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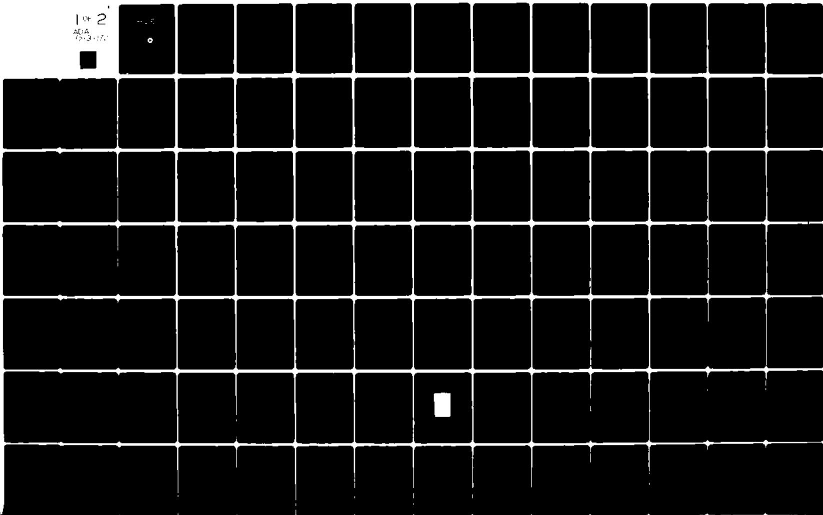

Report No. FAA-RD-80-11

FEDERAL AVIATION ADMINISTRATION-ELECTROMAGNETIC PULSE (EMP) PROTECTION STUDY: A REEXAMINATION AND UPDATE

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November 1979

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16. Abstract

In 1972, a study was performed to assess the potential effects of electromagnetic pulse (EMP) phenomenon on the Federal Aviation Administration electronic and electrical system. The purpose of this study is to update the previous investigation by incorporating existing and newly published results of EMP and its effect on new equipment which has been added to the FAA inventory.

The particular EMP model used is based upon the environment anticipated for a typical high altitude nuclear burst. The method of susceptibility assessment of the system has been to determine the effectiveness of protection at each of the various types of facilities in the FAA system.

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METRIC CONVERSION FACTORS

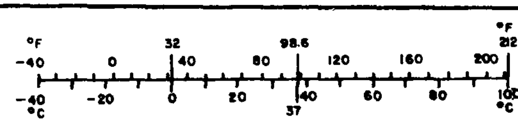
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This effort was conducted by Purdue University under the sponsorship of the Rome Air Development Center Post-Doctoral Program under the direction of Mr. Jacob Scherer. The Post-Doctoral Program is a cooperative venture between RADC and the sixty-five participating universities. Syracuse University (Department of Electrical and Computer Engineering), Clarkson College of Technology (Department of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other universities participating via sub-contracts with prime schools. The U. S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering) and Naval Post Graduate School (Department of Electrical Engineering) also participate in the program.

The Post-Doctoral Program provides the opportunity for faculty at the participating universities to spend up to one year full time on exploratory development and operational problem-solving efforts with the post-doctorals splitting their time between RADC (or the ultimate customer) and the educational institutions.

This effort was conducted via RADC for the Federal Aviation Administration. Mr. C. Andrasco was the FAA focal point and he participated closely in the technical coordination meetings as well as various phase of this study.

ACKNOWLEDGEMENT

The authors wish to acknowledge the contributions of Mr. Fred Sakate and Mr. C. Andrasco of the FAA and Mr. Jacob Scherer, of the RADC Post-Doctoral Program in formulating the program approach and for their guidance throughout the course of this study. Particular thanks are due to Messrs. E. Ellis and B. Brohman of Weir Cook Airport, Indianapolis, IN, Mr. Earl Neve of FAA Southeast Region and their associates for their splendid assistance and willing cooperation. They are indebted to Professor B. J. Leon of Purdue University for his support and encouragement.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

BIOGRAPHIES

Chin-Lin Chen was born in Honan, China on March 27, 1937. He received the B.S.E.E. degree from National Taiwan University, Taipei, Taiwan, China, in 1958, and the Ph.D. degree from Harvard University, Cambridge, Mass., in 1965.

He served as a teaching assistant at North Dakota State University from 1959 to 1961, and as a research assistant and Teaching Fellow at Harvard University from 1962 to 1965. From 1965 to 1966, he was a Research Fellow in the Division of Engineering and Applied Physics, Harvard University. In 1966, he joined the School of Electrical Engineering, Purdue University, West Lafayette, IN, as an Assistant Professor, and is now a Professor of Electrical Engineering. His research interests are in the areas of scattering and diffraction of electromagnetic waves, antenna radiation, surface acoustic wave devices, transient protection devices, the application of interactive computer graphics in electrical engineering education, and integrated optical components.

Dr. Chen is a member of Sigma Xi, Eta Kappa Nu, IEEE, SPIE, OSA and the American Society for engineering Education. Since 1966, he has been a reviewer for the IEEE Transactions on Antennas and Propagations.

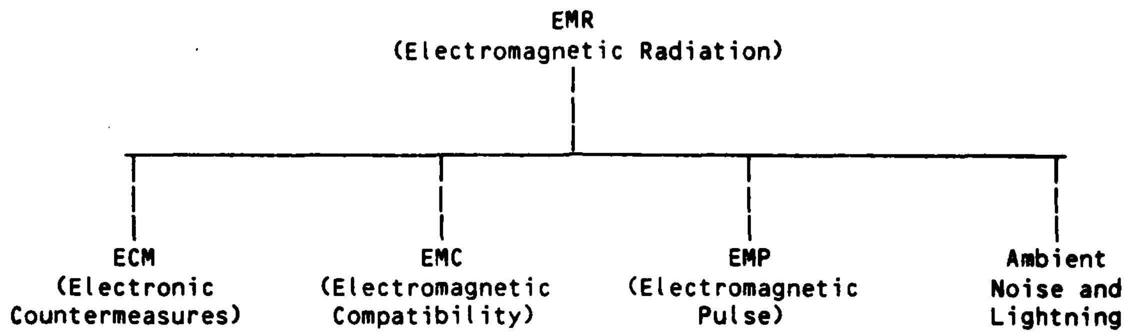
Warren D. Peele was Associate Professor of Electrical Engineering and Executive Officer of the Department of Electrical Engineering at the U.S. Air Force Academy. He joined the Purdue University, School of Electrical Engineering as a senior research engineer in July 1971 after receiving the BSEE degree (1964) and the MSEE degree (1965) from the University of Colorado. During his tenure at the Air Force Academy, he served as Project Engineer on the Post-Doctoral Program with research interests in synthesis and evaluation of communications-electronics systems. He was with ESD during the design and implementation of the NORAD Cheyenne Mountain Complex after serving eight years as an aircraft commander and pilot in SAC. Since 1970 he has worked in the areas of electromagnetic pulse and lightning protection. He is a senior member of the Institute of Electrical and Electronics Engineers, Armed Forces Communications Electronics Association, Eta Kappa Nu, and Tau Beta Pi.

CHAPTER 1

Introduction

In 1972, a study was performed to assess the susceptibility of the FAA system to the electromagnetic pulse (EMP) phenomenon. The purpose of the present investigation is to update the previous study [1] by incorporating existing and newly published results of EMP and its effect on new equipment. The particular EMP model which has been used is based upon the environment anticipated for a typical high altitude nuclear burst (see Chapter 2). Our method of susceptibility assessment of the system has been to determine the effectiveness of protection at each of the various types of facilities in the FAA system. These have included the control centers and supporting computer, the remote radars, short range radars, RCAG sites, the remote microwave relay sites (RML), control towers, RVR, Instrument Landing Systems, IFR rooms and related computers (ARTS III), runway and approach light systems. No effort was made to determine the susceptibility of the AT&T long lines system which supports the communications and radar data functions. At least one of each of these types of FAA facilities has been analyzed to determine effectiveness of existing building shielding (including nonconductive penetrations), the adequacy of protective devices on conductive penetrations, the adequacy of the grounding system, and the susceptibility of existing equipment to the EMP environment.

The EMP threat is actually a subset of the total Electromagnetic Radiation (EMR) problem which can be overviewed as shown here.



Electronic countermeasures (ECM) electromagnetic compatibility (EMC), and ambient noise/lightning effects round out the total electromagnetic radiation problem against which operating communications-electronics systems must be protected. In a gross fashion, one may consider EMP as the most difficult problem to protect against; but adequate EMP protection provides considerable protection against other elements of the EMR problem, particularly with respect to lightning and ambient noise. In some respects the incident fields, voltage and current surges resulting from nearby lightning strikes are similar to those caused by EMP, and this relationship is discussed in Chapter 2. Protection of facilities from the EMP environment will also control their vulnerability to all but direct-strike lightning effects, but standard lightning protection measures are generally not adequate to provide the desired EMP protection. The primary distinction is that the typical EMP field reaches its maximum intensity much more rapidly than the fields due to lightning, and EMP protective devices must therefore be able to react very rapidly. Protection against both threats can be provided by modifying and extending the usual lightning protection measures, and by increasing the shielding provided by the buildings within which the FAA's air traffic control equipment is housed.

It would be expected that the FAA system is susceptible to interruption and damage by an EMP environment. During the time period in which most systems were planned and designed little was known about EMP and in particular, about the high altitude (exo-atmospheric) phenomenon. The knowledge that was available was held suspect by many. Little was done anywhere to overcome the threat that EMP poses to the civilian sector of the community. The importance of EMP was not assessed as readily as the more obvious nuclear weapons effects such as blast, fire and ionizing radiation. The high altitude threat is particularly insidious. Systems which are well out of range of all other effects can still be severely damaged in ways which are difficult to predict and costly to remedy. For example, an exoatmospheric burst of average intensity over Saint Louis would result in peak field strengths of the order of 50,000 volts/meter over the entire contiguous continental United States, as well as a major portion of the remaining North American continent. In contrast, an average intensity burst near ground level results in rapid deterioration of field strength with distance to approximately 200 volts/meter at 1,000 km, 14 volts/meter at 5,000 km, and 1 volt/meter at 10,000 km [2]. The previous study concluded with a recommendation that all FAA building and equipment should provide a shielding of 60 dB at 10 kHz. It is believed that this recommendation is still valid.

Assuming the environment specified in Chapter 2, it is highly unlikely that the FAA system will be able to perform its mission during such conditions, and the aircraft control situation will be chaotic. Some of the equipment is exposed to the full strength of the EMP environment. These include the radar and microwave towers, the radar tower electronics, and electronic equipment within the control tower cabs. Other equipments which are housed in partially shielded buildings will be exposed to a threat that is somewhat attenuated. On balance the susceptibilities seem nearly equal since the more susceptible equipments are presently housed in the better protected facilities. In view of the current progress in changing over to integrated circuit devices and buildings with composite material, it seems logical to assume that all facilities will depend upon extra shielding enclosures during the time frame of interest. Examples of this modernization are: the installation of the common digitizers in the remote radar sites, solid state modulation-demodulation equipment in the microwave relay facilities, and digital computers in control towers. Enough solid state equipment is already installed in each system to justify the assumption that all types of facilities must be hardened to a level commensurate with their sensitivity.

Applying the existing hardness figures for each type of facility which is described in the appendices, our conclusions are that: computers will fail at the centers and towers, digitizing equipment will fail at remote radar sites, and the new modulation-demodulation equipment will fail at the RML facilities. The various mechanisms by which energy will couple to these devices are discussed in Chapters 2 through 5 and the supporting appendices. Communications are likely to be disrupted for a variety of reasons: soft local telephone systems, AT&T microwave system, atmospheric ionization, and communications equipment damage. Ample justification for these pessimistic conclusions is found throughout the report.

This bleak outlook is mitigated somewhat in certain facilities because they are already partially protected. Thus the job to be done is one of increasing the protection of partially shielded facilities rather than having to shield facilities which have no inherent hardness.

Specific recommendations for hardening are given in the appendices. Assuming that the system is to be protected, some more general items for consideration are offered here.

(1) Critical Site Concept

Due to the geographical expanse of the system and the numerous sites and equipment involved, a practical approach to the EMP protection problem may be a critical site concept. Such a concept would involve the identification of certain geographical areas, and therefore certain sites and communications links, which are considered essential during a nuclear threat situation. Then only these sites would be protected to the recommended levels, resulting in a large savings in the total protection cost.

(2) Signal Routing

In the present FAA system, radar data are transmitted over the FAA microwave system, with only one or two exceptions where buried lines are used, as at Indianapolis. Most voice communications are carried over the AT&T system, which is largely microwave, but includes some buried and elevated cables. Some backup channels are provided by the FAA microwave links to the long range radar sites. Installation of the common digitizer would ostensibly obviate the need for the FAA microwave system since the AT&T system could then accommodate the digitized radar data. At first glance this would provide path redundancy via the AT&T system. However, redundancy does not improve system reliability significantly. Since EMP is relatively uniform over thousands of square miles, even a low probability of interaction with individual segments of the system could result in significant interaction with the system. The hardness of the AT&T long lines microwave sites has been assessed only for those systems involved in the Sentinel system, and that data is about 10 years old. Unless the AT&T system is to be hardened, it is recommended that the FAA maintain its own hardened microwave system. An adequate number of backup voice communications channels should be maintained on the hardened FAA microwave system.

(3) Hardness Assurance Program

The necessity for protection against EMP is appreciated by most personnel at the technician level. However, many hardened facilities rapidly become soft through "normal" maintenance, addition of new equipment, and general deterioration of protective devices. A vigorous, on-going program of periodic inspections to ensure that EMP integrity is maintained is a necessity. After initial installation of protective equipment verification of shielding effectiveness should be accomplished on a sampling basis. Such testing would not only determine the quality of shielding but would provide a "benchmark" against which future results could be compared.

References

[1] W. D. Peele, V. Eveleigh and A. Ravay, Jr., "FAA Electromagnetic pulse (EMP) protection study," Report No. FAA-RD-72-68, (June, 1972).

[2] Chang, Hsi-Tien, "Interaction of Electromagnetic Radiation with an Airplane", Purdue 1972 Symposium on Electromagnetic Hazards, Pollution, and Environmental Quality, (May 8-9, 1972), Purdue University, Lafayette, IN.

CHAPTER 2

The Nuclear Blast and the Characteristics of the High Energy Electromagnetic Pulse (EMP) Phenomenon

The detonation of a nuclear weapon produces many extreme effects. We are not concerned with the detailed physical and electrical phenomena of the blast other than those which give rise to high intensity electromagnetic pulse (EMP) radiation. Nuclear bursts are generally classified as ground level, atmospheric or above ground by at least several thousand feet but well within the atmosphere (below 80-100,000 feet), and exoatmospheric or outside the atmosphere (above 100,000-200,000 feet). We will focus our attention here upon the exoatmospheric case, since this results in the widest range of electrical threat without danger of physical damage, and the electrical threat it produces is typical of the spectrum of events which might be anticipated. The terms "high altitude burst" are used interchangeably with "exoatmospheric burst" in much of the literature, and we will likewise use these terms interchangeably.

In subsequent sections we will describe briefly events leading to EMP. The typical EMP pulse is defined mathematically and spectrally decomposed, thereby defining the EMP frequency threat to electrical and electronic equipment. Much of the material presented here has been derived from Ref. [1], [2] and [3].

2.1. The Nuclear Burst Phenomenon

A nuclear blast involves the virtually instantaneous release of an extremely large amount of energy in a very small volume of space. For a high altitude burst, this energy is dissipated primarily in the form of heat, particle radiation, and electromagnetic radiation. Low altitude or ground bursts result in a significant part of the energy being dissipated in the pressure front, so the radiated components make up a smaller percentage of the total energy and they are attenuated more rapidly in passing through the atmosphere. Because the high altitude burst is representative of the typical EMP environment and results in radiated energy which may cover large areas at ground level. Since this environment could very likely be introduced often in a nuclear encounter involving retaliating missiles, we will concentrate upon the high altitude phenomenon.

The EMP phenomenon is electromagnetic in nature and has often been compared to lightning. Although both can result in large induced currents and voltages in electrical equipment, there are significant distinctions between the two phenomena. EMP and lightning are compared in a general way in Section 2.2.

For nuclear explosions well above the atmosphere, as illustrated in Figure 1, an intense burst of gamma rays is released and these gammas lie in a spherical shell whose radius expands at the speed of light. The downward motion of the shell begins to interact with the atmosphere at altitudes of 40 to 50 km. Most of the gammas are absorbed by the atmosphere by the time they reach the altitude of 30 km. As the gammas travel in the atmosphere, a large flux of Compton recoil electrons as well as positive ions are generated. These electrons and ions move generally away from the energy source, the electrons moving much more rapidly due to their lower mass, and additional particles are dislodged as subsequent atoms are encountered. Because the electrons move away from the source region much more rapidly than the heavier positive ions, a net current flow toward the source region occurs initially, followed by a net current flow away from the source region as the charged particles start to recombine under the influence of the electric field caused by the charge displacement. This movement and displacement of

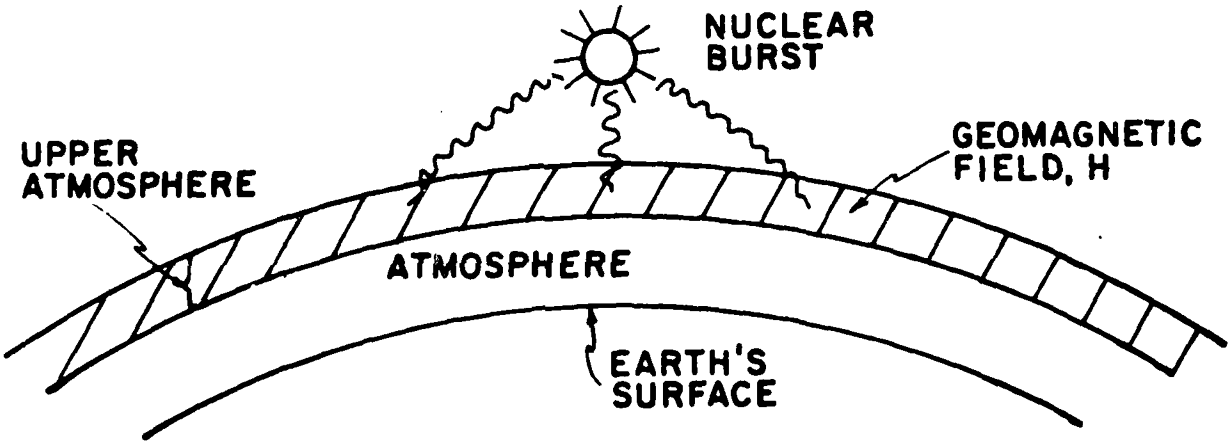


Figure 1. EMP radiation phenomena as produced by high altitude nuclear burst.

charged particles is the source of the high intensity EMP phenomenon with which we are concerned. It would not be unusual for peak field intensities of the order of 5×10^4 v/m to be introduced by a single high altitude blast over an area of the earth's surface comparable to the entire contiguous continental United States. It is this type of representative threat that we are attempting to protect against. The detailed EMP characteristics such as the pulse width, rise time and spectral content are considered in Section 2.2.

2.2. Typical EMP Characteristics

The specific fields produced by a high altitude burst will vary widely in amplitude, time dependence, and orientation, depending upon factors such as weapon yield, height of burst, relative location of the observer, and orientation of the geometry with respect to the earth's geomagnetic field. Typical variations of field strength with time which will not be exceeded by any significant amount, but which are also fairly close to the average situation encountered, are defined in [1], and will be used as a reference here.

Several waveforms of the radiated field from high altitude explosion have been published [1], [2], [3]. The usual waveforms used extensively in literatures as well as in civil defense studies are:

$$\text{Pulse A:} \quad E_a(t) = E_{01}\, f_\ell(t) \qquad (2.2.1)$$

$$\text{Pulse B:} \quad E_b(t) = E_{02}\, f_\ell(t) \qquad (2.2.2)$$

$$\text{Pulse C:} \quad E_c(t) = 1.2\, E_{01}\, f_s(t) \qquad (2.2.3)$$

$$\text{Pulse D:}\quad E_d(t) = 1.2\, E_{02}\, f_s(t) \tag{2.2.4}$$

where $E_{01} = 5.2 \times 10^4$ v/m

$E_{02} = 2.3 \times 10^4$ v/m

$$f_\ell(t) = \begin{cases} e^{-1.5\times10^6 t} - e^{-2.6\times10^8 t} & \text{, for } t > 0 \\ 0 & \text{, for } t < 0 \end{cases} \tag{2.2.5}$$

$$f_s(t) = \begin{cases} e^{-1.5\times10^7 t} - e^{-2.6\times10^8 t} & \text{, for } t > 0 \\ 0 & \text{, for } t < 0 \end{cases} \tag{2.2.6}$$

and t is time in seconds.

Waveform $f_\ell(t)$ represents a typical long pulse while $f_s(t)$ represents a relatively short pulse. Pulses A and C are good approximations for the horizontal component of E field in the high latitudes and pulses B and D are more typical for the vertical component of the E field.

A slightly complicated waveform has also been used to represent a typical EMP pulse [1]:

$$\text{Pulse E:}\quad E_e(t) = E_{01}[f_\ell(t) - 0.221\, f_c(t)] \tag{2.2.7}$$

where
$$f_c(t) = \begin{cases} e^{-2.0\times10^5 t} - e^{-5.0\times10^5 t} & \text{, for } t > 0 \\ 0 & \text{, for } t < 0 \end{cases} \tag{2.2.8}$$

The first part of $E_e(t)$, i.e. $f_\ell(t)$ produces a pulse with a rise time of 20 nanoseconds (2 shakes) and a width at the half maximum of 450 nanoseconds. The second part of Pulse E produces a negative pulse which lasts for about 25 microseconds. The existence of the negative pulse is postulated primarily on a theoretical basis, and it serves to force the time integral of the pulse to zero, as must be true if the charges displaced by the burst effects eventually recombine. The positive duration of the pulse is essentially the time it takes for the maximum charge displacements resulting from the blast to occur. The total pulse duration is indicative of the time it takes for the field in the upper atmosphere to relax or for most of the charges to recombine.

Figure 2 shows sketches of these pulses. The dependence of the magnetic fields H is of the same general form. As a matter of facts, H may be approximated by $H=E/\eta_0$ where η_0 is the free space intrinsic impedance and is numerically 377 Ohms. The orientation of E and H are arbitrary, except that E and H are generally perpendicular to each other. Of course, the actual field polarization will depend upon the burst-observer geometry.

The field components described above are the incident fields only. In general, the fields reflected by the earth's surface are not negligible and should be taken into account. Strictly speaking the reflected field can either add to or subtract from the incident field depending on the geometry and polarization. However, for the present purpose, we can simply assume that the incident and reflected fields interfere with each other constructively.

The spectral energy distribution, as a function of frequency, is obtained by Fourier transforming (2.2.1) - (2.2.8) to give:

$$\tilde{E}_a(\omega) = E_{01}\ \tilde{f}_\ell(\omega) \qquad (2.2.9)$$

$$\tilde{E}_b(\omega) = E_{02}\ \tilde{f}_\ell(\omega) \qquad (2.2.10)$$

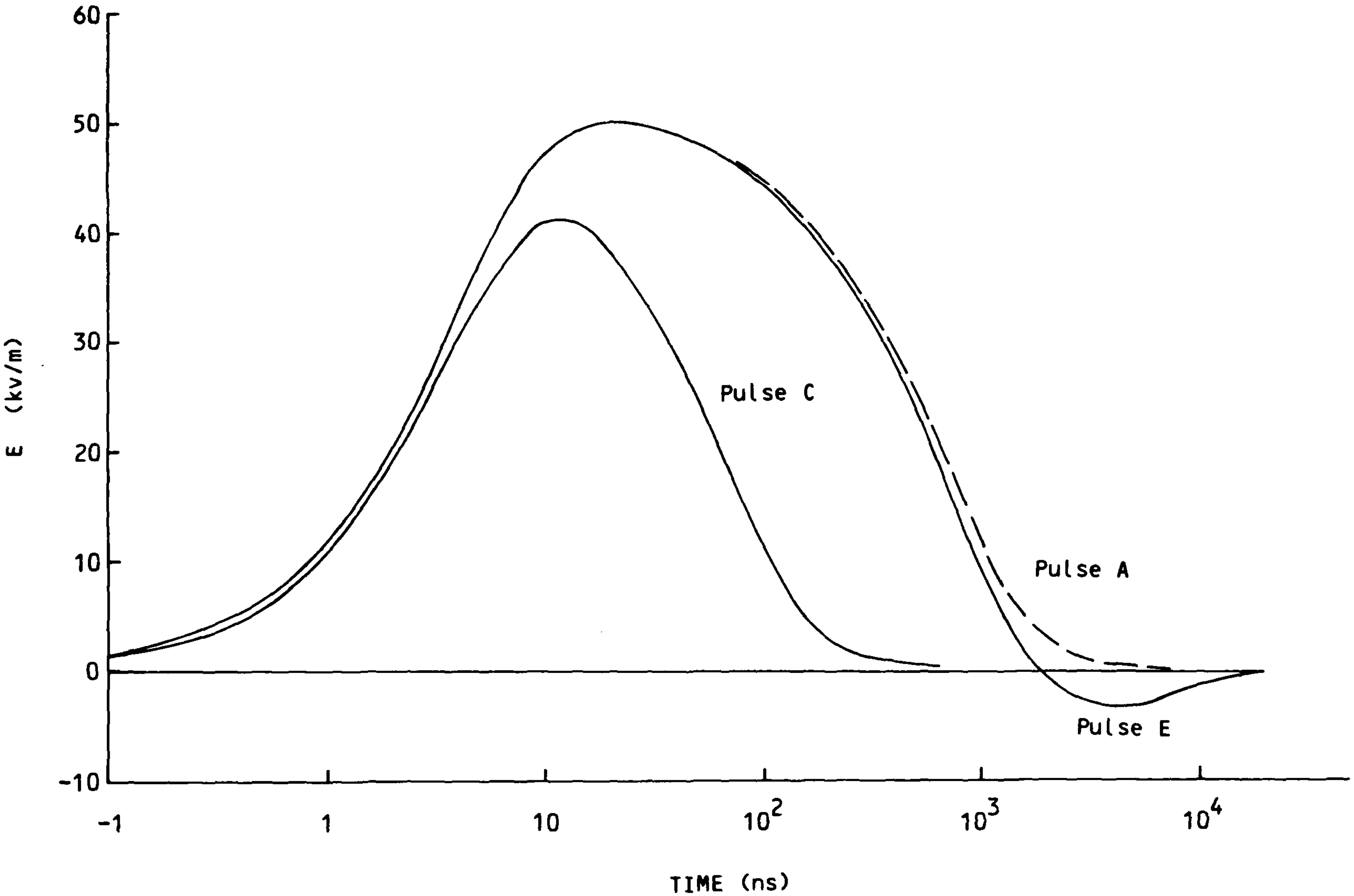


Figure 2. Electric field strength vs time for the representative EMP fields. (Pulses B and D are similar to and weaker than pulses A and C respectively.)

$$\tilde{E}_c(\omega) = 1.2E_{01}\ \tilde{f}_s(\omega) \tag{2.2.11}$$

$$\tilde{E}_d(\omega) = 1.2E_{02}\ \tilde{f}_s(\omega) \tag{2.2.12}$$

$$\tilde{E}_e(\omega) = E_{01}[\tilde{f}_\ell(\omega) - 0.221\ \tilde{f}_c(\omega)] \tag{2.2.13}$$

where

$$\tilde{f}_\ell(\omega) = \frac{1}{1.5\text{x}10^6+j\omega} - \frac{1}{2.6\text{x}10^8+j\omega} \tag{2.2.14}$$

$$\tilde{f}_s(\omega) = \frac{1}{1.5\text{x}10^7+j\omega} - \frac{1}{2.6\text{x}10^8+j\omega} \tag{2.2.15}$$

$$\tilde{f}_c(\omega) = \frac{1}{2.\text{x}10^5+j\omega} - \frac{1}{5.\text{x}10^5+j\omega} \tag{2.2.16}$$

and j is the usual imaginary argument designation and $\omega = 2\pi f$ is the radian frequency. The energy content versus frequency is proportional to $|\tilde{E}|^2$, the energy density function, which is shown in Figure 3. The data are normalized to 0 dB at the peak value. Take Figure 3 as an example, the peak occurs at $f_0 \cong 70{,}000$ Hz., and the peak value of $|\tilde{E}_e(\omega)|^2$ is approximately 0.00119 volts/m^2-Hz, which corresponds to (0.00119/377) joules/m^2-Hz. Thus, the total energy per Hz passing through a one m^2 area at the peak frequency f_0 = 70,000 Hz is (0.00119/377) joules, or 3.60 x 10^{-6} joules per m^2 per Hz of bandwidth. Fortunately, the energy level falls off rapidly with frequency on both sides of the peak.

Because of the large ranges of power levels and frequencies involved, a logarithmic scale is used for frequency, and the ordinate is presented in decibels (dB) in these figures. The term decibels are defined by

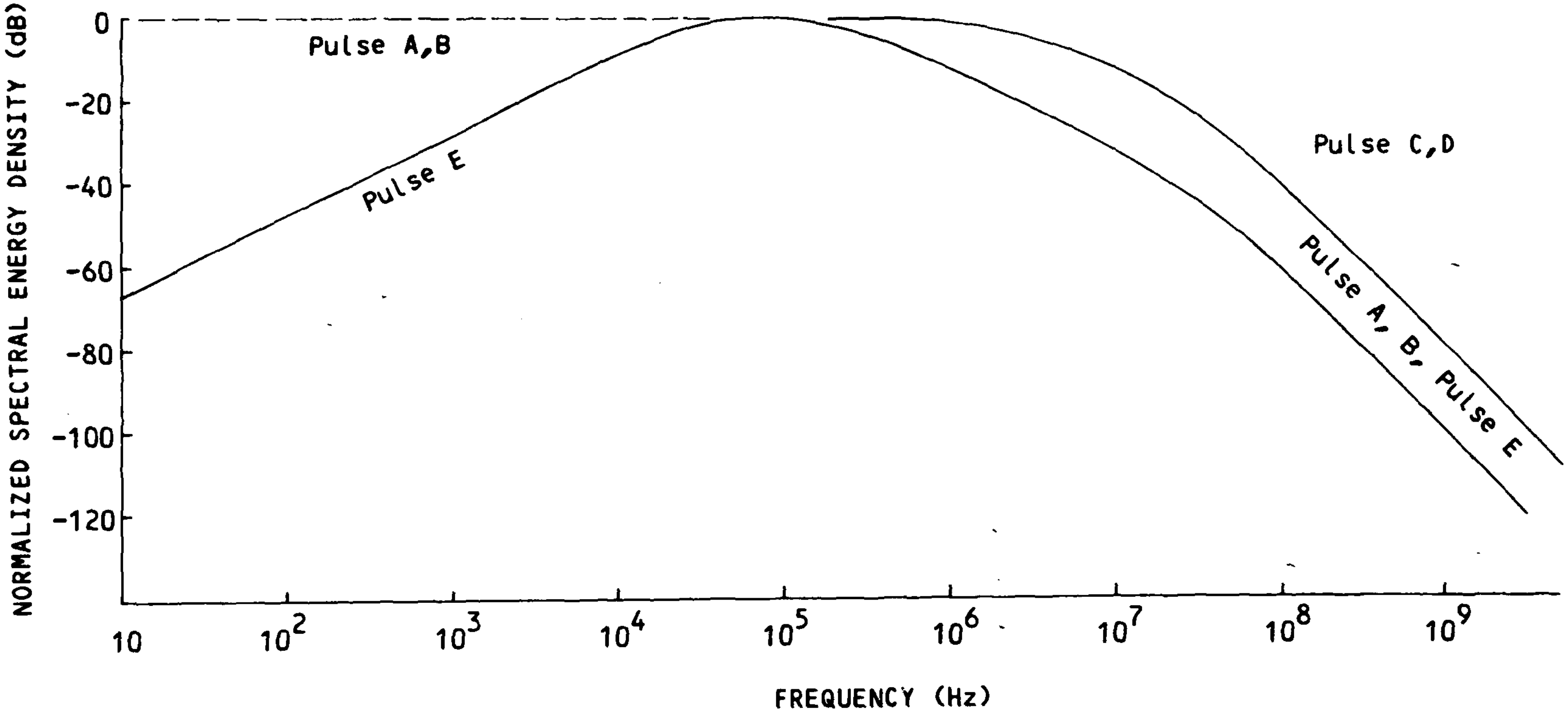


Figure 3. Spectral energy density for the typical EMP waveform `1.

$$G(\omega) = 10\log_{10} \frac{|E_i(\omega)|^2}{|E_i(\omega_0)|^2} \qquad (2.2.17)$$

The level of signal energy which is potentially damaging to equipment or could at least cause interruption of normal operation varies so much from one situation to another that it is difficult to establish absolute upper and lower frequency cutoffs for this spectrum. The EMP energy spectrum is definitely broadband in nature. A cursory study of Figure 3 shows that the spectral content of a typical EMP is roughly equivalent to the spectral band used by AM, shortwave, FM radio stations and VHF and UHF television stations. The peak is near the standard broadcast band, so fairly significant energy can be coupled through broadcast channels with little attenuation, thereby potentially causing damage to sensitive detectors and low power amplifiers.

Because of its broadband nature, the protection of equipment from damaging and/or disruptive effects of EMP is a challenging task. In most cases the frequency range of concern is from about 100-1000 Hz at the low end to 10^7 - 10^8 Hz at the high extreme. It has been recommended for Emergency Centers, which have a variety of communications and computer equipment similar to that used by the FAA, that about 80 dB of attenuation is necessary for the electric and high impedance fields in the range from 10^4 Hz to 10^5 Hz [1]. Similar attenuation levels should be appropriate for the typical FAA control center facilities.

It is of value to obtain the total energy density in joules per meter squared corresponding to the assumed threat pulse. The total energy in the pulse corresponds to the energy passing through a one meter square area and is given by

$$ {}_T = \int_0^\infty E(t)\, H(t)dt = \int_0^\infty \frac{E^2(t)}{377}\, dt \qquad (2.2.18)$$

If $E_e(t)$ is substituted in the above equation, we would have ${}_T$ = 2.5 Joules/m^2. This is only a representative figure. It is fairly common to use a somewhat narrower threat pulse approximation with a 50,000 Volt/meter peak, which results in lower values for ${}_T$. Numbers in the range from 1.0 - 2.0 Joules/m^2 are commonly used for ${}_T$. The exact value is of little consequence since it is only representative anyway. The EMP pulse approximation we are using here is a conservative one.

2.3. Comparison of Nuclear EMP to the Effects from a Lightning Stroke

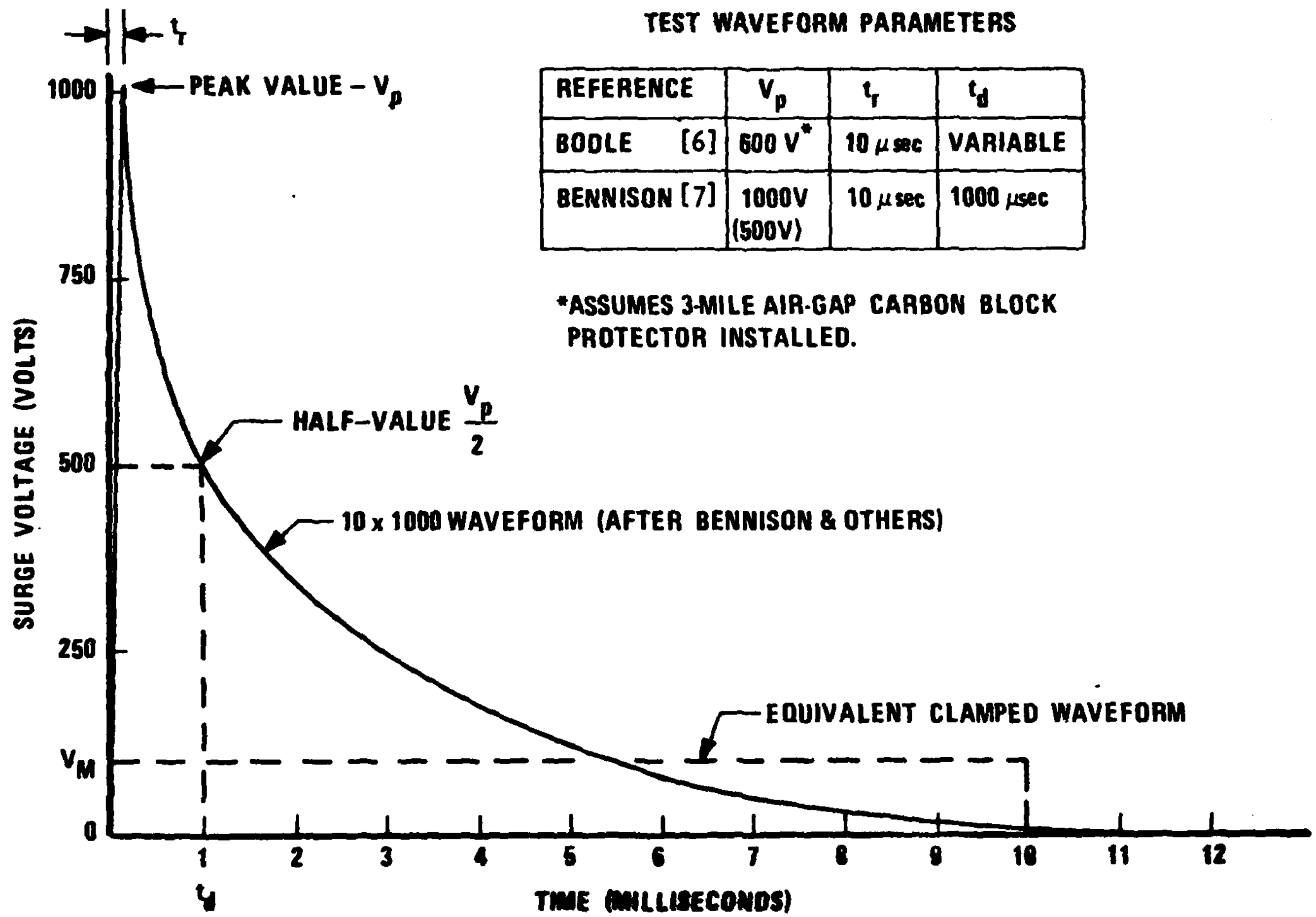
Although there are some similarities between EMP and lightning s rokes, they are caused by vastly different phenomena, and their distinctions are more pronounced than the similarities from the standpoint of what it takes to protect against each.

The similarities are easy to list. Both EMP and lightning result in large induced voltages and currents on long wires or other conductors. Both generate large electromagnetic fields for short time periods. But here the likeness ends. Before commenting on the difference between EMP and lightning related disturbances, it is appropriate to describe the basic characteristics of lightning induced surges.

Very little is known relative to the waveforms of the fields radiated by lightning strokes. However, huge amount of statistical data related to the current and voltage surges induced on the power or telephone lines or cables have been collected [5], [6] and [7]. These data indicate that a worse case surge voltage waveform can be adequately described by three parameters: rise time t_r to peak amplitude, the peak amplitude V_p, and the decay time t_d to one-half of peak value. (All times are measured from the origin.) Such a test waveform is shown in Figure 4 along with a table of waveform parameters cited in the literature. The test waveform parameters are based on long-term studies of actual surges on aerial and buried telephone cables. Statistically, the parameters cited by Bennison [7] yield a test waveform which includes 99.8% of lightning-induced voltage surges in open wire and cable. Actually, Bennison's study included buried cable with measured peak voltage of 440 volts; this fact is included in the table of Figure 4 as the 500-volt entry in parentheses.

The main difference between the lightning induced interferences and nuclear EMP is the risetime and duration of the pulses. As mentioned in the last section, a typical EMP as shown in Figure 2 has a risetime of the order of 20 ns, and a decay time of the order of 450 ns. In comparison, it is noted that the risetime and decay time of a "typical" lightning induced voltage pulse are of the order of 10 μs, and 500 to 1000 μs respectively, as shown in Figure 4.

The spatial distribution of these two types of disturbances are also quite different. For nuclear EMP, the electromagnetic field is distributed fairly uniformly over a wide area. Since the wires and cables are illuminated by an uniform field, the current and voltage pulses induced on the wires and subsequently incident upon the terminal or equipment are proportional to the length of the wires or cables connected to it. For lightning strokes, the field decays rapidly, and its radiated field affects only a restricted area directly. Thus the current and voltage pulses induced by the lightning strokes is relatively independent of the length of the wires or cables which guide the surges [9].



TEST WAVEFORM PARAMETERS

REFERENCE	V_p	t_r	t_d
BODLE [6]	600 V*	10 μsec	VARIABLE
BENNISON [7]	1000V (500V)	10 μsec	1000 μsec

*ASSUMES 3-MILE AIR-GAP CARBON BLOCK PROTECTOR INSTALLED.

Figure 4. Test waveform for lightning-induced voltages on buried control cables. [After [8]]

In protecting systems against EMP, it is important to insure that the protective devices used will react rapidly enough to protect against the very sharp leading edge. Devices used to protect against lightning surges are often not fast enough. If a given device will handle the typical EMP currents and reacts fast enough for EMP protection, however, it is probably adequate for lightning protection purposes.

2.4. The Methods by Which EMP May Cause Damage

The general conditions under which EMP may pose a threat to an installation may be broken down roughly into three categories:

1. Within the source region;
2. Outside the source region, but near a surface or atmospheric burst;
3. Within the large region illuminated by a high altitude, (exoatmospheric) burst.

We are not concerned with categories 1 or 2, since the affected areas are relatively restricted and only hardened sites can survive these conditions physically. Protection against the category 3 threat will assure that all equipment which can survive without physical damage will not be electrically damaged.

Most of the damage caused by the EMP threat occurs due to several fairly simple effects. The strong electromagnetic fields are converted into large voltages and currents on any power lines, towers, cables, conducting loops, etc. These large currents and voltages, which rise very rapidly, can destroy sensitive components, open protective relays, thereby requiring a recycle procedure, etc. Semiconductor devices are particularly sensitive to voltage and current surges. The strong fields associated with EMP may destroy computer memory, cause logic circuits to be randomly disarranged (thereby destroying computer or other electronic device effectiveness at least temporarily) and cause all sorts of similar results. EMP also produces severe distortion and disturbance of radar and communications systems, at least during the pulse itself. The degree of permanent damage, if any, depends upon such factors as frequency range, bandwidth, antenna size and orientation, and the types of components involved. Protection against this EMP threat thus involves several facets, each of which is addressed in one or more other sections of this report.

The effects of EMP may range all the way from temporary interference, as with a communications channel or a computer in which a sequence of calculations are caused to be in error, to permanent damage, as would result if a semiconductor detector or rectifier is burned out. Other intermediate effects such as computer memory destruction, requiring reprogramming and/or reinitialization, or interruption requiring system recycling to get back on the air are also possible. We are primarily concerned with protection to a level which will prevent hazards to personnel and destructive damage to equipment. Temporary interference, including complete loss of correct data for a short period such as a few seconds, can be tolerated by the system, but damage requiring component replacement and/or keeping the critical radar, communications, and processing equipment off the air for more than a few seconds must be avoided if the air traffic control system is to remain operative. Computer memory destruction would be particularly critical since, in addition to destroying past data, it could result in loss of the control program for the entire computer support system.

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CHAPTER 3

Radiated Interference

Radiated interference as used here applies to those effects which are caused by illumination of susceptible devices by undesirable and uncontrollable electromagnetic fields. Protection against radiated interference consists primarily of shielding; that is, reflection or absorption of energy. It is customary to classify the fields as the high impedance or low impedance fields. Here the term impedance refers to the ratio of the electric field to that of the accompanying magnetic field, E/H. In the regions close to electric charges, the electric field is quite strong and the magnetic field is rather weak. The ratio E/H, which has a dimension of Ohm/meter, is large and hence the name high impedance fields. Electric conductors, like copper or aluminum, are the idea material to use as shields against strong electric fields. On the other hand, for regions near electric current sources, the magnetic field is strong and the ratio E/H is small. To protect against this type of low impedance fields, the primary consideration is to attenuate the magnetic fields. The ideal material for this type of application would be "magnetic conductors". However, no such material exists, magnetic material, i.e., material with high magnetic permeability, such as iron or low-carbon steel, etc., are used instead. For the cases mentioned above, the ratio is determined not only by the source and the media involved, but also the distance between the source and point of observation. For regions far away from the sources, the ratio of E/H is roughly independent of the type of source involved and is approximately given by the intrinsic impedance of the medium. For example, in air or free space, the ratio is 377 Ohms/meter.

3.1 Direct Field Penetration through Walls

Shielding enclosures of interest in EMP considerations fall into three categories: solid shell enclosures, metallic mesh enclosures, and enclosures which are constructed with reinforcing bars.

Thin solid shell enclosures of highly conductive material (e.g., copper, aluminum) provide excellent protection against the high impedance electric field. For protection against low impedance magnetic fields, thicker and more permeable materials (e.g., iron, low carbon steel) are required. The magnetic field threat is present at distances relatively near the burst, a region in which other effects would predominate. The type of electromagnetic threat that FAA facilities are likely to experience is predominately the high impedance, electric field phenomenon.

The existing FAA centers present a variety of partially solid shell shielding configurations to an impinging wave. All of the solid shell is located at the centers (none at remote sites) and was probably installed for other purposes. For example, the exterior walls of the automation wings of the centers are covered with sheets of 20 gauge galvanized steel, backed by three inches of insulation and an inner liner of 22 gauge galvanized steel. These sheets are present only on the walls of the automation wings and the exterior of the control room and do not cover the interface between the control room building and that part of the older building which is used for administration. The ceiling of the first floor of the automation wing is covered with two sheets of 14 gauge metal. Disregarding, for the moment, the absence of siding on one side, proper installation of the metal roof and siding could have provided at least 60 dB at attenuation at 10 kHz and rising to 100 dB at 100-150 kHz. Attenuation would increase with frequency throughout the spectrum of interest up to the point where penetration through openings becomes significant.

Because the older buildings were designed without regard for the EMP environment, shielding effectiveness is considerably less than would have been possible if additional precautions had been taken during construction. This could have been done at a relatively low cost. The metal siding is not continuous around the building sides (e.g., the interface with other buildings); the metal siding ends approximately five feet above the ground level (architects design); the metal siding and roof of the first floor are not continuously-electrically bonded; the outer metal siding was dipped in tar and painted prior to installation; severely degrading the shielding effectiveness by insulating the sheets; the sheets of siding are attached to structural members by metal screws every 2-3 feet thus providing poor electrical contact with the grounding system.

From the above observations it appears the walls and ceiling of the automation wings could have provided excellent attenuation to an electromagnetic pulse at a small increase in cost if the EMP threat had been defined before the buildings were designed and appropriate precautions taken. Some towers, the remote radars, remote microwave link (RML), and remote air/ground communications (RCAG) sites are housed in non-metallic structures, like fiberglass or other composite material. These structures offer little or no shielding benefit at all.

The metallic mesh structures frequently used in wall construction can provide significant attenuation to RF signals. For example, mesh of four inch squares, which is well bonded and forms a complete enclosure, can provide attenuation in the range of 23 - 34 dB, at 10 kHz, depending on the size of the enclosure. In order for the metallic mesh that is installed in walls for structural purposes to provide appreciable attenuation it must be bonded to a good ground system; otherwise, a minimal amount of reflection occurs with the result being only a few dB of attenuation. In the FAA buildings, none of the wall screen was designed or installed to function as an electromagnetic barrier. Therefore, any shielding provided by these structures is small.

For better protection of sensitive, relatively small interior areas the so called "screen room" is effective but frequently awkward to use. For example, a commercial enclosure of 22 mesh, 15 mil copper wire will provide attenuation of 40 dB at 10 kHz rising to 74 dB at 1 MHz.

The steel reinforcement bars (rebars) used in concrete construction provide some shielding from electromagnetic fields if the bars are interconnected electrically at each junction to form a continuous set of loops around the building. The bars must be welded or otherwise connected together such that the electrical contact resistance at joints is comparable to the resistance of a loop made from a continuous bar. In general, rebar construction provides considerably less shielding than solid metal walls, but the degree of shielding may be adequate for some equipment. Remote radar site buildings, RML buildings, control towers and RCAG sites all contain rebar which could have provided shielding in the range of 20 -30 dB for frequencies such that wave length is much longer than the rebar spacing.

For the case of remote radar sites the present shielding appears adequate for the relatively nonsusceptible tube type equipment housed within the structure, but it is inadequate for solid-state equipment.

At present the shielding of the control tower equipment buildings is inadequate because of the solid state computers which are in use (e.g., O'Hare Tower). These structures presently have protection only from rebar. They would be somewhat expensive to protect by solid shell shielding of the entire structure. It appears that internal shielding of computers and cable runs may be adequate.

The RML sites are inadequately shielded for solid state equipment. However, these structures are relatively inexpensive to shield because of their structural simplicity.

3.2. Field Penetration Through Apertures in the Walls

When a shielding enclosure is properly designed and constructed, ideally it will have no opening or apertures in the electromagnetic sense. Well known methods are available to provide the necessary openings into the structure while maintaining electromagnetic shielding integrity. Openings for doors, hatches, ducts etc. require special shielding or protective techniques. Metallic hallways can serve as excellent high-pass filters under appropriate conditions, thus allowing personnel entrance without cumbersome and expensive metal doors for shielding. Hatch type penetrations can be effectively hardened by proper bolting and bonding. Air duct penetrations can be effectively shielded by use of metallic honeycomb which functions as a stack of very small waveguides. All of these types of unprotected penetrations are present in FAA facility buildings examined. Due to the relative softness of the buildings it would not be logical to provide protection at these penetrations prior to improving the building shielding because the effects of the fields entering these penetrations is insignificant when compared with the fields that penetrate the enclosure walls. (See Appendix C.)

3.3. Interior Fields Radiated from Connecting and Penetrating Structures

Cables, pipes, waveguides and other conductive penetrations into a shielded enclosure can couple damaging electromagnetic energy into the buildings. In order to estimate the energy coupled to the system by an exposed conductor it is necessary to know the characteristics of the penetration and the apparent load on the conductor. All metallic penetrations of the facility should preferably enter at one location and should be electrically bonded to the exterior surface of the building shield or to a grounding plate which is connected to earth if no overall building shield is available. Care should be taken in routing pipes, conduits and cables so as to avoid unnecessary proximity to sensitive equipment.

In the case of the FAA facilities examined, water, sewer, power conduits and signal conduits do not enter at a common location. Some are grounded at the entry point and some are not. In some cases water and sewer pipes have been routed overhead in the telephone room. The FAA microwave waveguide penetrates the building below the metal siding of the building and is poorly bonded to the ground ring or not grounded at all. (An example is given in Figure F.2. Electrical bonding (welding or brazing) of all penetrations to the exterior surface of the metal building shield is necessary, where such a shield is available. For good protection at metallic penetrations, a relatively thick (1/4") shield, or a plate which is well grounded, is required.

3.4. Shielding Summary

The present shielding of the facilities investigated is not adequate to protect against the EMP environment. Although shielding is only one facet of the EMP protection problem, it is the most critical. Hardening of penetrations is helpful in cases where sensitive equipment can be directly illuminated by a high level electromagnetic wave penetrating the walls.

For the control centers, considerable advantage could be gained by extending the area covered by the metal skin of the building, providing better bonding between the metal plates and between the metal plates and the metal roof. A good ground for current drain from this metal shell would also be required. Without regard for other type of penetrations, such a configuration could provide shielding in excess of 60 dB at 10 kHz. The attenuation would increase to approximately 100 dB at 150 kHz and remain at higher level for higher frequencies.

CHAPTER 4

Conducted Interference

The electromagnetic pulse can penetrate into a building through any of the interconnections of the building with the outside world. The EMP environment induces current to flow in any conducting lines which may then flow into the building through these interconnections. The lines are not limited to electrical power and signal lines but include water pipes, sewage pipes, fuel lines, etc.

We must be concerned with the following aspects:

1. How is the current induced by the EMP environment on the external lines? What can be done to decrease the amount of current induced?
2. How is the current coupled from one conductor to another or from a cable shield to an internal cable conductor? What can be done to reduce this effect?
3. How does the current penetrate the FAA buildings? What can be done to minimize the amount of current penetrating the enclosure?
4. Once inside the building, how does the current couple to more sensitive electronic circuits? What can be done to minimize the coupling and what can be done to the circuits to make them less susceptible?

The following sections discusses the methods by which conducted interference is coupled into the FAA system and the different protective measures that may be used to reduce the coupling. The last section examines various FAA buildings and facilities in detail.

4.1. Coupling of the EMP Environment to External Conductors

Currents induced on any lines that have conductivity less than the surrounding earth is very small and can be neglected. Thus, low-conductivity water, sewage or fuel lines in nonconductive piping may be neglected. These lines do, however, form openings in the shielding of the structure and must be treated accordingly; that is, waveguide beyond cutoff; honeycomb filters with sufficient sized openings to permit the material transport; waveguide extending inside building.

If the potable water, sewage, or fuel lines are in metallic piping, sections of nonconducting piping may be used to block the current flow into the building. The nonconducting section should have several feet long and the incoming metallic pipe should be thoroughly bonded to the building ground ring. The nonconductive gap should be long enough to prevent arcing.

For conductive lines exposed to the EMP environment, current flows due to two mechanisms - direct interaction with the EMP fields and diverted earth currents. The impinging EMP wave induces currents in insulated as well as uninsulated conductors just as an impinging radar pulse causes current flow in an insulated or uninsulated metallic object. The other mechanism is a secondary one. The EMP environment causes large current density to flow in the earth. The particular current flow pattern is complicated by variations in earth resistivity, location of water table, and buried metallic objects. The current density also varies with depth into the earth because of the skin effect. However, significant current density can exist to depths of tens of feet. Metallic conductors that are not insulated from the earth provide lower impedance routes for the current and thus may serve to channel current with magnitude which may be in excess of the values predicted by the direct EMP radiation. For the frequencies of interest in the EMP environment the amount of earth current picked up by the conductor is relatively independent of the conductor cross section mainly because only the current density within an earth skin depth radius notices the influence of the metallic conductor. However, the size of the conductor does have a great effect on the current density within the conductor. This is especially important when the current is picked up on a conduit or cable shield because the noise or disturbance coupled from the shield into the internal conductor depends largely upon the current density on the shield.

The conductor size and shape also affects the cable impedance which determines the waveform of the induced current. In general, smaller size means greater series inductance but smaller capacitance. It is impossible to prevent the EMP environment from inducing current into conductors exposed to the EMP.

The amount of current picked up may be calculated by considering short runs of external lines as collecting antenna. (See Appendix C). For runs exceeding a few hundred feet the induced current is independent of length. A current value of 1,000 Amperes is a good rule of thumb value in the absence of more exact calculations.

4.2. Protective Measures Against Conducted Interference

An obvious method of protection against EMP is to go to a mode of total isolation. This requires severing all external ties with the building. All lines to the outside are disconnected. The overall building shielding would be relied upon for survival against the EMP.

This might be an acceptable for some missions. It is not acceptable for the FAA mission which requires communication with the outside world so that it can give direction during the critical period of time when the EMP environment is likely to occur.

To protect the vulnerable equipment, the following techniques may be used:

1. Keep the amount of current induced on incoming lines to a minimum.
2. Divert or absorb the energy associated with the induced current before it gets inside the building to the equipment.
3. Use equipment that is less susceptible to the EMP current that is able to get inside the building.

It is difficult to completely prevent current from being coupled into incoming lines. It is equally difficult to filter out all of the EMP effects. And no present equipment could withstand the full effects of EMP. Thus relying upon anyone of these techniques alone would be cost prohibitive. Thus, the best alternative is to use a judicious combination of these three techniques. Cable shielding, filtering, bonding to the ground ring and adopting less susceptible equipment are the ways to achieve these objectives.

4.2.1. Cable Shielding

Solid conduit with welded or securely bonded joints provides the best shielding because the skin depth effect exposes the internal conductors and cables to the smaller current density on the inside of the shield. Braided shields are less effective since the fine braid wires are transposed and thus destroy the skin depth effects. A transfer impedance relating shield current and shield to internal conductor may be calculated or determined for a given cable. While the voltage induced between the shield and internal conductor is typically on the order of one hundred Volts, the differential voltage induced between conductors of a shielded twisted pair is significantly less. The shield itself should not serve as one of the electrical circuit conductors. Thus, coaxial lines should have a second, separate shield which does not serve as a return path. Cable shields should be bonded to the building shield and a low impedance path provided to ground at each entry to the building.

4.2.2. Filtering and Bonding

Each power line and signal line should be filtered including return lines (fourth or "neutral" wire of a three phase system). The shunt branch of the filter should be connected to safety (shield) ground. RFI type of filters bulkhead mounted with feed-through capacitors should be used. Low-pass or band-pass filters should be used, depending upon the signal characteristics. In addition to bypassing most of the current pulse energy, the filter changes the spectrum of the incoming wave and thus delays the sharp rise of the pulse. This has the effect of giving protection devices time to react. For power lines, the use of transformers having electrostatic shielding, connected to ground, between the primary and secondary windings, is most effective.

4.2.3. Low Susceptibility Circuits

Zener diode and other breakdown device circuitry can be added to increase the survivability of sensitive circuits.

4.3. Classification of FAA Buildings Interconnections

The building and enclosures under investigation are the FAA ARTCC (Air Traffic Control Centers) including the separate power building, the radar buildings at the long range radars, the airport traffic control towers, and microwave repeater site buildings or equipment enclosures.

These interconnection lines at these FAA facilities can be categorized according to their basic conductivity. Lines likely to be good conductors are listed in the "conductive" category; this includes electric power lines, electrical signal lines, metallic pipes and conduits, and may also include sewage or other waste materials that have a high electrolyte content. Under "nonconductive" would be included fuel, oil and low-conductivity water. If these nonconductive materials are transported in metallic pipes, the pipes must be classified as "conductive," however, it is possible to transport these materials through nonmetallic piping.

I. FAA Control Centers

Conductive Interconnections

1. Power Lines,

   a. Utility lines through transformers without electrostatic shield to power building. Power building to control center via 4" steel conduit.

2. Signal Lines,

   a. Telephone lines - two cables for redundancy. Enter building at the same point.

   b. Waveguide to adjacent microwave tower.

   c. Coaxial lines and control line bundles to nearby long range radar (Indianapolis only).

   d. Coaxial lines to back up antennas on the roof:

      1. VHF - half wave dipole, 135 MHz;

      2. UHF - half wave dipole, 250 MHz;

      3. Single sideband - 3 to 16 MHz:

         a. Long wire antenna;
         b. Whip antenna 35 feet;

      4. Time Source

         a. Folded half wave dipole, 5, 10, 15, 20 MHz.

3. Grounding ring connections,

4. Service connections,

   a. Potable water supply in galvanized pipes;

   b. Fire water supply in cast iron pipes;

c. Fuel lines - natural gas or oil in steel pipes;

d. Sewage lines in cast iron pipes.

Nonconductive Interconnections

Item 4 of the "conductive" listing above if transported in nonconducting piping or if, at least, a section of nonconducting pipe is inserted at the entry point outside the building.

II. FAA Control Towers

Conductive Interconnections

1. Power Lines - utility to transformer bank then approximately 100 feet of underground power cable to equipment building.

2. Signal Lines

   a. Airport Surveillance Radar - video and telephone lines through underground utility ducts (concrete, nonconductive) to manhole 40 feet from equipment building. The last fifty feet is in 4" steel ducts.

   b. Telephone lines - standard practice: last 100-300 feet in underground ducts.

   c. Airport Surface Detection (ASDE) Radar - located on top of control towers (O'Hare - Chicago). Waveguide and other lines come down inside the control tower (196 feet high).

3. Ground (water pipe serves as earth connection at Indianapolis International Airport).

4. Potable Water.

5. Sewage Lines.

6. Fuel.

7. Steam Lines (O'Hare Field) from control airport utilities building.

III. Long Range Radar - Equipment Building

Conductive Interconnections

1. Power Lines - Overhead utility lines to power pole approximately 50 feet from building. Regular distribution transformer.

2. Signal Lines,

a. Waveguide from long range radar antenna (LRR).

b. Control lines to and from LRR antennas are in heavy wall galvanized steel conduit:

   1. Synchro signal lines,

   2. Antenna driver power lines.

c. Waveguide to microwave relay tower for transmission to Control Center.

d. Coaxial lines for video plus control lines for position information to Control Center.

   Indianapolis site has two 4" conduit running 4082 feet to Control Center. One conduit includes 10 coax cables including plus and minus video cables for differential input. The second conduit contains 6 each twisted pairs (with third shield wire) for servo; 10 each twisted pairs for audio intercom; and 100 each twisted pairs for control signals. Manhole located every 300 yards.

e. Ground rods through floor at each equipment enclosure 10 feet - 1/2" rods - about 10 to 15 each site.

f. Potable water in galvanized pipe.

g. Sewage.

h. Fuel for building heat.

Nonconductive Lines

Potable water, sewage, fuel.

IV. Microwave Relay Station Building

Conductive Interconnections

1. Power Lines overhead utility lines to regular distribution transformer. From transformer to top of building through 2" trade size conduit.

2. Signal Lines:
   Microwave antenna located on roof with short section of waveguide (less than 5 feet) directly into building below.

3. Fuel lines underground to buried tanks supplying back-up diesel generator.

4. One ground rod, 6' x 5/8".

CHAPTER 5

Equipment Susceptibility

The degree of equipment susceptibility to a typical EMP environment depends upon many factors. Most of the FAA's equipment will be shielded to some extent by the metallic buildings and cabinets within which it is housed. Although it might be damaged or destroyed if left in the open, it may be relatively immune in its protected state. Equipment susceptibility is classified according to the probability that it will be damaged under its normal protected conditions. The susceptibility evaluations presented in this report are generally made for the current prevailing conditions. The detailed evaluation is presented in Appendix F.

5.1. Relative Susceptibilities of System and Circuit Elements

An expanded discussion of component susceptibility is presented in Appendix D.

Typical devices can be ordered according to their relative protection requirements as indicated in Table 5.1 [1]. The FAA has equipment which falls in each of these categories. In general, low power, high-frequency semiconductor devices are highly sensitive, and high-voltage, high-power equipment is relatively insensitive, as seen from the table.

The FAA's equipment can be separated into several categories based upon the EMP environment to which it will be exposed. This breakdown is summarized in Table 5.2. A large portion of the radar and communications equipment is in an unshielded environment, as is the telephone and power company equipment. Other equipment is shielded to some extent against the brunt of the EMP environment. Detailed individual evaluations are presented later.

The general procedure for evaluating system susceptibility involves the assignment of component damage probabilities, interpretation of these results to obtain circuit damage probabilities, and extension of these results to the sub-system and system levels. The details of this process are presented in Appendix D and E.

5.2. The Effects of Voltage Pulses Upon Semiconductor Junctions

Semiconductor devices are highly susceptible to damage from the typical EMP environment. Crystal detectors, high-frequency high-speed diodes, transistors and IC components are most sensitive, because of their small junction dimensions. Some such devices have a high probability of performance degradation or junction destruction for junction voltage drops of 10-15 Volts for the 500 nanosecond nominal EMP positive pulse duration. To prevent such situations from occurring, all such components must be well shielded and/or otherwise buffered from the EMP environment.

EMP induced voltage pulses can be imposed across semiconductor junctions in a variety of ways. Voltage surges may be induced upon the leads via the power supplies or power line circuitry. These sources can be controlled by proper shielding and filtering. Voltages may also be induced in typical circuit loops due to the rapid change in magnetic flux caused by the EMP field. This voltage is proportional to the loop area and the rate of change of magnetic flux density. Thus it may be controlled by shielding and by keeping all conducting loops small. Fortunately solid-state circuits are generally compact. For existing equipment, adequate shielding protection must be provided to reduce damage probabilities to acceptable levels.

The general phenomena by which junction damage is caused by short duration pulses such as those from EMP is considered briefly in Appendix E, where tabulated data are presented on the susceptibility levels of many junction devices. Examples are presented there will illustrate the procedures for estimating component susceptibility. It is shown that EMP field attenuation of 60-80 dB at 10 kHz is required in those areas where sensitive junction devices are in operation if the probability of damage is to be kept to a minimum.

The standard design criteria for Civil Defense Emergency Operating Centers, which contain electronic equipment similar in some aspects to that in the FAA control centers, should provide general guidelines for FAA equipment protection. For the predominately high-impedance electric field components from 10 kHz to 100 MHz 80 dB or more of attenuation is recommended. For the predominanly low impedance magnetic fields from 10 kHz - 100 kHz, 50 dB or more of attenuation is recommended. It is recommended that these should be adhered to for all sensitive FAA equipment.

5.3. EMP Susceptibility of the FAA Equipment

When we speak of susceptibility, we are concerned only with equipment damage, permanent functional degradation or failure. Temporary disruptions can be tolerated.

The most critical FAA equipment is the communication equipment which allows voice contact with the aircraft. If it fails, the air traffic control function as now structured is lost completely. Thus all communication equipment should be carefully protected from potential EMP damage. A large part of the FAA equipment uses high-speed, low-power level semiconductor devices which are highly susceptible to EMP damage. This includes virtually all of the control center equipment, the radar equipment, and the communications units. These systems must all be carefully shielded if the damage probability is to be reduced to a reasonable level. The computer systems are also highly susceptible because of the memory units and the high speed logic circuits, all of which are highly sensitive to radiation interference and damage. Interference resulting in modification of the control program in memory may not be physically destructive to the equipment, but destroys its ability to function properly in any event.

It is generally assumed that commercial power will be interrupted by an EMP environment. Thus the uninterruptible power systems and other types of back-up power units are critical to continued operation. Most of these systems are physically rugged and not highly susceptible to EMP damage, although some elements of the control circuitry should be shielded sufficiently to assure that it will remain functional. Any electrical connections to the fuel tank for monitoring purposes should be carefully protected against arcing.

The specific recommendations involve establishing proper shielding levels for the various FAA facilities, control of the signal penetrations, careful grounding of all systems, and cabinet shielding protection for highly sensitive equipment. The major adjustments required involve metal building shields, line surge protection, and other similar changes.

Reference

1. Department of Defense Manual TR-61A, "EMP Protection for Emergency Operating Centers," (May 1971).

Class 1 Protection (Normal Lightning Protection)

Power transmission lines
Transmitter towers, antennas, etc.

Class 2 Protection (Insensitive)

AC induction motors (no brushes or armature windings)
Filament and fluorescent lamps
Heaters, coffee pots, air conditioners, etc.
Series and shunt wound motors
Meters for line voltage and frequency measurement
Isolating motor-generator sets
60-400 Hz converters

Class 3 Protection (Moderately Sensitive)

Vacuum tube power supplies in general
Teletype equipment power supplies
Power supplies for high power (over 50 Watts) transmitters
Vacuum tube receivers - all types
Vacuum tube differential input circuits
Solid state receivers with isolation provided
Alarm system power
Telephone signal lines

Class 4 Protection (Sensitive)

Computer power - all types
Solid state power supplies - all types
Single ended or unbalanced coaxial system inputs
Computer line inputs - all types
Alarm system control leads
Intersite intercom signal leads
Antenna tracking system power
Antenna tracking control leads
Radar system power (and control where applicable)

Table 5.1. Equipment Categories for EMP Sensitivity

Class A Equipment Exposed to the Full EMP Threat

Antennas, antenna towers, microwave repeaters
Telephone communication lines (not buried)
Input power lines
Control tower - control deck

Class B Equipment Exposed to a Slightly Attenuated EMP Threat

Buried communication lines (not in ferrous conduit)
Auxiliary power equipment
Control tower equipment (other than the control deck)
Equipment in the radar hut, both long range and short range
Equipment near penetrations of the control center

Class C Equipment Exposed to a Significantly Attenuated EMP Threat

This includes all equipment contained in the main control center
Buried communication lines contained in ferrous conduit
Buried power lines contained in ferrous conduit (threaded connections)
Communications equipment in the main center
Computer equipment in the main center
Air traffic control consoles in the main center

Class D Carefully Protected Equipment

This includes any equipment contained within a specially shielded cabinet or room within the main control center
All RF shielded sub-assemblies in the main control center
Memory cabinets that are especially protected
Other individually shielded units

Table 5.2. General Equipment Breakdown for the FAA Facilities

APPENDIX A

Grounding

The fact that the electronic equipment is vulnerable to the electromagnetic disturbances is obvious. Since it is impossible to prevent the natural or man-make disturbances from occurring, it would be wise to isolate the electronic equipment from the noisy environment. A simple and effective way to achieve this objective is to put all electronic components in a metal enclosure. When properly designed the metal enclosure becomes a very effective shield against externally generated noise and disturbances. However it can not reduce the noise generated from sources inside the metal enclosure. Various grounding schemes may be used for the purpose of reducing the internally generated disturbances. Obviously it is necessary to run power as well as communication lines into the enclosure. If this is done incorrectly, the shielding and grounding will be rendered useless. Thus grounding, shielding and cabling deal with different aspects of the same problem. Before these subjects are discussed in detail and separately, it is desirable to have an overview of the entire problem, so as to consider the interconnected relationship between them. It is also helpful to establish some general rules to aid the understanding of the philosophy behind the current and acceptable practices in shielding, grounding and cabling.

A.1. Shielding and Grounding Topology [1]

Many ideas mentioned above are illustrated in Figure A.1. Suppose that the building has a solid metal surface. Because of lightning or EMP, intense current is induced on the surface of the building as well as on the overhead power lines, buried communication cables or waveguides. To prevent the current on the power lines and buried cables from entering the building,

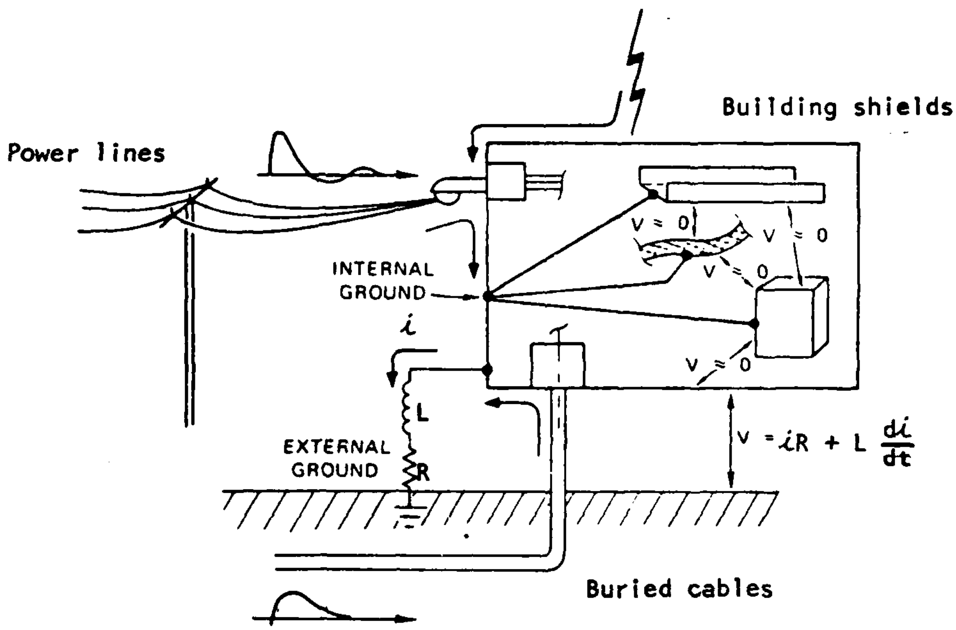


Figure A.1. Grounding, shielding, and cabling.

a by-pass route must be provided, i.e., the external ground. The induced voltage between the building and the "ground" is determined by

$$V = R\,i + L(di/dt)$$

where i is the current induced on the lines and cables, R and L are the resistance and inductance of the grounding electrodes and the connecting wires. Typically the conductors have an inductance of the order of a few microhenrys per meter. Since the current associated with EMP has a short risetime, the voltage due to the L(di/dt) term is very important. Thus one should pay careful attention to the inductance of the grounding electrodes as well as the conductors running from the building to the grounding electrodes.

For large systems like FAA's facilities, it is convenient to have several layers of shielding and subdivide the shielded region in various zones as depicted schematically in Figure A.2. For example, shield 1 may be the building or equipment van housing the whole equipment, shield 2 may be equipment cabinets or chassisses, while shield 3 may be special compartments to protect and screen particularly sensitive components. Note that each shield should be totally enclosed and has its own and separate ground. As to be explained later, the ground wires should never penetrate the shields. For example the wires connecting all grounds in zone 1, including shield 2, should be attached to the inner surface, not the outer skin, of shield 1. If any shield is penetrated by any wires or ground wires the effectiveness of that particular shield is greatly compromised. Two examples are shown schematically in Figure A.3.

When a conductor is terminated with a shield, the current carried by the conductor will naturally be transferred to the shield. It is important

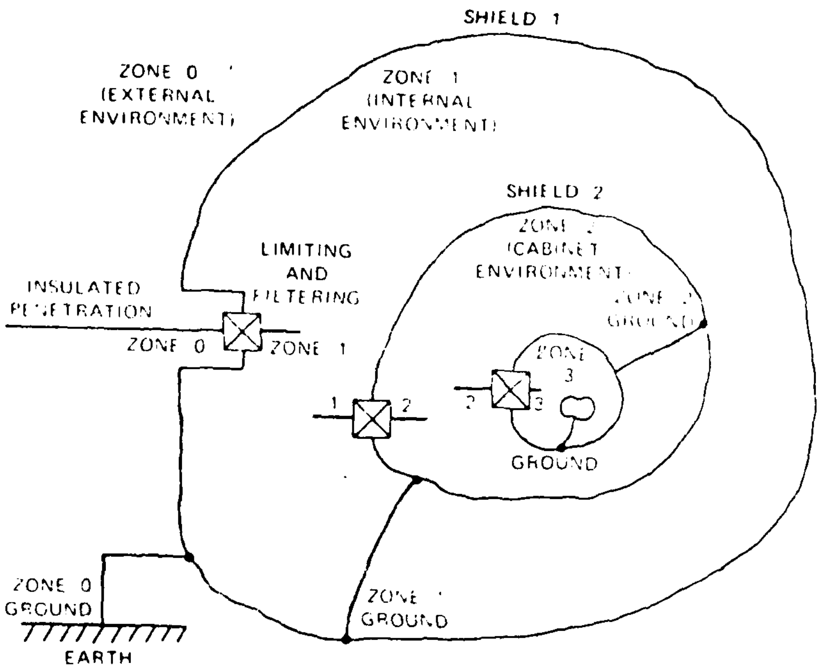
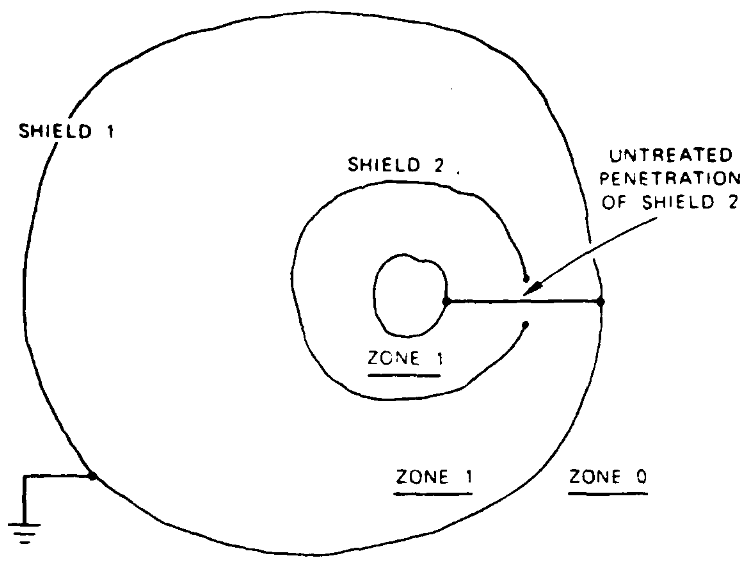
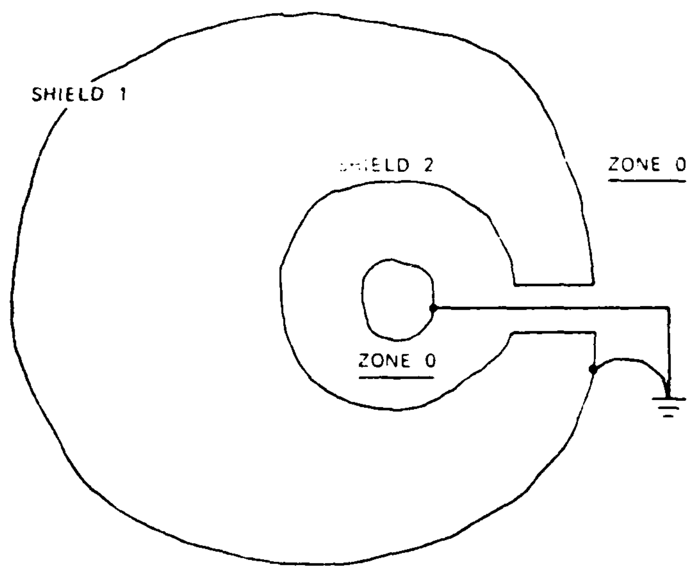


Figure A.2. Shielding and grounding zones in a complex facility.



(a) COMPROMISE OF SHIELD 2 BY UNTREATED PENETRATION



(b) COMPROMISE OF BOTH OUTER SHIELDS BY EXTERNAL GROUND CONNECTIONS

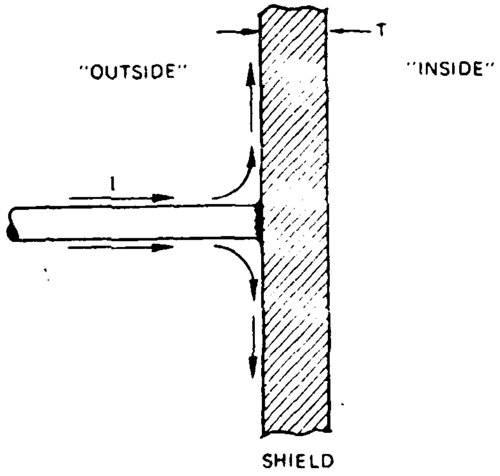
Figure [illegible].3. Common violations of shielding and grounding topology.

to note that the current on the shield will flow predominantly on the surface or side of the shield to which the conductor is attached, provided that the thickness of the shield is much larger than a few skin depths of the material. Figure A.4 shows the correct and incorrect ways of attaching ground wires to the shield. Additional examples are given in Figure A.5. Note that the transient protectors, surge arresters and filters should be treated in the same fashion.

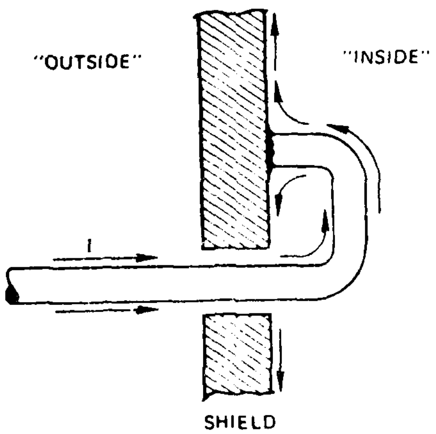
Occasionally it is necessary to route many wires or cables through a shield. It is natural to inquire if the wires should enter or leave the shield at single or multiple points. To answer this question, it is well to recognize that the field can be coupled into the shield through an aperture only if the presence of the aperture interrupts the current flow on the shield. In other words, fields cannot be coupled into the shield through the region of the shield where there is no current. If all wires and cables are collected and then terminated with a solid metallic panel before entering the shield, the current induced on the wires or cables will be concentrated in a restricted region of the shield where there is a solid conducting panel. Therefore the scheme of single entry point, as shown in Figure A.6, is much more effective than that of multiple entry points in reducing outside disturbance.

A.2. General Grounding Considerations [2,3]

The term "ground" may be used to indicate the reference node of an electric circuit, or the return for unbalanced three-phase current or fault current, or lightning discharge current in the context of power systems. No matter in what sense the term "ground" is used, it is always related to the concept of equipotential surfaces or regions. When a large amount of current is involved, the supposedly equipotential surfaces is no longer



(a) Conductor current confined to the outer surface of the shield. (Correct way of terminating the conductor.)



(b) Conductor current injected into the inside surface of the shield. (Incorrect way of terminating the conductor.)

Figure A.4. Correct and incorrect ways of terminating the conductors onto shields.

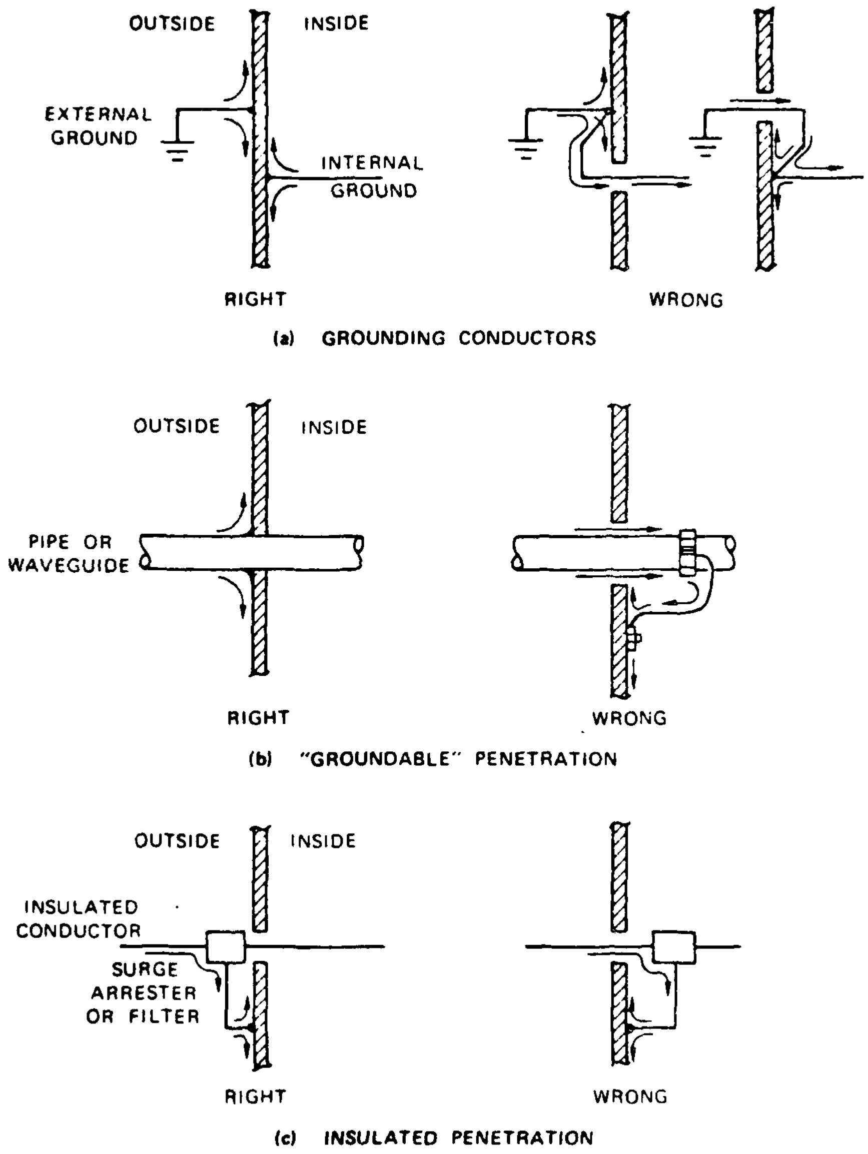


Figure A.5. Connections that preserve shielding integrity (right) and compromise the shield (wrong).

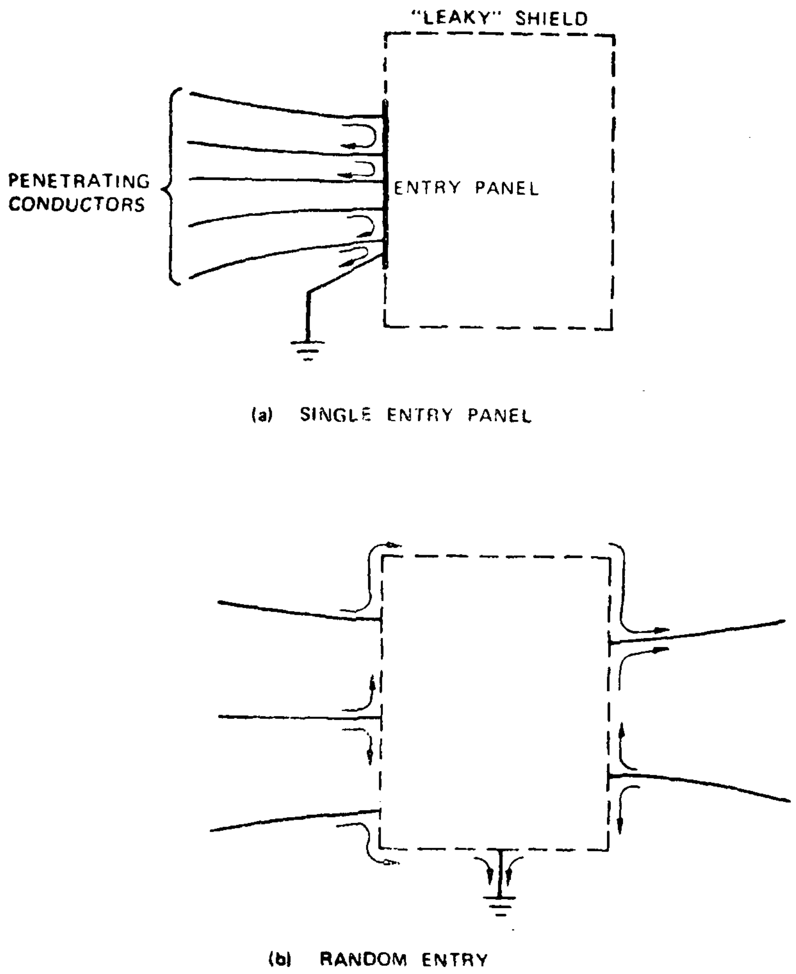


Figure A.6. Penetration current paths on shields.

equipotential because of the current flow in the "ground". To reduce the potential gradient, the resistance and inductance of the "ground" should be kept to a minimum.

Since the earth is an unavoidable part of any FAA facility or system it is used as the absolute potential reference. Every attempt must be made to assure that all parts of the ground system are as close a potential to this earth as possible. It should be emphasized that the earth ground must provide a low-impedance path at all frequencies to the soil immediately beneath the installation. The local soil condition should be measured and taken into account in designing the ground system for the installation in question. Needless to say, the local soil conductivity, which depends on the chemical composition and seasonal fluctuation of moisture and humidity, may vary drastically from site to site.

Figure A.7 shows a schematic representation of a ground system using the "tree" layout. The roots of the grounding "tree" form the <u>Earth Ground</u>. Ideally the System Grounds should be connected to the Earth Ground at only one point known as the <u>System Ground Point</u>, provided it does not penetrate shields.

The System Grounds which connect to the System Ground Point may be classified in two broad categories: <u>Safety Ground</u> and <u>Technical Ground</u>. The Technical Grounds include the <u>Power Ground</u> and the <u>Signal Grounds</u>. The purpose of the <u>Safety Ground</u> is to maintain equipment and structures at essentially equipotential by providing a low resistance drain for currents caused by internally or externally (including EMP) generated electromagnetic fields. A by-product of the Safety Ground is its shielding effect. The Safety Ground is connected to enclosures, equipment frames, conduit cable shields, building structural members, ducts, and piping. These connections

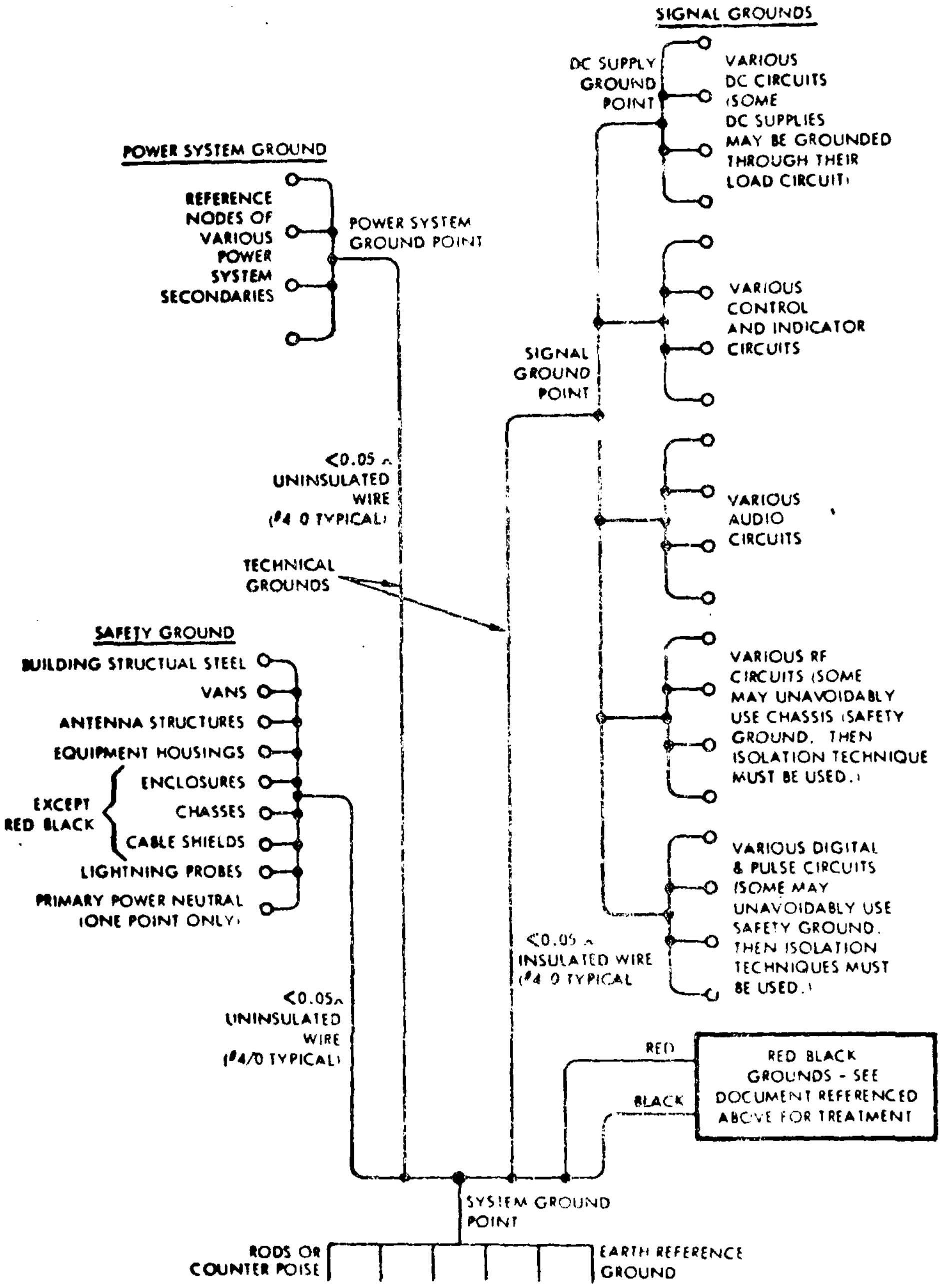


Figure A.7. Schematic representation of a grounding system using the "tree" layout.

should be made in a manner in which no loops are formed if at all possible. Naturally the structural members form loops. Separate safety grounds should not be run to two enclosures which are themselves interconnected by another line to form a loop. Figure A.8 shows the concept of safety ground applied to a system complex and to the grounding of equipment enclosures. When multiple grounds are used, it is crucial to keep the resistance between various ground points to a minimum value. At one radar site visited, the resistance between two grounds was found to be as high as 13 Ohms. The resistance values should be checked during routine maintenance. The lightning protection system is frequently tied to the safety ground if the structural members serve as part of the lightning path to earth. That is normally the case for microwave towers. It is worth mentioning that the primary purpose of a lightning rod is to let the electric charge leaked off gradually and thus to prevent a sufficient build up of opposite charge beneath a charged cloud and subsequent abrupt discharge. Only when the leak-off rate is unsufficient is a strike to the rod likely. Leak-off occurs over a relatively long time so that the d.c. resistance or low frequency impedance of the lightning rod to earth path is important. However, the high frequency impedance is also important for a strike to the lightning rod. For that reason it is important that the lightning rod to earth path not be composed of conductors having sharp bends of high resistance joints, rivets, or welds. To decrease the impedance, broad flat bonding straps should be used around structural joints, and from the structure to the ground rod.

The EMP effect also results in current pulses whose frequency spectrum is rich in high frequency. Therefore, for a grounding system to be effective against EMP as well as lightning, low impedance must be attained for low as well as high frequencies.

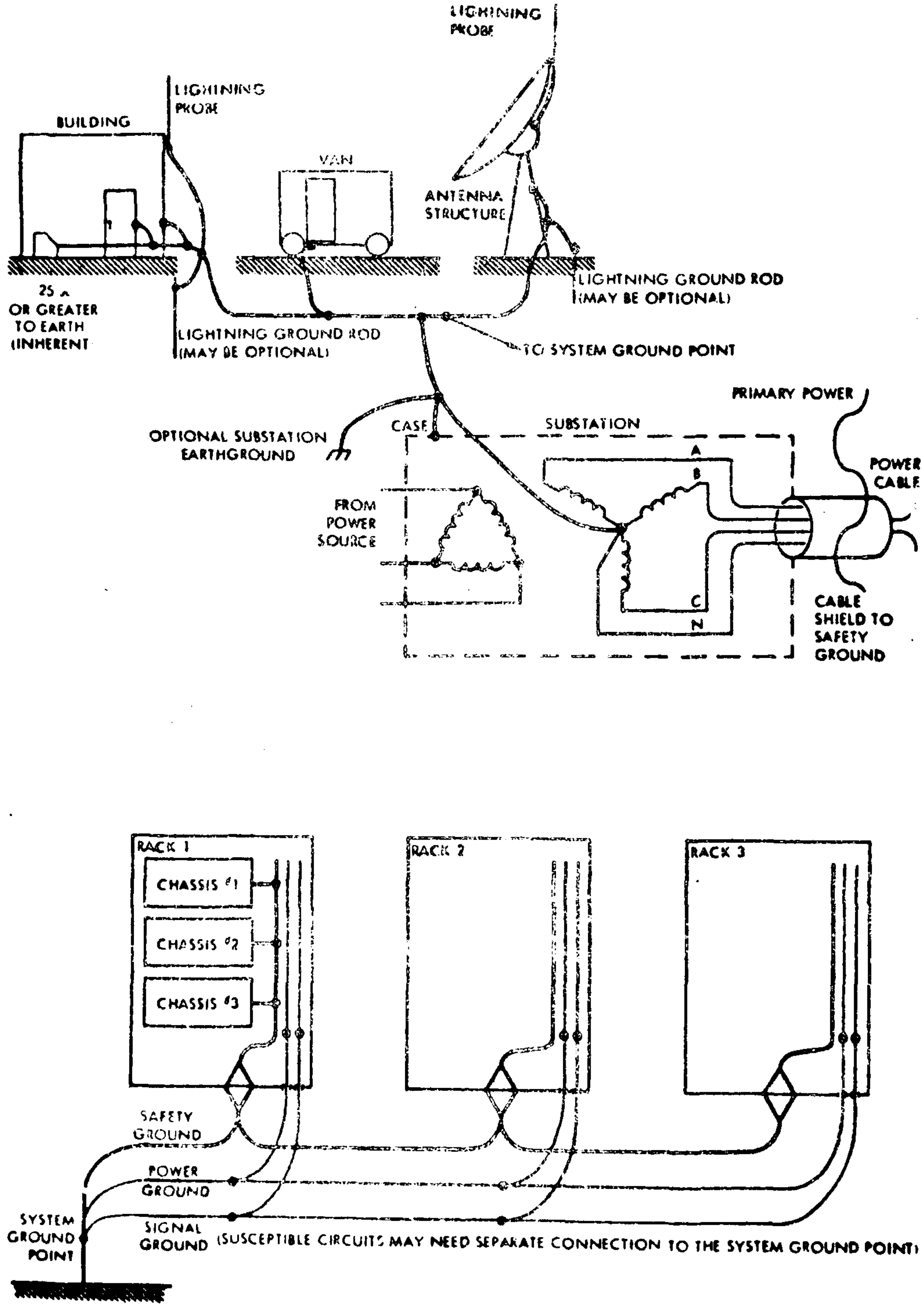


Figure A.8. Concept of safety ground applied to a system complex and equipment enclosures.

The Power Ground is composed of insulated wires which lead from the System Ground Point to each a.c. power secondary. It is a general rule that the neutral wire or common side of an a.c. power distribution circuit should be connected to the System Ground Point at one point only - usually at the transformer as shown in Figure A.9. All power leads are then treated as "hot" leads. Most electrical codes require that the primary power transformer have its wye connected secondary neutral connected to Safety Ground to assure proper operation of protective devices under fault conditions. No other point in the primary power circuits (i.e. up to the primary of the distribution transformer) should be connected to ground.

The Signal Grounds provide the reference potential for the electronic circuits. These circuits may be segregated into classes of circuits having similar characteristics such as d.c. power supplies, control and indicator circuits, audio circuits, radio frequency circuits including radar and video, and digital circuits. An insulated ground wire may go directly from the reference node of each individual circuit directly to the Signal Ground Point or may go to a ground point common to circuits of its type. The reason for such a grounding scheme is to reduce interaction among the various electronic circuits. It is especially important to separate circuits that are electrical noise producing (interference generators) from those that have high susceptibility.

The concept of single point grounding may and, in fact, must be violated when dealing with very high frequency circuits. When the conductor length approaches a quarter wavelength of the highest frequency signals, the cable and its shield act as an effective antenna. To prevent the buildup of standing waves the cable shields must be connected to Safety Ground at intervals with irregular spacings. These intervals should be kept as short as

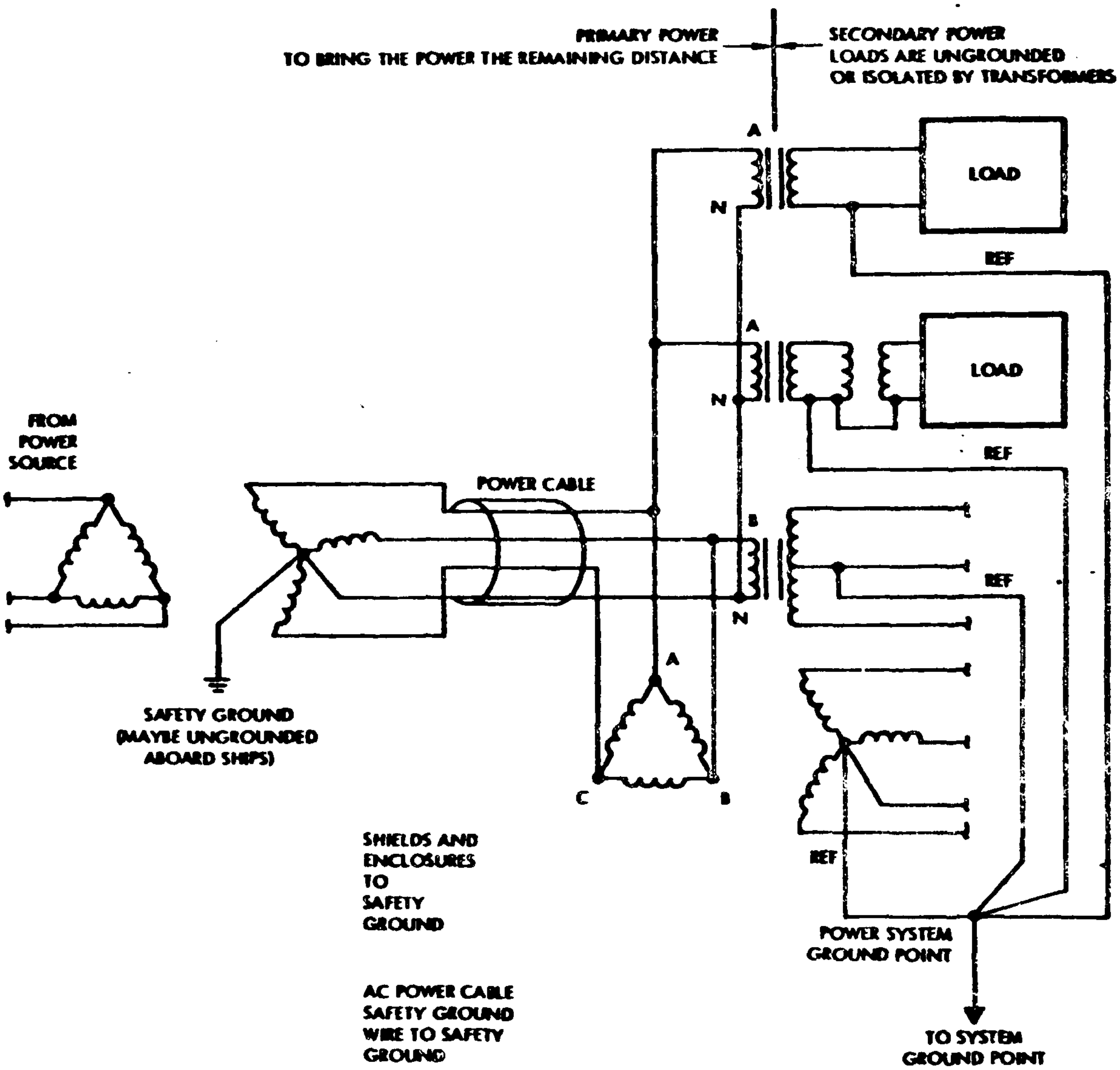


Figure A.9. Grounding of power distribution circuit.

possible and less than a tenth of a wavelength if it is feasible. Usually grounding the shield at each passage through a bulkhead ensures sufficient randomness. It is important that the multipoint RF ground, which is common with the Safety Ground, does not compromise the single point grounds of the interfacing audio circuits and d.c. supplies. The required isolation can be achieved through the use of isolation transformers, differential input amplifiers, double ended floated output amplifiers, and coaxial d.c. blocks.

A.3. Grounding at FAA Facilities

The survivability of the various FAA equipment depends on the amount of EMP energy coupled into the equipment circuits. The various types of FAA facilities have different grounding schemes. The first line of grounding defense against EMP is an effective treatment of the Safety Ground and the Earth Ground.

A.3.1. Control Centers

The Safety Ground and Earth Ground at the FAA Control Centers largely follows the tree concept discussed in Section A.2, except for a few important differences. The apparently intended Earth Ground is a buried bare cable surrounding the building connected to driven ground rods at each corner of the building and at the midpoint of the long spans. To prevent the corrosion of the ground ring and rods, thus assuring a good connection to earth, some form of cathodic protection should be employed. The connection of the external Earth Ground to the internal building ground buss in the power vault is by means of a single bare 500 MCM braided cable which forms the single System Ground Point. However, a connection to the commercial telephone safety ground both to the internal ground buss and to the potable water piping establishes the water piping external to the building as a second earth ground. It was not established if the water piping is connected to the ground ring outside of the building. If the telephone company practice would permit, the intended tree grounding scheme can be achieved by simply disconnecting the connection to the water pipe, going directly to the internal ground ring. The grounds from the various rooms and classes of equipment are brought to a common point of the internal grounding buss in the electrical power vault. All come by means of insulated conduits; some are further shielded by conduit. This indicates that the safety and technical grounds from equipment colocated in the same area of the building are brought to grounding plates in that area and then via a common cable to the System Ground Point in the power vault. A schematic of the grounding scheme is shown in Figure A.10.

A.3.2. Control Towers

The Control Tower itself is grounded by driven ground rods. The control tower equipment building (also known as the Base Building) is tied to the potable water supply. Thus, there are two connections which serve as Earth Ground. It is believed that the ground rods are of secondary importance because of their number and of the equipment tied to them so that the water pipe serves as the primary Earth Ground.

A.3.3. Long Range Radar

The Long Range Radar sites use driven rods. The equipment building uses driven rods at each equipment enclosure. The Safety Ground of the enclosures is connected to ground at more than one point. The towers which serve as the radar platform is grounded through two driven ground rods at diagonal corners of the tower legs. Figure A.11 is typical of the bonding of the tower structural steel to the ground rod. The tower joints should be bypassed with broad, flat braided bonding straps and the connection to the ground rod should also be through a low impedance connection. If there were

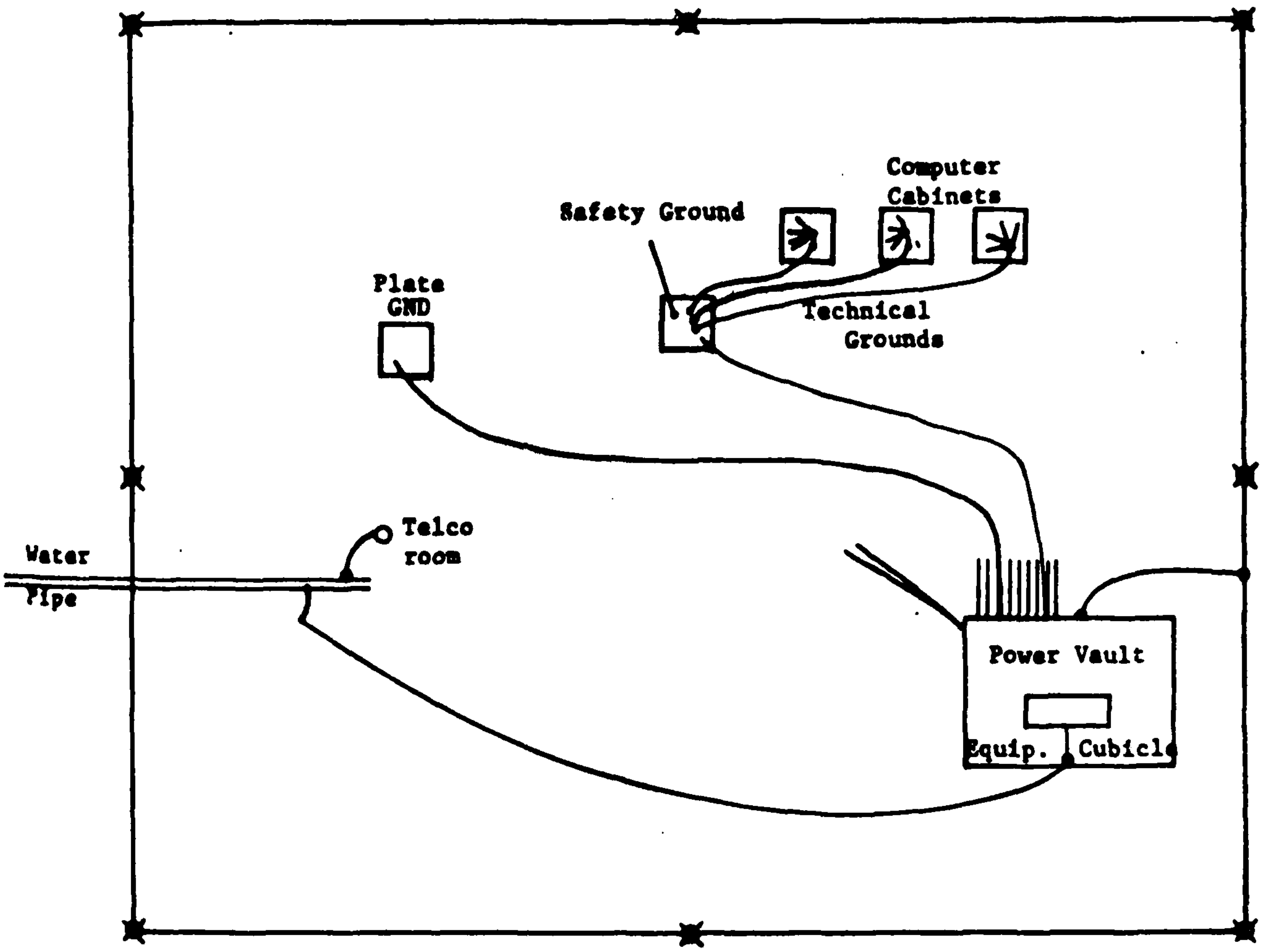


Figure A.10. Schematic of the grounding scheme.

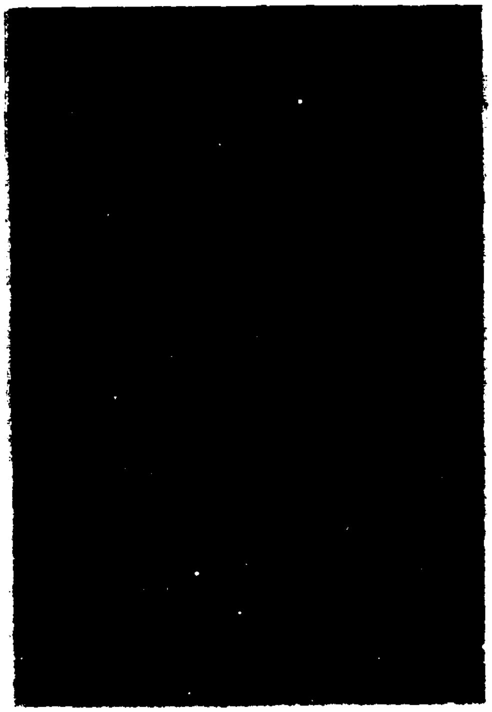


Figure A.11. Bonding and grounding of tower structure to ground rod. (Note the 4/0 wire.)

sharp bends on the conductor, it would present a high impedance to EMP or lightning induced current.

A.3.4. Remote Microwave Tower

The microwave towers are connected to ground as described in Section A.3.3 and Figure A.11. The equipment building grounds are connected to earth through one driven rod. Since the only other "conductive" input to the building is through the power cable the concept of single point ground is advised.

A.3.5. Instrument Landing Systems:

Since the equipment vans or shelters for the instrument landing systems, including the localizer, glide slope, inner, middle and outer markers, are usually situated in relatively open fields and alone, they must be well protected against lightning strikes. These protective measures would also helpful in reducing EMP related disturbances. The recommendation made by Kentron Hawaii, Ltd., [4], relative to Texas Instrument AN/GRN-27(V) ILS systems in particular, should be implemented. An example is illustrated in Figure A.12. Note that 2/0 AWS cables are recommended and all joints are to be brazed or welded to reduce resistance and to ensure electrical connection. It should also be mentioned that sharp bends should be avoided.

References

1. E. F. Vance, "Shielding and grounding topology for interference control," AFWL EMP Interaction Notes, No. 306, (April, 1977).

2. IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE Standard 142-1972, (1972).

3. O. M. Salati, "Grounding," Chapter 16 of Topics in Intersystem Electromagnetic Capability, Edited by W. W. Everett, Jr., Holt, Rinehard and Winston, Inc., (1972).

4. "Texas Instrument AN/GRN-27(V) Instrument Landing System cone of protection, bonding, shielding and grounding requirement", Preliminary report R-1, Kentron Hawaii, Ltd., (1975).

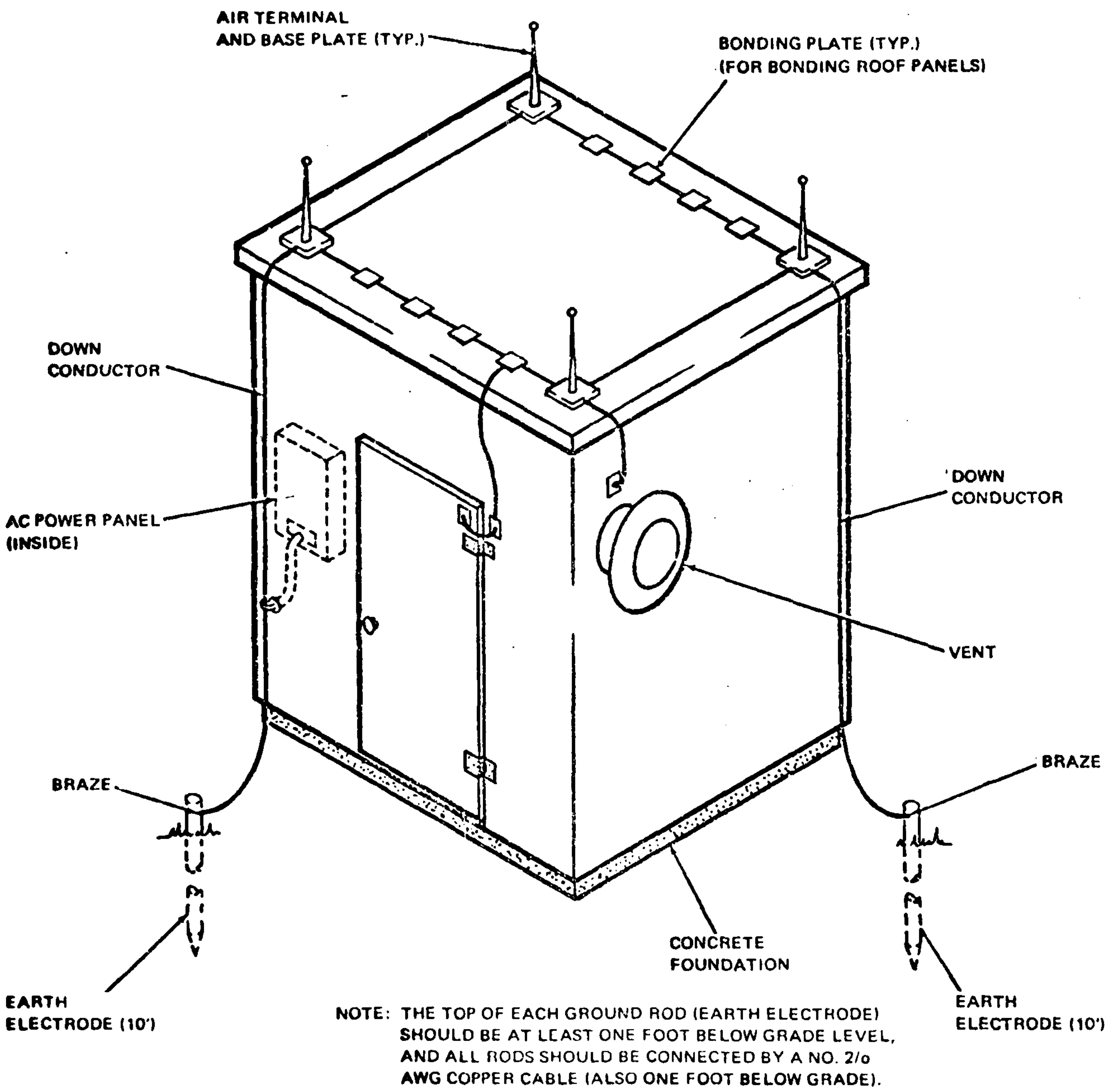


Figure A 12   Recommended protection for AN/GRN-27(v) shelters.

APPENDIX B

Cable Coupling and Metallic Penetration

B.1. Estimate of Current and Voltage Induced on Cables and Conduits

Conductors which are exposed to the EMP environment caused by a high altitude, exoatmospheric source have induced currents whose magnitude may be determined either by calculation or by the use of nomographs [1]. The magnitude of the current is a function of the earth conductivity and the conductor diameter for a given EMP environment. For the earth conductivities encountered in the continental United States, namely 0.05 to 15 millimhometers, the peak value of the induced currents can run as high as 60,000 Amperes as shown in Figure B.1. A typical peak value of current is 10,000 Amperes. Since there is considerable variation in the earth conductivity, each FAA site should be tested for earth conductivity when determining the degree of protection needed for that site.

If the exposed conductor is a conduit, the current flows on the conduit and the effect on the enclosed conductors is very much less. The conductor-to-conduit voltage may be calculated from charts such as Figure B.2. Since the current on the conduit acts as a distributed source, the conductor-to-conduit voltage is a function of conductor length. The conductor-to-conduit voltage increases with the number of conduit couplings and bends as shown in Figure B.3 and B.4. The conductor-to-conductor voltage induced in signal lines within the conduit are considerably smaller than the conductor-to-conduit voltage. Figures B.3 and B.4 also show that the induced voltage between conductors in a parallel pair (non-twisted) is about 10%, and that for a twisted pair is about 1% of the conductor-to-conduit voltage. The current that flows on these lines depends upon the in-

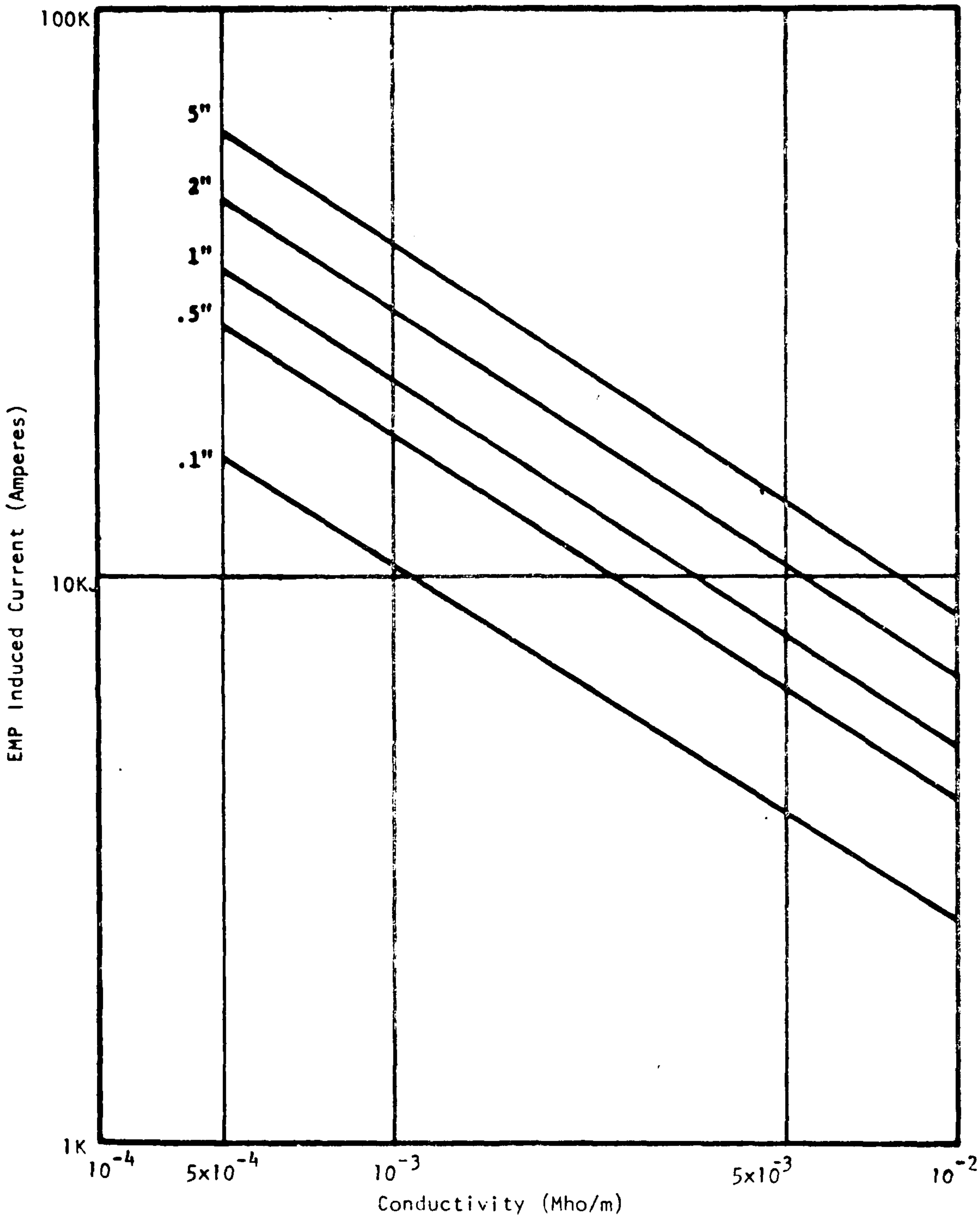


Figure B.1. Peak current induced on conductors for a function of conductor radii and earth conductivity.

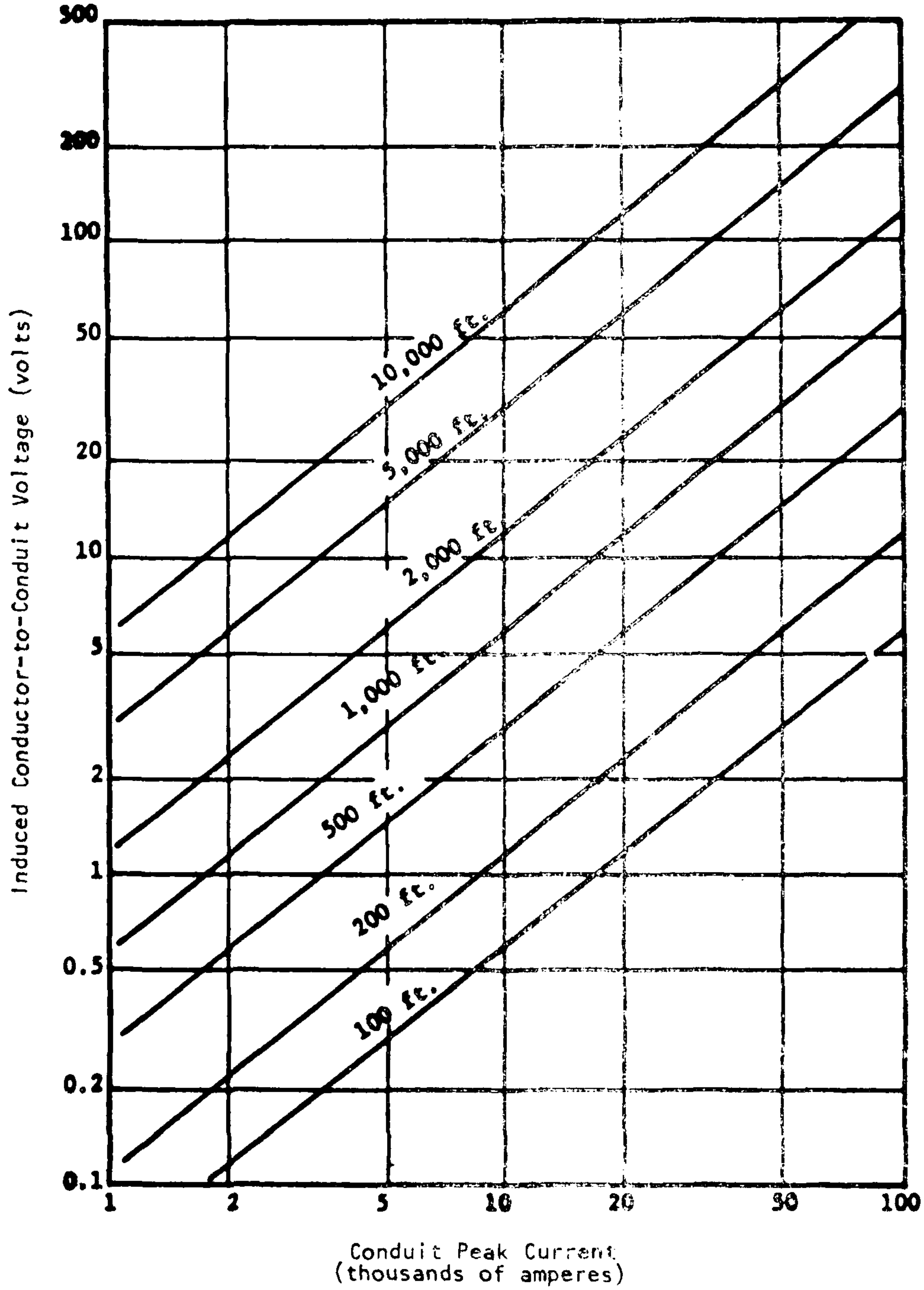


Figure B.2. Conductor voltage vs conduit peak current for varying lengths of standard rigid steel conduit 2-inch trade size or larger with welded joints or threaded couplings.

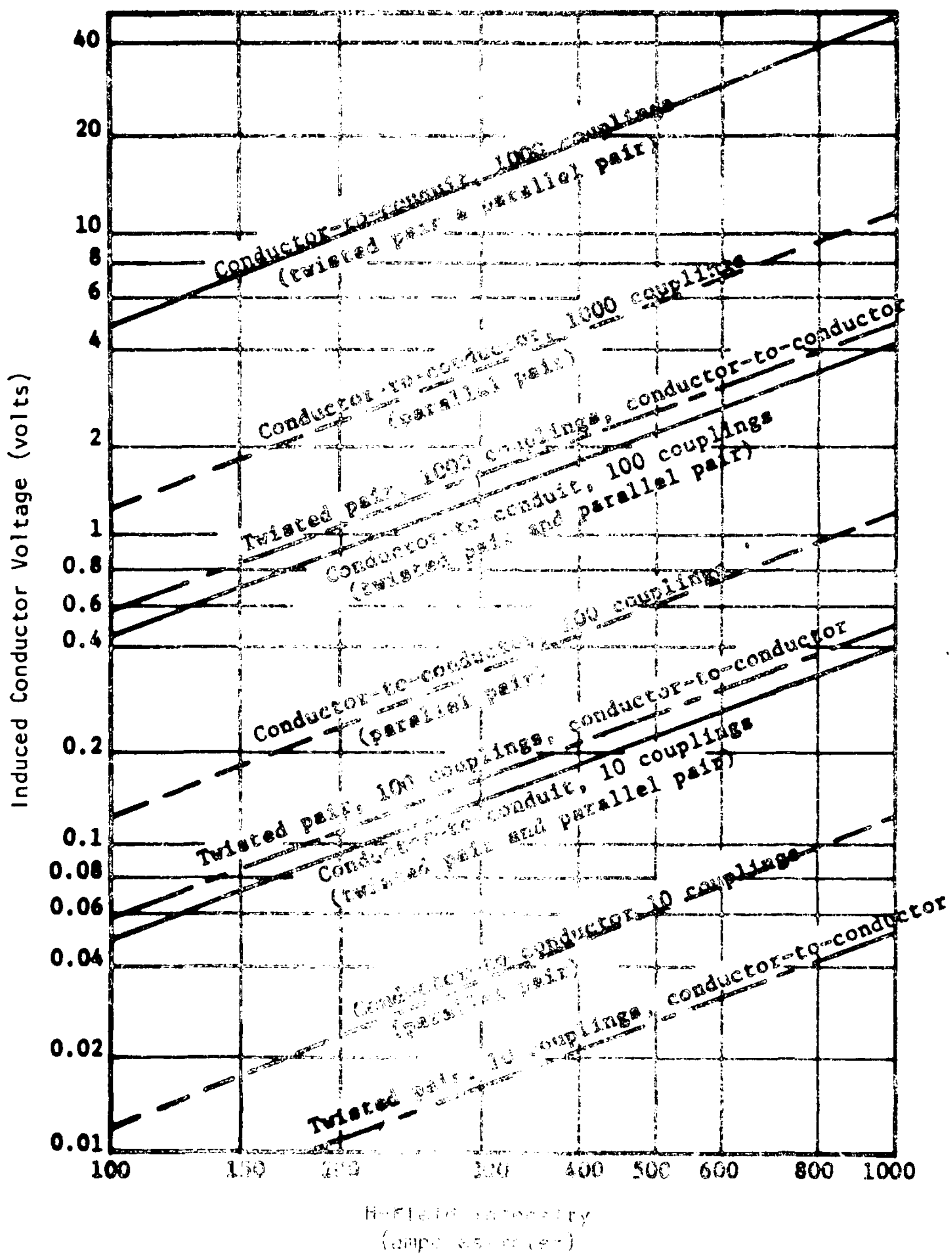


Figure B.3. Conductor voltage vs H-field intensity for varying number of couplings in standard rigid steel conduit, 2-inch trade size or larger.

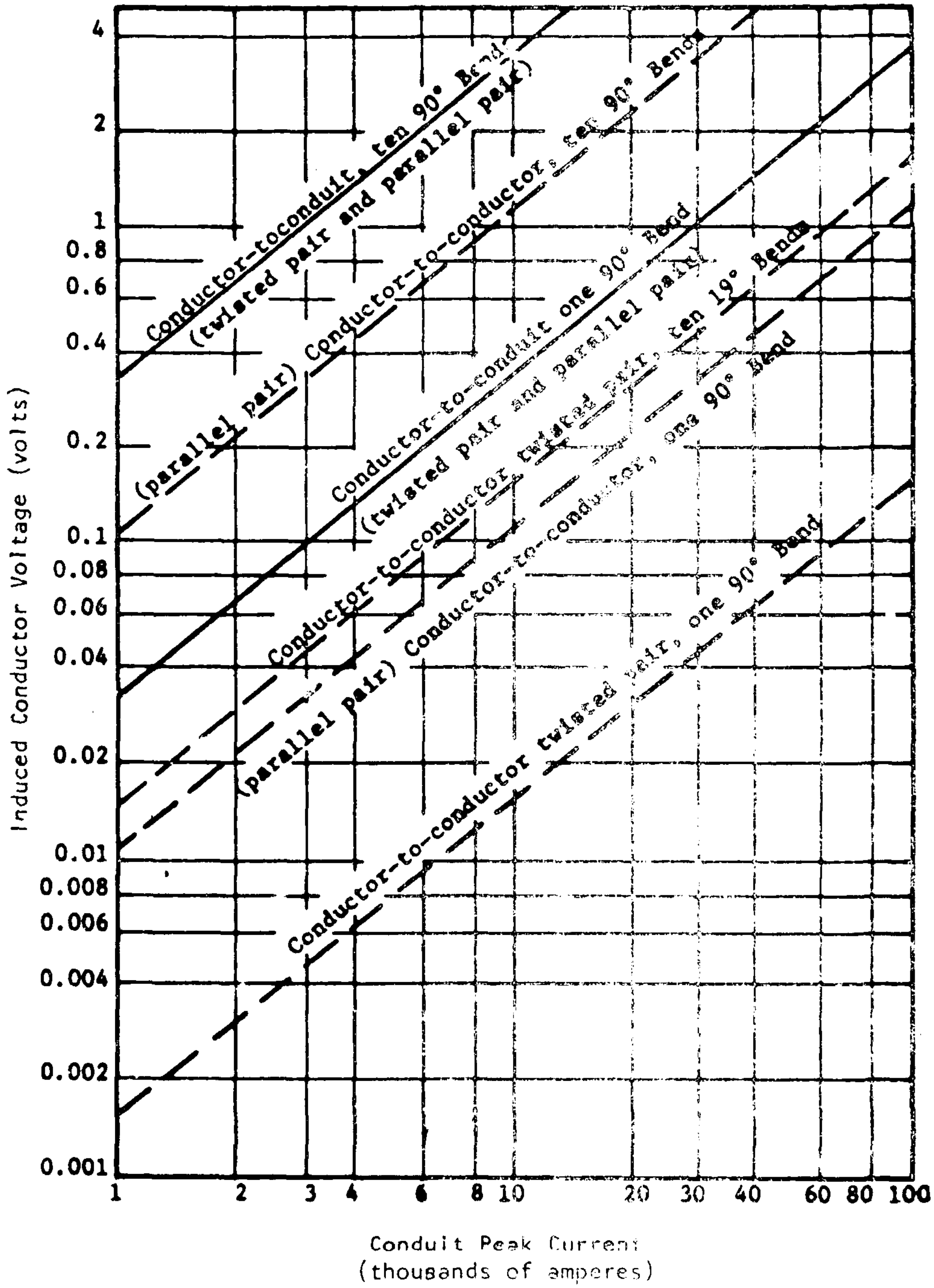


Figure B.4. Induced conductor voltage vs conduit peak current for varying number of bends in standard rigid steel conduit, 2-inch trade size or larger put impedance of the loads and/or the characteristic impedance of the lines which is typically 50 ohms or higher.

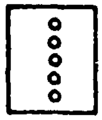
As an example, consider a 4" diameter telephone cable with a tin sheath running 1000 feet underground. The earth conductivity is 8 millimho-meters. The peak induced current from Figure B.1 is read as 9,500 Amperes. From Figure B.2 the conductor-to-conduit is about 5 Volts. The conductor-to-conductor voltage of an twisted pair inside the sheath is on the order of 0.05 Volts with a resulting current of less than 0.05 Amperes with 0.001 Ampere being a more likely value. Thus, the tin cable shield is quite effective.

If the cable were not shielded, the current on each conductor is $1/\sqrt{N}$, (see Figure B.5), times that predicted by the diameter of the cable bundle using Figure B.1. Assume the telephone cable has 25 pairs. Further assuming all are terminated, gives N equal to 50 conductors. Thus the current induced on each conductor is, $i_{\text{peak per conductor}} \approx 1343.7$ Amperes. This current is a "zero sequence" type of current. To get to the same level of current as the shielded cable requires filtering having an attenuation given by

$$\text{Attn} = -20 \log \frac{0.050}{1343.7} = 88.6 \text{ dB.}$$

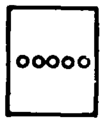
To get to 0.001 Ampere would require 34 dB additional attenuation for a total attenuation of 122.6 dB. If the number of telephone pairs in the cable were not so high, the filtering problem would be even greater.

Consider a power cable run from the power building to the control center as a second example. For illustration it is assumed that the run is 100 feet in 4" steel conduit having two bends and ten conduit couplings. Soil conductivity is 8 millimho-meters. Eight conduits each having 4 con-



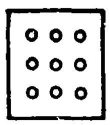
For a vertical conduit arrangement, the induced current on conduits, as determined by the nomograph, Figure B.2, must be multiplied by $1/\sqrt{N_V}$, where N_V is the number of conduits in the trench or duct.

A. Vertical arrangement of conduits in a duct or buried in a trench.



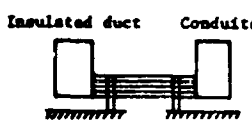
For a horizontal arrangement, the induced current on conduits as determined by the nomograph, Figure B.2, must be multiplied by $1/\sqrt{N_H}$, where N_H is the number of conduits in the trench.

B. Horizontal arrangement of conduits in a duct or buried in a trench.



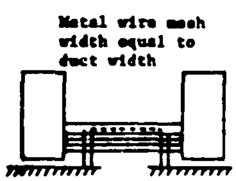
For a vertical and horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure B.2, must be multiplied by $1/\sqrt{N_V} \times 1/\sqrt{N_H}$, where N_V and N_H are as in A and B above.

C. Vertical and horizontal arrangement of conduits in a duct or buried in a trench.



When conduits are placed in insulated ducts, the induced conduit current, as determined by the nomograph, Figure B.2, must be multiplied by 1/1.25 in addition to the factor given above relating to conduit arrangement.

D. Conduits in insulated duct between buildings.



When a wire mesh is placed above conduits and connected to the grounding plate at both ends of the duct, the induced current on conduit, as determined by the nomograph, Figure B.2, must be multiplied by the following factors in addition to those given above relating to conduit arrangements: For wire mesh 2.5 feet above conduit, multiply by 1/2. For wire mesh 4.0 feet above conduit, multiply by 1/3.

E. Conduit ducts with metal wire mesh placed above conduits in duct.

Figure B.5. Physical conduit arrangement affecting the induced current on conduits and the resulting induced voltage on wiring.

ductors make up the run as shown in Figure B.3. From Figure B.1, the peak current is read as 9,500 Amperes. To account for the division among eight conduits, the factor $1/\sqrt{8}$ is used to give 3400 Amp/conduit, (Figure B.5). The induced conductor to conduit voltage is 0.2 Volts. Using Figures B.3 and B.4 as a guide, we predict an increase in induced voltage to about 2 Volts as an upper level value. The conductor-to-conductor voltage (parallel pair) would be about 0.2 Volts. A voltage of this value at power line voltage levels is relatively insignificant. However, if the cable were not in conduit, the induced current per cable, assuming 4 lines would be $(1/\sqrt{4})(3400)$ or 1700 peak Amperes per line. As mentioned earlier, these are "zero sequence" currents. Some means are required to divert this current. RFI filters of sufficient steady state current and voltage (60 Hz, 220V, 100 A) are available and four are needed in each 3 phase, 4 wire run (the neutral current rating may be about 1/10 of the hot lines or 10 A).

Both of the foregoing examples were for cable runs that presently have some degree of shielding. the integrity of the shield, i.e. low resistance joints, large radius bends, etc., was not investigated. However, there are many runs that are not shielded in the various FAA facilities. The examples above were to give an "order of magnitude" feeling for the problems.

The currents determined above are peak values. When regular circuit or RFI filters are involved, it is often more enlightening to determine the frequency spectrum of the induced currents. Then the frequency characteristics of the filter may be included to find the net frequency spectrum. Let us treat a cable run as an antenna and determine its energy collecting ability. The frequency spectrum of the EMP environment shown in Figure 3 is the source. For the moment let us simply take the source as $E(\omega)$, an E field spectral density i.e. ([Volts per meter] per Hz) whose magnitude is a function of frequency.

The amount of energy collected over any frequency interval depends upon effective aperture, A_{eff} of the antenna, energy per area in the electromagnetic field, and the bandwidth of the frequency interval:

$$_c(\omega) = A_{eff}\ (\frac{E^2(\omega)}{\eta}), \qquad \text{J/Hz}$$

where η = impedance of free space, 377 Ohms.

The energy collected by the antenna is also related to the induced current and its radiation resistance, R. Here the current is taken to be the sinusoidal maximum value, I_o.

$$_c(\omega) = (\frac{I_o(\omega)}{\sqrt{2}})^2\ R(\omega)$$

so that

$$I_o(\omega) = \sqrt{\frac{2\ A_{eff}}{\eta R(\omega)}}\ E(\omega)$$

This gives the spectral density of the induced cable or conduit current. If the current flows on a conduit, the induced conductor-to-conduit voltage may be calculated by means of the transfer impedance of the cable [2,3].

Take a 100 foot cable as an example. Its length is approximately 30 meters which is one wave length at 10 MHz. At 5 MHz it acts as a half-wave dipole, for frequencies less than 1 MHz it acts as a short dipole, and for frequencies greater than 100 MHz, it acts as a long wire antenna. If in addition the radius of the cable is known, the effective aperture and radiation resistance may be calculated. the relationship between induced current and the E field, which may be called a transfer conductance, is shown in Figure B.6. It also shows the induced current as a function of frequency for the given EMP environment.

Assume that the cable is an RG-12/U armored (shielded) cable, the transfer impedance is less than 1.8×10^{-2} Ohms for the frequency range from 10KHz to 10MHz, so that the conductor-to-shield voltage is numerically 37 dB less than the induced current spectrum. The conductor-to-conductor voltage is 0.01 (twisted pair) of this or 40 dB numerically.

B.2. Penetrations

As discussed in Chapter 4, it is of great importance that the current picked up on conduits, conductors, and service penetrations be prevented from entering the building. For each site and each building, an exhaustive list of all penetrations should be made. The following information should be gathered for each penetration: the diameter and thickness of cable shields, the number and size of conductors in a bundle, the length of the cable run from the building to the next point at which bleed-off of EMP can occur, such as the electrostatic shield of a distribution transformer, or a high speed current arrestor, etc. Ideally, all penetrations should enter the building at a common entry point, as discussed in Appendix A to prevent current from being picked up on one cable, passing through the building (by way of the shielding), and continuing out another cable on the opposite side of the building. Another advantage of a common entry point is that the cables partially shield each other. A slight disadvantage occurs in that a large amount of cable current must be taken off and handled by localized thicker shielding in that one vicinity. This single entry location should certainly be removed as far as possible from rooms containing sensitive electronics. The boiler room, air-conditioning room, or power vault would

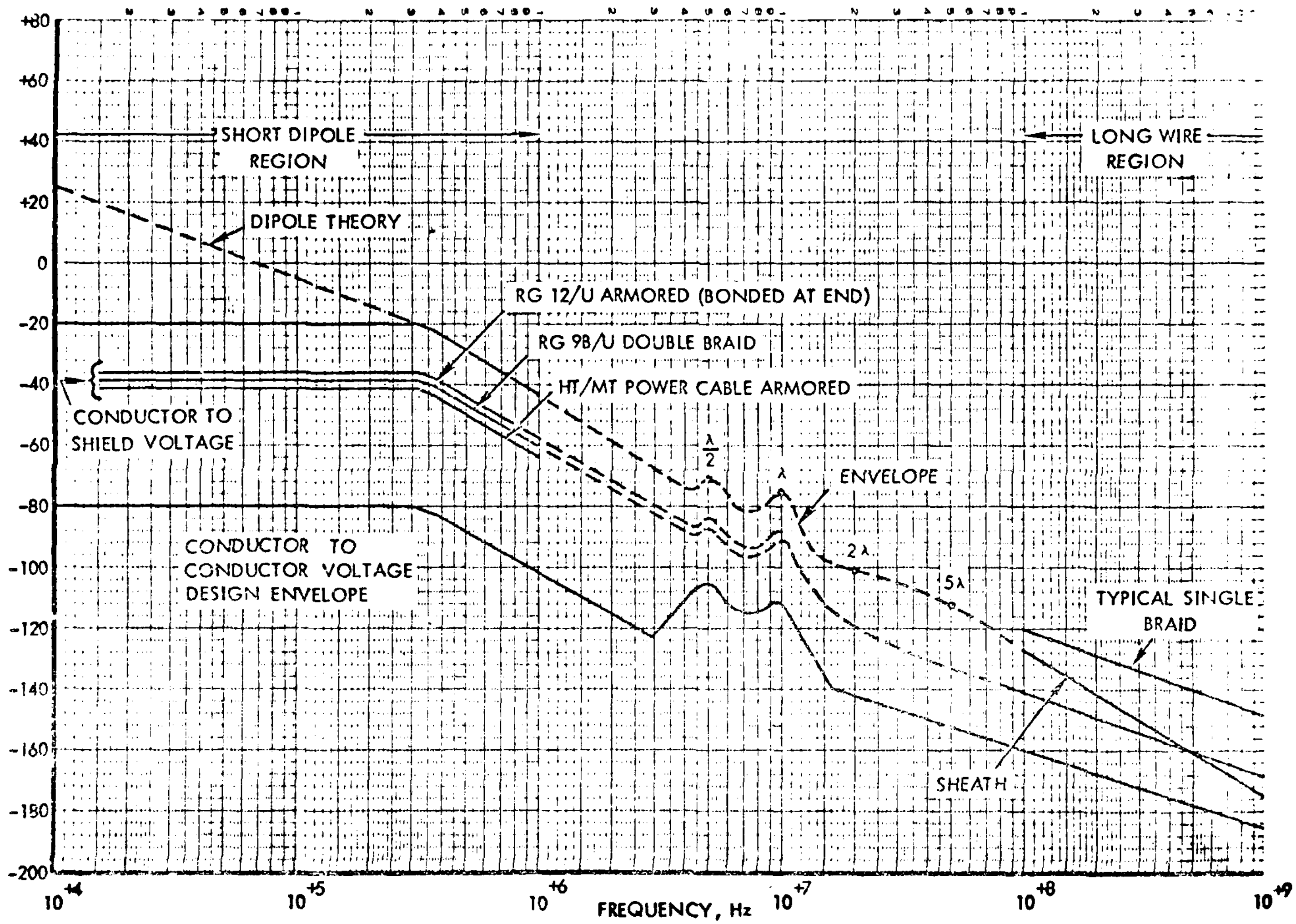


Figure B.6. Relationship between induced current and the E-field.

be the best location for this common entry. It is desirable to apply the EMI concept of separating cables carrying susceptible circuits, i.e., electronics, from those having relatively little susceptibility such as a.c. power. It is also desirable to insert nonconducting sections in service lines carrying non-conducting material such as potable water, sewage, fuel lines, steam lines from central building generation plant (e.g. O'Hare field), fire water lines, etc. A non-conducting section of approximately ten feet should suffice. The end of the metallic pipe away from the building should be grounded to the earth ground ring as shown in Figure B.7. The other end which may be essentially flush with the building (a projection on the other of two feet is tolerable) is treated as a building shield aperture. If the metallic pipe runs into the building, it acts as a waveguide beyond cutoff. If it is impossible for reasons of excessive pressure, etc. to insert a non-conducting section, use a collar or baffle plate attached to the pipe several feet from the building as shown in Figure B.7. The plate should be well bonded to the earth ground ring and an extra ground rod driven at that location. More than one baffle plate may be used if the predicted current warrants. The baffle plate acts as a reflector on a transmission line.

For conduits carrying power and signal lines this same treatment, using baffle plates and grounding, may be used. If the currents have a value of 10kA or less and if the circuits involved have low susceptibility, a treatment such as shown in Figure B.8 may be used. Note the welding should be done on the outer surface of the building or shield. Penetration through the wall may also be accomplished as shown in Figure B.9. The fillets and extra thickness of shield are required because of the large current density on the building shield in the vicinity of the penetration.

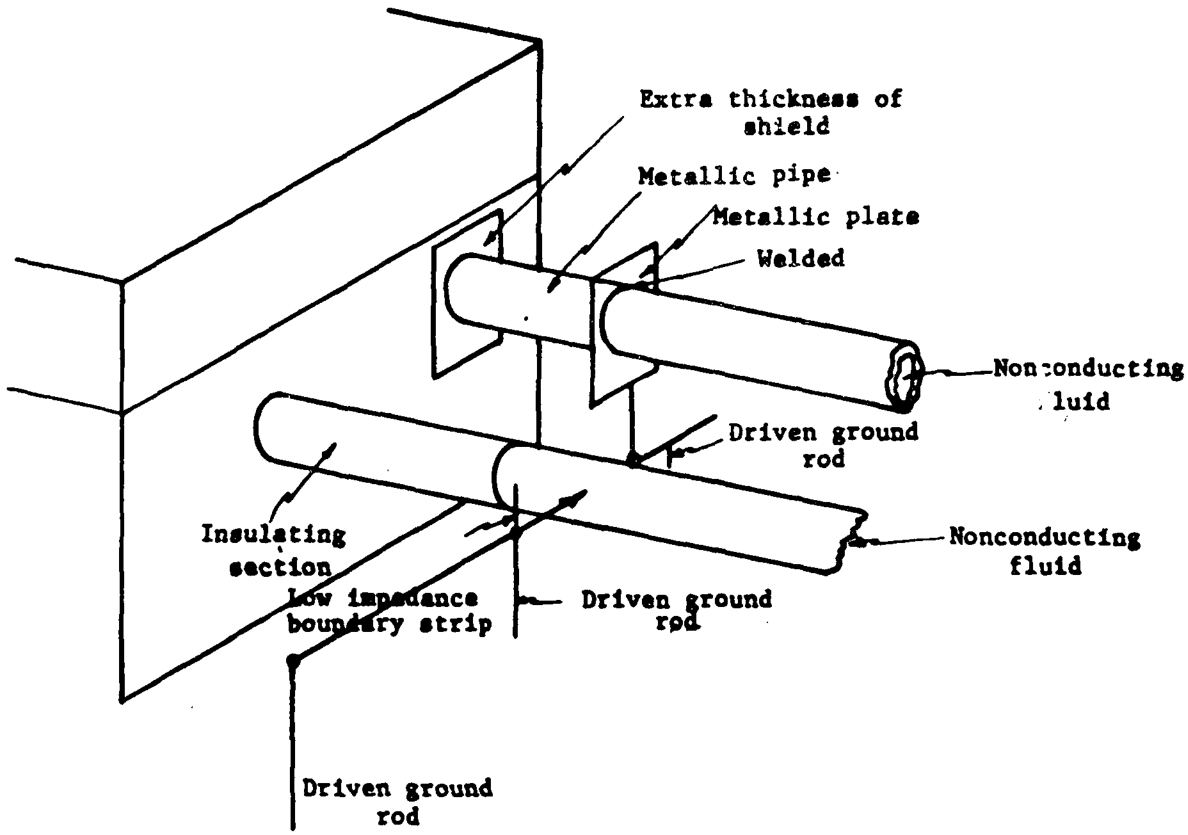


Figure B.7. Grounding of metallic pipe from building to earth ground ring.

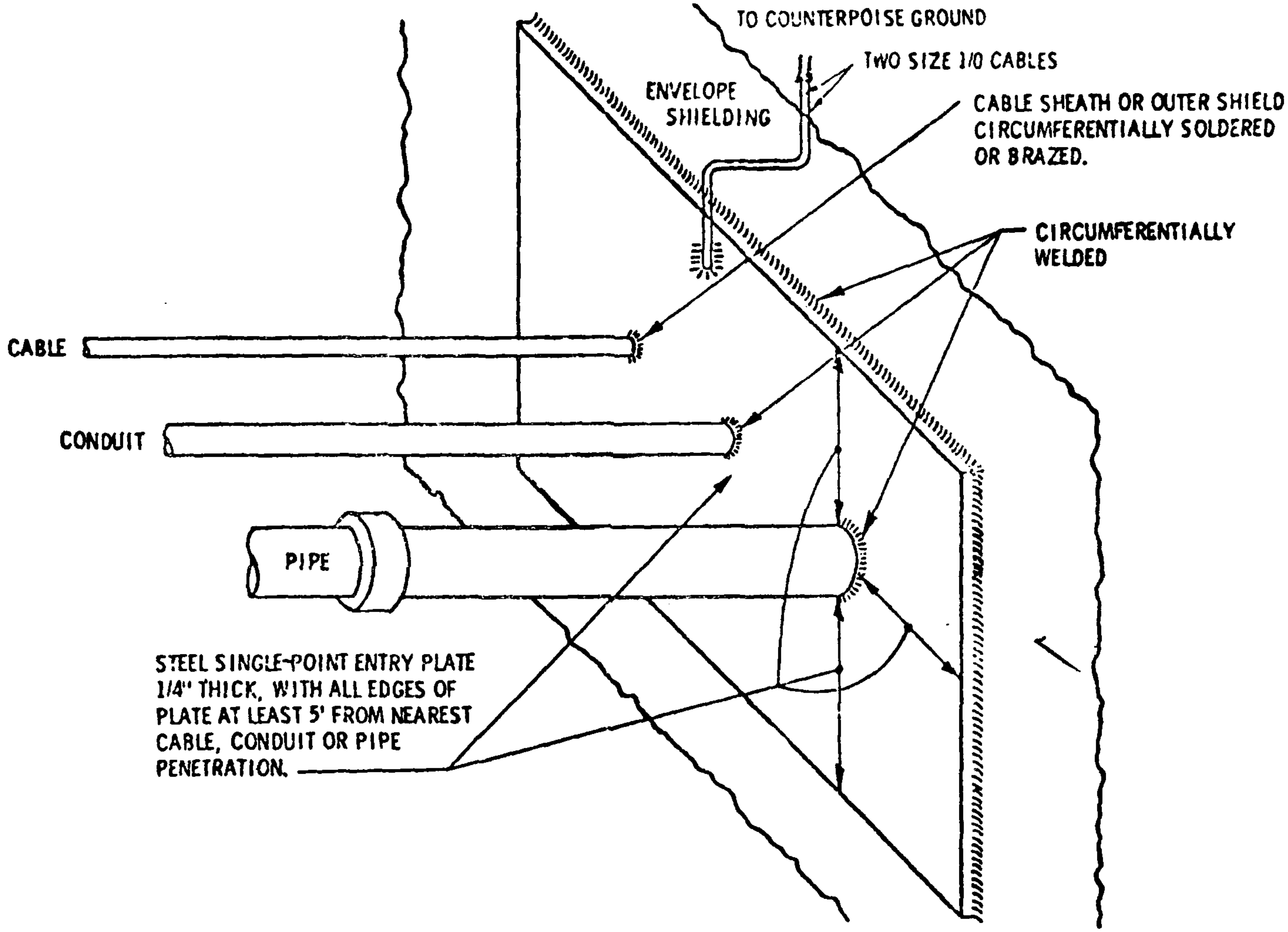


Figure 8.8. Single-point entry plate showing rigid cable conduit and pipe shielding penetrations.

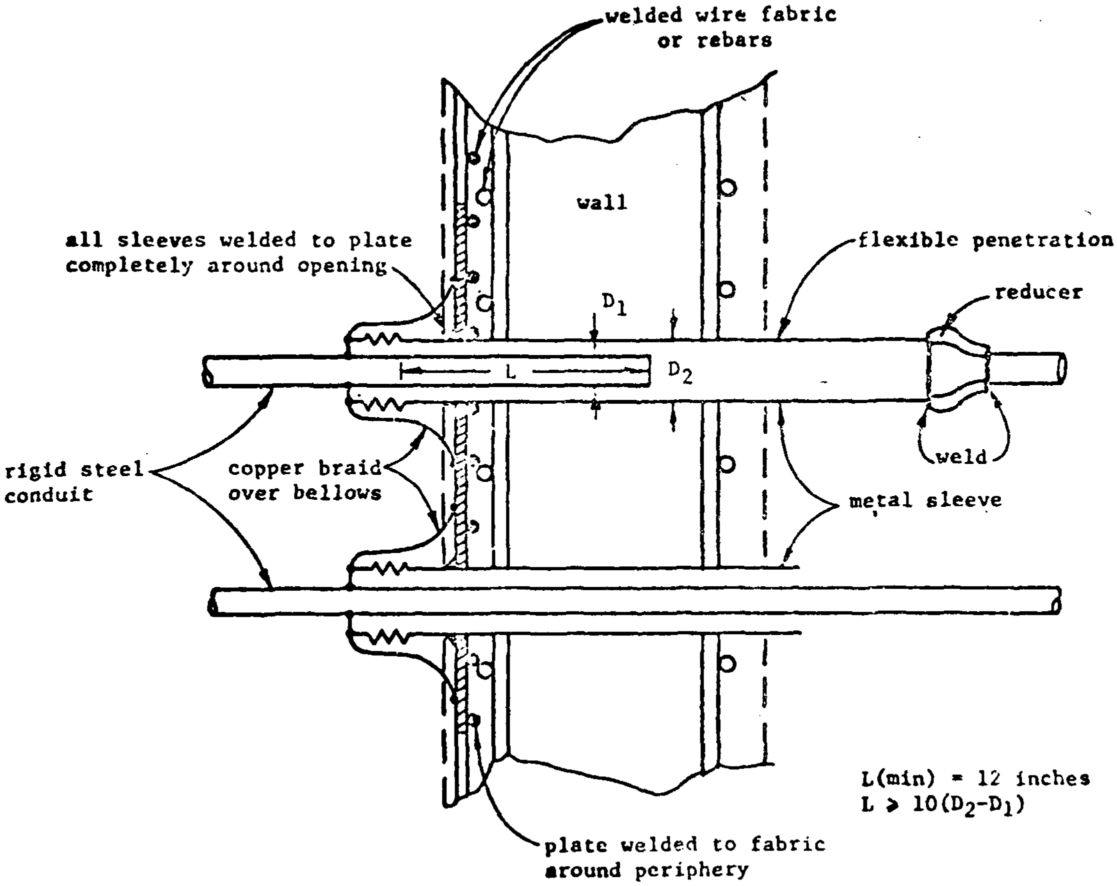


Figure B.9. Penetrations of outside wall with wall shielding.

If a conductive line does not have conduit then the conductor should be connected to a lightning arrestor device and then to a bulk head mounted filter before entering the building shield. Antenna leads and antenna mast also must be protected.

References

1. "EMP Protection for Emergency Operating Centers," Office of Civil Defense Manual, TR-61A (May 1971).

2. "DASA EMP (Electromagnetic Pulse) Handbook", DASA Information and Analysis Center, Santa Barbara, CA, (September 1968).

3. J. D. Nordgard and C. L. Chen, "FAA Lightning Protection Study: Lightning-Induced Transients on Buried Shielded Transmission Lines," Report FAA-RD-75-108, (1975).

4. J. D. Nordgard and C. L. Chen, "FAA Lightning Protection Study: Lightning-Induced Transients on Buried Shielded Transmission Lines: Numerical Analysis and Results," Report FAA-RD-77-83, (1977).

APPENDIX C

Shielding

In general, EMP shielding must protect against three aspects of EMP: radiated electric field, magnetic field, and earth currents. The importance of each of these and the subsequent shielding techniques required depend upon the spectral density and therefore, waveform of the EMP environment, and the distance between the source of EMP and equipment to be protected. For the environment specified in Chapter 2, only the electromagnetic field component, which may be treated primarily through its electric field component, is of major importance in the FAA situation.

C.1. General Shielding Considerations

In order to predict the effect of an electromagnetic pulse on electronic equipment it is necessary to obtain an estimate of the environment. Then a determination of the modification of that environment by shielding must be made.

Existing FAA facilities consist typically of enclosures of various sizes, shapes and types of construction, which are connected to the outside world by utility lines and pipes, communications lines, antennas, access and ventilation structures as depicted previously in Figure A.1. The exact determination of the interaction of an EMP with such a variety of structures is a complex and involved analytical problem. The only practical method of treating the problem is to consider each structure independently, as regards the existing shielding effectiveness and possibilities for improvement. The materials and methods of bonding discussed are limited to those which are considered practical for the FAA situation.

If the walls or skin panels of the buildings and equipment cabinets were made of perfect conductors with infinite conductivity, no field can penetrate through the shields. Unfortunately, such a material does not exist. If the conductivity of the walls or skin panels is finite, electromagnetic fields can diffuse through the shields. Useful measures of the shielding effects of particular materials are the electric and magnetic shielding factors:

$$\eta_E = \frac{\text{Amplitude of E inside the shielded region}}{\text{Amplitude of incident E on the shield}} \tag{C.1}$$

$$\eta_M = \frac{\text{Amplitude of H inside the shielded region}}{\text{Amplitude of incident H on the shield}} \tag{C.2}$$

In some cases the term "shielding effectiveness" S_E and S_M can also be used:

$$S_E = -20 \log_{10}(\eta_E) \quad \text{(in dB)} \tag{C.3}$$

$$S_M = -20 \log_{10}(\eta_M) \quad \text{(in dB)} \tag{C.4}$$

So far as the shielding effectiveness of walls or skin panels with large local radii of curvature is concerned, the most important parameters, but not the only parameters, are the conductivity and permeability of the material. These parameters determine directly the skin depth of the material at that particular frequency, and skin depth is the primary factor effecting the shielding characteristics of the material. Figure C.1 presents the shielding effectiveness of steel, aluminum, copper and titanium, of thickness 1.5 mm, against plane electromagnetic waves. It is interesting to note that although the conductivity of steel is relatively low, its shielding effectiveness is quite high at high frequencies because of its high permeability. Also shown in Figure C.2 is the magnetic shielding effectiveness

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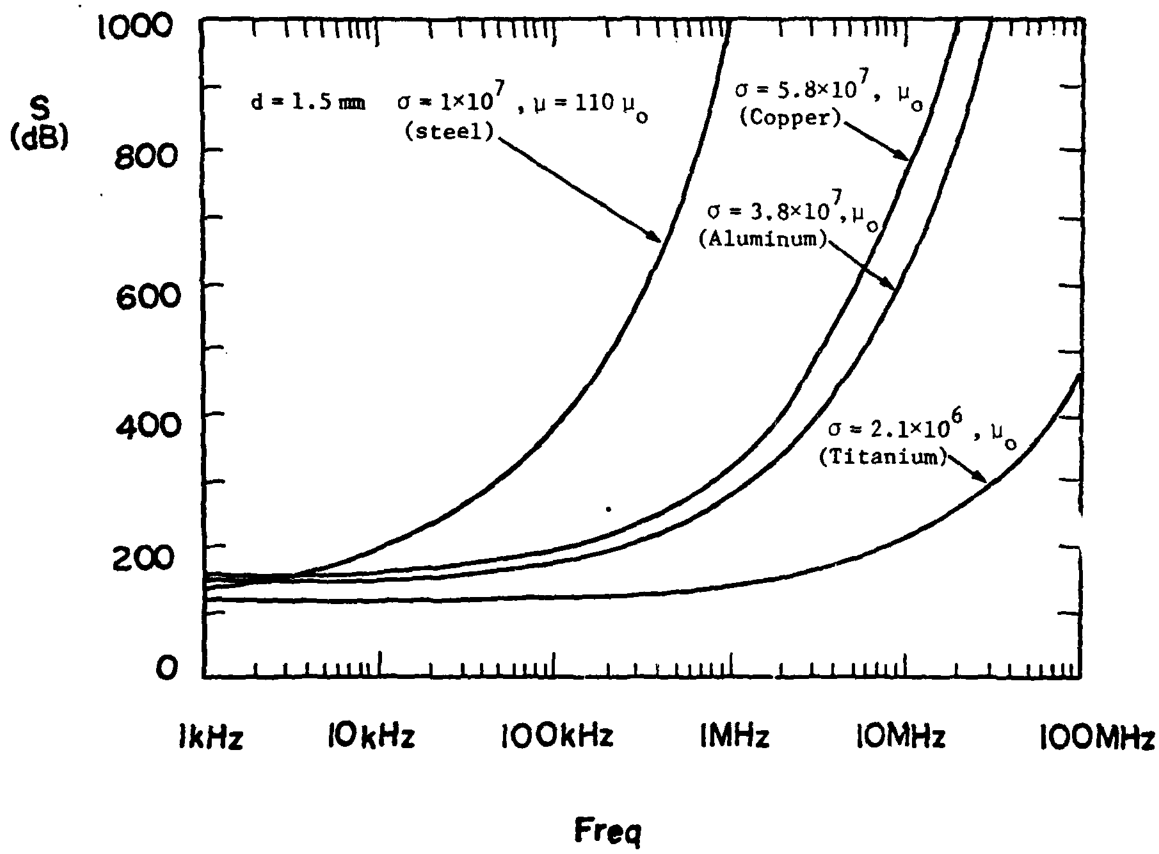
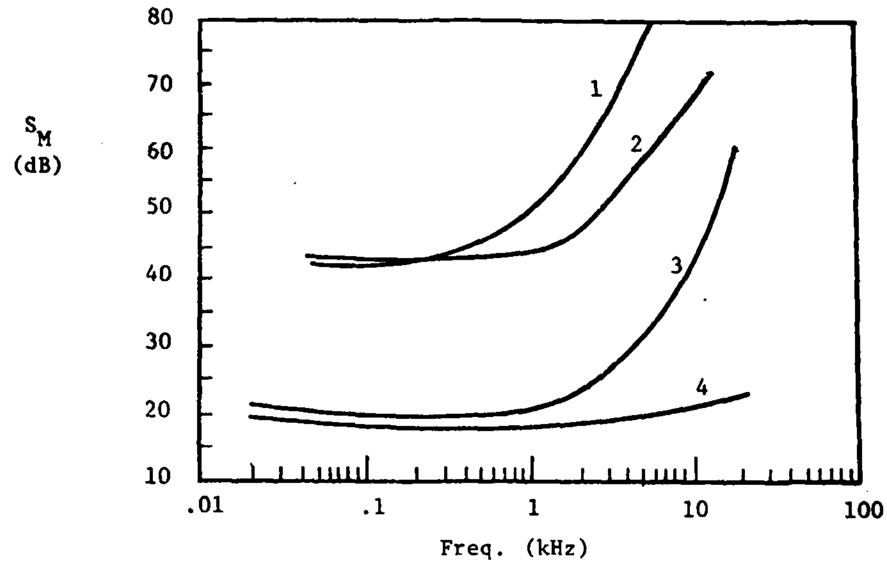


σ in mho/meter

Figure C.1. Shielding factor of a plane panel of thickness 1.5 mm of various materials.



1. Hy-mu .031"×24"×24"
2. AMPE-65 .014"×6.25"×24"
3. Galvanealed Steel .028"×10.75"×10.75"
4. Mu-metal .014"×12"×24"

Figure C.2. Measured shielding effectiveness of high permeability sheets.

of some high permeability material.

C.2. Solid Shell Shielding

Clearly, excellent protection would be provided by 1/4" to 3/8" welded steel structures, but at a prohibitive cost. Because the energy content of the low frequency part of the spectrum is relatively low, adequate shielding can be obtained using high frequency techniques which primarily take advantage of the reflective properties of the shield. Relatively thin galvanized paneling (18 gauge) can provide adequate shielding above 10 kHz. Bonding considerations indicate that thicker paneling (10 gauge, approximately 1/8") should be used.

It is noted that galvanized sheet steel has better attenuation properties than copper and can be purchased at fractional cost. This material effectively reflects waves at frequencies above 10 kHz and provides significant attenuation at frequencies down to 1 kHz. Figures C.3 and C.4 illustrates the potential shielding effectiveness of various thickness of sheet steel and low-carbon steel panels. Experience has shown, that when zinc coated, the high frequency characteristics are improved and preserved as well. Another desirable characteristic of zinc is that under moderate pressure, it makes good contact closure at panel or door joints. Hot-dip galvanization has been found to be excellent for exterior installations of thin steel sheets.

For thicker steel sheets 10 gauge or thicker, a better approach is to weld the seams. Since galvanized material cannot be welded effectively, painting would then be required for protecting against corrosion. Good welding provides shielding equivalent to the shield being used. Although continuous 18 gauge metal would provide the required shielding, 10 gauge is recommended because it provides better structural integrity, it is much

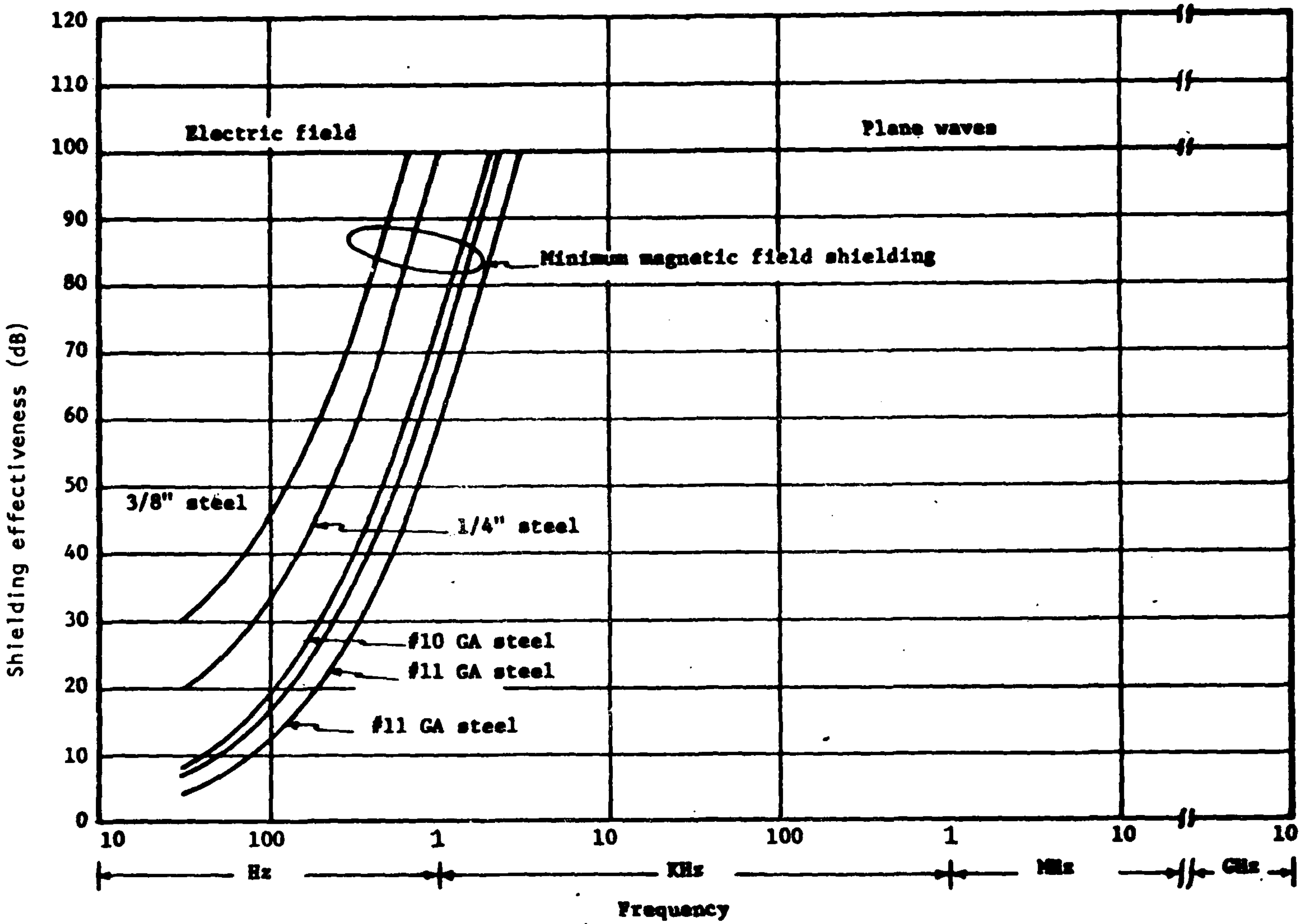


Figure C.3. Potential shielding effectiveness of various thicknesses of sheet metal.

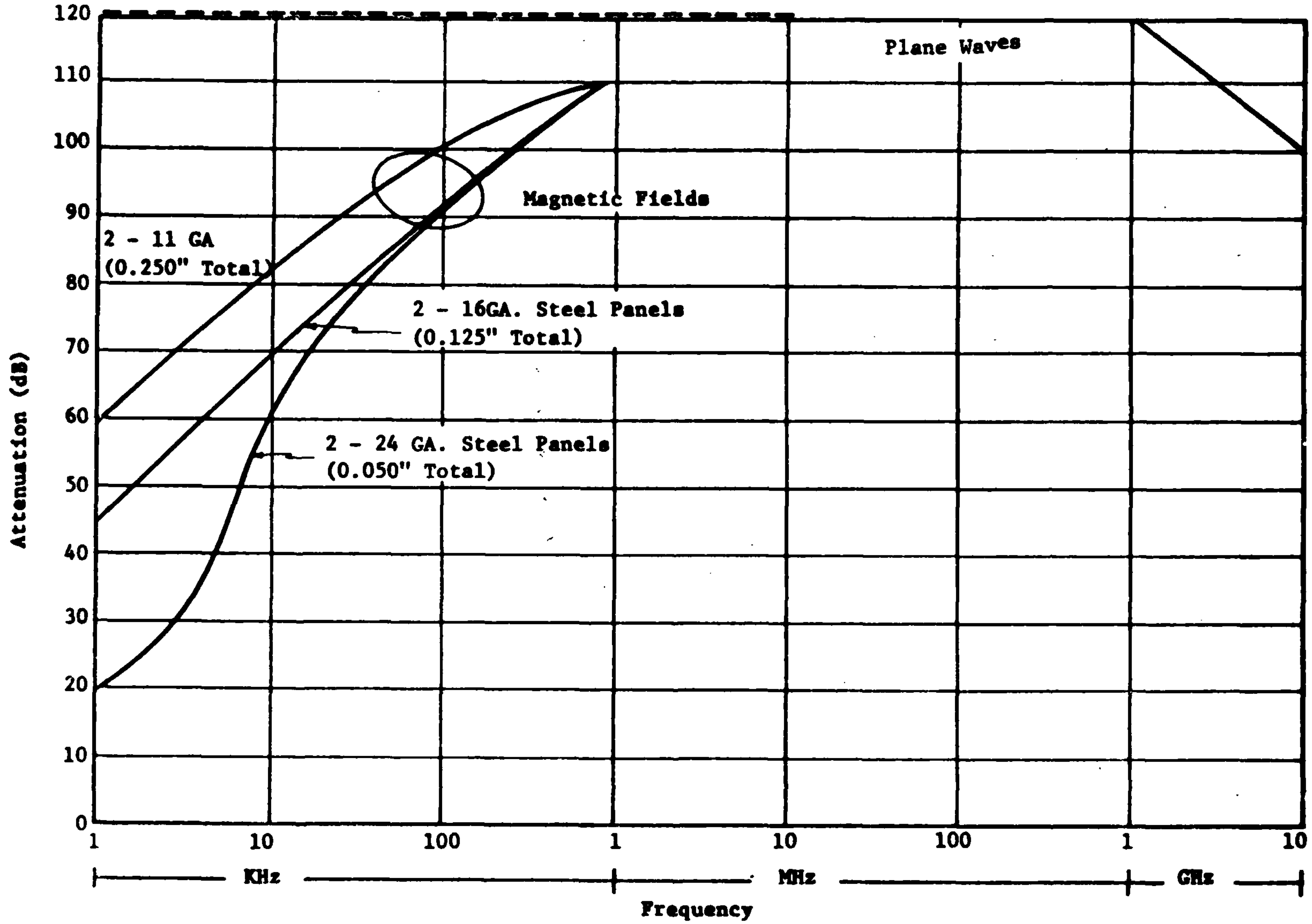


Figure C.4. Attenuation characteristics for low carbon steel.

easier welded to give better electromagnetic shielding, and the shielding integrity is preserved over a long period of time than with thinner materials. Solid shell room shielding is rapidly coming into use to provide additional shielding for hypersensitive devices within buildings. In addition to being superior to screen rooms, solid steel can provide protection throughout the spectrum of interest as depicted in Figure C.1 and electromagnetically hard penetrations are much easier to provide. Such structure can be used when it is desirable for all shielding to be within the facility.

C.3. Composite Materials as Electromagnetic Shields

The shielding characteristics of composite material, like graphite-epoxy, and screened boron-epoxy etc., against EMP-type disturbances have been investigated recently [1,2]. Graphite-epoxy composites have been modelled as isotropic, homogeneous conducting material while boron-epoxy composites are considered to be isotropic and homogeneous insulating dielectrics. The screen used in the screened boron-epoxy composites is modelled as thin wires with bonded junctions. Of course in reality the wire junctions may be imperfect due to oxidation at the junctions. It was found that these composite laminates are not as effective as panels made of good conductors in shielding against EMP penetrations. It is interesting to note that the principle difference between graphite and screened boron-epoxy composites is that the graphite composite tends to act as a low-pass filter while the latter behaves as a high-pass filter.

C.4. Metallic Mesh and Cabinet Shielding

The metallic structures, such as rebar and wire mesh used in normal building construction practice will provide a degree of shielding if the metal parts are electrically bonded and grounded. The shielding effectiveness calculations for commercial steel reinforcing bars are presented in [3]. Figure C.5 illustrates the application and gives attenuation factors which apply to the center of the structure. Attenuation factors are degraded for all types of shielding within a distance of approximately 5' of the shielding material as shown in Figure C.6. These figures indicate that for distances more than 5' from the wall, rebar enforced building of nominal size provide attenuation factors in the range of 20 to 30 dB depending upon bar diameter and bar spacing. Calculations for double rebar shielding have been also given in [3]. The calculations show that a second layer of rebar provides approximately 10 dB additional attenuation.

Welded wire fabric can also be effective as a shielding medium. Its effectiveness is also influenced by structure dimensions, wire diameter, mesh size and most critically by the degree of electrical bonding and grounding provided. Figures C.7 and C.8 which are excerpted from [4] demonstrate the center room attenuation factors for the conditions shown on the graphs.

Commercial shielding enclosures are available in several forms. Such enclosures might be required in order to provide additional shielding to hypersensitive equipment. For example, tests have shown that copper screens of 22 mesh made of 15 mil copper wires will provide 40 dB of attenuation down to 10 kHz as indicated in Figure C.9 (excerpted from [5]). These enclosures are awkward to use and difficult to penetrate satisfactorily; furthermore, the range and degree of protection is limited. For these rea-

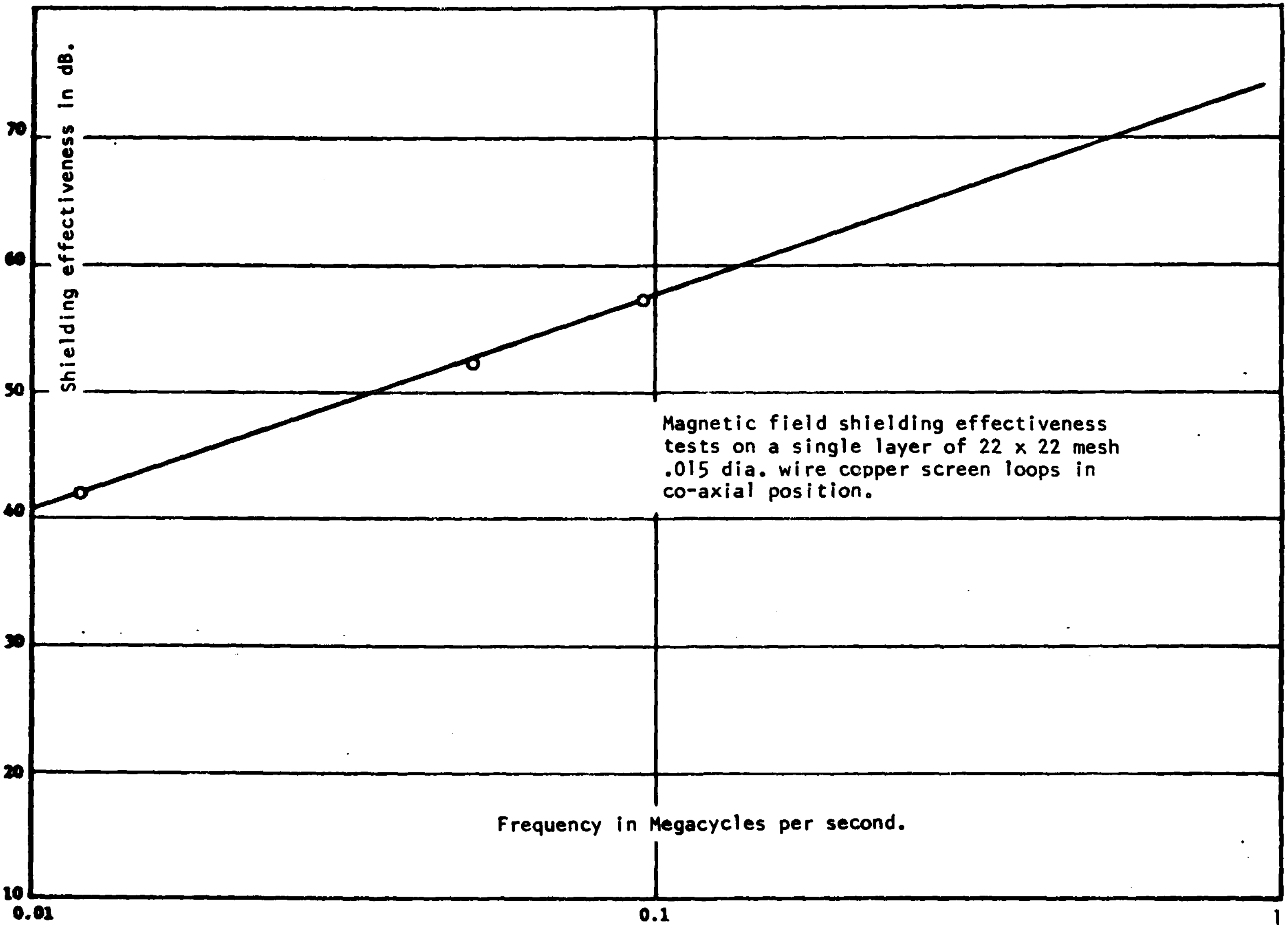


Figure C.5. Shielding effectiveness for commercial steel reinforcing bars.

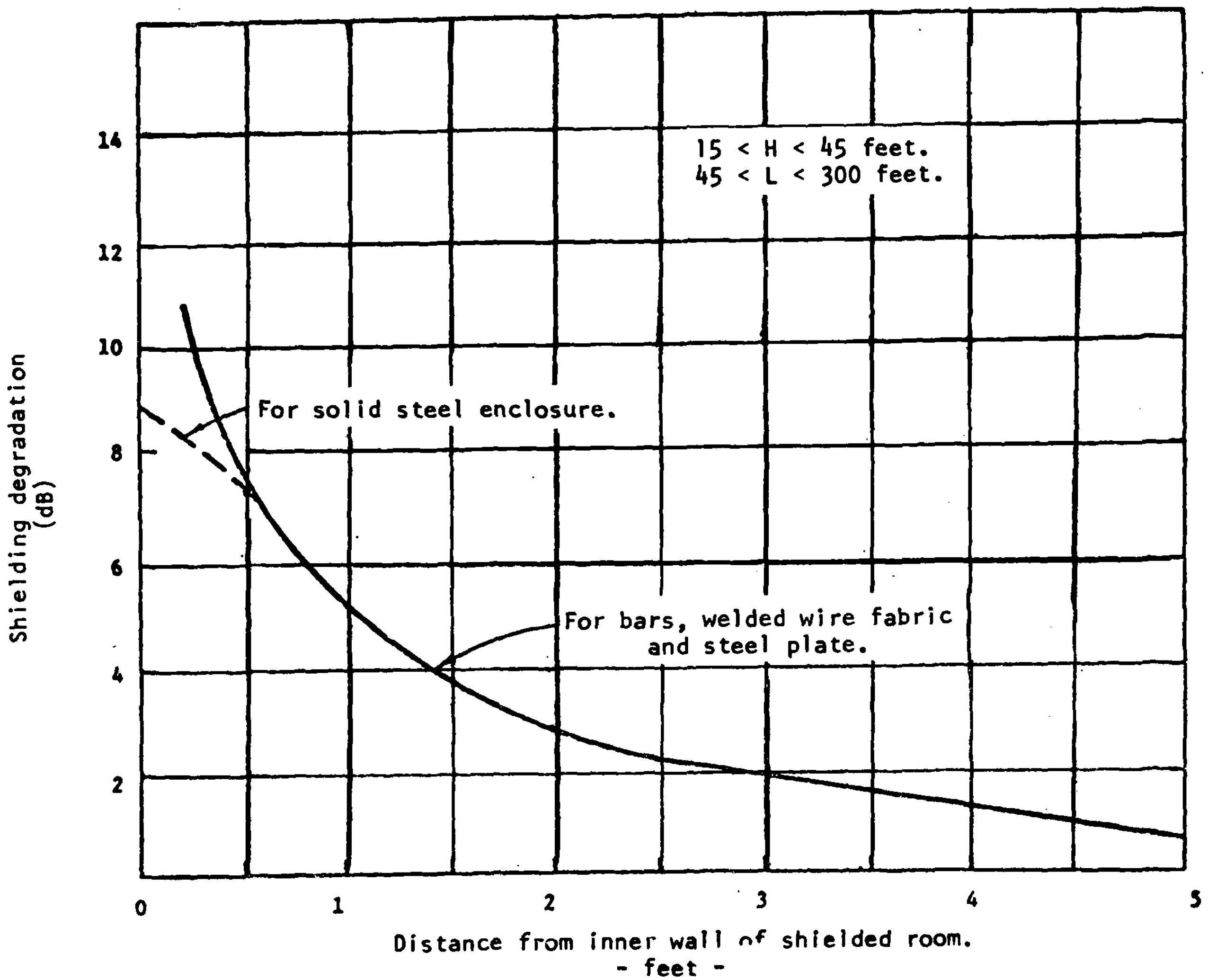


Figure C.6. Degraded attenuation factors for shielding within a 5-foot distance of the shielding material.

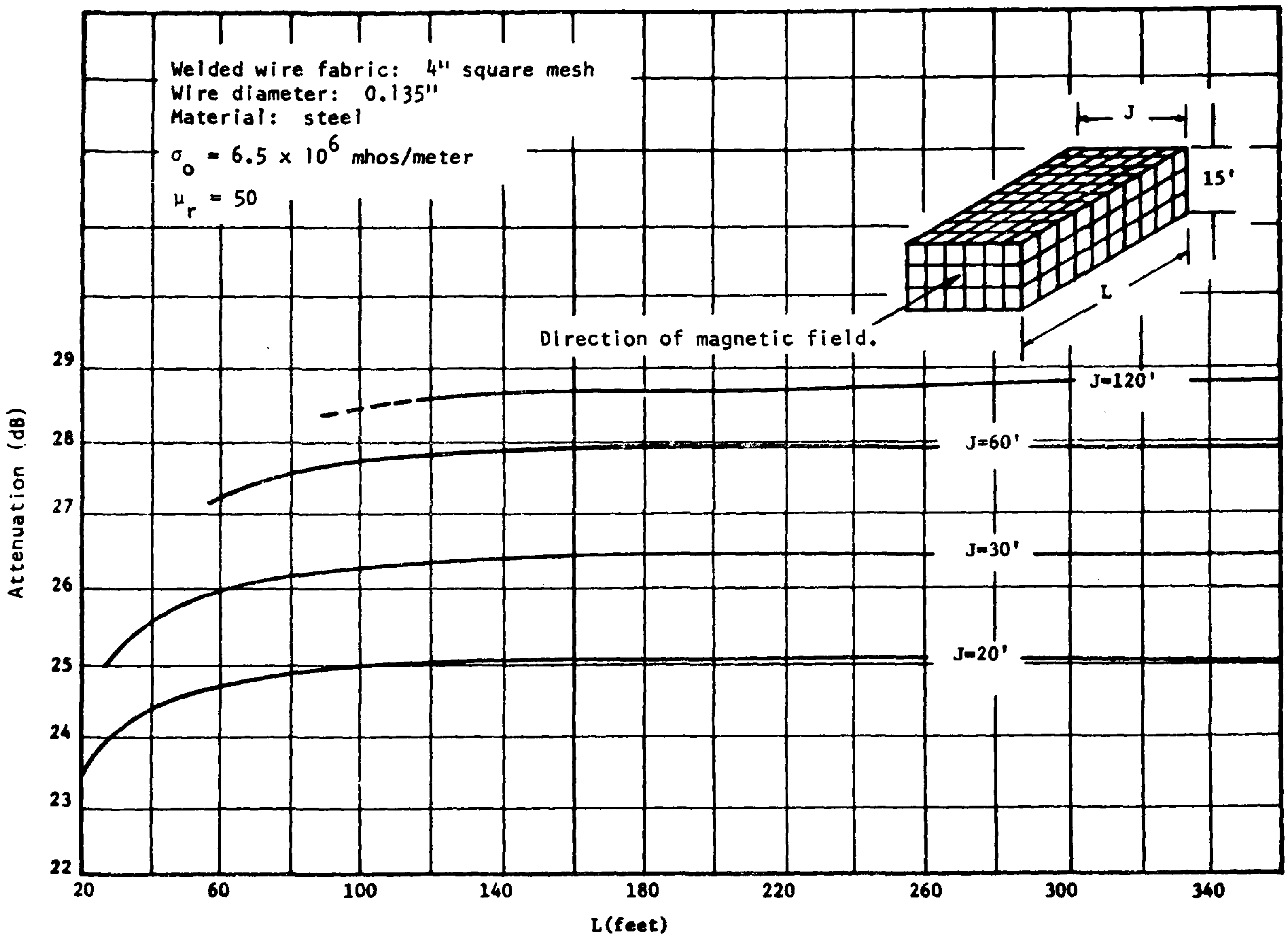


Figure C.7. Center room attenuation factors (specific conditions).

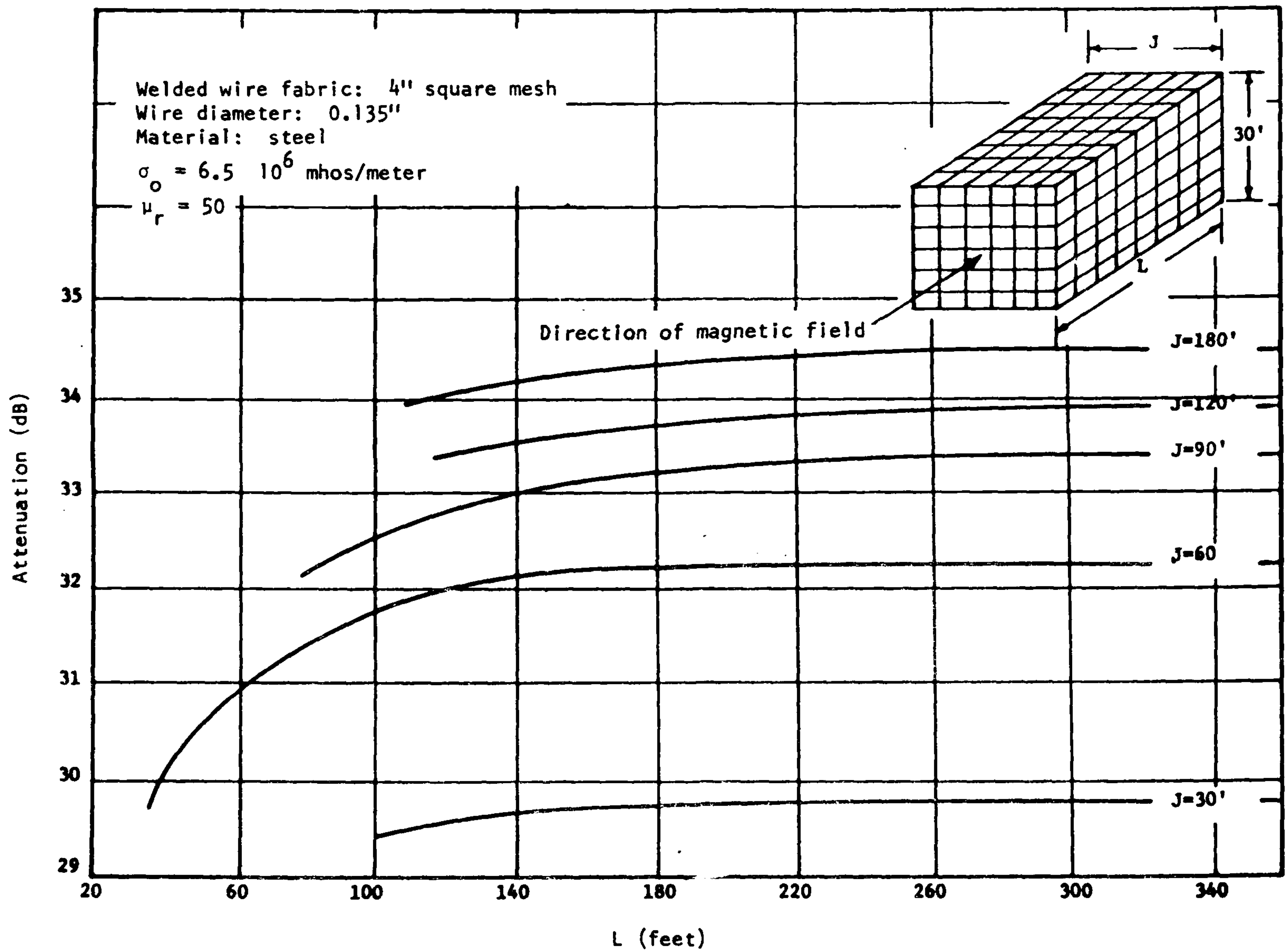


Figure C.8. Center room attenuation factors (specific conditions).

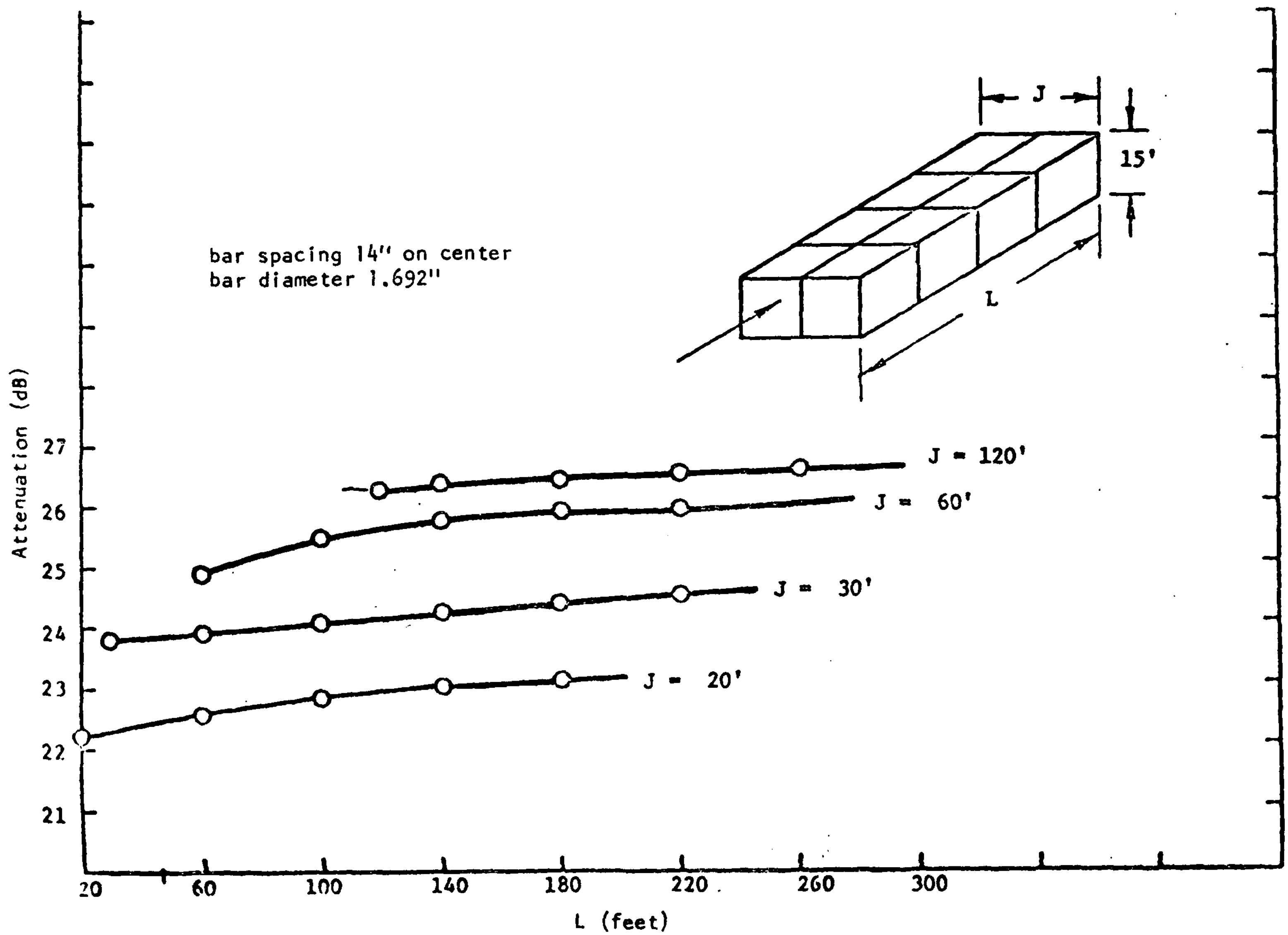


Figure C.9. Attenuation of copper screen mesh.

sons the solid shell steel rooms mentioned in Sec. C.2 are generally recommended.

Typical equipment cabinets in use do not have metal bottoms, therefore the attenuation within the structure varies radically with distance from the bottom. Cabinets with bottoms that are tightly bolted and have panels and doors lined with RF gasket material could provide up to 25 dB of attenuation down to 15 kHz. For the more typical type cabinet the attenuation factors for various cabinet sizes is given in Figure C.10 [5].

C.5. Small Apertures on the Shields

In many situations, it may be necessary to put doors, windows, ventilation ducts or hatches etc., on the building shields or the equipment cabinet. Some of the openings are created unintentionally. Electromagnetic fields can penetrate into the shields through these openings. Even if conductive gaskets are used to help prevent electromagnetic leakage, the integrity of the shields can also be compromised by the presence of slots in the shielding or seams on the gaskets. Thus the shielding of the equipment is not complete until all penetrations are accounted for and protected. This subsection is to address the problems associated with the openings or apertures on the shields.

The penetration of fields through an aperture of an arbitrary shape and size on the shield of an arbitrary contour and size is an extremely complicated problem. However if the maximum dimension of the aperture is small, and the radius of curvature of the shield in the region near the aperture is large, in comparison with the wavelength of the incoming wave, or the smallest wavelength of the significant portion of the incoming pulses, approximate solutions to the problem may be found. Under the conditions mentioned above the fields penetrated into the shield may be approximated by fields

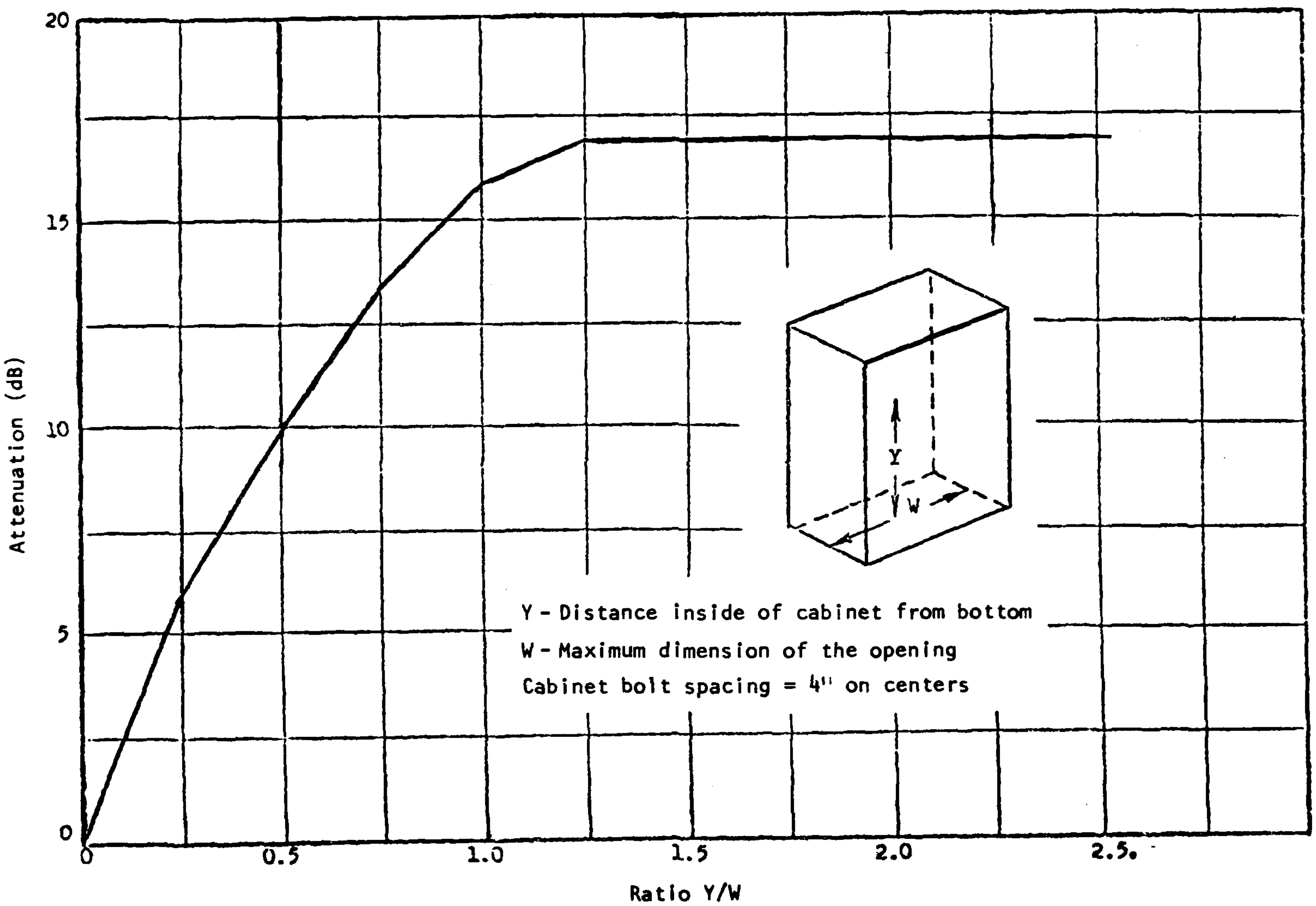


Figure C.10. Attenuation factors for various cabinet sizes.

penetrated through a small aperture on a planar screen of infinite extent. The planar screen is assumed to be perfectly conducting. Bethe showed that the fields coupled through a small aperture on an infinitely large, plana screen may calculated in the following fashion [6,7,8]. The first step is to replace the aperture with equivalent electric, magnetic dipoles, and a linear quadrupole. Since the contribution from the quadrupole is usually small and will be neglected entirely in the present discussion. These equivalent dipoles are located at the center of the aperture, and on the shadow side of the shield. Knowing the equivalent dipole sources, it is a relatively simple matter to calculate the fields radiated by these dipoles. It is understood that in the calculation for the radiated fields, these dipoles are backed by an infinitely large, and electrically conducting screen.

For simplicity, the planar screen may be taken as a horizontal plane coinciding with the xy plane of the coordinate system and the incident field comes from bottom side [z<0] of the screen. Let the incident electric and magnetic fields be

$$\vec{E}^{i} = \hat{x}\, E_x^{i}(x,y,z) + \hat{y}\, E_y^{i}(x,y,z) + \hat{z}\, E_z^{i}(x,y,z) \tag{C.5}$$

$$\vec{H}^{i} = \hat{x}\, H_x^{i}(x,y,z) + \hat{y}\, H_y^{i}(x,y,z) + \hat{z}\, H_z^{i}(x,y,z) \tag{C.6}$$

Then the equivalent electric and magnetic dipoles may be written as,

$$\vec{p} = 2\varepsilon_0\alpha_e\, E_z^{i}(x,y,o^-)\hat{z} \tag{C.7}$$

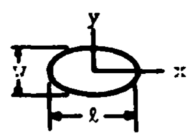
$$\vec{m} = -2[\alpha_{m,xx} H_x^i(x,y,o^-)\,\hat{x} + \alpha_{m,yy} H_y^i(x,y,o^-)\,\hat{y}] \qquad (C.8)$$

where α_e and α_m are the electric and magnetic polarizabilities. Note that for an aperture on the horizontal plane, the electric polarizability has one component (z-component) while the magnetic polarizability has two components $\alpha_{m,xx}$ and $\alpha_{m,yy}$. The polarizabilities of circles and ellipses may be expressed in closed forms as shown in Table C.1 [6,7,9,10]. For apertures of complicated shapes like rectangular slot, rounded-end slot, cross and dumbell etc., no analytic expressions for their polarizabilities are known and it is necessary to resort to numerical techniques to calculate them. The results of the numerical computations are shown in Figure C.11, C.12 and C.13, [11]. Comparison with experimental data shows that these expressions and numerical results are accurate within a few percent [12,13]. Simple expressions for the polarizabilities for hatches, under the assumption that the slot width is very narrow in comparison with all other dimensions, are available and are listed in Table C.2 [10].

Once the equivalent electric and magnetic dipoles are known, the fields radiated by these sources can be calculated by standard method. The relevent expressions are collected in Table C.3 for convenience [10]. Note that the expressions and numerical results quoted above are explicitly for waves of a given frequency. However, once the penetration of field through an aperture is known as a function of frequency, the time-domain behavior of electromagnetic pulses through aperture may be obtained by the application of Fourier transform. Figure C.14 shows the electromagnetic pulse penetrating through a rectangular slot [9,10].

TABLE C.1
APERTURE POLARIZABILITIES

Shape	α_e	$\alpha_{m,xx}$	$\alpha_{m,yy}$
Circle (D = Diameter)	$\frac{1}{12} D^3$	$\frac{1}{6} D^3$	$\frac{1}{6} D^3$
Ellipse[+]	$\frac{\pi}{24} \frac{w^2 \ell}{E(\epsilon)}$	$\frac{\pi}{24} \frac{\ell^3 \epsilon^2}{K(\epsilon) - E(\epsilon)}$	$\frac{\pi}{24} \frac{\ell^3 \epsilon^2}{\left(\frac{\ell}{w}\right)^2 E(\epsilon) - K(\epsilon)}$
Narrow Ellipse ($w \ll \ell$)	$\frac{\pi}{24} w^2 \ell$	$\frac{\pi}{24} \frac{\ell^3}{\ln\left(\frac{4\ell}{w}\right) - 1}$	$\frac{\pi}{24} w^2$



[+]Ellipse Eccentricity $\epsilon = \sqrt{1 - \left(\frac{w}{\ell}\right)^2}$

K and E are the complete elliptic integrals of the first and second kind, respectively:

$$K(\epsilon) = \int_{\phi=0}^{\pi/2} \frac{1}{\left[1 - \epsilon^2 \sin^2\phi\right]^{\frac{1}{2}}} d\phi \quad , \quad E(\epsilon) = \int_{\phi=0}^{\pi/2} \left[1 - \epsilon^2 \sin^2\phi\right]^{\frac{1}{2}} d\phi$$

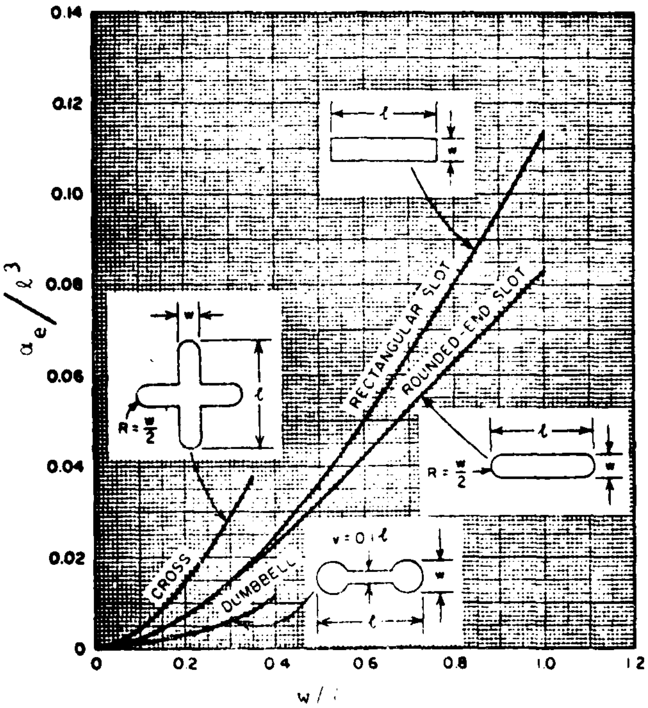


Figure C.11. Normalized Electric Polarizability $\left(\alpha_e / \ell^3\right)$.

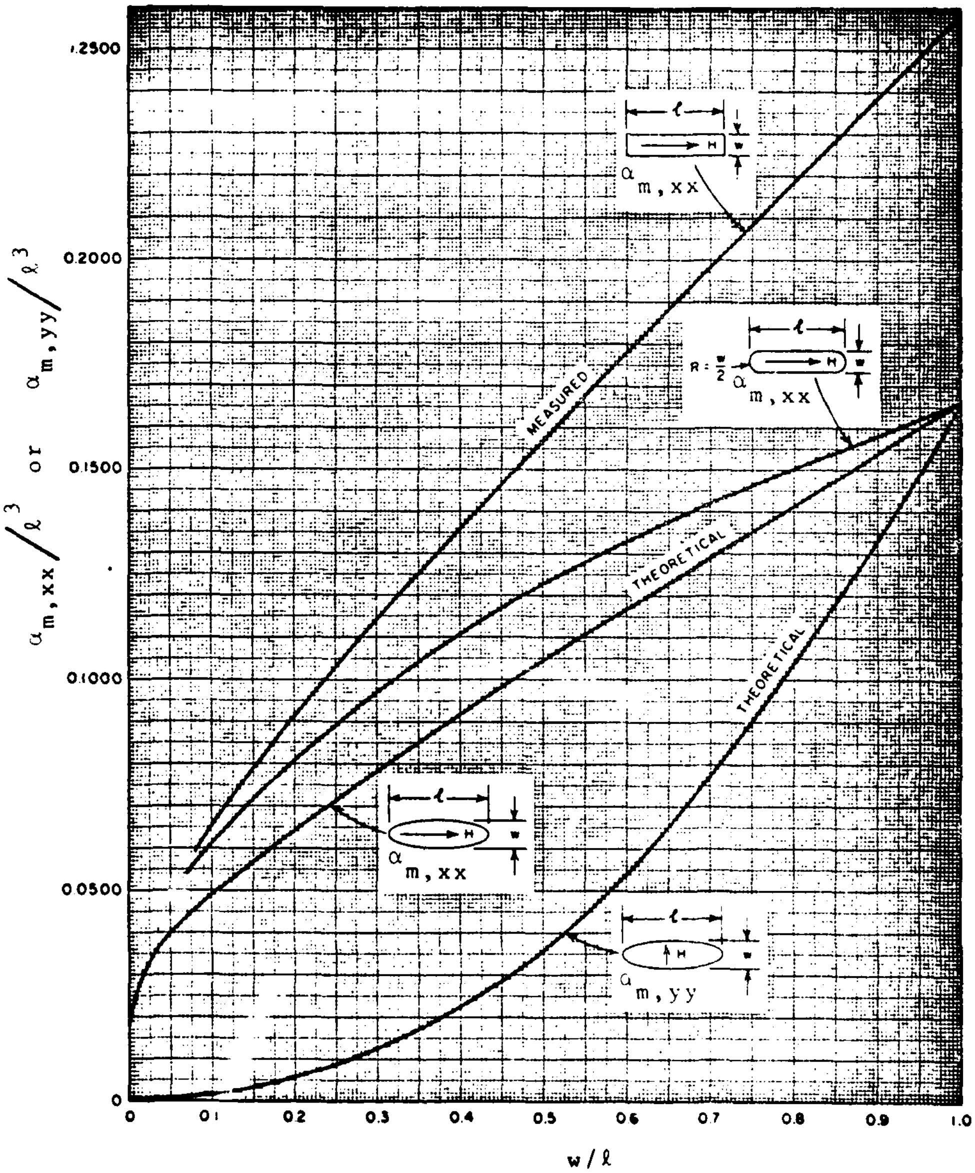


Figure C.12. Normalized Magnetic Polarizability
$\left(\alpha_{m,xx}/\ell^{3} \text{ or } \alpha_{m,yy}/\ell^{3}\right)$.

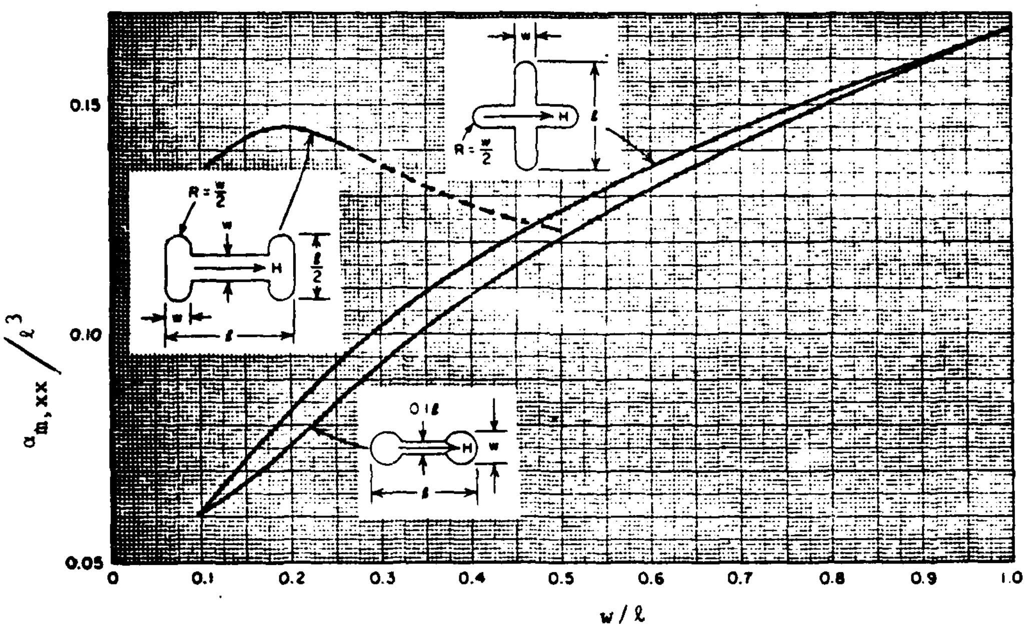


Figure C.13. Normalized magnetic polarizability $\left(\alpha_{m,xx}/\ell^{3}\right)$.

TABLE C.2

POLARIZABILITIES OF HATCH APERTURES

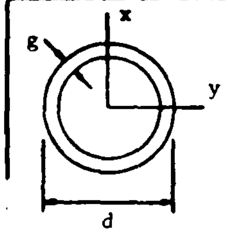
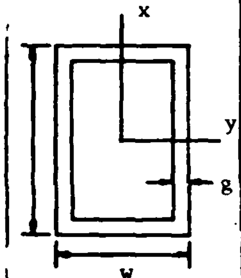
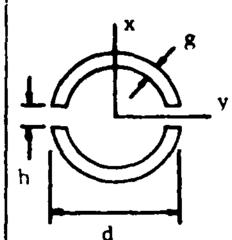
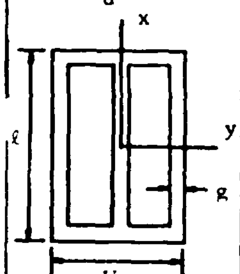
Aperture	α_e	$\alpha_{m,xx}$	$\alpha_{m,yy}$
	$\frac{\pi^2}{32} \frac{d^3}{\ln\left(16 \frac{d}{g}\right) - 2}$	$\frac{\pi^2}{16} \frac{d^3}{\ln\left(16 \frac{d}{g}\right) - 2}$	$\frac{\pi^2}{16} \frac{d^3}{\ln\left(16 \frac{d}{g}\right) - 2}$
	$\frac{\pi}{4} \frac{\ell^2 w}{\left(1 + \frac{\ell}{w}\right) \ln\left[4(\ell + w)/g\right]}$	$\frac{\pi}{12} \frac{\ell^3 \left[1 + 3\left(\frac{w}{\ell}\right)\right]}{\ln\left[4(\ell + w)/g\right]}$	$\frac{\pi}{12} \frac{w^3 \left[1 + 3\left(\frac{\ell}{w}\right)\right]}{\ln\left[4(\ell + w)/g\right]}$
		$\frac{\pi^2 d^3}{8\Omega} \left[1 - \frac{8/\pi 2}{1 + \Omega g^2/(8\pi d h)}\right]$ $\Omega = 2 \ln (16\ d/g)$	$\frac{\pi^2}{16} \frac{d^3}{\ln\left(16 \frac{d}{g}\right) - 2}$
	$\frac{\pi}{4} \frac{\ell^2 w}{\left(1 + \frac{\ell}{w}\right) \ln\left[4(\ell + w)/g\right]}$	$\frac{\pi}{24} \frac{\ell^3 \left[\frac{8}{3} + 7\left(\frac{w}{\ell}\right) + 2\left(\frac{w}{\ell}\right)^2\right]}{\ln\left[4(\ell + w)/g\right]}$	$\frac{\pi}{12} \frac{w^3 \left[1 + 3\left(\frac{\ell}{w}\right)\right]}{\ln\left[4(\ell + w)/g\right]}$

TABLE C.3

ELECTRIC FIELD COMPONENTS IN REGION $z > 0$ DUE TO AN ELECTRIC DIPOLE OF MOMENT $p\hat{z}$ AND A MAGNETIC DIPOLE OF MOMENT $\bar{m}$ $(= m_x\hat{x} + m_y\hat{y})$ BOTH LOCATED AT (0,0,0+) ON AN INFINITE, CONDUCTING SCREEN*

$$E_x = \frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{-\frac{p}{\varepsilon}\frac{xz}{r^2}\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right) + \eta m_y \frac{z}{r}\left(k^2 - j\frac{k}{r}\right)\right\}$$

$$E_y = -\frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{\frac{p}{\varepsilon}\frac{yz}{r^2}\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right) + \eta m_x \frac{z}{r}\left(k^2 - j\frac{k}{r}\right)\right\}$$

$$E_z = \frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{\frac{p}{\varepsilon}\left[\left(k^2 - j\frac{k}{r} - \frac{1}{r^2}\right) - \frac{z^2}{r^2}\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right)\right]\right.$$

$$\left. + \frac{\eta}{r}\left(ym_x - xm_y\right)\left(k^2 - j\frac{k}{r}\right)\right\}$$

* The screen is embedded in a homogeneous medium characterized by (μ,ε); $\eta = \sqrt{\mu/\varepsilon}$.

TABLE C.3 (Continued)

MAGNETIC FIELD COMPONENTS IN REGION $z > 0$ DUE TO AN ELECTRIC DIPOLE OF MOMENT $p\hat{z}$ AND A MAGNETIC DIPOLE OF MOMENT m $(= m_x\hat{x} + m_y\hat{y})$ BOTH LOCATED AT (0,0, 0+) ON AN INFINITE, CONDUCTING SCREEN*

$$H_x = \frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{\frac{p}{\epsilon\eta}\frac{y}{r}\left(k^2 - j\frac{k}{r}\right) + m_x\left(k^2 - j\frac{k}{r} - \frac{1}{r^2}\right) - \frac{x}{r^2}\left(xm_x + ym_y\right)\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right)\right\}$$

$$H_y = \frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{-\frac{p}{\epsilon\eta}\frac{x}{r}\left(k^2 - j\frac{k}{r}\right) + m_y\left(k^2 - j\frac{k}{r} - \frac{1}{r^2}\right) - \frac{y}{r^2}\left(xm_x + ym_y\right)\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right)\right\}$$

$$H_z = -\frac{1}{2\pi}\frac{e^{-jkr}}{r}\left\{\frac{z}{r^2}\left(xm_x + ym_y\right)\left(k^2 - j\frac{3k}{r} - \frac{3}{r^2}\right)\right\}$$

$$r = \left[x^2 + y^2 + z^2\right]^{\frac{1}{2}}$$

*The screen is embedded in a homogeneous medium characterized by (μ,ϵ); $\eta = \sqrt{\mu/\epsilon}$.

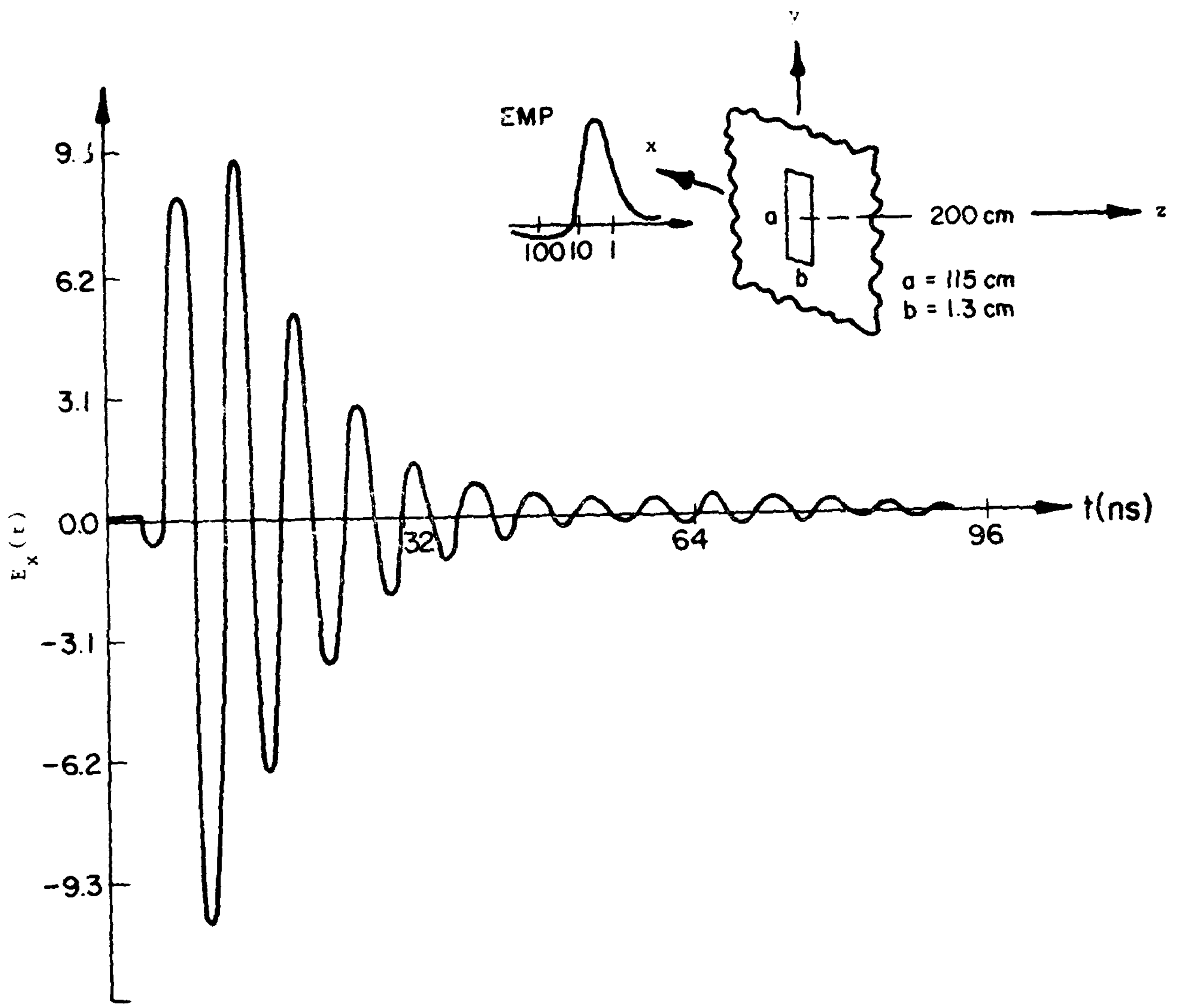


Figure C.14. Time domain behavior of the $E_x(t)$ field sampled at a point 2 meters behind a single aperture.

C.6. Large Apertures and Apertures of Moderate Sizes

There are two effective ways to protect against signals entering large doorways and other large openings. The most obvious one is to physically close the aperture with material equivalent to the building shield. In the case of seldom-used hatches, this method is effective and inexpensive. Conductive gaskets should be used to ensure a good electrical bond and the bolts should be close together (2") and torqued appropriately (depending upon the thickness of the shield).

For large apertures such as doors for personnel entrance, steel doors with seals are available. The door should have the same electromagnetic performance rating as the shielded enclosure. To insure good electrical conductivity an adequate frame must be specified. Multiple rows of copper finger stock or highly conductive gasket must be used. A brass strip should be welded to the steel frame of the door to ensure good electrical contact with the finger stock or gasket material. These types of doors are operationally cumbersome, difficult to install, expensive to maintain.

To attenuate signals below 50 MHz, waveguide hallways can be used. A typical waveguide cutoff characteristic is shown in Figure C.15. The cutoff frequency is proportional to the largest lateral dimension of the hallway, therefore a trade-off must be made between hallway size and attenuation characteristics. The waveguide could be constructed of 20 gauge or thicker low carbon steel supported by any structurally sound but non-conductive material. However, when properly installed they provide attenuation in excess of 100 dB from 100 Hz to well into the megahertz range. Consider a typical situation. A 6' x 8' rectangular waveguide will attenuate according to the relation:

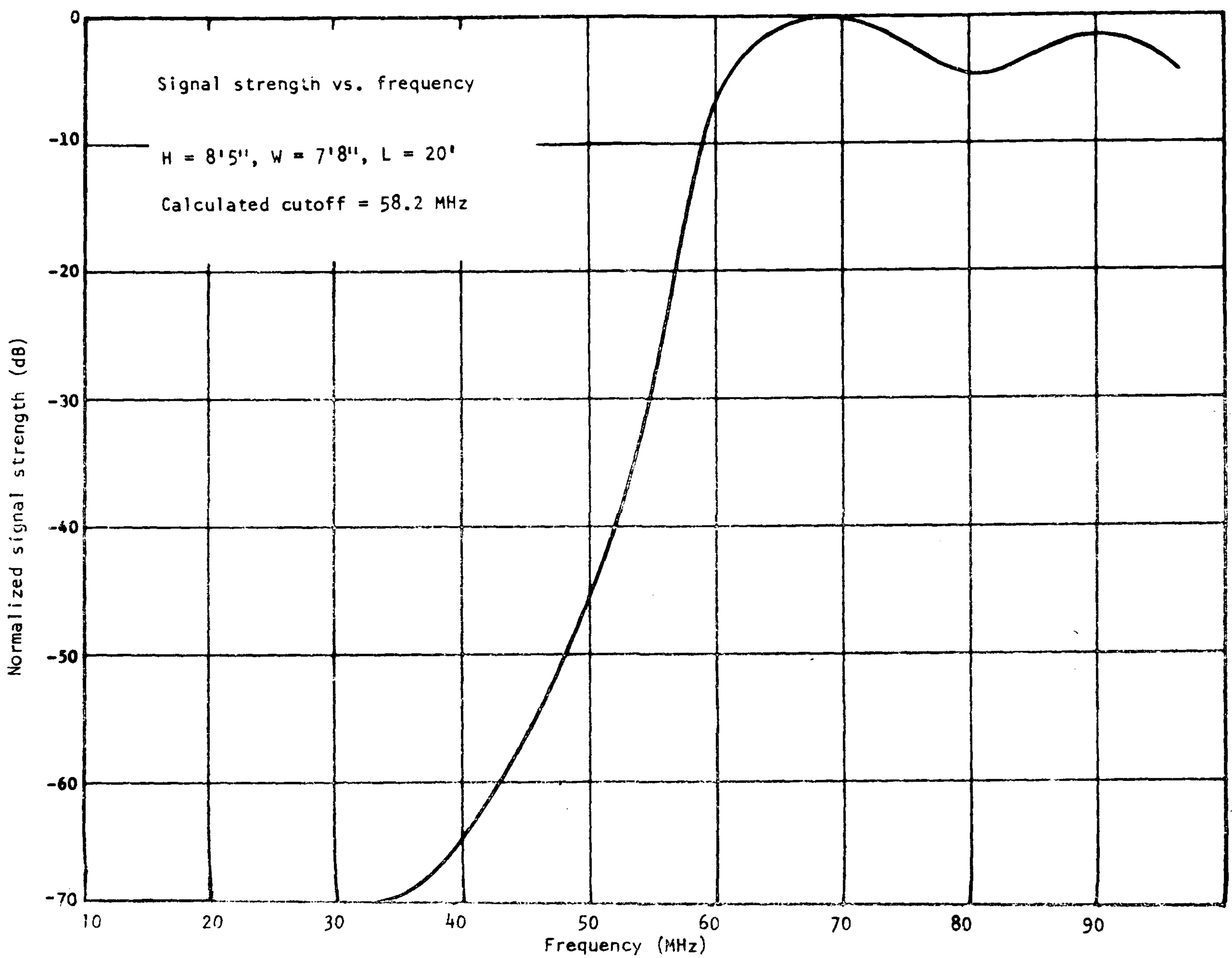


Figure C.15. Typical waveguide cut-off characteristic.

$$\alpha(dB) = \frac{54.61\ell}{\lambda_c}\sqrt{1 - (\frac{f}{f_c})^2} \tag{C.9}$$

Where λ_c is the cutoff wavelength, and ℓ is waveguide length in the same units as λ_c. For the dominant mode, λ_c = 2a and a is the largest lateral dimension. For frequencies well below cutoff ($f \ll f_c$), The attenuation per feet is $\frac{54.6}{\lambda_c} = \frac{54.6}{2a}$ which for this guide works out to be approximately 3.4 dB per ft. Obviously then, any required amount of attenuation can be achieved by the proper choice of hallway length. Application of this method is severely constrained by waveguide size. The choice of protective devices for personnel entrances is influenced by pedestrian traffic. The waveguide principle is extremely useful for small punctures which do not require the penetration of conducting materials. The introduction of conductive materials would effectively convert the waveguide to a coaxial structure which would conduct down to DC. For complexes which consist of more than one shielded building, heavy bellows or conduit can be run between buildings. This application is not really a waveguide application and such connections can be used for conductive paths so long as each building is a hardened complex. The underground connection from the auxiliary power buildings to the center building (1/4", 4" O.D. conduit) is an application of this principle.

An excellent method for protecting air intake and exhaust ducts is the installation of heavy metal fully welded honeycomb material inside the duct. The honeycomb acts as a stack of very small waveguides which will attenuate frequencies well into the gigahertz range. 100 dB of attenuation can be obtained if the depth of the honeycomb is 5 times the largest cross-sectional dimension of the honeycomb.

C.7. FAA Center Buildings

The center automation wings and all except one side of the control room are covered to within 5' of the ground with 2 layers of 20 - 22 gauge metal. The roof of the first floor consists of 14 gauge metal over the automation wing. The roof of the control room contains a thin lead sheet and expanded metal mesh. The metal in the two roofs is not connected. The bonding of this shielding material is poor and approximately 4220 sq. ft. of the area requiring protection has no metal siding and is protected only by unbonded metal mesh or rebar. Therefore, at best, attenuation of frequencies even above 10 kHz can be expected to be only about 36 dB. This attenuation factor is arrived at by considering only the protection afforded by the interface between the control room and the old buildings and the outer walls of the older building. This factor must be decreased from 36 dB to 26 dB because of vulnerable penetrations and poor rebar or screen connections. A value of 60 dB would be a more appropriate figure if the centers are to function during an EMP environment. It appears that the most practical way to shield the automation wings and ARTCC control room would be to bond and ground the existing material, extend it to ground level, and cover that portion of the control room adjacent to the cafeteria, and office section of the older building with one layer of 10 gauge sheets, also properly bonded.

Figure C.3 shows attenuation figures for single sheets without regard for penetrations. Figure C.4 shows the performance of two sheets of thinner material but the attenuation figures have been decreased to account for shielding degradation due to penetrations. Adequate bonding of the sheets already installed can be accomplished by spacing the screws 2" apart and brazing the corner connections where possible. If the sheets have been dipped in tar, the edges would have to be cleaned. Full penetration welding is recommended where new steel is being installed. Penetrations should be hardened in accordance with the recommendations of C.4 and C.5.

C.8. Radar Site Buildings

the remote long range radar site buildings are constructed of cinder block reinforced by single layered horizontal rebar on 8" centers and vertical rebar on 16" centers. The roof is covered with 1/8" metal. Rebar connections have been made using standard construction practice of wiring the bars together. Figure C.5 indicates an attenuation factor of 23 dB. However, due to the poor connections between the rebar and the unprotected penetrations a factor of 15 dB is a more appropriate estimate. A figure of 60 dB down to 10 kHz is desired for solid-state equipment.

C.9. Remote Microwave Link (RML) Buildings

The RML buildings would be relatively simple to harden. These buildings are constructed of cinder block reinforced by horizontal rebar on 7" centers and vertical rebar on 18" centers. The roof is covered with 18 gauge metal. The same recommendations that were made for the remote radar site buildings are applicable to the RML buildings. There are no water pipe or sewer penetrations and the standby diesel fuel is stored and piped underground. The existing doors should be adequate since they have two layers of metal. They could be bonded to the 10 gauge sheet steel shell with a conductive gasket material because of the small amount of pedestrian traffic into the buildings. The existing shielding effectiveness of the structure is estimated at 15 dB (Figure C.4), this being due to the rebar and metal roof. A shielding factor of 60 dB at 10 kHz is required for the solid state equipment.

C.10. Control Towers and Tower Buildings

Shielding the buildings at the base of the control towers is considered essential for the proper functioning of the computer and other electronic equipment installed therein. The walls of the building are concrete block 7-5/8" thick faced by 3-3/4" thick brick. There are three layers of horizontal rebar on 16" vertical centers but apparently no vertical rebar. The absence of vertical rebar greatly negates the effectiveness of rebar shielding. The roof is covered by #12 steel paneling. Above the steel paneling there is a metal screen. None of the metal is bonded to any of the rebar. These buildings are very vulnerable to EMP. To adequately shield the computer from the environment previously discussed 60 dB at 10 kHz is required. This amount of shielding can be provided by covering the sides with 10 gauge metal paneling. This material should be welded at panel joints and welded to the metal roof. In general the tower and control cabs do not have highly sensitive equipment. It should be sufficient to ensure that all cable runs to the cab in 1/4" steel conduit and that the conduit be well bonded and grounded at the lower end only. Filtering should be provided to prevent leads in the cab from picking up energy and conducting it back down to the computer room.

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APPENDIX D

System and Circuit Susceptibility

Although the voltages and currents induced in the system of interest may be large, the pulse duration is typically only about 500 nanoseconds, and the total energy involved is thereby limited. The typical model indicates that 1-2 Joules of total energy per meter-squared can be expected to penetrate any given region. A primary danger in circuits and components is from overvoltage breakdown, resulting damage, or welded contacts caused by arcing between conductors. Another undesirable effect is the permanent degradation or destruction of semiconductor junctions caused by momentary overloads. Fuses may be blown, circuit breakers may be activated, and overload protective sequencing circuits such as those used in radar systems may be initiated by the EMP environment.

High power level circuits and devices are, for the most part, relatively insensitive to EMP, whereas low power devices tend to be much more susceptible to damage. Typical electrical devices can be ranked according to their susceptibilities as in Table 5.1 which is excerpted from [1]. On the one hand we have equipment such as high voltage transmission lines and vacuum tube equipment which require only the usual lightning protection measures. At the other extreme are LSI components, computer logic circuits, and magnetic memory cores, all of which are highly sensitive to EMP and should be carefully protected. The FAA has equipment which falls in each of these categories.

Equipment susceptibility depends upon the maximum field strength levels a device can safely withstand relative to the maximum levels anticipated in the area where the equipment is deployed. Assumptions must be made regarding the anticipated EMP environment before the FAA equipment susceptibility can be assessed. The specific assumptions made are indicated throughout our discussion. Although some assumptions are arbitrary, all of them are intended to be reasonable.

The FAA equipment can be broken down into EMP exposure categories as shown in Table 5.2. All equipment in the main control center will benefit from the building shielding effectiveness, which is estimated at 26 dB and should be increased to 60 dB or more at 10 kHz, and is in this case exposed to significantly reduced field levels. Most of the radar, communications, telephone, and primary power equipment is in an unshielded or only slightly shielded environment. The auxiliary power unit is in a separate building which is estimated to provide 10-15 dB of EMP shielding. Some circuits and devices will be adequately protected by the building in which they are housed. Some highly sensitive devices will require additional protection despite their location within an effective building shield.

It is important to determine the susceptibility of components, such as vacuum tubes, semiconductor diodes or transistors, to the typical EMP environment. Note that the susceptibility of any device depends upon how it is connected in a circuit arrangement and upon the neighboring circuit components with which it reacts in normal operations. For example, although a low-power, high-frequency transistor is very susceptible to EMP because of its small junction dimensions (area and thickness) in most normal circuit configurations, it would not be damaged by EMP if not connected in some type of circuit which would allow current to flow, nor would it be likely to suffer damage if connected in an extremely high impedance network where the currents would be limited primarily by the other circuit elements. Unfortunately this latter configuration is of little or no practical value, and transistors contained in normal circuit configurations have EMP susceptibility which generally increases with decreasing voltage, decreasing power, and increasing maximum frequency limits. Semiconductor devices are normally classified as either susceptible or highly susceptible to EMP.

The EMP susceptibility of a circuit depends in a general way upon the susceptibilities of its constituent components. If all components are unsusceptible in the configuration involved, the circuit would be classified as unsusceptible. A susceptibility number can be applied to the circuit, if desire, according to the probability of circuit damage. This same basic idea can be extended to sub-system susceptibility, and a number can be assigned to each sub-system according to the probability that it will be damaged by the typical EMP environment. It is fairly standard practice to assume that the component probabilities are independent in this evaluation. System susceptibility can be evaluated by similarly extending the sub-system results.

Assume that a circuit is made up of N_c components, each of which has a probability that it will be damaged by the typical EMP environment of P_n for the configuration involved and under the shielding conditions anticipated. The probability of circuit damage, P_c, assuming independence between the effects, is thus given by

$$P_c = 1 - \prod_{n=1}^{N_c} (1-P_n) \qquad \text{(D.1)}$$

where $(1-P_n)$ is the probability that the nth component will not be damaged, and $\prod_{n=1}^{N_c} (1-P_n)$ is the probability that none of the components will be damaged (i.e. the system will be undamaged). Similarly, the probability of sub-system damage, P_{ss}, can be evaluated as

$$P_{ss} = 1 - \prod_{n=1}^{N_{ss}} (1-P_{cn}) \qquad (D.2)$$

where N_{ss} denotes the number of circuits in the sub-system and P_{cn} denotes the probability of damage for the n-th circuit as obtained from (D.1). The probability of system damage, P_s, is

$$P_s = 1 - \prod_{n=1}^{N_s} (1-P_{ssn}) \qquad (D.3)$$

where P_{ssn} is obtained from (D.2) and N_s is the number of sub-systems making up the system.

Most systems consist of many subsystems and hundreds or even thousands of circuits and components. It would normally be impractical to determine equipment susceptibility by detailed analysis of each component, circuit, etc. Computer programs have been developed to automate this process, and can be applied to whatever conditions are encountered but in most cases it it unnecessary to resort to such drastic measures. In a typical system only a few of its elements are really critical. System susceptibility often depends primarily upon the ability to protect the critical elements. In some cases there are many elements of roughly the same susceptibility, and overall susceptibility can only be limited by reducing each of these individual susceptibilies to a very small value.

Our evaluation of FAA equipment susceptibility is based upon the general observation that only by reducing the susceptibility of each non-redundant system component to a level approaching zero can the overall system susceptibility be made small, since a large number of components are involved. No effort has been made to determine an overall damage probability, or even specific damage probabilities for the sybsystem or circuit elements in most cases. A subsystem is considered susceptible if it contains one or more susceptible components, or if it contains sufficiently large numbers of less susceptible components that the overall susceptibility is still high.

Reference

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APPENDIX E

Susceptibility of Electronic Components to Electromagnetic Disturbances

Of all electronic components, semiconductor devices, including discrete diodes and transistors, and multiple-junction integrated circuit components, are most vulnerable to lightning, EMP or other types of electromagnetic disturbances. However they are not the only electronic components which are susceptible to various disturbances. Table E.1 lists the energy levels for damage or degradation for various electronic components [1,2].

E.1. Failure of Semiconductor Devices

The difficulty with semiconductor devices may be traced to the smallness of the active regions, such as the p-n junction region and to the long thermal time constant of the material. Since large amount of energy is to be dissipated in the vicinity of the active p-n junction regions, and the thermal time constant is very long in comparison with the time scale of EMP disturbance, heat generated by the disturbance is confined to small and restricted regions and the temperature in the region could be as high as the melting point of the material. Because the thermal time constant is long, there is very little thermal diffusion, the temperature in the neighboring region remains low and, a large temperature gradient and associated mechanical stress between the junction region and its neighboring region are created by the disturbance. Failures caused by metallization melt, dielectric breakdown, and metallization to metallization arc-over have also been observed. The threshold for failure depends not only on the voltage level but also on the waveform of the disturbance and bias condition.

For a given level of energy pickup, a junction device is much less likely to be damaged by induced voltage which forward biases the junction

Table E.1

Estimated energy level for degradation.

Device type	Energy (μJ)
Point-contact diodes 1N82A–1N69A	0.7–12[a]
Integrated circuits μA709	10[a]
Low-power transistors 2N930–2N1116A	20–1000[a]
High-power transistors 2N1039 (Ge)	1000[a]
Switching diodes 1N914–1N933J	70–100[a]
Zener diodes 1N702A	1000[a]
Rectifiers 1N537	500[a]
Relays[b] (welded contacts)	2–100 × 10^3
Resistors (0.25 W carbon)	10^4

[a] Energy required to damage semiconductors having a 1-μs square pulse.

than by the same level of energy dissipation resulting in a reverse biased condition. In the forward biased direction the semiconductor junction presents a low impedance to current flow and a large percentage of the induced energy is usually dissipated in the series impedance elements other than the junction, thus reducing the probability of damage. When the junction is back-biased by the induced voltage, a large percentage of the total voltage appears across the junction, and several types of degradation or destruction can occur. Arcing around or through the junction is possible, and permanent shorts or low impedance paths can thereby be produced. The junction is not uniformly thick, and avalanching can occur in small regions of the junction, producing hot spots and permanent damage. These phenomena are relatively empirical in nature and there remain some differences of opinion among the leading researchers regarding precisely what happens to the device. A summary of minimum observed burnout energy levels for a number of standard transistors and other electronic components in response to typical EMP type excitation is presented in Table E.2, [3]. It should be noted that in many cases (particularly the high frequency, low power devices such as the RF amplifiers and microwave diodes) extremely small energy levels can result in junction damage.

The data shown in Table E.2 illustrates the minimum energy from EMP-like induced signals required to cause damage or degradation as indicated for the designated components or circuits. It should be observed that very small levels of energy are required for junction or memory erasure, and many orders of magnitude less for interference and upset of various kinds. Collector to base and collector to emitter breakdown voltages of 10-40 or 50 Volts, and base to emitter breakdown voltages of 5-10 Volts are common, and damage can result almost immediately once breakdown occurs. Energy pickup

Table E.2

Minimum observed energy to cause burnout of diodes, transistors, varistors, and vacuum tubes.

TYPE	MINIMUM JOULE ENERGY	MATERIAL	OTHER DATA
2N36	4 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N43A	7 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N291	4 $\times 10^{-3}$	Ge	PNP Audio Transistor
2N331	1 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N226	1.5 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N224	5 $\times 10^{-3}$	Ge	PNP Audio Transistor
2N327A	1.6 $\times 10^{-2}$	Si	PNP Audio Transistor
2N1041	2 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N526	1.2 $\times 10^{-2}$	Ge	PNP Audio Transistor
2N1308	5 $\times 10^{-5}$	Ge	NPN Switching Transistors
2N706	6 $\times 10^{-5}$	Si	NPN Switching Transistors
2N594	6 $\times 10^{-3}$	Ge	NPN Switching Transistors
2N358	4 $\times 10^{-3}$	Ge	NPN Switching Transistors
2N661	8 $\times 10^{-4}$	Ge	PNP Switching Transistors
2N1017	2 $\times 10^{-4}$	Ge	PNP Switching Transistors
2N123	8 $\times 10^{-3}$	Ge	PNP Switching Transistors
2N1309	8 $\times 10^{-4}$	Ge	PNP Switching Transistors
2N398	8 $\times 10^{-4}$	Ge	PNP Switching Transistors
2N240	1 $\times 10^{-2}$	Ge	PNP Switching Transistors
2N393	1 $\times 10^{-2}$	Ge	PNP Switching Transistors
2N1305	8 $\times 10^{-3}$	Ge	PNP Switching Transistors
2N404	1 $\times 10^{-3}$	Ge	PNP Switching Transistors
MC715	8 $\times 10^{-5}$	Si	Data Input Gate Integrated Circuit
2N1066	3 $\times 10^{-4}$	Ge	PNP HF Drift Transistor
2N2188	1 $\times 10^{-4}$	Ge	PNP UHF Alloy-Diffusion Transistor
RCA CA3005	8 $\times 10^{-6}$	Si	RF Analog Integrated Circuit
2N4220	1 $\times 10^{-5}$	Si	RF General Purpose FET
2N4224	3 $\times 10^{-5}$	Si	VHF Amp and Mixer FET
2N3796	2 $\times 10^{-5}$	Si	Audio Low-Power Fet
IN3659	8 $\times 10^{-3}$	Si	Automative Rectifier Diode
IN457	3 $\times 10^{-4}$	Si	General Purpose Diode
IN277	2 $\times 10^{-5}$	Ge	High Speed Switching Diode
IN647	2 $\times 10^{-3}$	Si	General Purpose Diode
IN538	6 $\times 10^{-4}$	Si	Rectifier Diode
IN126 A	1 $\times 10^{-5}$	Ge	General Purpose Diode
IN3720	5 $\times 10^{-4}$		Tunnel Diode
IN238	1 $\times 10^{-7}$	Si	Microwave Diode
2N3528	3 $\times 10^{-3}$	Si	Silicon Controlled Rectifier
67D-5010	1 $\times 10^{-4}$ [a]		G.E. Varistor (30-joule rating)
6AF4	1 $\times 10^{0}$		UHF Oscillator Vacuum Tube
66N8	2 $\times 10^{0}$		General Purpose Triode Vacuum Tube

NOTE: [a] Energy to cause varistor to fail V-J spec.

levels of 10^{-4} Joules or more are not at all unlikely under anticipated EMP induced conditions for typical circuit loops, and loop induced voltages of hundreds of Volts or more are easily possible.

There exist four different, yet related techniques for predicting the threshold levels. Each technique allows the prediction of a constant B relating the damage power P_D or energy E_D levels with the pulse width γ:

$$P_D = B\ \gamma^{-\frac{1}{2}} \tag{E.1}$$

$$E_D = B\ \gamma^{\frac{1}{2}} \tag{E.2}$$

Three techniques are based on the manufacturer supplied data on the junction area, thermal resistance or the junction capacitance of the device and are known as the junction area technique, the thermal resistance technique and the junction capacitance technique respectively. The fourth technique is based on the susceptibility data on various circuits and components compiles by various agencies. If the statistical data on the specific device is known, the fourth method is the most meaningful one [2,4,5].

E.2. Failure of Resistors

The basic failure mechanism for resistors is voltage breakdown. Arcing could happen externally or internally to the resistors. Although the dc power ratings for resistors are usually supplied by the manufacturers, ratings under pulsed conditions are rarely known. The pulsed data for wire-wound, metal-film and carbon-composite resistors have been measured by Lennox [6], and his data are the only known experimental results for resistors. Lennox's work has been extracted by Ricketts, Bridges and Miletta [2] and is duplicated here as Table E.3.

Table E.3

Damage characteristics of resistors under pulsed conditions.

(a) Wire-wound resistors.

Manufacturer and Type	Power Rating (W)	Nominal Resistance (Ω)	Maximum Safe Voltage (kV)	Pulse Width (μs)	Pulse Power (MW)
Dale NS-2	2	50	8	20	1.3
Dale NS-2	2	100	12	20	1.4
Dale NS-2	2	600	16	20	0.4
Dale NS-2	2	1,000	14	20	0.2
Dale NS-2	2	3,000	20	20	0.13
Dale RS-2C	3	200	12	20	0.75
Dale RS-2C	3	499	14	20	0.40
Dale RS-2C	3	1,000	12	20	0.14
Dale RS-2C	3	3,000	16	20	0.09
Dale RS-5	5	50	> 10	20	> 2
Dale NS-5	5	100	20	20	4
Dale RS-5	5	200	24	20	2.9
Dale RS-5	5	499	22	20	1.0
Dale NS-5	5	100	20	20	0.4
Dale NS-5	5	400	< 28	20	0.2
Dale NS-5	5	500	24	20	0.12
Dale RS-5	5	600	20	20	0.07
Dale NS-5	5	1,000	24	20	0.06
Dale RS-5	5	1,200	30	20	0.07
Dale NS-10	10	50	> 10	20	> 2
Dale NS-10	10	100	> 24	20	> 6
Dale NS-10	10	200	40	20	8
Dale RS-10	10	499	40	20	3.3
Dale NS-10	10	1,000	30	20	0.9
Sprague	10	450	36	20	0.3
Dale RS-10	10	499	48	20	0.5
Dale NS-10	10	1,000	45	20	0.2
Ohmite	10	3,000	20	20	--
Dale NS-10	10	3,700	44	20	0.05
Sprague	10	7,000	20	20	

Table E.3 (Continued)

(b) Metal-film resistors.

Manufacturer and Type	Power Rating (W)	Nominal Resistance (Ω)	Maximum Safe Voltage (V)	Pulse Width (μs)	Pulse Power (W)
IRC MEA	0.125	100	200	20	400
IRC MEA	0.125	178	250	20	350
IRC MEA	0.125	442	200	20	90
IRC MEA	0.125	825	600	20	450
IRC MEA	0.125	1,100	1,250	20	1400
IRC MEA	0.125	1,540	500	20	166
IRC MEA	0.125	3,480	1,250	20	400
IRC MEA	0.125	6,191	1,000	20	160
IRC MEA	0.125	1,100	1,250	20	145
IRC MEB	0.25	100	150	20	225
IRC MEB	0.25	196	200	20	200
IRC MEB	0.25	365	300	20	250
IRC MEB	0.25	750	400	20	210
IRC MEB	0.25	1,050	700	20	490
IRC MEB	0.25	1,960	1,250	20	800
IRC MEB	0.25	4,220	1,750	20	700
IRC MEB	0.25	1,050	1,500	20	225
IRC MEB	0.25	2,000	200	20	200
IRC MEB	0.25	4,000	350	20	300
IRC MEB	0.25	6,000	500	20	400
IRC MEB	0.25	7,500	600	20	480
IRC MEB	0.25	10,000	700	20	500
IRC MEB	0.25	15,000	700	20	330
IRC MEB	0.25	21,500	1,200	20	700
IRC MEB	0.25	48,700	1,200	20	300
IRC MEC	0.5	100	400	20	1.6
IRC MEC	0.5	200	600	20	1.8
IRC MEC	0.5	300	600	20	1.2
IRC MEC	0.5	600	700	20	0.8
IRC MEC	0.5	1,000	800	20	0.6
IRC MEC	0.5	1,620	1,500	20	1.5
IRC MEC	0.5	3,160	1,500	20	0.8
IRC MEC	0.5	5,900	>2,000	20	0.7
IRC MEC	0.5	8,600	>2,000	20	0.5
IRC MEC	0.5	5,000	600	20	0.7
IRC MEC	0.5	10,000	700	20	0.5
IRC MEC	0.5	46,400	1,600	20	0.5
IRC MEC	0.5	75,000	1,600	20	0.3
IRC MEC	0.5	90,900	1,600	20	0.3
IRC MEF	1	200	600	20	1.8
IRC MEF	1	100	200	20	4.0
IRC MEF	1	1,000	800	20	6.4
IRC MEF	1	10,000	1,800	20	3.6
IRC MEF	1	1,000,000	3,200	20	1.0
Dale	1	3,000,000	2,800	20	0.3
IRC MEH	2	100	300	20	9
IRC MEH	2	1,000	4,000	20	160
IRC MEH	2	10,000	4,600	20	23
Dale	2	1,000,000	5,000	20	2.5
Dale	2	5,000,000	5,000	20	0.5

Table E.3 (Continued)

(c) Carbon-composition resistors.

Manufacturer and Type	Power Rating (W)	Nominal Resistance (Ω)	Maximum Safe Voltage (V)	Pulse Width (μs)	Pulse Power (kW)
Allen-Bradley	0.25	51	200	20	0.8
Allen-Bradley	0.25	100	500	20	2.5
Allen-Bradley	0.25	200	500	20	1.2
Allen-Bradley	0.25	300	1,250	20	5.0
Allen-Bradley	0.25	500	2,000	20	8.0
Allen-Bradley	0.25	750	2,000	20	5.0
Allen-Bradley	0.25	1,000	750	20	0.6
Allen-Bradley	0.25	2,000	200	20	2.0
Allen-Bradley	0.25	5,100	200	20	0.8
Allen-Bradley	0.25	7,500	200	20	0.5
Allen-Bradley	0.25	1,000	400	20	1.6
Allen-Bradley	0.25	5,100	600	20	0.7
Allen-Bradley	0.25	7,500	800	20	0.9
Allen-Bradley	0.25	11,000	900	20	0.7
Allen-Bradley	0.25	15,000	1,000	20	0.7
Allen-Bradley	0.25	20,000	800	20	0.3
Allen-Bradley	0.25	1,200,000	1,000	20	0.1
Allen-Bradley	0.5	51	750	20	11
Allen-Bradley	0.5	100	750	20	5.6
Allen-Bradley	0.5	200	750	20	2.8
Allen-Bradley	0.5	300	750	20	1.9
Allen-Bradley	0.5	500	750	20	1.1
Allen-Bradley	0.5	100	200	20	4.[illegible]
Allen-Bradley	0.5	200	200	20	2.0
Allen-Bradley	0.5	2,000	1,200	20	[illegible].0
Allen-Bradley	0.5	5,600	2,400	20	4.0
Allen-Bradley	0.5	10,000	700	20	0.5
Allen-Bradley	0.5	16,000	1,100	20	0.8
Allen-Bradley	0.5	39,000	1,200	20	0.4
Allen-Bradley	0.5	1,000,000	1,200	20	0.1
Allen-Bradley	1	51	> 100	20	> 2
Allen-Bradley	1	110	> 100	20	> 1.0
Allen-Bradley	1	200	> 200	20	> 20
Allen-Bradley	1	240	800	20	250
Allen-Bradley	1	390	800	20	130
Allen-Bradley	1	100	800	20	64
Allen-Bradley	1	220	1,200	20	67
Allen-Bradley	1	360	1,400	20	58
Allen-Bradley	1	620	1,600	20	40
Allen-Bradley	1	910	1,400	20	22
Allen-Bradley	1	2,000	2,000	20	20
Allen-Bradley	1	3,900	1,800	20	8
Allen-Bradley	1	6,200	1,800	20	5
Allen-Bradley	1	22,000	1,800	20	1.4
Allen-Bradley	1	1,100,000	1,800	20	0.3

E.3. Failure of Capacitors

The damage levels of various capacitors under rectangular voltage pulse excitation are listed in Table E.4 [2]. It is noted that nonpolar dielectric capacitors usually can withstand stress of pulsed voltage of the order of 4-6 times of the dc rated voltage values, provided that the pulses are relatively short, of the order of a few microseconds. In general the electrolytic capacitors are much more vulnerable to damage, and its damage level varies with its capacitance value, voltage rating and its construction. Note in particular that failure levels of solid tantalum capacitors could be as low as those for semiconductor devices.

The damage energy levels for relays, fuses, memory cores etc., are listed in Tables E.5 and E.6.

E.4. Simple Protective Measures

The primary effect of the typical EMP environment upon transistor circuits is to subject them to a very-short-duration pulse of voltage which may result in excessive voltage levels across the semiconductor junctions in either the forward or the reverse directions. A number of design approaches are available which result in circuits far less susceptible to EMP than the standard designs. In all cases the intention is to dissipate as much energy as possible in the external circuit away from the transistor junction, thereby (hopefully) protecting the junction from damage. Of course the best protection is to shield and isolate susceptible circuits and devices from the EMP phenomenon, but it may not always be possible to provide as much shielding as would be required to protect the circuits by shielding alone.

Protection against voltage surges in either the collector or bias lines can be provided for each circuit unit by connecting a filter capacitor between the line and the common ground terminal at the point where power

Table E.4

Failure levels of capacitors.

Capacitor/Description	Manufacturer	Voltage[a] (V)	Pulse Width (μs)	Energy (μJ)	Failure
0.5 μF; 100 V dc etched tantalum foil	General Electric	F >250	0.1	>1300	No
		R >250	0.1	>1300	No
0.56 μF; 35 V dc solid tantalum	General Electric	F >80	0.1	>490	No
		R >80	0.1	>490	No
5.0 μF; 50 V dc wet tantalum slug	General Electric	F >32	0.1	>190	No
		R >32	0.1	>190	No
DD 500 50 pF; 1000 V dc ceramic	USCC Centralab	10,000/7300[b]	—	—	Yes
5HK E10 1000 pF; 1000 V dc ceramic	Sprague	6000/4900[b]	—	--	Yes
472X9035A2 0.004 μF; 35 V dc solid tantalum	Sprague	F 150/90[b]	0.25[c]	86[d]	Yes
		R 110/65[b]	0.7	61[d]	Yes
225X9035B2 2.2 μF; 35 V dc solid tantalum	Sprague	F 150/90[b]	5.5[c]	3500[d]	Yes
		R 110/65[b]	1.2	3300[d]	Yes
225X9015A2 2.2 μF; 15 V dc solid tantalum	Sprague	F 140/68[b]	0.1[c]	1100[d]	Yes
		R 54/43[b]	2[c]	1200[d]	Yes
C100K 10 pF	Cornell-Dublier	1000	8		No (10 pulses)
CK62 4700 pF; 500 V dc	Cornell-Dublier	1000	8		No (10 pulses)
96P 1 μF; 200 V dc	Sprague	1000	8		No (10 pulses)
KF223KM 0.00 μF; 600 V dc	WES CAP	1000	8		No (10 pulses)
CL25BL101TB3 100 μF; 75 V dc	Cornell-Dublier	R 2250	2		No (13 pulses)
CL25BE401VP3 400 μF; 15 V dc	Cornell-Dublier	R 2250	2		No (3 pulses)

[a] F = forward polarity; R = reverse polarity.
[b] Mean/minimum.
[c] Pulse width determined from pulse start to sharp drop in voltage waveform (corresponding to sharp rise in current waveform).
[d] Lowest energy from test sample.

Table E.5

Energy levels to cause permanent degradation.

DESIGNATION	MINIMUM JOULE ENERGY	MALFUNCTION	OTHER DATA
Relay	2×10^{-3}	Welded Contact	Potter-Brumfield (539) low-current relay
Relay	1×10^{-1}	Welded Contact	Sigma (IIF) one-ampere relay
Microammeter	3×10^{-3}	Slammed Meter	Simpson Microammeter (Model 1212C)
Explosive Bolt	6×10^{-4}	Ignition	EBW 8 amp for 10 μsec detonator, MKI
Squib	2×10^{-5}	Ignition	Electric Squib, N8 3.5 watts for 5 μsec detonator
Fuel Vapors	3×10^{-3}	Ignition	Propane-air mixture 1.75 mm ignition gap

Table E.6

Energy levels to cause upset or interference.

DESIGNATION	MINIMUM JOULE ENERGY	MALFUNCTION	OTHER DATA
Logic Card	3×10^{-9}	Circuit Upset	Typical logic transistor inverter gate
Logic Card	1×10^{-9}	Circuit Upset	Typical flip-flop transistor assembly
Integrated	4×10^{-10}	Circuit Upset	Sylvania J-K flip-flop monolithic integrated circuit (SF50)
Memory Core	2×10^{-9}	Core Erasure Via Wiring	Burroughs fast computer core memory (FC2001)
Memory Core	5×10^{-8}	Core Erasure Via Wiring	Burroughs medium speed computer core memory (FC8001)
Memory Core	3×10^{-9}	Core Erasure Via Wiring	RCA medium, core memory (269M1)
Memory Core	2×10^{-8}		
Amplifier	4×10^{-21}	Interference	Minimum observable energy in a typical high-gain amplifier

enters the unit. Since the EMP phenomenon is of short duration, a reasonable degree of protection can often be provided by using a capacitor which is not unduly large if the circuit in question is in the control line.

All circuit cards should be contained within a shielded enclosure to assume that the most severe EMP effects cannot penetrate. It is reasonably easy to get 20-40 dB of shielding from the cabinets and individual circuit shields, and even 100 dB of shielding effect can be obtained through careful design for critically sensitive units. Circuit layouts should be arranged to minimize the cross-sectional areas of the conducting loops in which sensitive components are connected.

When biased in the forward direction, most junction resistances are a small part of the total resistance in any loop. By designing circuits with higher resistance levels, the percentage of EMP power dissipated in the critical junctions can be controlled to some extent, thereby lowering the level of damage susceptibility. When EMP results in backward bias across junctions, the junction generally acts as a near open circuit until an avalanche effect occurs, after which damage may occur very quickly due to the development of hot spots in the junction, junction edge arc-over, or junction puncture (arc-through). Voltage drop across other resistive elements does not protect the junction appreciably in this case, but damage can often be prevented by providing a parallel diode path which becomes forward biased as the junction of concern is biased backward, or perhaps one or two Volts away from this point. A number of such design precautions can be taken to reduce the EMP susceptibility of semiconductor circuits. Original designs may be developed from this point of view, but existing designs can also be modified to reduce their susceptibility levels.

E.5. Two Examples

In the following, two examples are given to illustrate the methods of estimating the energy pickup for a given circuit configuration and the component susceptibility to EMP disturbance.

In the first example, consider a pickup loop having cross sectional area A in a plane normal to the H field. The loop is assumed to be conductive, and terminates in resistance R, which is simply the total resistance around the loop. The variation of H with time is approximated as shown in Figure E.1, for convenience in the analysis. The end results should not be particularly different if the actual waveform were used. We also assume that the loop inductance is negligible; this assumption is reasonable and provides conservative results. We know that the magnetic flux density is given by

$$B = \mu_0 H \qquad \text{(E.3)}$$

where

B = flux density, Webers/m^2

μ_0 = permeability of free space $= 4\pi \times 10^{-7}$ Henry/meter

H = field intensity, Ampere/m.

Also, the magnetic flux linked by the loop, denoted by $\emptyset$, is

$$\emptyset = AB = \mu_0 HA. \qquad \text{(E.4)}$$

The voltage induced on the loop is

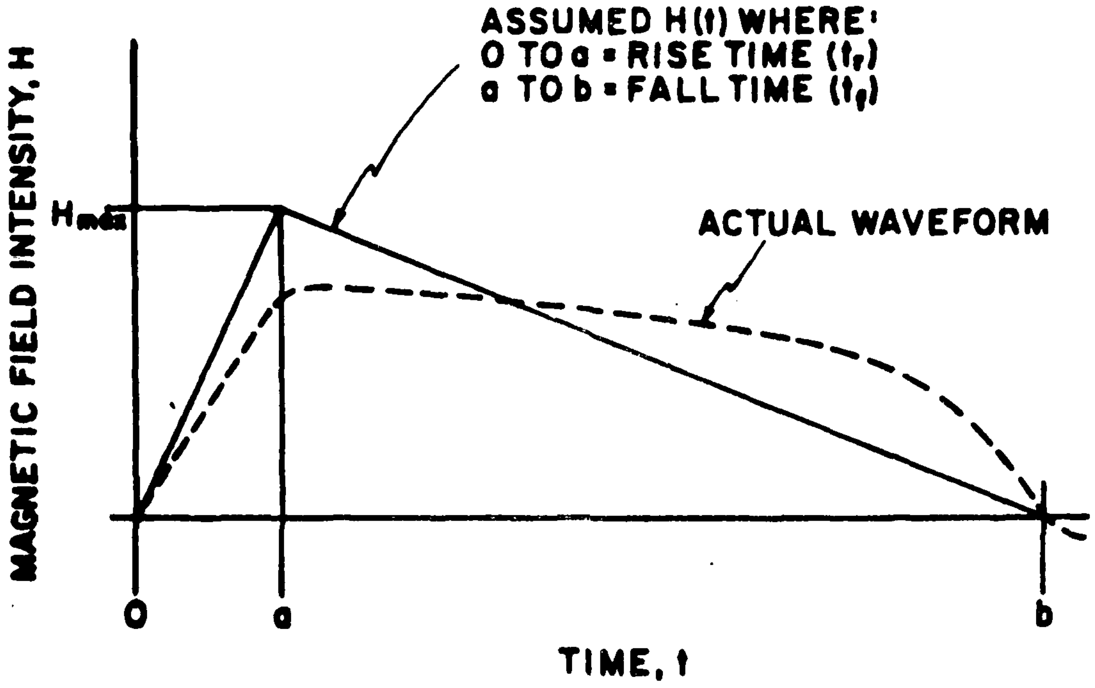

Figure E.1. Assumed waveform of H(t).

$$e = \frac{d\phi}{dt} = \mu_0 A \frac{dH}{dt} \tag{E.5}$$

and the induced current is

$$i = \frac{\mu_0 A}{R} \frac{dH}{dt} \tag{E.6}$$

The energy absorbed by R, denoted by , is thus

$$\mathcal{E} = \int_0^b \frac{1}{R} [\mu_0 A \frac{dH}{dt}]^2 dt = \frac{\mu_0^2 A^2}{R} [\int_0^a [\frac{dH}{dt}]^2 dt + \int_a^b [\frac{dH}{dt}]^2 dt] \tag{E.7}$$

On the interval [0,a],

$$\frac{dH}{dt} \leq \frac{H_{max}}{t_r} \simeq \frac{H_{max}}{a} \tag{E.8}$$

and on the interval [a,b],

$$\frac{dH}{dt} \leq \frac{H_{max}}{t_f} \simeq \frac{H_{max}}{b-a} \tag{E.9}$$

Thus (E.7) becomes

$$\mathcal{E} \leq \frac{1}{R} [\mu_0 A \frac{H_{max}}{t_r}]^2 t_r + \frac{1}{R} [\mu_0 A \frac{H_{max}}{t_f}]^2 t_f$$

$$\leq \frac{\mu_0^2 A^2 H_{max}^2}{R} [\frac{1}{t_r} + \frac{1}{t_f}]. \tag{E.10}$$

Since $t_r << t_f$, $1/t_r >> 1/t_f$, and the total energy delivered to R is adequately approximated by

$$\mathcal{E} \approx \frac{\mu_0^2 A^2 H_{max}^2}{R t_r}. \tag{E.11}$$

This result may be used to approximate the energy delivered to a typical circuit by the typical EMP threat. A problem may arise in approximating R. Since R often includes a semiconductor junction which may be driven to an avalanche condition in the reverse direction, R can be a highly nonlinear function of the induced voltage and the current flow, and some approximation must be made for it. It is conservative to assume that R is the avalanche resistance of the junction plus whatever other series resistance is present, provided the avalanche voltage is exceeded during the rise time of the pulse.

A representative peak value of the nuclear EMP induced E field from a high altitude burst is E_{max} = 50,000 Volt/meter and H_{max} = 133 Amp/meter and the risetime is t_r = 10 ns = 10^{-8} s. Assume that the total resistance in the loop is about 100 Ohms and the loop has a cross sectional area, projected to the incoming B field, of 0.1 m^2, then the total energy absorbed by the junction is given by (E.11) as

$$\mathcal{E} = \frac{0.01\ \mu_0^2\ H_{max}^2}{100 t_r}.$$

$$= \frac{10^{-2} \times (4\times10^{-7})^2\ (132.5)^2}{100 \times 10^{-8}} = 2.78\times10^{-4} \text{ Juoles}$$

As noted previously that energy levels of 10^{-4} Joules or more absorbed from this type of pulse will often result in damage to many transistors. The loop size assumed is quite reasonable. It is thus concluded that many transistor circuits <u>must</u> be shielded or otherwise protected from the EMP threat if the probability of permanent damage is to be kept acceptably small.

The maximum voltage induced on the circuit can be found from (E.5)

$$e_{max} \approx \mu_0 A \frac{H_{max}}{t_r} \tag{E.12}$$

Using the same numerical values for H_{max} and t_r, we have

$$e_{max} \approx (1.67\times10^4) A \tag{E.13}$$

where A is the cross sectional area (in m^2) exposed to the field. For A = $0.1m^2$, e_{max} is about 1.67×10^3 Volts. (E.13) will often prove useful in assessing equipment susceptibility. Much of the FAA equipment is shielded to some extent. The peak voltage induced in a circuit loop is obtained in the shielded case by using (E.13) with the coefficient 1.67×10^4 appropriately reduced, depending upon the amount of shielding present. As discussed in Appendix C shielding effectiveness S_E is defined as

$$S_E = 20 \log_{10} \frac{E_1}{E_2} \tag{E.14}$$

where E_1 is the voltage induced (peak field strength) without shielding and E_2 is the voltage induced (peak field strength) with shielding. The coefficient in (E.18) is decreased by a factor of 10 for each 20 dB of shielding provided. Thus 60 dB of field attenuation (shielding) reduced the voltages induced in typical loops to levels that can be tolerated in most cases. Highly sensitive circuits and/or devices can be enclosed in secondary shields to provide additional protection where necessary. 100 dB or more of attenuation can be provided with careful design.

As a specific example of equipment susceptibility to the EMP phenomenon, consider the Texas Instruments 2N2222 transistor. This transistor is a low power NPN unit with a maximum collector voltage rating of 75 Volts and a maximum power rating of 800 milliwatts. It has been shown in tests that permanent junction damage generally occurs at an energy level of approximately 10^{-4} Joules for 100 nanoseconds pulse widths. The avalanche resistance of this transistor is approximately 100 Ohms. Thus from the previous example we see that the maximum energy picked up by a circuit can easily reach this value if the cross section area of the circuit loop is of the order of $0.1m^2$, and 2N2222 may be damaged.

When 30 V. reverse bias is placed across the base to emitter junction of 2N2222 from a low impedance source, 300 mA of current typically flows through the junction. The current level increases rapidly for larger voltages. This reverse bias level need not be increased very much before the 10^{-4} Joule energy level will be approached for 100 nanosecond pulses and a high probability of damage results. If the coupling area of the circuit loop is as small as $10^{-3}m^2$, the loop voltage for the typical EMP threat becomes 16.7 Volts [see (E.13)], and the probability of junction damage is not insignificant at such levels. Since $10^{-3}m^2$ is provided by a square loop just slightly larger than 1 inch on a side, loop areas two or more orders of magnitude larger than this are common in typical circuit layouts, and significant attenuation of the EMP field will be necessary to avoid trouble. Many of the transistors and diodes in common use have lower voltage and power ratings than the 2N2222 which is used here as a representative example primarily because more detailed data is available upon its susceptibility to EMP fields.

In summary, semiconductor circuits can be designed and/or modified to minimize their EMP susceptibility. No effort has been made here to do anything more than give a general illustration of these procedures since they are relatively straightforward. Such techniques have long been used in designing solid-state receivers and transmitters which are exposed to potential damage from lightning, and the EMP environment is similar to that caused by a close lighting strike in so far as potential junction damage is concerned.

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APPENDIX F

EMP Susceptibility of FAA Systems

In this appendix, attempt is made to asses the EMP susceptibility of some FAA systems. The vulnerability of some FAA systems has been studied previously [1] and will not be repeated here, except noting that most remarks made in the previous report remain valid.

F.1. ARSR-3 and ASR-8 Radars

Most equipment in the radar towers, such as the antenna rotation motors, and angular position synchros etc., are relatively insensitive to EMP disturbance. However, the solid-state controlling and monitoring devices are susceptible to EMP or lightning related surges. All units are shielded to some extent by the building structure. However, for a radar site visited, there are three unscreened windows (approximately 3'x2.5' each), which would greatly compromise the effectiveness of the building shields.

In most cases, the domes and towers are carefully grounded, as they should be. All signal and power lines and cables leaving and entering the buildings are and should be placed in metal conduits. As mentioned in Appendix C these conduits should be properly grounded and terminated before entering the building shields.

The equipment building housing ARSR-3 surveillance radar, ATCBI-5 beacon, modem, radio and radar microwave link equipment etc., is a metal structure. The power plant, switchgear and monitoring equipment are housed in a separated and similar structure. If the metal panels of the buildings are installed correctly and carefully to insure the electrical contacts between panels, these buildings would be an excellent shield against EMP. Since the detailed procedures used to construct these panels are unknown to us, the usefulness of these structures as electromagnetic shields remains questionable. However, it should be noted that the equipment inside the buildings is highly sophisticated and advanced electronic systems, they cannot survive in a "typical" EMP environment unless the building and the equipment cabinet provide an attenuation of 80 dB.

The buildings are connected to the site grounding counterpoise consisting of an in-ground wire mesh and ground rods. Although these ground rods and wire-mesh were designed mainly to protected against lightning strikes, they are also useful to some extend in protecting against EMP related disturbances.

Compared with the ARSR-3 radar system, the ASR-8 system we visited is a relative "old" system. Nevertheless, the susceptibilities of these radars are roughly comparable. Since the ASR-8 system is "old", the construction of its building is even more uncertain. It should be emphasized that all cables and waveguides should be properly terminated and ground before entering the building shields. However, at least in one case the penetration of waveguide through the building shield is not done correctly as depicted in Figure F.1.

F.2. Instrument Landing Systems

The AN/GRN-27(V) ILS and Wilcox ILS in Indianapolis International Airport were studied. So far as the EMP susceptibilities of these two ILS are concerned, they are roughly comparable. Some of the equipment is housed in fiberglass trailers. Although there are metal structures around the trailer, its usefulness as shields against EMP disturbance is minimal. It was also noticed that the equipment cabinets have gaps or slits of various widths. The width of these slits varies from 1/8" to 1/4" typically. But some of the gaps, particularly near the top of the cabinets, are as wide as

Figure F.1. The effectiveness of building shield is compromised by the waveguide penetration.

1.5", (see Figure F.2). In the absence of the shielding provided by the building or equipment shack, the equipment cabinets would be the first-line defense against EMP. The presence of these wide slots would seriously compromise the ability of these electronic equipment to survive during a nuclear attack.

It was quite gratifying to see that all signal and control lines were retrofitted with transient protectors of various kinds and brands, [2]. These transient protection kits should be quite useful in protecting the equipment against lightning related surges, if the values of the components are chosen correctly [3,4,5,6]. To be useful against EMP disturbances, the lead wires should be kept to absolutely minimal. In addition that ground wires or strips should also be kept as short as possible. The ground strips or grounding plates depicted in Figure F.3 are quite good. But in some cases the ground wires used are quite long and thin. In one case, #9 wires were used as ground conductors.

It should be noted these kinds of retrofit kits can only be used on control lines where the impedance mismatch is of no major importance. One should be careful in inserting transient devices into signal lines. If transient devices with large capacitance, such as zener diodes or Transorbs, are inserted into the signal line without considering their effect on the impedance, the functions of the signal line will be seriously affected.

F.3. RVR Transmissometers

The RVR visited is an old vacuum-tube device and is totally enclosed in a metal box. The power and control lines going into the box are protected by transient protectors to protect against lightning. Of all electronic equipment studied by us, this RVR is the least susceptible one.

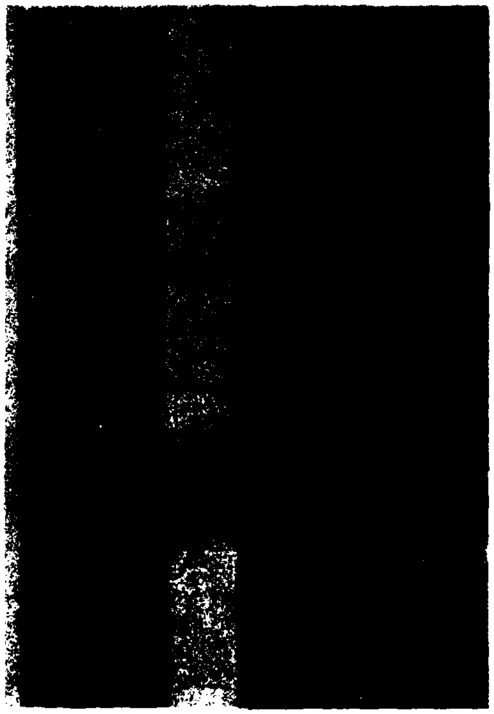

Figure F.2. Wide gaps in the equipment cabinets.

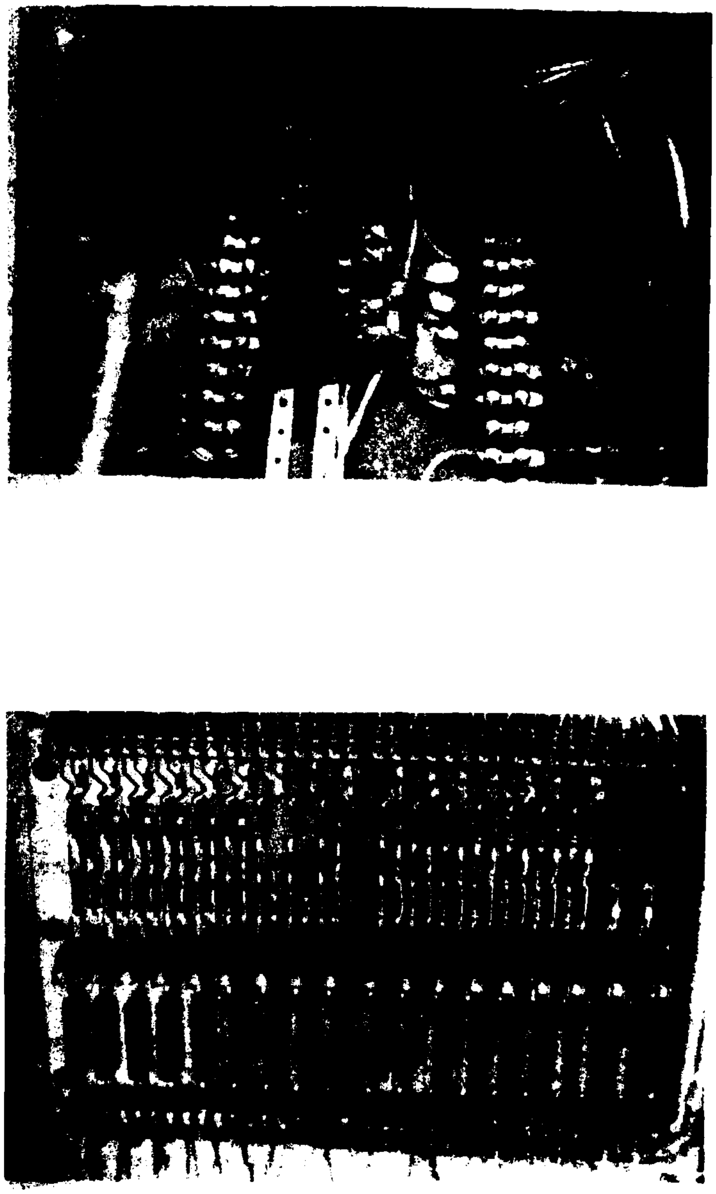

Figure F.3. Junction boxes with retrofitted transient protective kits.

F.4. Runway Lights and Approach Lights

The runway lights and approach lights of Indianapolis International Airport were also studied. These controls and monitoring devices are relatively old, (of 1950 vintage). The controls are performed through relays and mechanical contacts. Except for some discrete diode rectifiers, and some zener diodes used as protective devices, there are no other solid-state components. Besides these controls are designed on the fail-safe principle: if anything fails, the runway and approach lights go on at full brightness. Thus so far as the controlling and monitoring devices for these lights are concerned, they are immune from EMP upset. However, commercial power is used to power these lights. The susceptibility of these commercial power lines against EMP upset or disturbances is quite questionable.

F.5. Telephone Equipment Susceptibility

The telephone equipment is used primarily to carry the voice communications between the operators and the aircrafts. This equipment is extremely critical to the air traffic control functions. If communication with the pilots is lost, traffic control is impossible. Extreme care should be taken to protect the communication links, and thus the telephone equipment, from EMP for this reason. A variety of telephone equipment is involved, only a small part of which is under FAA control. Some of this provides redundant paths, but in many cases only one path is available. The telephone companies generally use good grounding and shielding practices to protect against lightning, but this does not necessarily mean that their equipment is insensitive to the EMP environment.

Some, but not all, of the telephones lines observed were still protected by carbon block surge protectors. While carbon blocks are good for the protection of vacuum-tube equipment against lightning surges, they are useless for semiconductor devices in lightning or EMP disturbances.

F.6. Susceptibility of the Power System

It is highly likely that the commercial power source would be destroyed or temporarily damaged by the typical EMP environment. The power transformers should be provided with electrostatic shields. For most sites and systems visited, power line inputs are protected by fast acting surge arrestors. Despite these precautions, which are included primarily to limit the building penetrations, a backup power supply is necessary.

Some of the major facilities do have uninterruptible power supplies and other alternative power sources, such as diesel generators. It should be noted that the uninterruptible power supplies have sophisticated solid-state circuits and need to be protected against EMP threats. In other words, the backup power source should also be enclosed in a building which provides a reasonable level of shielding protection. The power cables should be shielded and carried through buried grounded ferrous conduit to the main building, where surge protection should be provided at the point of entry. Electronic instrumentation for measuring fuel level should be carefully protected against a potential arc-over.

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