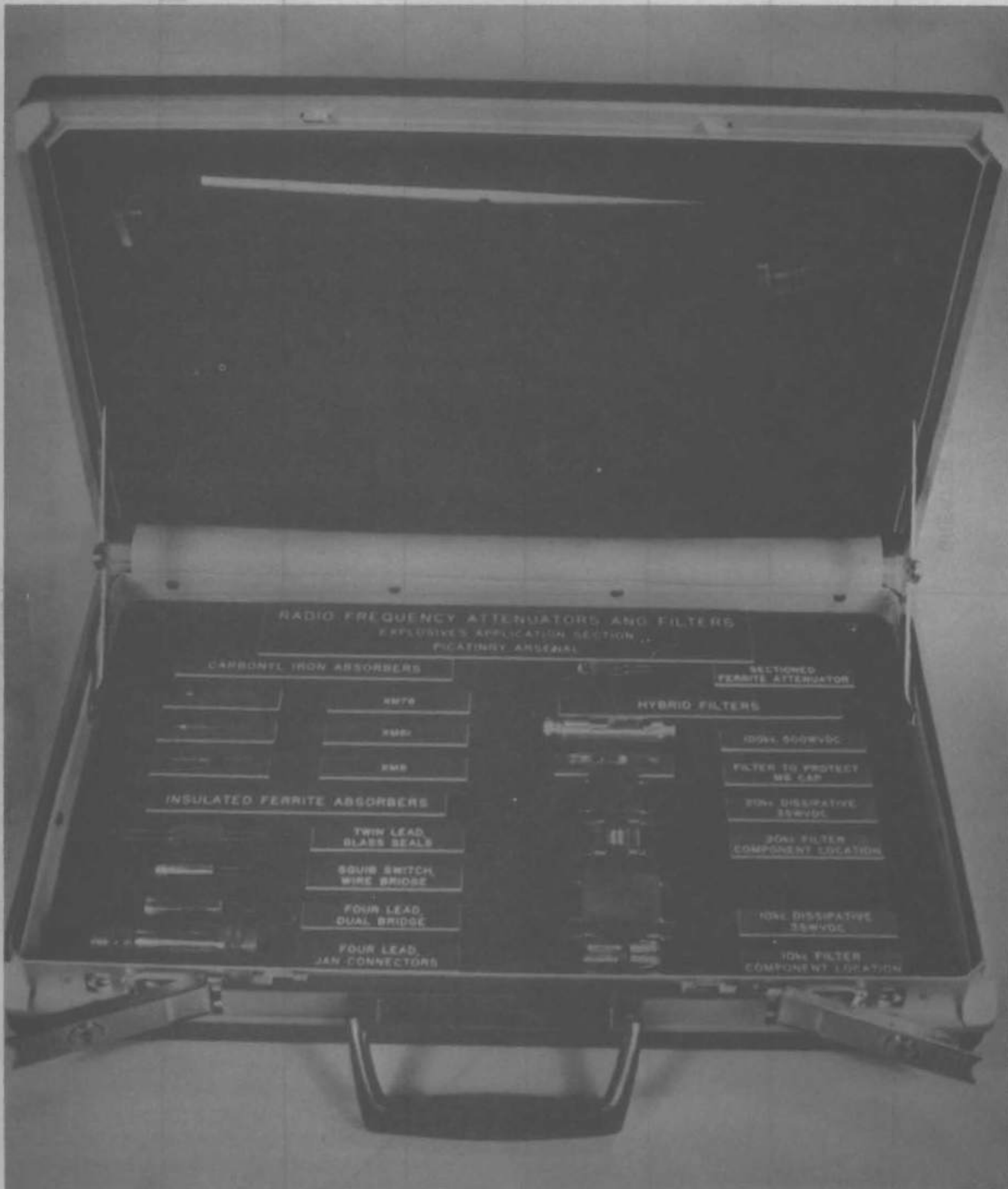


Fig. 4-81. Army Developed Ferrite Attenuators[50]

disadvantages of the RIG are its weight (1 15 grams) and the 9 dB of attenuation it presents to a dc stimulus.

4-4.3.6 Transformer Filter (Ref. 53)

In audio frequency systems, one of the more difficult problems is to build a transformer that will operate up to 100 kHz. At high frequencies the leakage reactance and shunt capacitance, in conjunction with winding resistance, form a low Q series resonant circuit. Above this resonant frequency the gain (transfer efficiency from primary to secondary) falls off rapidly.

Transformer effect can also be used in reverse. An EED can be connected to the secondary of a transformer so designed that its high frequency response is poor; hence, signals above 100 kHz will be attenuated when applied to the primary. Such a transformer filter was designed by the Naval Weapons Laboratory (Ref. 16). A second and similar type, called an inductively coupled filter, was developed for the Air Force; it can also be considered a transformer type (Ref. 54). Both of these units require that the secondary be completely shielded from the primary so that coupling due to the capacitance between windings is minimized.

Since these units are based on transformer operation, they also exhibit poor transfer at very low frequencies, i.e., they will not respond to a steady dc current; however, a dc transient can be coupled through them. A nominal value of 20 dB is assigned as the dc attenuation. Dc attenuation is disadvantageous since it represents a waste of power.

4-4.3.7 Relays

'The Army does not make use of relays as a RF suppression device; however, the Navy has developed a relay to protect EED's from RF (Ref. 55). A metal barrier separates the input circuit from the output. When the firing stimulus is applied. the relay plunger pierces the metal barrier and connects the input leads to the leads going to the EED. If there is any RF energy in the system, it does not matter since the EED now is supposed to initiate.

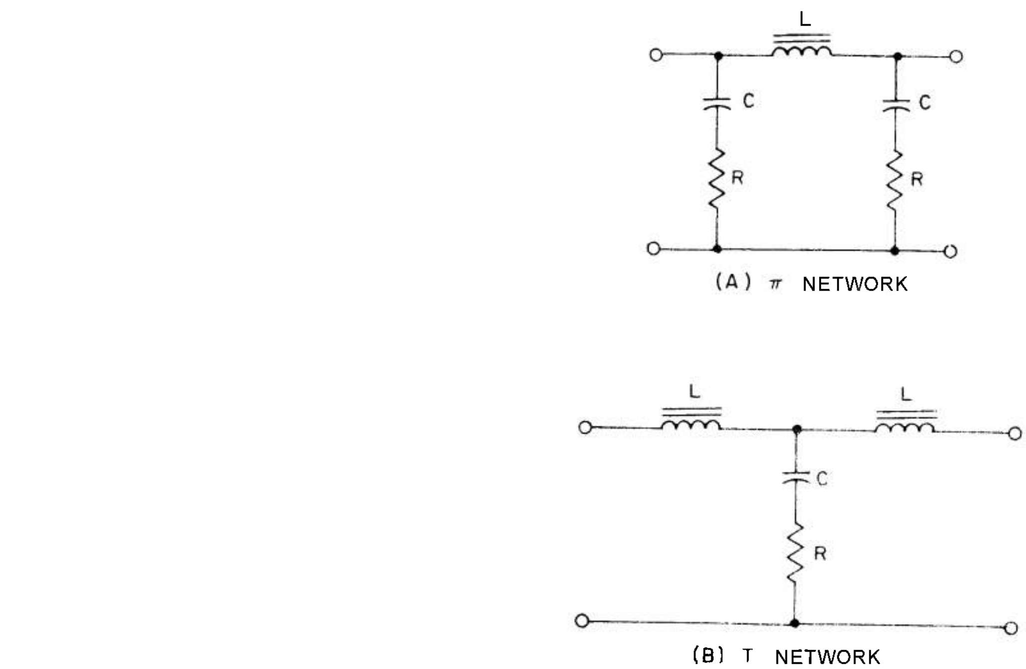


Fig. 4-82. Two Types of LCR Filters

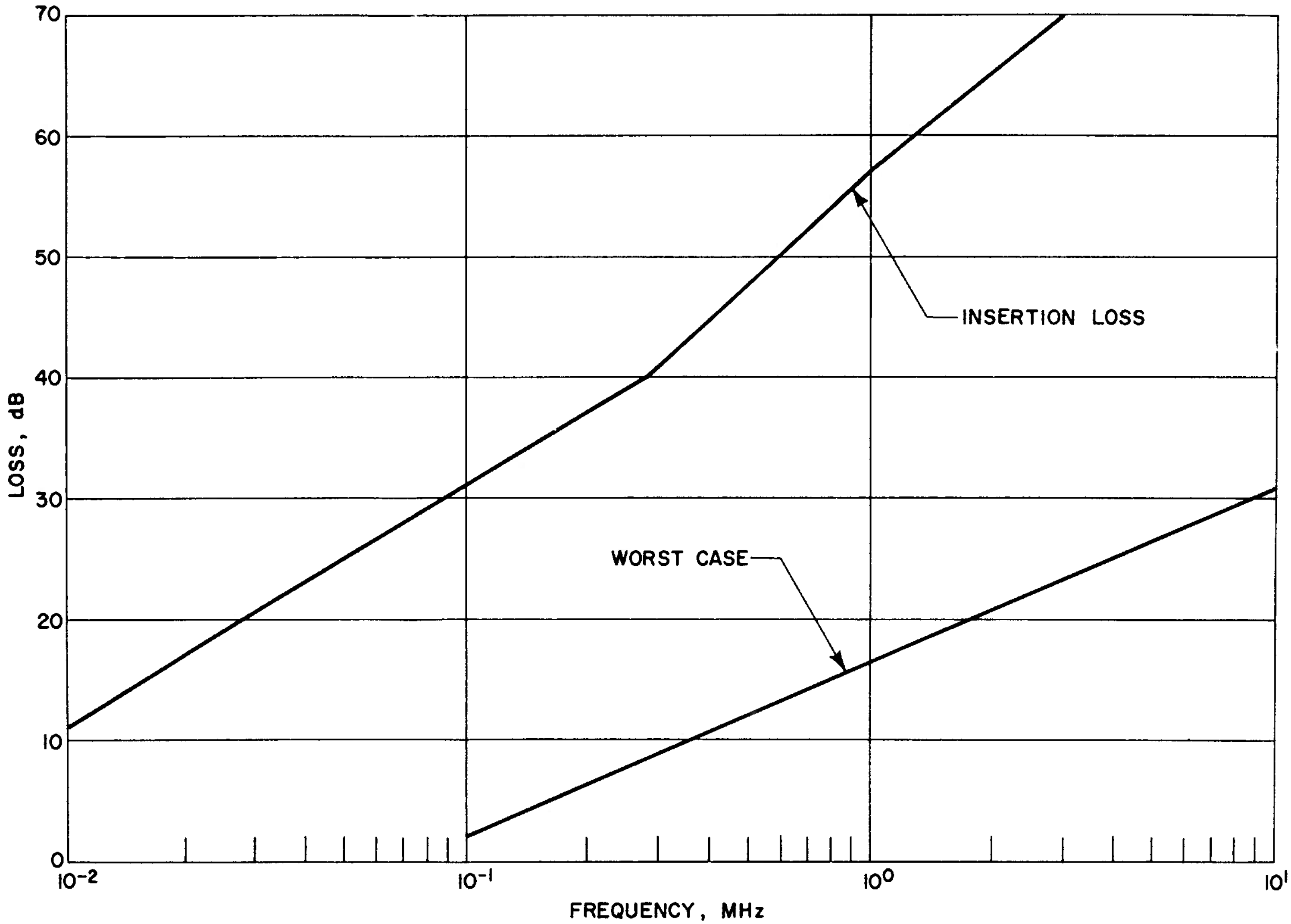


Fig. 4-83. Comparison of Insertion Loss and Worst Case Attenuation of an LCR Filter

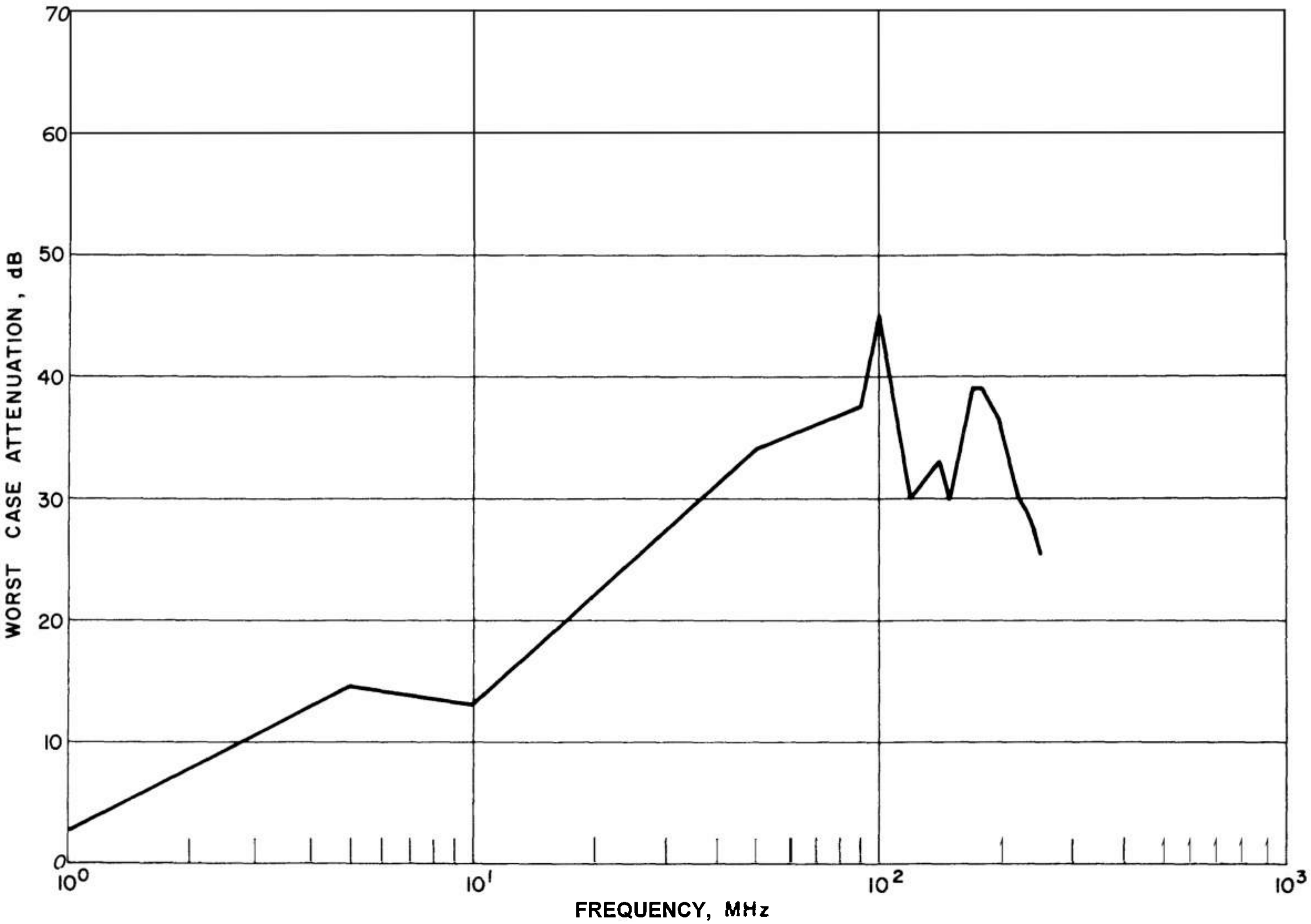


Fig. 4-84. Worst Case Attenuation of a Tantalum Feed-through Capacitor

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CHAPTER 5

TECHNIQUES USED TO EVALUATE WEAPON SYSTEMS

The problem of protecting a weapon system against radio frequency energy, lightning, and static electricity is complex. Even if the designer knew how to design each circuit to make it secure it is unlikely that the final design could incorporate all of these ideas. There usually are compromises somewhere in the design because of weight, size, cost, or incompatibility with other circuits. Also, there will be changes that occur in the production of the system, small changes which the manufacturer does not realize will affect RF susceptibility. The result of the accumulation of changes is a final product that is not as RF-hardened as the designer originally envisioned.

The users of weapon systems are aware of this problem and have set up certain test facilities to help determine the susceptibility of these systems. Subsystems and materials can be evaluated before being assembled into the final system. Those that fail to meet specification should be modified and then retested. This procedure can be repeated until the subsystem or material is found acceptable. This chapter is devoted to briefly describing the systems that the Army has available for susceptibility testing. Several reports on weapon systems are listed in the Bibliography which the designer can consult for insight on how these tests are conducted.

5-1 RADIO FREQUENCY TEST PROGRAM

The evaluation of the radio frequency susceptibility of a weapon system can be treated in two ways: (1) testing of individual components and subsystems, and (2) evaluation of the complete system. There are several factors to be considered when determining whether a complete system should be evaluated rather than individual components or subsystems. Individual subsystems and components are smaller; therefore, they are simpler to handle than a complete system, failure is easier to pin-point since only one unit is involved, and the environment can usually be more accurately controlled on a small scale. Evaluating the complete system has an advantage in that the testing is being performed on the system as it is actually used. The next several paragraphs discuss why and how these tests are run.

5-1.1 RADIO FREQUENCY SUSCEPTIBILITY OF COMPONENTS

The parts of a weapon system that should be considered from a radio frequency hazard standpoint are the electroexplosive systems, electronic circuits or guidance subsystems, and the propulsion subsystem. The individual components of a subsystem respond differently to a given RF stimulus and, therefore, require different testing techniques. The test procedures which follow are developed to help obtain information on the RF susceptibility of these components.

5-1.1.1 Electroexplosive Systems

One of the components in the electroexplosive system that is usually considered susceptible to external energy is the electroexplosive device. **Par. 4-3** presents a detailed discussion of electroexplosive devices, and lists those (Table **4-**17) that have been evaluated for RF sensitivity. **A** portion of this chapter gives the designer a brief idea as to how these electroexplosive devices are evaluated.

The designer is usually supplied with data on the all-fire current and the no-fire current of the EED. If not, **he** should refer to the sources listed in par. **4-3.1.2.** The all-fire current is used to establish the magnitude of current that must be supplied from the power source for reliable initiation of the EED. The no-fire current is that current which sets the safety level for the circuit.

To allow for system and measurement uncertainty, a value of 10 dB below the no-fire level is used. Under no conditions should currents greater than this no-fire level appear in the circuit prior to firing. If they do, the circuit cannot be considered safe. This type of reasoning is carried over into RF susceptibility except that power is used as the hazard criterion. Conversion to power is necessary since it is the only parameter that can be accurately measured from dc to 10 GHz. Voltage and current measurements are difficult and, in most situations, meaningless at high frequencies since the impedance at the point of measurement is usually unknown. A thermocouple used to sense the heat in a bridgewire is actually measuring power even though it is calibrated in terms of dc current.

An approximation of the **EED's** power sensitivity can be achieved by using the **EED's** dc bridgewire resistance R and its current I to compute power P from $P = I^2R$. Typical curves of **EED's** sensitivity to RF are shown in Figs. 4-59 and 4-60. In order to obtain the all-fire level and the no-fire level, the devices are usually evaluated using the Bruceton Technique (Ref. 1) or the Probit Technique (Ref. 2).

For the system designer the 0.1% firing level is the most important datum when considered from a hardening viewpoint. This 0.1% firing level designates where there is a 0.1% probability that a given **EED** will fire. The 0.1% power level sets the maximum amount of power that the circuit containing the **EED** can pick up without the **EED** being considered in a hazardous condition (Ref. 3). It must be remembered that this 0.1% level is obtained statistically and represents the possibility that one out of a thousand items will fire when exposed to this level. As mentioned previously, to permit a safety factor to be placed on this 0.1% level, it has become standard practice to designate the no-fire level as 10 dB below the 0.1% level.

The two test methods most commonly used for **EED** evaluations are the Bruceton and the Probit. Of these, the Bruceton is more widely used since it can usually be conducted with a smaller quantity of devices. However, in instances where confirmation of an estimated probability at one particular level is required, the Probit test is preferred.

5-1.1.1.1 Techniques

5-1.1.1.1.1 Bruceton Technique

The Bruceton type of statistical testing is an experimental procedure that established sensitivity characteristics of components. With this technique the length of time that the stimulus is applied to the component under test is fixed while the magnitude of the stimulus is either raised or lowered by a fixed increment before each individual test, depending upon whether the preceding observation produced a function or a nonfunction. As an example, suppose that the voltage breakdown level for a group of capacitors is being determined, the test procedure would consist of the following steps:

a. Choose a stimulus level h to which the first specimen will be exposed.

b. Choose a positive incremental difference d.

c. If the first specimen breaks down when exposed at h, the second specimen is exposed at the next lower level $h - d$. If the first specimen does not break down the second specimen is exposed at the next higher level $h + d$.

d. The test is continued for the desired number of specimens, the stimulus for each device being stepped down or up one level, according to whether the previous one did or did not break down. In this manner one obtains a sequence of functions *(X)* and nonfunctions (0) from which can be derived a mean (50%) level and standard deviation.

From a statistical analysis the prediction is obtained of the maximum voltage at which these capacitors should be rated. A sample Bruceton test form documenting the results of a test on an **EED** is shown in Fig. 5-1.

5-1.1.1.1.2 Probit Technique

A typical example of a Probit analysis follows. Consider the data on p. 5-5 obtained from evaluating **EED's** (or any other component) at several power levels where X represents initiation (function) and 0 a nonfire (nonfunction).

Plotting these data for percent firings versus power input and drawing a line through the points, the graph in Fig. 5-2 is obtained. Since the data points do not fall in a straight line, a judgment has to be made concerning where to draw the line. Values taken from this estimated line and the original test data can be entered into a set of equations that will generate a new line that will present the best mathematical fit for the experimental data. Once this second line is drawn, an estimate of any firing level can be made.

The Probit techique is ordinarily used where one's interest is in specific probability levels. By expending greater quantities of **EED's** at or near the level of interest the estimate of the level is improved. If, for example, the 90 percent probability level is accurately required, then the majority of the items would be tested around this level. By so doing, an accurate determination

* * * B R U C E T O N   A N A L Y S I S * * *

DATA,RF-500,P-P MODE,10CW,207D,32190-01,5/4/64

SER. NO.	RES. (OHMS)	FUNCT. TIMES. (mSEC)		LEVELS 1	2	3	4	5	6	7	8	9	10
401	.18	290.723	1				X						
402	.16	324.303	2			X							
403	.16	-	3		O								
404	.17	-	4			O							
405	.17	974.659	5				X						
406	.17	-	6			O							
407	.17	860.413	7				X						
408	.15	450.667	8			X							
409	.16	-	9		O								
410	.17		10			O							
411	.17	288.110	11				X						
412	.16	-	12			O							
413	.17	565.846	13				X						
414	.16	-	14			O							
415	.17	592.925	15				X						
416	.16	-	16			O							
417	.17	903.088	17				X						
418	.17	-	18			O							
419	.18	548.519	19				X						
420	.15		20			O							
421	.16	379.508	21				X						
422	.17	-	22			O							
423	.16	917.414	23				X						
424	.17	288.191	24			X							
425	.17	-	25		O								
426	.17	343.866	26			X							
427	.15	301.890	27		X								
428	.17	-	28	O									
429	.17	-	29		O								
430	.17	-	30			O							
431	.17	163.519	31				X						
432	.15	-	32			O							
433	.17	213.972	33				X						
434	.17	-	34			O							
435	.17	323.072	35				X						
436	.16	270.507	36			X							
441	.17	-	37		O								
442	.17	-	38			O							
443	.17	209.801	39				X						
444	.17	526.464	40			X							

LEVEL NO.	STIMULUS (WATTS)	I	I*I	NO	NX	VALIDITY TESTS
1	.2936-00	0	0	1	0	EQUALITY OF
2	.3295-00	1	1	5	1	OCCURRENCE -OK
3	.3697-00	2	4	13	6	
4	.4148-00	3	9	0	14	NO. OF RUNS- 29
5	.0000	4	16	0	0	
6	.0000	5	25	0	0	LENGTH OF
7	.0000	6	36	0	0	RUNS- 3
8	.0000	7	49	0	0	
9	.0000	8	64	0	0	
10	.0000	9	81	0	0	
				NO=19	NX=21	

LOG OF FIRST LEVEL= -.53220 D= .050

AO= 31 AX= 55

BO= 57 BX= 151

MO= .33795 MX= .33107

MEANO= -.42562 MEANX= -.42625

SIGMO= .03054 SIGMX= .02989 SIGMA= .03020

S= .60394 G= 1.069 G*G= 1.142379

H= 1.236 H*H= 1.528367

CONFIDENCE INTERVAL= .04670

LOG OF 99.9%(95%CONF)= -.28594 99.9%(95%CONF)= .518 WATTS

LOG OF MEAN(50%)LEVEL= -.42595 MEAN(50%)= .375 WATTS

LOG OF 0.1%(95%CONF) = -.56596 0.1%(95%CONF)= .272 WATTS

Fig. 5-1. Bruceton Data Sheet

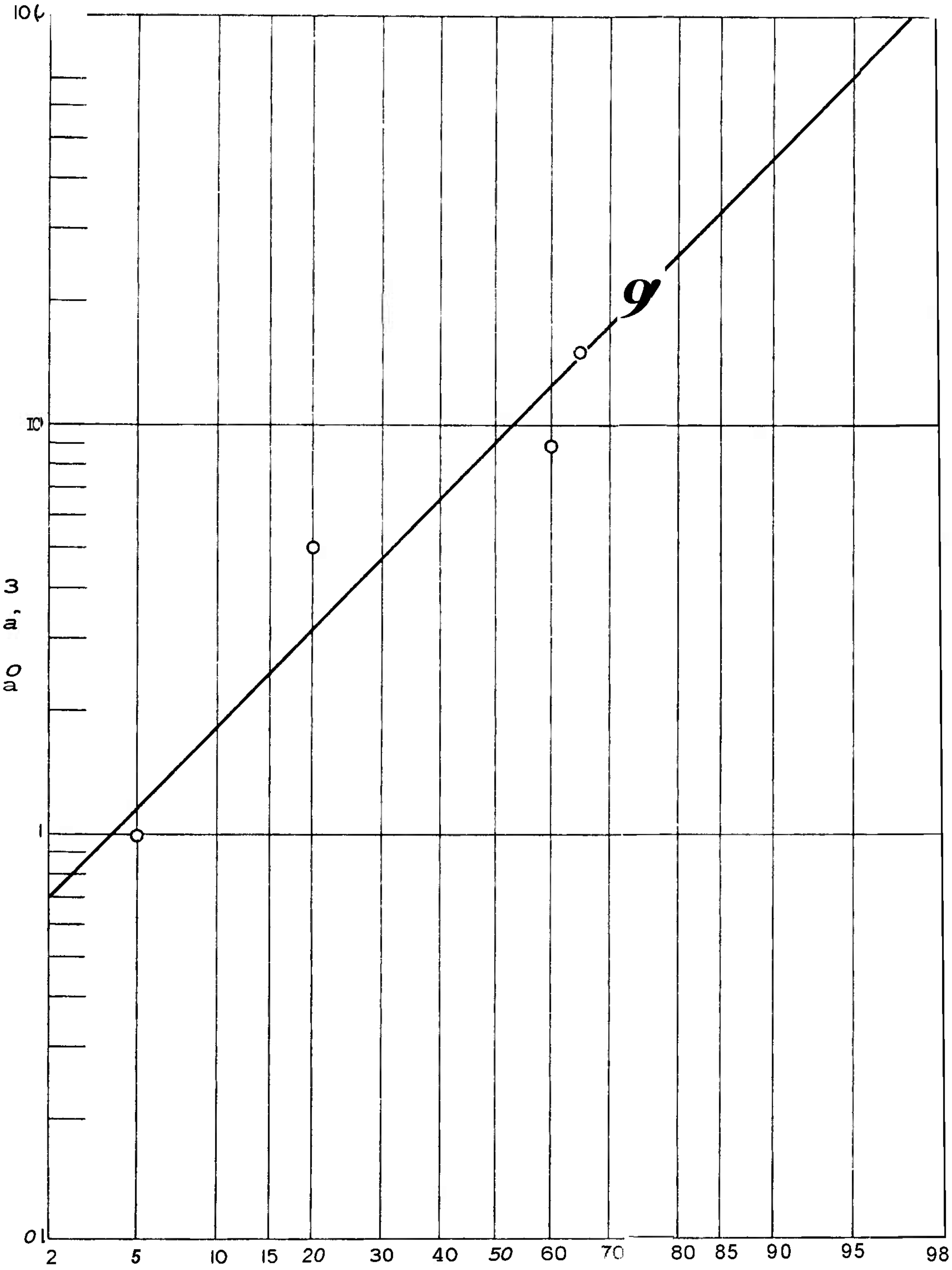

Fig. 5-2. Probit Estimate

POWER LEVEL, W	TEST RESULTS	NO. FIRED, %
1	00000000000000X00000	5
5	0X0000X000	20
9	X0X0X0XX0X	60
15	XXX0X0X0XX00XX00XXXX	65
22	X0XXXXXXX00XXX0X	75

would be made at this level, at the expense of information at other levels.

If tests are planned for extreme levels (99%, 1%) many samples will be required. The actual quantity required to insure that both fires and nonfires will be observed can be estimated by a binomial distribution (Ref. 4).

In its application to RF testing, the Probit method is infrequently used due to the limited amount of hardware usually available. There are, however, certain conditions under which it is desirable: (1) accurate estimate of a single point, and (2) recovery of data from a Rruceton test that was found to have errors in the assigned levels. These can be put in chart form and plotted as a Probit.

5-1.1.1.2 Evaluation Equipment

The basic equipment (Ref. 5) used in performing RF sensitivity tests is shown in Fig. 5-3. The RF generator supplies power to the transmission line while both the forward and the reflected power in the line are monitored. A switch permits the selection of either a standard termination (a fixed load which is capable of absorbing all of the incident power) or a termination consisting of a matching network followed by the EED in a specially designed mounting fixture. 4 chronograph determines functioning time. It is started by the application of the KF power and stopped by a signal from a flash detector. Other components include a variable attenuator to adjust the power delivered to the test specimen and the instrumentation needed for system calibration.

It is mandatory that the impedance of the specimen under test by transformed or matched to the 50-ohm impedance* of the system. This is done by a matching network consisting of variable reactive elements which may be either lumped or distributed, depending on the test frequency,

When the matching network is properly adjusted, there is no reflected power in the transmission line preceding the matching network (see par. 4-4 for a discussion of impedance matching). A null in the reflected power indicator shows that a match has been obtained. If the component losses in the matching network are small enough to be neglected, it can then be assumed that all of the incident power will be absorbed by the electroexplosive device.

While making the matching adjustments, very low power levels are used so as not to alter the (characteristics of the device under test. A satisfactory match is assumed when the reflected power is less than 1% of the forward power. In setting the power to the full test level, the fixed load is used. The test exposure is started by diverting the power flow from the fixed load to the matched EED. The incident power level does not change during this operation since the input impedance of the fixed load is identical to that of the transmission line terminated by the matched EED, thereby leaving circuit conditions effectively changed.

Matching elements whose loss is negligible when correcting a 2-to-1 mismatch cannot be assumed lossless when the mismatch reaches a value of 10-to-1 or more, a situation which exists with most EED terminations. For this reason it is important in each situation to correct for these losses. The slotted line and variable probe indicated in Fig. 5-3 are used to obtain a correction factor that accounts for the loss in the matching network.

5-1.1.2 Electronic Circuits or Guidance Subsystems

The only test program that exists for electronic circuits is that contained in MIL-STD-461 and MIL-STD-462 (see 'Table 6-1) which are radio frequency interference specifications. Two portions of these

*There are two reasons for using 50 ohms as the standard: (1) most of the equipment on the market is 50 ohms, and (2) low impedance systems, such as 2-ohm strip line, are very lossy due to the use of a solid dielectric rather than air.

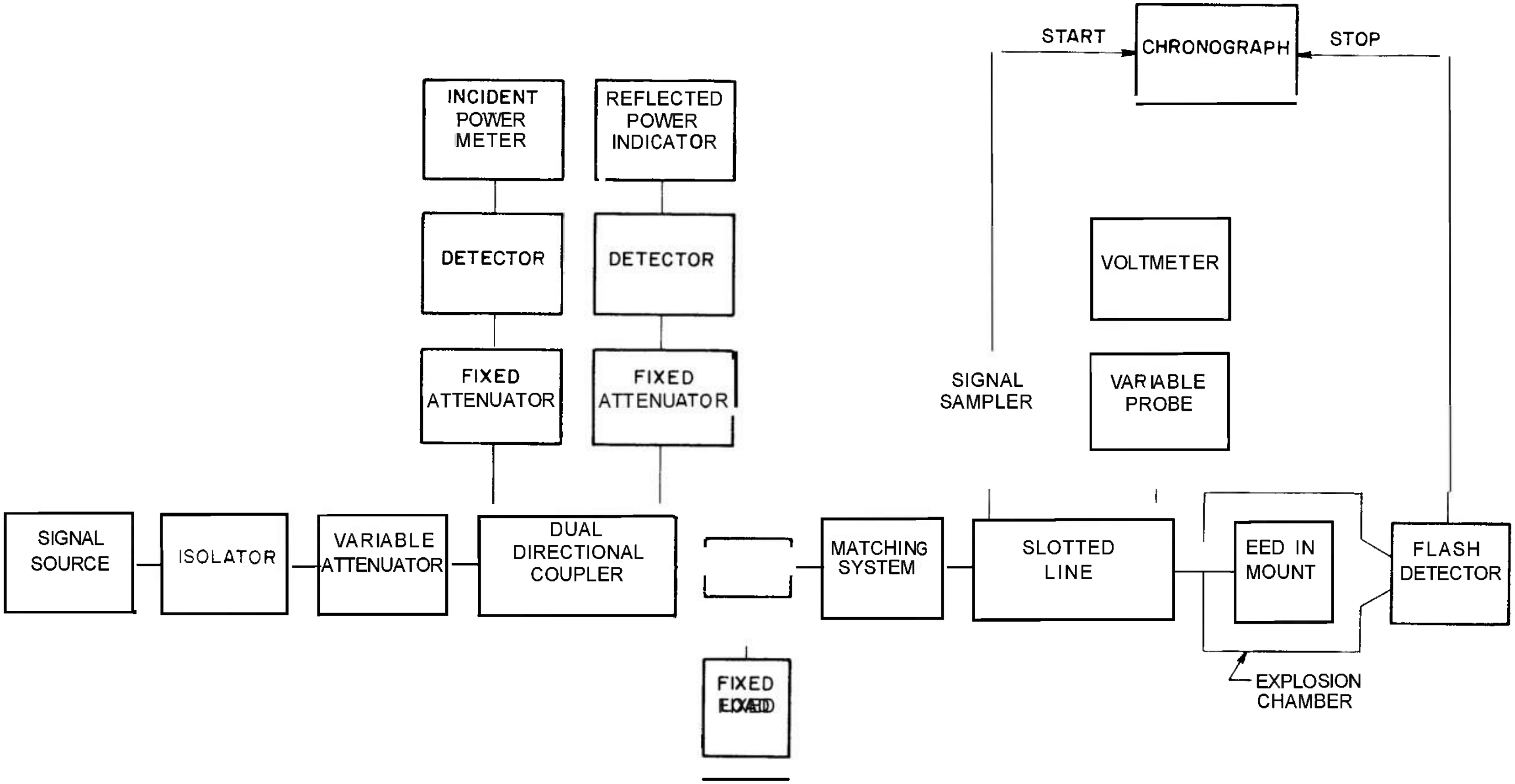

Fig. 5-3. Basic Equipment Used in Performing RF Sensitivity Tests of an EED

specifications are of interest for this work: (1) the radiated susceptibility, and (2) the conducted susceptibility. Under the first condition the circuit under consideration is irradiated by specified electromagnetic fields from 0.1 MHz to 10 GHz. To be considered not susceptible, the performance of the circuit must be unaffected by this exposure. The second test, conducted interference, consists of actually connecting the RF source to the power leads of the circuit. Once again the criterion for satisfactory operation is that the RF shall not affect the operation of the electronic circuit.

The field intensity specified by these two documents was not developed for the purpose of ascertaining the damage to a circuit under high intensity irradiation; the levels used are for interference malfunction determinations. Most subsystems such as receivers, amplifiers, servos, computers, etc., are required to meet MIL-STD-461 and MIL-STD-462; however, if the designer wishes to know how these electronic systems will function in an electromagnetic environment 100 times greater than that called for in these specifications, special tests will have to be specified. Tests of this type can be performed at certain Army facilities. These facilities and how the tests are performed are discussed in par. 5-1.2.2.

5-1.1.3 Propulsion Systems

The effect of radio frequency energy on propulsion systems appears to be negligible. No record of initiation or degradation has been reported since missile systems came into use. The one exception that should be noted is the situation where an EED is used to ignite the propulsion system. Under this condition the sensitivity level as defined in par. 5-1.1.1 should be used.

5-1.2 RADIO FREQUENCY SUSCEPTIBILITY OF A COMPLETE SYSTEM

With all of the complicating and generally uncontrollable factors, how then can one evaluate the potential RF hazard to a complete system? The answer at the present state-of-the-art is that it cannot be done with great precision for anything but a very specifically defined case; however, two methods are now in general use that can give a qualitative answer.

The first method is the application of analytical techniques to the system to determine the extent of RF hazard. This approach in its present form has two distinct advantages: (1) properly conducted the results are always on the safe side and, should it be demonstrated by this approach that a system is safe in a given field and at a specific frequency, its safety can practically be guaranteed; and (2) the analysis is reasonably inexpensive. The main expense comes from the fact that to perform the analysis properly the RF sensitivity of the device terminating the system must be determined. The exception occurs when the circuits are so well designed from an RF standpoint that it can be demonstrated analytically that protection levels are so large that the sensitivity of the terminating device is not a factor after installation in these circuits. The main objection to the present analytic method is that it can place unusually stringent restrictions on the circuits so that only the very well designed systems can be shown to be safe; in other words, the safety factor afforded thereby can be unreasonably large. This method is in wide use by the Air Force and was used extensively to evaluate ordnance circuits in both MINUTEMAN II (Ref. 6) and AGENA D (Ref. 7). The Army has used this approach on a limited scale; an example is the SPRINT program (Ref. 8).

The second method, stated briefly, is to irradiate directly the system in question with a variety of high-powered transmitters and to observe the **RF** levels that arrive at the component or subsystem under test. The method is appealing, although expensive, since it is a direct approach which appears to simulate the actual conditons that will occur. But, while such tests are often used and have a definite place in the scheme of things, there are disadvantages that should be noted. The chief weaknesses of the method include inadequacy of present RF detectors, inability to determine field strengths accurately, and the risk of assuming that tests on one or two systems can be extended to all such systems.

To minimize the effect of these various problems, irradiation tests are often conducted with an arbitrary safety factor added to the acceptable RF pickup at the detector (see par. 5-1.1.1). In addition, it should be recognized that the only positive result of a field irradiation test is to demonstrate that a hazard exists for the system being irradiated at certain frequencies, irradiation angles, polarizations, and orientations of the irradiating antenna. Specifically, a field irradiation test can never assure complete RF safety since only a finite number of frequencies, polarizations, etc., can be tested from the literally infinite number of situations that can develop in the actual use of the system. Part of this problem can be resolved by using swept frequencies. Properly conducted field tests, however, can give considerable assurance regarding RF safety.

5-1.2.1 Analytical Technique

The procedure for establishing the extent of the RF hazard to any system by means of the analytic method is:

a. The RF sensitivity of the particular device, subsystem, or system is determined over the entire frequency range of interest, for both continuous wave (CW) and pulsed RF signals and for all possible modes of damage such as through the regular leads or between the leads and the case or any other damage mode.

b. The details of the actual physical systems are established by using circuit and wiring diagrams; observation of the actual systems; observations and discussions of the handling, installation, and checkout procedures; and discussions with the engineers directly concerned. These details include such things as length of cables, locations of wiring breakouts, and separation between leads and the ground plane.

c. Mathematical models are constructed which closely resemble the actual wiring systems, and which can be handled with analytic techniques. These models are constructed for all phases of the problem; i.e., handling, check out, and installed. In the situation involving EED's, for example, pin-to-pin, pins-to-case, and bridgewire-to-bridgewire effects are also considered. All known parameters of the circuits are used such as the length of unshielded portions, and the physical shape. Whenever a parameter cannot be properly defined, a worst case assumption is made. For example, it is normally assumed that a given circuit is oriented with respect to the RF field for maximum pick-up of energy; that the entire circuit is in a simple plane; and that all impedances in the circuit are matched for optimum pick-up and transfer of energy.

d. The mathematical model is analyzed to establish the amount of RF energy that can be extracted from any incident RF field and subsequently transferred to the device under consideration. The analysis gives, for a particular circuit, a quantity known as "aperture" *a measure of ability to pick up energy.* The aperture as a function of frequency plot can be applied to any assumed field intensity.

e. For any assumed field intensity and frequency the amount of RF energy that could be delivered to the device being considered is obtained by the product of the incident power density and the aperture, and this value compared with its **RF** sensitivity. The degree of potential hazard is thereby established. Under the assumptions which are made, an indicated safe condition should be quite safe; an indicated hazardous condition may or may not be hazardous.

These data are usually presented graphically and in such a manner that as long as the same circuits and test items are employed, the analysis can be immediately applied to any change, present or future, in the incident field densities. Only those circuits which are completely different need be analyzed; for example, in the case of redundant circuits only one analysis need be conducted if the two circuits are similar.

This approach is often designated a worst case analysis, however, it should be noted that this is a mild misnomer. In actual fact, all of the known or reasonably obtained data bearing upon any circuit is used. For example, such details as actual sizes of loops, length of unshielded wire runs, separation distance of cable from frame, RF sensitivity and impedance of terminating device, quality of shielding material used, and attenuation provided by switches and arming devices used in the circuit are carefully determined. Actual values are used in the calculations wherever possible. On the other hand, those characteristics which could be variable from vehicle to vehicle or are very expensive to determine are assumed to be at their worst. For example, orientation of all circuits is assumed to be optimized in the incident field, impedances throughout the circuit are generally assumed to be matched in such a manner as to give maximum transfer of RF energy to the terminating device, RF pickup from all loops is assumed to be in phase, and missile skins (except under unusual circumstances) are assumed to offer no attenuation. Experience has shown this last assumption to be quite valid.

As a result, the analysis produces values of RF power delivered to the termination which are always on the conservative side, occasionally by rather large amounts. This leads to the statement made earlier–i.e., if under the worst case approach a system is found to be safe, it is most likely quite safe; if on the other hand a hazard is indicated, the system may still be safe.

Three additional points should be noted, however. First, experience has shown that if the weapon system is considered to be exposed to a wide frequency band there is a good probability that at some point in the frequency spectrum the worst case assumptions will come close to being satisfied, and the analysis and the real conditions will come close to coinciding. Second, attempts to assign probability values to the worst case assumptions so as to modify the worst case analysis are extremely difficult to accomplish in any meaningful manner. Even if sufficient data were obtained in one or two systems to permit assignment of such probabilities, the next system may be so different that practically all of the former data is not applicable. Third, systems carefully designed with the RF hazard problem in mind will generally be shown to be safe by even this worst case analysis. Only those circuits which have serious deficiencies in this respect tend to fail and these circuits should in general be corrected anyway.

5-1.2.1.1 Detailed Analysis Procedures

The purpose of the paragraphs which follow is to describe in detail the mathematical procedures necessary to conduct an RF analysis on a system.

Before proceeding, a few of the general considerations should be stated. The object of the analysis is to determine the maximum amount of power which can be delivered to any particular failure mode of the device under consideration. It is assumed that the incident RF field is essentially TEM; i.e., far field. Under these conditions the power density PD can be expressed as

$$PD = |\overline{PD}| = |\overline{E} \times \overline{H}| = \frac{|\overline{E}|^2}{Z_o} = |\overline{H}|^2 Z_o \qquad (5\text{-}1)$$

where

$\overline{PD}$ = power density, W/m^2
$|\overline{PD}|$ = power density, absolute, W/m^2
E = electric field, V/m
H = magnetic field, A/m
Z_o = impedance of free space, 377 Ω.

The bars above the letters indicate vector notation.

With an incident TEM field, the basic antenna formulas can be applied and the hazard expressed in terms of the effective aperture Ae which is defined by

$$Ae = \frac{W}{PD}, \text{ m}^2 \qquad (5\text{-}2)$$

where

Ae = effective aperture, m^2
PD = power density, W/m^2
W = power dissipated in the antenna load, W

This concept of aperture is used in all the analyses which follow.

A general equation (Ref. 9) for expressing the effective aperture is

$$Ae = \frac{V^2 R_T}{PD\left[(R_R + R_A + R_T)^2 + (X_A + X_T)^2\right]} \qquad (5\text{-}3)$$

where

V = total voltage induced in the antenna, V
R_R = radiation resistance, Ω
R_A = loss resistance of the antenna, Ω
R_T = termination resistance, Ω
X_T = termination reactance, Ω
X_A = antenna reactance, Ω

This basic equation is used to formulate many of the analyses.

In an actual computation the effective aperture must be calculated for each frequency of interest using the applicable equations. If the product of the effective aperture and incident power density at any given frequency is now formed, the result is the actual RF power delivered to the load under the assumed conditions. This value can then be compared with the sensitivity of the terminating device at that frequency to establish the possibility of RF susceptibility.

It is important to restate that the most important and necessary part of the analysis is to properly characterize the antennas represented. Experience has shown that the majority of present weapon system (circuitsfall into one of two categories. The first of t'hese is the circuit which contains breakout of the shields going to circuit boards, through bulkhead connectors, or to other circuits. Most of these breakouts can be characterized as loops of varying dimensions. The second type is the circuit which is completely shielded from end to end and through 360" i.e., circumferentially. The paragraphs which follow will treat these two possibilities.

5-1.2.1.2 Circuits With Shielding Gaps

Let us consider an ordnance circuit of a typical weapon system. Many EED firing systems use shielded cables between the S&A device and the EED, or if no S&A unit is used, between the timers or firing switches and the EED. For such circuits the first assumption used in arriving at the antenna models to be used is that the power coupled to the EED firing mode impedances through the braided shield of the cables is negligible in relation to that coupled to these impedances by the nonshielded portions of the wiring. In consequence, the models chosen represent the physical characteristics of the gaps or breaks in the shielding. Fig. 5-4 diagrams a typical break or gap in a shielded firing lead, and Fig. 5-5 diagrams the equivalent antenna model used for this gap. The dimensions given are representative of commonly used separation switches, i.e., switches that isolate EED's from firing units.

The impedances Z_{s1} and Z_{s2} are considered to be completely unknown while Z_{pp} and Z_{pc} represent the firing mode impedances (pin-to-pin impedance Z_{pp} and pins-to-case impedance Z_{pc}) of the EED transformed along the connecting lines to the separation switch. The models for pin-to-pin and pins-to-case pickup are thus seen to be, for the lower frequencies at least, small loops loaded with the indicated impedance. Further, assume that the transmission lines formed by the shielded cables that connect the gaps and the EED are lossless. This is to be expected since these cables are constructed of good conductors and good insulators, and the gap length will be small.

(not drawn to scale)

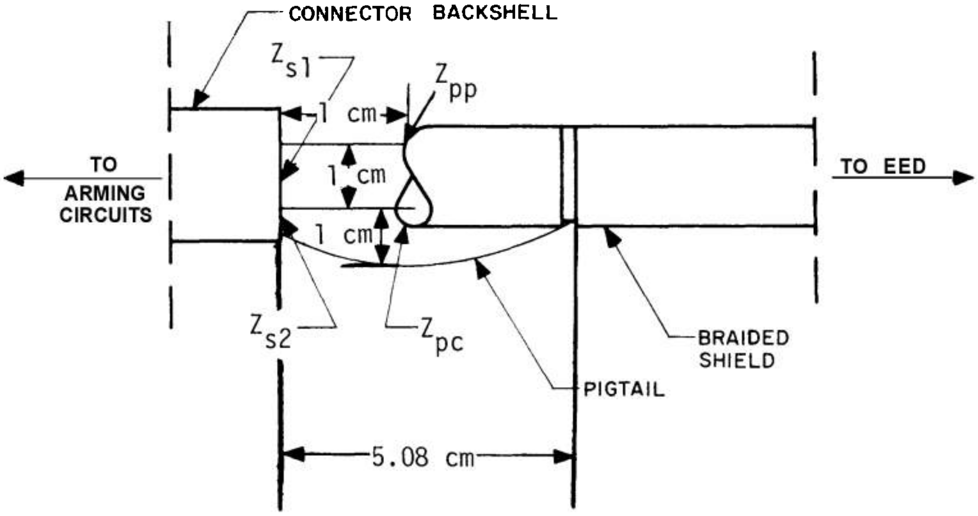

Fig. 5-4. A Typical Shielding Gap Configuration

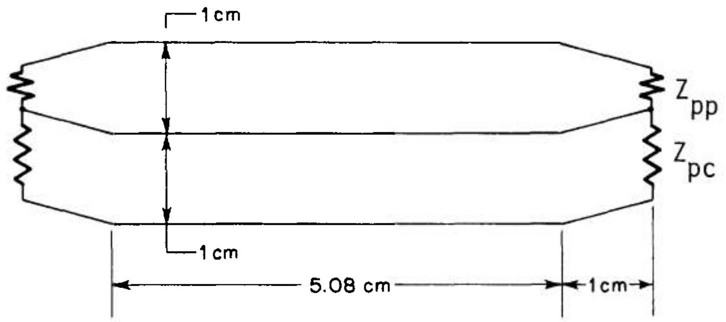

Fig. 5-5. Basic Antenna Model for a Shielding Gap

Once the loop has been reduced to its diagrammatic representation as shown in Fig. 5-5, the aperture for this loop can be calculated from the same equations as developed before. For wavelengths up to twice the perimeter of the loop, **Eq. 5-4** applies. For shorter wavelengths, **Eq. 5-5** applies.

$$Ae = \frac{4.67 \times 10^4 (Ar)^2}{\pi \lambda^2 R_T} \quad (5\text{-}4)$$

$$Aem = \frac{D\lambda^2}{4\pi} \quad (5\text{-}5)$$

where

Ae = effective aperture, m^2
Aem = maximum aperture, m^2
Ar = area of loop, m^2
R_T = termination resistance, ohm
D = directivity (ratio of maximum radiation intensity to average radiation intensity), dimensionless
λ = wavelength, m

These methods predict the maximum possible aperture of a single loop across the frequency range of interest. If more than one loop exists in the same firing circuit the composite aperture of the combined loops is obtained, at all frequencies such that $2\ell < \lambda$, from

$$Aec = \frac{4.67 \times 10^4}{\pi \lambda^2 R_T} (Ar_1 + Ar_2 + Ar_3 + \ldots + Ar + \ldots + Ar_n)^2 \quad (5\text{-}6)$$

where Aec is the composite effective aperture of n loops and Ar_m is the *area* of the *m*th loop. This result reflects the fact that the methods employed in this frequency range are based on a maximum voltage and, since the voltage contributions of the individual loops could add in phase, they must be considered as a worst case possibility. In fact, at the lower frequencies where the wavelengths could be considerably longer than the circuit considered, this is a distinct possibility.

At the higher frequencies such that $2\ell \geq \lambda$ a similar procedure must be used; here the composite aperture is calculated from

$$Aec = \left[\sqrt{Aem_1} + \sqrt{Aem_2} + \ldots + \sqrt{Aem_q} + \ldots + \sqrt{Aem_n}\right]^2 \quad (5\text{-}7)$$

where Aem_q is the maximum aperture of the *q*th gap and Aec is the composite aperture of *n* gaps.

Fig. 5-6 shows the pin-to-pin aperture computed by these methods for a small shielding gap in a 6.4-Ω (dc resistance) EED firing circuit. The geometry of the gap is shown on the figure.

5-1.2.1.3 Example of an Evaluation

Fig. 5-7 is a schematic drawing of a simple system configuration taken from a weapon system. Fig. 5-8 is an approximation of this configuration shown as a simple loop, and finally Fig. 5-9 shows the antenna configuration for analysis derived from the actual circuit. R_T is the dc resistance of the EED.

The antenna configuration is a single loop; therefore, Eq. 5-4 can be used to compute the aperture for all wave lengths up to $\lambda = 2$ times the perimeter of the loop, i.e., for all wave lengths up to 76 cm or a frequency of 395 MHz. Above this frequency Eq. 5-5 is used. For each frequency of interest, and sufficient frequencies should be chosen to define the curve, one must calculate an aperture using the appropriate equation. Fig. 5-10 is a plot of such calculations made for the circuit under consideration.

The final step consists of using this aperture versus frequency data to produce a plot of RF power received at the EED as a function of the RF field incident on the system and to compare this RF pick-up with the RF sensitivity of the EED (refer to par. 4-3.1). Fig. 5-11 shows such a plot where the incident RF power density was assumed to be 2 W/m^2 up to 50 MHz and 100 W/m^2 above 50 MHz. The data for this plot were obtained by multiplying chosen points on the aperture curve of Fig. 5-10 by the assumed incident power density at the same point. Superimposed on the power pick-up curve of Fig. 5-11 is the RF sensitivity curve of the EED used in the installation. The conclusion one would draw from this plot is that, should this system be exposed to 100 W/m^2 fields across the frequency spectrum from 10 MHz to 10^5 MHz, safety could be guaranteed on the basis of the analysis only from 10 MHz to 80 MHz and from approximately 1600 MHz to 8500 MHz.

5-1.2.1.4 Completely Shielded Circuits

The situation where circuits are completely shielded with no gaps is desirable and it should be noted immediately that when this is done there is rarely any RF hazard problem involved with such circuits. However, it is sometimes necessary to demonstrate by analysis that such is the case. This situation is covered in detail in par. 4-1.

5-1.2.2 Irradiation Technique

The Army has two facilities that can be used to irradiate a complete weapon system. One of these facilities is located at White Sands Missile Range, New Mexico, and the other is located at Picatinny Arsenal, Dover, New Jersey. Both of these facilities can supply RF power from below 1 MHz to 10 GHz at very high power levels.

a. White Sands RF Facilities

Tests for determining the RF susceptibility of a complete weapon system can be conducted at the White Sands Missile Range. Fig. 5-12 shows a part of the SPRINT missile being irradiated by a low-frequency field at this facility. The frequency spectrum and the field intensity available at White Sands are documented in Fig. 5-13. These data were obtained early in 1968 and are constantly changing as new equipment is added.

b. Picatinny Arsenal RF Facilities

The **RF** hazard facility located at Picatinny Arsenal, Dover, New Jersey, is capable of generating the electromagnetic fields recorded in Fig. 5-14 (Ref. 10). A photograph of the facility looking toward the building that houses all of the power generators is shown in Fig.

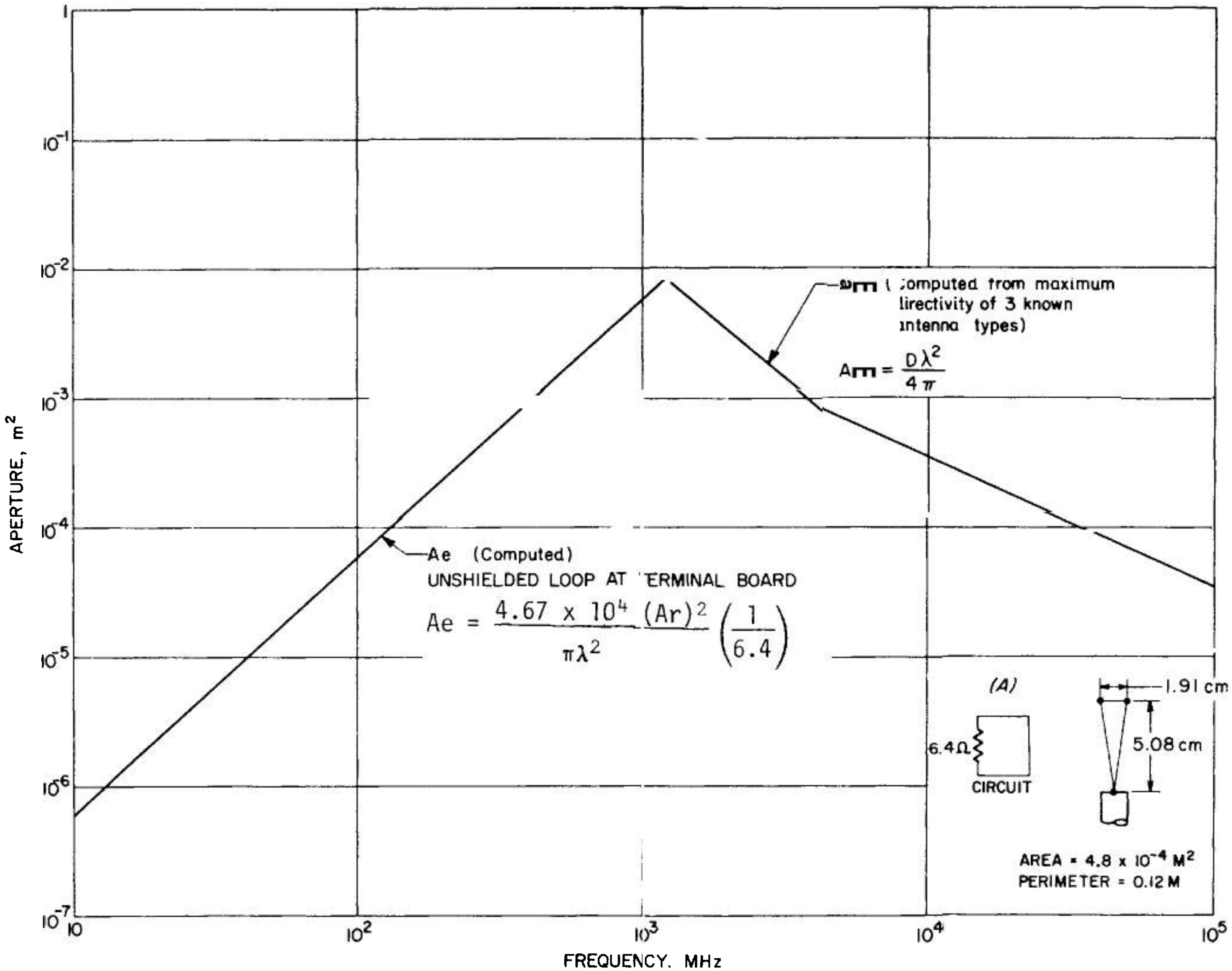

Fig. 5-6. Aperture of Loop as Shown in (A) at a Typical Terminal Board

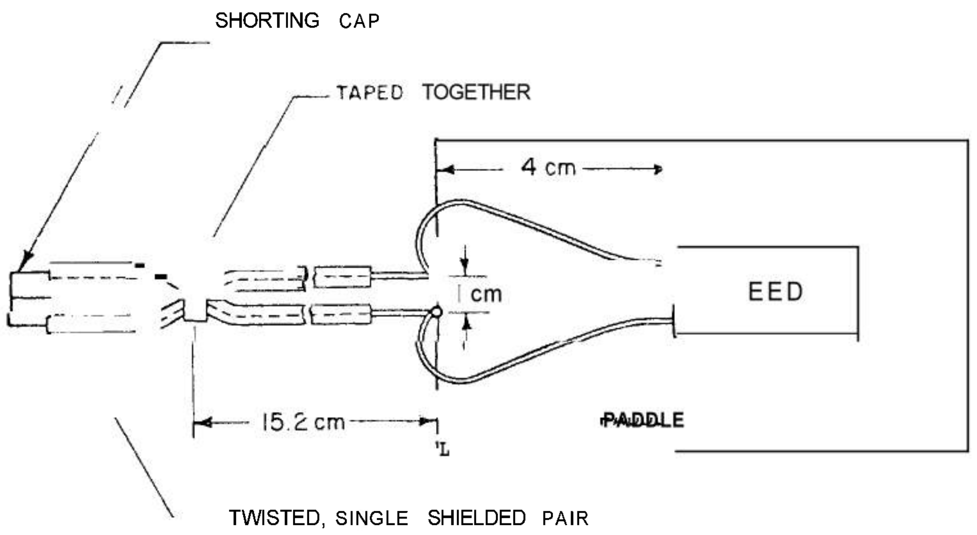

Fig. 5-7. Schematic Drawing of System To Be Analyzed

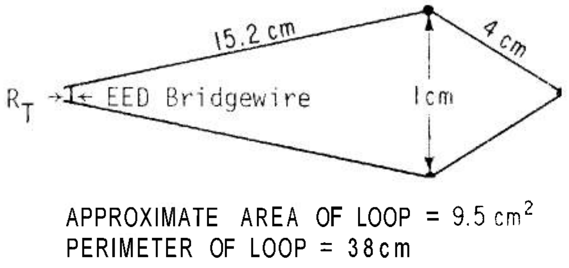

Fig. 5-8. Loop Approximation of System Shown in Fig. 5-7

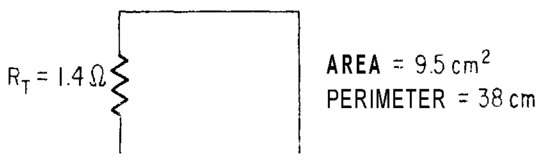

Fig. 5-9. Antenna Configuration for Evaluation Derived from Fig. 5-7

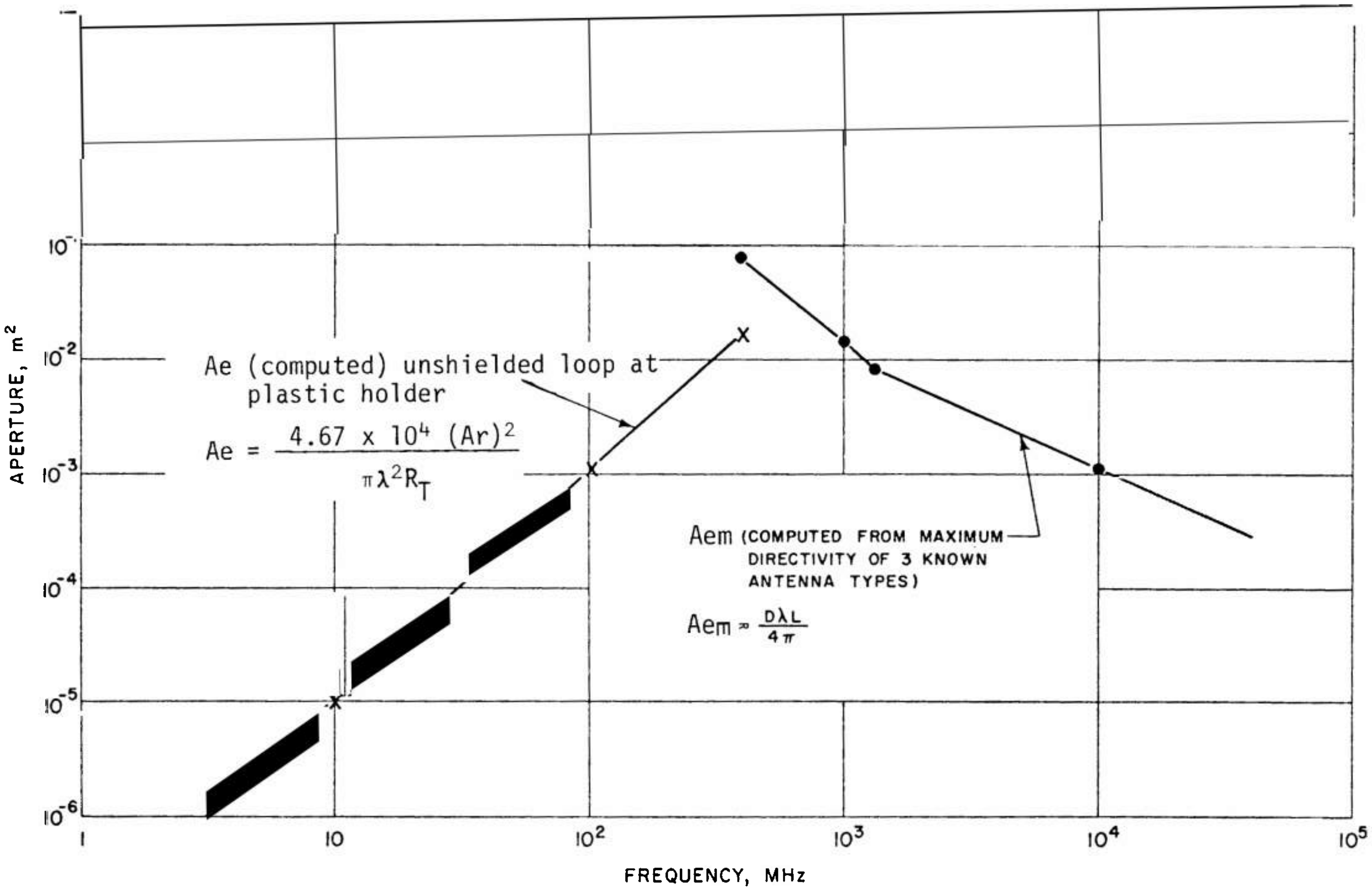

Fig. 5-10. Aperture of Loop Configuration at Paddle (Pin-to-pin Mode)

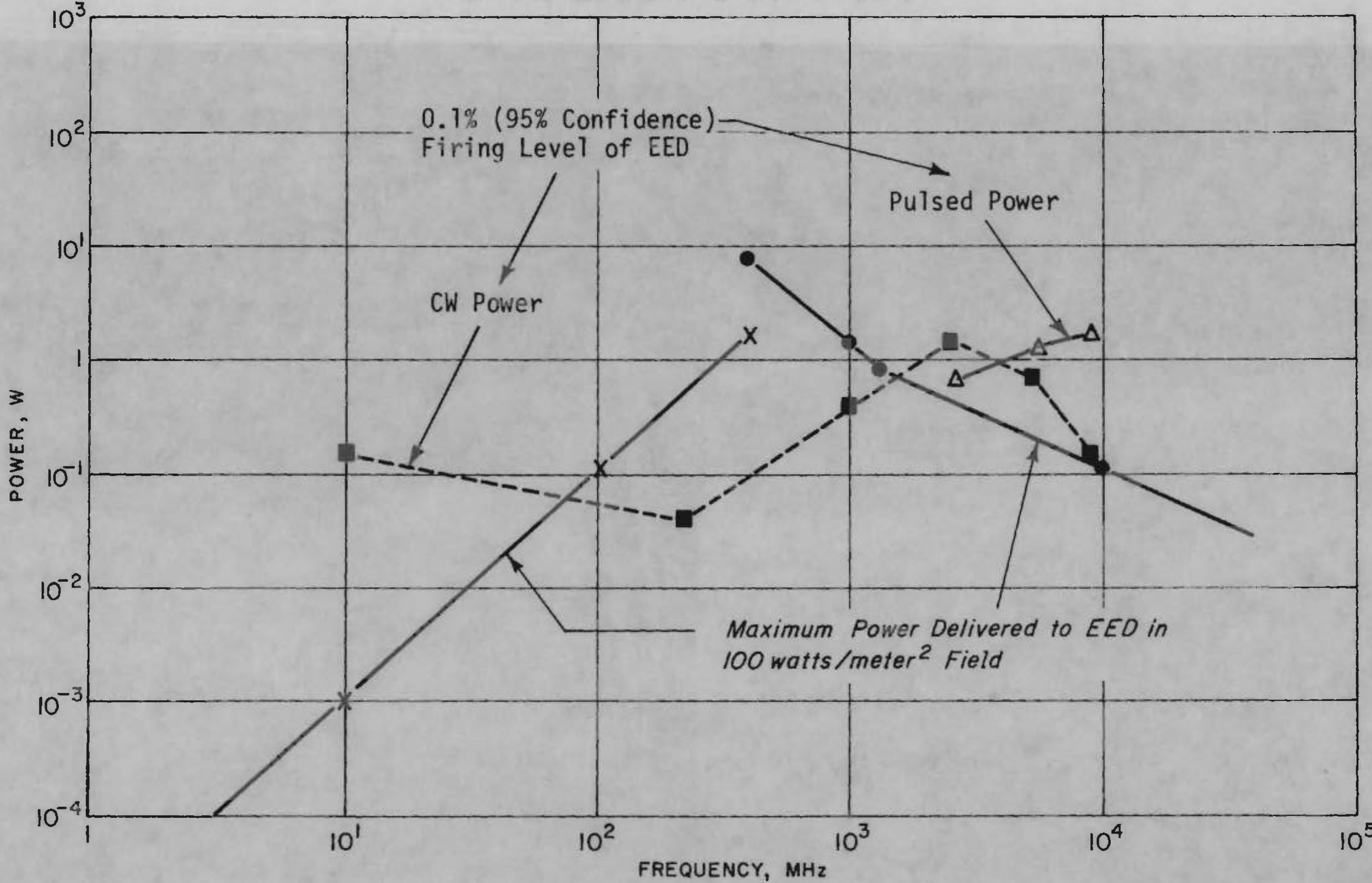

Fig. 5-11. Comparison of 0.1% Firing Level of the EED With Maximum Power Pick-up

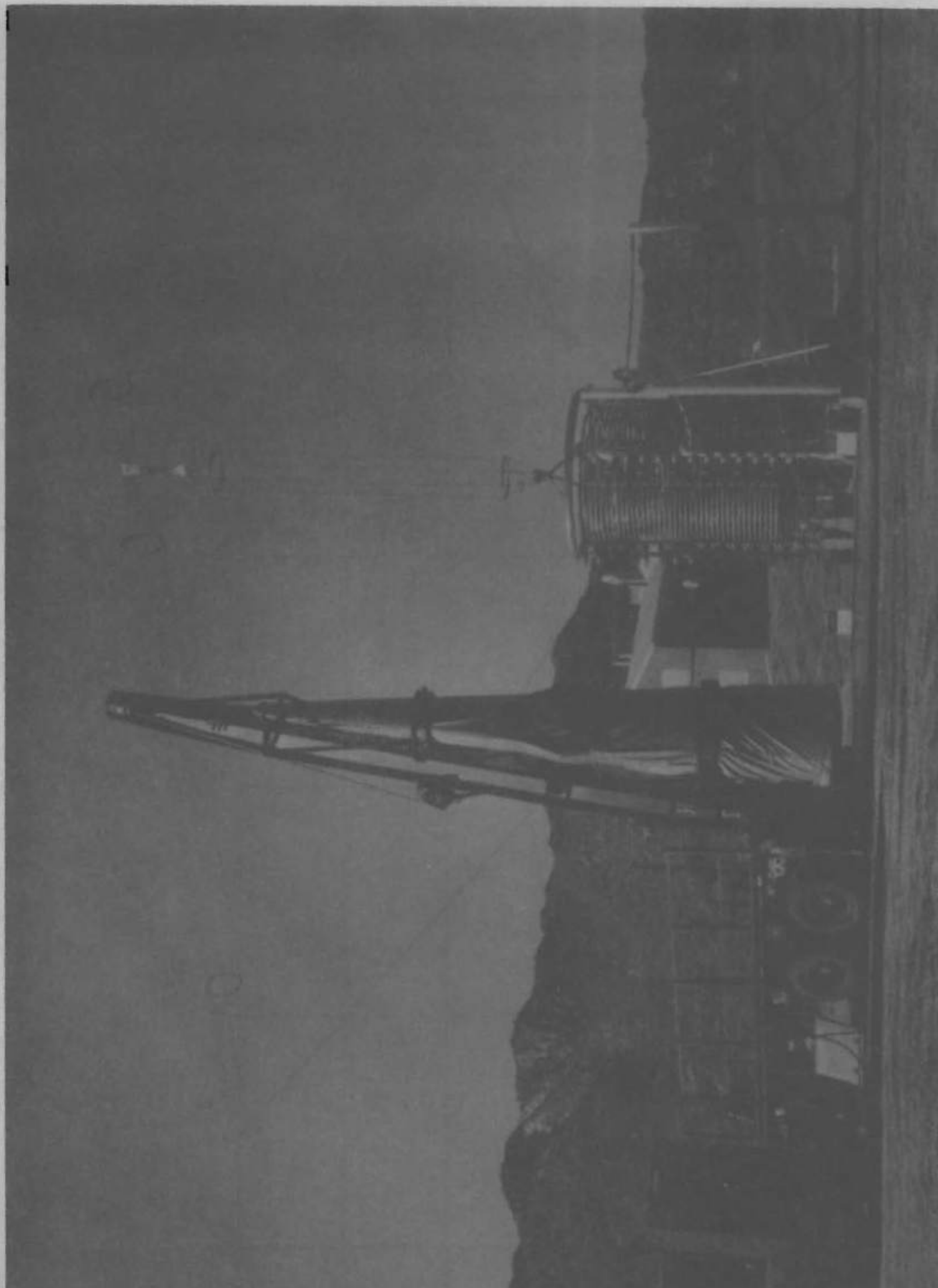

Fig. 5-12. SPRINT Missile Being Irradiated

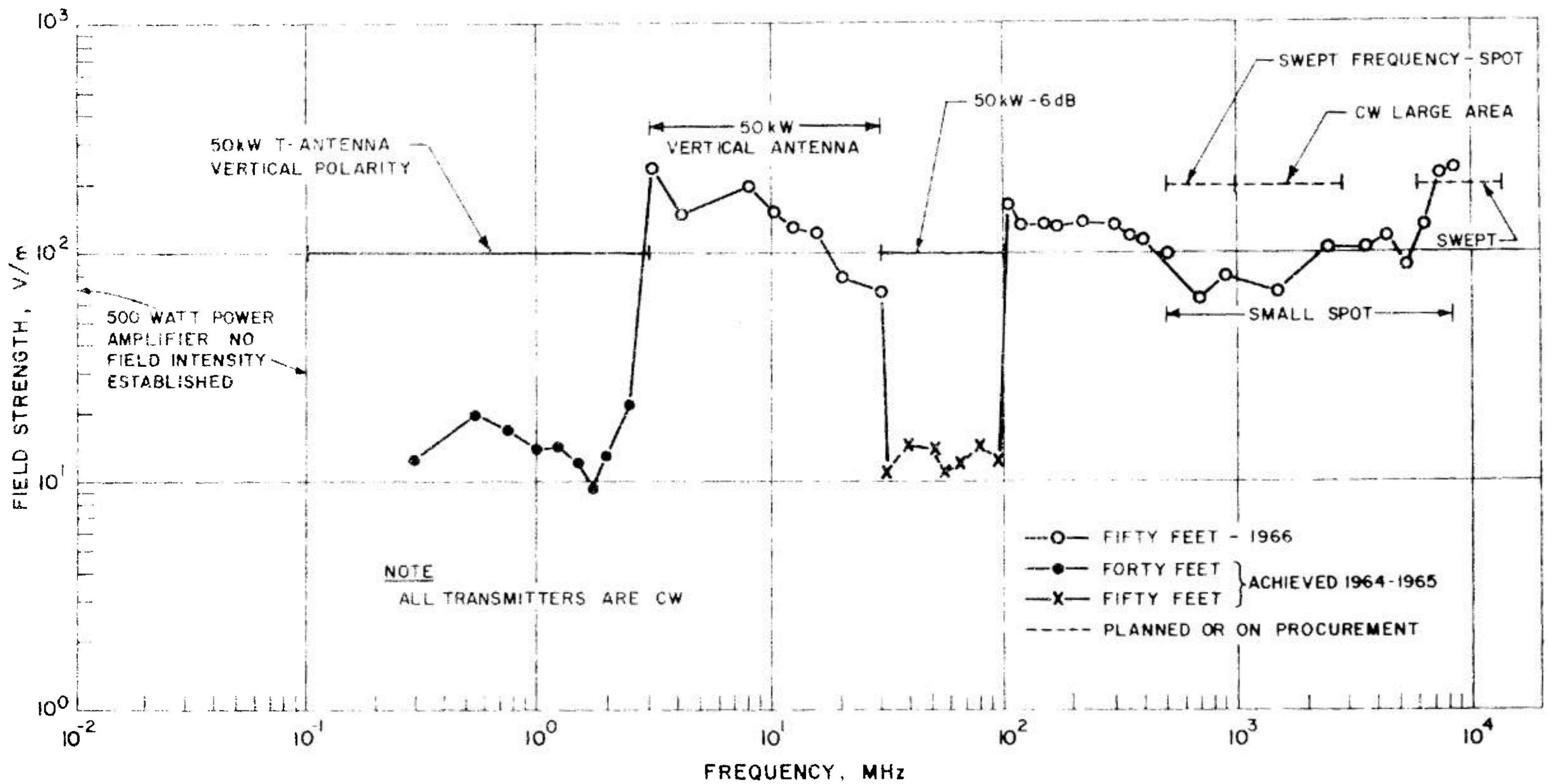

Fig. 5-13. Radiation Environment Available at White Sands Missile Range

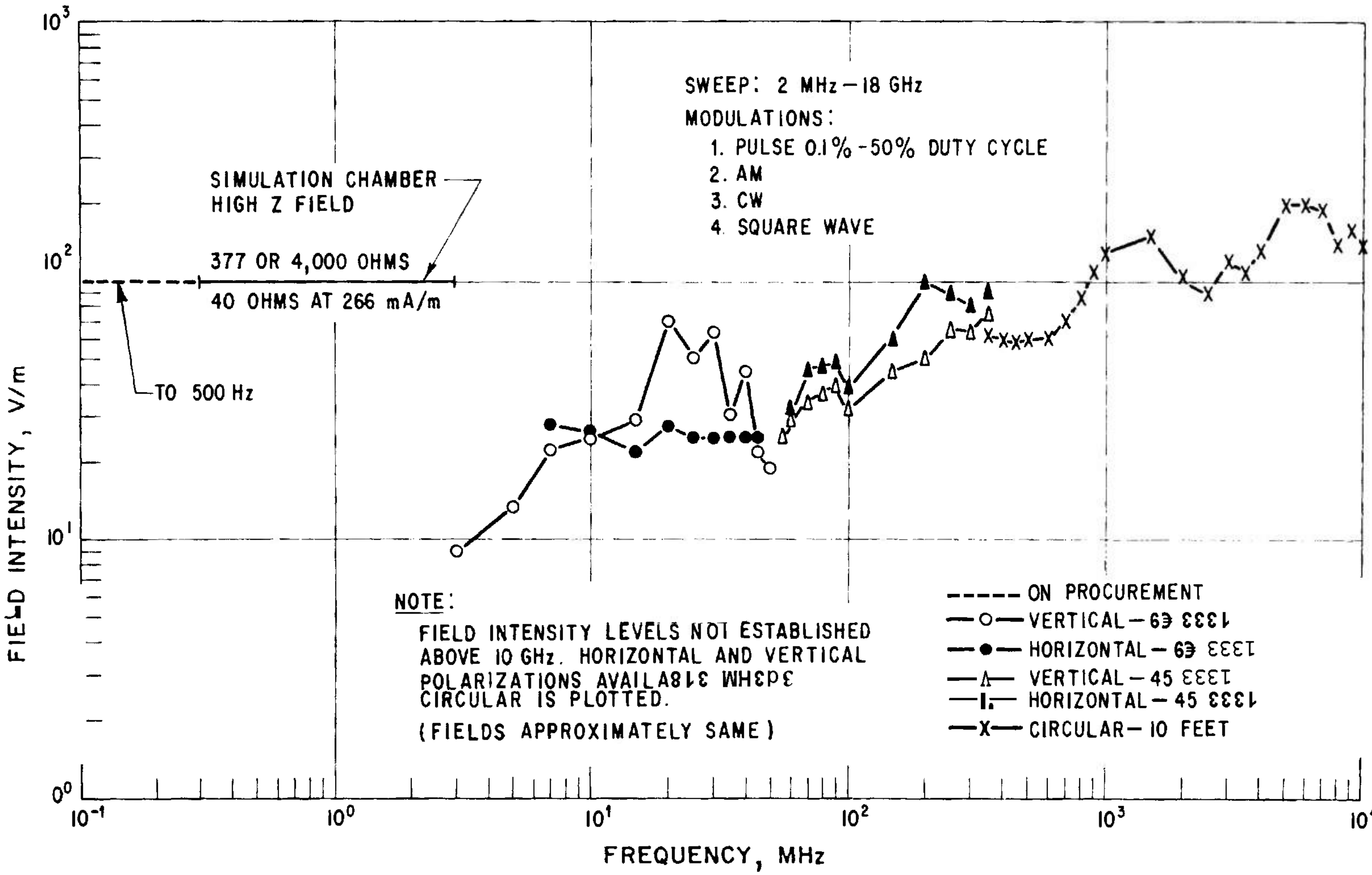

Fig. 5-14. Radiation Environment Available at Picatinny Arsenal

5-15. The facility includes a large ground plane in the center of the radiation pattern.

The dashed line in Fig. 5-14 represents the RF environment capability of the simulation chamber. The capability of the simulation chamber is as follows: A field intensity of 100 V/m is obtainable from 300 kHz to 3 MHz at a field impedance of either 377 ohms or 4,000 ohms; a 266 V/m field may also be obtained at a field impedance of 40 ohms. A transmitter is being procured to extend this simulation chamber capability down to 500 Hz. This chamber, shown in Fig. 5-16, is designed to produce a uniform field pattern so that a component or a system placed inside the chamber will be irradiated uniformly. The system is designed to accommodate weapon systems with major dimensions of 15 ft although items as large as 60 ft can be accommodated with certain limitations.

A list of reports generated by Picatinny Arsenal dealing with the RF susceptibility of weapon systems is contained in the Bibliography.

c. *Naval Weapons Laboratories RF Facilities*

The Navy has a facility located at the Naval Weapons Laboratories, Dahlgren, Va., for irradiating weapon systems with RF energy. This range may also be used by the Army for irradiation tests. A unique feature of this facility is the large metal ground plane (240 ft by 100 ft) located in the center of the radiation pattern (Ref. 11).

5-1.3 DETECTORS FOR RADIO FREQUENCY AND STRAY VOLTAGE HAZARD IDENTIFICATION

Irradiation tests performed on a weapon system can either damage or impair the later functioning of a particular component. If damage occurs, then the system is said to be vulnerable–at least to that frequency and field intensity that caused the damage; however, if no damage is noted, the question remains as to how close the test levels came to the damage point. To answer this question, components are instrumented to measure the amount of RF power being delivered to them when the system is irradiated. Tests are usually conducted at field intensities below that which damages the component or subsystem.

5-1.3.1 Electroexplosive Devices

5-1.3.1.1 Purpose of Detectors

In the study of the hazardous effects of RF energy on EED's, detectors capable of revealing quantitative information about the effects of an incident RF field have played an important role.

The most useful type of detector is the type that is used in a circuit in conjunction with or in place of an EED to determine the quantity of RF energy that would arrive at the device under a given set of RF input conditions. Such detectors are extremely valuable, both in the laboratory and the field. In the laboratory and field they can be substituted for live EED's for such tasks as determining the response of the test items at levels far below that which would normally cause any observable reaction in the live devices.

5-1.3.1.2 Types of Detectors

Several types of detectors have been or are being developed for use with simulated (inert) EED's. Most of these would be applicable to other types of electrical components as well. RF detectors may be broadly divided into two classes: (1) those that detect heat, and (2) those that detect voltage. The paragraphs which follow contain a general discussion of several types of detectors now in use or under consideration for use. Table 5-1 compares these detectors on the bases of sensitivity, pulse response, and instrumentation required.

a. *Heat-sensing Detectors:* Heat-sensing detectors are used primarily to detect the rise in temperature of a bridgewire caused by dissipation of RF energy in the bridgewire. The following are typical of the present state-of-the-art developments.

(1) The Clairex CL-404 detector is a cadmium sulfide cell, with a peak spectral response at 0.68 micron and extends beyond 1 micron into the infrared. As radiation from the bridgewire falls on the cell, the cell's resistance decreases. In most cases the cell can detect a bridgewire's infrared radiation which precedes visible glow. This detector, therefore, is useful for testing at the firing level of most initiators or at a few dB above the no-fire level. The ohmmeter scale of a multimeter may be used as an output meter for this Clairex cell.

(2) The Kodak Ektron N2 detector is a lead sulfide cell with a peak spectral response at 2 microns (Ref. 12) and extends to about 3.5 microns. These detectors are usually operated as matched pairs in a bridge circuit where one cell is exposed to ambient temperature and the radiating source. For optimum results a chopper should be used between the radiating source and the exposed detector. With the

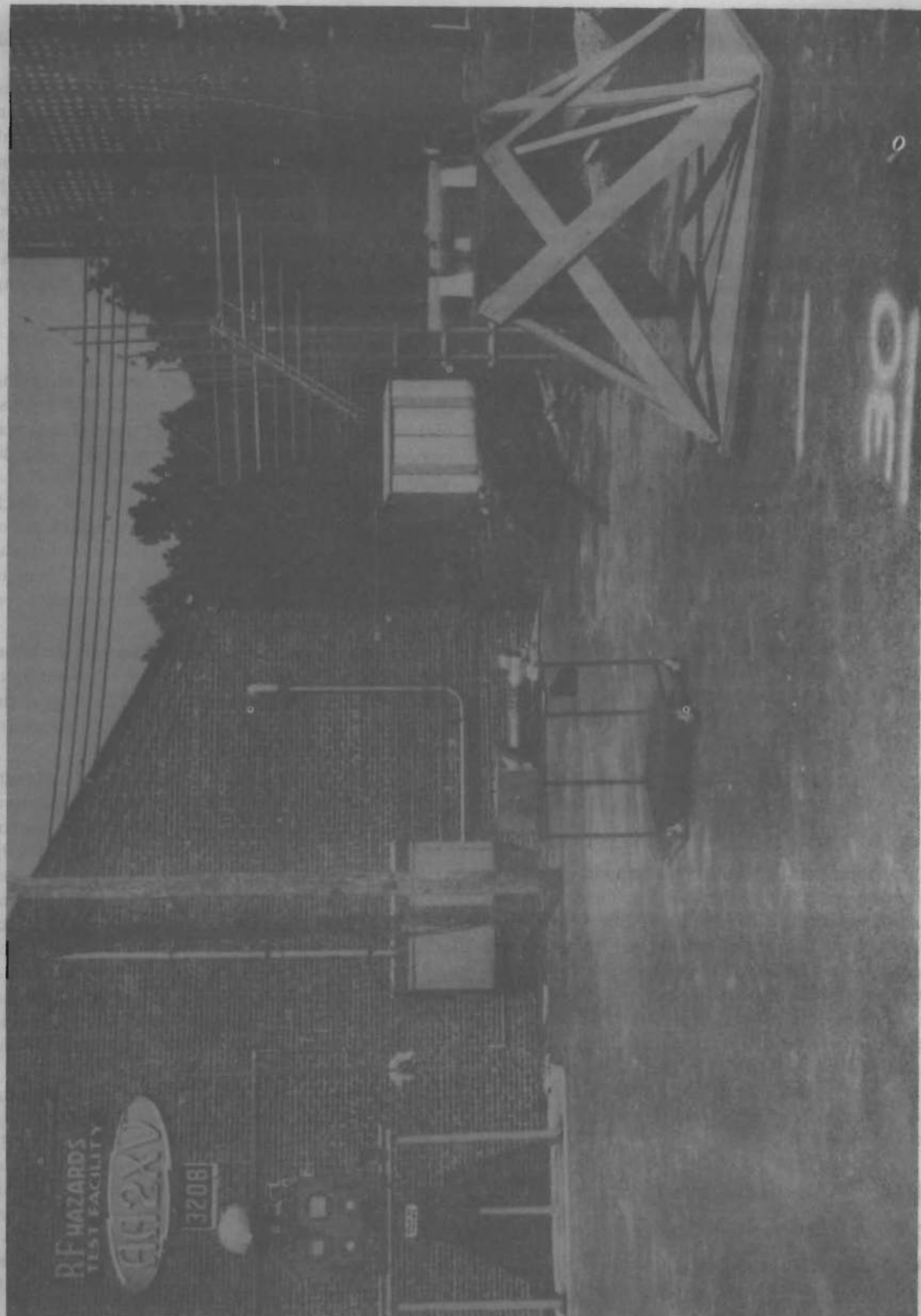

Fig. 5-15. DRAGON Missile System in Test

TABLE 5-1

COMPARISON OF DETECTORS

Type Detector	Maker of Basic Detector Element	Application to EED Developed By	Class	Power Sensitivity,[1] dB	Response (To Pulse)	Common Mode Rejection, dB	Minimum Auxiliary Instrumentation Required for Readout
CL-404 photo-conductive cell	Clairex Corporation	Franklin Institute Research Labs.	Temperature Rise	+3	Poor	>60	Ohmmeter scale of multimeter
Ektron N-2 Cell	Eastman Kodak Co.	Franklin Institute Research Labs.	Temperature Rise	**−8**	Poor	>60	1000 **Hz** bridge circuit **with** amplifier and oscilloscope
Vacuum deposited thermocouple	NWL PA	Naval Weapons Lab., Picatinny Arsenal	Temperature Rise	−32	Poor	>60	Sensitive dc microvolt meter
NWL Colay Cell PEDRO	NWL	Naval Weapons Lab., Dahlgren, Va.	Temperature Rise	−28	Poor	>60	Specially developed instrumentation
VECO AX1364-E Thermistor	Victory Engineering	Applied to M3 squib in LITTLE JOHN at Redstone	Temperature Rise	−23	Poor	>60	dc bridge circuit and sensitive dc microvolt meter
Microminiature Thermocouple	Baldwin-Lima-Hamilton	Martin Co.	Temperature Rise	0	Poor	>60	Sensitive dc microvolt meter
1N830 diode (detector)	Sylvania	Applied to 207D and other EED's at Franklin Institute Research Labs.	Voltage	−40	Good[2]	20	Sensitive dc microvolt meter
Current Probe	Jansky & Baily		Current		Poor	>60	

(1) The number in this column represents the dB below the no-firing level that *can* be read.

(2) An oscilloscope can be used as the indicator.

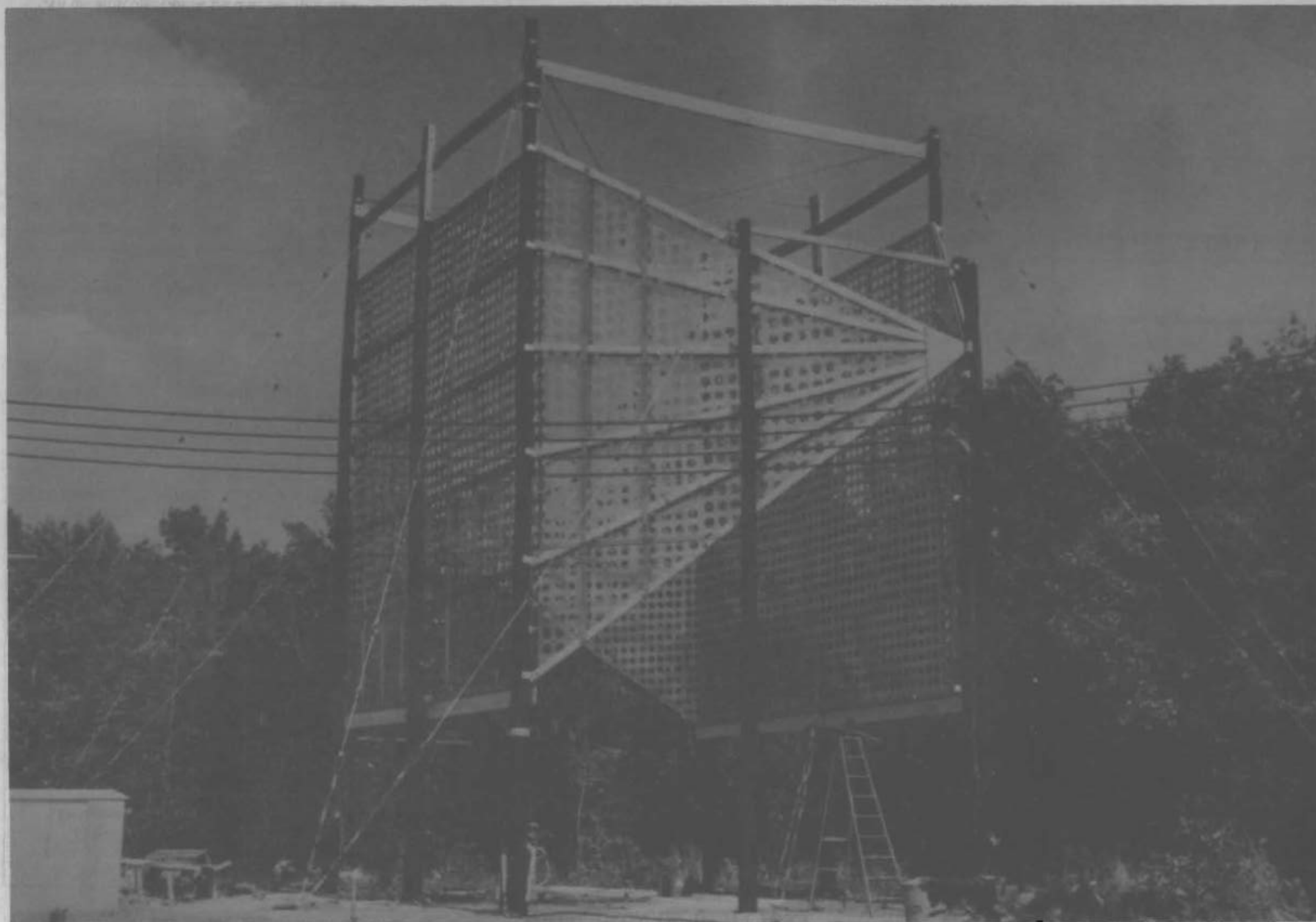

Fig. 5-16. Picatinny Arsenal RF Hazard Simulation Chamber, 300 kHz to 3 MHz, (To Be Extended Down to 10 kHz) 100 V/m, 266 mA/m, 377 ohms, 4,000 ohms, or 40 ohms (Preliminary Checkout)

present system, bridgewire power levels 8 dB below the no-fire level of many conventional initiators can be measured.

(3) A thermocouple may be used to sense the temperature of a heated bridgewire. A vacuum-deposited thermocouple installed within 0.003 in. of the bridgewire was developed by the Naval Weapons Laboratory (Ref. 13). The output of the thermocouple is read on a sensitive recorder or microvoltmeter and has a threshold sensitivity of 50 μW. Tests at the Denver Research Institute indicated good correlation of dc heating with ac heating up to 3 GHz. These are difficult to use above 800 MHz, however, because RF coupling causes spurious signals in the thermocouple output circuit. A later version developed by Picatinny Arsenal, using tellurium-palladium, can measure as low as 12.5 μW dissipation. Tests have also been conducted using a microminiature thermocouple (Ref. 14). Fig. 5-17 shows a BLH Electronics Co. TCRC-ES-25 chromel-alumel microminiature thermocouple mounted above the bridgewire of an EED. These units are easy to assemble but lack the sensitivity of the vacuum deposited thermocouple.

(4) Thermistors–extremely small bead type–are now available. Such thermistors with a nominal resistance of 5,000 ohms exhibit a resistance change of approximately 70 ohms per °F of temperature excursion. If one of these thermistors is mounted above the bridgewire of an initiator, it is possible to detect a relatively small temperature rise in the bridgewire. The thermistors are normally used in matched pairs in a bridge circuit where the second thermistor compensates for changes in ambient temperature. Even with matched pairs, the drift problem associated with significant ambient temperature changes is of such magnitude as to render this technique impractical.

A thermistor-type squib hazard detector was adapted to the LITTLEJOHN missile system at the Propulsion Laboratory, U.S. Army Missile Command, Redstone Arsenal, Alabama (Ref. 15). This detector system had four thermistors as arms of a Wheatstone bridge. Two of the four thermistors were mounted above the bridgewire for increased sensitivity.

(5) The Golay Cell is another type of heat sensing device. A Golay Cell is a gas chamber where

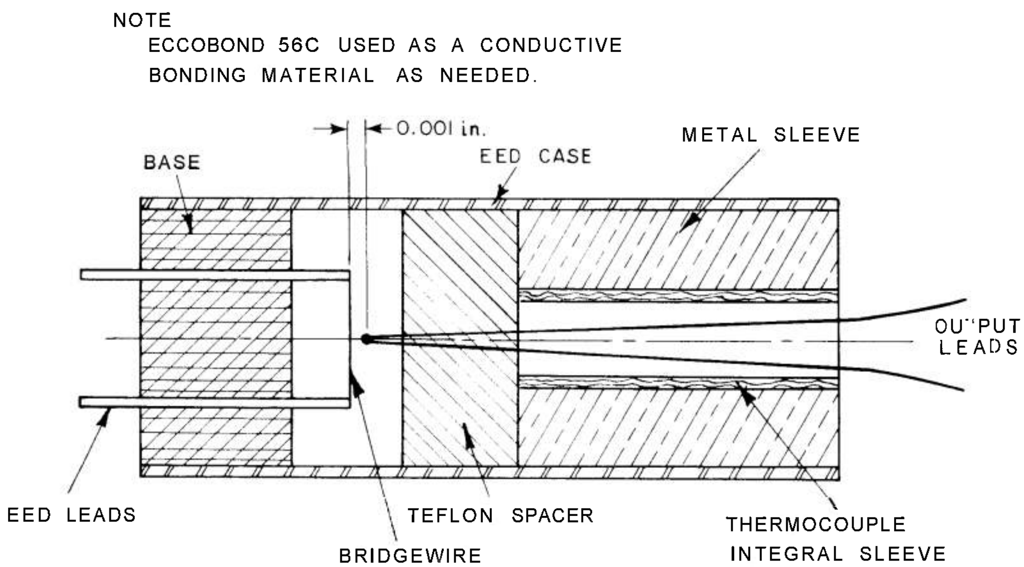

Fig. 5-17. EED Instrumented With a Microminiature Thermocouple

the pneumatic pressure in the chamber is increased when the gas is heated by the energy transferred from the bridgewire. An adaption of this principle was developed by the **U.S.** Naval Weapons Laboratories and incorporated in an inert MK1 Squib (Ref. 16). Heating of the bridgewire raises the chamber pressure and changes the curvature of a flexible mirrored diaphragm in the head of the squib. A remotely located light source and photocell detect the change in curvature of the diaphragm by means of fiber optics, thus avoiding influencing the RF signals being measured. This detector is in the experimental stage.

b. *Voltage-sensing Detectors:* The following instruments are typical of the state-of-the-art developments:

(1) The crystal diode detector is a typical example of the voltage-sensing type (Refs. 17, 18). Fig. 5-18 is a block diagram of one type of crystal diode detector and its associated instrumentation. The leads (points *A* and *B* in Fig. 5-18) are connected across the test device at the spot where RF voltage detection is desired. In most devices this has been directly across the bridgewire, but the detector can be mounted across other parts of the device, for example, between the pins and the case or bridgewire-to-bridgewire in dual bridge EED's. Properly designed, this detector has only minimal effects on the input impedance of the test item, exhibits fast response, and can be very sensitive; however, it is not linear with frequency. Calibration is normally direct, i.e., the calibration curve normally presents detector voltage as a function of input RF power to the test device. The common mode rejection is about 20 dB; therefore, 10% of the output is from the other mode. Table 5-1 compares characteristics of this detector with the heat-sensing types discussed previously. An indication of how small an EED can be–and still be instrumented–may be seen by the example in Fig. 5-19.

(2) The stray voltage detector (SVD) serves the frequent need for a one-shot type of detector which can be placed in the circuit being studied in place of the EED, and which will indicate if predetermined transient levels are exceeded at any time during the test or checkout phase. These SVD's, by closing a switch or triggering an alarm, can be made to indicate the time at which the predetermined level is exceeded.

An SVD that simulates a dual bridgewire EED is shown in Fig. 5-20. It comprises an EED which has a firing sensitivity selected to result in firing at the specified point of input energy, and whose output will be nondestructive. Circuits are built into the SVD so that it will simulate as closely as possible the device which it replaces. For the device shown in Fig. 5-20 it was desired that the SVD should fire on a stray current less than, but close to, the maximum no-fire level of the actual EED. Fig. 5-21 shows the response of the EED and the SVD (Ref. 19). SVD's of this lumped parameter type are not applicable to the detection of stray RF currents since the impedances at various frequencies will not resemble that of the EED.

5-1.3.2 Electronic Circuits

Development of detectors to instrument electronic components such as transistors, capacitors, inductors, resistors, etc., has not been accomplished. There is some work being done using current probes, but these are insensitive and are limited in their frequency response. At the present time, the only criteria are whether the components are damaged when irradiated or whether interference affects their performance in accordance with MIL-STD-461 and MIL-STD-462.

5-2 LIGHTNING

The facilities for evaluating a weapon system's vulnerability to lightning are not as extensive as those for RF irradiation. A portable 1.5×10^6 volt - 1.25×10^4 ampere Artificial Atmospheric Generator (Ref. 20) is available from the Army's Fort Monmouth Laboratory, Fort Monmouth, New Jersey.

Tests on components and subsystems (including warheads) can be conducted at the lightning Transient Research Institute, Minneapolis, Minn. Picatinny Arsenal also has provisions for making lightning tests on components and subsystems. The Picatinny Arsenal equipment illustrated in Fig. 5-22 is rated at 6×10^4 V and 4×10^4 A.

5-3 ELECTROMAGNETIC PULSE (EMP)

Measuring the effect of EMP under actual conditions is not practical since it would require a nuclear detonation above ground; therefore, several EMP simulation facilities have been constructed. One such installation

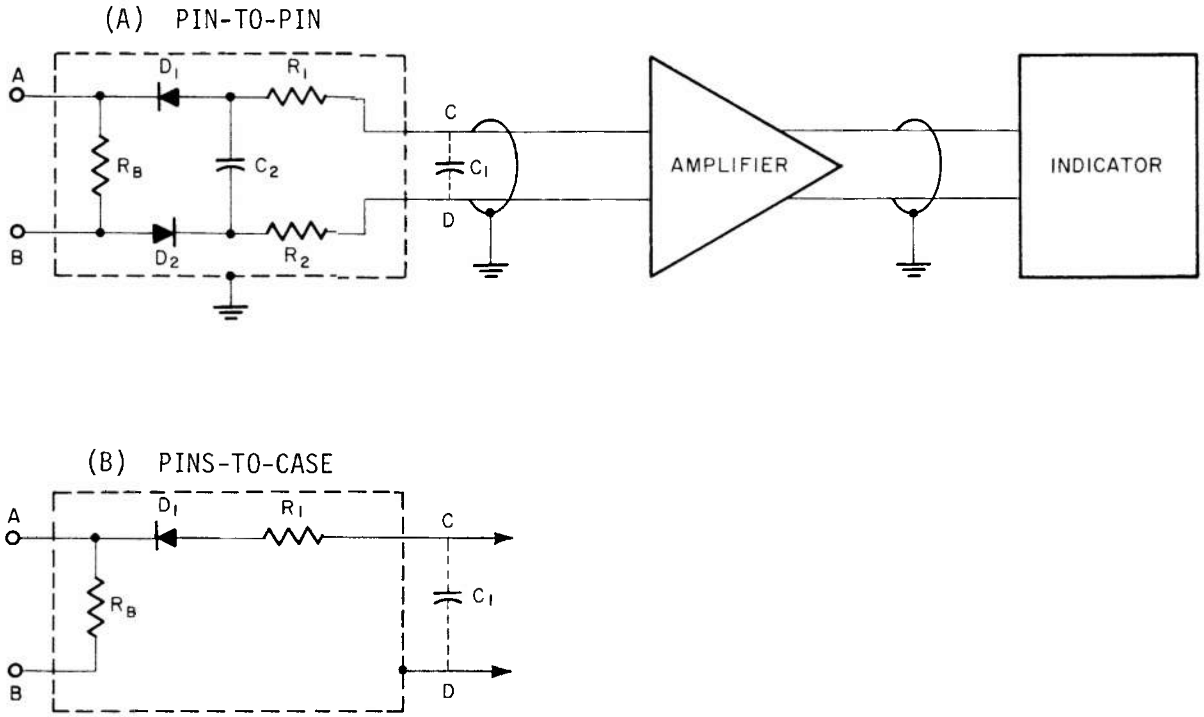

Fig. 5-18. Block Diagram of Crystal Diode Detector a[illegible] Instrumentation

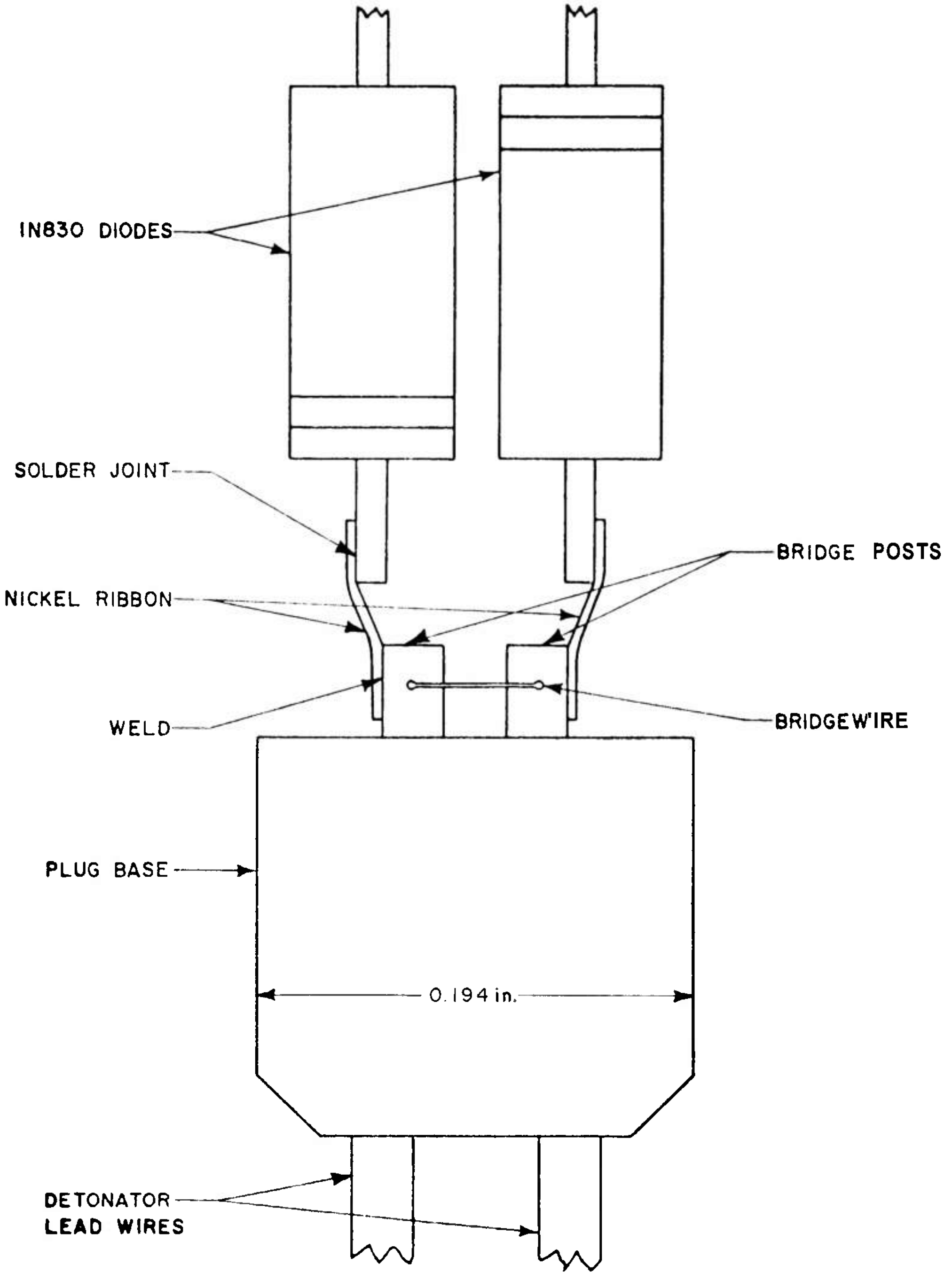

Fig. 5-19. Diode Detector Mounted on a Detonator Plug

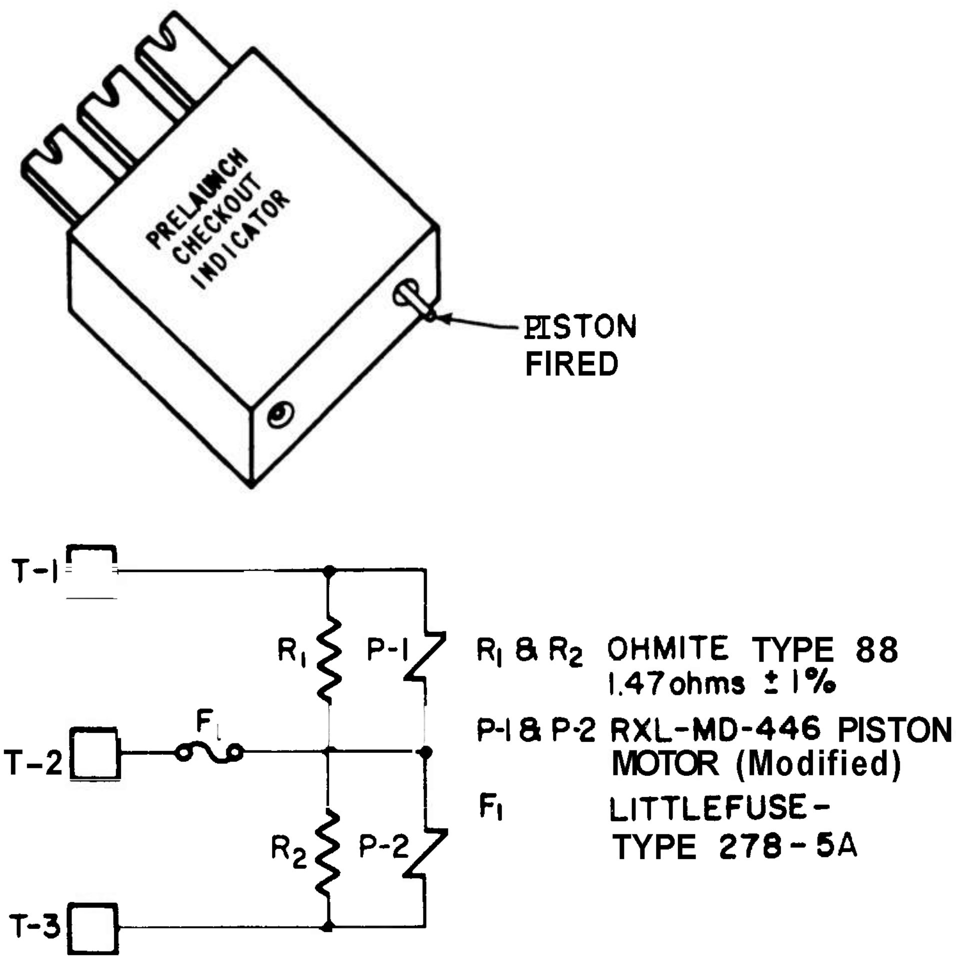

Fig. 5-20. Dual Bridgewire SVD

is the Facility for Research in Electromagnetic Effects (FREME) located at the U.S. Army Mobility Equipment Research and Development Center (USA-MERDC), Ft. Belvoir, Virginia. Full-scale electromagnetic fields, indicative of the intermediate and late time characteristics of the environment created by a surface burst, are reliably simulated at this facility over the dimensions of all but the largest tactical Army systems. The FREME, like other EMP simulators, is capable of producing realistic environments over a portion of the time regime that is significant from an energy standpoint. It must be used in conjunction with other experimental techniques to cover the entire time regime of the EMP. The principal electromagnetic field source at the FREME consists of a conducting cylindrical coil, 51 ft in diameter and 60 ft in axial length, containing a set of thin conducting parallel plates electrically isolated from the conducting cylindrical skin. Horizontal magnetic fields and vertical electric fields are created independently within this coil by using five separate Marx generators, each capable of producing 1×10^6 V, as the drive system. The magnetic field is essentially uniform and unidirectional within the structure. The uniformity of the electric field depends upon temporary, voltage-divided guard rings, which are spaced between the conducting plates during particular experiments. An autonomous, transportable instrumentation system has been developed at USAMERDC for use with the FREME. The magnetic field is monitored with large, shielded, single-turn loops, differential

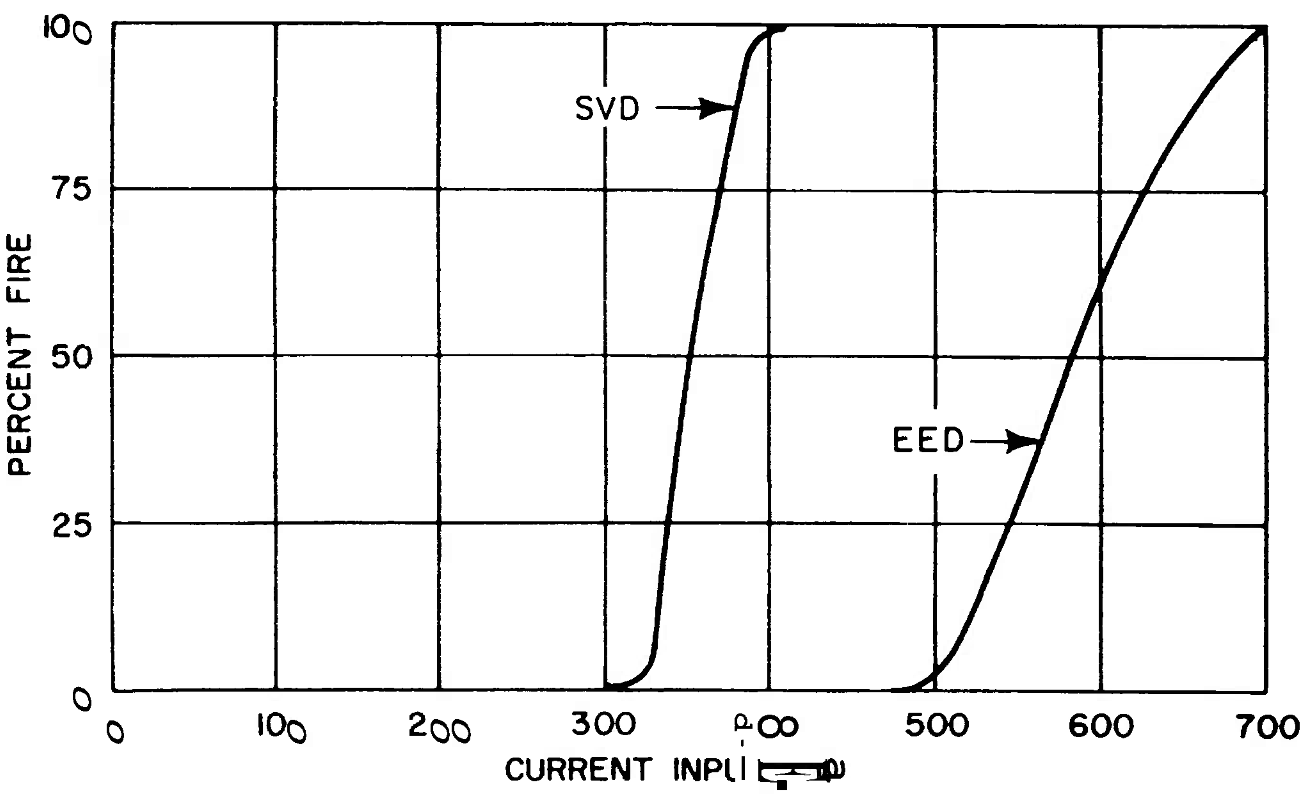

Fig. 5-21. Measured Response of SVD Compared to Replaced EED

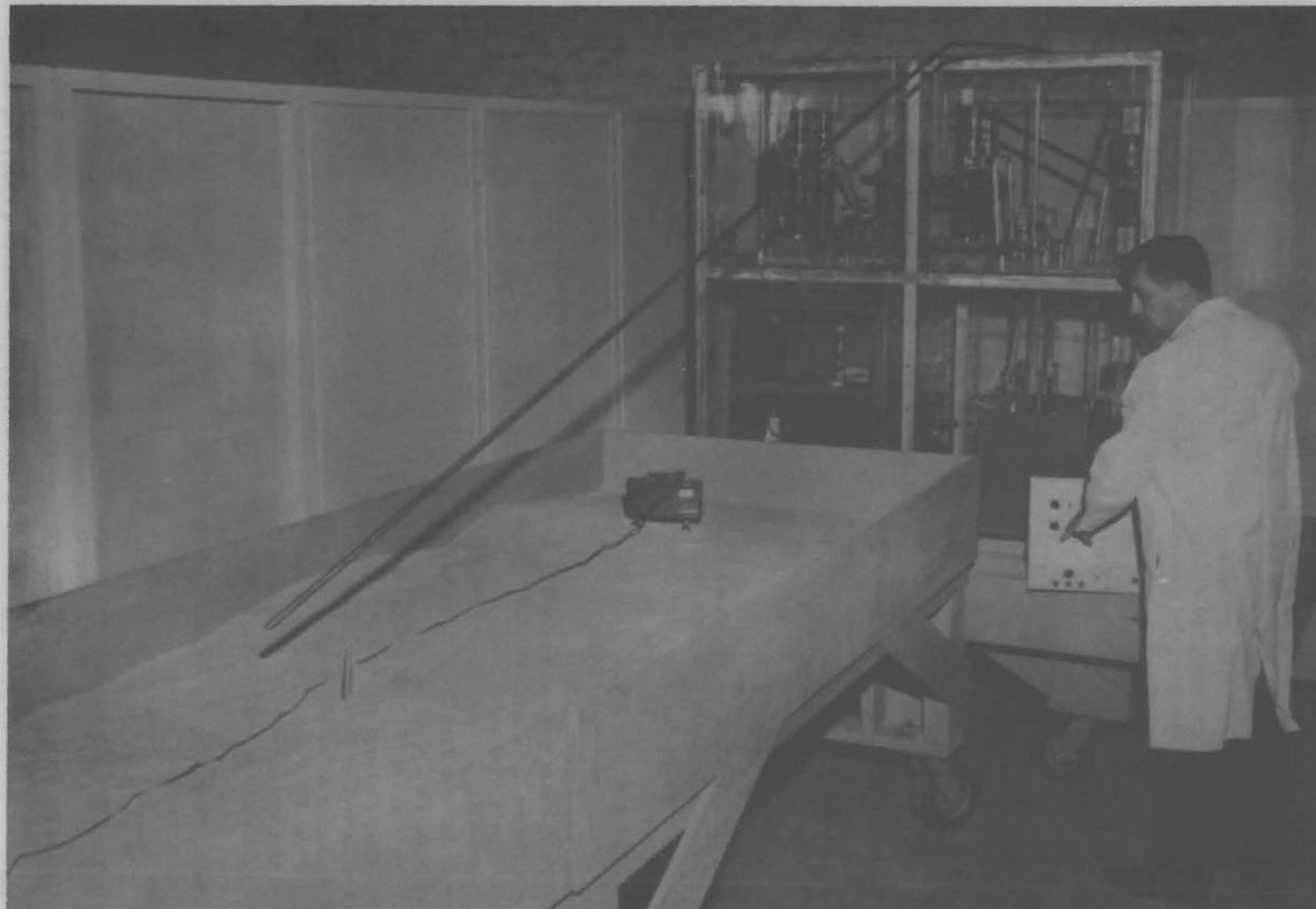

Fig. 5-22. Picatinny Arsenal Lightning Facility

cable, attenuators, and oscilloscopes. A 6-channel optical data link is used to measure the electric field, the voltages on components of equipment under study, and the currents within this equipment. This instrumentation system consists of a small battery-operated package containing a suitable sensor, amplifier, and gallium-arsenide diode to drive 12 ft of light pipe; a stationary light repeater containing photodiodes, amplifiers, gallium-arsenide diodes, and a lens; and photo multipliers with line drivers connecting to oscilloscopes. The system eliminates cables which cause field distortion, current injection into inclosures, and noise pickup. Portable, battery-operated oscilloscopes, with cameras, also may be used to gather data. A number of modifications are being considered to enhance the physical and electromagnetic characteristics of the FREME. These modifications include: increasing the energy storage capacity by 60 percent; decreasing the rise time of the electromagnetic environment; and developing alternate antenna configurations for producing meaningful EMP environments.

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CHAPTER 6

MILITARY SPECIFICATIONS FOR RADIO FREQUENCY INTERFERENCE/ELECTROMAGNETIC INTERFERENCE

6-1 INTRODUCTION

The first four chapters of this handbook are concerned with design techniques that will aid the designer in the development of a weapon system that is invulnerable to RF energy. There are, however, several Military Specifications that are concerned with the effects that an RFI/EMI environment will have on electrical and electronic equipment, and these specifications must be adhered to also. In the course of designing the system, the designer should be aware that the various pieces of equipment must perform without malfunction when exposed to a specified RF environment and must not itself radiate so as to influence other equipment.

6-2 APPLICABLE STANDARDS AND SPECIFICATIONS

To ascertain whether these requirements are being met, the Department of Defense has specified that certain tests be conducted. These tests are listed in Tables **6-1** and 6-2 along with a description of their scope and some brief comments. It should be noted that these Military Specifications were written for the control of RFI/EMI and not as a means of determining the vulnerability of a weapon system. The maximum field intensity for RFI/EMI tests is **10** V/m while vulnerability tests could require the use of several hundred V/m as a survivability standard. However, if the recommendations set forth in this handbook are followed, meeting the RFI/EMI specifications should not constitute a problem.

6-3 OTHER STANDARDS AND SPECIFICATIONS

There are other Military Specifications that deal indirectly with RFI/EMI and are encountered by the designer when he surveys the specifications. Many of these are not applicable to the immediate problem but this is difficult to ascertain by reading the titles of the documents. **As** a means of ready reference, these additional specifications are listed in Table **6-3.**

6-4 COMPLIANCE WITH RFI/EMI SPECIFICATIONS

Electrical and electronic equipment used in military systems must meet certain RFI/EMI requirements in order to prevent degradation and interference. These requirements are called out in certain Military Specifications. Four of these specifications contain information on shielding, grounding, and circuit configurations. Many of the practices suggested in these documents are similar to those recommended in this handbook. To acquaint the designer with contents of these four documents, excerpts have been taken from them and placed in pars. **6-4.1** to **6-4.4.** It should be noted that these are excerpts and do not constitute the total specifications. The purpose of this portion of the handbook is to present only the type of data that can be found in these type of documents. For complete information, both the total specification and the documents that they refer to should be read. When using these specifications, the designer should check to see if he has the latest issue. **As** an example, consider **MIL-STD-449C** listed in Table **6-1.** The date on this document is 1 March **1965** and it supersedes MIL-STD-**449B** dated 20 July **1963.** Up-to-date listing of the specifications can be found in *Department of Defense Index of Specifications and Standards.*

When the designer refers to the numerous RFI/EMI specifications, he is faced with the task of trying to decide which ones are applicable. The Department of

TABLE 6-1

APPLICABLE MILITARY STANDARDS

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
449c	RADIO FREQUENCY SPECTRUM CHARACTERISTICS, MEASUREMENT OF	Army, Navy, Air Force	This technical standard establishes uniform measurement techniques that are applicable to the determination of the spectral characteristics of radio-frequency transmitters and receivers. The ultimate goal is to ensure the compatibility of present and future systems.	Successful operation of most weapon systems depends upon the transfer of information to and from the system usually in the form of radio waves. Operation is degraded if other energy sources interfere with this flow of information, therefore, it is desirable to know the spectral characteristics of both the on-board and support receivers and transmitters. This standard establishes uniform measurement techniques of the spectral characteristics of the receivers and transmitters and gives forms for recording these data. This information is available to the designer and can be used to determine the characteristics of the receivers and transmitters that will be associated with the weapon system.
461	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, REQUIREMENTS FOR	Army, Navy, Air Force	This standard establishes the requirements for the measurement and determination of electromagnetic interference characteristics (emission and susceptibility) of equipment, systems, and subsystems.	The purposes of the standard are as follows: (a) To ensure that interference control design is incorporated into equipment, subsystems, and systems, and that applicable requirements are met. (b) To specify levels of electromagnetic interference emanation and interference susceptibility for equipment and subsystems that will enable compatible operation in a complex electromagnetic environment. The limits and referenced tests are established to increase the probability that operational systems or equipment will be compatible.

TABLE 6-1

APPLICABLE MILITARY STANDARDS (Cont.)

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
461 (con't)				This standard contains the requirements which are to be met when performing the tests specified for the electronic, electrical, or electromechanical equipment being purchased. The required tests referenced in this standard are found in MIL-STD-462.
462	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, MEASUREMENT OF	Army, Navy, Air Force	This standard establishes the accepted techniques used for the measurement and determination of electromagnetic interference characteristics (emission and susceptibility) of electrical, electronic and electromechanical equipment, subsystems, and systems in the frequency range of 20 Hz to 20 GHz (optional 40 GHz).	This standard takes the requirements set forth in MIL-STD-461 and presents a detailed discussion on how the tests are to be conducted.
463	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, DEFINITIONS AND SYSTEM-OF-UNITS	Army, Navy, Air Force	This standard establishes the system of units to be used.	The International System of Units, as adopted by the United States Bureau of Standards, is used in MIL-STD-461 and MIL-STD-462. MIL-STD-463 contains a complete description of these units.
826	ELECTROMAGNETIC INTERFERENCE TEST REQUIREMENTS AND TEST METHODS	Air Force	This standard establishes uniform test methods for testing equipment, systems, 3nd subsystems to determine their electromagnetic interference and susceptibllity characteristics.	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 6-1.

APPLICABLE MILITARY STANDARDS (Cont.)

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
833	MINIMIZATION OF HAZARDS OF ELECTROMAGNETIC RADIATION TO ELECTROEXPLOSIVE DEVICES	Air Force	This standard delineates criteria to be applied to the design of electroexplosive devices (EED's) and their application in systems. The purpose of this standard is to minimize the hazards of electromagnetic radiation to electroexplosive devices. The standard will apply to the design selection and application of electroexplosive devices and their firing circuits for all new development programs of systems that use electroexplosive devices.	This standard is used by the Air Force. It differs from the other MIL-STD's in that it deals with the hazard of electromagnetic energy to electroexplosive devices (EED's). EED's are required to meet one of the following standards: a. EED's will not fire as a result of the application of 1 watt of direct-current power for 5 minutes and also will not fire as a result of the application of 1 ampere of direct-current for 5 minutes. This requirement must be met without the use of external shunts. b. EED's with electroexplosive elements that do not meet the above I-watt/1-ampere/5-minute standard will be designed *so* that the integral unit will survive in an electromagnetic field intensity of 100 watts per square meter. c. Recommended circuit configuration and shielding practices are included (see par. 6-4.4).

TABLE 6-2

MIL-No.	TITLE	Mandatory Use by	Scope	Comments
A-3933B	ATTENUATORS, FIXED	Navy, Air Force, Army	This specification covers attenuators for use as attenuating elements in coaxial lines and waveguide. These attenuators are used for Armed Services application in the transmission lines of radar, radio and associated equipment.	This specification documents the various methods of measuring the worst case loss of an attenuator using matching systems.
B-5087B	BONDING, ELECTRICAL, AND LIGHTNING PROTECTION, FOR AEROSPACE SYSTEMS	Navy, Air Force	This specification covers the characteristics, application, and testing of electrical bonding for aerospace systems, as well as bonding for the installation and interconnection of electrical and electronic equipment therein, and lightning protection.	This specification is used by the Air Force and the Navy and deals with the bonding of metal-to-metal surfaces to provide protection against RF, lightning, and static electricity. Recommended procedures for preparing of the surface of the two metals to be joined is given. Methods of bonding are illustrated.
E-6051C	ELECTRICAL-ELECTRONIC SYSTEM COMPATIBILITY AND INTERFERENCE CONTROL REQUIREMENTS FOR AERONAUTICAL WEAPON SYSTEMS, ASSOCIATED SURSYSTEMS AND AIRCRAFT	Army, Navy, Air Force	This specification outlines design requirements and tests necessary to control the electronic interference environment of weapon systems, associated electronic and electrical subsystems, and aircraft.	This specification can be considered as a guide for the contractor who is submitting equipment for approval. It tells what tests must be run but does not tell how to conduct the test. Test procedures are referred to MIL-I-6181D. Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 6-2

APPLICABLE MILITARY SPECIFICATIONS (Cont.)

MIL-No.	TITLE	Mandatory Use by	Scope	Comments
E-55301	ELECTROMAGNETIC COMPATIBILITY	Army	This specification covers the electromagnetic interference reduction design requirements, emission and susceptibility limits, and test procedures for assuring the electromagnetic compatibility of all equipments and systems intended for use by the Department of the Army. It includes all types of items that are capable of generating or being adversely affected by electromagnetic interference.	Superseded by MIL-STD-461 and MIL-STD-462.
I-6181D	INTERFERENCE CONTROL REQUIREMENTS, AIRCRAFT EQUIPMENT	Army, Navy, Air Force	This specification covers design requirements, interference test procedures, and limits for electrical and electronic aeronautical equipment to be installed in or closely associated with aircraft.	Superseded by MIL-STD-461 and MIL-STD-462.
P-24014	PRECLUSION OF HAZARDS FROM ELECTROMAGNETIC RADIATION TO ORDNANCE, GENERAL REQUIREMENTS FOR	Navy	This specification establishes general requirements for weapon systems to preclude hazards from environmental electromagnetic fields in the frequency range of 10 Hz to 40 GHz. These requirements apply to all Navy weapon systems, including safety and emergency devices and other ancillary equipment, which contain electrically initiated, explosive or pyrotechnic components.	This specification is used by the Navy and deals with the hazards of electromagnetic energy to electroexplosive devices.

TABLE 6-3

OTHER RFI/EMI SPECIFICATIONS

MIL-NO.	TITLE	Mandatory Use by	Scope
E-4957A	ENCLOSURE, ELECTROMAGNETIC-SHIELDING, DEMOUNTABLE, PREFABRICATED FOR ELECTRONICS TEST PURPOSES	Navy, Air Force	This specification covers shielding enclosures, (screen rooms) which are to provide specified frequency ranges for the purpose of test and alignment of electronics equipment and other related purposes.
E-8881A	ENCLOSURE, ELECTROMAGNETIC-SHIELDING DEMOUNTABLE, PREFABRICATED GENERAL SPECIFICATION FOR	Army, Navy, Air Force	This specification covers shielding enclosures which provide specified degrees of attenuation of electromagnetic fields for the purpose of test and alignment of electronic equipment.
E-18639A	ENCLOSURES, ELECTROMAGNETIC-SHIELDING, KNOCKDOWN DESIGN	Navy	This specification covers shielding enclosures which shall provide stated minimum degrees of attenuation to electromagnetic fields for the purpose of test alignment of electronic equipment and for other related purposes.
F-15733D	FILTERS, RADIO INTERFERENCE, GENERAL SPECIFICATION FOR	Army, Navy, Air Force	This specification covers the general requirements for current-carrying filters (alternating current (ac) and direct current (dc)), for use primarily in the reduction of broadband radio interference.
I-11683B	INTERFERENCE SUPPRESSION, RADIO, REQUIREMENTS FOR ENGINE GENERATORS AND MISCELLANEOUS ENGINES	Army	Superseded by MIL-STD-461 and MIL-STD-462.
1-25171	INTERFERENCE LIMITS AND TESTS FOR MODIFIED OR RECONDITIONED AIRCRAFT	Air Force	This specification covers interference limits applicable to aircraft being modified or reconditioned.
1-26600	INTERFERENCE CONTROL REQUIREMENTS, AERONAUTICAL EQUIPMENT	Air Force	Superseded by MIL-STD-461 and MIL-STD-462

TABLE 6-3

OTHER RFI/EMI SPECIFICATIONS (Cont.)

MIL-No.	TITLE	Mandatory Use by	Scope
S-5786	SUPPRESSOR, ELECTRICAL NOISE, RADIO FREQUENCY	Air Force	This specification covers one type of radio frequency noise suppressor.
S-10379A	SUPPRESSION, RADIO INTERFERENCE GENERAL REQUIREMENTS FOR VEHICLES (AND VEHICULAR SUB-ASSEMBLIES)	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
S-12348A	SUPPRESSION, RADIO INTERFERENCE GENERAL REQUIREMENTS FOR RAILWAY ROLLING STOCK, AND MAINTENANCE OF WAY EQUIPMENT	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
S-13237A	SUPPRESSION, RADIO INTERFERENCE REQUIREMENTS FOR WATERCRAFT	Army	Superseded by MIL-STD-461 AND MIL-STD-462.
STD-220A	METHOD OF INSERTION-LOSS MEASUREMENT FOR RADIO-FREQUENCY FILTERS	Army, Navy, Air Force	This standard covers a method of measuring, in a 50-ohm system, the insertion loss of single and multiple-circuit radio-frequency filters at frequencies up to 1 GHz.
I-11748B	INTERFERENCE REDUCTION FOR ELECTRICAL AND ELECTRONIC EQUIPMENT	Army	Superseded by MIL-STD-461 and MIL-STD-462.
I-16165D	INTERFERENCE SHIELDING, ENGINE ELECTRICAL SYSTEMS	Navy	This specification covers requirements for interference shielding items and shielded harnesses for engine electrical systems aboard Naval ships, at advance bases, and in the vicinity of electronic installations. It includes the allowable interference limits for such items and the permissible limits for auxiliary devices normally installed on electrical wiring systems associated with these engines.

TABLE 6-3

MIL-NO.	TITLE	Mandatory Use by	Scope
I-16910C	INTERFERENCE MEASUREMENT, ELECTROMAGNETIC, METHODS AND LIMITS	Navy	Superseded by MIL-STD-461 and MIL-STD-462.
I-17623A	INTERFERENCE MEASUREMENT, ELECTROMAGNETIC; METHODS AND LIMITS, FOR ELECTRIC OFFICE MACHINES, PRINTING AND LITHOGRAPHIC EQUIPMENT	Navy	Superseded by MIL-STD-461 and MIL-STD-462.
STD-285	ATTENUATION MEASUREMENTS FOR ENCLOSURES, ELECTRO-MAGNETIC SHIELDING, FOR ELECTRONIC TEST PURPOSES, METHOD OF	Army, Navy, Air Force	This standard covers a method of measuring the attenuation characteristics of electromagnetic shielding enclosures used for electronic test purposes.

Defense has become aware of this problem, and at the time of issue of this handbook, MIL-STD-461, MIL-STD-462, and MIL-STD-463 are to take precedence over the other RFI/EMI specifications.

6-4.1 MIL-B-5087B

6-4.1.1 Bonding Surface Preparation

Surface preparation for an electrical bond shall be accomplished by removing all anodic film, grease, paint, lacquer, or other high-resistance properties from the immediate area to insure negligible radio frequency (RF) impedance between adjacent metal parts. Abrasives which cause corrosion, if embedded in the metal, shall not be used. If abrasives or scrapers are used to remove any protective finish, they shall be of such a nature that produces a clean, smooth surface without removing excessive material under the protective finish. Chemical cleaning and surface preparation shall be in accordance with standard practice.

6-4.1.2 Classes of Application

Electrical bond classes of application shall be as specified in Table 6-4.

TABLE 6-4

ELECTRICAL BOND CLASSES OF APPLICATION

Class	Application
A	Antenna installation
C	Current path return
H	Shock hazard
L	Lightning protection
R	RF potentials
S	Static charge

Where a single bond is used to serve two or more classes of application, the design shall conform to the most critical requirement of bonding.

6-4.1.2.1 Class A Bonding (Antenna Installations)

a. ***Return path.*** Antennas, so designed that efficient operation depends on low resistance, shall have the bond installed so that RF currents flowing on the external surface of a vehicle will have a low-impedance path of minimum length to the appropriate metal portion of the antenna.

b. *Coaxial antenna.* Provisions shall be made for circumferential (360" connection) RF continuity between outer conductors of coaxial antenna transmission lines and ground planes of antennas.

6-4.1.2.2 Class C Bonding (Current Path Return)

a. *Current capacity.* The bond between equipment and vehicle structure should not be used as a ground return in Army systems, rather a return wire or cable should be used. Table 6-5 shows the size of cable recommended.

b. *Voltage drop.* The total impedance of wires and cables shall be such that the voltage drop between the point of regulation and the load does not exceed the limits shown in Table 6-6. For current return leads of size AN-4(AWG-4), or larger wire, the bonding connection shall not be made directly to a structure but shall be made to a tab of sufficient size that is properly attached to the structure.

6-4.1.2.3 Class H Bonding (Shock Hazard)

a. ***Resistance.*** Metallic conduit-carrying electrical wiring shall have a low-resistance bond of less than 0.1 Ω to structure at each terminating and break point. The bonding path may be through the equipment at which the conduit terminates.

b. ***Grounding.*** Exposed conducting frames or parts of electrical or electronic equipment shall have a low-resistance bond of less than 0.1 Ω to structure. If the equipment design includes a ground terminal or pin which is internally connected to such exposed parts, a ground wire connection to such terminal or pin shall be provided. (Once again it should be noted that this is for shock protection and not a current return.)

6-4.1.2.4 Class L Bonding (Lightning Protection) (Except for Antenna Systems)

Lightning protection shall be provided at all possible points of lightning entry into the aircraft (or in this situation, any missile system). The entry points include but are not limited to the following:

a. Navigation lights

b. Fuel filler caps

c. Fuel gage covers

d. Refueling booms

e. Fuel vents

f. Antennas.

The bonding requirements which follow are designed to achieve protection against lightning discharge

TABLE 6-5

CURRENT-CARRYING CAPACITY OF WIRES AND CABLES

Wire or cable size		Continuous-duty current - A	
Aluminum	Copper	Single wire in free air	Wires and cables in conduit or bundles
	AN-22	--	5
	AN-20	11	7.5
	AN-18	16	10
	AN-16	22	13
	AN-14	32	17
	AN-12	41	23
	AN-10	55	33
	AN-8	73	46
	AN-6	101	60
	AN-4	135	80
	AN-2	181	100
	AN-1	211	125
	AN-0	245	150
	AN-00	283	175
	AN-000	328	200
	AN-0000	380	225
AL-8		60	36
AL-6		83	50
AL-4		108	66
AL-2		152	82
AL-1		174	105
AL-0		202	123
AL-00		235	145
AL-000		266	162
AL-0000		303	190

TABLE 6-6

Nominal system voltage	Maximum allowable voltage drop	
	Equipment operation	
	Continuous	Intermittent
28	1	2
115	4	8
200	7	14

current carried between the extremities of an airborne vehicle without risk of damaging flight controls or producing sparking or voltages within the vehicle in excess of 500 V. These requirements are based upon a lightning current waveform of 200,000 A, peak; a width of 5 to 10 psec at the 90-percent point; not less than 20 psec width at the 50-percent point; and a rate of rise of at least 100,000 A/μsec.

a. *Size of conductor.* Individual bonding jumpers for lightning protection shall be not less than No. 12 AWG for tinned stranded copper wire or No. 10 AWG for stranded aluminum wire. These wire sizes are valid only when a minimum of two jumpers are installed to carry the lightning current and when the jumpers are not subject to a direct arc. When the jumpers may be subject to arcing, substantially larger wire sizes 40,000 circular mils (AWG-4) minimum are required for protection against multiple strokes.

b. *Soldered connections.* Soldered connections shall not be used on jumpers that are required to carry lightning currents.

c. *Bonding conductor restrictions.* Conductors shall be equal to, or larger than, 6,530 circular mils (AWG-12) for copper or 10,380 circular mils (AWG-10) for aluminum, where the conductor will not be subject to arcing. Where the conductor is subject to arcing, a minimum of 20,820 mils (AWG-7) for copper, or 33,100 mils (AWG-5) for aluminum, shall apply.

d. *Riveted skin construction.* Close riveted skin construction which divides any lightning current over a number of rivets is considered adequate to provide a lightning discharge current path.

6-4.1.2.5 Class R Bonding (RF Potentials)

a. *Grounding.* All electrical and electronic units or components which produce electromagnetic energy shall be installed to provide a continuous low-impedance path from the equipment enclosure to the structure. The contractor shall demonstrate by test that his proposed method results in a direct current impedance of less than 2.5 mΩ from enclosure to structure. The bond from the equipment enclosure to the mounting plate furnished with the equipment shall comply also with these requirements, except that suitable jumpers may be used across any necessary vibration isolators.

b. *Nearby conductors.* All conducing items having any linear dimension of 12 in. or more installed within 1 ft of unshielded transmitting antenna lead-ins shall have a bond to structure. Direct metal-to-metal contact is preferred. If a jumper is used, the jumper shall be as short as possible.

c. *Vehicle skin.* Vehicle skin shall be so designed that a uniform low-impedance skin is produced through inherent RF bonding during construction. RF bonding must be accomplished between all structural components comprising the vehicle; i.e., wings, fuselage, etc. Hatches, access doors, etc., not in the proximity of interference sources or wiring shall be either bonded to or permanently insulated from vehicle skin, except for the protective static bond. Consideration shall be given to the design to operational vibration and resultant breakdown of insulating finished or intermittent electrical contact.

6-4.1.2.6 Class S Bonding (Static Charge)

All isolated conducting items (except antennas) having any linear dimension greater than 3 in.–which are external to the vehicle, carry fluids in motion, or otherwise are subject to frictional charging–shall have a mechanically secure connection to the vehicle structure. The resistance of the connection shall be less than 1 Ω when dry.

6-4.2 MIL-1-6181D

6-4.2.1 Susceptiblity

The equipment shall be designed to minimize susceptibility to interference from other sources. The enclosing case construction shall be designed not only to minimize interference propagation, but also to minimize interference pickup from external sources. Where conducted energy on the power leads or any external leads might cause interference, the leads shall be isolated from other leads to avoid coupling and, where necessary, shall have line filters at their entry into the enclosing case. Receiving antenna imputs, or any other low-level signal circuits shall be low impedance, or of balanced design, so that coaxial or other shielded transmission lines can be used to insure an interference-free installation. Routing of receiving antenna input or any low-level signal circuit within the equipment shall be so designed and installed that interference is not picked up from power or control leads owing to common conductive paths with other circuits, or with enclosing case grounding path.

6-4.2.2 Case Shielding

The number of mechanical discontinuities in the case (such as covers, inspection plates, and joints) shall be kept to a minimum. All necessary mechanical discontinuities in the case shall be electrically continuous across the interface of the discontinuity so as to provide a low impedance current path. Multiple-point spring-located contacts are suggested as a desirable method of obtaining low impedance continuity. Ventilation openings shall be designed to permit conformance to the radiated interference limits. Electrical bonding shall be provided where access doors or cover plates form a part of the shielding. Hinges, in themselves, are not considered satisfactory conductive paths.

6-4.2.3 Chassis, Case, and Mounting Continuity

The mating surface of the chassis, case, and mounting shall be free of all insulating finishes in order to provide a continuous electrical bond between these items and to enable the installing activity to accomplish bonding contact to the basic structure. Such surfaces shall be covered with removable protective coating to prevent corrosion prior to assembly. This requirement shall take precedence over any conflicting requirements in specifications on finishes.

6-4.2.4 Component Placement

Components shall be placed and circuitry arranged to obtain minimum undesired coupling and to require a minimum number of filter components.

6-4.2.5 Line Shielding

It is preferred that interference reduction be accomplished inside the equipment when such means give results equal to or better than the use of a shielded line. Any line shielding used shall be approved by the procuring activity and shall be prescribed as an installation requirement.

Under no condition shall line shielding be used for primary power leads to equipment.

Equipment requiring antennas, but not employing waveguides, shall be designed to utilize shielded coaxial cable as lead-in. When it has been determined that a single braid shield is not adequate, a double or triple braid or a solid shield shall be used as required.

6-4.3 MIL-P-24014

6-4.3.1 Firing Circuits

Firing circuits to EED's shall be electrically balanced to and isolated from the EED case and other conducting parts of the weapon. If some part of a firing circuit must be grounded or connected to a common power supply, there shall be only one such grounding point or interconnection with other electrical circuits. However, static-discharge resistors of not less than 100 kΩ may be connected to firing circuit conductors at any point where the application requires.

The conductors of the firing circuit shall be twisted to maintain electrical balance.

6-4.3.2 Attenuation

Equipment, weapon, or system enclosures shall attenuate RF energy by at least 60 dB from 1 MHz to 20 GHz. From 1 MHz the attenuation requirement may be diminished linearly to 40 dB at 100 kHz. The enclosure shall be constructed of material which provides good electromagnetic shielding. Environmental levels of field strengths and power densities are given in Table 6-7. When necessary to provide the required attenuation, each conductor which penetrates the enclosure shall be provided at its point of entry with a feed-through low-pass filter which meets the requirements of MIL-F-15733 appropriate to the specific application. Insertion loss of the filter shall at least equal the insertion loss characteristic K of MIL-F-15733. To assist in obtaining the required degree of shielding, the following features are required:

a. Each mechanical discontinuity in any shield shall be electrically continuous across the interface so as to provide low-impedance current paths. Multiple-point, spring-loaded contacts, or knitted-wire gaskets are recommended. Hinges and bonding wires are not considered satisfactory conductive paths.

b. There should be no holes or gaps in the shields exceeding 1/4 in. in greatest diameter. The number of holes with diameters less than **1/4** in. shall be held to a minimum. No unshielded conductor shall be located within one inch of any hole having a depth of less than 1 in.

c. EED firing circuits shall be isolated from each other and from other circuits by means of individual shields. Shielded EED firing circuits may be routed together in a common shield.

d. Metallic shields for firing circuit leads and other conductors shall be connected to the EED shield throughout its entire periphery to form a continuous shield without electrical discontinuities or gaps.

e. Mating connectors shall provide a shield which is electrically continuous through the connector and completely surrounds the conductor pins without any gaps. This shield shall not be used as a return circuit.

6-4.3.3 System Design

The following features are required for system shielding:

a. All sections of an assembled weapon and their skins shall be in good electrical contact with each other. Mating surfaces shall be free of insulating coatings or film. Such surfaces shall be of corrosive resistant materials or shall be covered with strippable protective coating to prevent corrosion prior to assembly.

TABLE 6-7

ENVIRONMENTAL LEVELS

Frequency, MHz	Electric Field, V/m	Average Power Density, W/m^2
Communications Equipment (continuous wave, unmoldulated carrier values)		
0.25 - 0.535	300	239
2 - 32	100	26
100 - 156	239	1
225 -400	26.5	1
Radar Equipment		
200 - 225	194	100
400 - 450	61	10
1000 - 1300	61	10
2700 - 3600	194	100
5400 - 5900	614	1000
8500 -10300	614	1000

b. EED systems, including firing circuits, shall be mechanically isolated as much as possible from other electrical devices and circuits and in no event shall the firing circuits be cabled with other circuits, except as may be necessary at a weapon/aircraft system interface.

c. Access doors which penetrate the weapon shield shall be held at a minimum. Such doors, when closed, shall provide reliable continuity of the shield for the EED's. The system design should not require such doors to be opened while the system is located in electromagnetic fields of the magnitude indicated in Table 6-6 unless, when so doing, the system will continue to not be adversely affected by opening such doors.

d. There shall be no more than one cable connecting weapons to other structures. This cable shall be shielded and as short as practicable with the shield connected to the external surface of the weapon or equipment case or frame. Shield connections shall completely surround the cable, without gaps. The cable shall be provided with connectors designed to completely mate with the outer shell (shield) surface before any of the inner conductors make contact; and when being unmated, shall completely open circuit all conductor pins before the shell (shield) contact surface has broken contact. The pins on the inner conductors of the portion of the connector toward the EED shall be female and recessed into the insulator to prevent unintentional contact by fingers or tools. In addition, the tips of the female pins shall be recessed well below the lip of the surrounding shield to provide additional shielding. A metal cap shall be provided for the connector on the EED side for installation when the weapon is not in use.

e. Grounding of the weapon shall be in accordance with **MIL-B-5087,** Class R bonding. Provisions shall be made to electrically bond the weapon case directly to its launcher or other component.

f. Weapon-launcher system design shall provide convenient and easy connection of the cable between weapon and launcher after the weapon case has made good electrical contact with the launcher. Protective coatings applied to the launcher or weapon shall not prevent good electrical continuity at contacting surfaces.

6-4.4 MIL-STD-833

a. EED firing circuits will be isolated from other circuits and each other by means of individual shields.

Shielded EED circuits may be routed together in a common secondary shield.

b. Circuits to EED's will be balanced to and isolated from the EED case and other conducting parts of the weapon. If a circuit must be grounded, there will be only one interconnection with other circuits. Static discharge resistors of 100,000 Ω or more may be connected to firing circuits.

c. Firing circuit conductors will be twisted to maintain electrical balance and reduce induction.

d. Firing circuit wiring will be kept to a minimum.

e. All conductors that connect the EED with other weapon components will be provided with metallic shields to provide an integral shield without electrical discontinuities or gaps.

f. Connectors will be kept to a minimum. Connector construction will be such that, when being mated, the shield contacting surfaces will mate before any of the inner conductors and will not break contact until after all inner conductors have broken contact. Also, the inner conductors of the connector on the EED side will be recessed in the shield opening.

g. Wiring within an EED will be isolated from any metallic case or enclosure. The impedance to case from each conductor will be equal and high as practicable.

APPENDIX A

DERIVATION OF THE GENERAL SHIELDING EFFECTIVENESS FORMULA

A relatively easy solution to a shielding problem is available if both the shield and the incident field exhibit rectangular, cylindrical, or spherical symmetery. Fig. A-1 illustrates the simplest of these configurations in section. Here the incident wave impinges normally on the solid metal shield of thickness t. The shield is assumed to extend to infinity and thereby divides space into two separate volumes. It should be noted that all solid shields divide space into two volumes; one containing the electromagnetic source (or assumed incident field), and a second the point at which the field reduction due to the insertion of the shield is to be calculated. Shielding that has large holes or otherwise fails to completely separate the incident field from the field calculation point usually presents more difficulty.

The field incident on the shield is assumed to be a function of the z coordinate only, and the individual electric and magnetic field components are assumed to be perpendicular to each other in the xy-plane. A wave of this type is termed a plane wave. Plane waves are the easiest dynamic solution to Maxwell's equations and will be the main concern in shielding problems. In free space, the electromagnetic field will propagate in every direction away from the source; thus, in any limited portion of space the fields show a spherical shape. At large distances from the source, a finite portion of the surface of this sphere is a plane, and the fields are plane waves. Strictly speaking, no perfectly plane wave can be produced in practice due to the effects of other bodies in space, but many actual fields approximate plane waves so well that present measurement techniques show no difference.

The solution of Maxwell's equations for the geometry of Fig. A-1 consists of a pair of electromagnetic fields, traveling in the $+z$ and $-z$ directions, in each of the volumes A, B and C. For this particular problem the wave traveling in the $-z$ direction in volume C has zero magnitude and can be ignored; this results from assuming that volume C extends infinitely in the $+z$ direction. The electromagnetic field traveling in the $+z$ direction in volume ***A*** will be called the incident field and is the field that would exist at point P (a measurement point in volume C) if the shield were absent.

The magnitude and phase of the remaining fields are determined, in terms of the incident field, by the electromagnetic properties of the materials filling volumes A, B, and C and the thickness of B. The mathematical procedure for determining the remaining fields involves matching the fields at the volume interfaces so that the electromagnetic boundary conditions implicit in Maxwell's equations are satisfied. For the geometry of Fig. A-1 there is an exact analog of the electromagnetic field equations in the more familiar transmission line equations. Use of the transmission line equations will help to systematize the matching of the various electromagnetic fields at the interfaces. If we adapt the transmission line variables to this problem, the total reduction of the electric or magnetic field strength at point P, due to the insertion of the shield (volume B in Fig. A-1), can be calculated from

$$\left|\frac{\text{Field (Shield Present)}}{\text{Field (Shield Absent)}}\right| = \left|\tau_{in} \exp\left[-\gamma_s t\right] \tau_{out}\right| \qquad \text{(A - 1)}$$

where t is the thickness of the shield, γ_s is a function of the shield's electrical parameters, and the τ's, or transmission coefficients, are defined at each interface in the problem. The vertical lines denote the magnitude of the probably complex enclosed quantity.

The electrical parameters of the shielding medium that are needed for a numerical solution in terms of the transmission line variable formulation are:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}\text{, meters, the propagation constant of the medium}$$

$$Z = R + jX = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}\text{ ohms, the intrinsic impedance of the medium} \qquad \text{(A-2)}$$

where

ω = angular source frequency ($2\pi f$)
μ = permeability of medium
σ = conductivity of medium

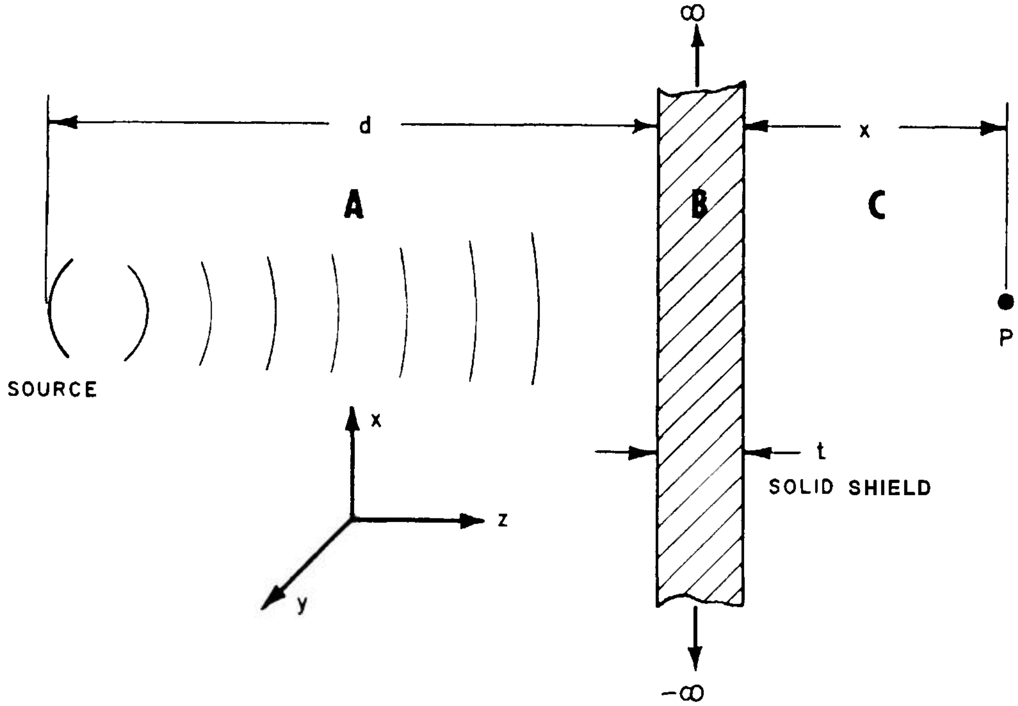


Fig. A-1. Geometric Representation of a Practical Shielding Problem

ϵ = permittivity of medium
f = frequency in hertz

It must be remembered that the electromagnetic properties–μ, σ, ϵ–are functions of the frequency f. These parameters, as indicated above, are generally complex quantities. α, the real part of the propagation constant γ, is the attenuation constant; β, the imaginary part of γ, is the phase constant. The square roots in **Eq. A-2** are chosen such that they result in a positive real part, thus making the results consistent with the usual, though arbitrary, interpretation.

For free space–and as an excellent approximation for air–$\sigma = 0$, $\mu = 4\pi \times 10^{-7}$ H/m, and $\epsilon = 8.85 \times 10^{-12}$ F/m. After making these substitutions the following values are obtained:

$$\gamma_A = j\left(\frac{2\pi f_{MHz}}{300}\right), \text{ m}^{-1} \qquad \text{(A-3)}$$

$$Z_A = 377, \ \Omega$$

where f_{MHz} is frequency in megahertz.

For metals, and hence for the shield, the conductivity σ is much larger than the $\omega\epsilon$ product for all frequencies likely to be encountered. For example, a metal that is 100 times less conductive than copper (whose ϵ is equal to that of free space) will still have a conductivity at least one hundred times the $\sigma\epsilon$ product for all frequencies up to approximately 100 MHz. In consequence, values for the shield are:

$$Z_s = R_s + jX_s = (1+j)\sqrt{\frac{\omega\mu_s}{2\sigma_s}}$$

$$= (1+j)2.61\times10^{-4}\sqrt{\frac{\mu_r f_{MHz}}{G_R}}, \ \Omega$$

and
$$\gamma_s = \alpha_s + j\beta_s = (1+j)\sqrt{\frac{\omega\mu_s\sigma_s}{2}} \qquad \text{(A-4)}$$

$$= (1+j)0.384\sqrt{\mu_r f_{MHz} G_R}, \text{ mils}^{-1}$$

where μ_r is the permeability of the shield in relation to free space and G_R is the conductivity of the shield in relation to annealed copper.

The transmission coefficient (dimensionless) at any interface is given by

$$\tau = \frac{2Z_t}{Z_I + Z_t} \qquad \text{(A-5)}$$

where Z_I is the intrinsic impedance of the medium on the source side of the interface and Z is the impedance seen looking into the medium on the side away from the source. The impedance looking into a medium is given by

$$Z_{in} = Z_o \left(\frac{Z_L + Z_o \tanh \gamma_o t}{Z_o + Z_L \tanh \gamma_o t} \right) \text{ ohms} \qquad \text{(A-6)}$$

where Z_{in} is the "input" impedance of a medium with intrinsic impedance Z_o, propagation constant γ_o, and thickness t. This medium in turn is terminated with another medium which has an "input" impedance Z_L.

Note that Eq. **A-6** will equal Z_o if the real part of $\gamma_o t$ is large because this forces $\tanh \gamma_o t$ to approach a limit of 1.

For the problem specified in Fig. **A-1**, the transmission coefficient at the shield interface away from the source field is

$$\tau_{out} = \frac{2Z_A}{Z_s + Z_A} \qquad \text{(A-7)}$$

where Z_s is the intrinsic impedance of the shield and Z_A is the intrinsic impedance of air. The transmission coefficient at the source side of the shield is

$$\tau_{in} = \frac{2Z_{in}}{Z_A + Z_{in}} \qquad \text{(A-8)}$$

$$= \frac{2Z_s (Z_a + Z_s \tanh \gamma_s t)}{Z_A (Z_s + Z_A \tanh \gamma_s t) + Z_s (Z_A + Z_s \tanh \gamma_s t)}$$

where Z_{in} is computed from Eq. **A-6** using $Z_o = Z_s$, $Z_L = Z_A$ and $\gamma_o = \gamma_s$.

The total field reduction expressed in dB is given by 20 log of Eq. **A-1**, using the above expressions for transmission coefficients. Inverting the expression to obtain a positive value for dB,

$$dB_{loss} = 20 \log \left| e^{\gamma_s t} \frac{(Z_s + Z_a)}{4Z_s Z_A} \left[\frac{Z_A (Z_s + Z_A \tanh \gamma_s t) + Z_s (Z_A + Z_s \tanh \gamma_s t)}{Z_A + Z_s \tanh \gamma_s t} \right] \right| \qquad \text{(A-9)}$$

This formula is the basis for most far-field shielding effectiveness calculations. If the real part of $\gamma_s t$ is sufficiently large, tanh ? approaches 1 and the equation reduces to

$$dB_{loss} = 20 \log \left| e^{\alpha_s t} \frac{(Z_A + Z_s)^2}{4 Z_A Z_s} \right| \qquad \text{(A-10)}$$

Fig. **A-2** plots the magnitude and phase of $\tanh \gamma_s t$ for selected values of a, t, and indicates that Eq. **A-10** should be accurate to a few percent if $\alpha_s t$ is larger than 2.

Fig. **A-3** plots, as a function of frequency, the shield thickness required, for nonmagnetic metals of various conductivities, to have $\alpha_s t$ equal to 2. The relative permeabilities (at 150 kHz) of various metals are given in Table **4-3.**

In general most common metals that are used for shielding (copper, aluminum, etc.) have an a, t product which is greater than 2 at frequencies above 1 MHz, provided the shield is thicker than 20 or 30 mils. This is convenient since it is usually necessary to make a shield at least this thick in order to make it self-supporting.

If the magnitudes of the intrinsic impedances of air and typical metal shields are compared (Eqs. **A-3** and **A-4**), it becomes evident that the magnitude of the shield's intrinsic impedance will be very much smaller than that for air at all frequencies below 10^5 MHz. Incorporating $Z_s << Z_A$ in Eq. **A-10**, total loss will be, to a very good approximation,

$$dB_{loss} = 20 \log \left| e^{\alpha_s t} \frac{Z_A}{4Z_s} \right| = 3.34 \left(\sqrt{f_{MHz} \mu_r \sigma_r} \right) t - 10 \log \left(\frac{f_{MHz} \mu_r}{\sigma_r} \right) = 108.2 \qquad \text{(A-11)}$$

where the thickness of the shield t is in mils.

A more practical shielding example for the same geometry is shown in Fig. **A-4.** Consider an impinging field that, although it is propagating through air, has a general wave impedance of Z_w. Incident fields of impedance different than Z_A are found close to sources and may also be created by reflection from objects near the shield even if the shield is far from the source. In Fig. **A-4** an impedance is also associated with the measurement point. This impedance &must be considered as different from Z_A since we are now considering an object inserted into the protected volume that we previously considered as extending indefinitely, This problem can be treated by the same transmission line techniques that we used earlier. The general result is (Ref. **1**):

$$\frac{\text{Field}_p \text{ [Shield Present]}}{\text{Field}_p \text{ [Shield Absent]}} = \frac{2Z_s (Z_w + Z_\ell) e^{-\gamma_s t}}{(Z_w + Z_s)(Z_s + Z_\ell)} \left[1 - \frac{(Z_w - Z_s)(Z_\ell - Z_s)}{(Z_w + Z_s)(Z_s + Z_\ell)} e^{-2\gamma_s t} \right]^{-1} \qquad \text{(A-12)}$$

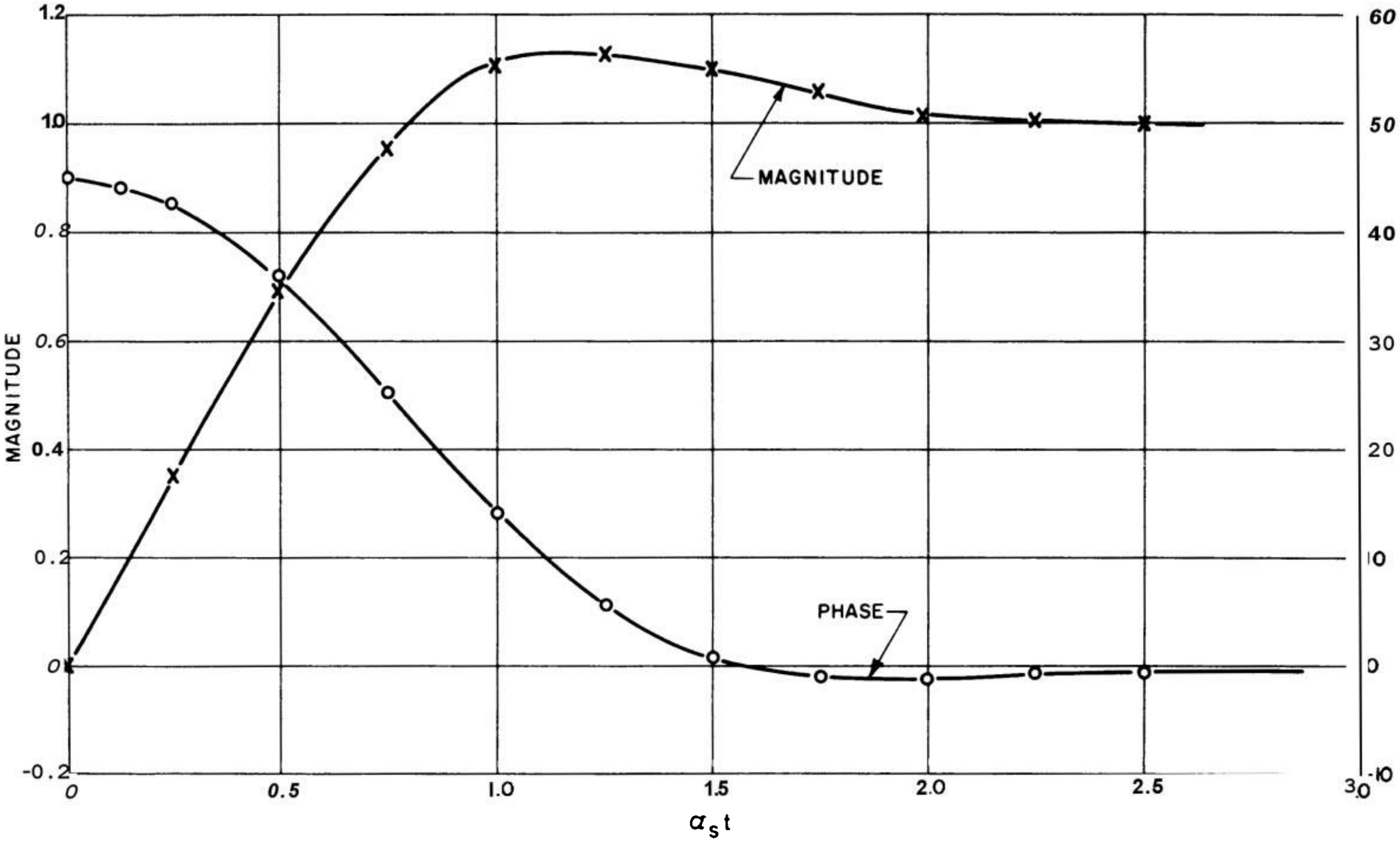


Fig. A-2. Magnitude and Phase Angle of tanh $(\gamma_s t)$ for Various Values of $\gamma_s t$ When $\gamma_s t = \alpha_s t(1 + j)$

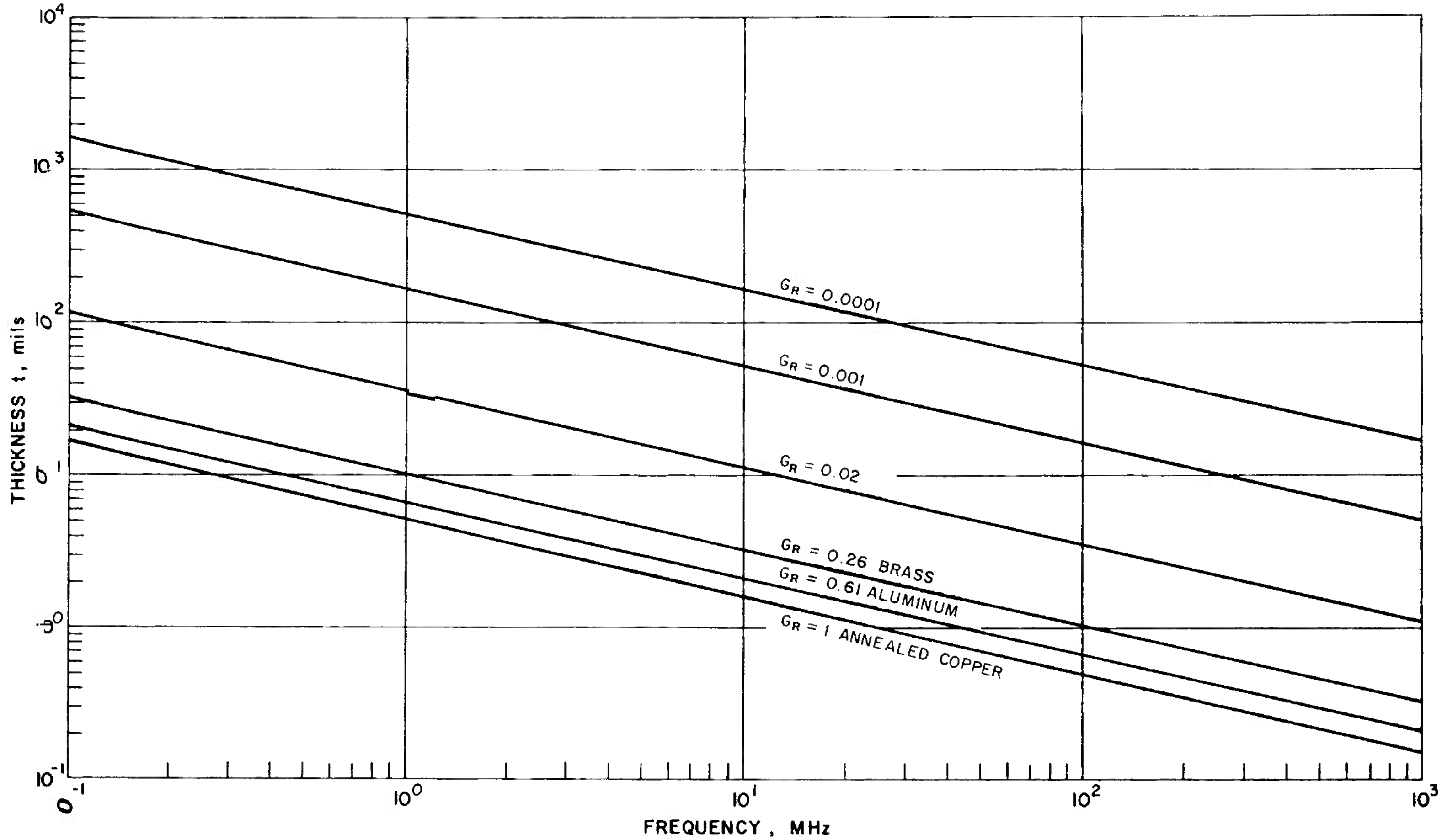


Fig. A-3. Thickness Required for $\alpha_s t = 2$

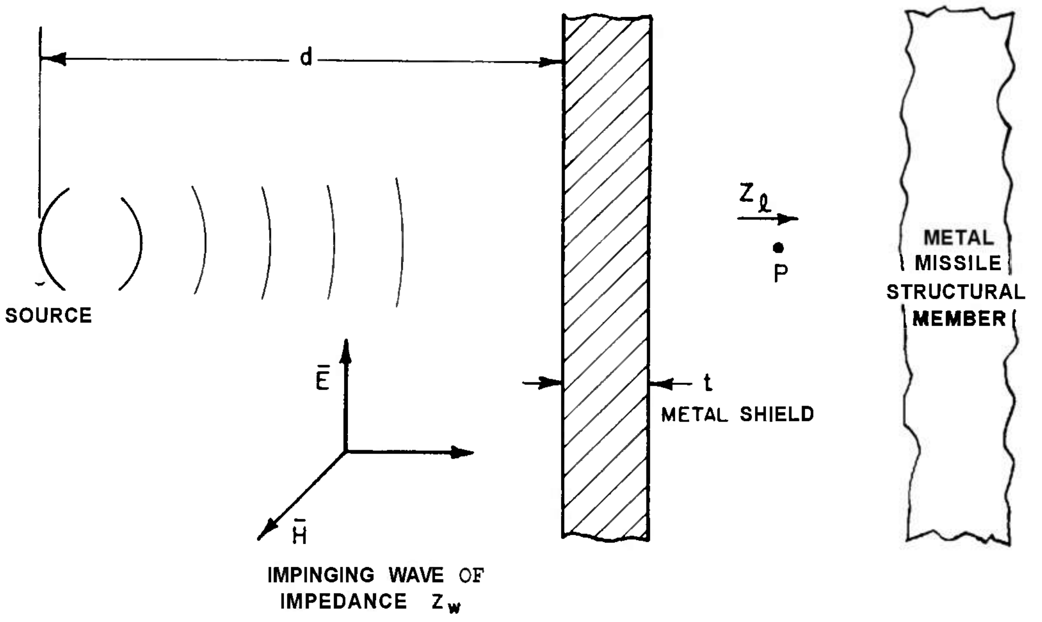
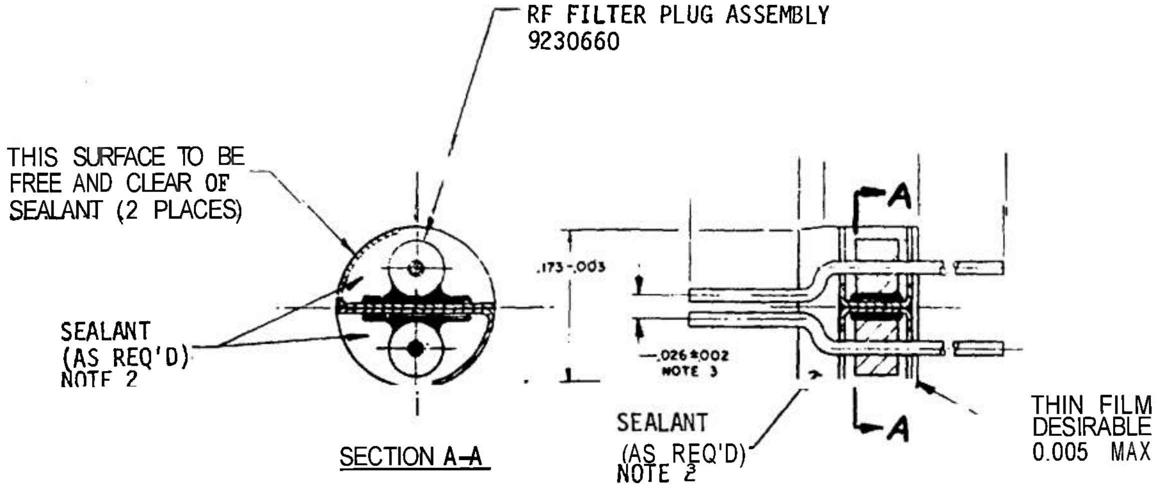


Fig. A-4. A Practical Shielding Problem

REFERENCE

1. D. S. Bunk and T. J. Donovan, "Electromagnetic Shielding", *Machine Design,* Supplement 16-C, July 6, 1967.

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL
-	EOPA50764-1/2-13-68(REV)	2-13-68	



NOTES:

1. MIL-A-2550 and PA-PD-2916 apply.
2. Material: Adhesive Sealant, Silicone, RTV per MIL-A-46106.
3. Dimension applies at face of plug.
4. The resistance between lead wires shall be 50 megohms min as determined by a megohmmeter; the time of electrification shall be 60±1 sec; and the applied voltage shall be 500 V dc. Readings shall be taken at the termination of the 60-sec period.
5. Lead to lead dielectric system (voltage breakdown) shall be a min of 500 V(60 cycles); the rate of voltage application shall be 100 V/sec.
6. Insertion loss shall be measured in accordance with MIL-STD-220. Preproduction approval must be obtained from Picatinny Arsenal. This approval will be based on worst case attenuation measurements performed by Picatinny Arsenal. See Table for acceptable values; see also Note 10.
7. Lead wire shall withstand an axial pull of 7-1/2 lb min without showing signs of slippage in the plug.
8. Delay: Any dc pulse time of filter must not exceed 50 nanosec max.
9. For advisory process see Drawing A9230667.
10. Picatinny Arsenal Standard Test Fixture as specified in EL9230659 will be used to measure attenuation or insertion loss.

TABLE (Notes 6 and 10)

Frequency, MHz	Attenuation, dB	Insertion Loss dB
10 - 50	15 min	20 min
51 - 10,000	25 min	30 min

Suggested test points in ranges shown above.

For associated lists see 9230659.

9217666	XM81		
9223104	10021		
NEXT ASSY	USED ON		
APPLICATION			
DO NOT	APPLY PART NO.		

MECHANICAL PROPERTIES: YP, TS, EL2, RA, BH, RH

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON DECIMALS ±
FRACTIONS ± ANGLES ±
MATERIAL
HEAT TREATMENT
FINAL PROTECTIVE FINISH

ORIGINAL DATE OF DRAWING 13 FEB 1968
DRAFTSMAN MCS CHECKER
ENGR ENGR
ENGR ENGR

PICATINNY ARSENAL DOVER, NEW JERSEY

SIZE C | CODE IDENT NO. 19203 | 9230659

Fig. 4-73. RF Filter and Plug Assembly, M78E1

GLOSSARY

A

absorption. Transfer of electromagnetic wave energy to a substance being traversed by the wave.

antenna array. A system of antenna elements arranged to obtain the desired directional radiation pattern.

antenna field. *See:* **antenna pattern.**

antenna pattern. A diagrammatic representation of the radiation field from an antenna, usually in terms of loci representing equal power levels.

arming. 1. The technique of completing the firing signal transfer path through the safing and arming device. 2. The changing from a safe condition to a state of readiness for functioning.

arming device. Device for arming of a fuze under controlled conditions.

arming system. *See:* **safing and arming mechanism or device.**

B

balanced circuit. A circuit having its two sides electrically alike and symmetrical with respect to a common reference point, usually ground.

bond. An electrical connection between metal parts of a structure.

bonding. A system of connections between metal parts of a system forming a continuous electrical unit.

braided shield. The woven multi-strand electrically conductive shield enclosing a cable of insulated wires.

breakdown. Disruptive electric discharge through insulation on wires, insulators, or other materials separating circuits.

breakdown voltage. The voltage at which an insulating material ceases to insulate and becomes electrically conductive.

C

chassis. The metallic base on which the parts of electronic circuits are mounted.

circuit component. One of the simple parts of the whole complex circuit.

circuit element. *See:* **element.**

compatibility. A characteristic ascribed to the overall system with reference to how well its various subsystems work together.

conductor. A wire, cable, or other material which will freely permit the passage of an electric current, when a difference of potential is applied.

corona discharge. A luminous, electrical discharge caused by ionization of air surrounding a high voltage conductor.

D

dart leader. A charge column extending from earth to cloud that precedes all strokes other than the first.

decibel (dB). A dimensionless measure of the ratio of two powers, equal to ten times the logarithm to the base ten of the ratio of the two powers.

detector. A device to sense presence or change in some environmental condition.

detonator. An explosive device initiated by electrical or mechanical means.

diathermy. The therapeutic heating of tissues beneath the skin by means of high-frequency electrical oscillation; also, the apparatus used.

dipole. A combination of the two electrically or magnetically charged particles of opposite sign which are separated by a very small distance.

dipole antenna. A straight radiator, usually fed in the center, and producing a maximum of radiation in the plane normal to its axis. The length specified is the overall length.

displacement current. The current which is proportional to the time rate of change of electric displacement flux through any surface in an isotropic dielectric.

dissipation. The loss of energy through resistive forces, which ultimately appear as heat loss.

duty. A requirement of electric power supply service which defines the degree of regularity of the load.

duty cycle. The ratio of the on time interval to the total time of one operating cycle.

E

electroexplosive device (EED). An explosive device that is initiated by an electric stimulus. See Table **4-1** for the specific types of **EED's.**

electromagnetic compatibility (EMC). The ability of a system of electrical components to operate properly and without degredation despite the coupling of spurious electrical stimuli between them.

electromagnetic environment. The RF field or fields existing at a specific place.

electromagnetic interference (EMI). The designation for all unwanted voltages or currents resulting from unwanted electromagnetic fields that tend to impair equipment performance.

electromagnetic pulse (EMP). The electric and magnetic fields (energy) propagating from a nuclear explosion.

electromagnetic spectrum. The ordered array of known electromagnetic radiations, extending from the shortest cosmic rays through gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, and including microwave and all other wavelengths of radio energy.

electrostatic. Relating to, possessing, or employing electric charges and their characteristics.

electrostatic induction. The mechanism by which a body becomes charged when it approaches a charged body, and before physical contact is established between them.

element. Any electrical device (such as inductor, resistor, capacitor, line) with terminals at which it may be directly connected to other electrical devices.

environment. An external condition in which a piece of equipment or system operates.

F

field intensity. *See:* **field strength.**

field strength. For any physical field, the flux density, intensity or gradient of the field at the point in question (magnitude of the field vector).

filter. A term widely applied to many kinds of devices that permit selectively the passage of only certain frequencies.

flux. The rate of transferring energy across a given surface.

fuse. A protective device, used in an electric circuit, containing a wire, bar, or strip of fusible metal. When the current increases beyond the rated strength of the fuse, the metal melts and thus the circuit is broken.

fuze. A device designed to initiate a detonation under desired conditions.

G

gain. A general term to denote an increase in signal power in transmission from one point to another.

grid. Pertaining to or measured from a reference line.

ground. A conducting connection between an electric circuit or equipment and earth, or to some conducting body which serves in place of the earth.

ground loop. An undesired mutual coupling between circuits caused by equipment grounding methods.

guard ring. An auxiliary electrode used to control potential gradients, reduce insulator leakage, and to define the sensitive volume.

H

hardening. Protection against or decoupling from an external environment.

I

igniter. *See:* **electroexplosive device.**

incident. Falling or striking on a surface.

incident wave. A wave traveling through a medium which impinges on a discontinuity or a medium of different propagation characteristics.

induction. The act or process by which an object is electrified, magnetized, or given an induced voltage by exposure to a field.

initiation. The application of a fuze signal to the first elements of an explosive train.

initiator. See: **electroexplosive device.**

insertion loss. The ratio of received power before and after the insertion of shielding between a source and a receiver of electromagnetic energy.

insertion loss, transducer. The loss resulting from the insertion of a transducer in a transmission system, which is the ratio of the power delivered to that part of the system which will follow the transducer, before insertion of the transducer, to the power delivered to that same part of the system after insertion of the transducer.

interference. An extraneous signal which tends to disturb the reception of the desired signal, or the disturbance of signals which results.

ionization. The process by which neutral atoms become electrically charged, either positively or negatively, by the loss or gain of electrons.

irradiation. The exposure of material to radiation.

isotropic. In general, pertaining to a state in which a quantity or spatial derivatives thereof are independent of direction.

J

jumper. A short length of conductor used to complete an electrical circuit, usually temporary between terminals, or to bypass an existing circuit.

L

leader. A primary or terminal shoot of a lightning stroke.

load. The device which receives signal power from a source.

M

matching. The connecting of two circuits in such a way that the correct impedance exists in each circuit for maximum transfer of energy.

matching impedance. The technique of minimizing the standing-wave ratio when two devices having unlike impedances are coupled. This process maximizes power flow between the two devices.

mobile stations. A missile launch complex designed for mobile use in forward combat areas.

mode. A functioning position or arrangement that allows for the performance of a given task.

N

noise. That portion of the unwanted signal which is statistically random.

nuclear radiation. A pulse of neutrons and photons (X-ray and gamma ray energy band) radiating from a detonating nuclear weapon.

P

pigtail. A flexible metallic conductor, frequently stranded, attached to a terminal of a circuit component, and used for connection into the circuit.

pilot streamer. The initial cloud to ground discharge in a lightning stroke.

potential gradient. In general, the local space rate of change of any potential.

power density. The real part of the Poynting Vector at a point in space.

power rating. The power transfer or power dissipation capabilities.

propagation. The travel of waves through or along a medium.

pulse. A single disturbance of definite amplitude and time length, propagated as a wave of electric current.

R

radiation pattern. A graphical representation of the radiation of an antenna as a function of direction.

radiator. Any source of radiant energy, especially electromagnetic radiation.

radio energy. Electromagnetic radiation of wavelength greater than 0.01 centimeter.

radio frequency interference (RFI). Any interfering signal capable of being detected on a receiver tuned to a radio frequency.

radio interference. Any electrical noise which interferes with the reception of a desired signal.

rating. A designated limit of operating characteristics based on definite conditions.

reflection. The process whereby a surface of discontinuity turns back a portion of the incident radiation into the medium through which the radiation approached.

reflection loss. The part of the transmission loss due to the reflection of power at a discontinuity.

reflective attenuation. The loss of part of the power available to a matched load because of mismatch at the input and output terminals of an attenuator inserted between generator and load.

S

safing and arming mechanism or device (S&A). A switching device to mechanically interrupt the functional path between fuze and warhead until after proper launching has taken place; arming consists of completing the functional path at the proper time.

saturation. The state of being satisfied. Magnetic saturation is the maximum magnetization of which a body or substance is capable.

sensitivity. In general, the degree of response to external action.

shield. A bond of material used to prevent or reduce the passage of radiation or particles.

shorting cap. A device to provide a short circuit across an EED during storage, shipment, and handling.

signal. A visual, audible, or other indication used to convey information.

spectrum. Short for electromagnetic spectrum.

spectrum. A continuous wide range of frequencies within which waves have some specified common characteristic, e.g., **RF** spectrum.

squib. *See:* **electroexplosive device.**

static electricity. A charge of electricity accumulated by an object, which charge creates a spark when the object comes near another object to which it may transmit its charge, or from which it may receive a charge.

subsystem. A major functional assembly within a system.

surge. A voltage or current of large magnitude and short duration (a transient rise) caused by an abrupt discontinuity in a circuit or system.

survivability. The ability of a device or system to perform its proper function during or following an adverse environment.

susceptibility. The lack of ability to resist external stimuli. The response (transfer function) of the device or system as a function of the interference level.

system. A major devision of a given network that performs one or more vital functions.

T

termination. A synonym for load.

thermal radiation. The electromagnetic radiation emitted by any substance as the result of the thermal excitation of its molecules.

thermal stacking. The increase in temperature of a device resulting from the application of repetitive pulses at a rate and magnitude exceeding its capabilities to dissipate the heat.

time constant. Generally, the time required for an instrument to indicate a given percentage of the final reading resulting from an input signal.

transient. That part of the forced oscillation of a linear system which decays more or less rapidly after the imposition of the force. The nonpermanent terms in the response of an electric network to a stimulus.

twisted pair. A cable composed of two insulated conductors twisted together either with or without a common covering.

U

unidirectional. Having only a single well-defined direction.

V

vulnerability. The openness of a target to a damage agent. The threshold level above which the interference causes the device or system to malfunction during or following an adverse environment.

W

waveform. The graphical representation of a wave, showing variation of amplitude with time.

waveguide. A system of boundaries capable of guiding waves.

weapon system. A group of tactical devices which together perform a mission.

worst case attenuation. The minimum attenuation that a system can exhibit regardless of the system's impedance.

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