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ON
COMPUTATION OF RF HAZARDS

by

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ABSTRACT

This monograph presents a method for analyzing the potential RF susceptibility to the electrical components and systems used in typical space vehciles. It presents the philosophy, applicability and limitations of this approach. While not exhaustive, enough mathematics is presented to permit analysis of a very large percentage of the types of problems which normally occur. Where the actual development of equations is not given in detail, suitable references are provided. Familiarization with the test and the cited references should provide the reader with the necessary information to analyze most systems and the general procedures to handle those situations which are beyond the scope of this monograph.

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a = Radius of Connector Shell Opening - Meters
A = Area - Square Meters
A_c = Circular Aperture - Square Meters
A_e = Effective Aperture - Square Meters
A_{ec} = Effective Composite Aperture - Square Meters
A_{em} = Maximum Effective Aperture - Square Meters
A_{em_q} = Maximum Effective Aperture of qth gap - Square Meters
A_m = Area of mth loop - Square Meters
b = Length of Lead Wire or Largest Length of Opening in Shield Braid - Meters
$\bar{B}$ = Magnetic Flux Density -Webers per Square Meter (Vector Notation)
c = Velocity of Light, 3×10^8 Meters per Second
d = Lead Wire Spacing or Pin Spacing - Meters
dB = Decibels
D = Directivity of Antenna
$\bar{E}$ = Electric Field Intensity - Volts per Meter (Vector Notation)
$|\bar{E}|$ = Magnitude of Electric Field Intensity - Volts per Meter
$|E_{r_1}|^2$ = Square of Magnitude of Electric Field Intensity at radius r_1
EED = Electroexplosive Device
f_{Hz} = Frequency - Hertz
f_{MHz} = Frequency - Megahertz
G = Gain of Antenna
$\bar{H}$ = Magnetic Field Intensity - Amperes per Meter (Vector Notation)
$|\bar{H}|$ = Magnitude of Magnetic Field Intensity - Amperes per Meter
I_o = Current on Antenna - Amperes
$Im\{Z_c\}$ = Imaginary Part of Surface Impedance - Ohms
K = $\frac{2\pi}{\lambda}$ - Meter^{-1}

LIST OF SYMBOLS (cont)

ℓ = Length - Meters

ℓ_D = Length of Dipole - Meters

max = Maximum

n = Total Number of Loops or Gaps

P = Poynting Vector

$\bar{P}$ = Power Density - Watts per Square Meter (Vector Notation)

$|\bar{P}|$ = Magnitude of Power Density - Watts per Square Meter

P_i = Incident TEM Field Power Density - Watts per Square Meter

P_o = Average Power Density at Inner Surface of Shield - Watts per Square Meter

P_T = Power Density at Outer Surface of Shield - Watts per Square Meter

Q = Ratio of Solid Area to Hole Area in the Shield

r = Radius of Poynting Vector - Meters

$\mathrm{Re}\{Z_c\}$ = Real Part of Surface Impedance - Ohms

RF = Radio Frequency

R_L = Loss Resistance of Antenna - Ohms

R_R = Radiation Resistance of Antenna - Ohms

R_T = Termination Resistance - Ohms

t = Thickness of Braid - Inches

TEM = Transverse Electromagnetic Wave

T_{wc} = Transmission Coefficient

U_m = Maximum Radiation Intensity - Watts per Square Radian

U_o = Average Radiation Intensity - Watts per Square Radian

V = Total Voltage Reduced in Antenna - Volts

W = Power Dissipated in Load - Watts

X_T = Termination Reactance - Ohms

X_R = Antenna Reactance - Ohms

Z_c = Surface Impedance - Ohms

Z_o = Impedance of Free Space, 377 Ohms

Z_{pc} = Pins-to-Case Impedance of EED - Ohms

LIST OF SYMBOLS (cont)

Z_{pct} = Pins-to-Case Firing Mode Impedance of EED (Z_{pc}) Transformed Along Connecting Lines - Ohms

Z_{pp} = Pin-to-Pin Impedance of EED - Ohms

Z_{ppt} = Pin-to-Pin Firing Mode Impedance of EED (Z_{pp}) Transformed Along Connecting Lines - Ohms

Z_{u_1} = Unknown Pin-to-Pin Impedance Looking Toward Arming Circuits - Ohms

z_{u_2} = Unknown Pins-to-Case Impedance Looking Toward Arming Circuits - Ohms

α = Attenuation - Nepers per Unit Length

β = $\frac{2\pi}{\lambda}$ - Meter^{-1}

$\frac{\partial \bar{B}}{\partial t}$ = Partial Derivative of $\bar{B}$ with Respect to Time

ε_o = Permittivity of Free Space, 8.85×10^{-12} Farad per Meter

μ_o = Permeability of Free Space, 12.5×10^{-7} Henry per Meter

θ, ϕ, ψ = Angles - Radians

ω = $2\pi f_{Hz}$

δ = Skin Depth - Inches

ρ = Reflection Coefficient

λ = Wave Length - Meters

λ_c = Cutoff Wavelength - Meters

1. INTRODUCTION

The determination of the potential radio frequency (RF) hazard to any system exposed to an incident RF field is a very complex problem. Consider, for example, a typical electroexplosive device (EED) and its associated firing circuit mounted in a missile. To begin with, the missile may be transported to the launch site with some or all of its circuits installed and could conceivably be exposed to a wide variety of RF signals along the way. At the launch site it may be necessary to install some of the EEDs or electronic components while in an RF environment. This would permit the possibility of the individual components being irradiated during handling and, subsequently, after installation in its circuit. In addition check out procedures often result in altering the circuits, connecting temporary new circuits to the potentially vulnerable component and such actions as the opening and closing of vents and ports in the missile skin. Furthermore, there would probably be constant movement of vehicles and personnel in the area and this movement would cause continual fluctuation in local RF field intensities. All of these factors would contribute to a constantly changing and very difficult to define set of conditions with respect to RF hazards. It should be noted that localized field intensity conditions can exceed the overall field intensity that would be determined by measuring the field produced at a given point by a radiating transmitter. Unless one can measure the field at the exact point of interest, under the actual conditions and with all equipment that will be in the area and without serious perturbation of the field by the measuring equipment one can be certain only of an approximation of the actual field conditions.

Even if one could accomplish a testing program which would cover all of the conditions, the inherent variation from missile to missile would introduce another large variable. Slight changes in the arrangement of the wiring or in the orientation of the missile with respect to the RF field might well produce large variations in the amount of RF energy delivered to the device under investigation, identical electrical impedance conditions cannot be maintained from missile to missile and on board transmitters may directly interact with the vulnerable circuits.

Of course, if the circuit designer were free to design his circuits with nothing else in mind but to make them insensitive to RF, the RF problem could be essentially eliminated. Complete continuous shielding of the entire systems would in general reduce RF levels at the components to safe values. However, this is often almost impossible, for in our modern complex electric circuits it is usually necessary to break branch circuits out of the shield, to terminate on circuit boards open to RF signals or to follow other procedures which compromise RF safety. In addition, other design groups may argue for and obtain different concepts for wiring to accomplish their ends, and in so doing may also seriously compromise the RF protection.

On the other hand it is often suggested that even with circuits poorly designed from the RF viewpoint, there have been relatively few accidents directly attributed to RF and therefore the problem must be negligible. This could be a very dangerous viewpoint. First of all, information on accidents of any nature is usually very poorly disseminated so that it is difficult to know what accidents have occurred and what situations surrounded such accidents. This is particularly true of accidents which do not result in severe injury to personnel or very large property damage. Second, the determination of the cause of an accident after it has happened is a very difficult business. This is particularly true when trying to evaluate the after-the-fact influence of anything as variable as the potential RF hazard. Furthermore if the investigators do not fully understand how RF energy can be transferred they will easily miss many possibilities. Third, at the present time most RF fields in proximity of vulnerable systems are of reasonably low intensity or are turned off during possibly critical periods. Every year, however, the RF environmental levels are increasing, and RF silence may not always be possible. Systems which are now marginal may eventually become quite vulnerable.

With all of these complicating and generally uncontrollable factors, how can one even evaluate the potential RF hazard to any critical system? Unfortunately, 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, the hazard can sometimes be evaluated in such a manner that it can be conclusively stated that no hazard exists if this should be the case.

Two methods are now in general use. Both of these require that the RF sensitivity of the device in question be known. There are laboratory techniques for determining this with reasonable precision; unfortunately, the RF sensitivity is of the device is not always so determined and this in general will negate the effectiveness of either method unless suitable precautions are taken.

The first method, stated briefly, is to directly radiate the system in question with a variety of high powered transmitters and to observe the RF levels that arrive at the device under test. The method is appealing, if expensive, since it is a direct approach which superficially appears to simulate the actual conditions that will occur. But, while such tests are much used, and have a definite place in the scheme of things, there are many pitfalls that generally make them unsatisfactory for a really valid hazard determination. The chief weaknesses of the method include inadequacy of present RF detectors, inability to determine field strengths accurately, the very large expense of suitably powerful transmitters, the risk of assuming that tests on one or two systems can be extended to all such systems and the lack of complete understanding by most field testers of the mechanisms of RF damage on the vulnerable devices.

To minimize the effect of these various problems, irradiation tests are often conducted with an arbitrary safety factor added to the acceptable RF pick up at the detector. Many times this factor is not large enough for all conditions. In addition it should be recognized that the only positive result of a field irradiation is to demonstrate that a hazard exists for certain frequencies, irradiation angles, polarizations and orientations of the irradiating antenna and the system being irradiated. 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. However, properly conducted, field tests can give considerable reassurance regarding RF safety.

The second method is the application of analytical techniques to the systems to determine the extent of RF hazard. This approach in its present form has two distinct advantages: first, 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; second, the actual analysis is reasonably inexpensive. The main expense comes from the fact that to perform the analysis properly the RF sensitivity of the device in question must be determined, but as was pointed out earlier, this should also be done in the case of the direct radiation method. The one exception to this 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 device is not a factor after installation in these circuits. The main objection to the analytic method in its present form is that it can put 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. In contrast to the irradiation method, it should be noted that the only positive result of the analytical approach is to show that a given system is safe. Specifically, the analysis can not show that a system is hazardous since the worst case assumptions implicit in the analysis can never be guaranteed to exist.

1.1 General Approach

The procedure for establishing the extent of the RF hazard to any system by means of the analytic method is as follows:

a. The RF sensitivity of the particular device or devices in each of the circuits in the 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 potential damage mode which exists.

b. Using circuit diagrams, wiring diagrams, observation of the actual systems, observations and discussions of the handling, installation and checkout procedures and discussions with the engineers directly concerned the details of the actual physical systems are established. These details include such things as length of cables, locations of wiring breakouts, and separation of distance between firing leads and between the firing 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, installation, check out and installed; and treat circuits, in the case of EED's for example, for pin-to-pin, pins-to-case and bridgewire-to-bridgewire effects, as applicable. All known parameters of the circuits are used such as the length of unshielded portions, and the physical shape; but wherever 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 single 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, for example, the EED terminating the circuit. 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 test item 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 desnities. 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 very similar. In a few rare cases the evaluation of the RF sensitivity of the device under test can be eliminated. The usual case occurs when preliminary investigations of the circuits indicates that they are so well designed from an RF standpoint that only a small amount of energy can be extracted from even a very strong incident field; then the sensitivity of the test device may be of secondary importance. However, RF sensitive EEDs should always be avoided if possible.

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, pin configuration of test device, RF sensitivity of test device, impedance of test device, quality of shielding material used and attenuation provided by switches and arming devices used in the circuit are carefully determined and actual values are used in the calculations wherever possible. On the other hand, those characteristics which could be variable from test vehicle to test vehicle or 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 throughtout the circuit are generally assumed to be matched in such a manner as to give maximum transfer of RF energy to the test 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 test device which are always on the conservative side, occasionally by rather large amounts. This leads to the statement made earlier that 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 missile system is considered across 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 is extremely difficult to do in any meaningful manner. Even if sufficient data was 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.

2. DETAILED ANALYSIS PROCEDURES

It is the purpose of this section to describe in detail most of the mathematical procedures necessary to conduct an RF analysis on a component. From the start it should be carefully noted that when analyzing the potential hazard to a component such as an EED every pertinent aspect of its history must be carefully considered in its own specific situation. For example, the circuit attached to an EED when it is installed in a space vehicle may have very different RF pickup characteristics than the circuit which might be temporarily attached to check the resistance or some other parameter of the EED. If the EED is installed in a vehicle with the shorting cap attached and the shorting cap is removed to attach the functioning circuit while an RF field is present, possible RF hazard must be considered for the EED with shorting cap, without shorting cap and installed in circuit. Should a monitoring circuit be included in the EED, the RF pickup associated with this circuit must be considered along with its possible coupling to the EED functioning circuit. In short, the engineer performing the analysis must become intimately familar with all aspects of the device, its associated circuits usually back to the power source and its history insofar as handling, installation, checkout and final installed condition are concerned.

In addition the engineer must consider all of the possible functioning modes of a device. For a wire bridge EED this would include the following: through the bridgewire, between the bridgewire and the case and between the bridgewires, if applicable.

For each condition, the engineer must characterize the system as to its most likely manner of acting as a receiving antenna. In its simplest form one might consider a wire lead EED with its leads twisted together at the end. This system could probably be most directly characterized as a small loop antenna terminated in the bridgewire impedance. The same EED installed in a complex missile circuit may be much more elusive to characterize, however. A typical configuration would result in shielding of the cables leading to the EED but no attachment of the shield to the case of the EED. If single point grounding of the shield philosophy is also followed, the engineer may find that a large loop is formed and attached to the pins-to-case mode of the EED.

In summary, and it cannot be said too strongly, when applying the analytical techniques discussed here, it is most important to consider all possible configurations and hazard modes and to characterize the systems being considered into their proper patterns. This step is the single most important and time consuming element of the analysis.

Before proceeding to specific cases a few of the general considerations under which we will operate should be stated. The object of all of the analyses to be presented here is to determine the maximum amount of power which can be delivered to any particular failure mode of the EED or device under consideration. It is assumed that the incident RF field is essentially TEM; i.e., far field. Under these conditions the power density P can be expressed as

$$P = |\bar{P}| = |\bar{E}|\,|\bar{H}| = \frac{|\bar{E}|^2}{Z_o} = |\bar{H}|^2 Z_o \qquad (2\text{-}1)$$

where

$\bar{P}$ is the power density,
$\bar{E}$ is the electric field,
$\bar{H}$ is the magnetic field,
Z_o is the impedance of free space, 377 ohms.

The lines 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 (A_e) which is defined by

$$A_e = \frac{W}{P} \text{ meter}^2 \tag{2-2}$$

where

A_e = effective aperture (square meters),
P = power density, (watts/square meter),
W = power dissipated in the antenna load, the EED, (watts).

This concept of aperture is used in all of our analyses.

A general equation(1) for expressing the effective aperture is

$$A_e = \frac{V^2 R_T}{P\,[(R_R + R_L + R_T)^2 + (X_R + X_T)^2]} \tag{2-3}$$

where

V = the total voltage induced in the antenna,
R_R = radiation resistance,
R_L = loss resistance of the antenna,
R_T = termination resistance,
X_T = termination reactance,
X_R = antenna reactance.

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 EED under the assumed conditions. This value can then be compared with the sensitivity of the EED at that frequency to establish the possibility of RF susceptibility.

With respect to specific cases we are concerned with only two conditions for the EED: disconnected; i.e., not attached to any firing or testing circuit; and connected. In the former, we are concerned with the physical and electrical structure of the EED alone including any shorting or shielding caps. This would be the normal condition for the various analyses designated as hand held, transportation (when the EEDs are not installed) and installation (before the circuits are attached). In the latter or connected condition we are concerned with the EED as a component in an electrical system. This would be the normal condition whenever the device is installed or during check out or other electrical testing procedures. It is these two conditions that we will now examine in more detail.

2.1 EED Disconnected

In order to determine the potential hazard to an EED resulting from exposure to an incident RF field during handling and installation (hand-held mode) it is necessary to analyze the physical body of the initiator in terms of its ability to pick up and deliver energy to its explosive components. The method of analysis depends heavily upon the connector type: twin-lead, coaxial or others. Various analytical methods are available which include similitude to a small loop, a coaxial aperture, or a circular aperture. In all of these methods, we assume that the field is essentially TEM or far field. With an incident TEM field, the basic antenna formulas can be applied considering the initiator or initiator assembly positioned for maximum power pick up. The various firing modes (pin-to-pin, pins-to-case and bridgewire-to-bridgewire) must also be considered both for continuous wave (CW) and for pulsed power.

2.1.1 Multipin Connector Type

In this section we are concerned with EEDs in which the input uses some form of the standard type metal shelled, multipin connector. The analysis applies even if there is only a single pin such as in the coaxial type. Over the years we have developed numerous analysis procedures for models in which it was assumed that the model was a coaxial line; i.e., the pins in the connector are assumed to be the inner conductor of a coaxial line and the connector body the outer connector, a two wire end driven line (the connector body if assumed to be removed and the exposed pins end driven) and a small loop formed by the connector pins (connector body removed). However, it was determined that the worst case aperture exists when the axis of the connector on the EED lies along the direction of propagation of the incident radiation. In this case we assume that the power delivered to the initiator is not more than that which would be transmitted through a circular aperture (of the same diameter as the inside diameter of the pin shield) in an infinite conducting screen normal to the direction of propagation. This approach is now used for all connector type EEDs whether shorted or unshorted and for all excitation modes (pin-to-pin, pins-to-case or bridge-to-bridge),and while this approach produces a "worst-worst case" value of aperture, the values are in general so low that no hazard exists in reasonable incident RF fields and the overall calculation is simplified. The circular aperture is given by

$$A_c = T_{wc} A \tag{2-4}$$

where

A = area of the opening of the pin shield in square meters,

T_{wc} = transmission coefficient as given in Figure 2-1.

Figure 2-1 is a straight line approximation we developed from the relationship of transmission coefficient to the radius of the circular aperture which is given in reference (2), page 126.

In practice, for any given frequency we can compute a value of Ka where $K = \frac{2\pi}{\lambda}$ and a = the radius of the aperture; a and λ should be in the same units. T_{wc} can then be obtained from Figure 2-1 for the calculated value of Ka and the circular aperture can be calculated from Equation 2-4. This calculation must be repeated for each frequency of interest.

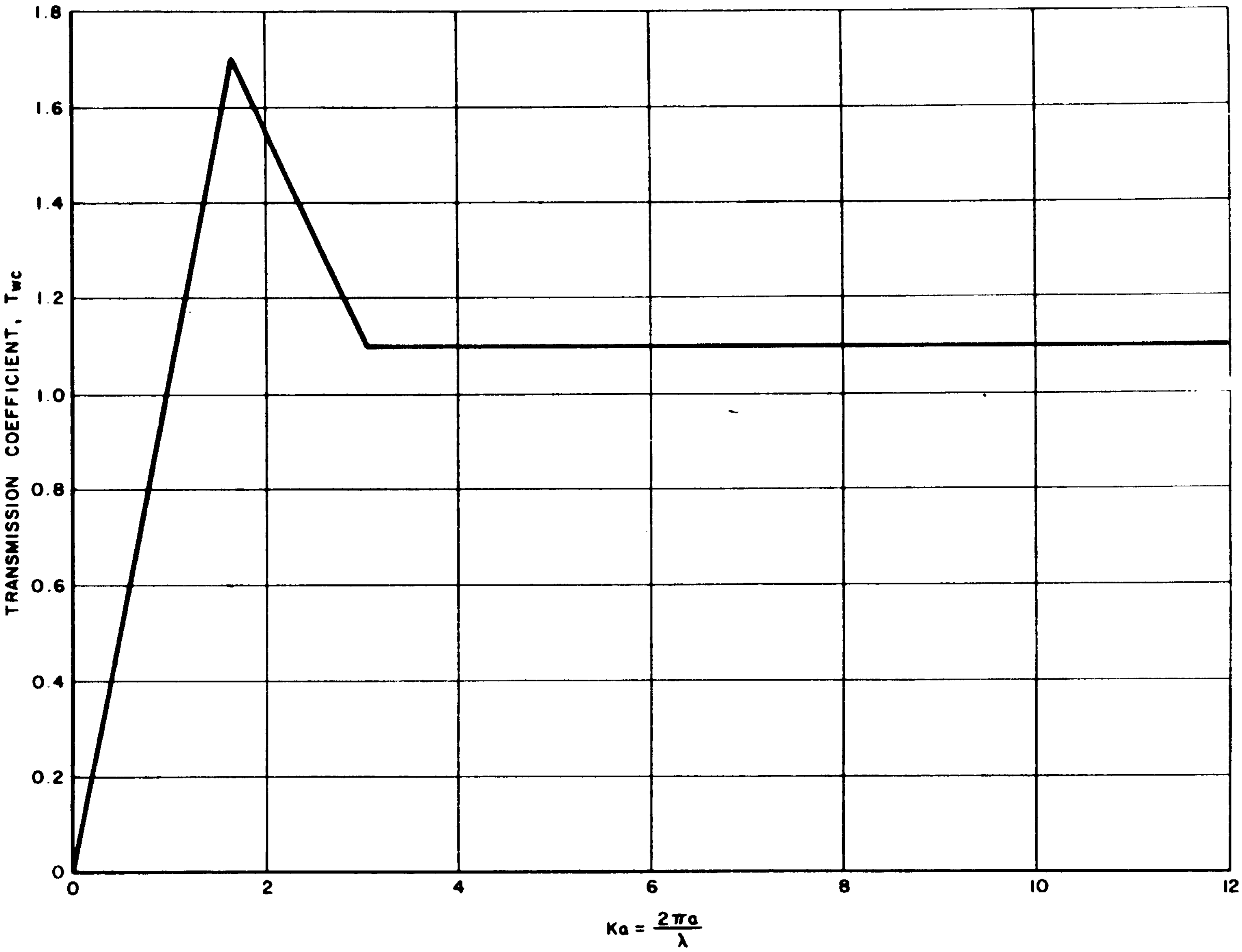


Fig. 2-1 - Transmission Coefficient of Circular Apertures of Radius a (Meters), Straight Line Approximation

2.1.2 Wire Lead Type

The other most common type of EED which is in usage is the wire lead type in which the pins to which the bridgewire is applied are wires which extend through the base plug and are used to make connections to the EED. These wires may be very short or as long as several feet although the most common length is 6 to 8 inches. For the EED disconnected we are interested in both the shorted and unshorted case.

2.1.2.1 Unshorted Wire Lead Type (Pin-to-Pin)

Figure 2-2 sketches this type configuration and its antenna model. This configuration is also often formed by firing system wiring. We can evaluate the maximum possible aperture of this configuration by using (from reference (1))

$$A_{em} = \frac{G\lambda^2}{4\pi} \qquad (2-5)$$

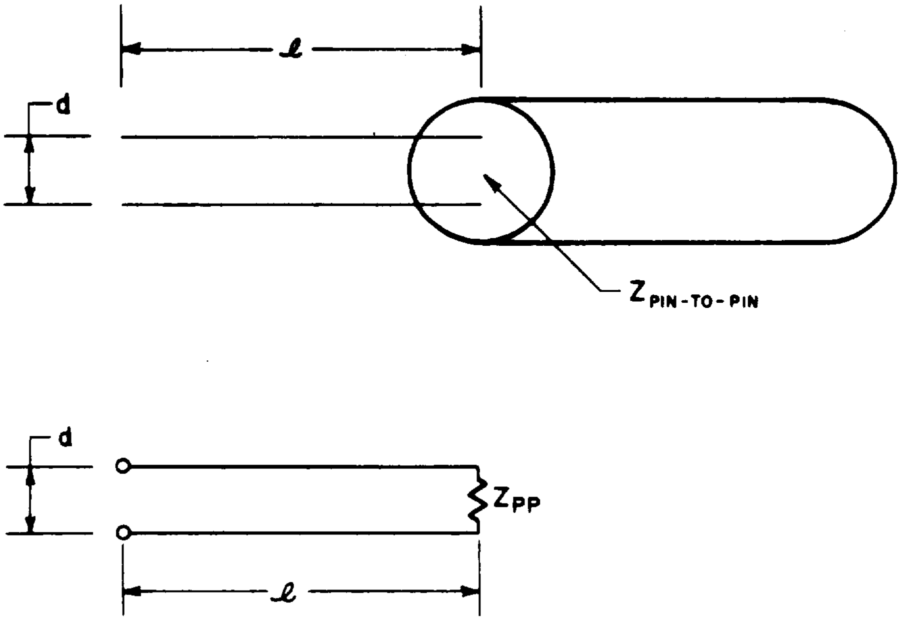


Fig. 2-2 - Unshorted EED and Its Antenna Model

Here we must compute the gain G of the antenna, where G is defined for a lossless antenna, (which is clearly necessary for prediction for maximum aperture) as equal to the directivity D. D in turn is defined by

$$D = \frac{\text{maximum radiation intensity}}{\text{average radiation intensity}} = \frac{U_m}{U_o} \qquad (2\text{-}6)$$

The units of U are watts per square radian and since a sphere contains 4π square radians,

$$D = \frac{4\pi\ U_m}{\text{total power radiated}} \qquad (2\text{-}7)$$

At large values of r we will have TEM propagation and therefore the Poynting vector will be real and perpencidular to the surface of a sphere centered at the antenna. Using P_{r_1} as the magnitude of the Poynting vector at a large radius r_1 and the definition of U_m at radius r_1 as

$$U_{m_{r_1}} = r_1^{\,2}\ P_{r_1 max} \qquad (2\text{-}8)$$

then

$$D = \frac{4\pi\ r_1^{\,2}\ P_{r_1 max}}{\oiint_{r_1} P_{r_1}\ ds} \qquad (2\text{-}9)$$

Combining Equations (2-5) and (2-6) gives, for a lossless antenna,

$$A_{em} = \frac{\lambda^2\ r_1^{\,2}\ P_{r_1 max}}{\oiint_{r_1} P_{r_1}\ ds} \qquad (2\text{-}10)$$

where r_1 is a very large radius. The Poynting vector at a large radius may be computed from Equation (2-1), and we obtain

$$A_{em} = \frac{\lambda^2 r_1^2 \frac{\left|\bar{E}_{r_1}\right|^2_{max}}{Z_o}}{I_o^2 R_R} \tag{2-11}$$

where I_o is the current on the antenna and R_R is the radiation resistance. I_o must be the current actually passing thru R_R in the equivalent circuit. The denominator of Equation (2-10) is the total power radiated and $I_o^2 R_R$ is also equal to the total power.

If in Equation (2-3), an impedance match is assumed; i.e.,

$$(R_R = R_T, R_L = 0, X_T = -X_R)$$

we obtain

$$A_e = A_{em} = \frac{V^2}{4 PR_R} \tag{2-12}$$

since this must be the maximum aperture. This may be equated to Equation (2-11), yielding

$$V^2 = \frac{4 P \lambda^2 r_1^2 \left|\bar{E}_{r_1}\right|^2_{max}}{Z_o I_o^2} \tag{2-13}$$

If we now can find $\left|\bar{E}_{r_1}\right|_{max}$ for our configuration we will have found V^2, the induced voltage squared. Substitution of this in Equation (2-3) will then yield

$$A_e = \frac{4 \lambda^2 r_1^2 R_T \left|\bar{E}_{r_1}\right|^2_{max}}{Z_o I_o^2 [(R_R + R_L + R_T)^2 + (X_R + X_T)^2]} \tag{2-14}$$

If we now maximize Equation (2-13) in relation to the unknowns we obtain, for $X_R = -X_T$, $R_L = 0$, $R_R = 0$,

$$A_e = \frac{4\ \lambda^2\ r_1^2\ \left|\bar{E}_{r_1}\right|^2_{max}}{Z_o\ I_o^2\ R_T} \tag{2-15}$$

and our only unknown is $\left|\bar{E}_{r_1}\right|_{max}$. Figure 2-3 shows the configuration to be evaluated for the $\bar{E}$ field at a large r. A similar case with a different phase relationship between the currents has already been analyzed(3). Substitution of our value of phase difference (i.e., 180°) in this analysis yields

$$\left|\bar{E}_{r_1}\right|^2 = \frac{Z_o^2\ I_o^2\ \ell^2}{\lambda^2\ r_1^2} (1 - \sin^2 \phi \sin^2 \theta) \sin^2 (\frac{\beta d}{2} \cos \theta) \tag{2-16}$$

where

$$\beta = \frac{2\Pi}{\lambda}$$

This expression has a maximum value, at $\theta = 0$, of

$$\left|\bar{E}_{r_1}\right|^2 \max = \frac{Z_o^2\ I_o^2\ \ell^2}{\lambda^2\ r_1^2} \sin^2 (\frac{\beta d}{2}) \tag{2-17}$$

Substituting this result in Equation (2-5), yields

$$A_e = \frac{4\ Z_o\ \ell^2}{R_T} \cdot \sin^2 (\frac{\beta d}{2}) \tag{2-18}$$

The above derivation is subject to the restriction that $\ell << \lambda$ since we have considered the currents as linear, whereas they are actually, to a first approximation at least, distributed sinusoidally along the wires.

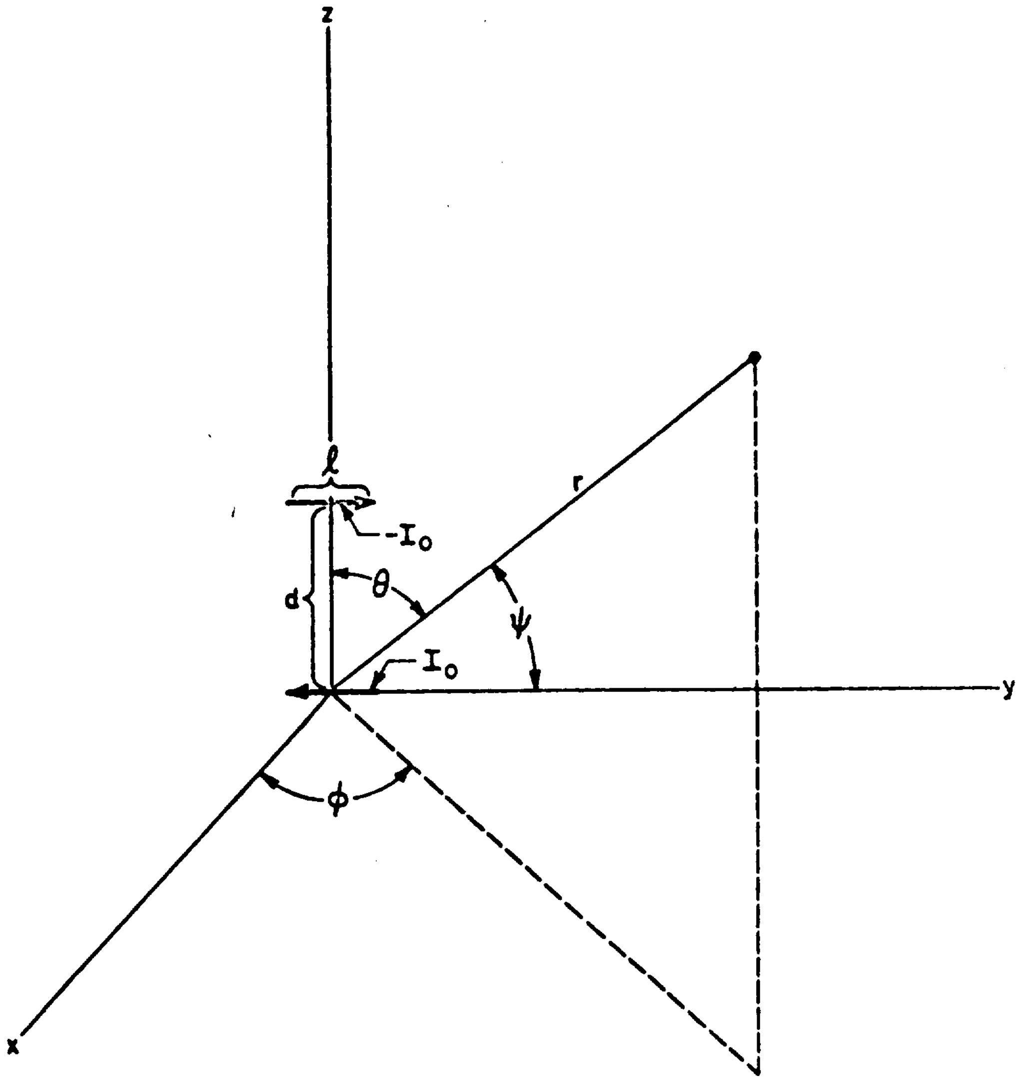


Fig. 2-3 - Coordinate System Employed in Calculating Electric Field of the Antenna Configuration

For $\ell << \lambda$, $d < \ell$,

$$\sin\left(\frac{\beta d}{2}\right) \rightarrow \frac{\pi d}{\lambda}$$

and

$$A_e = \frac{4\pi^2 Z_o \ell^2 d^2}{R_T \lambda^2} = \frac{4\pi^2 Z_o A^2}{R_T \lambda^2} \qquad (2\text{-}19)$$

A can be considered the area of the antenna given by the product of d and ℓ.

2.1.2.2 Shorted Wire Lead Type (Pin-to-Pin)

The standard method of shorting a wire lead type EED is to twist the ends of the wires together. This forms the leads into a loop antenna.

On page 171 of Reference (1) it is shown that for a small loop whose area, A, is less than $r^2/100$ the radiation resistance is given by:

$$R_R = \frac{320\ \pi^4 A^2}{\lambda^4} = \frac{3.12 \times 10^4 A^2}{\lambda^4} \qquad (2\text{-}20)$$

and that the directivity, D, of the small loop is 3/2. Using the formula for maximum effective aperture of a lossless antenna$^{(1)}$,

$$A_{em} = \frac{D\lambda^2}{4\pi} = \frac{W_{max}}{P} \qquad (2\text{-}21)$$

which is evaluated when the terminating resistance equals the radiation resistance and the reactances cancel, we can obtain for the induced voltage

$$\left(\frac{V}{2}\right)^2 \frac{1}{R_R} = W_{max} = \frac{PD\lambda^2}{4\pi} \qquad (2\text{-}22)$$

Substituting for R_R, we get

$$V^2 = \frac{P \times 4.67 \times 10^4 A^2}{\pi \lambda^2} \tag{2-23}$$

Substituting this expression and $R_L = 0$, $X_R = -X_T$ in Equation (2-3) we obtain

$$A_e = \frac{4.67 \times 10^4 A^2}{\pi \lambda^2} \frac{R_T}{(R_T + R_R)^2} \tag{2-24}$$

At large λ, the λ^4 term in the expression for the radiation resistance (Equation 2-20) dominates and the radiation resistance becomes very small (for reasonable areas, <0.01 m^2) in relation to the other resistance in the circuits; we therefore may assume $R_R = 0$. Using this approximation, Equation (2-24) becomes

$$A_e = \frac{4.67 \times 10^4 A^2}{\pi \lambda^2 R_T} \tag{2-25}$$

This equation represents the aperture of a small loop assuming a reactive match between antenna and load, no dissipation of power in the radiation resistance (which we have seen is very low for small loops), and orientation of the loop for maximum pickup.

An alternate method of deriving the maximum aperture of a small loop is to obtain an expression for the voltage induced in the loop. Consider that the magnetic flux density is uniform over the loop. The total voltage around the loop is then given by

$$|V| = \left| - \oint \frac{\partial \bar{B}}{\partial t} \cdot ds \right| = A \mu_o \omega |\bar{H}| \tag{2-26}$$

where

A = area of the loop,
$\omega = 2\pi f = 6\pi \times 10^8/\lambda$,
f = frequency,
λ = wavelength,

μ_o = permeability of free space, 12.5 x $1\bar{0}^7$ h/m,
$\bar{B}$ = magnetic flux density.

If we express $|\bar{H}|^2$ in terms of P and Z_o from Equation (2-1) and frequency in terms of wavelength and substitute these into the square of Equation (2-26) we obtain

$$|V|^2 = \frac{A^2\ 4\ \pi^2\ P\ \mu_o\ c^2}{Z_o\ \lambda^2} \tag{2-27}$$

where $c = f\lambda = 3 \times 10^8$ m/sec.

If we now make use of

$$c = \frac{1}{\sqrt{\mu_o\ \varepsilon_o}} = 300 \times 10^6 \text{ and } z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377$$

where ε_o is the permittivity of free space, we can write Equation 2-27 as

$$|V|^2 = \frac{A^2\ 4\ \pi^2\ P\ Z_o}{\lambda^2} = \frac{1.48 \times 10^4\ A^2 P}{\lambda^2} \tag{2-28}$$

Substitution of Equation(2-28) in (2-3) with $R_L = 0$, $X_R = -X_T$ gives

$$A_e = \frac{1.48 \times 10^4\ A^2}{\lambda^2} \cdot \frac{R_T}{(R_T + R_R)^2} \tag{2-29}$$

Using the assumption that $R_R = 0$ as before, Equation (2-29) can be rewritten as

$$A_e = \frac{4.67 \times 10^4\ A^2}{\pi\ \lambda^2\ R_T} \tag{2-30}$$

which is identical to Equation (2-25).

Furthermore, if we now compare this result with Equation (2-19), the expression for unshorted wire lead configuration, we find that the two expressions are also identical. Therefore, the effective aperture for a wire lead EED in the pin-to-pin mode is the same whether the leads are shorted together or not, if the physical dimensions are the same.

2.1.2.3 Wire Lead Type (Pins-to-Case)

The two preceeding sections discuss the case for pin-to-pin or "through-the-bridgewire" conditions; however, a pins-to-case functioning mode is also possible. Figure 2-4 shows a typical EED and the corresponding antenna equivalent. As shown, the approximation of this configuration as an antenna is an end driven short dipole where the impedance that must be used is the real part of the pins-to-case impedance. This must be obtained by measurement at the frequencies of interest. The formula for calculating the maximum power pickup in this impedance from an end driven dipole is as follows:

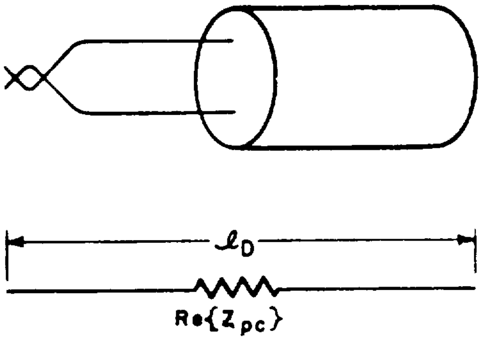


Fig. 2-4 - Antenna Equivalent Circuit for Wire Lead EED in Pins-to-Case Mode

$$W = \frac{|\bar{E}|^2 \ell_D^2}{\mathrm{Re}\ \{Z_{pc}\}} \qquad (2\text{-}31)$$

where

W = maximum power in watts,

$|\bar{E}|$ = magnitude of field density in volts/meter,

ℓ_D = length of dipole in meters,

$\mathrm{Re}\ \{Z_{pc}\}$ = real part of pins-to-case impedance in ohms.

This formula utilizes the fact that the effective height of a short dipole is its physical length and therefore the total open circuit voltage in the antenna equivalent circuit will be equal to the magnitude of the electric field times the dipole length. The worst case assumption for series impedances of this model is that the radiation and terminating impedances have equal and opposite reactances and that the radiation resistance is zero. From Equation (2-2) it can be seen that Equation (2-31) can be expressed as an aperture by dividing both sides by the incident power density (P_i).

$$A_e = \frac{W}{P_i} = \frac{\ell_D^{\,2}\, Z_o}{\mathrm{Re}\{Z_{pc}\}} \text{ Meter}^2 \qquad (2\text{-}32)$$

where Z_o = impedance of free space in ohms.

2.1.2.4 Wire Lead Type (High Frequency Calculations)

In the preceding three sections we have discussed the methods of analyzing the RF pickup of a wire lead device in all of its various configurations and hazard modes. However, each of these approaches has the limitation that the wavelength must be long with respect to the physical dimensions of the receiving antennas. When the wave length becomes too short the assumptions which lead to the various calculations are no longer valid due to non uniform current distribution in the antennas. For the unshorted loop the shortest applicable wavelength occurs at $\lambda = 20\ell$ where ℓ is the length of one of the leads. For the shorted loop the shortest applicable wavelength is $\lambda = 2\ell$ where ℓ is the perimeter of the loop. For the end driven dipole, the shortest applicable wavelength is $\lambda = 10\ell_D$ where ℓ_D is the length of the dipole. In each case the equations are valid for any wavelength longer than these conditions.

At the shorter wave lengths; i.e., the higher frequencies, the maximum effective aperture (A_{em}) can be calculated from

$$A_{em} = \frac{D\lambda^2}{4\pi} \qquad (2-33)$$

which holds for a lossless antenna. In this formula A_{em} is the maximum possible aperture, assuming a complete impedance match, and D is the directivity of the antenna. Generally, at these higher frequencies the directivity of the actual configuration under consideration as a function of frequency is not known; but if we assume that it can be no more than that of an antenna of known directivity we can calculate A_{em}, the maximum effective aperture.

Another reference(4), shows curves of directivity for three types of antennas: the unterminated rhombic, the long wire and the circular loop. It is reasonable to assume that our configuration will be no more directive than these, since these are among the most directional linear antennas known.

Figure 2-5 is a composite plot of the greatest directivity of these antennas types as a function of overall lead length. The plot was made directly from the above reference. Using Figure 2-5 and Equation (2-33) the maximum effective aperture of our antenna configurations can be calculated. The maximum effective aperture (A_{em}) is calculated under the assumption that the lead configuration will be no more directive than an unterminated rhombic, a long wire or a circular loop antenna of equal linear dimension. The calculation is straightforward.

It is interesting to note at this point the previous determinations for effective aperture (A_e) at the lower frequencies were calculated with the following assumptions: the terminating bridgewire resistance is no less than the dc resistance, the antenna is reactively matched, loss resistance is zero, and the radiation resistance is zero.

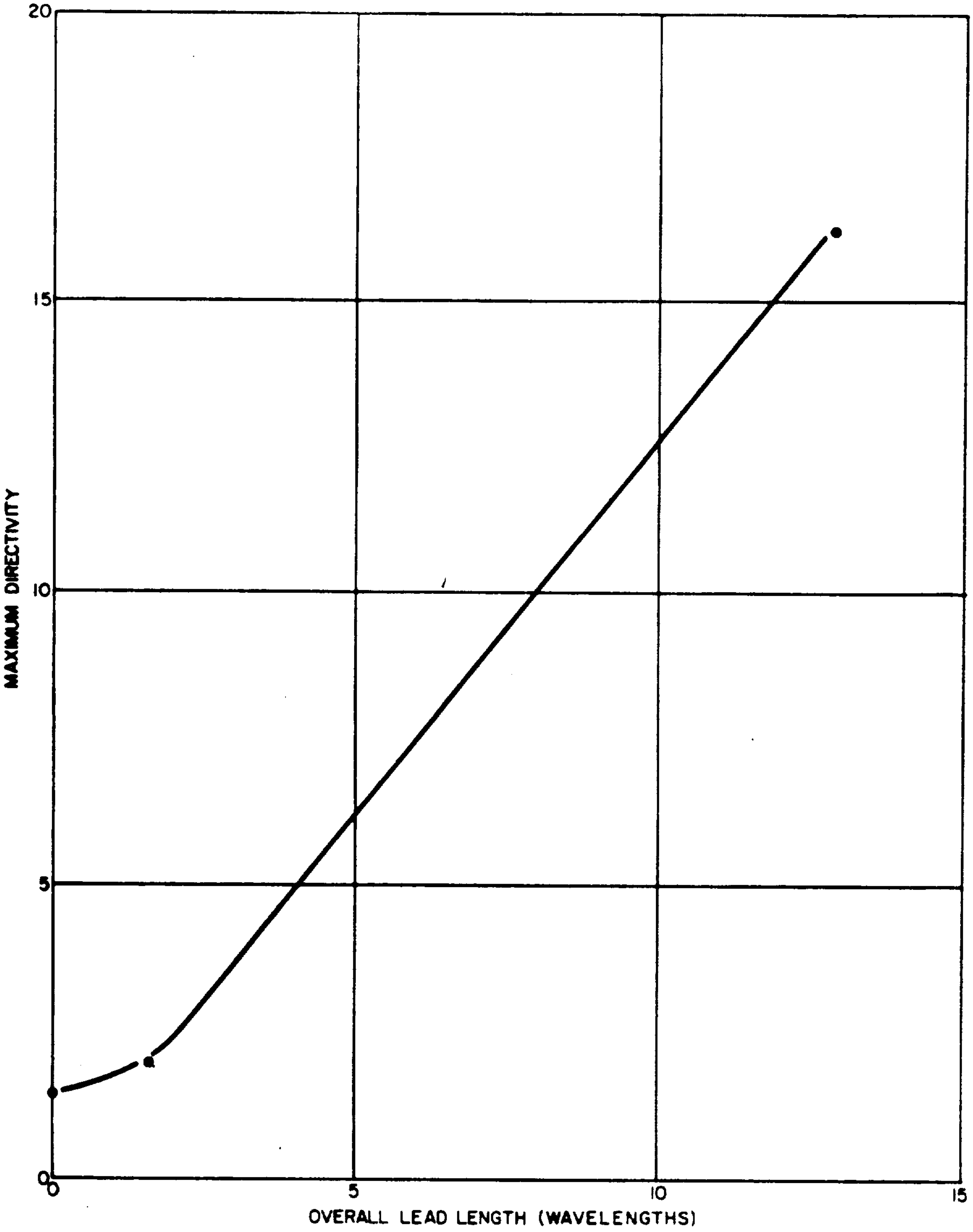


Fig. 2-5 - Maximum Directivity of Three Known Antenna Configurations

Note that these last assumptions effectively maximize the A_e expression (see Equation (2-3) where V^2 is considered constant). These calculations contain a seeming anomaly since the effective aperture curve, if continued, would rise above the maximum effective aperture curve. This is a result of considering the radiation resistance to be equal to zero in our maximizing procedure of the effective aperture. If the radiation resistance were taken into consideration the curves would not intersect so abruptly but the effective aperture curve would roll over at the higher frequencies to meet the maximum effective aperture curve.

2.2 EED Connected

The preceding discussions provided the necessary formulas to determine the worst case RF pick up of the majority of EED disconnected situations that one is likely to come upon and which would be applicable for hand-held, installation and transportation considerations. In turning our attention to the EED connected in its various circuits, for example installed and checkout, it is important to restate that the most important and necessary part of the analysis is to properly characterize the antennas represented and that this procedure is considerably more complicated when the EED is connected. However, experience has shown that the majority of present missile circuits fall into one of two categories. The first of these is the circuit which contains breakout of the shields to go to circuit boards, through bulkhead connectors, to other circuits or at the EED itself. A common occurrence is for the shielding to terminate just prior to the EED, for example. Most of these breakouts can be characterized as loops of varying dimensions. One must pay particular attention to possible pins-to-case loops in these systems. The second type is the circuit which is completely shielded from end to end and through 360°. In this section we will treat these two possibilities.

2.2.1 Circuits with Shielding Caps

Many EED firing systems use shielded cables between the safe/arm device and the EED, or if no safe/arm 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 non-shielded portions of the wiring. In consequence the models chosen represent the physical characteristics of the gaps or breaks in the shielding. Figure 2-6 diagrams a typical break or gap in a shielded firing lead and Figure 2-7 diagrams the equivalent antenna model used for this gap. The dimensions given are representative of commonly used separation switches.

The impedances Z_{u_1} and Z_{u_2} are considered to be completely unknown while Z_{ppt} and Z_{pct} represent the firing mode impedances (Z_{pp} and 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. We 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. In addition we have made measurements on many typical types of two wire twisted shielded cable in the low frequency ranges and although attenuation is not zero it is usually small for the lengths of cable considered in these ranges. The only worst case assumption that can be made, without extensive and expensive measurements, is that the loss is zero.

Once the loop has been reduced to its diagrammatic representation as shown in Figure 2-7, 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, Equation (2-25) applies. For shorter wavelengths Equation (2-33) applies.

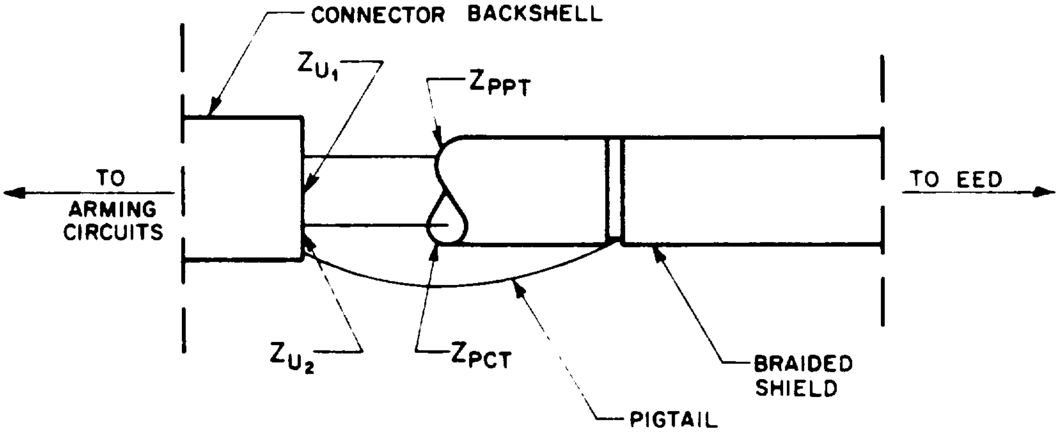


Fig. 2-6 - A Typical Shielding Gap Configuration

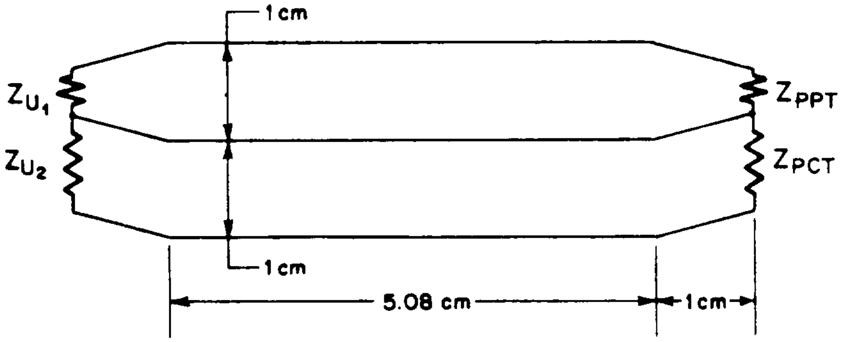


Fig. 2-7 - Basic Antenna Model for a Shielding Gap

$$A_e = \frac{4.67 \times 10^4 A^2}{\pi \lambda^2 R_T} \tag{2-25}$$

$$A_{em} = \frac{D\lambda^2}{4\pi} \tag{2-33}$$

The above methods allow us to 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

$$A_{ec} = \frac{4.67 \times 10^4}{\pi \lambda^2 R_T} (A_1 + A_2 + A_3 + \ldots + A_m + \ldots + A_n)^2 \tag{2-34}$$

where A_{ec} is the composite effective aperture of n loops and A_m is the area of the mth 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, we must consider this 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

$$A_{ec} = \left(\sqrt{A_{em_1}} + \sqrt{A_{em_2}} + \ldots + \sqrt{A_{em_q}} + \ldots + \sqrt{A_{em_n}}\right)^2 \tag{2-35}$$

where A_{em_q} is the maximum aperture of the qth gap and A_{ec} is the composite aperture.

Figure 2-8 shows the pin-to-pin aperture computed by the above methods for a small shielding gap in a 6.4 ohm (dc resistance) EED firing circuit. The geometry of the gap is shown on the figure.

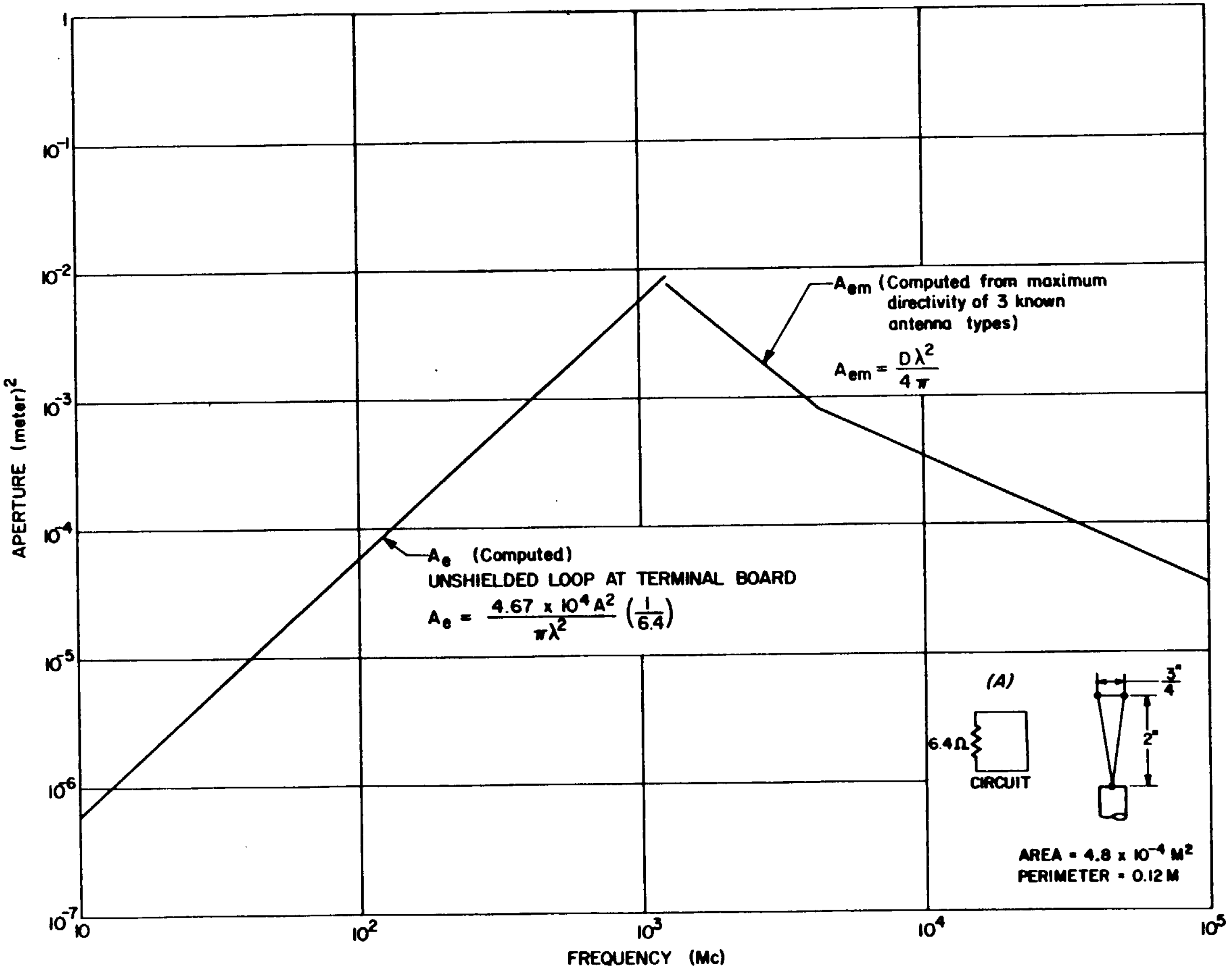


FIG. 2-8 APERTURE OF LOOP AS SHOWN IN FIGURE (A) AT TYPICAL TERMINAL BOARD

2.2.2 Completely Shielded Circuits

The case where circuits are completely shielded with no gaps is comparatively rare 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.

Since in such a system the shields completely enclose the EED, shorting switch, power supply and interconnecting wires, the analysis can be broken into the following parts:

1. Determining the total power into the outer surface of the shield as a function of frequency and of the incident field assuming matched conditions inside the shield.
2. Determining the total power loss of the shield assuming matched conditions inside the shield.
3. Using the results of steps one and two to calculate the maximum possible power that can be delivered to the EED as a function of frequency and incident field, assuming the EED to be installed in the longest firing circuit.
4. Comparing the results of step three to a composite 0.1% firing level that is the minimum 0.1% level for all the EEDs under consideration for any firing mode.

Dividing the analysis into the parts given above implies the assumption that the field that is reradiated by any structure within the shield or by the boundary between the inner surface of the shield and the region internal to the shield will, at the outer surface of the shield, be very small in relation to the field induced on the outer surface by the incident radiation. A worst case approach which insures the above is to assume that all power that penetrates the shield is perfectly matched to the EED. If this were the case, there would be no reflection from either the shield/internal region boundary or any internal structure. We may further assume that the power that penetrates the shield can be matched to any of the firing modes' impedances.

2.2.2.1 Calculation of the Maximum Power Density at the Outer Surface of the Braided Shield

As a start toward determining the maximum power density at the surface of the braid, we assume that the entire surface of the cable is illuminated by a TEM field at normal incidence and the field has a power density P_i. We realize that generation of such a field (normal to an irregular convex surface) is well nigh impossible, but it is surely the worst case TEM field assumption. The maximum power density (P_T) at the surface of the shield is given by

$$P_T = P_i \; (1 - |\rho|^2) \tag{2-36}$$

where

P_T is the power density at the surface of the braid,

P_i is the incident TEM field power density,

$\rho = \dfrac{Z_c - Z_o}{Z_c + Z_o}$,

Z_o = 377 ohms,

$Z_c = (1 + j) \times 2.59 \times 10^{-4} \sqrt{f_{MHz}}$ = the surface impedance of a copper sheet in ohms,

f_{MHz} = frequency in megahertz.

If we note that Re $\{Z_c\}$ = Im $\{Z_c\} << Z_o$ we can write Equation (2-36) as

$$P_T = P_i \frac{4 \text{ Re } \{Z_c\}}{Z_o} = P_i \times 2.75 \times 10^{-6} \sqrt{f_{MHz}} \tag{2-37}$$

with negligible error. It can be shown that this equation provides a worst case estimate of surface power density.

2.2.2.2 Calculation of the Power Density at the Inner Surface of the Braided Shield

Power passes through the shield by two separate paths: propagation through the copper ribbon of the braid and propagation through the interstices. The loss in the metallic path is a dissipative attenuation, and that produced by the small holes is due to reflection. The copper loss can be evaluated by the planar attenuation which is

$$dB = 8.68 \frac{t}{\delta} \tag{2-38}$$

where t is the thickness of the braid and δ is the skin depth. The justification of the use of planar attenuation instead of the attenuation of the curved surface of the shield can be found on page 248 of reference (5) where it is shown that as long as the radius of the cable divided by the skin depth is more than 7.55, the planar approximation leads to very small errors. If we use the minimum thickness of the ribbon that makes up the braid as t and calculate δ for copper we obtain

$$dB_{copper} = 5 \sqrt{f_{MHz}} \tag{2-39}$$

where f_{MHz} is frequency in megahertz.

The attenuation of the small holes can be computed from that of a waveguide operating below cutoff frequency. From page 346 of reference (5), we obtain, for a cutoff rectangular guide

$$\alpha = \frac{2\pi}{\lambda_c} \sqrt{1 - \left(\frac{\lambda_c}{\lambda}\right)^2} \tag{2-40}$$

where α is the attenuation in nepers per unit length,

λ_c is the cutoff wavelength of the guide,

λ is the free space wavelength of the propagating energy.

The applicable cutoff wavelength is given by

$$\lambda_c = 2b \qquad (2-41)$$

where b is the largest dimension of a rectangular guide. Converting to nepers gives

$$dB = 8.68\alpha t \qquad (2-42)$$

where t is the thickness of the shield.

Since the power density at the surface of the shield has been assumed constant and since the ratio of open to solid area of the shield can be determined, a symbolic equation can be written for the average power density out of the inner surface of the shield. If P_o is the average power density at the inner surface of the cable, P_T is the outer surface power density and Q is the ratio of solid area to hole area in the shield.

$$P_o = (1-Q)\ P_T\ [\text{down } 8.68\alpha t \text{ dB}] + QP_T\ [\text{down } 8.68\frac{t}{\delta} \text{ dB}] \qquad (2-43)$$

It should be noted that shielded cable varies greatly in construction and quality and to apply the above system it is necessary to carefully investigate the shield in question to determine thickness, material and ratio of hole area to solid area. General construction should also be noted.

It is now possible at any one frequency to use Equation (2-36) and Equation (2-43) to establish the maximum amount of RF power arriving at the inside of the shield in terms of the RF field incident upon the cable. If this is now adjusted for the total area of cable exposed, the total maximum RF power inside the shield will have been determined. By our original assumptions all of this power is assumed to be delivered to the EED. For consistency we could construct a symbolic aperture equation as follows:

$$A_{em} = \frac{P_oA}{P_i} = \frac{A}{P_i}\left[(1-Q)P_T[\text{down } 8.68\alpha t \text{ dB}] + QP_T[\text{down } 8.68\frac{t}{\delta} \text{ dB}]\right] \qquad (2-44)$$

where

A is the total surface area of the cable.

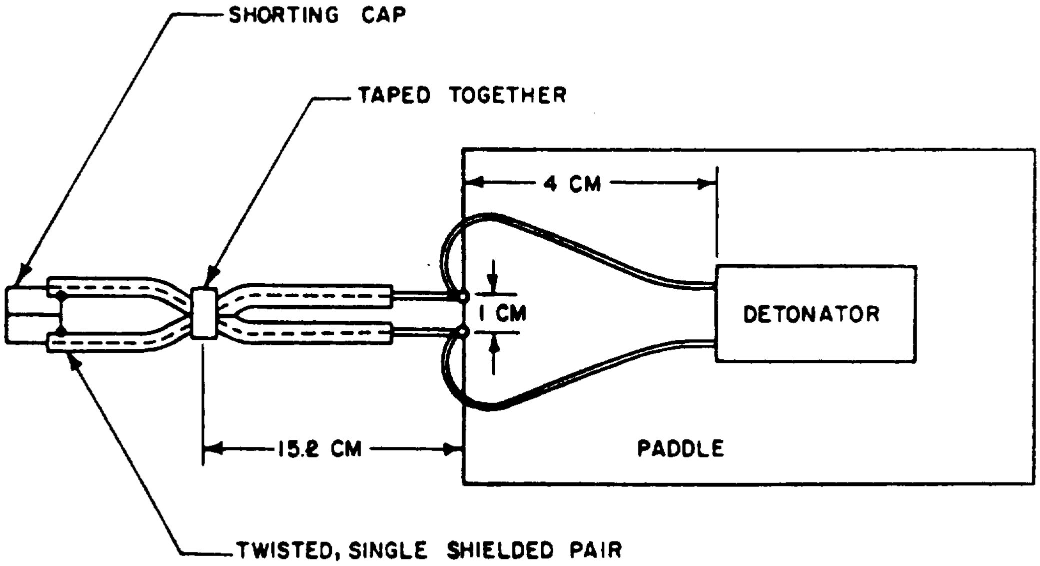


Fig. 3-1 - Schematic Drawing of System to be Analysed

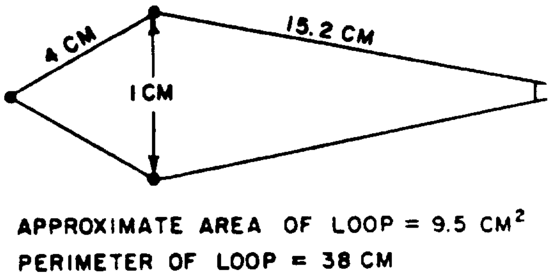


Fig. 3-2 - Loop Approximation of System Shown in Fig. 3-1

3. EXAMPLE OF AN EVALUATION

Figure 3-1 is a schematic drawing of a simple system configuration actually used on a space vehicle. Figure 3-2 is an approximation of this configuration shown as a simple loop and finally Figure 3-3 shows the antenna configuration for analysis derived from the actual circuit. R_{dc} is the dc resistance of the initiator.

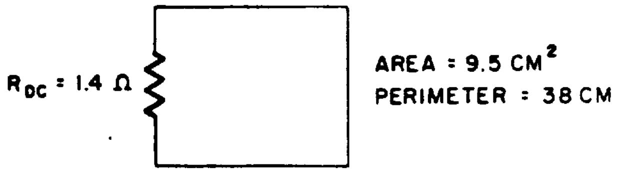


Fig. 3-3 - Antenna Configuration for Evaluation Derived from Fig. 3-2

While this is an installed mode, the final antenna configuration is a single loop. Therefore Equation (2-25) 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 Equation (2-33) 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. Figure 3-4 is a plot of such calculations made for the circuit under consideration here.

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 established by testing. Figure 3-5 shows such a plot where the incident RF power density was assumed to be 2 watts/meter^2 up to 50 MHz and 100 watts/meter^2 above 50 MHz. The data for this plot was obtained by multiplying chosen points on the aperture curve of Figure 3-4 by the assumed incident power density at the same point. Superimposed on the power pick-up

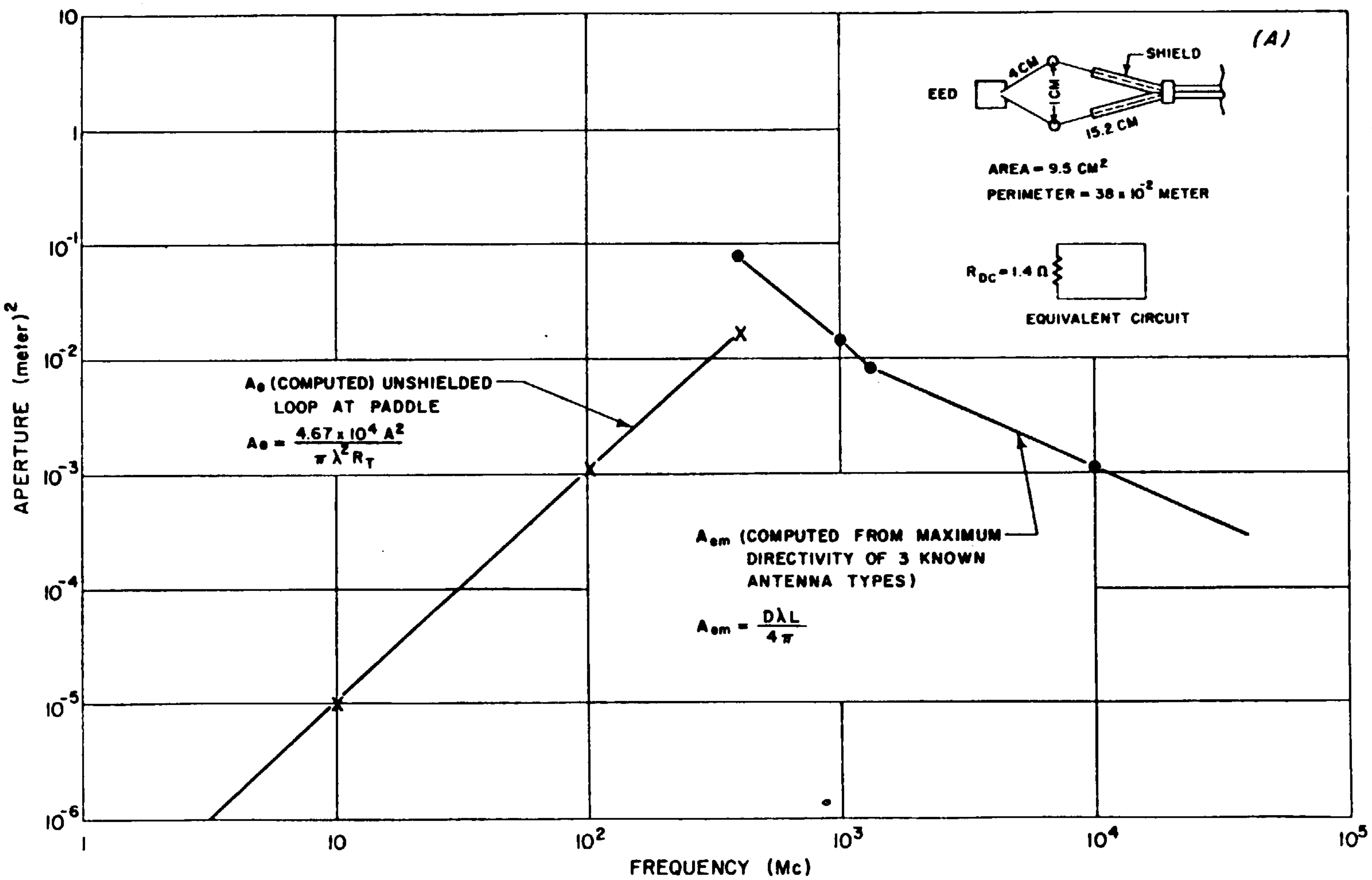


FIG. 3-4. APERTURE OF LOOP CONFIGURATION AT PADDLE

(Pin-to-Pin Mode)

curve of Figure 3-5 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 watts/meter^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.

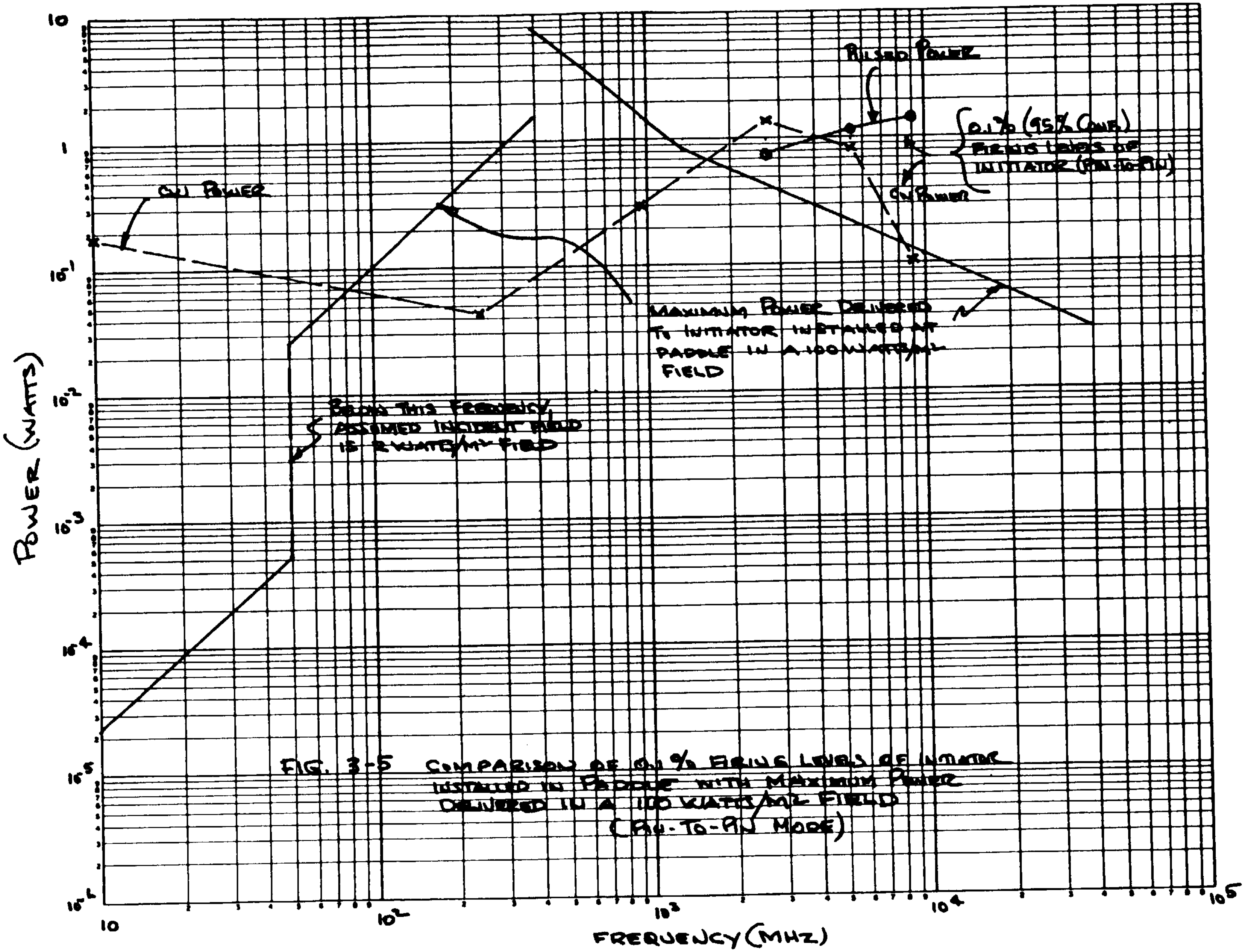


FIG. 3-5 COMPARISON OF 0.1% FIRING LEVELS OF INITIATOR INSTALLED IN PADDLE WITH MAXIMUM POWER DELIVERED IN A 100 WATTS/M2 FIELD (PIN-TO-PIN MODE)

4. SUMMARY

As indicated in the beginning of this monograph there has been no attempt to be exhaustive in coverage since it is almost impossible to predict all of the possible circuit characteristics that one may be faced with in any given analysis. However, our experience has shown that most problems fall into the general categories discussed here. We have not touched on the special case of near field, for example, nor have we considered devices other than wire bridge type EEDs. It should be apparent, however, that the general philosophy and methods of approach can be used for any type of field, any type of circuit and component. In general, to apply the technique three conditions must be met:

a) Knowledge of all of the failure modes for the component being considered and the RF levels that will cause failure or degradation of these components.

b) Proper construction of a mathematical model which accurately simulates the actual circuits involved so that the system connected to the device in question can be characterized in terms of a workable RF receiving antenna. Once again it is essential to consider all possible failure modes.

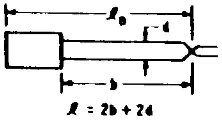
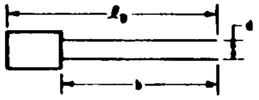
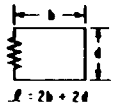
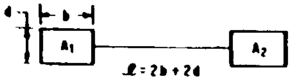
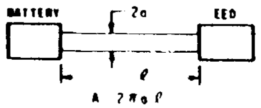
c) Proper application of electromagnetic theory principles to this model.

No one part of this sequence can be taken lightly since a failure to properly conduct any one part could cause a failure of the entire approach. To be successful the engineer must be painstaking and methodical in his approach and must accept no unsupported heresay regarding any elements of the device or circuits.

It should be remembered that, properly applied, the analysis approach is only semi worst case and every attempt should be made in constructing the model to use actual conditions wherever possible. Note that in a very general way the analytical approach can prove that a circuit is safe, but cannot always prove that a system indicated to be in trouble is really unsafe. In contrast the field test approach can only show that a system is in trouble and cannot prove that a system is absolutely safe.

In conclusion Table 4-1 summarizes the conditions and equations we have presented in this monograph.

Table 4-1 - Summary of Analytical Methods for RF Hazard Evaluation

Configuration	Equation (Pin-to-Pin)	Limit of Validity	Equation (Pins-to-Case)	Limit of Validity	Equation (Pin-to-Pin)	Overall Lead Length	Limit of Validity	Equation (Pins-to-Case)	Overall Lead Length	Limit of Validity
	HANDLING, TRANSPORT, AND STORAGE									
	LOW FREQUENCY APERTURE				**HIGH FREQUENCY APERTURE**					
WIRE LEAD DEVICE (SHORTED)  	$A_e = \frac{4.67 \times 10^4 A^2}{\pi A^2 R_T}$	$\lambda \geq 2\ell$	$A_e = \frac{\ell_D^2 Z_0}{Re(Z_{po})}$	$\lambda \geq 10\ \ell_D$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ_D	$\lambda \leq 10\ \ell_D$
CONNECTOR TYPE (WITH SHORTING CAP) 	$A_o = T_{wo} A$	$f_{MHz} \leq 10^5$ MHz	$A_o = T_{wo} A$	$f_{MHz} \leq 10^5$ MHz	--	--	--	--	--	--
	INSTALLATION									
WIRE LEAD DEVICE (UNSHORTED)  	$A_e = \frac{4 Z_0 \ell^2}{R_T} \left(\frac{\beta d}{2}\right)^2$	$\lambda \geq 20\ \ell$	$A_e = \frac{\ell_D^2 Z_0}{Re(Z_{po})}$	$\lambda \geq 10\ \ell_D$	$A_{em} = \frac{D\lambda^2}{4\pi}$	$2\ \ell$	$\lambda \leq 20\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ_D	$\lambda \leq 10\ell_D$
CONNECTOR TYPE (NO SHORTING CAP) 	$A_o = T_{wo} A$	$f_{MHz} \leq 10^5$ MHz	$A_o = T_{wo} A$	$f_{MHz} \leq 10^5$ MHz	--	--	--	--	--	--
	INSTALLED (Shield Breakouts)									
ONE LOOP  	$A_e = \frac{4.67 \times 10^4 A^2}{\pi \lambda^2 R_T}$	$\lambda \geq 2\ell$	$A_e = \frac{4.67 \times 10^4 A^2}{\pi\lambda^2 Re(Z_{po})}$	$\lambda \geq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$
MULTIPLE LOOPS  	$A_e = \frac{4.67 \times 10^4}{\pi \lambda^2 R_T} (n_1 A_1 + n_2 A_2 ---)^2$	$\lambda \geq 2\ell$ (Equal Loops)	$A_e = \frac{4.67 \times 10^4 A^2}{\pi\lambda^2 Re(Z_{po})}$	$\lambda \geq 2\ \ell$ (Equal Loops)	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$
	" "	$\lambda \geq 2\ \ell$ = perimeter of smallest loop (Unequal Loops)	"	$\lambda \geq 2\ \ell$ = perimeter of smallest loop (Unequal Loops)	"	ℓ	$\lambda \leq 2\ell$	"	ℓ	$\lambda \leq 2\ell$
	INSTALLED (360° Completely Shielded)									
 	**TOTAL APERTURE** $A_{em} = \frac{P_s A}{P_1} = \frac{A}{P_1}\{(1-\alpha) P_T [\text{down } 8.68 \alpha t \text{ dB}] + Q P_T [\text{down } 8.68 \frac{t}{\delta} \text{ dB}]\}$				**LIMIT OF VALIDITY** $f_{MHz} \leq 10^5$ MHz typical, but depends on shield characteristics					

5. REFERENCES

1. Kraus, J. D., Antennas, McGraw-Hill, New York 1950.

2. King and Wu, The Scattering and Diffraction of Waves, Harvard University Press, Cambridge, Mass. 1959.

3. Plonsey and Collin, Principles and Application of Electromagnetic Fields, New York, 1961 p. 404.

4. Rawls, Stilwell, McDonald, RF Radiation Hazards, Air Force Missile Test Center Report AFMTC-TM-59-4; July 1959, p.16.

5. Ramo and Whinnery, Fields and Waves in Modern Radio, John Wiley & Sons, New York, 1953.

APPENDIX A

NOTES ON RF SENSITIVITY OF EEDs AND THE NEED FOR TESTING

Throughout this monograph reference is made to various functioning modes of EEDs. While it is not the purpose of this document to present a comprehensive picture of EED's behavior under RF irradiation a brief discussion should help clarify the situation.

A standard EED normally contains a transducer to which electrical energy can be applied. Some of this energy is usually converted to heat which in turn initiates the explosive mix next to the transducer. It is in this manner that EEDs are normally designed to operate and this is what we have designated as the pin-to-pin mode. However, there are other modes in which an EED can be caused to fire which were not planned in the original design. The most common such mode is designated pins-to-case.

In this mode an electrical signal impressed between the pins leading to the normal transducer and the case of the EED can cause a voltage breakdown or some other disruptive phenomena directly through the explosives between the bridgewire posts and the case. This mode is frequently overlooked but is of vital interest in the case of irradiation by RF and spurious electrostatic potentials.

In addition some EEDs contain an additional circuit either to permit monitoring of proper connection or to support a redundant transducer. In this case, in a manner similar to the pins-to-case phenomena, signals can appear between the two circuits and once again directly across the explosive mix. This is the bridge-to-bridge mode.

Frequently, when a group is considering the possibility of RF hazard in connection with an EED the assumption is made that the RF sensitivity of the EED can be characterized as no greater than the dc no fire level, or, in some more conservative cases, to be no greater than an arbitrarily chosen 6 db below the no fire level. The reasoning behind this seems to stem from the concept that the RF probably heats up the transducer in the same manner as dc. Were it not for the other modes this assumption would be reasonably valid at least over part of the frequency spectrum. Experience gained in performing RF sensitivity tests on over 75 different EEDs has indicated that up to approximately 1000 MHz and for RF applied directly to the normal transducer, i.e., pin-to-pin, the functioning sensitivity of hot wire type EEDs is no greater than the dc constant current sensitivity for long pulses of 10 seconds or more duration. However, RF signals applied between the pins and the case or between dual bridgewires may frequently produce sensitivities much greater than the dc sensitivity over the frequency range. Above 1000 MHz, and particularly when pulsed RF signals are applied, the sensitivity may be greater than dc in all modes including through the bridgewire. In many cases this sensitivity is increased by considerabely more than the 6 dB safety factor sometimes used, and since the pins-to-case and bridge-to-bridge mode have very little to do with the normal functioning mode, insensitivity to dc signals in the normal firing mode (pin-to-pin) is no protection. Many 1 ampere -1 watt devices are more sensitive in the pins-to-case mode than EEDs designed to be considerably more sensitive in the normal functioning mode.

On the other side of the ledger many EEDs are far less sensitive to RF than they are to dc particularly in the pin-to-pin mode. In these cases assumption of the dc level as the sensitivity could so severely penalize the evaluation of the EED circuits as to make acceptable circuits appear quite hazardous.

All of these pitfalls can be avoided by adequate RF testing of the EEDs. Procedures and equipment are available which permit accurate determination of the amount of RF power required to be delivered to an EED in any functioning mode to produce functioning or degrading. The expense of the hardware required for such tests is frequently a deterrent, but more often than not it is false economy to avoid this step.

APPENDIX B

NOTES ON MULTIPLE SOURCES

While the analysis procedures discussed in this monograph assume that the magnitude of the incident RF field is already known it is frequently necessary for the engineer to make some judgments of this field himself. A classical case of this occurs when several RF sources exist at or near the same frequency and while an incident field can be calculated for each source, the question arises as to the effect of all of the sources combined.

It can be shown that the worst case average power absorbed (P_A) by a given load from n sources at the same frequency is given by

$$\bar{P}_A = \{\sqrt{P_1} + \sqrt{P_2} + \sqrt{P_q} + \ldots + \sqrt{P_n}\}^2 \qquad \text{(B-1)}$$

where P_q is the power supplied by the qth source with other sources quiescent and when the phase angles of the individual sources are chosen to maximize the simultaneous absorbed power. The use of the above equation as a worst case condition should be limited, however, to continuous wave sources of precisely the same frequencies. If the frequencies differ by even a small amount and average power (P_A) is defined as

$$P_A = \underset{q \to \infty}{\text{limit}} \frac{1}{q} \int_0^q P_I \, dt \qquad \text{(B-2)}$$

where P_I is the instantaneous simultaneous power, then the worst case average power is given by

$$P_A = P_1 + P_2 + P_q + \ldots + P_n \qquad \text{(B-3)}$$

where P_q is defined as before.

This equation is a worst case condition for either continuous wave or pulsed sources of differing frequency and in addition is independent of the starting times of individual pulses of the pulsed sources.

The technique of combining power densitities for closely spaced frequencies and then predicting worst case possible hazard at the widely spaced frequency groups so obtained is founded on the assumption that the worst case conditions assumed in the pickup analysis will not occur more than once in the entire frequency band of interest. Due to the complicated frequency dependence of many of the parameters that are worst case approximated we believe this assumption to be conservative. The alternative to this technique is to combine power densities at all frequencies and use this result throughout the frequency range of interest. In our judgement this technique is overly conservative.

APPENDIX C

NOTES ON FIELD TESTS

One approach to determining the extent of RF vulnerability of a system is to place the system in question in the fields of various RF transmitters and to observe the effects produced on the system components. This technique has been extensively applied to missile systems containing firing circuits terminated in electroexplosive devices (EEDs) but the basic technique is applicable to circuits containing components other than EEDs. If the data obtained are to be anything more than go/no-go information for the particular RF field intensity used it is necessary to put detectors in place of the components being evaluated; these detectors must give an indication of the amount of RF energy delivered to the component. In general this approach to hazard determination is particularly appealing because it is direct and appears to be a test which closely approximates the actual conditions which would exist in a operational situation. However, in most cases the technique falls somewhat short of the ideal.

Among the major problems in using this technique is the extension of information received on one system to other systems of the same type. The number of more or less uncontrollable variables makes any generalized correlation very difficult. For example, determination of the actual RF field incident on a given circuit at the time of test can be very difficult since environmental factors can greatly influence localized field strengths and variation of circuit orientation and circuit design from test vehicle to test vehicle can present a problem. Frequently, this situation is handled by using an arbitrary safety factor in connection with the results; in a sense, "worst casing" the field tests.

A more definitive problem grows out of the same problem that was discussed in the notes on EED sensitivity; i.e., the detectors used in the field tests consider only the pin-to-pin mode and are calibrated on the basis of dc sensitivity and with dc signals only.

There are two steps that can be taken to alleviate this problem. A full determination of the RF sensitivity of the devices under consideration removes any doubt involved in making inferences from dc values, and provides the information needed for precise calibration of the detector with RF signals in terms of sensitivity as a function of frequency, obviously preferable to assuming a sensitivity based on bridgewire heating. In addition it is possible to build detectors which will give some measure of the sensitivity in the pins-to-case mode or other modes; this would permit detection of the possibility of initiations in these modes. There are still, however, many questions to be answered about such detectors; and they can be used only if carefully calibrated in terms of the information obtained in the RF sensitivity evaluation of the EEDs themselves.

Programs are continuing in this field to solve these problems and others, and the situation is continually being improved. As in nearly any other approach to the RF problem, the technique can be valuable if one fully understands the limitations and properly qualifies the data obtained.

APPENDIX D

NOTES ON PROTECTION OF EED SYSTEMS AGAINST RF

Basically, there are three general methods commonly used to minimize the RF hazard to EED systems: Use of components less sensitive to RF; proper design of circuits; and use of RF filters. The first of these is somewhat out of control of the circuit designer. While it is possible to lower the RF susceptibility of an EED circuit by using less sensitive EEDs most manufacturers have as yet done comparatively little work on this phase particularly with respect to hazard modes other than pin-to-pin. Furthermore, most approaches to lowering the RF sensitivity in the pin-to-pin mode also make the EED considerably less sensitive to normal functioning signals thereby requiring larger power sources with increased weight. However, to the extent that he can, a designer should select EEDs that have no marked RF sensitivity.

The most straightforeward and certain protection can be gained by properly designing the circuits to minimize the RF hazard. In general this means that firing circuits should be separate from other circuits, wires should be twisted pairs, all circuits should be shielded end to end and through 360° and the shields should be grounded at as many places as possible. There are many specification documents that go into considerable detail on the proper design of EED circuits. However, in actual practice the designer often finds it difficult to comply with all of the requirements. The physical layout and the complexity of the system often force him to break the shields. Furthermore the wiring philosophy is often in conflict with other philosophies. The primary example of this is the multiple point grounds versus the single point ground philosophy. And yet the single point ground combined with discontinuous shields frequently leads to large pins-to-case RF pickup problems.

The third solution is the use of RF filters. Ideally these filters should be broadband, very light and small and should not affect the EED's dc firing characteristics. In addition, the filter should in no way compromise system reliability. The optimum solution would have the filter as an integral part of the EED; however this is not very common. It is more common to mount the filter separately but close to the EED. When this is done the wiring between the filter and the EED must be completely shielded.

While RF filters are a valid solution to the problem, the designer must be certain that the filter is capable of accomplishing the task he desires. To do this he must be certain of the information on the filters. The parameter of major interest is attenuation as a function of frequency. Frequently filter values are quoted in terms of insertion loss which has meaning only in the specific measuring system used. What is worse, occasionally attenuation, or true loss, is used interchangeably with the term insertion loss. If the designer is uncertain of how published data was obtained and is unable to find out, he should make certain the proper tests are performed.

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MONOGRAPH
ON
COMPUTATION OF RF HAZARDS

by

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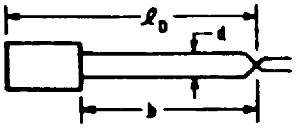
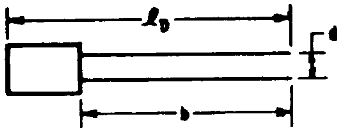
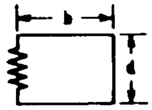
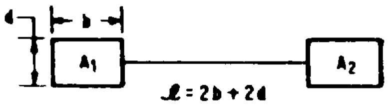
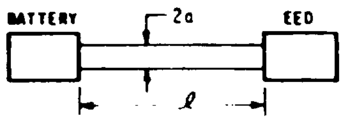
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

THE FRANKLIN INSTITUTE RESEARCH LABORATORIES

Table 4-1 - Summary of

	LOW FREQUENCY APE		
Configuration	**Equation (Pin-to-Pin)**	**Limit of Validity**	(F
WIRE LEAD DEVICE (SHORTED)  $\ell = 2b + 2d$	$A_e = \frac{4.67 \times 10^4 A^2}{\pi A^2 R_T}$	$\lambda \geq 2\ell$	A_e
CONNECTOR TYPE (WITH SHORTING CAP) 	$A_c = T_{wc} A$	$f_{MHz} \leq 10^5$ MHz	A_c
WIRE LEAD DEVICE (UNSHORTED) 	$A_e = \frac{4Z_0\ell^2}{R_T} \left(\frac{\beta d}{2}\right)^2$	$\lambda \geq 20\ell$	A_e
CONNECTOR TYPE (NO SHORTING CAP) 	$A_o = T_{wc} A$	$f_{MHz} \leq 10^5$ MHz	A_o =
ONE LOOP  $\ell = 2b + 2d$	$A_e = \frac{4.67 \times 10^4 A^2}{\pi \lambda^2 R_T}$	$\lambda \geq 2\ell$	A_e -
MULTIPLE LOOPS  $\ell = 2b + 2d$	$A_e = \frac{4.67 \times 10^4}{\pi \lambda^2 R_T} (n_1 A_1 + n_2 A_2 ---)^2$	$\lambda \geq 2\ell$ (Equal Loops)	A_e -
	" "	$\lambda \geq 2\ell$ = perimeter of smallest loop (Unequal Loops)	
 $A = 2\pi a \ell$	TOTAL APERTURE $A_{em} = \frac{P_o A}{P_1} = \frac{A}{P_1} \{ (1-Q) P_T [$ down 8.68		

nalytical Methods for RF Hazard Evaluation

RE				HIGH FREQUENCY APERTURE			
ation -to-Case)	Limit of Validity	Equation (Pin-to-Pin)	Overall Lead Length	Limit of Validity	Equation (Pins-to-Case)	Overall Lead Length	Limit of Validity
	HANDLING, TRANSPORT, AND STORAGE						
$\frac{\ell_D^2 Z_0}{\text{e}\ (Z_{po})}$	$\lambda \geq 10\ \ell_D$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ_D	$\lambda \leq 10\ \ell_D$
${}_{wo}{}^{A}$	$f_{MHz} \leq 10^5$ MHz	--	--	--	--	--	--
	INSTALLATION						
$\frac{\ell_D^2 Z_0}{\text{e}\ (Z_{po})}$	$\lambda \geq 10\ \ell_D$	$A_{em} = \frac{D\lambda^2}{4\pi}$	2ℓ	$\lambda \leq 20\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ_D	$\lambda \leq 10\ell_D$
${}_{c}{}^{A}$	$f_{MHz} \leq 10^5$ MHz	--	--	--	--	--	--
	INSTALLED (Shield Breakouts)						
$\frac{67 \times 10^4 A^2}{{}^2 Re\ (Z_{pc})}$	$\lambda \geq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$
$\frac{67 \times 10^4 A^2}{{}^2 Re(Z_{po})}$	$\lambda \geq 2\ell$ (Equal Loops)	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$	$A_{em} = \frac{D\lambda^2}{4\pi}$	ℓ	$\lambda \leq 2\ell$
"	$\lambda \geq 2\ell$ = perimeter of smallest loop (Unequal Loops)	"	ℓ	$\lambda \leq 2\ell$	"	ℓ	$\lambda \leq 2\ell$
	INSTALLED (360° Completely Shielded)			LIMIT OF VALIDITY			
dB $]$ + $Q\ P_T\ [$down $8.68\ \frac{t}{\delta}$ dB$]\}$				$f_{MHz} \leq 10^5$ MHz typical, but depends on shield characteristics			