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☒ CONTRACT NO. F34601-85-D-3427

☐ IR&D

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PREPARED ON Xerox Memorywriter
DOCUMENT NO. D500-11659-1

FILED UNDER

MODEL B-52

TITLE Nuclear Weapons Effects Seminar

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ORIGINAL RELEASE DATE

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Nuclear Weapons Effects Seminar

Document Number D500-11659-1

April 10, 1987

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NTIS CRA&I	<input checked="" type="checkbox"/>
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FOREWORD

"Don't worry. It can't happen."

Those words were the title of an article by Jean Harrington that appeared in *Scientific American* in 1940. The statement is in reference to the fears that an explosion might occur as the result of a chain reaction of uranium fissions. Only about a year before the article was written, two German physicists, Hahn and Strassmann, had managed to split a uranium atom, releasing 200,000,000 electron volts of energy. Follow-up research by Paris scientists Joliot, von Halban, Kowarski, and Perrin provided evidence that, due to the superheat created in fission, a chain reaction could not happen. Most of the scientific community agreed their findings were probably true.

But then, on December 2, 1942, scientists assigned to the World War II "Manhattan Project" managed to build up a nuclear pile to critical mass, subsequently achieving the first self sustaining atomic chain reaction. Less than three years later, on July 16, 1945, the first nuclear bomb was exploded in the Trinity test at Alamogordo, New Mexico. Next, not even one full month later, on August 6 at 8:16 a.m., Hiroshima, Japan experienced the destructive power of a nuclear explosion when it was used for the first time as a weapon. With these events, America was launched into the "nuclear age" and the nuclear threat became a reality.

The impact of this nuclear threat and how to survive it is a growing area of concern. Increasing importance is being placed on making our weapon systems hardened to the effects and monitoring and maintaining that hardness. An example of the Air Force's recognition of the "Survivability" problem is found in AFR 80-38 which says each Air Logistic Center (ALC) Materiel Management Engineering Division (MME) will designate a survivability Office of Prime Responsibility (OPR) within the division, thus providing a central core of engineering survivability expertise for the System Program Managers (SPM's) and Item Managers (IM's) support after Program Management responsibility Transfer (PMRT). At Oklahoma City Air Logistic Center (OC-ALC), the section assigned this responsibility is MMEAS.

The material presented herein is intended to be used in conjunction with and supplemental to the "Nuclear Weapons Effects" seminar developed for the U.S. Air Force by the Boeing Military Airplane Company (BMAC). Development of the seminar material was performed under OC-ALC/MME contract F3460185-D-3427, Engineering Assignment MMEAS 85-004.

The purpose of the seminar is to provide the following information to newly assigned MMEAS survivability engineers:

- a. An awareness of the magnitude and complexity of the varied nuclear threats.
- b. An overview of general and specific Air Force policies and procedures in these areas:
 - 1. A.F. Tech Order system
 - 2. Maintenance Data Collection system
 - 3. Hardness Maintenance/Hardness Surveillance
 - 4. Configuration control

- c. A detailed look at the "electronic" threat, *Electromagnetic Pulse (EMP)*, and how to safeguard against it.
- d. Methods of detecting degradations in the hardness of a system or sub-system through testing and inspection.

The seminar includes some theoretical background data, but focuses on practical applications.

Material presented during this seminar is provided as guidance and is not to be taken as directive in nature.

Acknowledgment is hereby given to the following people for their contribution to the preparation of this document: Brent DeMoss, Jim Patton, Tom Siria, Bob Haney and Peter Richeson.

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ACRONYMS AND ABBREVIATIONS

<i>A/C</i>	<i>Aircraft</i>
<i>AFB</i>	<i>Air Force Base</i>
<i>AFLC</i>	<i>Air Force Logistics Command</i>
<i>AFR</i>	<i>Air Force Regulation</i>
<i>AFSC</i>	<i>Air Force Systems Command</i>
<i>AFWL</i>	<i>Air Force Weapons Lab</i>
<i>ALC</i>	<i>Air Logistics Center</i>
<i>ANSI</i>	<i>American National Standards Institute</i>
<i>ASD</i>	<i>Aeronautical Systems Division</i>
<i>ASTM</i>	<i>American Society for Testing and Materials</i>
<i>BMAC</i>	<i>Boeing Military Airplane Company</i>
<i>CI</i>	<i>Configuration Item</i>
<i>CI</i>	<i>Critical Item</i>
<i>DDI</i>	<i>Direct Drive Injection</i>
<i>DESC</i>	<i>Defense Electronics Supply Center</i>
<i>DITMCO</i>	<i>Drive-In Theater Movie Company</i>
<i>DNA</i>	<i>Defense Nuclear Agency</i>
<i>DOD</i>	<i>Department of Defense</i>
<i>DODISS</i>	<i>Department of Defense Index of Specifications and Standards</i>
<i>ECP</i>	<i>Engineering Change Proposal</i>
<i>EMI</i>	<i>Electromagnetic Interference</i>
<i>EMP</i>	<i>Electromagnetic Pulse</i>
<i>FET</i>	<i>Field Effect Transistor</i>
<i>FSC</i>	<i>Federal Supply Class</i>
<i>FSD</i>	<i>Full Scale Development</i>
<i>FSED</i>	<i>Full Scale Engineering Development</i>

HA	<i>Hardness Assurance</i>
HADD	<i>Hardness Assurance Design Documentation</i>
HCI	<i>Hardness Critical Item</i>
HCP	<i>Hardness Critical Process</i>
HDI	<i>Hardness Dedicated Item</i>
HM	<i>Hardness Maintenance</i>
HOB	<i>Height of Burst</i>
HPD	<i>Horizontally Polarized Dipole</i>
HS	<i>Hardness Surveillance</i>
IEEE	<i>Institute of Electrical and Electronics Engineers</i>
IM	<i>Item Manager</i>
LCS	<i>Life Cycle Survivability</i>
LPA	<i>Log Periodic Antenna</i>
LRU	<i>Line Replaceable Unit</i>
MDC	<i>Maintenance Data Collection</i>
MME	<i>Material Management Engineering</i>
MMICS	<i>Maintenance Management Information and Control System</i>
NSN	<i>National Stock Number</i>
OC-ALC	<i>Oklahoma City Air Logistics Center</i>
OPR	<i>Office of Prime Responsibility</i>
PMD	<i>Program Management Directive</i>
PMRT	<i>Program Management Responsibility Transfer</i>
PTO	<i>Preliminary Technical Order</i>
R & D	<i>Research and Development</i>
RFP	<i>Request for Proposal</i>
SAC	<i>Strategic Air Command</i>
SAP	<i>System Analysis Program</i>
SCORCH	<i>Source for Component Overstress Response Characteristics</i>

SCR	<i>Silicon Controlled Rectifier</i>
SEU	<i>Single Event Upset</i>
SGEMP	<i>System Generated Electromagnetic Pulse</i>
SMR	<i>Source, Maintenance, and Recoverability</i>
SON	<i>Statement of Operational Need</i>
SPM	<i>System Program Manager</i>
SPO	<i>System Program Office</i>
SRU	<i>Shop Replaceable Unit</i>
TAC	<i>Tactical Air Command</i>
TCTO	<i>Time Compliance Technical Order</i>
T.O.	<i>Technical Order</i>
TPD	<i>Terminal Protection Device</i>
TREE	<i>Transient - Radiation Effects on Electronics</i>
USAF	<i>United States Air Force</i>
UV	<i>Ultraviolet</i>
VAR	<i>Vulnerability Analysis Report</i>
VPD	<i>Vertically Polarized Dipole</i>
VSWR	<i>Voltage Standing Wave Ratio</i>
WUC	<i>Work Unit Code</i>

NOMENCLATURE

GREEK ALPHABET

Greek letter	Greek name	English equivalent	Greek letter	Greek name	English equivalent
A α	Alpha	a	N ν	Nu	n
B β	Beta	b	Ξ ξ	Xi	x
Γ γ	Gamma	g	Ο ο	Omicron	o
Δ δ	Delta	d	Π π	Pi	p
Ε ε	Epsilon	ε	Ρ ρ	Rho	r
Ζ ζ	Zeta	z	Σ σ ς	Sigma	s
Η η	Eta	ē	Τ τ	Tau	t
Θ θ ϑ	Theta	th	Υ υ	Upsilon	u
Ι ι	Iota	i	Φ φ ϕ	Phi	ph
Κ κ	Kappa	k	Χ χ	Chi	ch
Λ λ	Lambda	l	Ψ ψ	Psi	ps
Μ μ	Mu	m	Ω ω	Omega	o

<i>c</i>	<i>number of carriers</i>
<i>E₀</i>	<i>free field EMP (V/m)</i>
<i>F</i>	<i>fill</i>
<i>I₀</i>	<i>total current (amps)</i>
<i>j</i>	<i>the imaginary operator in a complex number (j = (-1)^{0.5})</i>
<i>KT</i>	<i>kiloton</i>
<i>KV/m</i>	<i>1000 volts/meter</i>
<i>l</i>	<i>length</i>
<i>MeV</i>	<i>million electron volt</i>
<i>MT</i>	<i>megaton</i>
<i>Mv</i>	<i>million volts</i>
<i>N</i>	<i>number of ends in a carrier</i>
<i>e</i>	<i>electric shielding factor</i>
$\binom{n}{k}$	<i>n given $k = \frac{n!}{(n-k)! k!}$</i>
<i>m</i>	<i>magnetic shielding factor</i>
<i>P</i>	<i>picks</i>
<i>R_h</i>	<i>ground reflection coefficient for horizontal polarization</i>
<i>R₀</i>	<i>D.C. resistance per unit length (ohms)</i>
<i>R_v</i>	<i>ground reflection coefficient for vertical polarization</i>

NOMENCLATURE (cont'd)

S	shield effectiveness (dB)
V/m	volts per meter
V_o	voltage between cable and ground plane (volts)
V_{oc}	open-circuit voltage
W	weapon yield
Z_c	characteristic impedance (ohms)
Z_g	internal impedance per unit length of a ground plane (ohms)
Z_m	Impedance of a metal shield
Z_t	transfer impedance (ohms)
α	real part of propagation constant
β	imaginary part of propagation constant
γ	propagation constant
δ	skin depth (meters)
ϵ	permittivity (farad/meter)
μ	permeability (henry/meter)
σ	conductivity (mhos)
ω	frequency (radians/sec.)

λ

CHAPTER 1: THE THREAT

The destructive power of a weapon is due to the rapid release of high levels of energy in a small area when the weapon explodes. The magnitude and form of damage resulting from a weapon detonation are dependent upon the weapon type, the amount of energy being released from the weapon, the distance from the explosion, and the amount of time elapsed between the time of explosion and the time the effects of the explosion reach the target.

There are two primary types of explosive devices: chemical, such as T.N.T., and nuclear. For either of these, the "output," or the effective yield, is measured in terms of the total amount of energy released in the explosion, relative to the amount by weight of TNT. which would produce the same total energy. The yield for a nuclear device is typically given in terms of kilo-tons (thousand tons), or mega-tons (million tons). These are abbreviated as KT and MT respectively. In terms of energy, one KT yields approximately 10^{12} calories. The energy output from an explosion is detectable in the forms: blast and shock, the change in pressure due to an explosion; thermal, the sudden increase in temperature; and nuclear radiation, the result of radioactive elements in a nuclear explosion.

SECTION 1

PRINCIPLES OF NUCLEAR EXPLOSIONS

Nuclear explosions are classified as fission reactions or fusion reactions. Fission refers to the splitting of the nucleus of a fissionable atom. Fusion is accomplished by the uniting of two light nuclei to form the nucleus of a heavier atom. In either case, the resultant nuclei have less mass than the original with the difference being converted to energy. That energy appears in the form of blast, heat, x-rays, gamma rays, neutrons, etc., all of which will be discussed later.

Fission occurs when a free neutron, while traveling through the isotope material strikes the nucleus of one of the atoms and causes the nucleus to break in two. When this fission occurs, there is an energy release of approximately 200 MeV or 32×10^{-6} Joules and there will also be 2 or 3 neutrons thrown free from the split atom. The neutrons freed by the fission process are then able to move in such a manner as to possibly collide with another nucleus, thus causing another fission. A fission created by a neutron released from a previous fission constitutes a chain reaction. When the number of fissions occurring during one generation is equal to or greater than the number of fissions which took place in the preceding generation, the chain reaction is said to be self sustaining. Using select isotopes of uranium and plutonium, a fission or fusion explosion can emit about 2×10^{26} neutrons per megaton yield.

The history of the split uranium atom goes back to just prior to January 26, 1939. It was on this date that the news was released to the Fifth Washington Conference on Theoretical Physics that Dr. Otto Hahn had, only a few weeks earlier, shattered a uranium atom using neutron bombardment. Dr. Hahn, a noted German physicist working at the Kaiser Wilhelm Institute in Berlin, was rummaging through the remains of one of his experiments and found that barium was one of the products resulting from neutron bullets blasting a uranium nucleus in two. Barium is only slightly heavier than half the weight of uranium. Others, having inside information, scrambled to duplicate Hahn's find. Ten days before the conference, Frisch and Meitner, in Copenhagen, verified the results and on January 25, one day before the conference, a group of Columbia University physicists carried out a similar experiment. By the termination of the conference on January 28, Carnegie Institution of Washington, Johns Hopkins, and the University of California laboratories had provided three more confirmations.

Whether or not a fission takes place and whether or not a chain reaction of fissions occurs and whether or not the number of fissions increase rapidly enough to have an explosion are all dependent upon the mass of the fissionable material, the container in which the material is housed, and the presence of other elements having lighter nuclei. For large amounts of nuclear energy to be released, a chain reaction of fissions must occur. The fission of one pound of uranium or plutonium produces approximately an 8 KT burst.

The mass factor is divided into three classifications: subcritical, critical, and supercritical. For the purposes of this discussion, the symbol "f" will be used to represent the fission rate factor which will define the criticality of the mass. This factor in equation form is given as:

$$f = \frac{\text{number of fissions in generation } n}{\text{number of fissions in generation } n-1}$$

When " f " is less than 1, the mass is considered subcritical, for " f " greater than 1, the mass is supercritical, and a factor " f " of unity represents critical mass. When the mass is critical, the chain reaction is such that no explosion will occur, but the heat generated by the fissions will cause the substance to melt down or alter in form toward subcritical. To create an explosion, supercritical mass is required. Subcritical mass provides for a non-explosive decay of the radioactive material. The decay takes place as neutrons are lost by escaping from the substance.

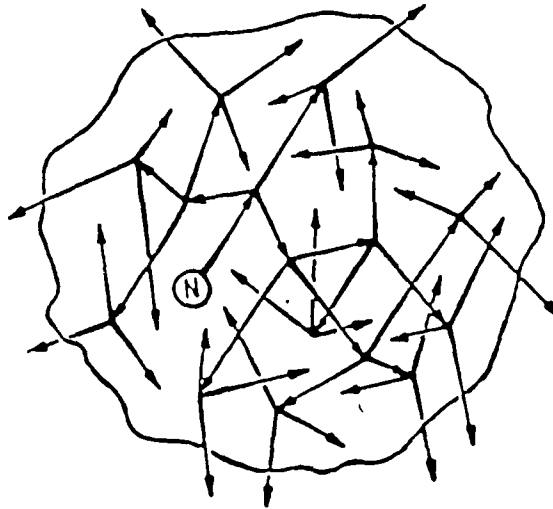


FIGURE 1-1. Neutron Scattering.
Neutrons liberated by a fission are capable of causing another fission, or may be lost through non-fission reactions, or escape.

Fusion is the combining of nuclei of hydrogen isotopes (deuterium and tritium) to form a heavier element. In order to obtain a fusion, temperatures in the range of tens of millions of degrees are required to excite the isotope nuclei to a high energy level. Typically, the most efficient method for generating that kind of heat is to have a fission reaction. By combining the fissionable products with the fusionable isotopes, a weapon of much greater power than a fission only weapon is produced. These fission triggered, fusion weapons are generally referred to as "thermonuclear" weapons.

ENERGY FORMS

For a nuclear explosion the energy yield is in blast and shock, thermal, and radiation form. The approximate split for an atmospheric explosion is: 50% blast and shock, 35% thermal, and 15% radiation. The energy form which poses the greatest threat is dependent upon the altitude of the explosion, the recipient of the threat (i.e. people, buildings, electronic equipment, etc.), and the distance between the blast and the recipient.

BURST CLASSIFICATION

Because the nuclear threat factors are a function of the height of burst, explosions are classified as one of the four: subsurface, surface, air, or high altitude. For example, blast, shock, and thermal threats are more significant from a surface burst than from a high altitude burst. EMP, on the other hand, is a greater concern as a result of a high altitude blast.

A subsurface burst is one in which the weapon's center of gravity is beneath the ground or under the surface of water. A fully contained subsurface burst is one in which the fireball does not reach the surface. A surface burst is one which occurs either on the earth's surface or slightly above. The allowable distance above the surface which will differentiate between a surface burst and an air burst is determined by the size of the fireball. When the altitude is such that the burst is within the atmosphere (under 100,000 feet), and the fireball, at its greatest intensity no longer touches land or water, the explosion is called an air burst. A fireball can grow to over one mile across at its maximum brilliance, requiring a detonation altitude of over 2,500 feet to be an air burst. A high altitude burst is generally defined as one which occurs above 100,000 feet (above the altitude where there is any significant atmosphere).

SECTION 2

BLAST AND SHOCK

An explosion will cause an increase in pressure and the rapid expansion of the compressed gasses is an energy release called "shock wave" or "blast wave." There are two factors of concern resulting from a blast wave: overpressure and underpressure. Overpressure is the difference between the ambient pressure and the total pressure at a given point during the blast.

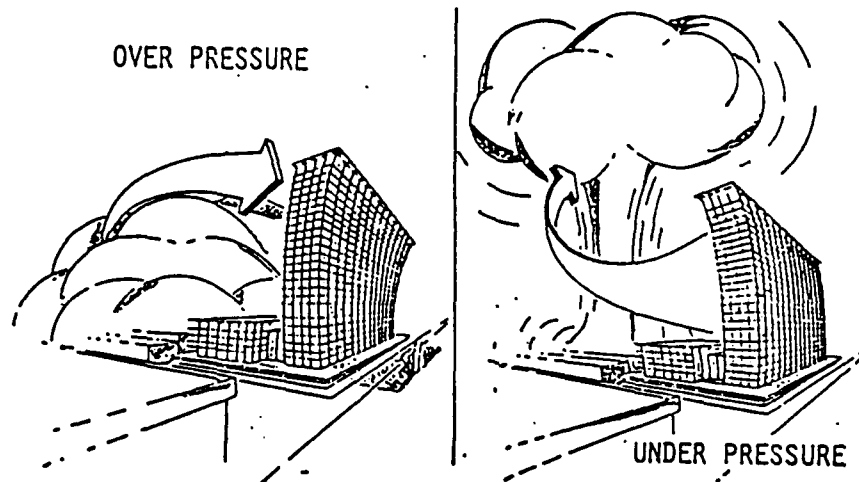


FIGURE 2-1. Overpressure will occur as the blast force is moving outward from the detonation, and underpressure occurs during the period of "suction" toward the blast area.

Overpressure occurs as the blast radiates outward from the explosion and is called the positive phase (Phase I) of the blast wave. This rapid outward movement of air causes a vacuum to be formed which leads to phase two of the blast, the return to pressure equilibrium. Phase II, or the negative phase, is the period of underpressure or the interval of pressures less than ambient.

Testing of both high explosive conventional and nuclear weapons have provided evidence that a given pressure will occur at some distance from the explosion in proportion to the cube root of the energy yield. This assumption gives an approximation into the megaton range.

$$(r/r_1) = (W/W_1)^{1/3}$$

(Eqtn 2-1)

Where r_1 and W_1 are the reference slant range and energy yield, respectively, W is the energy yield of the weapon in question, and r is the slant range at the pressure of interest.

EXAMPLE 2-1:

GIVEN: A 1KT weapon produces a 200 psi overpressure 275 feet from the blast.

FIND: At what distance would a 10KT blast provide the same level of overpressure?

SOLUTION: $r_1 = 275\text{ft}$, $W_1 = 1\text{KT}$, $W = 10\text{KT}$

$$r = r_1 (W/W_1)^{1/3}$$

$$r = 592 \text{ feet.}$$

The same relationship exists between the time of arrival of the positive phase of the blast and the energy yields, as shown in Equation 2-2.

$$(t/t_1) = (W/W_1)^{1/3}$$

(Eqtn 2-2)

Where t_1 is the reference time and t is the time in question.

The preceding relationships are very simplistic and do not take into account such factors as height of burst, reflection of the blast front off of a surface, etc.

Typical physical characteristics of a blast wave are shown in Figure 2-2. As shown, the shock front moves away from the burst center and the incident wave is reflected by the earth. When the reflected wave intercepts the incident wave, a combining of pressures is created. The point where this combination occurs is known as the "triple point" and the area below the triple point is called the "Mach Stem Region".

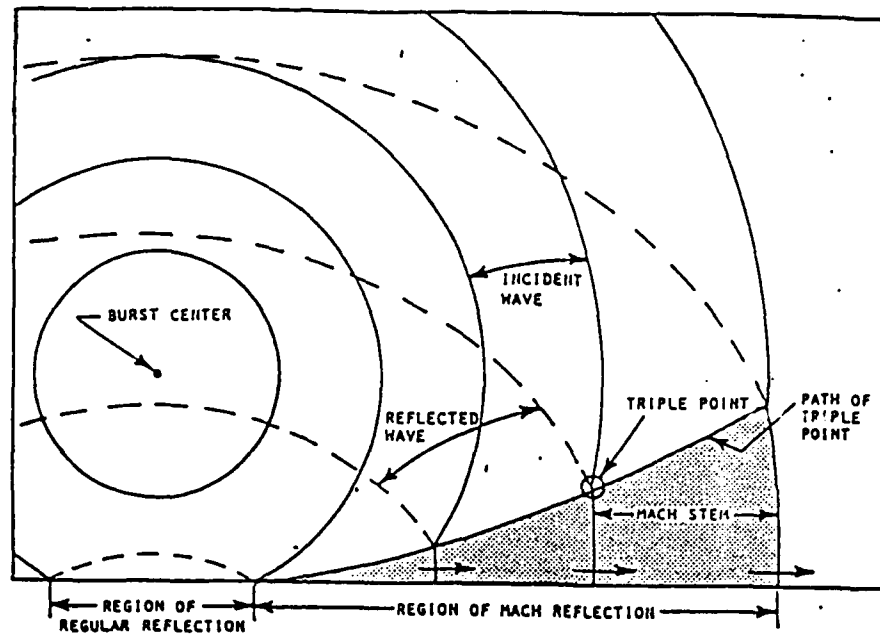
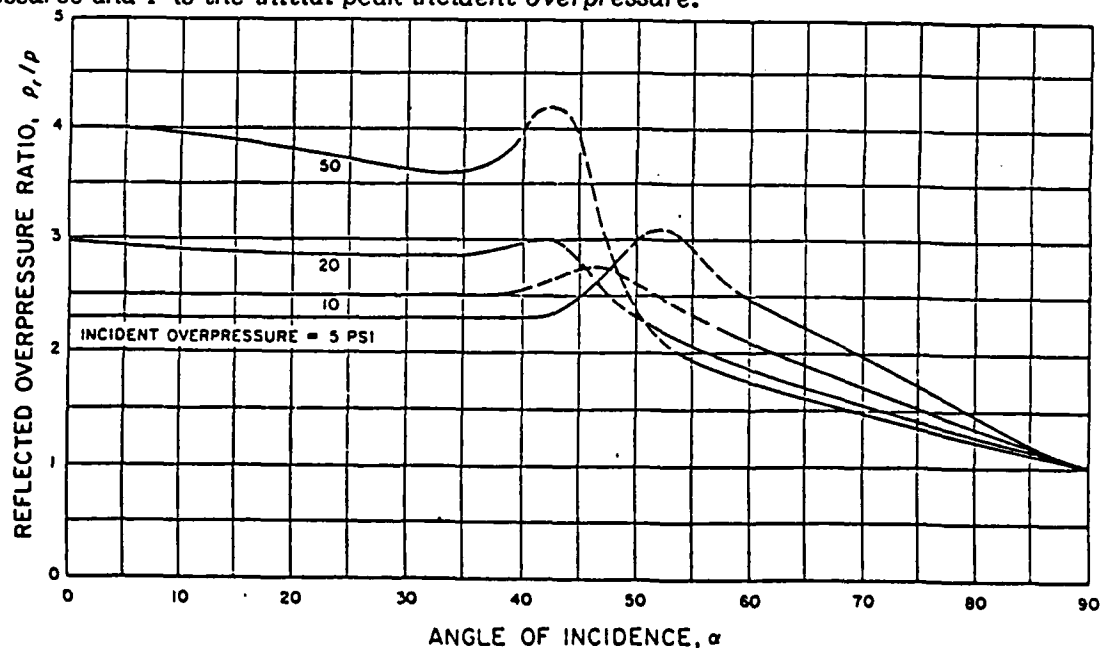


FIGURE 2-2. The Mach Stem Region, (shaded area), is the region in which the incident blast wave and the reflected wave result in additive pressures.

Ideally, the pressure generated at the shock front would be the simple addition of the incident and reflected wave pressures, but this is not the case. The pressure below the triple point is dependent on the incident overpressure, P , and the angle of incidence, α .

The following graph (2-1) shows the relationship between the incident and reflected pressures for angles of incidence between zero and 90°. P_r is the reflected blast overpressures and P is the initial peak incident overpressure.



GRAPH 2-1. Reflected Overpressures Ratio.

To use this graph, when the incident pressure and angle of incidence are known, simply locate the point of intersection of the two, read the corresponding ratio from the left side of the graph, and multiply the incident pressure by the factor read.

EXAMPLE 2-2:

GIVEN: An incident wave of 50 psi overpressure strikes a surface at 40°.

FIND: What is the "mach stem" pressure?

SOLUTION: The 50 psi overpressure line intersects the 40° reference line at the point where the reflected overpressure ratio is 4. Multiply the incident pressure of 50 psi by 4 to get 200 psi mach stem pressure.

Another parameter is "peak overpressure" or, as the phrase implies, the maximum amount of overpressure felt from a blast front. The peak overpressure at a given range can be analytically determined, within a factor of 2, by:

$$P_{op} = (3000) (W/1MT) (1000 \text{ feet}/r)^3 + (192) (W/1MT)^{1/2} (1000 \text{ feet}/r)^{3/2} \text{ psi} \quad (\text{Eqtn 2-3})$$

Referring back to the example in which it was calculated that a 200 psi overpressure would be felt at 592 feet from a 10KT blast, those figures can be used to work backward to show the relationship of the two equations.

EXAMPLE 2-3:

$$\begin{aligned} P_{op} &= (3000) (10KT/1MT) (1000/592)^3 \\ &+ (192) (10KT/1MT)^{1/2} (1000/592)^{3/2} \text{ psi} \\ &= 187 \text{ psi.} \end{aligned}$$

This shows an error of only 6.5% difference and should provide an acceptable approximation.

Another factor in the blast category is dynamic pressure. Dynamic pressure is a pressure related to the winds developed by an explosion. The dynamic pressure is proportional to the square of the velocity of the wind preceding the shock front. Dynamic pressures can be greater than or less than the magnitude of overpressures, dependent on weapon yield. Very strong shocks will produce higher dynamic pressures vs. overpressures, whereas lighter shocks will cause overpressures greater than dynamic.

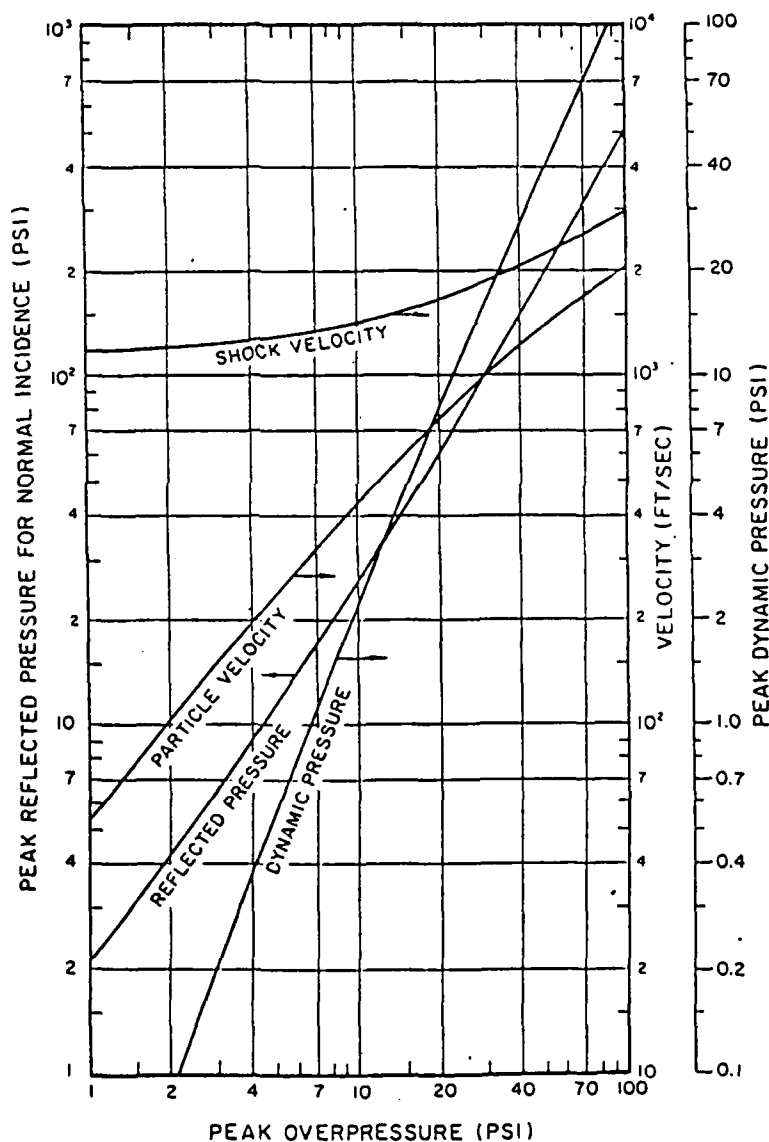
A relationship for the dynamic pressure can be related to the velocity of the wind by:

$$q = 1/2 (\rho v^2) \quad (\text{Eqtn 2-4})$$

Where ρ is the density of air behind the shock front, and v is the velocity of the air moving behind the shock front.

RELATIONSHIPS OF BLAST FACTORS

As engineers at an Air Logistics Center (ALC), your involvement with the effects of shock will likely be minimal, if not nonexistent. The information provided is therefore, only introductory. Since imitation is the sincerest form of flattery, Messrs. Glasstone and Dolan should feel gratified that nearly all material herein on shock (and thermal radiation) is a condensed version of their "The Effects of Nuclear Weapons."



GRAPH 2-2. Blast Wave Characteristics.

The "Blast Wave Characteristics" graph (2-2) allows a comparison look at the various factors making up the blast and shock threat. Some examples of the things that are shown in this graph include:

- 1) Peak overpressure and reflected pressure start at about the same magnitude when pressures are low, but at maximum values shown, reflected pressure is five times greater than peak overpressure.
- 2) Dynamic pressure is less than peak overpressure in ranges below 70 psi, and larger than peak overpressure for ranges above 70 psi.

The following pages contain various graphs showing blast factor relationships. With each graph, there is a description, as well as a problem solving example.

Graph 2-3 shows peak overpressure as a function of Height of Burst (HOB) and distance from ground zero. These values are scaled to a 1 KT burst using the cube root rule:

$$\frac{d}{d_1} = \frac{t}{t_1} = \frac{h}{h_1} = w^{1/3} \quad (\text{Eqtn 2-4})$$

An example illustrating the use of this graph is shown below:

EXAMPLE 2-4:

GIVEN: An 80 KT detonation at a height of 860 feet.

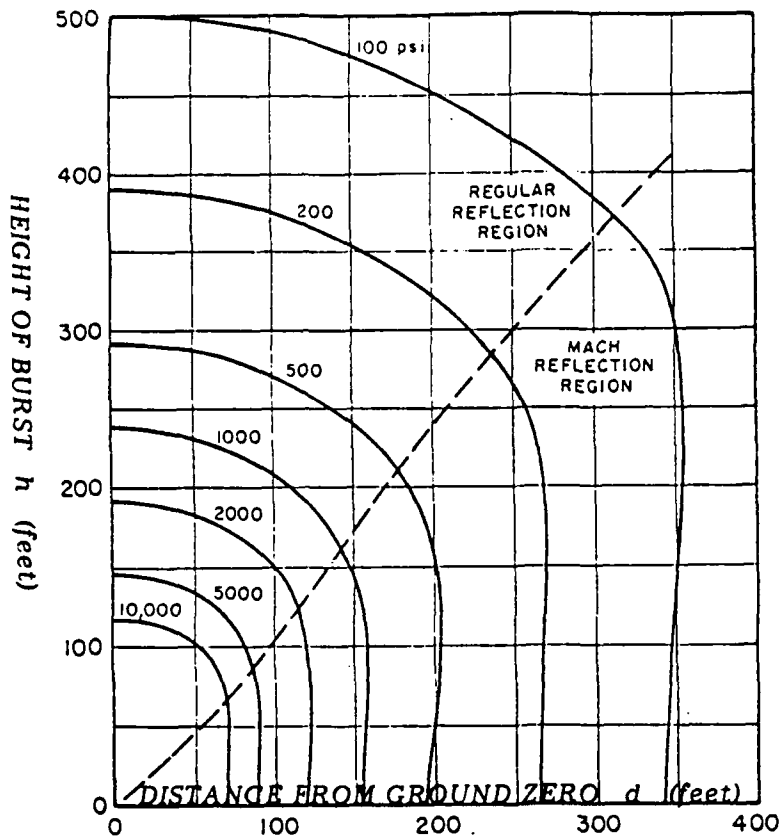
FIND: The distance from ground zero to which 1,000 psi overpressure extends.

SOLUTION: The corresponding height of burst for 1 KT, i.e., the scaled height, is:

$$h_1 = \frac{h}{w^{1/3}} = \frac{860}{(80)^{1/3}} = 200 \text{ feet.}$$

From graph 2-3, an overpressure of 1,000 psi extends 110 feet from ground zero for a 200-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT burst is:

$$d = d_1 w^{1/3} = 110 \times (80)^{1/3} = 475 \text{ feet.}$$



GRAPH 2-3. Peak overpressures in Mach Stem Region (1KT burst) (pressure on the ground).

Graph 2-4 serves the same purpose as graph 2-3, but for an extended range. A sample problem is:

EXAMPLE 2-5:

GIVEN:

A 100 KT detonation at a height of 2,320 feet.

FIND:

The peak overpressure at 1,860 feet from ground zero.

SOLUTION:

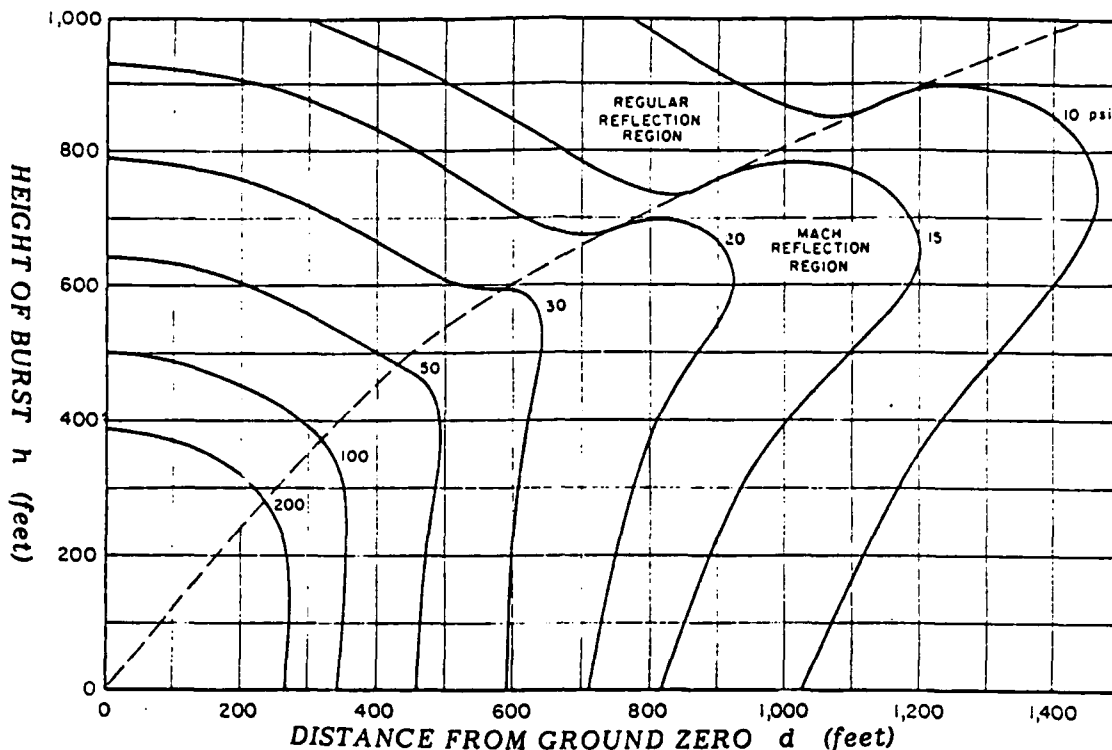
The corresponding height of burst for 1 KT is:

$$h_1 = \frac{h}{w^{1/3}} = \frac{2,320}{(100)^{1/3}} = 500 \text{ feet}$$

and the ground distance is:

$$d_1 = \frac{d}{w^{1/3}} = \frac{1,860}{(100)^{1/3}} = 400 \text{ feet}$$

From graph 2-4, at a ground distance of 400 feet and a burst height of 500 feet, the peak overpressure is 50 psi.



GRAPH 2-4. Peak overpressures on the ground (1 KT burst).

Graph 2-5 is the last of a set of three which show peak overpressure as a function of HOB and distance from ground zero. This graph illustrates far range blast wave characteristics.

EXAMPLE 2-6:

GIVEN: A 125 KT detonation.

FIND: The maximum distance from ground zero to which 4 psi extends, and the height of burst at which 4 psi extends to this distance.

SOLUTION: From graph 2-5, the maximum ground distance to which 4 psi extends for a 1 KT weapon is 2,600 feet. This occurs for a burst height of approximately 1,100 feet. Hence, for a 125 KT detonation, the required burst height is:

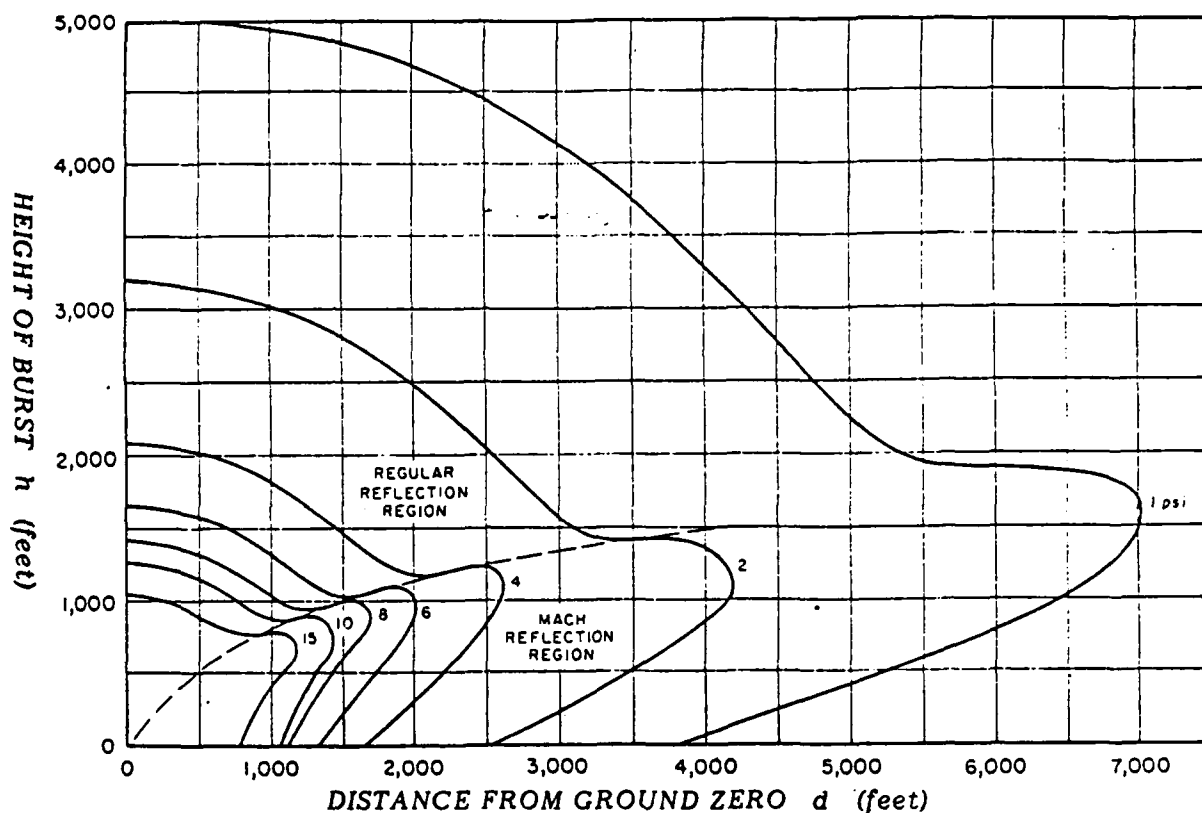
$$h = h_1 w^{1/3} = 1,100 \times (125)^{1/3}$$

$$h = 5,500 \text{ feet.}$$

The distance from ground zero is then:

$$d = d_1 w^{1/3} = 2,600 \times (125)^{1/3}$$

$$d = 13,000 \text{ feet.}$$



GRAPH 2-5. Peak overpressures on the ground (1KT burst).

DYNAMIC PRESSURE

The curves in graph 2-6 show the values of the horizontal component of dynamic pressure as a function of HOB and distance from ground zero. These figures represent approximately ideal surface conditions. For terrain variations, additional data would be required. Use of this graph relies on the same distance to weapon yield relationships and, as in previous graphs, normalization to 1 KT is required.

EXAMPLE 2-7:

GIVEN:

A 160 KT burst at a height of 3,000 feet.

FIND:

The horizontal component of peak dynamic pressure on the surface at 6,000 feet from ground zero.

SOLUTION:

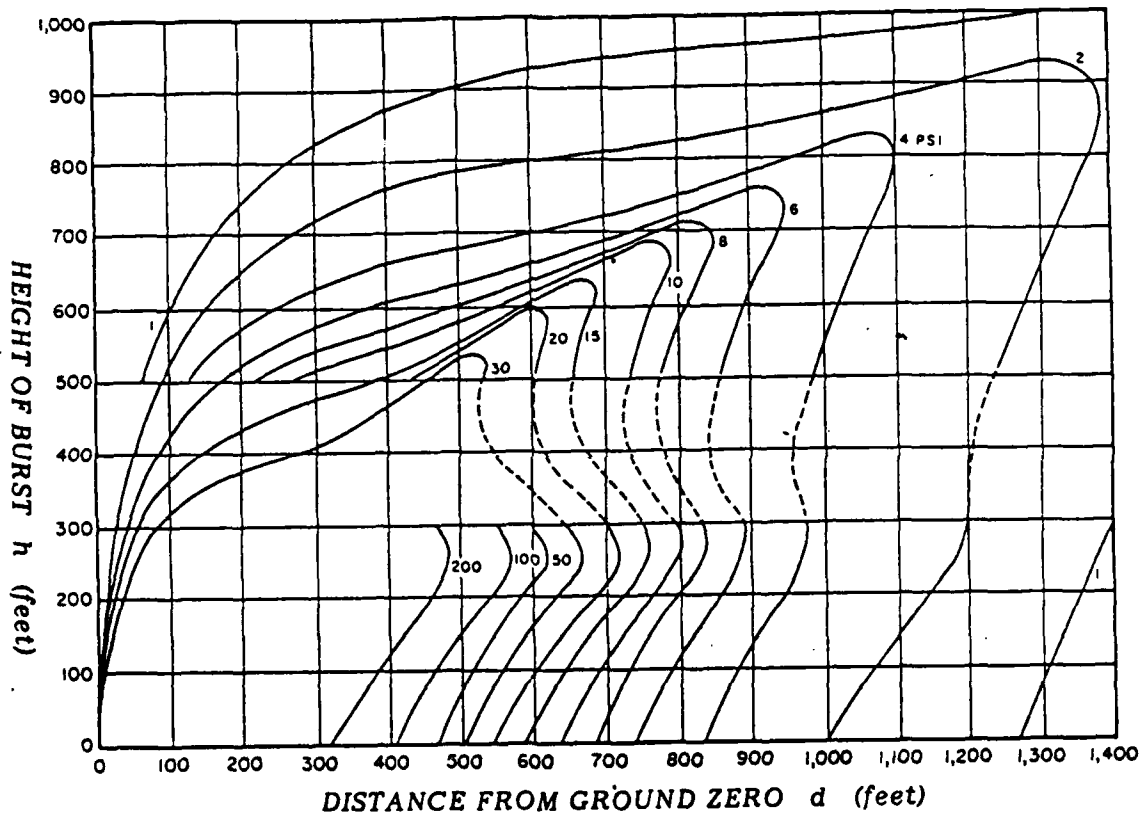
The corresponding height of burst for 1 KT is:

$$h_1 = \frac{h}{w^{1/3}} = \frac{3,000}{(160)^{1/3}} = 553 \text{ feet}$$

The corresponding distance for 1 KT is:

$$d_1 = \frac{d}{w^{1/3}} = \frac{6,000}{(160)^{1/3}} = 1,105 \text{ feet}$$

From graph 2-6, at a distance of 1,105 feet from ground zero, and a burst height of 553 feet, the horizontal component of the peak dynamic pressure is approximately 3 psi.



GRAPH 2-6. Peak Dynamic Pressure. Horizontal component (1 KT burst).

The durations of the overpressure phase and the dynamic pressure as a function of HOB and distance from ground zero are given in graph 2-7. Scaling to a 1 KT burst, the reference time, t_1 , can be found and from that, the durations of the pressures. Once again, the cube root scaling is:

$$\frac{d}{d_1} = \frac{h}{h_1} = \frac{t}{t_1} = w^{1/3}$$

EXAMPLE 2-8:

GIVEN:

A 160 KT explosion at a height of 3,000 feet.

FIND:

The positive phase duration on the ground at a distance of 4,000 feet from ground zero of (a) the overpressure, (b) the dynamic pressure.

SOLUTION:

The corresponding height of burst for 1 KT is:

$$h_1 = \frac{h}{w^{1/3}} = \frac{3,000}{(160)^{1/3}} = 553 \text{ feet.}$$

and the corresponding distance from ground zero is:

$$d_1 = \frac{d}{w^{1/3}} = \frac{4,000}{(160)^{1/3}} = 737 \text{ feet.}$$

- (a) From graph 2-7, the positive phase duration of the overpressure for a 1 KT at 737 feet from ground zero and a burst height of 553 feet is 0.18 seconds. The corresponding duration of the overpressure positive phase for 160 KT is, therefore:

$$\begin{aligned} t &= t_1 w^{1/3} = 0.18 \times (160)^{1/3} \\ t &= 0.98 \text{ seconds.} \end{aligned}$$

- (b) Also from graph 2-7, the positive phase duration of the dynamic pressure for 1KT at 737 feet from ground zero and a burst height of 553 feet is 0.34 second. The corresponding duration of the dynamic pressure positive phase for 160 KT is, therefore:

$$\begin{aligned} t &= t_1 w^{1/3} = 0.34 \times (160)^{1/3} \\ t &= 1.8 \text{ seconds.} \end{aligned}$$

EXAMPLE 2-9:

GIVEN:

A 1 MT explosion at a height of 5,000 feet.

FIND:

The time of arrival of the blast wave at a distance of 10 miles from ground zero.

SOLUTION:

The corresponding burst height for 1 KT is:

$$h_1 = \frac{h}{W^{1/3}} = \frac{5,000}{(1,000)^{1/3}} = 500 \text{ feet.}$$

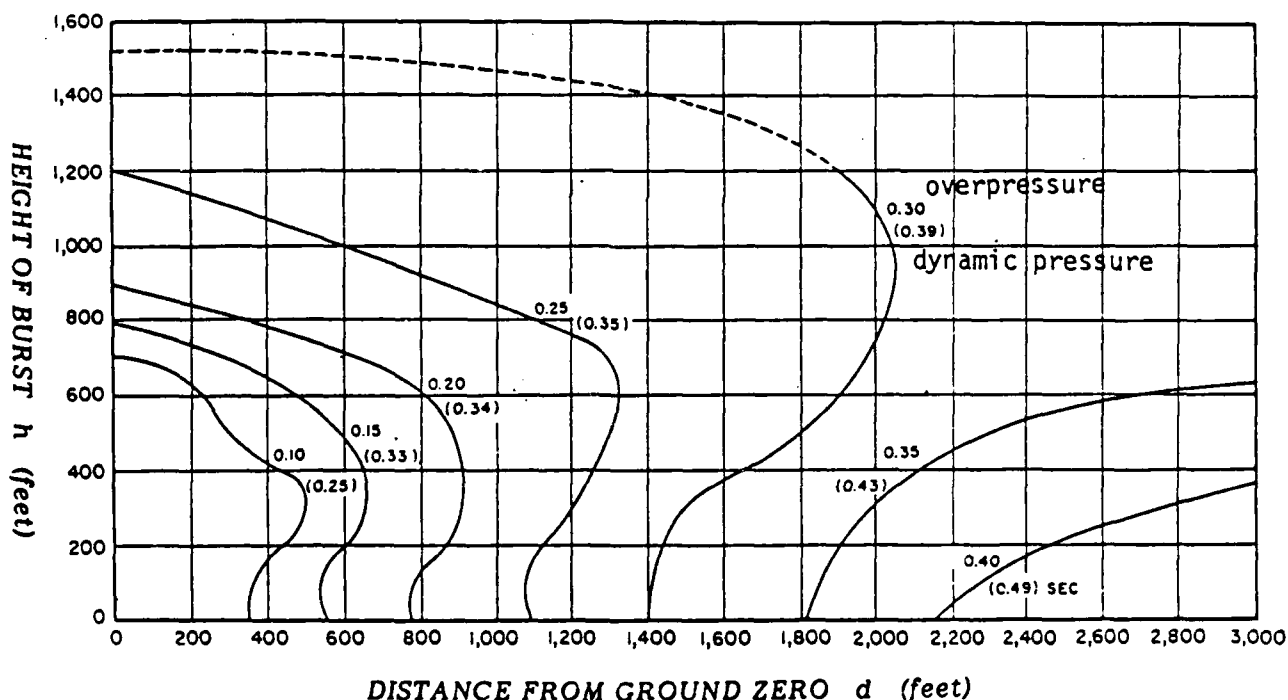
The corresponding distance from ground zero for 1 KT is:

$$d_1 = \frac{d}{W^{1/3}} = \frac{5,280 \text{ feet/mile} \times 10 \text{ miles}}{(1,000)^{1/3}} = 5,280 \text{ feet.}$$

From Graph 2-9, at a height of burst of 500 feet, and a distance of 5,280 feet from ground zero, the arrival time is 4.0 seconds for 1 KT. The corresponding arrival time for 1 MT is:

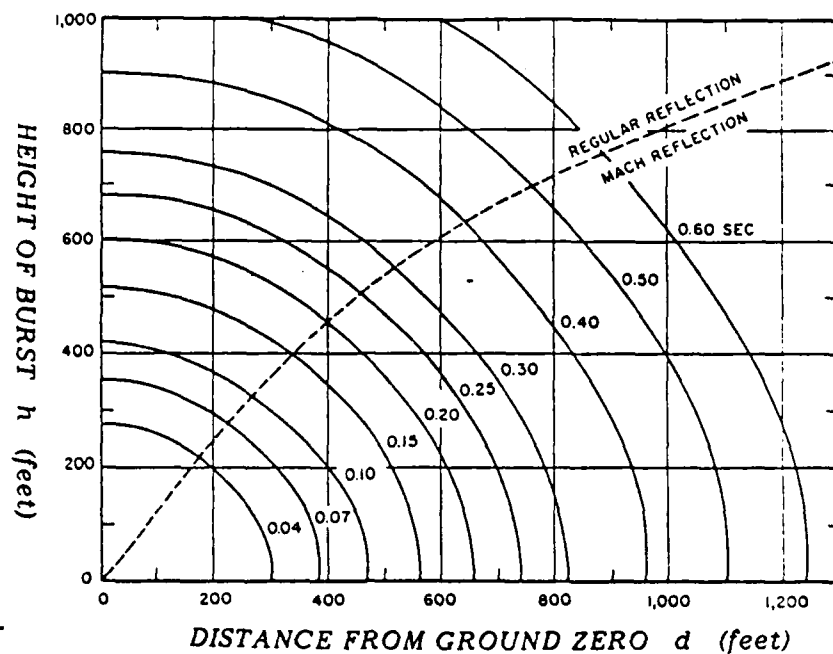
$$t = t_1 W^{1/3} = 4.0 \times (1,000)^{1/3}$$

$$t = 40 \text{ seconds.}$$

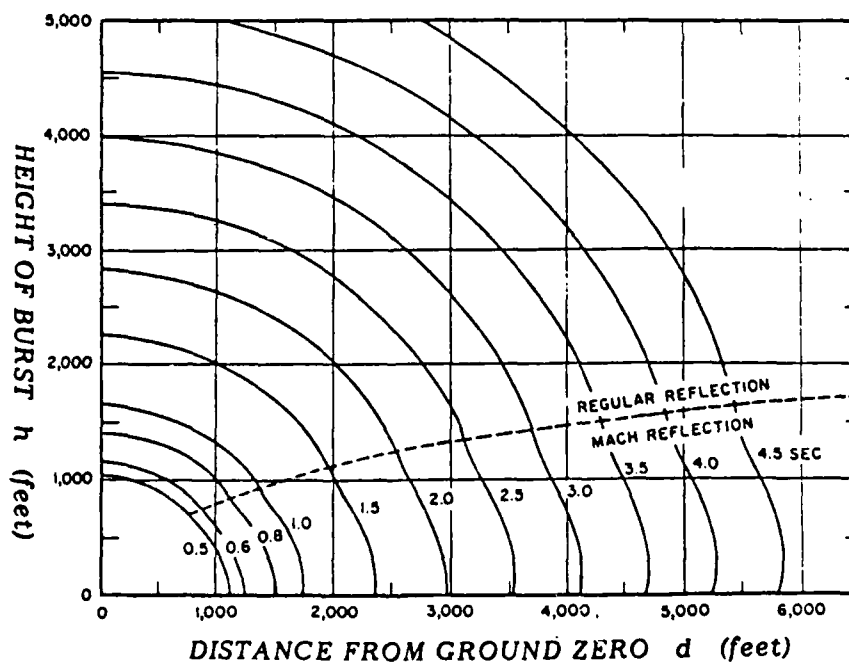


GRAPH 2-7. Duration of overpressure on ground (1 KT burst).

The curves on Graphs 2-8 and 2-9 show the length of time required for a blast front to hit a specific point on the ground, which is dependent upon the HOB and the distance from ground zero to the point. Differences in the two graphs are in the ranges covered. Both are used similarly and both are scaled to 1 KT.



GRAPH 2-8. Blast wave travel time to ground
(1 KT burst).



GRAPH 2-9. Blast wave travel time to ground
(1 KT burst).

SECTION 3

THERMAL

A conventional explosion produces thermal energy with temperatures of a few thousand degrees. In contrast, the fireball of a nuclear detonation will typically be as hot as the surface of the sun, having temperatures of tens of millions of degrees. Heat from the fireball is high in intensity and short in duration. Due to the high intensity, heat caused by air absorption is rapidly generated. The short period of exposure time does not allow for very much heat conduction and the heat is therefore not transferred very deep within a material. The result of these factors is a very high surface temperature. Estimates of the effects of explosions in Japan indicate the ground surface temperatures directly beneath the burst reached 5,000 to 7,000 degrees F and as much as 3,300 degrees F as far as 0.6 miles away.

Another hazard related to the thermal radiation of a nuclear blast is flash blindness from the brilliance of the fireball. As with the blast and shock energy, the effects of thermal radiation experienced are dependent upon the distance from the explosion, and the amount of elapsed time since the blast.

Thermal radiation contacting any object is either reflected from, absorbed by, or transmitted through that object. The absorption is what causes damage. Absorption levels depend upon the objects consistency, color, shape, etc. Dark objects will absorb more than light ones. Smooth, highly polished objects are more reflective than rough surfaced, porous materials, and so on. Absorption, put very simply, increases the temperature of the object which is absorbing. Increased temperatures can cause burns, ignite combustible materials, and melt some materials.

Other factors influencing the effects of thermal radiation are the attenuation factors: absorption and scattering of the air. The attenuation of thermal effects are related to the square of the distance. For example, the thermal energy present 2 miles from a nuclear explosion is four times greater than that felt at 4 miles. Ultraviolet (UV) energy, because of its short wavelength, is especially susceptible to being absorbed by atoms and molecules in the air. Reradiation of the UV is likely to occur after absorption. However, it would be in all directions thereby 'diluting' the concentration in any given area. Attenuation of the UV is particularly important to biological survival, as it is more harmful than the infrared or visible ray forms of energy. Attenuation by scattering is simply the diffusion of the radiation as it encounters particles in the air or obstacles between the blast and the area of concern.

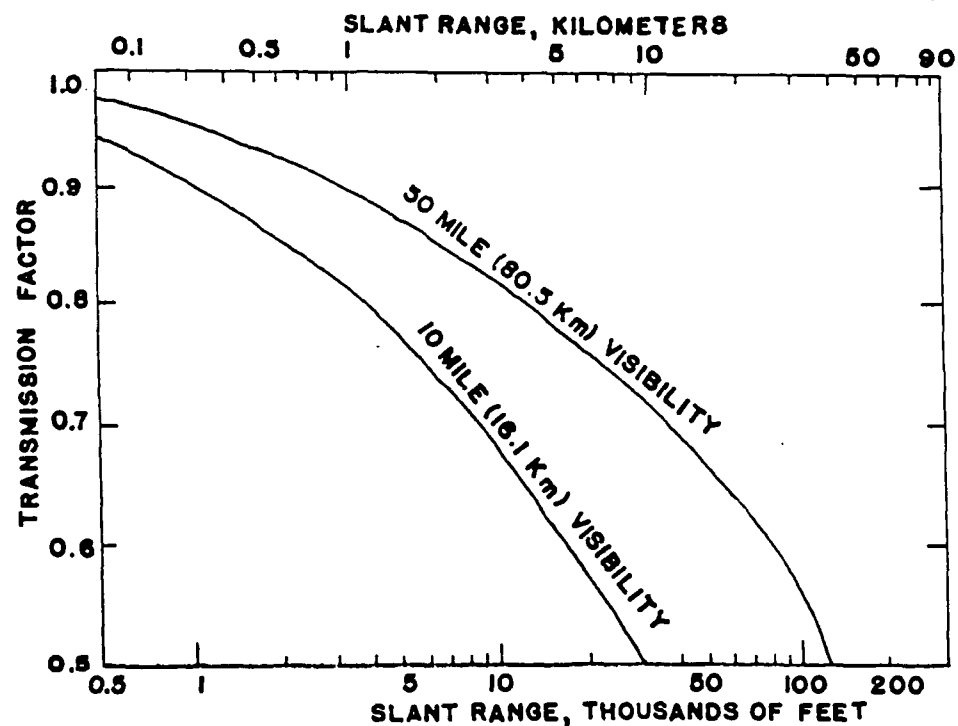
Attenuation depends on the concentration and size of the particles and the wavelength of the rays. UV, infrared (IR), and visible rays will all attenuate differently, but for analytical purposes, a uniform attenuation across the spectrum is assumed.

Prompt thermal radiation is emitted in two pulses. The first is very short in duration (micro - milli seconds) and contains only approximately one percent of the total energy yield of the weapon. The second, longer pulse, accounts for about one third of the total yield. The duration of the two pulses is proportional to the weapon yield, ranging from less than a half second for a 1 KT blast to around half a minute for a 10 MT yield.

Calculating the amount of thermal (F_t) radiation at a given distance from a blast is difficult, due to the widely varying attenuation factors. An approximation can be made using equation 3-1:

$$F_t = 2.8 \times 10^4 \tau W (1000/r)^2 \text{ calories/cm}^2 \quad (\text{Eqtn 3-1})$$

Where τ = transmission factor due only to scattering, and r = distance in feet.



GRAPH 3-1. Transmission Factor Curves.

A " τ " of unity signifies infinite visibility while a less than perfect visibility will cause " τ " to decrease. Graph 3-1 shows two sample curves for visibilities less than infinite. To use this chart, match the slant range with the appropriate visibility level to find the transmission factor " τ ". For worst case, " τ " will always be unity.

"On a clear day, you can see forever," is only true in a song. Actually, on a clear day, you can see about 12 miles. The following table (Table 3-1) provides some comparisons of atmospheric conditions with visibility ranges.

TABLE 3-1. Visibility as a function of atmospheric conditions.

ATMOSPHERIC CONDITIONS	VISIBILITY IN MILES
Exceptionally clear	170
Very clear	31
Clear	12
Light haze	6
Haze	2.5
Thin fog	1.2
Light to thick fog	0.6 or less

To preclude the misconception that visibility of an object from the point of detonation is a prerequisite for thermal impact, it is stressed that decreased visibility will attenuate, but not stop thermal radiation. Even opaque materials can pass the harmful radiations. Also, even if protected by an obstacle which does not pass any radiation, the scattering of rays does attenuate the "straight line" strength but, at the same time, allows the rays to "go around corners."

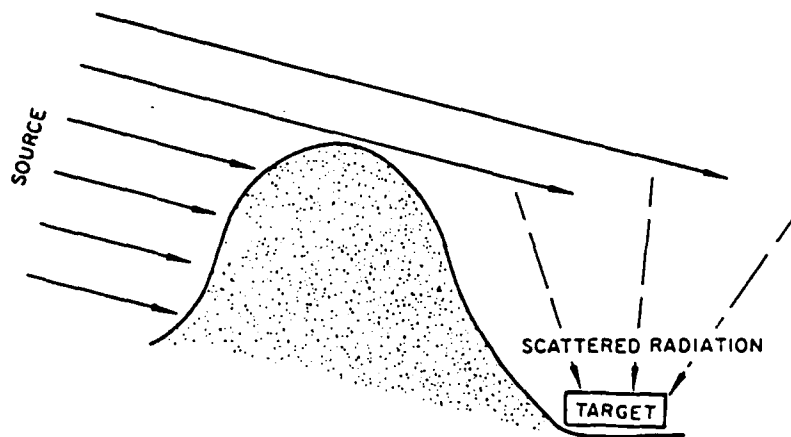


FIGURE 3-1. RAD going around corners.

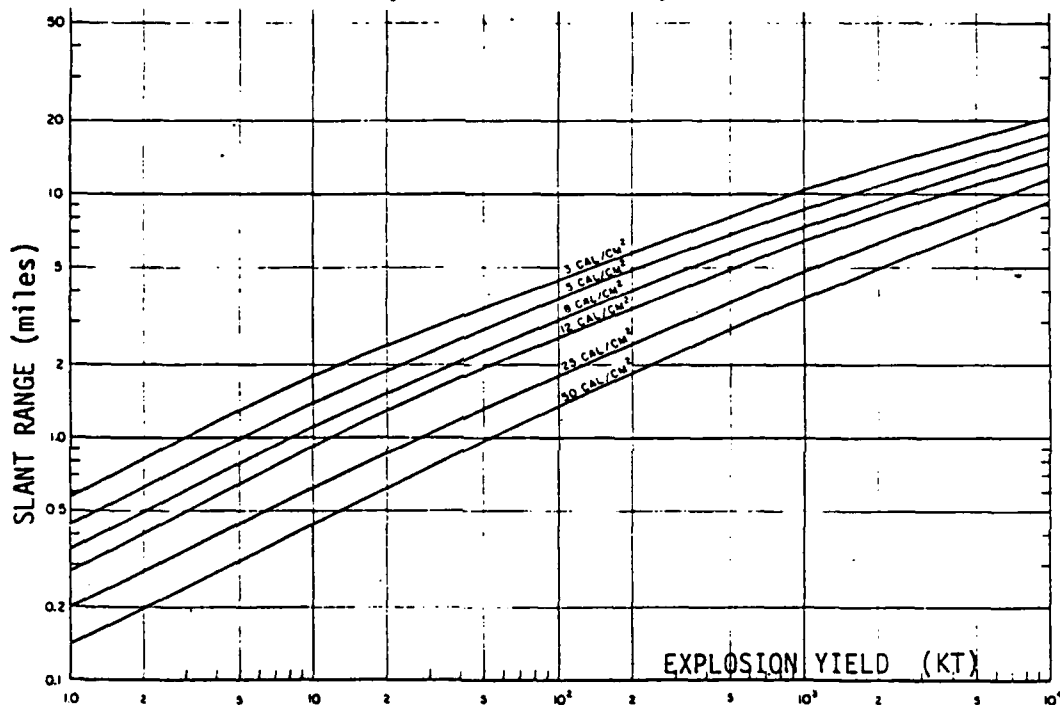
The extent of damage caused by thermal radiation depends on the amount of energy reaching an object and the duration of the exposure. Radiant exposure is the amount of thermal radiation energy incident on a given material. The common unit of measurement is calories per square centimeter (cal/cm^2). Typically, the level of thermal energy generated per KT is 3.5×10^{11} calories or 410,000 KW hours. The amount of radiant exposure for a low air burst is usually analyzed as a uniform quantity for HOBs up to 15,000 feet, as a function only of weapon yield and visibility. For these cases, air density is not a factor and the thermal partition (the percentage of total energy yield in the form of thermal radiation) is considered to be 35%. The minimum HOB for these low air bursts is calculated as $200 W^{0.4}$ feet (W is in KT). This is the minimum height needed in order for the fireball not to touch the ground.

See graph 3-2 for curves of various radiant exposures at different slant ranges as a function of weapon yield.

EXAMPLE 3-1:

GIVEN: A 1MT burst where HOB is between 3,170 feet ($200W^{0.4}$) and 15,000 feet, at a slant range of 5 miles will produce radiant exposure equal to just less than 25 cal/cm².

(NOTE: This level of exposure is sufficient to ignite many clothing fabrics and most paper products. It will also blister paint and char wood.)



GRAPH 3-2. Radiant exposures for low air bursts on a clear day as a function of weapon energy yield.

The amount of exposure falls off with distance because of a uniform spread over an increasing area.

If the thermal energy from a thermonuclear blast is considered to be uniformly distributed at all points equidistant from the blast, then the area of coverage can be shown as a sphere surrounding the blast and having a radius "D". Then, the area of uniform distribution is $4\pi D^2$. If the energy produced by the explosion is "E", then the energy at any point "D" distance from the blast is shown as $E/(4\pi D^2)$ if, and only if, no attenuation exists. It can be seen from this, that even without any attenuation from atmospheric conditions, the range from the blast is a large factor in the level of exposure. The energy at one mile from the blast is going to be four times greater than the energy two miles from the blast.

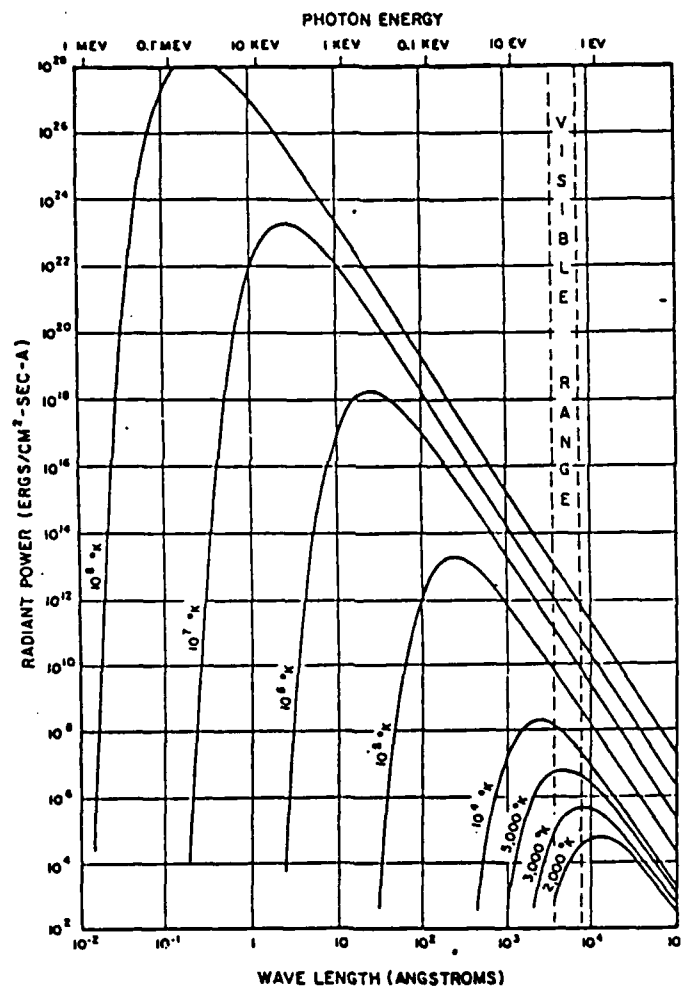
TECHNICAL ASPECTS OF THERMAL RADIATION

The fireball of a thermonuclear detonation can be interpreted approximately as behaving like a black body with respect to thermal radiation emission characteristics.

The radiant heat transmission (Q) from a black body is given as:

$$Q = 1.36 \times 10^{-12} T^4 \text{ cal/cm}^2\text{-sec} \quad (\text{Eqtn 3-2})$$

Where T is the absolute temperature of the body. ($0^\circ\text{C} = 273.15^\circ\text{K}$)



GRAPH 3-3. Black body radiant power as a function of wavelength and temperature.

To determine the total radiated power (P) from a fireball, simply multiply " Q " by the area of the fireball:

$$P = 4\pi D^2 Q \quad (\text{Eqtn 3-3})$$

$$P = 1.71 \times 10^{-11} T^4 D^2 \text{ cal/sec.} \quad (\text{Eqtn 3-4})$$

D = Radius of fireball.

Where " T " is the absolute temperature and D is given in cm.

This equation represents the total power of all wavelengths radiated from a black body. Comparison curves which show the power contribution for different wavelengths and different temperatures are shown in Graph 3-3.

Experiments have provided substantial data to use the approximations:

$$P_{\max} = 3.18 W^{0.56} \text{ kilotons/sec} \quad (\text{Eqtn 3-5})$$

Where P_{\max} is the maximum thermal power at the time " t_{\max} " of the second phase maximum, and:

$$t_{\max} = 0.0417 W^{0.44} \text{ sec} \quad (\text{Eqtn 3-6})$$

for HOB between $200 W^{0.4}$ and 15,000 feet.

Calculations for bursts above 15,000 feet must take air density into account. Actual data is not abundant, but theoretical calculations indicate the following relationships will suffice.

$$P_{\max} = \frac{3.56(W)^{0.59}}{[\rho_{(h)}/\rho_o]^{0.45}} \frac{\text{kilotons}}{\text{second}} \quad (\text{Eqtn 3-7})$$

Where " $\rho_{(h)}$ " is the ambient air density at HOB and $1.225 \times 10^{-3} \text{ g/cm}^3$ is normal sea level air density ρ_o .

$$t_{\max} = 0.038(W)^{0.44} [\rho_{(h)}/\rho_o]^{0.36} \text{ sec.} \quad (\text{Eqtn 3-8})$$

Atmospheric density ratios are provided in Table 3-2.

TABLE 3-2. Atmospheric Density Ratios.

Altitude (feet)	Density Ratio, $\rho(h)/\rho_0$	Altitude (feet)	Density Ratio, $\rho(h)/\rho_0$
15,000	0.63	60,000	0.095
20,000	0.53	65,000	0.075
25,000	0.45	70,000	0.059
30,000	0.37	75,000	0.046
35,000	0.31	80,000	0.036
40,000	0.24	85,000	0.028
45,000	0.19	90,000	0.022
50,000	0.15	95,000	0.017
55,000	0.12	100,000	0.014

The two sets of equations for P_{max} provide a discontinuity at 15,000 feet. For that altitude, both should be tried to determine which to use, based on how conservative the calculations need be.

Thermal partition (f), the percentage of the total energy yield which is in the form of thermal radiation, varies with HOB and with total yield. The thermal partition for various combinations is shown in Table 3-3.

TABLE 3-3. Thermal Partition for various explosion yields at different altitudes.

Height of Burst (kilofeet)	Thermal Partition, f				
	Total Yield (kilotons)				
	1	10	100	1,000	10,000
Up to 15	0.35	0.35	0.35	0.35	0.35
20	0.35	0.36	0.39	0.41	0.43
30	0.35	0.36	0.39	0.41	0.43
40	0.35	0.36	0.38	0.40	0.42
50	0.35	0.36	0.38	0.40	0.42
60	0.35	0.37	0.38	0.40	0.42
70	0.36	0.37	0.39	0.40	0.42
80	0.37	0.38	0.39	0.41	0.43
90	0.38	0.39	0.40	0.41	0.43
100	0.40	0.40	0.41	0.42	0.45

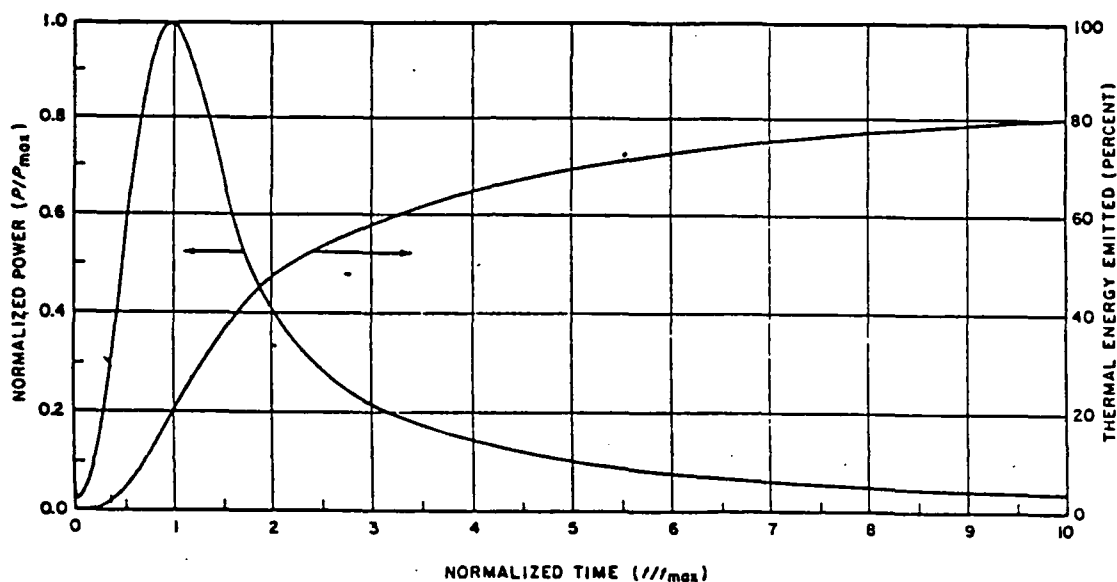
Thermal partition values for heights between 100,000 feet and 160,000 feet are $f = 0.6$. This is due to the fact that high altitude shock waves form less readily in the thinner air and the fireball is able to radiate thermal energy that normally at lower

altitudes would be transferred to hydrodynamic energy of the blast wave.

Above 160,000 feet, thermal x-rays become important and $f = 0.25$ at 200,000 feet and remains at this value up to 260,000 feet. This results from the x-rays traveling greater distances in the thinner air before being absorbed and therefore make no contribution to the energy in the fireball.

Scaled power and time are given as P/P_{max} and t/t_{max} , respectively.

Graph 3-4 is used to predict rate of thermal energy emission and total thermal energy emitted at a given time independent of the yield of the explosion.



**GRAPH 3-4. Normalized power and thermal energy as a function of normalized time.
(For bursts under 100,000 feet.)**

Calculation of the total thermal energy, E_{tot} , generated by a nuclear explosion, can be determined for all cases of burst height by the relationship of:

$$E_{tot} = fW \quad (\text{Eqtn 3-9})$$

Where " f " is the thermal partition function and " W " is the weapon yield.

EXAMPLE 3-2:

GIVEN: A 500KT burst at an altitude of 5,000 feet.

FIND: a) The rate of emission of thermal energy.
b) The total amount of thermal energy emitted at 1 second after the explosion.

SOLUTION:

$$t_{\max} = .0417 W^{0.44} \text{ sec (for bursts under 15,000 feet)}$$
$$= .0417 (500)^{0.44} \text{ sec}$$
$$= 0.64 \text{ sec}$$

$$P_{\max} = 3.18 W^{0.56} \text{ (for bursts under 15,000 feet)}$$
$$= 3.18 (500)^{0.56}$$
$$= 103 \text{ kilotons/sec}$$

a) $t/t_{\max} = 1/0.64 \text{ sec (normalized time)}$

$$= 1.56 \text{ sec}$$

from graph 3-4 at $t/t_{\max} = 1.56$, $P/P_{\max} = 0.59$

$$P = 0.59 P_{\max}$$
$$= 0.59 \times 103 \text{ kilotons/sec}$$
$$= 60.8 \text{ kilotons/sec}$$

Using $1\text{KT} = 10^{12} \text{ cal}$,

$$P = 60.8 \times 10^{12} \text{ cal/sec}$$

b) from thermal partition table (3-3), $f = 0.35$

$$f = E_{\text{tot}}/W$$

$$E_{\text{tot}} = f W = 0.35 (500)$$

$$= 175 \text{ KT}$$

at scaled time = 1.56,

From graph 3-4

$$E/E_{\text{tot}} = 0.40$$

$$E = 0.40 \times 175 = 70 \text{ kilotons}$$

$$= 70 \times 10^{12} \text{ cal}$$

RADIANT EXPOSURE AS A FUNCTION OF DISTANCE

If R = radiant exposure, d = slant range distance from explosion, and E_{tot} = thermal radiation energy, then without attenuation:

$$R = \frac{E_{tot}}{4\pi d^2} \quad (\text{Eqtn 3-10})$$

For attenuation due only to absorption in a uniform atmosphere, the attenuation factor, e^{-Kd} would be multiplied to the quantity R .

Where K = average absorption coefficient, averaged over the whole spectrum of wavelengths. This results in the following equation:

$$R = \frac{E_{tot}}{4\pi d^2} e^{-Kd} \quad (\text{Eqtn 3-11})$$

for an exponential decay with distance.

Addition of scattering causes the attenuation factor to change with distance, visibility, and so on.

By replacing the exponential factor, e^{-Kd} , with τ where τ is a complex function of:

visibility (scattering factor)
absorption
distance

and is given in Graph 3-5 then,

$$R = \frac{E_{tot} \tau}{4\pi d^2} \quad (\text{Eqtn 3-12})$$

since $E_{tot} = f W$

where f = thermal partition,

then,

$$R = \frac{f\tau W}{4\pi d^2} \quad (\text{Eqtn 3-13})$$

and since

$1KT = 10^{12}$ cal,

$$R \text{ (cal/cm}^2\text{)} = \frac{f\tau W (10^{12})}{4\pi d^2} \quad (\text{Eqtn 3-14})$$

Where W is in KT , and d in cm .

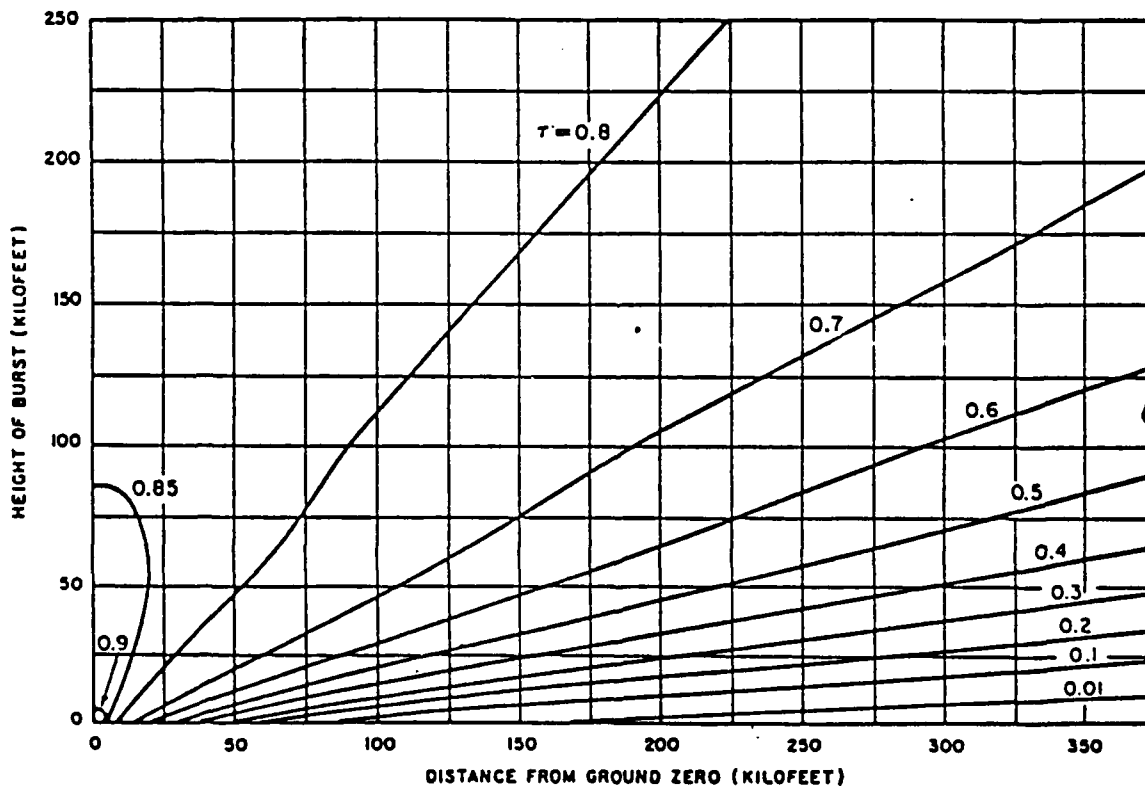
Other forms of this equation are:

$$R \text{ (cal/cm}^2\text{)} = \frac{85.6 f W \tau}{d^2} \quad (d \text{ in kilofeet}), \quad (\text{Eqtn 3-15})$$

and,

$$R \text{ (cal/cm}^2\text{)} = \frac{3.07 f W \tau}{d^2} \quad (d \text{ in miles}). \quad (\text{Eqtn 3-16})$$

Graph 3-5 below, shows transmittance values (τ) for a clear day.



GRAPH 3-5. Transmittance, τ , to a target on the ground (visibility = 12 miles).

EXAMPLE 3-3:

GIVEN:

A 1 MT blast at 28 miles from ground zero when the HOB is 25,000 feet. (Assume a clear day.)

FIND:

Radiant exposure for above.

SOLUTION:

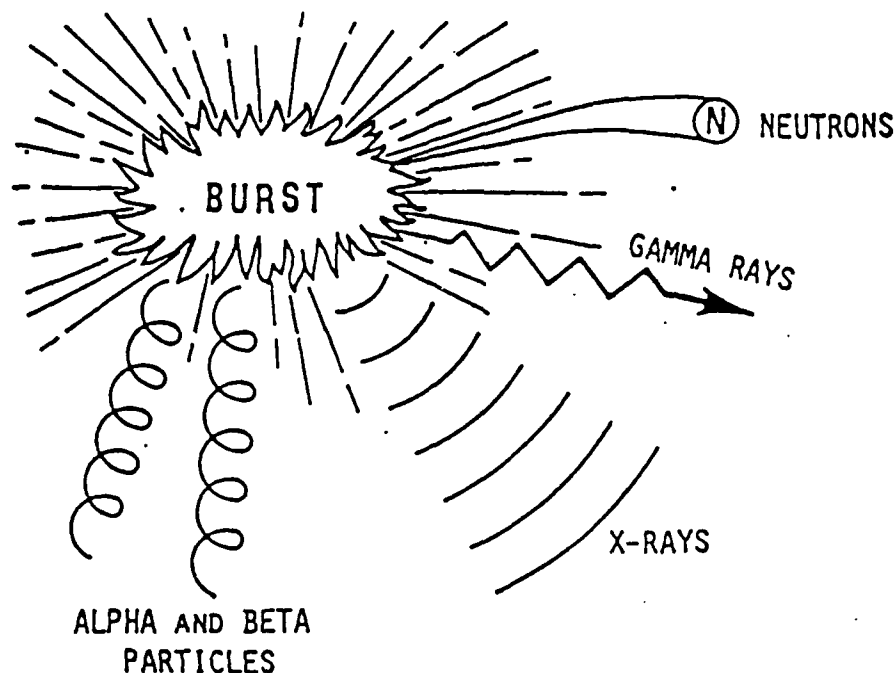
Since the distance is in miles, use Equation 3-16. Next, find the value of the thermal partition, f_0 . This is found in Table 3-3 on page 24, and is 0.41. τ can be found on Graph 3-5, and is 0.4. Putting these values into Equation 3-16 and crunching, the radiant exposure is found to be 0.64 cal/cm².

$$R = \frac{3.07(.41)(1000)(0.4)}{(28)^2} = 0.64 \text{ cal/cm}^2$$

Now, assume the same conditions except set $D = 14$ miles

$$R = \frac{3.07(.41)(1000)(0.64)}{14^2} = 4.11 \text{ cal/cm}^2$$

SECTION 4



NUCLEAR RADIATION

The third form of energy of which a thermonuclear detonation is comprised is nuclear radiation. Nuclear radiation includes: X-rays, gamma rays, alpha and beta particles and neutrons. Because the differences in effects from nuclear radiation are dependent upon time, nuclear radiation is categorized as initial radiation or residual radiation. Initial radiation is that which occurs during the first minute after a detonation, and residual being that which exists beyond the one minute boundary. Each of these are explained separately in the following pages.

INITIAL RADIATION

Invisible, penetrating energy, called "initial radiation" accounts for approximately 3% of the total energy yield. This ionizing radiation is in the form of neutrons, gamma photons, and fission fragments. "Prompt" is used to describe the various radiation elements during the initial radiation period, e.g., prompt neutrons are those neutrons emitted during the first minute after an explosion. The initial radiation is the only portion of nuclear radiation which contributes to the weapon's total energy yield. Residual radiation is not a part of that measurement.

The fission and fusion processes taking place during the explosion generate most of the neutrons and part of the gamma rays. Alpha and beta particles are emitted during the radioactive decay of unfissioned uranium or plutonium or the fragments produced during fission. Alpha and beta particles have such a short range that, generally speaking, they are not considered important in analyzing the nuclear environment threat. X-rays behave much the same as gamma rays, and are therefore not discussed separately.

The gamma rays and neutrons are far reaching and offer the greatest threat to

both electronic and biological systems.

Shielding against gamma rays and neutrons is a more difficult problem than shielding against thermal radiation. Due to the penetrating capabilities of each, the only effective shields would be, in most cases, too thick, bulky, etc. to be practical. As an example, 1 mile from a 1 MT blast, a 24 inch concrete barrier would far exceed the requirement for shielding against thermal radiation, but would pass enough nuclear radiation to be a lethal dose to humans behind the barrier. The effects of both of these radiation forms will be discussed separately.

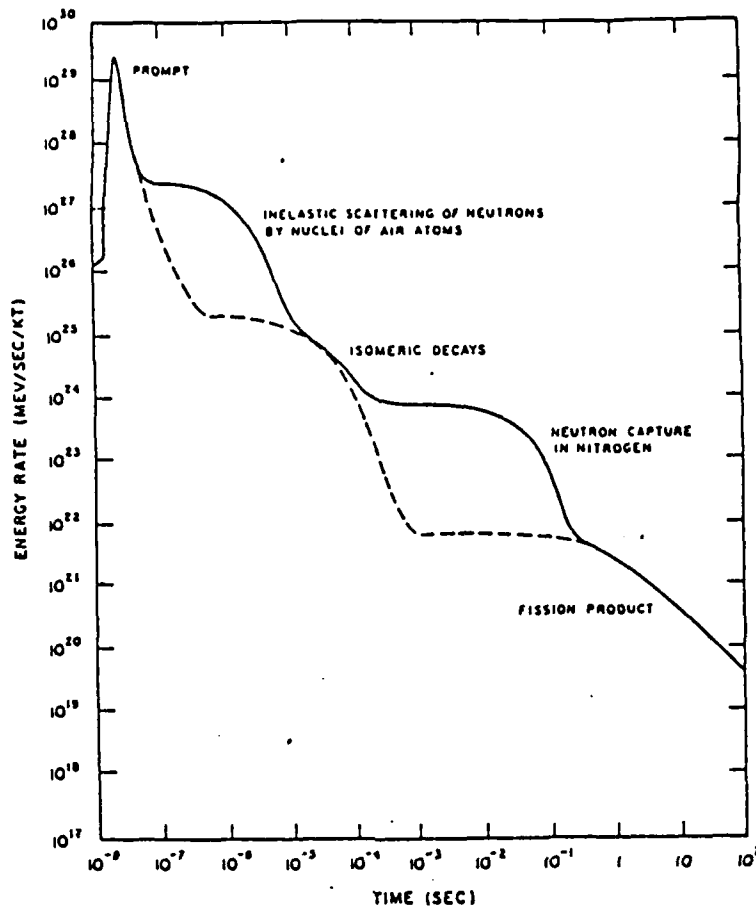
GAMMA RAYS

A large percentage of the prompt gammas developed during the explosion are absorbed by the weapon material residue and only about 1 percent manage to get beyond the blast area. However, there are other sources for the gamma rays that are a part of initial nuclear radiation. One of these "other sources is due to a neutron striking the nucleus of some non-fissionable material which leaves that nucleus in a high energy state. As that nucleus attempts to return to a stable state, the excess energy is thrown off as gamma radiation. This neutron capture process yields what is termed "capture gamma rays." The process is called radiative capture.

A second source also involves the collision of a neutron with a nucleus, but in this case, the neutron is a "fast" neutron or one having a high level of kinetic energy. Instead of neutron capture, the neutron merely transfers a portion of its energy to the nucleus, leaving the nucleus in an excited state. Once again, the energy is released from the nucleus in the form of gamma radiation. This process is known as inelastic scattering. Inelastic scattering can take place with nuclei in the weapon material or in the air.

Gamma rays are also produced through the natural radioactive decay of some of the "excited" fragments resulting from the fission reaction.

There is a time dependence of the gamma ray production which is related to the various half-lives of the radionuclides. Graph 4-1 shows a predicted rate of gamma energy production as a function of time. The solid line curve is for an atmospheric burst where there would be more interaction with air and nitrogen. The dotted line curve shows the absence of those interactions such as might be experienced in a very high (exoatmospheric) burst.



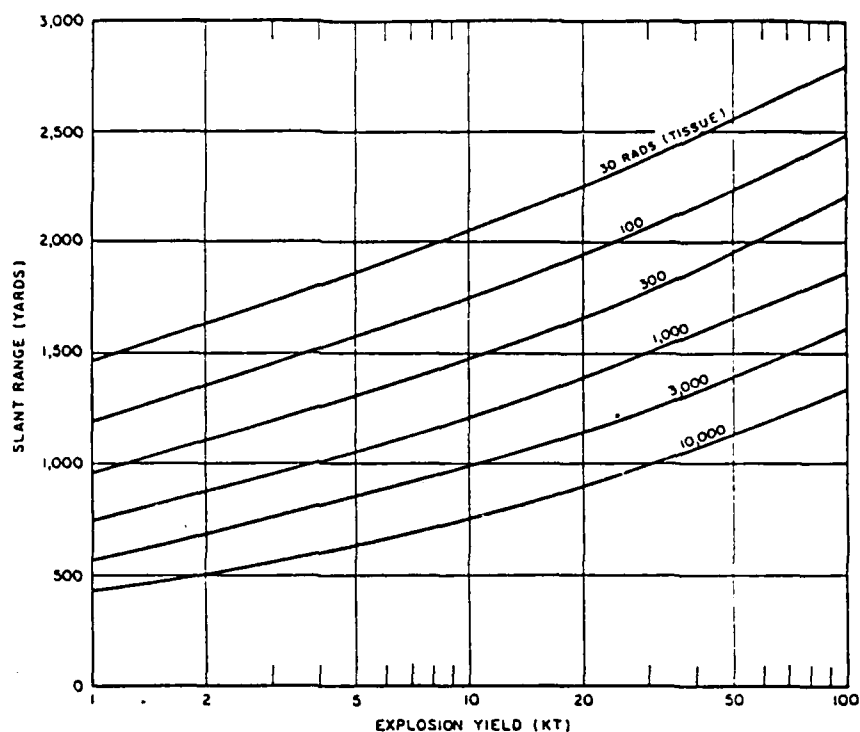
GRAPH 4-1. Predicted gamma-ray energy, per kiloton yield, as a function of time.

In addition to time, gamma ray dose is dependent upon weapon yield and distance. As with thermal radiation, the dose will decrease with distance from the blast, according to the inverse square law, simply because of the larger area of coverage. Attenuation due to scattering and absorption also applies to gamma radiation.

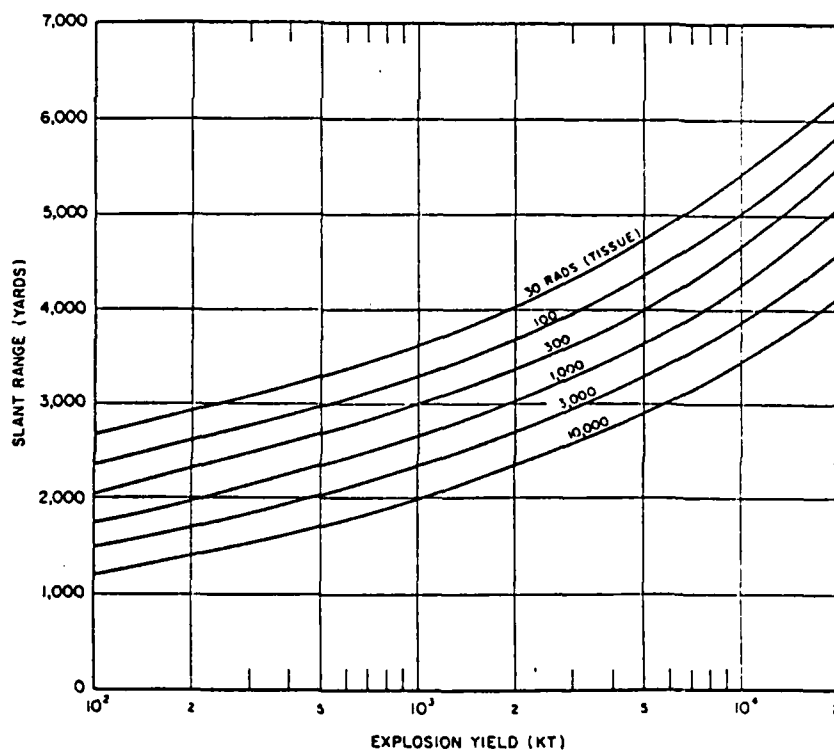
Testing and measurement of gamma radiations and computer calculations of the results have provided enough data to predict gamma doses as a function of weapon yield and distance from the detonation. Graph 4-2 shows various dose curves for an air burst fission device as related to slant range and yield (in kilotons). Graph 4-3 shows the same information for a 50% fission, thermonuclear device.

The sharp increase is due to the sustained low air density following the passage of the positive phase of the shock wave, particularly for explosions of high energy yields.

Both of these graphs are based on an air density equal to 90% of normal sea level value. Gamma dose will increase or decrease, according to any deviations from air density as calculated.



GRAPH 4-2. *Slant ranges for specified gamma-ray doses for targets near the ground.*



GRAPH 4-3. *Slant ranges for specified gamma-ray doses for targets near the ground from a thermonuclear weapon with 50% fission.*

SHIELDING AGAINST GAMMA RAYS

Shielding or attenuation against gamma radiation from a nuclear explosion does not follow the tenth-value thickness concept. The tenth value thickness is that thickness of material needed to attenuate the radiation to one tenth of its original value. This is due to the fact that the gamma-ray energies cover too wide a range and are spread out over a very large area. The most accurate way of estimating attenuation is the use of an effective tenth-value thickness. Some materials of interest in radiation shielding are shown in Table 4-1. Notice the thickness of any material required to decrease the nitrogen capture gamma rays to one-tenth the original value is about 50% greater than for the fission product gamma rays; this is because the former have considerably higher energy.

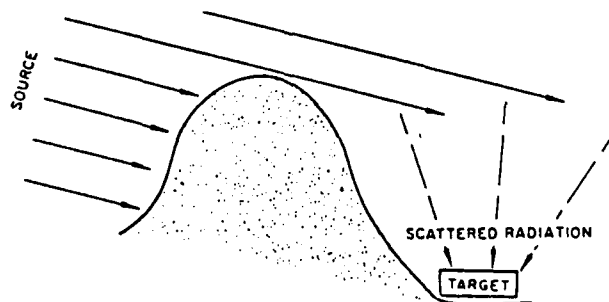
APPROXIMATE EFFECTIVE TENTH-VALUE THICKNESSES FOR FISSION PRODUCT AND NITROGEN CAPTURE GAMMA RAYS

Material	Density (lb/cu ft)	Fission Product		Nitrogen Capture	
		Tenth- Value Thickness (inches)	$D \times T$ (lb/sq ft)	Tenth- Value Thickness (inches)	$D \times T$ (lb/sq ft)
Steel (Iron)	490	3.3	135	4.3	176
Concrete	146	11	134	16	194
Earth	100	16	133	24	200
Water	62.4	24	125	39	201
Wood	40	38	127	63	210

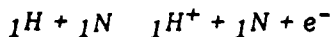
TABLE 4-1. Approximate effective tenth-value thickness for fission product and nitrogen capture gamma rays.

An estimate of the protection that can be provided by a particular shield between the radiation source and the target must take a number of considerations into account. These include the energy distribution of the gamma radiation falling on the shield, the angle of incidence, and the geometry of the shielding material. This is best accomplished by the usage of computer methods and applications and is beyond the scope of this text.

The fact that gamma rays can reach a target from directions other than that of the burst point has an important bearing on the problem of shielding. This particular phenomena of scattered radiation is called "sky shine" and is illustrated in Figure 4-1. To provide adequate protection a shield must be designed to protect against radiation from all directions.

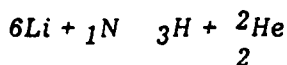


Target exposed to scattered gamma radiation.



This interaction with hydrogen (or with any substance containing hydrogen) can cause indirect ionization or excitation to occur.

Neutrons in the low to moderate speeds can produce ionization and excitation indirectly by combining (capture) with lighter isotopes.



SHIELDING AGAINST NEUTRONS

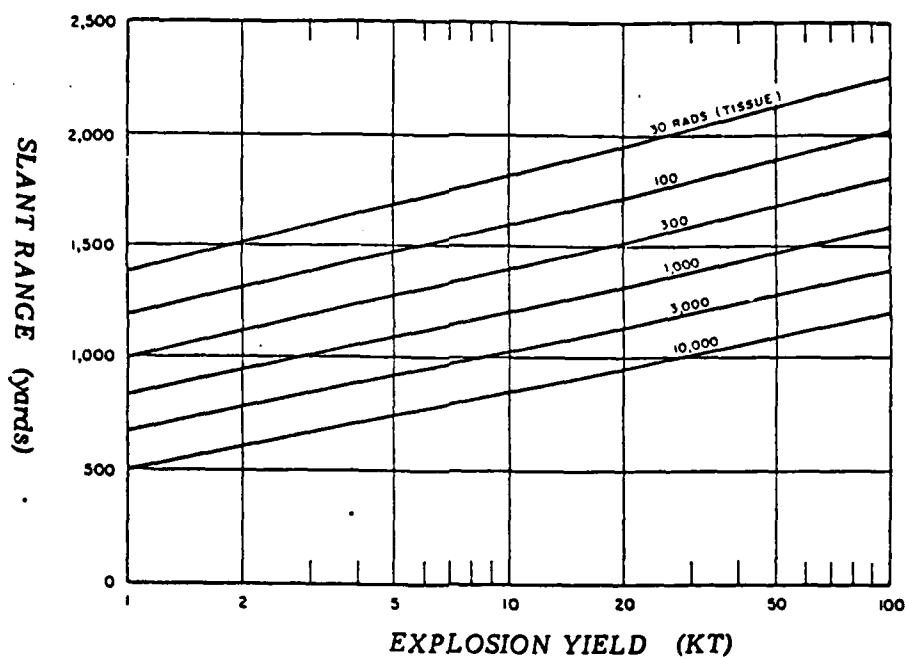
Neutron shielding is a different and more difficult problem than shielding against gamma rays. As discussed earlier, by placing a sufficient mass of material between the gamma ray source and the target, a good reduction in dosage can be obtained. However, this method is not quite as satisfactory for neutron shielding. First, the very fast neutrons must be slowed down into the moderately fast range. This requires a suitable (inelastic) scattering material, such as barium or iron. Then, the moderately fast neutrons have to be decelerated (by elastic scattering) into the slow range by means of a low atomic weight element. Water is useful in this respect since hydrogen and oxygen have low atomic weights. The slow thermal neutrons must then be absorbed, which hydrogen within the water could accomplish. However, inelastic scattering reactions of neutrons and most neutron captures result in the emission of gamma rays which must be accounted for in the overall shielding scheme.

Estimates of the shielding by various structures are given in terms called a dose transmission factor, which is the ratio of the dose received behind the shield to the dose at the same location in the absence of shielding (see Table 4-2).

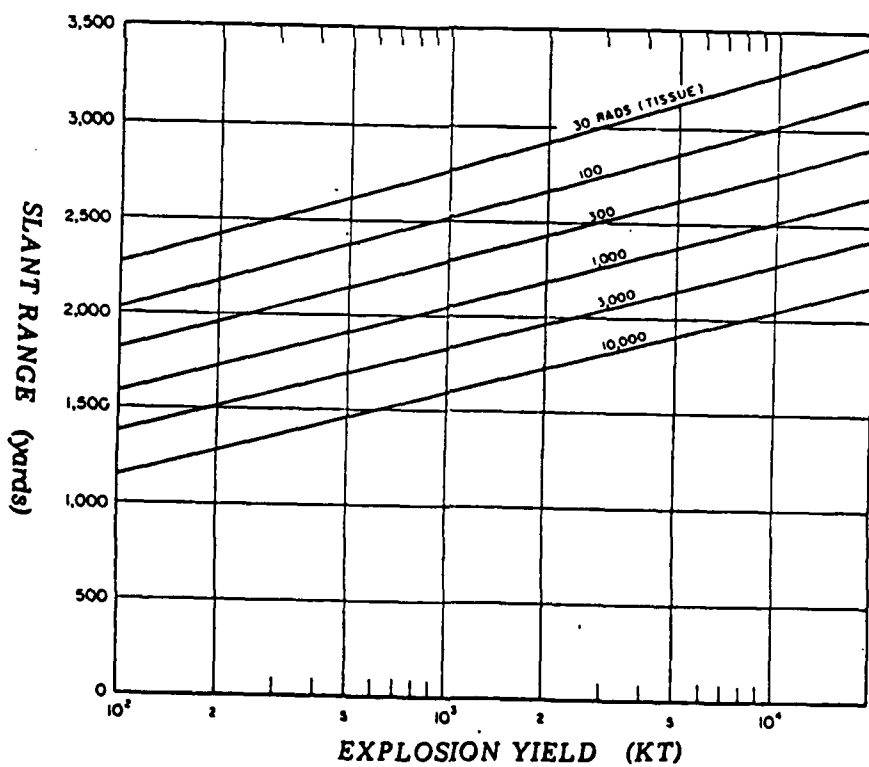
Structure	Initial Gamma Rays	Neutrons
Three feet underground	0.002-0.004	0.002-0.01
Frame House	0.8-1.0	0.3-0.8
Basement	0.1-0.6	0.1-0.8
Multistory building (apartment type):		
Upper stories	0.8-0.9	0.9-1.0
Lower stories	0.3-0.6	0.3-0.8
Concrete blockhouse shelter:		
9-in. walls	0.1-0.2	0.3-0.5
12-in. walls	0.05-0.1	0.2-0.4
24-in. walls	0.007-0.02	0.1-0.2
Shelter, partly above grade:		
With 2 ft earth cover	0.03-0.07	0.02-0.08
With 3 ft earth cover	0.007-0.02	0.01-0.05

TABLE 4-2. Dose transmission factors for various structures.

Once again, the inverse square law, absorption, scattering, and weapon yield become



GRAPH 4-4. *Slant ranges for specified neutron doses for targets near the earth.*



GRAPH 4-5. *Slant ranges for specified neutron doses for targets near the ground for thermonuclear weapons.*

factors in the rate of neutron dose. Graphs 4-4, and 4-5 give approximations of neutron doses as a function of distance from the blast and the energy yield of the blast. The first, is for a low air-burst from a fission device. The second is for a thermonuclear device with 50% fission. Each is based on a 90% sea-level air density.

It is evident that the actual number of neutrons emitted per kiloton of explosion yield, as well as their energy distribution, may differ not only for weapons of different types (fission, fusion), but also for weapons of the same kind. Therefore, these curves that indicate the variation of neutron dose with yield and distance cannot be correct for all situations and reliability factors should be taken into account.

Graphs 4-4 and 4-5 may be applied to air bursts directly. For contact surface burst, the prompt neutron dose may be taken as one half the value for a corresponding air burst. For HOB below 300 feet, the dose may be interpolated between the values for an air burst and a contact surface burst.

INITIAL RADIATION DOSE

Various methods have been found to be effective in predicting initial radiation dose with reasonable accuracy. The total initial radiation dose is composed of three types of radiation: neutron (D_n), secondary gamma D_{γ_s} , and fission products gamma (D_{γ_f}). Some example problems with accompanying graphs are included on the following pages. All of these assume a .9 normal sea-level air density and low air burst.

This first radiation dose graph, (Graph 4-6), is a prediction of initial neutron dose for a fission weapon. It is scaled to a 1 kiloton burst and a HOB of 300 feet or higher. For a contact surface burst, one in which the device is detonated on the ground, a correction factor of 0.5 is required. For heights between 0 and 300 feet, interpolation of the scaling factor should be made.

EXAMPLE 4-1:

GIVEN:

A 10 KT fission weapon is exploded at a height of 300 feet.

FIND:

The neutron dose at a slant range of 1,500 yards that is conservative from the defensive standpoint.

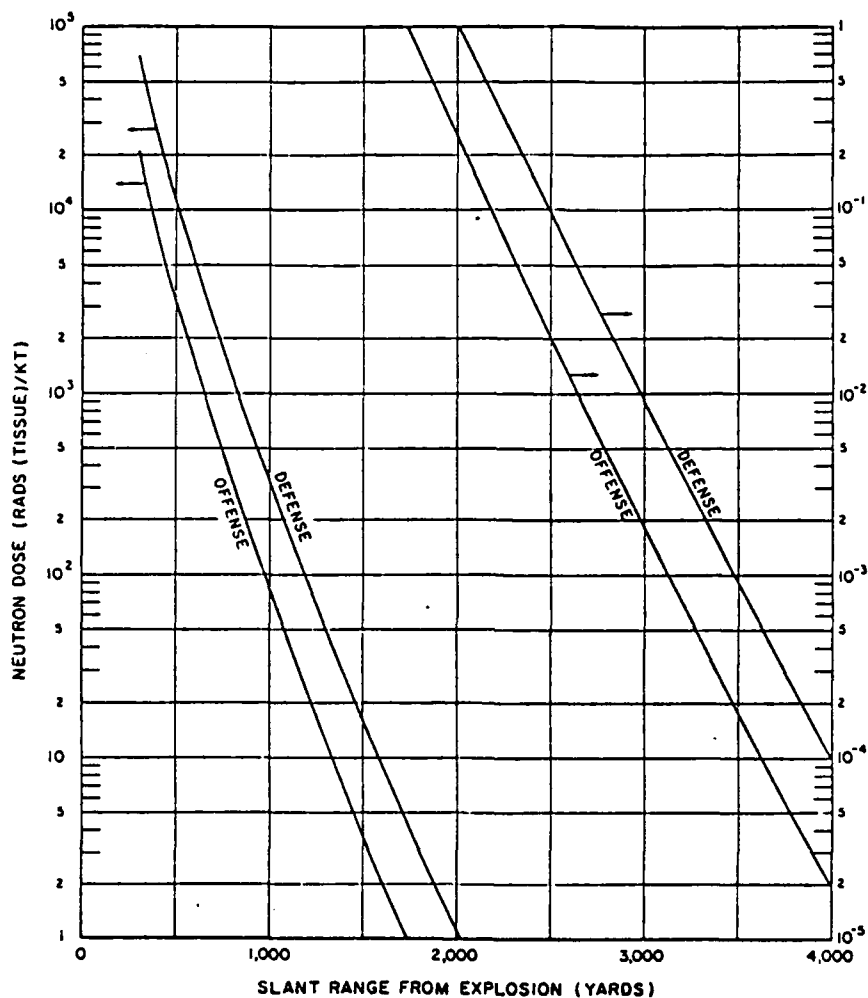
SOLUTION:

Since the height of burst is 300 feet, no height correction is necessary. From the upper ("defense") curve in Graph 4-6, the neutron dose per kiloton yield at a slant range of 1,500 yards from an explosion is 16 rads. The corresponding dose, D , from a 10 KT explosion is then 10 times the amount:

$$D = 10 \times 16 = 160 \text{ rads. (tissue)}$$

for $h < 300$ a correction factor must be used.

for $h = 0$ the correction factor is 0.5.

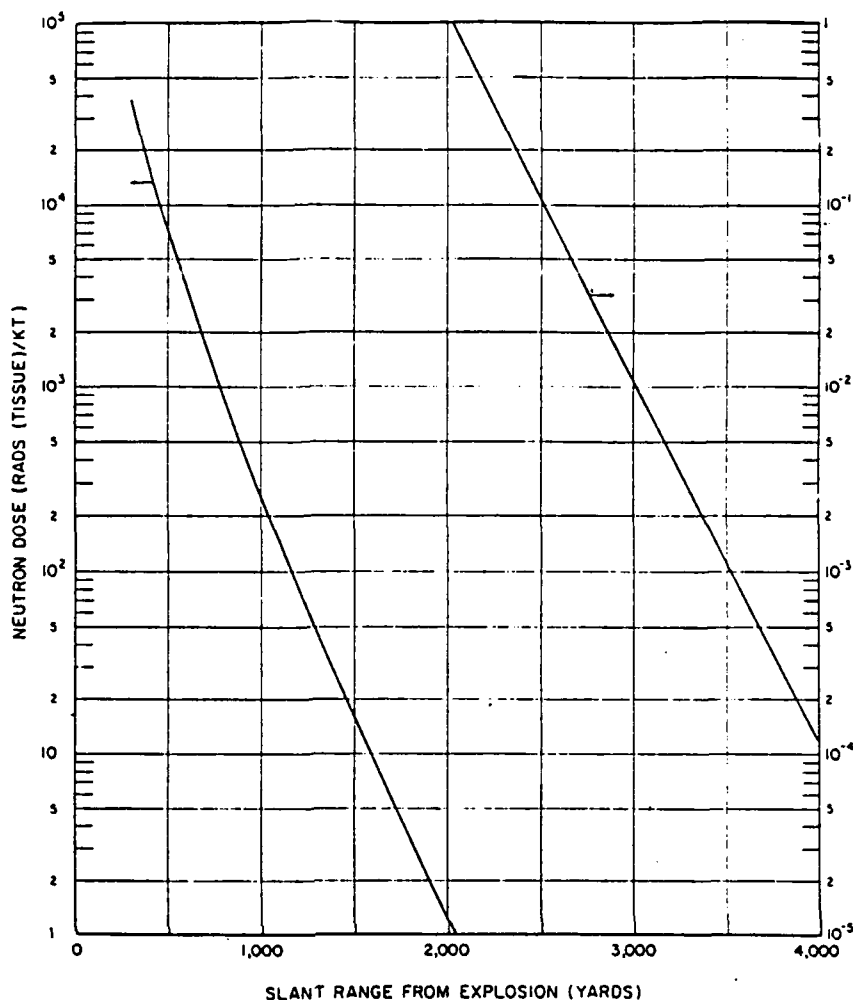


GRAPH 4-6. Initial neutron dose per kiloton from fission device.

It is suggested that the upper curve be used to obtain a conservative estimate of the neutron dose from fission weapons for defensive purposes and that the lower curve be used for a conservative estimate for offensive purposes.

For a contact surface burst, the values in Graph 4-6 and 4-7 should be multiplied by 0.5 and can be linearly interpolated to HOB of 300 feet where the exact graph value can be used.

The next graph is also a prediction of initial neutron dose. The only difference is that Graph 4-7 is for a 50% fission thermonuclear device.



GRAPH 4-7. Initial neutron dose per kiloton from a thermonuclear device.

The following example, and graphs 4-8 and 4-9 are used for finding the secondary gamma contribution to initial radiation dose. They are also scaled to 1KT and 300 feet.

EXAMPLE 4-2:

GIVEN:

A 20 KT fission weapon is exploded on the surface (contact surface burst).

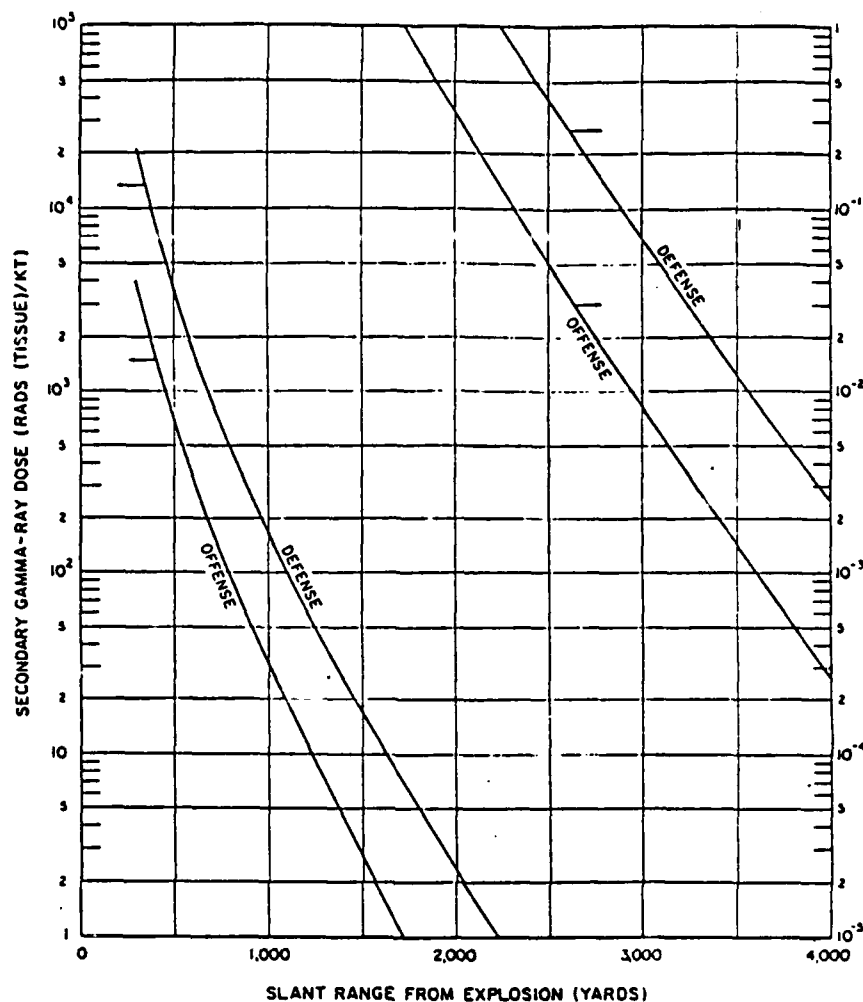
FIND:

The secondary gamma-ray dose at a slant range of 1,000 yards that is conservative from the offensive standpoint.

SOLUTION:

Since this is a contact surface burst, a correction factor of 0.5 must be applied to the value obtained from graph 4-8. From the lower ("offense") curve in Graph 4-8, the secondary gamma-ray dose per kiloton yield at a slant range of 1,000 yards from an explosion at or above 300 feet is 30 rads. The corresponding dose, *D*, from a surface burst 20 KT explosion is:

$$\begin{aligned}
 D(\text{total dose}) &= 20\text{KT} \times 0.5 \times 30 \text{ rads.} \\
 &= 300 \text{ rads.}
 \end{aligned}$$



GRAPH 4-8. Air-secondary gamma-ray component of initial radiation as a function of slant range for a fission weapon.

The third factor in initial radiation dose, fission product gamma dose, is calculated as using graphs 4-10 and 4-11, or 4-12.

Graph 4-11 is used to find the effective yield of a low air fission weapon. Graph 4-12 is for a surface burst. The effective yield is then used with graph 4-10 to find the fission product gamma-ray component.

EXAMPLE 4-3:

GIVEN:

A 20 KT fission weapon is exploded on the surface (contact surface burst).

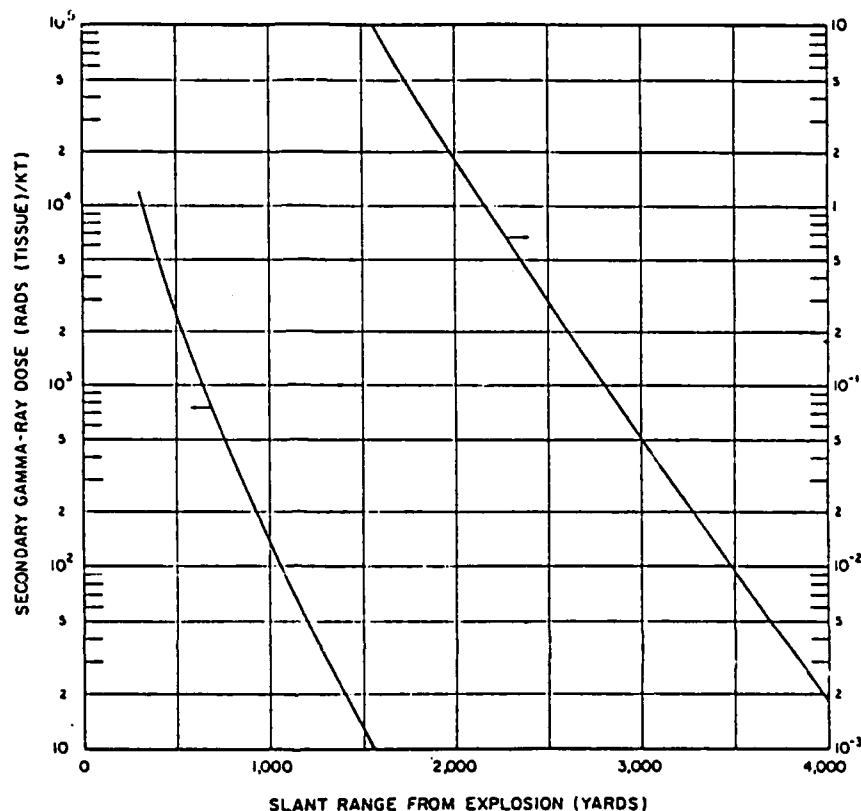
FIND:

The fission product gamma-ray dose at a slant range of 1,000 yards.

SOLUTION:

From Graph 4-10, the initial radiation, fission product gamma-ray dose per kiloton yield at a slant range of 1,000 yards is 75 rads. From Graph 4-12, the effective yield at a slant range of 1,000 yards from a 20 KT explosion on the surface is 45 KT. The fission product gamma-ray dose for the desired conditions is therefore:

$$D(\text{total dose}) = 75 (\text{rads}) \times 45\text{KT} = 3,375 \text{ rads.}$$



GRAPH 4-9. Air-secondary gamma-ray component from a thermonuclear weapon.

This example requires that all three contributing factors, neutron dose, fission product gamma dose, and secondary gamma dose, be calculated to determine total initial radiation dose. Bear in mind that a great deal of assumptions are being made, such as: 90% normal sea level air density, gamma dose and neutron dose equivalence, etc. The quantities derived from these predictions must be recognized as only approximations. Accuracy is in the range of "predicted dose -50%/+100%."

EXAMPLE 4-4:**GIVEN:**

A 1 MT thermonuclear weapon with 50 percent of its energy yield derived from fission is exploded at a height of 3,200 feet.

FIND:

The total initial nuclear radiation dose at a slant range of 4,000 yards.

SOLUTION:

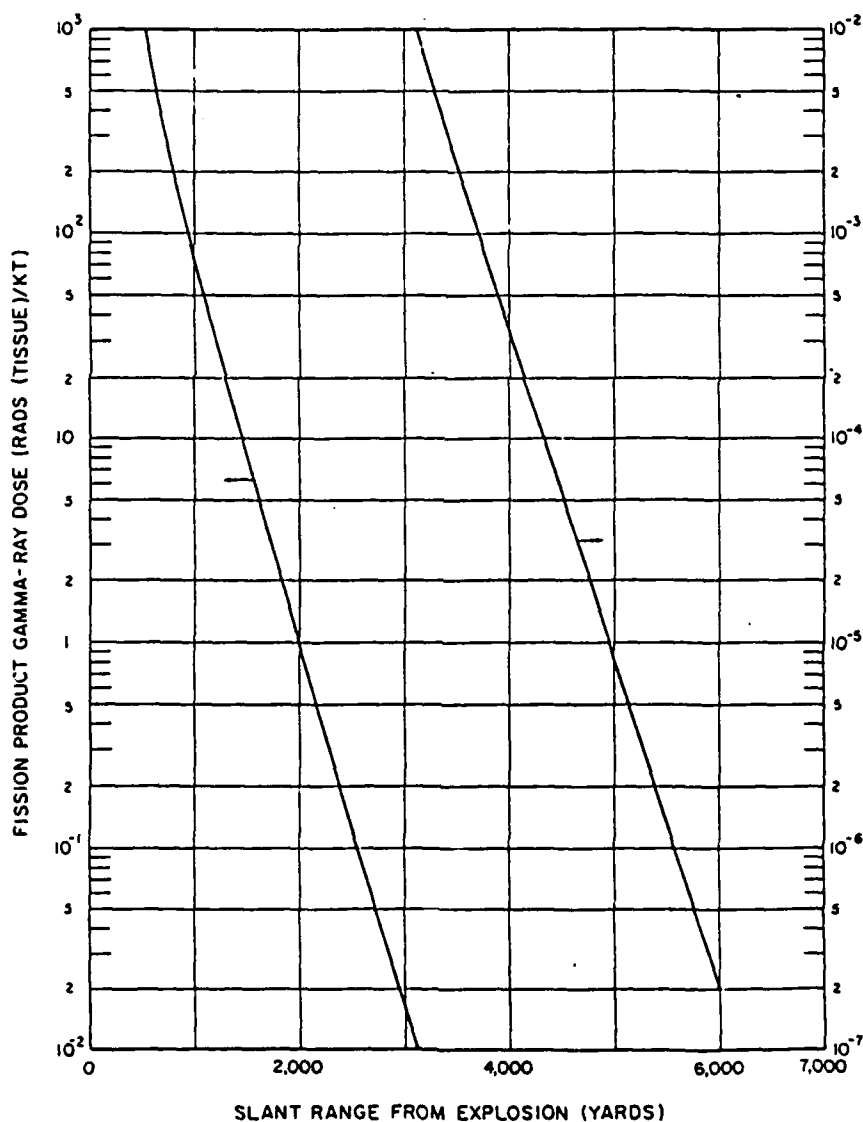
The total initial nuclear radiation dose is the sum of the initial neutron dose, the secondary gamma-ray dose, and the fission product gamma-ray dose. From graph 4-7, the neutron dose per kiloton yield, is 1.2×10^{-4} rad at a slant range of 4,000 yards from a low air burst.

The corresponding dose from a 1 MT explosion is:

$$D_1 = 1.2 \times 10^{-4} \times 10^3 = 0.12 \text{ rad.}$$

From Graph 4-9, the secondary gamma-ray dose per kiloton yield is 1.8×10^{-3} rad at a slant range of 4,000 yards from a low air burst. The corresponding dose from a 1 MT explosion is:

$$D_1 = 1.8 \times 10^{-3} \times 10^3 = 1.8 \text{ rads.}$$



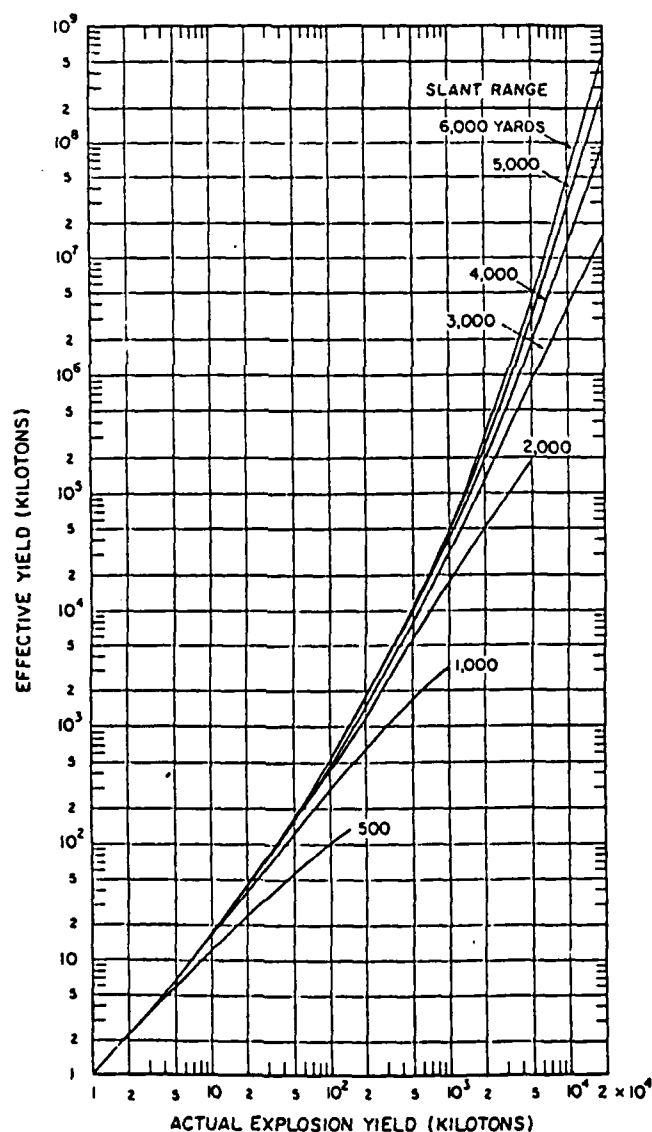
GRAPH 4-10. Fission product gamma-ray component of initial radiation dose as a function of slant range.

From Graph 4-10, the fission product gamma-ray dose per kiloton fission yield at a slant range of 4,000 yards from the explosion is 3.2×10^{-4} rad. The height of burst, 3,200 feet, is sufficiently close to the scaled height of $200 W^{0.4}$, i.e., 3,170 feet, that graph 4-11 should provide an accurate value of the effective yield. From graph 4-11, the effective yield at a slant range of 4,000 yards from a low air burst 1 MT explosion is 4×10^4 KT (or 40 MT). Since only 50 percent of the total yield is derived from fission, a correction factor of 0.5 must be applied. The fission product gamma-ray dose is:

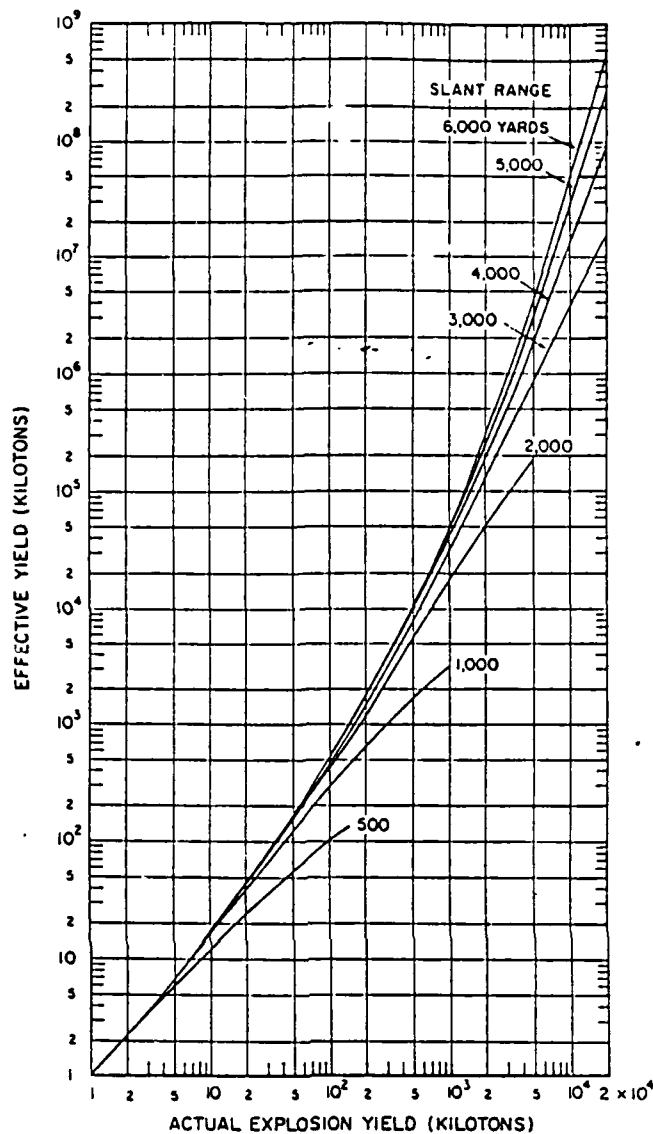
$$D_2 = 0.5 \times 3.2 \times 10^{-4} \times 4 \times 10^4 = 6.4 \text{ rads.}$$

The total initial nuclear radiation dose is:

$$\begin{aligned} D &= D_0 + D_1 + D_2 \\ &= 0.12 + 1.8 + 6.4 \\ &= 8.3 \text{ rads.} \end{aligned}$$



GRAPH 4-11. Effective yield as a function of actual yield for the fission product gamma-ray dose for a low air burst.



GRAPH 4-12. Effective yield as a function of actual yield for a surface burst.

RESIDUAL RADIATION

Residual radiation, commonly called "fallout," is similar to initial radiation, but includes the radioactive substances remaining for an extended period of time after a nuclear explosion. This time period is usually considered to begin at about one minute after the instant of explosion. These substances include the residue from the materials of the bomb plus dirt, water, and other particles near the explosion which become radioactive from exposure. The radioactive fallout is such that wind currents carry it over long distances and their effects may be felt at distances well beyond the range of the other effects of a nuclear explosion.

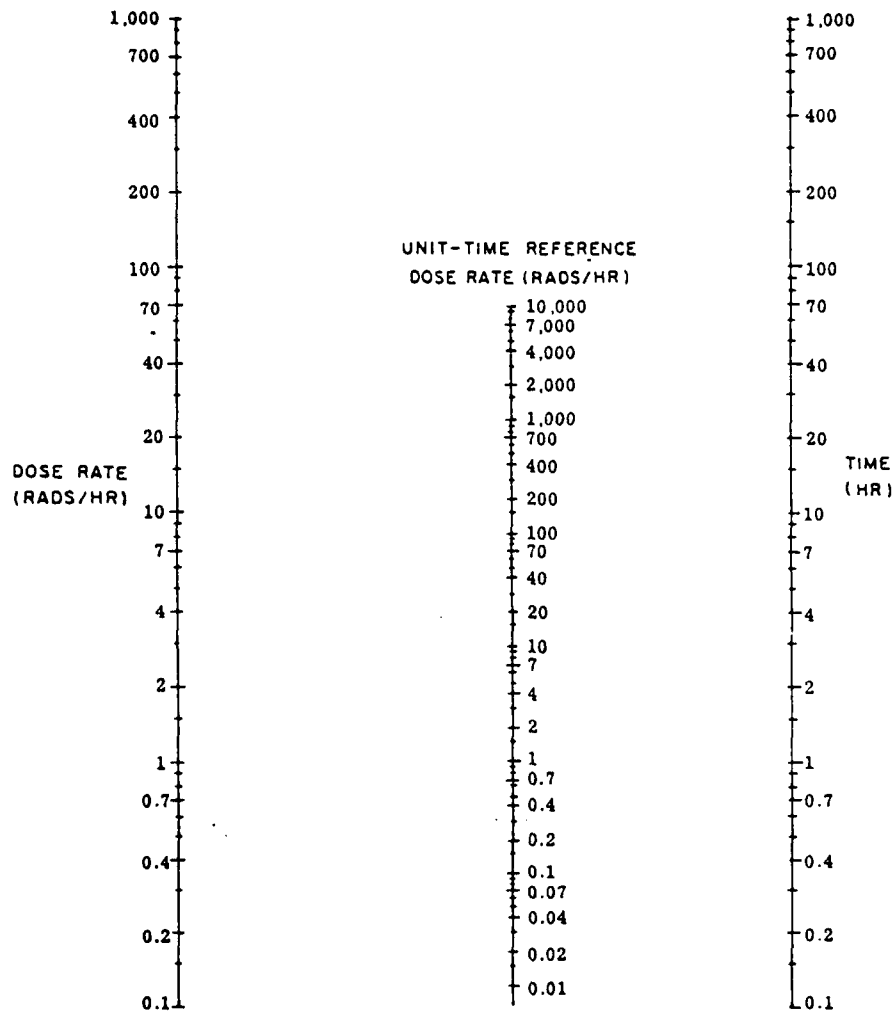
The primary concern with nuclear radiation is the rate of exposure, and the "total dose" accumulated over a period of time.

DOSE

Dose refers to the amount of absorbed ionizing radiation. The unit of measurement

for dose is the rad. One rad is the measure of absorption of 100 ergs of radiation per gram of absorbing substance and 1 erg is equal to 10^7 Joules. Dose rate is the amount of absorbed radiation per unit time commonly referred to as rads per hour.

A dose rate nomograph can be used for calculating approximate dose rates, given that a unit-time reference value is known. A dose rate nomograph is shown in Graph 4-13, below:



GRAPH 4-13. Dose Rate Nomograph.

EXAMPLE 4-5:

GIVEN:

A dose rate is known to be 8 rads per hour, 6 hours after a nuclear explosion.

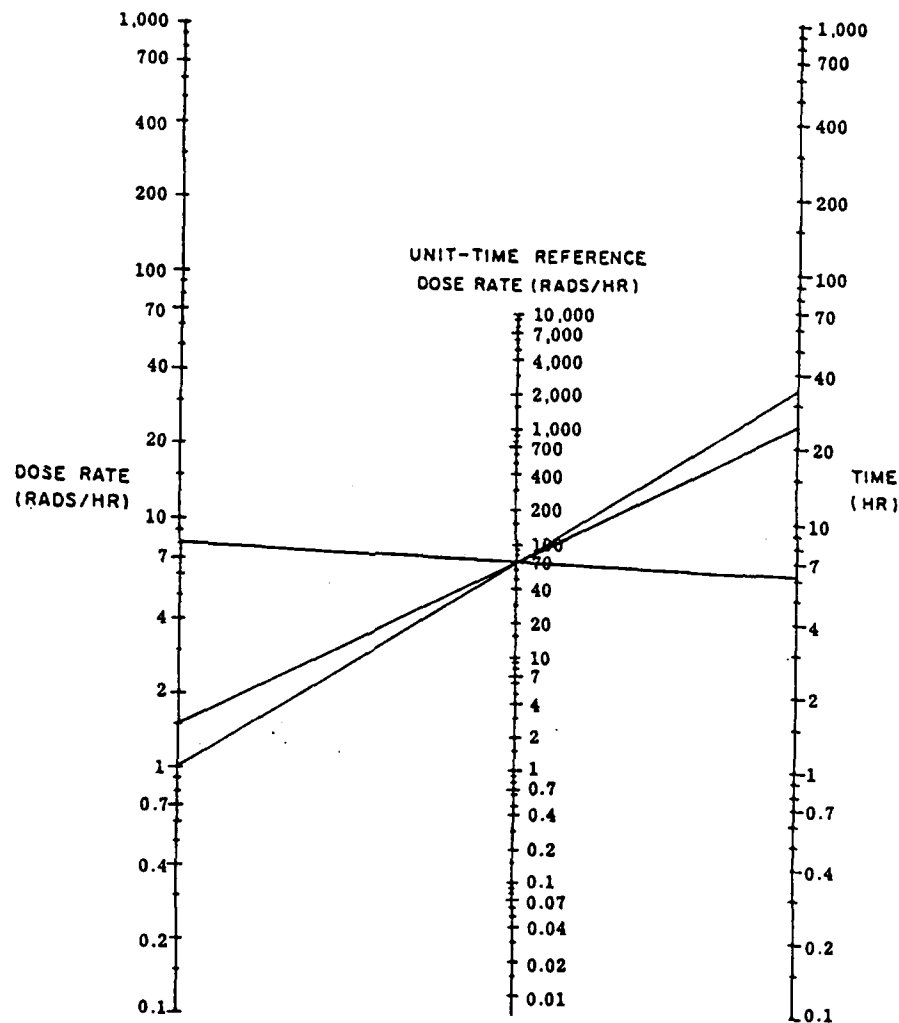
FIND:

- (a) the dose rate 24 hours after the burst.
- (b) the time after the burst at which the dose rate is 1 rad/hour.

SOLUTION:

First, establish the unit-time reference dose rate on the nomograph

by connecting the "8" on the dose rate line with the "6" on the time line with a straight line. The reference number as read from the unit-time reference dose rate line is "69." To find the dose rate 24 hours after the burst, draw another straight line from "24" on the time line, through the reference "69," and across to the dose rate line. Read "1.5" as the dose rate at the point of intersection. A third straight line from 1 rad/hr., through reference "69" and to the time line. Where the intersection occurs, read 34 hours.

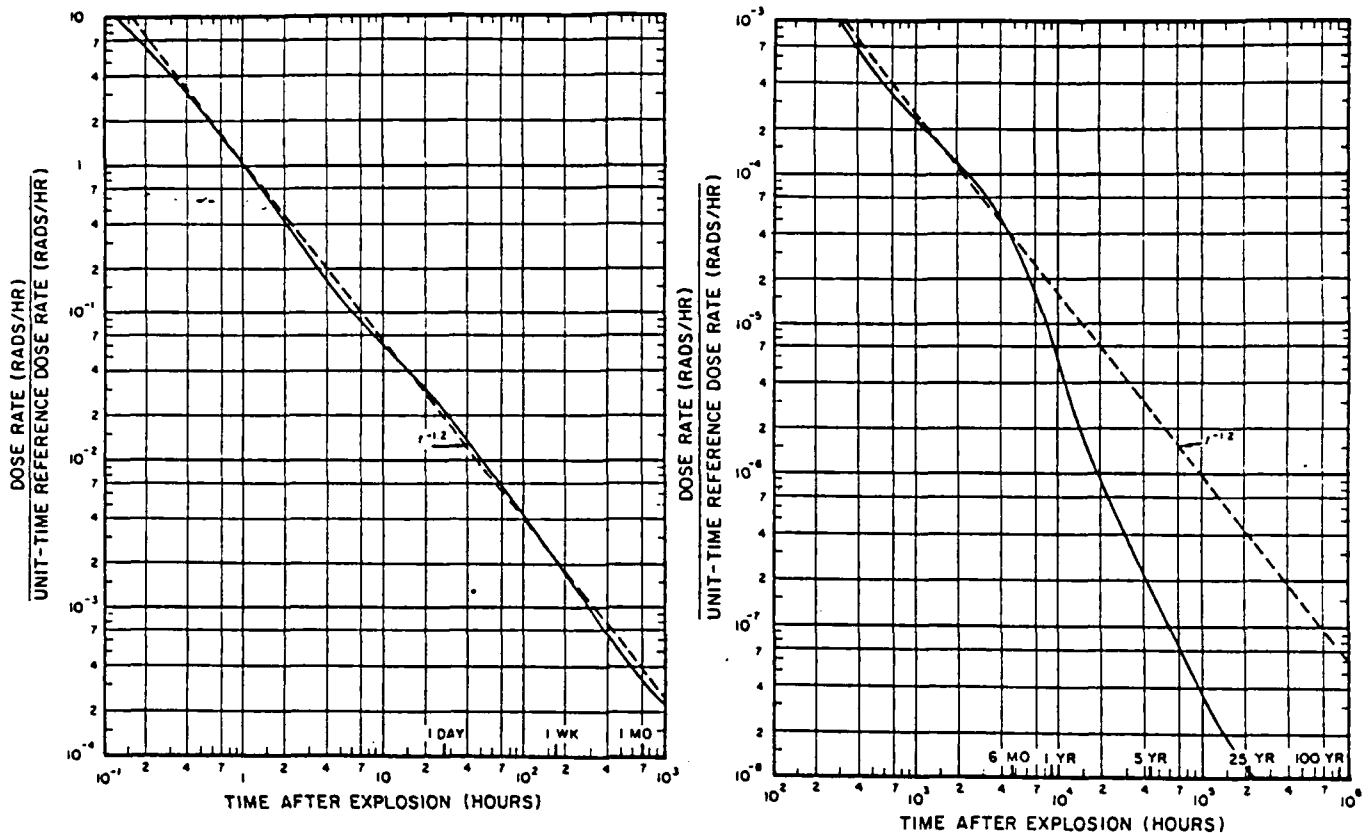


GRAPH 4-14. Dose Rate Nomograph.

DELAY OF RADIATION

Graphs 4-15 and 4-16 show the time dependence of the exposure dose rate. The first graph covers the period of time between one tenth of an hour and 1000 hours following a detonation. The second graph covers 100 hours through 1 million hours (roughly 115 years). There are two curves shown on the graphs. The solid line shows the predicted rate based on complex calculations which is not within the scope of this text. The dashed

line is just a straight line approximation from $Kt^{-1.2}$ where "K" is the normalized rate at 1 hour after the explosion and "t" is the time, in hours, following the explosion.



GRAPHS 4-15 and 4-16. Time dependence of nuclear radiation dose rate.

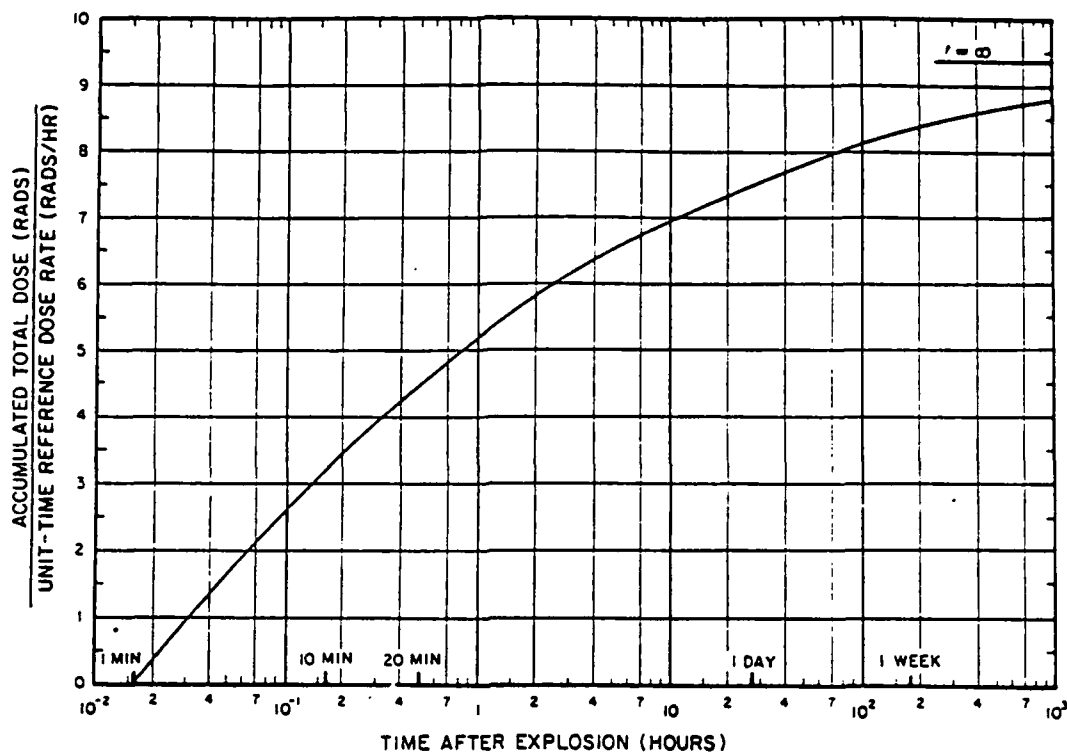
Each curve in these graphs uses a unity factor for $t = 1$ hour. The value read from the graph for a given time would therefore be a multiplier for the actual dose rate at one hour after the explosion. It can be seen on Graph 4-16 that the straight line approximation does not fall off as rapidly as the more closely approximated curve starting at about the four month time frame.

Another way to approximate the dose rate is called the "sevenfold rule." It states that for each multiple of seven hours from the explosion time, a decade decrease in dose rate will occur. The following equation shows this expression:

$$K_n = 0.1^n K_0 \text{ when } t = 7^n \text{ hours} \quad (\text{Eqtn 4-1})$$

Where K_0 is the dose rate at one hour after explosion, K_n is the new dose rate, and $n = 1, 2, 3 \text{ \& } 4$. For time, $t = 7^n$ hours.

The next graph (Graph 4-17) is used in conjunction with Graphs 4-15 and 4-16 to calculate the total dose accumulated over a given period of time after entering a contaminated area.



GRAPH 4-17. Curve for calculating total accumulated dose.

In order to use this graph, the dose rate at the time of entering the contaminated area and the length of stay must both be known.

To explain the use of this graph, the following example will be calculated:

EXAMPLE 4-6:

GIVEN:

Suppose an individual becomes exposed to a certain quantity of radiation 2 hours after a nuclear explosion and the dose rate, measured at that time, is found to be 1.5 rads/hr.

FIND:

The total dose accumulated during the subsequent 12 hours, i.e., by 14 hours after the explosion? The first step is to determine the unit-time reference dose rate. From Graph 4-15 it is seen that:

SOLUTION:

$$\frac{\text{Dose rate at 2 hours after explosion}}{\text{Unit-time reference dose rate}} = 0.40$$

and, since the dose rate at 2 hours is known to be 1.5 rads/hr, the reference value is $1.5/0.40 = 3.8$ rads/hr. Next, from Graph 4-17, it is found that for 2 hours and 14 hours, respectively, after

the explosion:

$$\frac{\text{Accumulated dose at 14 hours after explosion}}{\text{Unit-time reference dose rate}} = 7.1$$

$$\frac{\text{Accumulated dose at 2 hours after explosion}}{\text{Unit-time reference dose rate}} = 5.8$$

Hence, by subtraction:

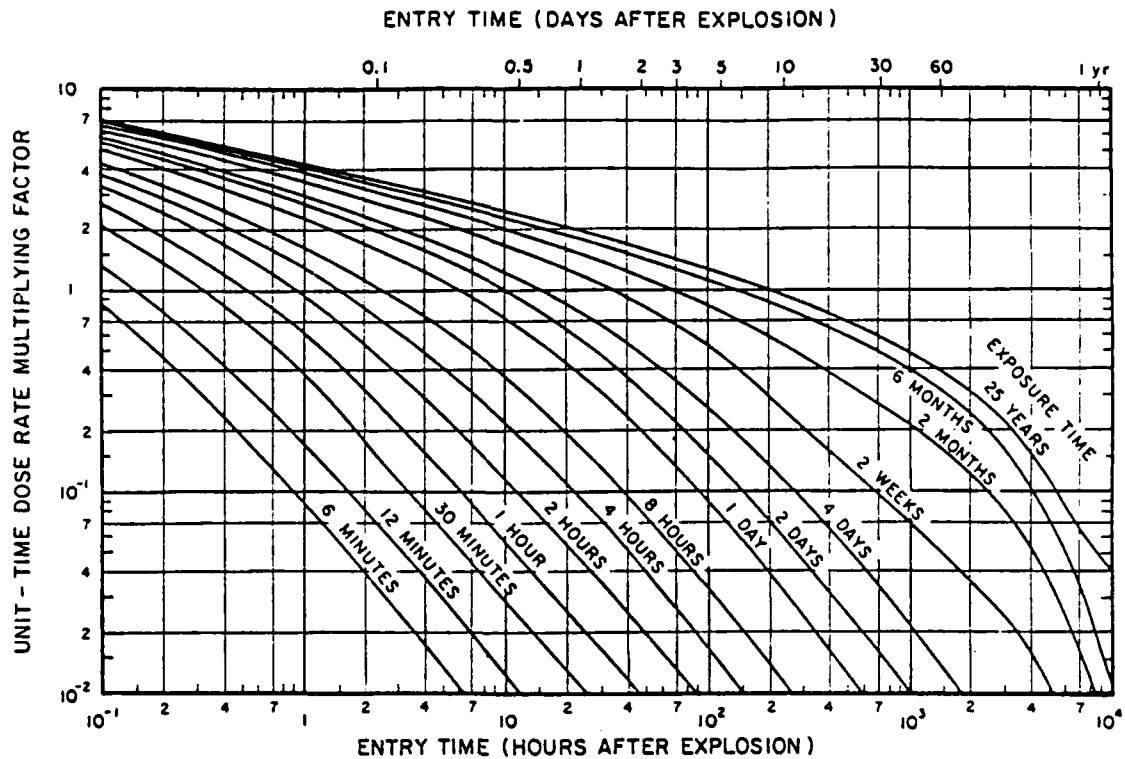
$$\frac{\text{Accumulated dose between 2 and 14 hours after explosion}}{\text{Unit-time reference dose rate}} = 1.3$$

$$7.1 - 5.8 = 1.3$$

The unit-time reference dose rate is 3.8 rads/hr, and so the accumulated dose received in the 12 hours, between 2 and 14 hours after the explosion, is $3.8 \times 1.3 = 4.9$ rads.

The total accumulated radiation dose received from early fallout during any specified exposure in a contaminated area can be estimated if the dose rate at some definite time after the explosion is known. Also, the time can be calculated for commencing an operation requiring a specified stay in a defined total radiation dose.

On the following pages, examples are provided to illustrate the use of two additional graphs (Graphs 4-18 and 4-19) for calculating total radiation dose.



GRAPH 4-18. Curves for calculating total accumulated dose, based on unit-time reference dose rate.

EXAMPLE 4-7:

GIVEN:

The dose rate at 1 hours after a nuclear explosion is 6 rads/hr.

FIND:

- (a) The total accumulated dose received during a period of 2 hours commencing at 6 hours after the explosion.
- (b) The time after the explosion when an operation requiring a stay of 5 hours can be started if the total dose is to be 4 rads.

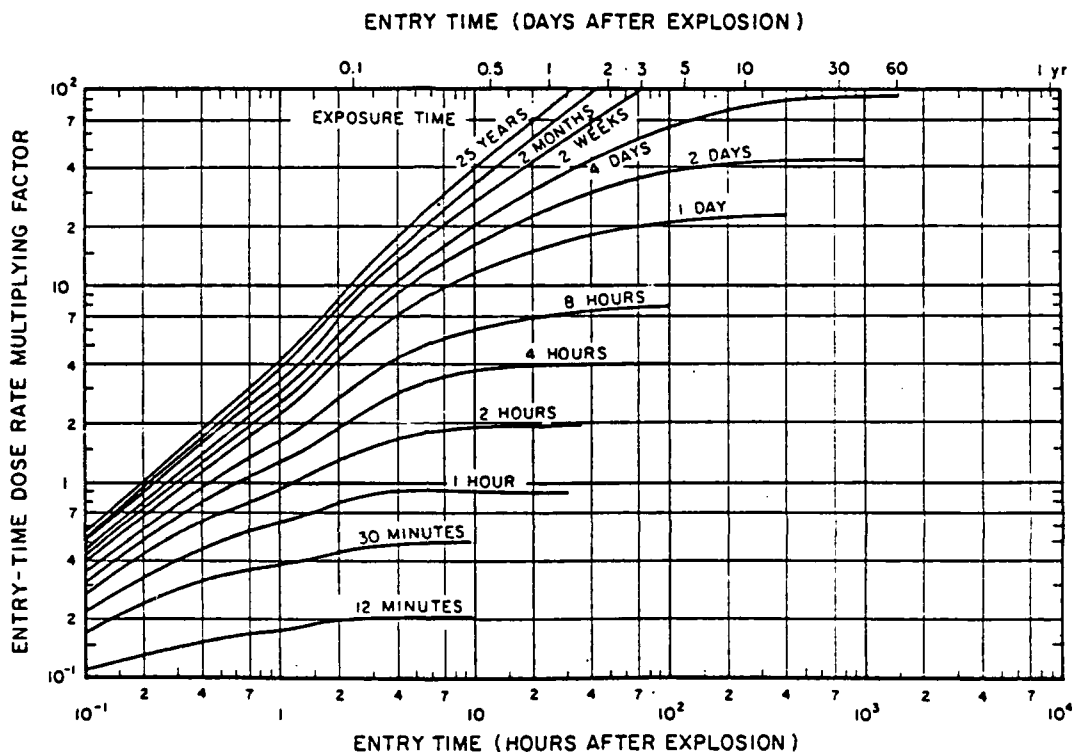
SOLUTION:

The first step is to determine the unit-time reference dose rate (R_1). From Graph 4-13, a straight line connecting 6 rads/hr on the left scale with 4 hours on the right scale intersects the middle scale at 32 rads/hr; this is the value of R_1 .

- (a) Enter Graph 4-18 at 6 hours after the explosion (horizontal scale) and move up to the curve representing a time of stay of 2 hours. The corresponding reading on the vertical scale, which gives the multiplying factor to convert R_1 to the required total dose, is seen to be 0.19. Hence, the accumulated dose is:

$$0.19 \times 32 = 6.1 \text{ rads.}$$

- (b) Since the accumulated dose is given as 4 rads and R_1 is 32 rads/hr, the multiplying factor is $4/32 = 0.125$. Entering Graph 4-18 at this point on the vertical scale and moving across until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the horizontal scale, giving the time after the explosion, is seen to be 21 hours.



GRAPH 4-19. Curves for calculating total accumulated dose, based on dose rate at time of entry.

It is essential to understand that the tables and figures given above, and the calculations of radiation dose rates, and doses in which they are used, are based on the assumption that a target is exposed to a certain quantity of early fallout and remains exposed continuously (without protection) to this same quantity for a period of time. In an actual fallout situation, these conditions probably would not exist. Shelters would attenuate radiation and weather conditions will disperse fallout particles in some areas and concentrate them in others. Therefore, there may be a change in the quantity of fallout at a given location during the time of exposure.

EXAMPLE 4-8:

GIVEN:

Upon entering a contaminated area at 12 hours after a nuclear

explosion, the dose rate is 5 rads/hr.

FIND:

- (a) The total accumulated radiation dose received for a stay of 2 hours.
- (b) The time of stay for a total accumulated dose of 20 rads.

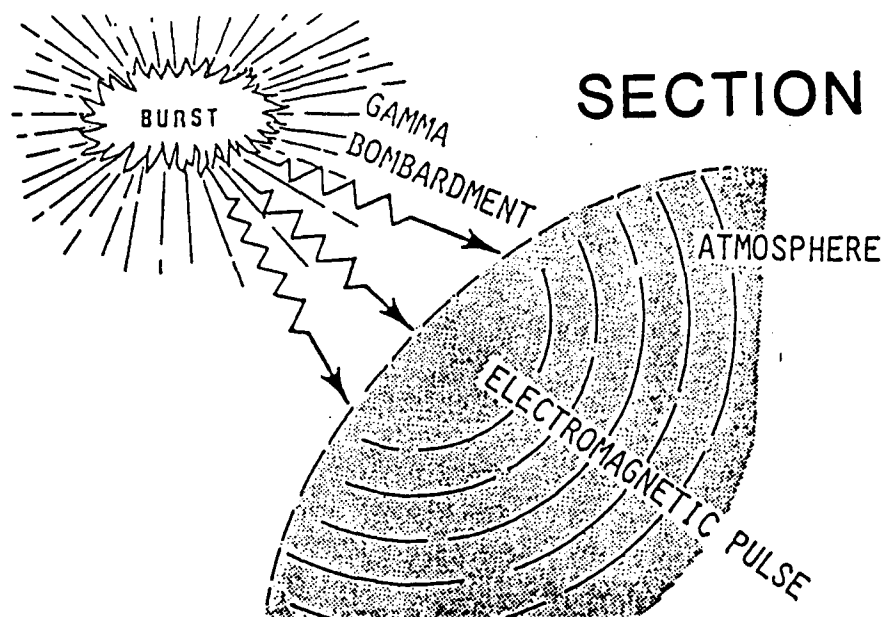
SOLUTION:

- (a) Start at the point on Graph 4-19 representing 12 hours after the explosion on the horizontal scale and move up to the curve representing a time of stay of 2 hours. The multiplying factor for the dose rate at the time of entry, as read from the vertical scale, is seen to be 1.9. Hence, the total accumulated dose received is:

$$1.9 \times 5 = 9.5 \text{ rads.}$$

- (b) The total accumulated dose is 20 rads and the dose rate at the time of entry is 5 rads/hr; hence, the multiplying factor is $20/5 = 4.0$. Enter Graph 4-19 at the point corresponding to 4.0 on the vertical scale and move horizontally to meet a vertical line which starts from the point representing 12 hours after the explosion on the horizontal scale. The two lines are found to intersect at a point indicating a time of stay of about $4\frac{1}{2}$ hours.

SECTION 5



BASIC ELECTROMAGNETIC THEORY

In order to better grasp the sections to follow, a very brief, general discussion of electromagnetic field theory is required. There are basically only 4 topics that need to be reviewed; vectors, electric fields, magnetic fields, and the combined electromagnetic fields.

VECTORS

A vector is a quantity that has both magnitude and direction associated with it. This differs from the scalar, in that the scalar only describes the magnitude of properties, and is independent of the direction. Vectors are geometrically represented by arrows, whose length indicates magnitude and whose orientation indicates direction. They can be represented in any coordinate system, but for this text will only be presented in the cartesian coordinate system. Vectors may be separated into individual components, each showing one coordinate direction and its corresponding magnitude. Vectors are useful in simplifying the abstraction associated with the behavior of electromagnetic fields.

ELECTRIC FIELDS

In 1784, Augustine de Coulomb studied the interacting forces between two point charges. By moving a "test point charge" about a fixed charge, he could measure exerted forces on the test charge. The well known phenomenon can be explained by stating that within a vicinity of any charge, there exists a medium of electric field. This electric field exerts forces on charges within the field, in proportion to the magnitude of charges, and inversely proportional to the square of distance between them.

The electric field is said to exist at a point, if a force of electrical origin is exerted on a stationary charged body placed at that point.

Michael Faraday introduced the concept of field lines to represent the electric field. The field lines are imaginary lines drawn in such a way that their direction at any point is the same as the direction of the field at that point. The magnitude of the field is proportional to the number of field lines per unit area crossing a surface at right angles to the direction of the field.

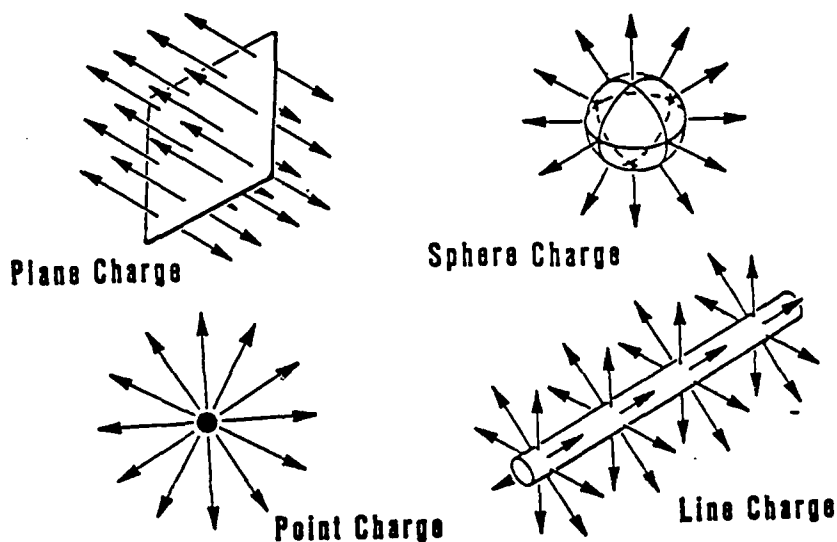


FIGURE 5-1. Electric Field Lines.

The electric field is generally expressed in terms of volts/meter, and will be the only expression used in this text. (Newtons/Coulomb is an acceptable unit used in other texts.) The field strength can be explained by imagining two point charges with a 1 volt potential difference separated by one meter. (See Figure 5-2.) These two charges create an electric field of one volt per meter (1V/m). Although a single point charge creates an electric field, there must be additional charge located where the field is to be measured. The field varies with distance R depending on the charge distribution. For the spherical and point charge cases, it varies as $1/R^2$. For the line charge case it varies as $1/R$. However, for the infinite planar charge the field is independent of the distance from the charged plane and does not decrease inversely with the square of the distance. As the charge producing the field increases, the intensity of the field increases, as does the force exerted on other charges in the field.

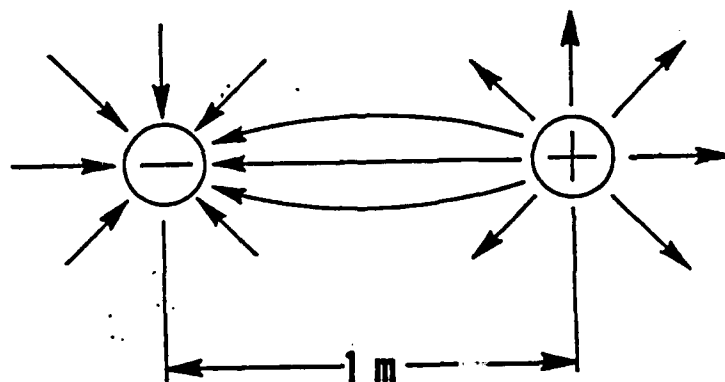


FIGURE 5-2. Electrical Field of 1 V/M

The electric fields associated with a nuclear explosion are tremendous and very harmful when coupled to electrical systems. The coupling methods will be presented later in the text, as well as procedures to protect against unwanted coupling.

MAGNETIC FIELDS

The first magnetic phenomena observed, were those associated with naturally occurring magnets; fragments of iron ore found near the ancient city of Magnesia (thus the term "magnet"). These natural magnets attracted pieces of unmagnetized iron at very pronounced regions of the magnet, later named the poles.

As early as 121 A.D., the Chinese discovered that iron rods brought close to a natural magnet would maintain the characteristics of the magnet, and would align themselves in a North-South direction.

Moreover, the use of magnets as aids to navigation has been found as early as the eleventh century. It wasn't, however, until 1819 that the study of the magnetic phenomena was accelerated. In that year, the Danish scientist, Hans Christian Oersted, observed that a pivoted magnet (a compass) was deflected in the presence of a wire carrying current. Twelve years later, the English physicist, Michael Faraday, found that a momentary current existed in a circuit, while the current in a nearby circuit was being started or stopped. Soon afterward, it was discovered that the motion of a magnet toward or away from the circuit would produce the same effect.

Oersted demonstrated that magnetic effects could be produced by moving electric charges, while Faraday showed that currents could be produced by moving magnets.

It is now known that magnetic fields, as well as electric fields are set up by charges in motion. Magnetic fields are generally considered to be composed of flux lines (as are electric fields), and their intensity is determined by the number of flux lines per unit area. Although the magnetic lines of flux do not exist in any tangible form, they do have a direction that can be determined at any point in space. (See Figure 5-3.) The earth has magnetic flux lines extending from the North magnetic pole, near the North geographic pole, to the South magnetic pole, near the South geographic pole. These flux lines are called the geomagnetic field lines.

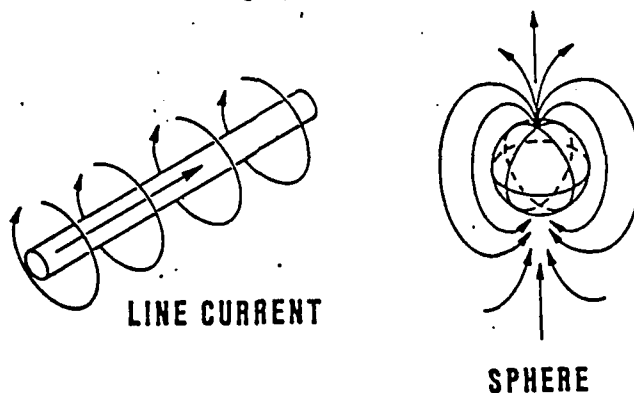


FIGURE 5-3. Magnetic Field Lines.

The importance of magnetic fields, in the context of this text, is that they induce currents on wires when a relative motion exists between the field and the wire. It is independent of which media moves, the field or the wires. (See Figure 5-4) This is a very important phenomenon in the study of electromagnetic pulse coupling (which will be discussed in great detail later).

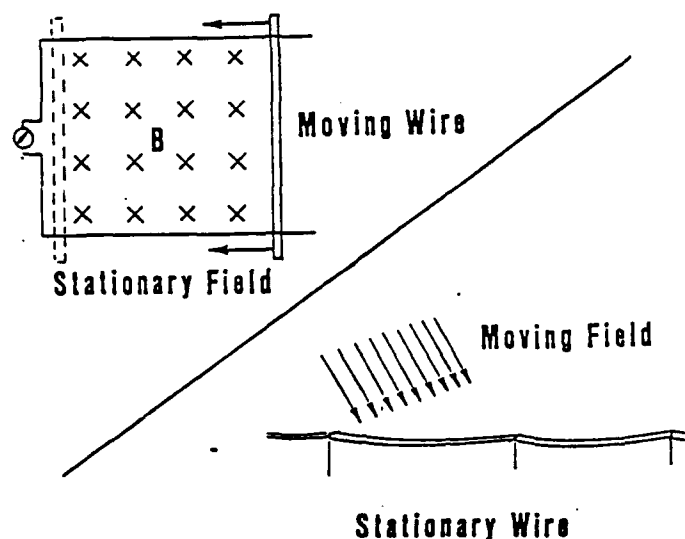


FIGURE 5-4. Relative motion induces currents.

ELECTROMAGNETIC FIELDS

An electromagnetic field is a combination of electric and magnetic fields, with the electric lines of force perpendicular to the magnetic lines of force at all points in space. (See Figure 5-5.) As this "plane wave" propagates through space, it moves in a direction perpendicular to both the electric and magnetic components.

Propagating electromagnetic fields are produced when charged particles are subjected to acceleration. The most familiar example of an accelerating charged particle, is an electron in a conductor carrying an alternating current. Since the electron's velocity is constantly changing, a fluctuating magnetic field is generated, resulting in a propagating electromagnetic field outward from the conductor. The frequency of the field is the same as the frequency of the alternating current in the conductor.

Radiated electromagnetic fields will be considered to be plane waves in the remainder of this text. A plane wave is simply a propagating field, which is uniform over any plane, perpendicular to the direction of propagation.

There are many forms of an electromagnetic field, from visible light and infrared rays, to gamma rays, x-rays, radio waves, and the major concern of this text, electromagnetic pulse from a nuclear explosion.

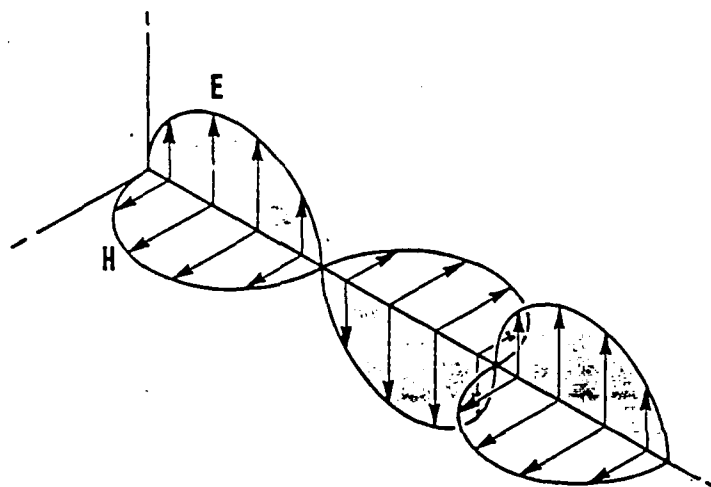


FIGURE 5-5. Electromagnetic Fields.

GENERAL THEORY

The electromagnetic pulse (EMP) is a very harmful and often little noticed effect of a nuclear detonation. It is roughly comparable to the electromagnetic fields associated with lightning, but with several significant differences. It is a narrow pulse with a very fast rise time (generally a few nanoseconds), while a lightning pulse is much wider (2 orders of magnitude), and has a slower rise time (approximately 1-5 microseconds). EMP is on the order of 50,000 V/m, while lightning is roughly 100 to 1000 V/m, and the area of coverage from EMP is very large and capable of covering the entire United States, where that of a lightning strike is confined to a small, localized area.

Operating regions for the purpose of EMP analysis are categorized as: Ground, lower atmosphere (less than 20 km), upper atmosphere (20-50 km), and exoatmosphere (greater than 50 km).

MAJOR DIFFERENCES BETWEEN LIGHTNING AND ELECTROMAGNETIC PULSE

ELECTROMAGNETIC PULSE

Narrow Pulse (1 to 2 microseconds)
Very fast rise time (nanoseconds)
Large amplitudes (50,000
volts/meter)
Large area of coverage (possibly
entire U.S.)
Large frequency spectrum

LIGHTNING

Wide pulse (hundreds of microseconds)
Slow rise time (1 to 5 microseconds)
Small amplitudes (100 to 1000
volts/meter)
Small area of coverage (very localized
area)
Small frequency spectrum

EMP can have a very harmful effect, even at altitudes where there are no other appreciable weapon effects. In fact, the most harmful EMP comes from high altitude bursts where the blast, shock, and thermal radiations are unnoticeable on the earth.

EMP is most harmful to devices which use integrated circuits, semiconductors, or other solid state circuitry. Digital computers, intercom systems, and electronic sensors are but a few of those devices. Devices which use vacuum tubes and inductors, rather than solid state electronics are much less susceptible to the EMP, but can still be damaged. Power supplies and transmitters or receivers fall into this category. Also somewhat susceptible are devices which use low current switches, relays, and meters, such as: life support systems, panel indicators, status boards, and power distribution systems, all of which can be found to some extent on Military aircraft. Many devices, however, are not susceptible to EMP. These include those devices which are designed for high power, high current operation, such as transformers, and motors. These devices are capable of withstanding the EMP without any added protection.

DEGREE OF SUSCEPTIBILITY TO EMP

<u>VERY SUSCEPTIBLE</u>	<u>NOT AS SUSCEPTIBLE</u>	<u>NOT SUSCEPTIBLE</u>
DEVICES THAT USE:	DEVICES THAT USE:	DEVICES THAT USE:
- INTEGRATED CIRCUITS - SEMICONDUCTORS OTHER SOLID STATE COMPONENTS	- VACUUM TUBES AND INDUCTORS - LOW CURRENT SWITCHES - LOW CURRENT RELAYS AND METERS	- HIGH CURRENT/HIGH POWER OPERATION, SUCH AS TRANSFORMERS AND MOTORS

EMP from a nuclear detonation is divided into the following three regions: burst, source, and radiating. (See Figure 5-6.)

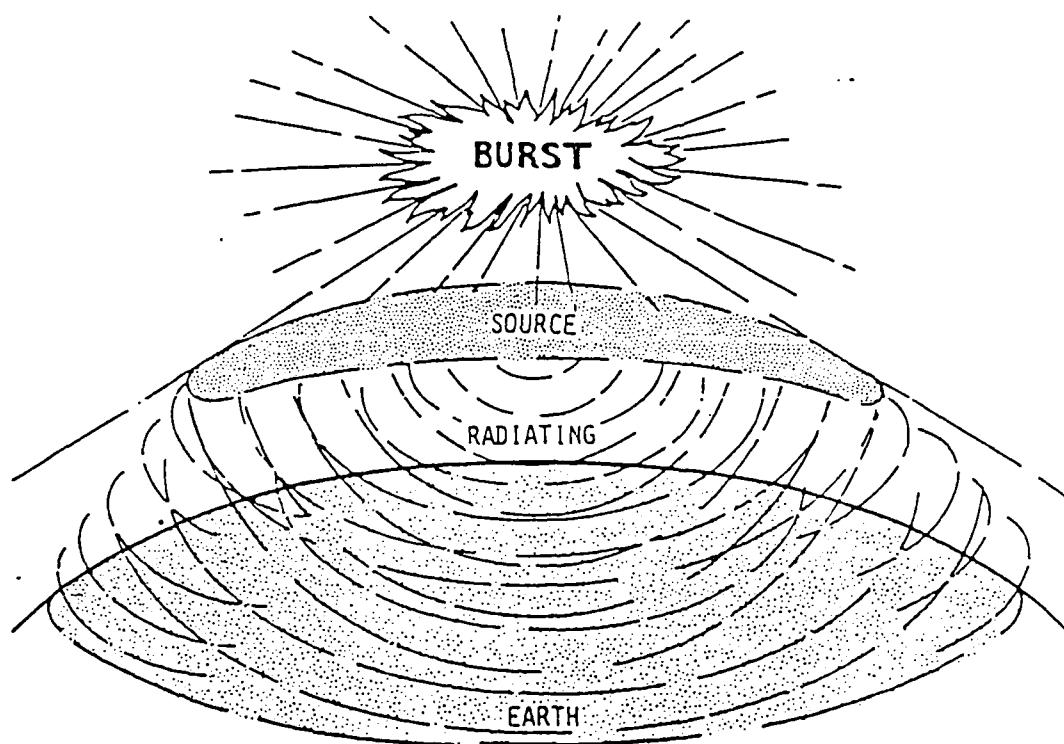


FIGURE 5-6. Detonation Regions.

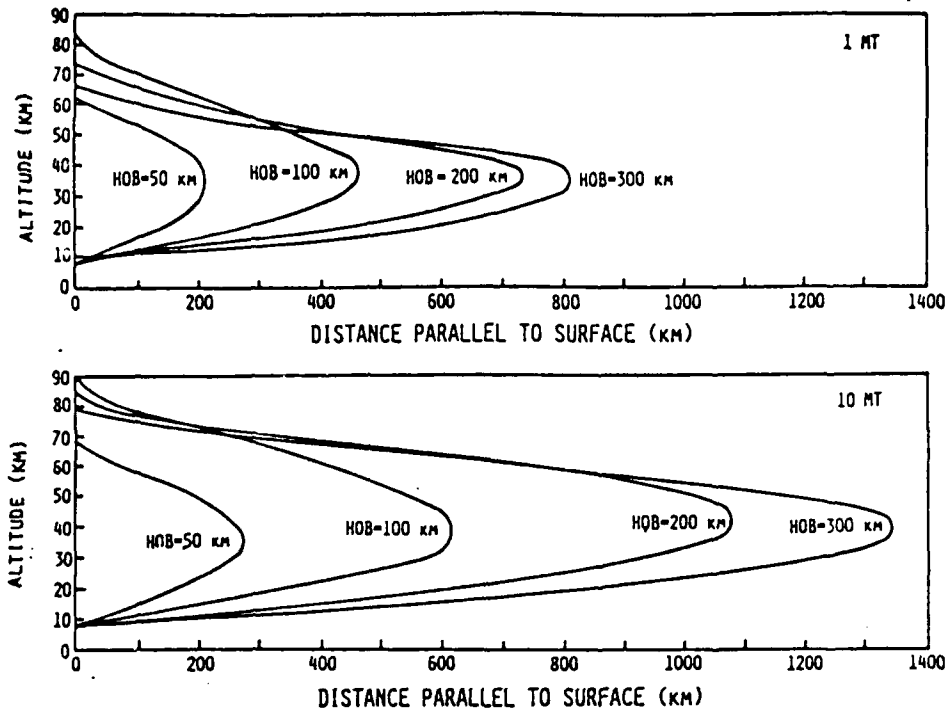
The Burst region is where the blast initiates. This is, for HEMP, at or above approximately 40 km.

The deposition source region is where approximately all of the gamma rays will be absorbed and EMP generated.

The accompanying diagram (Graph 5-1) shows how the source region varies with both weapon yield and height of burst. The cross sections shown are for weapon yields of 1 and 10MT, with various burst heights. These curves were computed from estimated gamma-ray emissions from the explosions and the known absorption coefficients of the air at various altitudes. The deposition region is thicker at small ground distances from ground zero, i.e. immediately below the burst and then thins as the ground distance increases.

The third region is the radiating region. The radiating region has 3 general characteristics: 1) The direction of propagation is radially outward from the burst; 2) The electric field and the magnetic field vectors are in a plane perpendicular to the direction of propagation; and 3) The fields have a far-field range dependence of $1/R$. (See Figure 5-7).

SOURCE REGION FOR HEMP
FOR VARIOUS BURST HEIGHTS



GRAPH 5-1. Source region for HEMP for various burst heights.

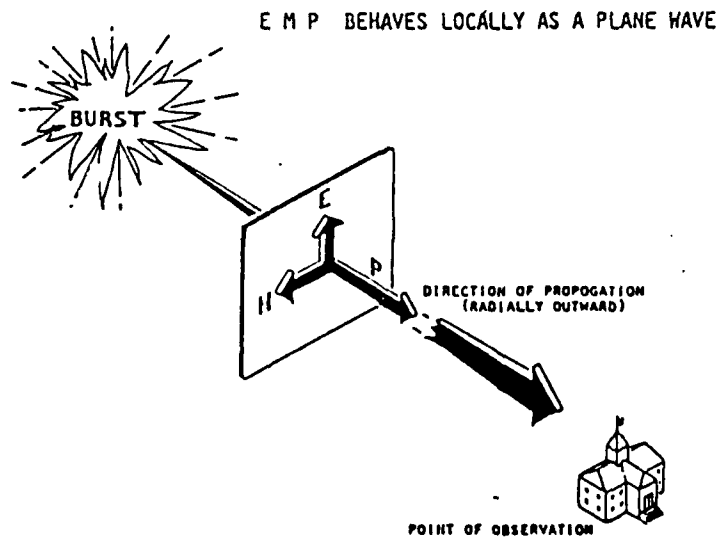


FIGURE 5-7. Propagation of EMP.

PRODUCTION

GENERAL THEORY

EMP is produced in several different ways, dependent upon where the burst occurs. Remember, a burst is classified as either; 1) a High Altitude burst (detonation above 40 Km), 2) an Air burst (detonation between approximately 2 and 20 Km), 3) a Surface burst (detonation on or near the surface of the earth), or 4) a Subsurface burst (detonation below ground or water level) (See Figure 5-8). However, we are generally only concerned with the EMP from a high altitude burst, a low altitude burst (or air burst) or a surface burst. Moreover, the majority of our attention will be focused on the high altitude burst since, as stated, this is where the most harmful effects come from. The lower altitude EMP is attenuated rapidly, is very localized and presents less threat than the other major nuclear weapons effects at the same altitude.

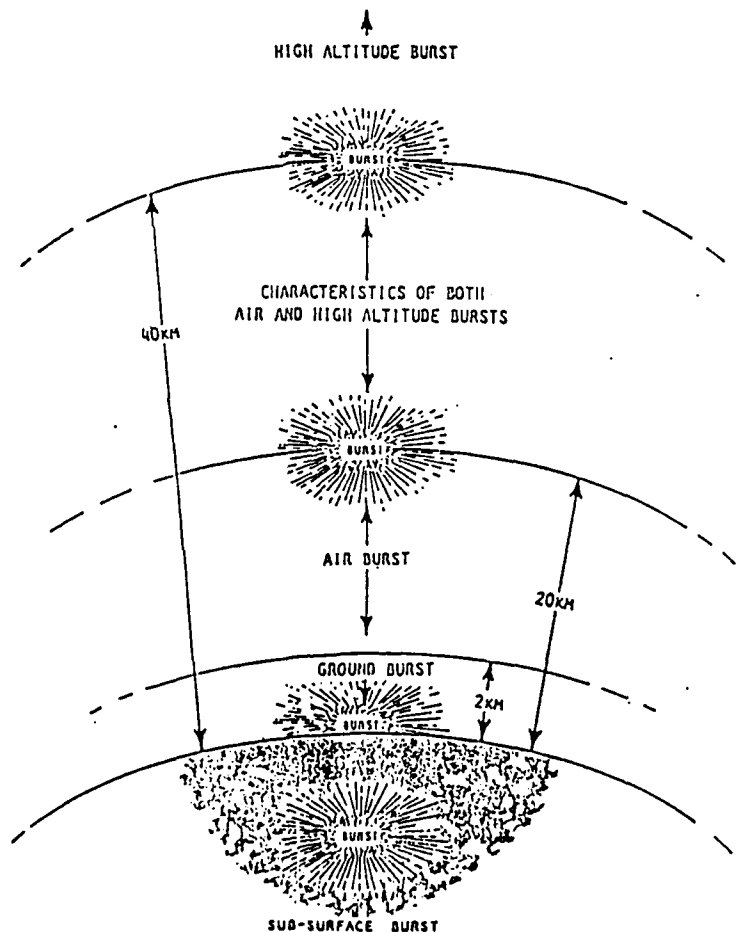


FIGURE 5-8. Burst Elevation.

COMPTON SCATTERING AND CHARGE SEPARATION

Compton scattering is the process which converts high energy photons into EMP and is the major contributor of EMP.

The process is initiated immediately upon weapon detonation. Gamma rays (photons) are emitted radially outward from the burst. Some will soon collide with air molecules in the atmosphere. In this collision, much of the photons energy is imparted upon the molecules' electrons, thus freeing one or more electrons and accelerating them from the molecule. Since the photons are emitted radially outward, the scattered electron, or Compton electron, travels in predominantly the same direction. This results in an expanding volume of negative charge, known as the Compton current. Since the Compton electron leaves behind a heavier, positively charged ion, a charge separation is induced, producing a strong electric field. In order for this field to propagate, there must exist a non-uniform, or asymmetrical medium. A perfectly symmetrical medium cancels the field everywhere. As the symmetry is destroyed, a portion of the field is not cancelled, and is propagated. The magnitude of the field increases as the symmetry decreases. The asymmetry is accomplished in several different ways, and is directly dependent upon the burst height.

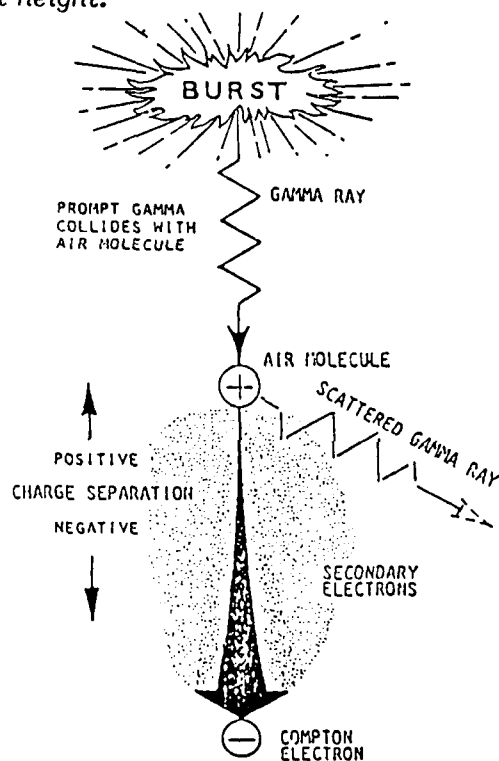


FIGURE 5-9. The Compton Effect.

For high altitude bursts, the asymmetry is produced by the differing levels of air density. As the photons travel radially from the burst, those moving toward the earth encounter the atmosphere and produce numerous compton electrons. However, those moving away from the earth do not experience the dense air, and thus produce fewer electrons. Since there is a much greater charge separation near the earth, the electric field radiates towards the earth. (It should be noted, however, that this is not the major contributor of High altitude EMP [HEMP]. The major contributing process, the transverse compton current, will be discussed later.)

An air burst has a much more uniform medium (the air density does not significantly change above or below the burst). However, a small propagation does occur from the slight changes in air density. It is the same process as the high altitude burst, but on

a much smaller scale. For this reason, the fields do not propagate great distances, are very localized, and have much lower amplitudes.

For a surface burst, the ground-air interface provides the asymmetry needed for propagation.

As the Compton electron, generated from the photon's collision with air molecules, continues traveling radially outward, it collides with other air molecules. These collisions are similar to the photon/air molecule collision, and they too free electrons. However, these electrons, referred to as secondary electrons, have much lower energies than the original Compton electron. The secondary electrons are quickly drawn inward toward the burst region, producing a second current called the conduction current. Eventually, the conduction current becomes as large as the Compton current and a condition of saturation is reached.

When the gamma ray collides with the air molecule, most of its energy is lost. However, if the gamma ray retains enough energy after the collision, it will continue radiating outward until it collides with another air molecule, producing another Compton electron. This process continues until all gamma rays, emitted from the burst, have lost their energy.

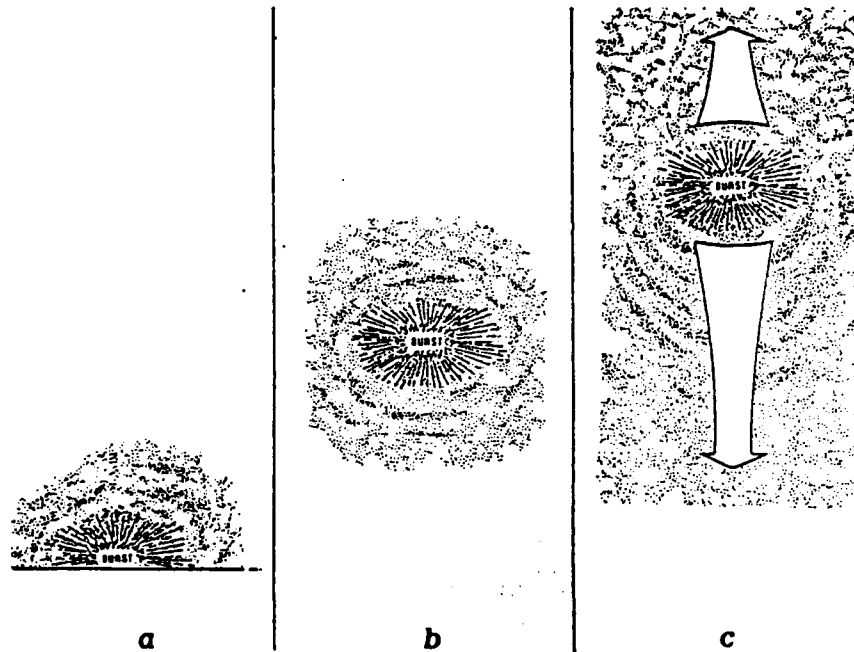


FIGURE 5-10. Burst Asymmetry. How the asymmetry needed for EMP wave propagation is provided.

FROM GROUND (SURFACE) BURST

The generation of EMP by a surface burst begins with the Compton Scattering and Charge Separation discussed above. In its source region, which generally extends to 5 Km, the radial E-field produced has significant amplitudes (in excess of 100 KV/m, occasionally approaching 1MV/m) and very fast rise times. The majority of its energy, however, is at lower frequencies than high altitude EMP (below 100 KHz). The strong

radial field causes the conduction currents to flow in the ground (since the ground is much more highly conducting than the air at early times), in opposite directions to the Compton current in the air. These resultant current loops (the Compton current traveling outward and the conduction current traveling inward) produce azimuthal magnetic fields which are strongest at the earth's surface, and diffuse both upward and downward from the ground-air interface. A vertical E-field is also generated and propagated (in the radiating region, which may be extended beyond 10 Km) because of this interface. By not allowing the Compton electrons to travel downward, there is a net positive charge on the ground and a net negative charge in the air. This separation creates what behaves like a net vertical dipole, which in turn radiates a vertical electrical field. Thus, for a surface burst, there are radial and vertical electric fields and an azimuthal magnetic field.

There are other components in the EMP produced, due to surface irregularities and varying ground properties, that complicate its analysis. The soil and air conductivity, for example, will greatly vary depending on whether the burst occurs in the dry Arizona desert or the humid coastal regions. The analysis is further complicated by the EMP introduced within or near a system, by the impinging gamma rays from the nearby burst. This is known as system generated EMP, and will be discussed later in more detail. Surface burst EMP has very large electric and magnetic field intensities, but is very localized. Because of this smaller area of coverage, it presents less of a threat than high altitude EMP. However, since surface burst EMP radiates a vertical electric field, and has a very large portion of it in the lower frequencies, the system impact may supersede that of HEMP for some systems (even though HEMP field magnitudes are generally larger).

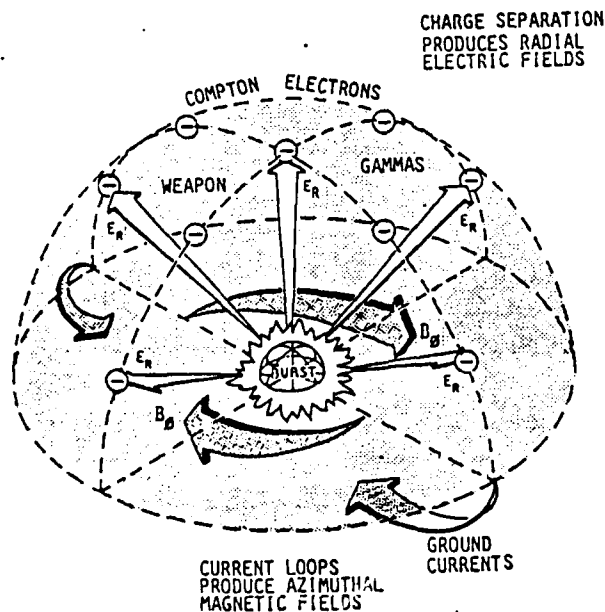


FIGURE 5-11. Charge separation.

FROM AN AIR BURST

The generation of EMP by an air burst also begins with the Compton Scattering

and Charge separation processes (see Figure 5-12). The radial electric field behaves much like that of a surface burst, except in an air burst, there is no return path through ground for the conduction current. Thus, no current loops are formed, and the large azimuthal magnetic fields, characteristic of the surface burst, are not generated. The asymmetry needed to propagate the radial electric field is provided by the atmospheric density gradient. Different densities permit the Compton electrons to travel further upward than downward. The asymmetry is reinforced by the typical decrease in water vapor density with increasing altitude. However, even with these two effects combined, the asymmetry produced is much weaker than that of a surface burst, and typical field strengths are much smaller (approximately 300 V/m at 5 Km). Since there is a slight asymmetry, there is a small vertical electric field which, in turn produces a small, very weak azimuthal magnetic field. These fields share characteristics of both surface burst EMP and HEMP, but are much less significant. Any system hardened to withstand HEMP can also withstand Air Burst EMP. Therefore, we will now turn our attention to High Altitude EMP.

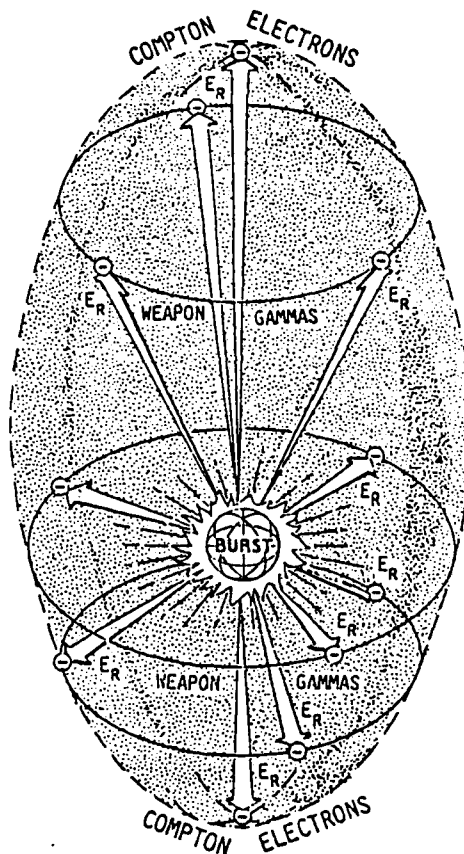


FIGURE 5-12. Air Burst EMP.

FROM HIGH ALTITUDE BURST

The generation of EMP by a high altitude burst begins as the surface burst and air burst with Compton Scattering and Charge Separation. The asymmetry required for field propagation is produced by the space-atmosphere interface. However, the electric field due to the charge separation is not the major contributor of HEMP. The major contribution is a result of a new phenomenon called Transverse Compton Current.

This new current is a result of the Compton electron's interaction with the earth's magnetic field lines (geomagnetic lines). As the electrons travel radially from the burst, they encounter the geomagnetic lines, which in turn causes them to spiral about the lines, generally with a radius of approximately 100 meters. The spiraling effect can better be seen by applying the right hand force rule of magnetics (see Figure 5-13). Begin by placing your thumb, forefinger, and middle finger at right angles to each other. Now, point your middle finger in the direction of electron flow, and your forefinger in the direction of the magnetic field line. Your thumb (if you kept your fingers at right angles) now points in the direction of the force the electron experiences. Now, we can apply the rule to the spiraling effect. As the electron travels away from the burst, it does not feel the earth's magnetic field, and therefore continues in approximately a straight line. However, the further it gets from the burst, the more force it experiences. Since the force and direction of travel are always at right angles to each other, the electron's path begins to curve. Eventually, the electron is spiraling around the field lines. The spiraling, and thus accelerating electron, radiates a very large electromagnetic field that propagates in the forward direction. Because the electrons spiral around the earth's field lines, the EMP is radiated over a very large spatial area. Which, depending on the height of burst, can be as large as the entire United States. It is this large coverage combined with the very fast rise time, and extremely large amplitudes that make the high altitude EMP the most harmful. More will be said of the rise times and amplitudes later.

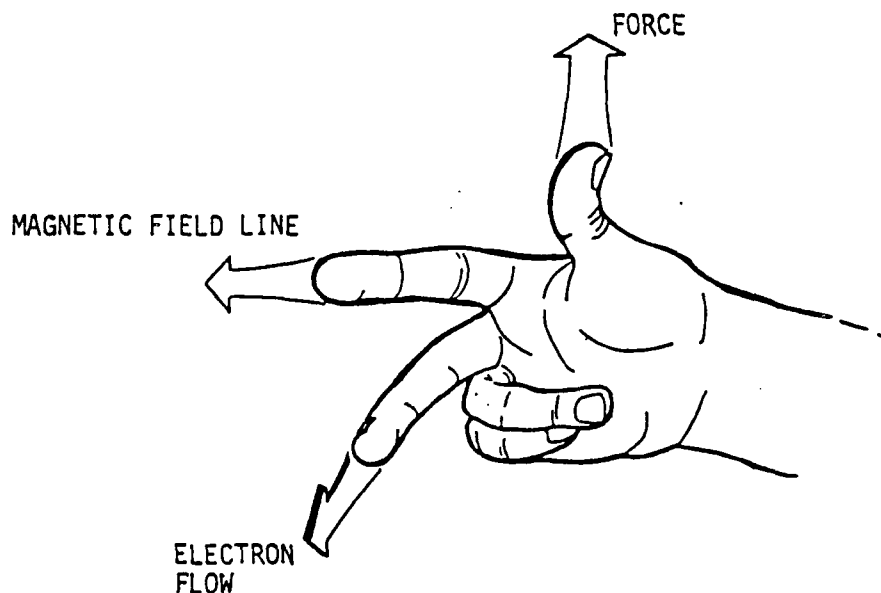


FIGURE 5-13. Right Hand Rule for Force.

MAGNETOHYDRODYNAMIC EMP

Magnetohydrodynamic EMP (MHD-EMP) is the late time component of EMP in a high altitude burst. There are two different portions of MHD-EMP corresponding to the length of time after burst detonation. The first portion, "early phase," lasts from 0.1 to 10 seconds after the detonation. The second portion, the "late phase," extends from 10 seconds out to 1000 seconds. The MHD-EMP fields are characterized by low amplitudes, very large spatial content, and very low frequency. These fields can pose a threat for very long landlines, such as telephone cables and power distribution cables or submarine cables. A detailed analysis of MHD-EMP production can be found in BDM Document BDM/W-82-305-TR, entitled "DNA EMP Course Study Guide."

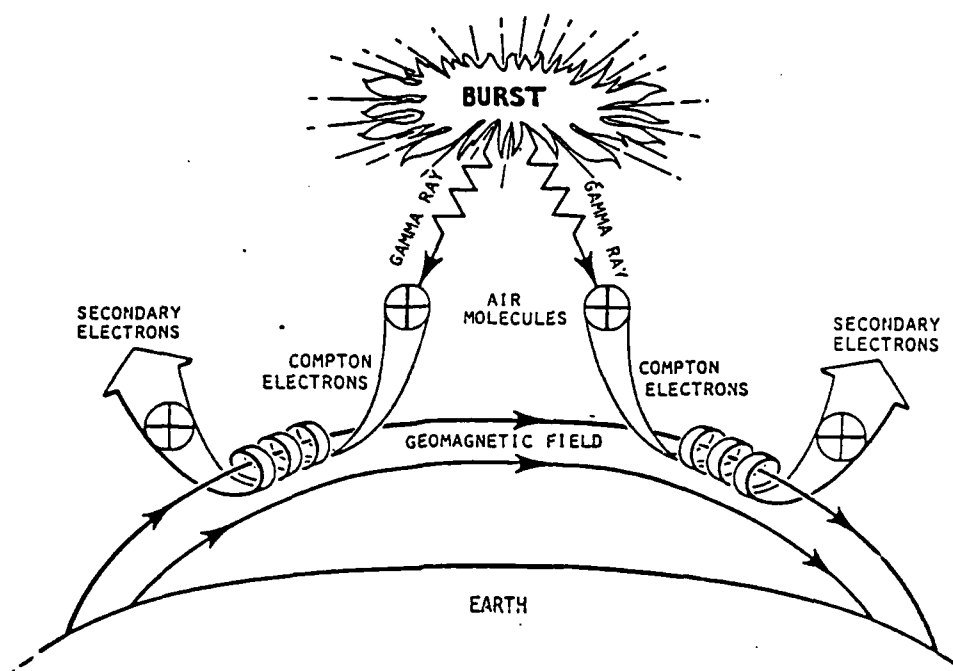


FIGURE 5-14. Transverse Compton Currents.

SYSTEM GENERATED EMP

The EMP that has been addressed thus far arises from the interaction of gamma rays with the atmosphere. There is, however, another type of EMP that arises from the interaction of the explosion's gamma rays and x-rays with the system. This "System Generated EMP" (SGEMP) begins when the rays come in contact with the system's outer surface. Whether this is the actual solid material of the electronic system or the shielding designed to protect the system, their atoms are heavier than those present in the air. Consequently, interaction with the rays produces electrons by the Compton and photoelectric effects. The Compton effect has been discussed in detail: The photoelectric effect is the phenomenon associated with the excitation of electrons and their removal from a metal after being exposed to light of sufficiently short wavelengths. In turn, these electrons produce secondary electrons by ionizing more of the metal's atoms. Some electrons produced, whether directly or indirectly, will have a velocity component perpendicular to the surface and will be emitted from the system. As a result, an electric field is generated near the surface. Internal EMP (IEMP) is also generated in the system from electrons emitted from internal walls. Appreciable currents and voltages capable of causing failure or disruption of the system can be developed from SGEMP or IEMP just as it could with the other types of EMP.

MISSILE IN FLIGHT

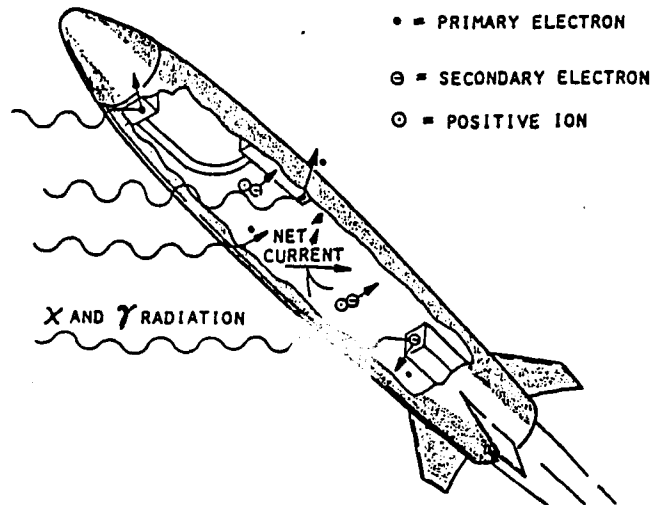


FIGURE 5-15. System Generated EMP.

ANALYSIS METHODS

GROUND COVERAGE FOR HEMP

EMP from transverse Compton current can travel great distances around the earth. However, the most harmful effects cover the line of sight region from the burst to the earth. (See Figure 5-16).

Assuming the earth to be a sphere, the edge of this region is a circle with a radius of R_t . This is known as the tangent radius because the line of sight from the burst is at a tangent to the earth. If the height of burst is known, the tangent radius can easily be determined from equation 5-1. Graph 5-2a shows the tangent radius as a function of the height of burst.

$$R_t = R_e \cos^{-1} (R_e / (R_e + HOB)) \quad (\text{Eqtn 5-1})$$

Where R_t is the Tangent Radius (in Km), R_e is the Earth's Radius (approximately 6370 Km) and HOB is the Height of Burst (in Km).

The surface area of coverage can be found from the following equation:

$$A_t = \frac{2\pi R_e^2 HOB}{R_e + HOB} \quad (\text{Eqtn 5-2})$$

Where: A_t is the Surface Area (in KM^2), R_e is the Radius of Earth (approximately 6370 Km), R_e is 3.1415, and HOB is the Height of Burst (in Km).

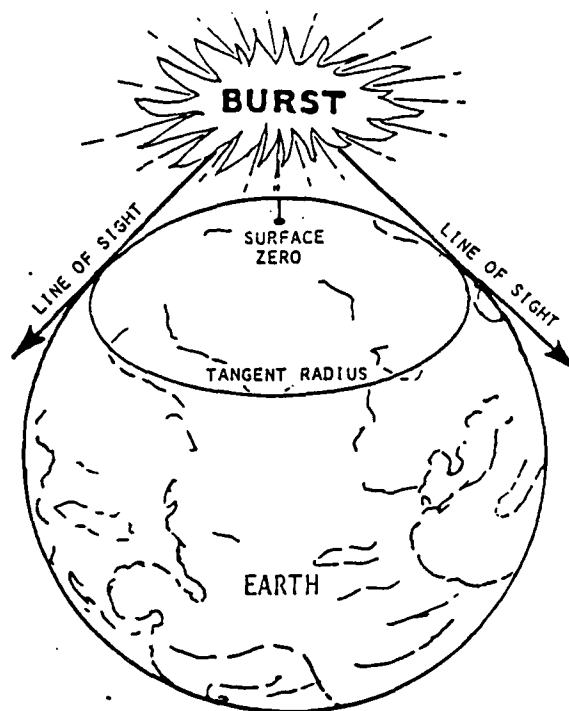
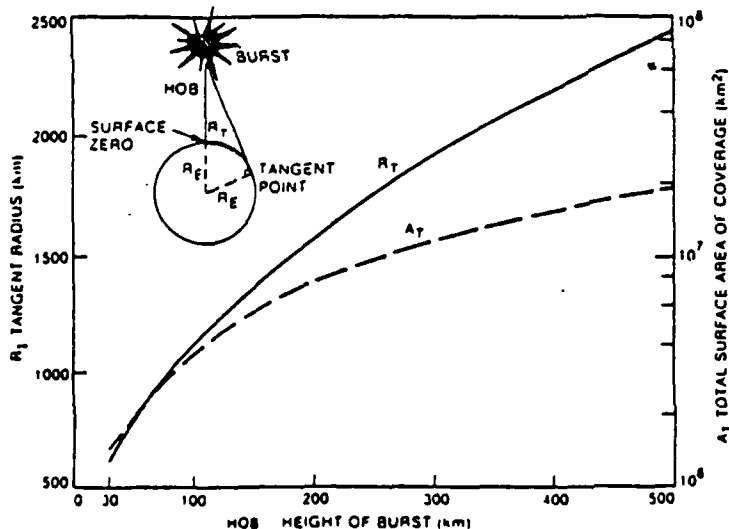
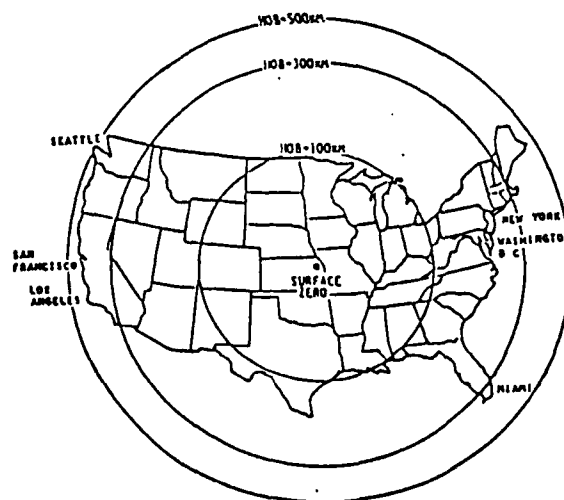


FIGURE 5-16. Region of EMP coverage.

Graph 5-2a also shows the total surface area covered as a function of the height of burst. Graph 5-2b relates this information to the United States; for burst heights of 100, 300 and 500 kilometers.



GRAPH 5-2a. Tangent radius and surface area



GRAPH 5-2b. Surface area as related to the U.S.

FIELD STRENGTH

The magnitude of the electric field varies considerably over the area of coverage. The ratio of the magnitude of the electric field strength to the magnitude of the magnetic field strength is equal to the impedance of free space (assuming the EMP to be a plane

wave over the area of coverage). There are many factors which affect the magnitude of the EMP, including: Height of burst, weapon yield, geometric location of the burst, and point of observation of the burst. However, the electric field waveform can closely be approximated with the following equation:

$$E(t) = E_0 K (e^{-\alpha t} - e^{-\beta t}) \text{ V/m} \quad (\text{Eqtn 5-3})$$

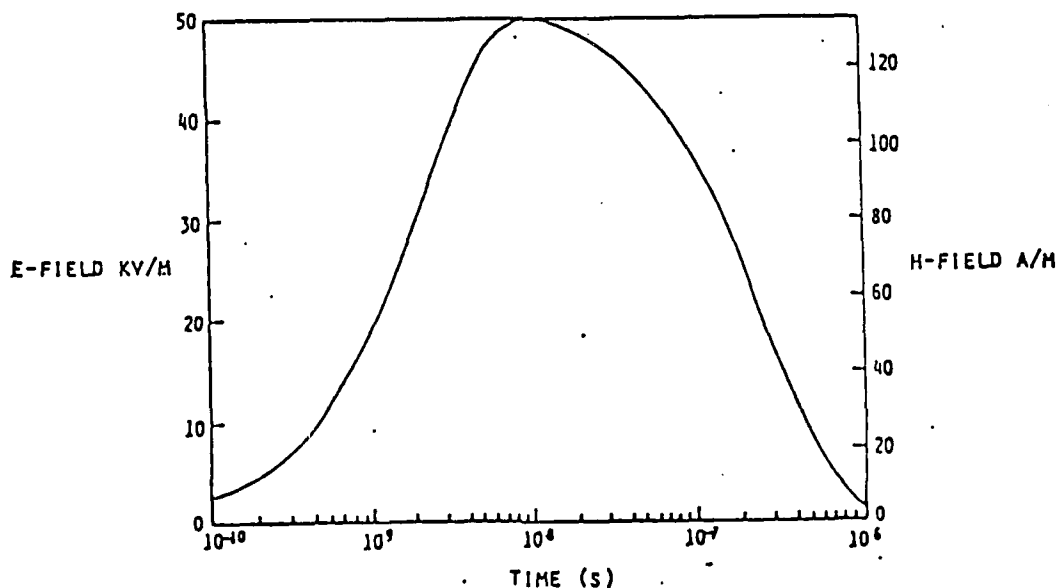
for $t \geq 0$

Where β is the Rise constant of $4.76 \times 10^8 \text{ s}^{-1}$, α is the Decay rate of $4 \times 10^6 \text{ s}^{-1}$, K is 1.050 (Constant allowing $E(t)$ to reach E_0), t is Time in seconds, and E_0 is the Peak Electric Field

Substituting these values into the equation, and assuming a peak Electric field (E_0) of 50 KV/m, provides the equation for a high yield, high altitude burst.

$$E(t) = 5.25 \times 10^4 (\exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t)) (\text{V/m}) \quad (\text{Eqtn 5-4})$$

This equation has a rise time of 5 nanoseconds and a time to half value of 200 nanoseconds. Graph 5-3 shows the time waveform of the EMP for equation 5-3 and also relates the magnetic field to the electric field.



GRAPH 5-3. Generalized EMP time waveform.

FREQUENCY RESPONSE

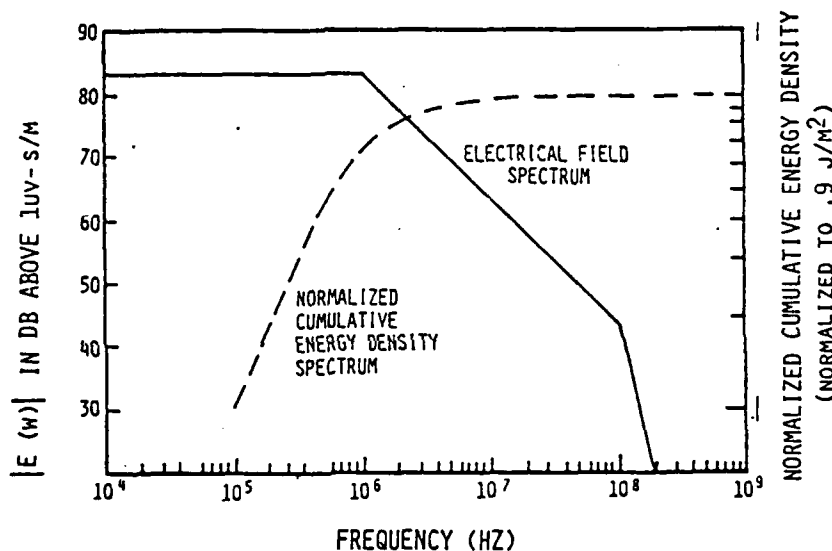
A great deal of EMP collectors are frequency selective. Therefore, it is very

important to determine the distribution of EMP energy in the frequency domain. This is easily accomplished by obtaining the Fourier transform of equation 5-3. This yields the following equation:

$$E(\omega) = \frac{2.47 \times 10^{13}}{(j\omega + 4 \times 10^6)(j\omega + 4.76 \times 10^8)} \quad \text{V-s-m}^{-1} \quad (\text{Eqtn 5-5})$$

Where ω is radian frequency.

A bode plot of this equation is shown in Graph 5-4 below. This diagram shows that the electric field strength is relatively constant between 10 and 100 kHz, decreases by a factor of 100 between 1 MHz and 100 MHz and then continues to rapidly decrease for frequencies greater than 100 MHz. Moreover, the majority of the fields energy can be seen to lie below about 100 MHz.



GRAPH 5-4. Frequency domain plot of EMP energy.

SMILE DIAGRAMS

The smile diagram is a convenient method of determining relative field strengths. The accompanying Figure 5-17 is an example of a smile diagram for high altitude bursts, ranging in heights from 100 to 500 Km. The results in this figure apply for a ground zero location between approximately 30° and 60° North latitude; or approximately over the continental United States. The reason ground zero must be specified, is that the Compton electrons must intersect the geomagnetic field lines in order to produce any EMP. Thus, the Compton electrons parallel to the field lines will not produce any EMP. The null area directly north of ground zero is because of this parallel effect. The typical dip angle of the geomagnetic field over the United States is approximately 67°.

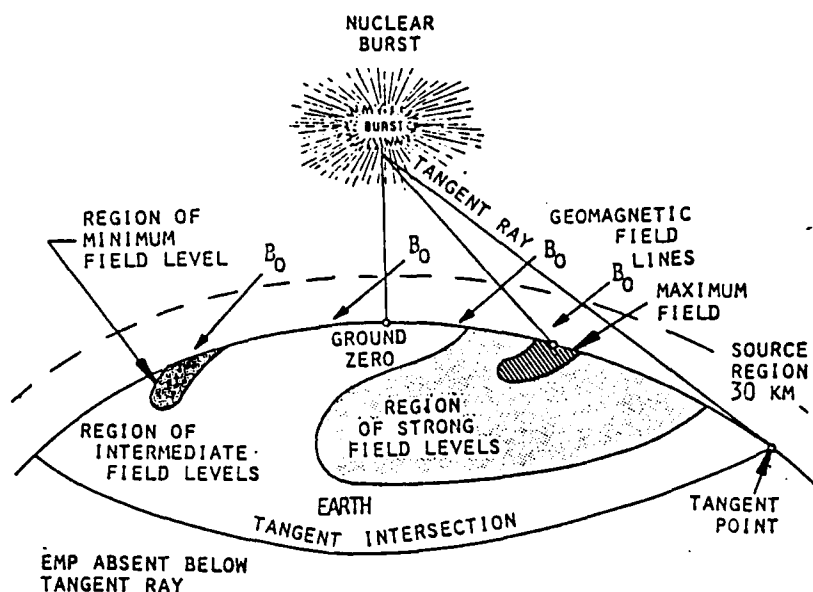


FIGURE 5-17. Field strengths due to Compton electrons relationship with geomagnetic field.

Although the magnitude of the maximum field strength probably does not vary significantly with the latitude of the burst, the spatial distribution of the field strength does vary with the dip angle. As the dip angle increases to 90° (or, as ground zero approaches the magnetic pole), the contours become more and more circular. And, conversely, as the dip angle decreases below 50° (or, as ground zero decreases below approximately 30°), the contours become less circular, as shown in Figure 5-18.

The peak field location can easily be found by aligning magnetic north on the diagram with magnetic north at surface zero (for bursts over the continental United States, Magnetic north and true north are essentially the same).

This diagram is also applicable in areas south of the geomagnetic equator by simply substituting South and West, for North and East, respectively.

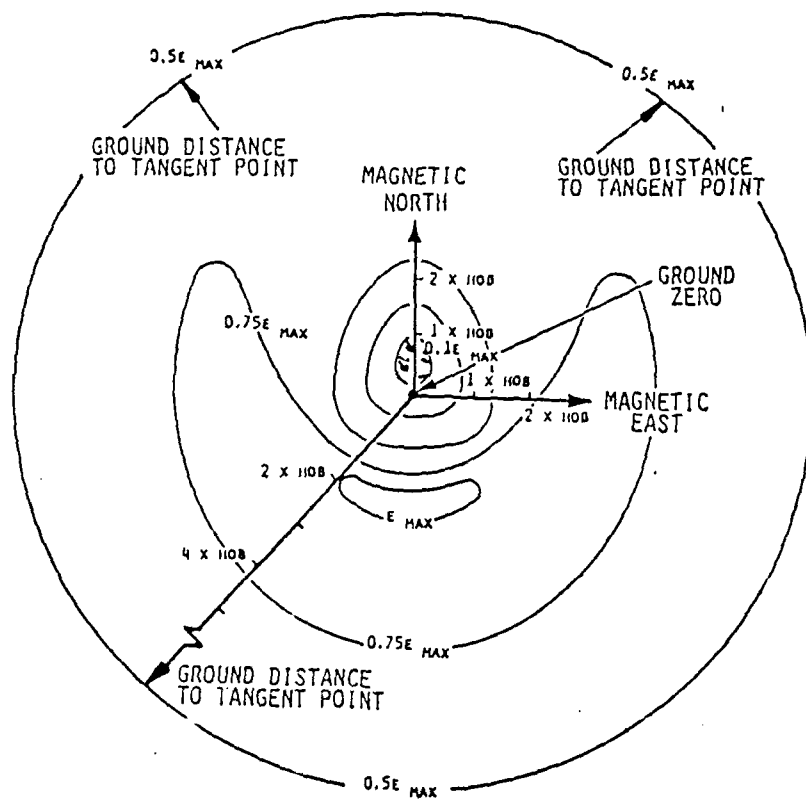


FIGURE 5-18. Smile diagram showing relative electric field strengths.

COUPLING THEORY

An electric field is measured in volts per meter (v/m). A potential of one volt, separated by one meter, produces an E field of 1 v/m. If the electric field vector is in the plane of incidence, then the field is said to be vertically polarized. If it is perpendicular to the plane of incidence, then it is horizontally polarized.

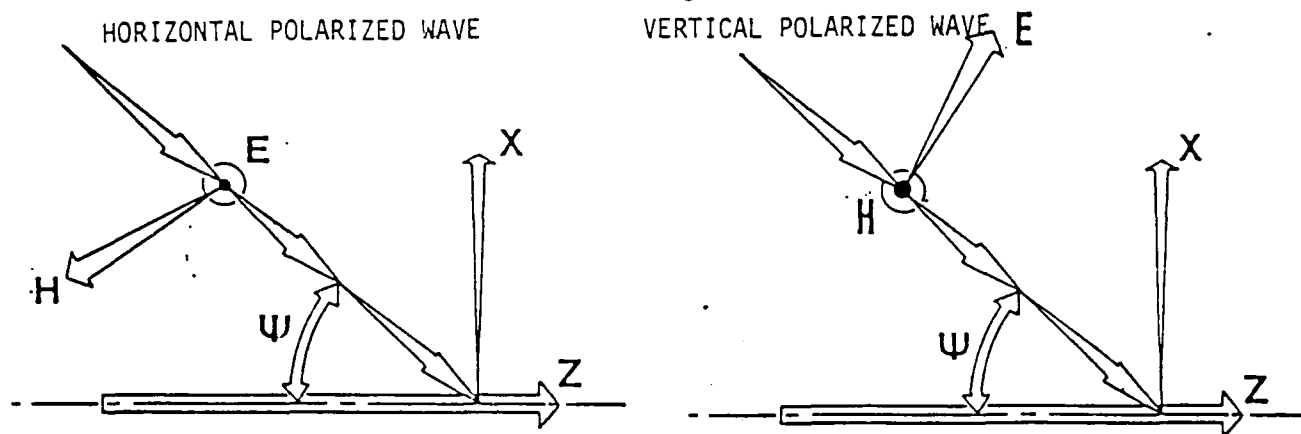


FIGURE 5-19. Horizontal and vertical polarized waves.

A conducting media, such as a piece of wire, exposed to this field will have a voltage induced on it and a current flowing in it. The amount of the current is dependent on the voltage that is induced on it and the resistance of the wire. The voltage induced is dependent on the electric field and the angle that the field makes with the wire. This field will induce a voltage and a current on any conducting media it encounters, such as an airplane skin, an antenna, power lines, etc. The induced current will produce a secondary electromagnetic field, but this field is small compared to the EMP and can, in most instances, be ignored. There are a few exceptions that will be pointed out later.

There are two types of coupling devices: intentional (antennas), and nonintentional (power lines, telephone lines, etc.). Coupling through an antenna is a straightforward exercise in antenna theory, and will not be covered. A very good distinction of how EMP couples to antenna's can be found in the "DNA EMP Handbook," (DNA-3466F).

EMP can be coupled into a protected area by anything penetrating the area, such as: power or telephone lines, or cabling (both electrical and mechanical). Also, cabling that is totally inside the protected area but passes next to a door, or a non-protected penetration, i.e. a control cable, can pick up a sufficient amount of EMP to cause damage. This is why it is important to decouple all penetrations. For instance, the energy coupled from a control cable to a data bus is from the secondary electromagnetic field mentioned earlier.

A mathematical model will be developed to define the voltage induced on overhead power lines by EMP. From this model, the voltages and currents induced in different types of lines can be estimated. Mathematical models will then be developed for currents coupled to inner conductors of shielded cables. Next, different types of shielded cables

will be covered, along with connectors and splices, followed by a brief look at aperture penetration. This section will be completed by looking at coupling to buried cables, and coupling to towers.

VOLTAGE ON A LONG LINE

The Cartesian Coordinate System shown in Figure 5-20 will be used in this section with the Z axis representing the wire, and where the y,z plane is parallel to the ground.

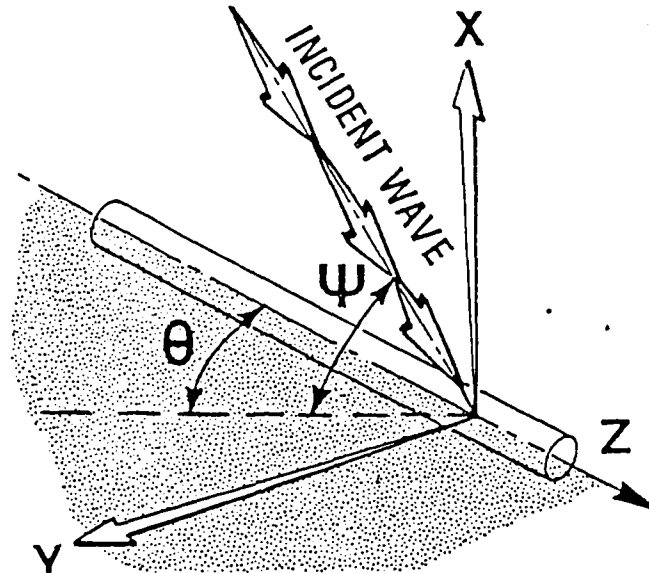


FIGURE 5-20. Reference coordinate system to be used.

THE CRITICAL LENGTH OF A SEMI-INFINITE LINE

The primary concern is the peak voltage and current, the "critical length" " l_c " will be defined as the length of a finite line, whose peak terminal response is the same as if the line were infinite. This length is $l_c = cT_p / [1 - \cos(\theta)\cos(\psi)]$, where " T_p " is the time to peak and c is the speed of light. This is the distance that the field will travel down the line, in the time from zero to peak field. This is the only part of the line that effects the peak voltage. The remaining length only affects the response after the peak voltage is attained.

TIME-HARMONIC OPEN-CIRCUIT RESPONSE

The complete response to EMP in general, requires the time-harmonic open-circuit Voltage (V_{oc}) response. When an EMP field illuminates a long line, a voltage $E_z \Delta Z$ is impressed upon each element Z of the conductor. This acts like many voltage sources distributed along the line. This has the effect of producing very large V_{oc} . The time-harmonic open-circuit response is the summation of all the sources, and is given by:

$$V_{oc}(\omega) = \int_{-\infty}^{\infty} e^{(\gamma z)} E_z(x_i, y_i, z, \omega) dz \quad (\text{Eqtn 5-6})$$

Where E_z is the total longitudinal electric field at the average height of the line. The $e^{(Yz)}$ term is a scaling factor produced by the progression of the primary wave, toward the terminal, and the reflected wave coming from the open terminal. This wave is, in general, composed of both a vertical and a horizontal component, and each component has an incident and a reflected part. The horizontally polarized part of the wave is given by:

$$E_z^h(x, y, z, \omega) = E_0(x, y, z, \omega) [Y_0 \cos(\theta) + Z_0 \sin(\theta)]$$

The z component is therefore:

$$E_z^h = E_0 \sin(\theta)$$

The z component of the ground-reflected electric-field vector is found by multiplying E_z^h by the reflection coefficient. For horizontal, it will be:

$$E_z^h = E_0 \sin(\theta) R_h e^{-2jkhsin(\psi)}$$

$$R_h = \frac{\sin(\psi) - [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2(\psi)]^{\frac{1}{2}}}{\sin(\psi) + [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2(\psi)]^{\frac{1}{2}}}$$

Where k is the wave number, h is the height of the wire, ϵ_r is the relative permittivity and σ_g is the conductivity of the ground.

R_h is the ground reflection coefficient for horizontal polarization. The total longitudinal electric field at the conductor for horizontal polarization is the sum of the incident, and reflected component, and is:

$$E_z^h = E_0 \sin(\theta) [1 + R_h e^{-j2khsin(\psi)}] e^{-jkz \cos(\theta) \cos(\psi)} \quad (\text{Eqtn 5-7})$$

Where $[e^{-jkz \cos(\theta) \cos(\psi)}]$ accounts for the phase variance down the line, and " k " is the wave number, and is equivalent to one over wave length).

Similarly, the total longitudinal electric field at the conductor for vertical polarization is:

$$E_z^v = E_0 \sin(\psi) \cos(\theta) [1 - R_v e^{-j2khsin(\psi)}] e^{-jkz \cos(\theta) \cos(\psi)} \quad (\text{Eqtn 5-8})$$

Where R_v is the ground reflection coefficient for vertical polarization.

$$R_v = \frac{r(1 + \sigma_g/j\omega\epsilon) \sin(\psi) - [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2(\psi)]^{\frac{1}{2}}}{r(1 + \sigma_g/j\omega\epsilon) \sin(\psi) + [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2(\psi)]^{\frac{1}{2}}} \quad (\text{Eqtn 5-9})$$

IMPULSE RESPONSE

Substituting equations (5-7) and (5-8) into equation (5-6) setting $E_0=1$ and taking into account the phase variation gives the common-mode V_{OC} at the terminals for horizontal and vertical polarizations, where $\Upsilon=\Upsilon_0 H(j\omega)$:

$$V_{OC}^h = \frac{\sin(\theta)[1+R_h e^{-j2khsin(\psi)}]}{\Upsilon - jk\cos(\theta)\cos(\psi)} \quad (\text{Eqtn 5-10})$$

$$V_{OC}^v = \frac{\sin(\psi)\cos(\theta)[1-R_v e^{-j2khsin(\psi)}]}{\Upsilon - jk\cos(\theta)\cos(\psi)} \quad (\text{Eqtn 5-11})$$

If the line and ground planes are perfect conductors, the propagation constant $\Upsilon = jk = j\omega/c$ and the reflection coefficients R_h and R_v become -1 and +1, respectively. Equations (5-10) and (5-11) then become:

$$V_{OC}^h = cD_h(\theta, \psi)(1 - e^{-j\omega T_c})/j\omega$$

$$V_{OC}^v = cD_v(\theta, \psi)(1 - e^{-j\omega T_c})/j\omega$$

Where T_c is the time delay between incident and reflected planes of equal phase, also called the clear time, and D_h , D_v are the directivity functions.

$$T_c = 2hsin(\psi)/c$$

$$D_h(\theta, \psi) = \sin(\theta)/[1 - \cos(\theta)\cos(\psi)]$$

$$D_v(\theta, \psi) = \sin(\psi)\cos(\theta)/[1 - \cos(\theta)\cos(\psi)]$$

The inverse Fourier transformations of V_{OC}^h and V_{OC}^v yield the system impulse response:

$$h_{OC}^h = \begin{cases} cD_h(\theta, \psi) & 0 \leq t < T_c \\ 0 & t > T_c \end{cases} \quad (\text{Eqtn 5-12})$$

and

$$h_{OC}^v = \begin{cases} cD_v(\theta, \psi) & 0 \leq t < T_c \\ 0 & t > T_c \end{cases} \quad (\text{Eqtn 5-13})$$

To find the power-line V_{OC} response to EMP, you must convolve the system response, equation (5-12) or (5-13), with the EMP time dependent waveform.

This convolution produces:

$$(1/\beta) (e^{-\beta t} - 1) - (1/\alpha) (e^{-\alpha t} - 1) \quad 0 \leq t < T_c \quad (\text{Eqtn 5-14a})$$

$$V_{OC}^h(t) = c D_h(\theta, \psi) E_0$$

$$(1/\beta) e^{-\beta t} (1 - e^{\beta T_c}) - (1/\alpha) e^{-\alpha t} (1 - e^{\alpha T_c}) \quad t > T_c \quad (\text{Eqtn 5-14b})$$

$$(1/\beta) (e^{-\beta t} - 1) - (1/\alpha) (e^{-\alpha t} - 1) \quad 0 \leq t \leq T_c \quad (\text{Eqtn 5-14c})$$

$$V_{OC}^v(t) = c D_v(\theta, \psi) E_0$$

$$(1/\beta) e^{-\beta t} (1 - e^{\beta T_c}) - (1/\alpha) e^{-\alpha t} (1 - e^{\alpha T_c}) \quad t > T_c \quad (\text{Eqtn 5-14d})$$

Where α and β are the time constants for the EMP, and T_c is the clear time.

These equations show that the V_{OC} for a lossless line depends on the direction of incidence, the time for the reflected wavefront to reach the conductors, and the parameters of the EMP time waveform. The response before T_c is due only to the direct incident wavefront. The response after T_c is the result of the combination of two wavefronts, one traveling in the positive direction, and one traveling in the negative direction. The combination of these two waves has a limiting effect on the maximum V_{OC} .

EXAMPLE 5-1:

GIVEN:

A cable that is 5-cm in diameter, and is 0.5 meters above a metal ground plane, is illuminated by a 15kv/m EMP wave. The angles of incidence, θ and ψ are 0° and 30° , respectively. Find the peak V_{OC} at $T = 10.83 \times 10^{-9}$ sec.

FIND:

Using equation 5-14d, the first value to find is T_c , the clear time.

SOLUTION:

$$T_c = 2(0.5) \sin(30^\circ) / 3 \times 10^8 = 1.667 \times 10^{-9}$$

Next, find the directivity function value:

$$D_v(0^\circ, 30^\circ) = [\sin(30^\circ) \cos(0^\circ)] / [1 - \cos(0^\circ) \cos(30^\circ)] = 3.732$$

The V_{OC}^v can now be found by:

$$V_{OC} = (15 \times 10^3)(3 \times 10^8)(3.732)$$

$$\left[\frac{e^{-476 \times 10^6 (10.83 \times 10^{-9})} (1 - e^{-476 \times 10^6 (1.667 \times 10^{-9})})}{476 \times 10^6} \right.$$

$$\left. - \left[\frac{e^{-4 \times 10^6 (10.83 \times 10^{-9})} (1 - e^{-4 \times 10^6 (1.667 \times 10^{-9})})}{4 \times 10^6} \right] \right]$$

$$\begin{aligned}
&= 16.79 \times 10^{12} [12.12 \times 10^{-12} (-1.211)] - [239.4 \times 10^{-9} (-6.69 \times 10^{-3})] \\
&= 16.79 \times 10^{12} [-14.68 \times 10^{-12}] - [-1.602 \times 10^{-9}] \\
&= 16.79 \times 10^{12} [1.59 \times 10^{-9}] = 26.70 \text{ kv}
\end{aligned}$$

To generalize, for a line that has an average height of 10 meters, a ψ of 90° , (directly overhead), the V_{OC} for a horizontal polarized wavefront, peaks at about 900k volts in 70 nanoseconds. At grazing, ($\psi=0$) the peak is about 1 megavolt in about 10 nanoseconds. For a vertical polarized wavefront, the peak can be as much as 2 megavolts.

It can be shown that the horizontal directivity function is greatest with respect to θ when $\theta = \psi$ for a fixed elevation angle.

$$D_h(\theta, \psi) \Big|_{\theta = \psi} = 1/\sin(\psi) \quad (\text{Eqn 5-15})$$

The combination of equations (5-14b) and (5-15) gives an expression for the maximum V_{OC}^h as a function of ψ .

$$V_{OC}^h \Big|_{\text{Peak}} = [cE_0/\sin(\psi)] [(1/\beta)e^{-\beta t_p(1-e^{\beta T_c})} - (1/\alpha)e^{-\alpha t_p(1-e^{\alpha T_c})}]$$

Where t_p is the time to peak.

$$t_p = [1/(\beta - \alpha)] \ln[(1 - e^{\beta T_c})/(1 - e^{\alpha T_c})]$$

The theoretical maximum peak V_{OC}^h occurs at grazing, $\psi = \theta$, and is $2hE_0$.

The peak V_{OC}^v for vertical polarization for a given angle ψ is maximized with respect to θ , when $\theta = 0$. As with horizontal polarization, the peak of the V_{OC} increases, and the time to peak decreases as the elevation angle approaches grazing.

The peak V_{OC} for vertical polarization is:

$$V_{OC}^v \Big|_{\text{Peak}} = \frac{cE_0 \sin(\psi)}{[1 - \cos(\psi)]} \left[\left(\frac{1}{\beta} \right) e^{-\beta t_p(1 - e^{-\beta T_c})} - \left(\frac{1}{\alpha} \right) e^{-\alpha t_p(1 - e^{-\alpha T_c})} \right]$$

The V_{OC} for vertical ranges from about 900kv at normal incidence, to a maximum of 2 megavolts at grazing. The time to peak also increases from about 70 nanoseconds for $\psi=90^\circ$, to 10 nanoseconds for $\psi=0$. The maximum V_{OC} for vertical is given as:

$$V_{OC}^v = 4hE_0$$

This is twice as large as the peak voltage for horizontal.

SEMI-INFINITE LOSSY LINE

Up to this point, all the materials have been perfect: perfect conductors and perfect insulators. In the "real world" there is no such thing as a perfect conductor or insulator. Therefore, if a "real world" voltage is to be found, "real world" material must be considered. This means that the assumption that $\tau=1$ can no longer be made.

Substitution of the "real world" lossy line propagation constant ($\gamma = \gamma_0 H(j\omega)$) into equations (5-10) and (5-11), yields the V_{OC} transfer function for a lossy line:

$$V_{OC}^h(j\omega) = c \sin(\theta) [(1 + R_h e^{-j\omega T_c})] / j\omega [H(j\omega) - \cos(\theta) \cos(\psi)]$$

$$V_{OC}^v(j\omega) = c \sin(\psi) \cos(\theta) [(1 - R_v e^{-j\omega T_c})] / j\omega [H(j\omega) - \cos(\theta) \cos(\psi)]$$

Noting that the Fourier transform of the EMP waveform is:

$$E(\omega) = \frac{(\beta - \alpha) E_0}{(j\omega + \alpha)(j\omega + \beta)}$$

The complete "real world" response can now be found. To get the time domain response, the inverse Fourier transform must be found. This is no easy matter. Equation 5-16 and 5-17 show the integral that must be solved.

$$V_{OC}^h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V_{OC}^h(j\omega) E(\omega) e^{j\omega t} d\omega \quad (\text{Eqtn 5-16})$$

$$V_{OC}^v(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V_{OC}^v(j\omega) E(\omega) e^{j\omega t} d\omega \quad (\text{Eqtn 5-17})$$

Numerical techniques must be used to evaluate the integrals in equation (5-16) and (5-17). A fast fourier inversion routine was used to obtain results for worst-case angles of incidence over a range of typical earth conductivities, (10^{-3} to 10^{-1} mhos per meter) and a nominal line height of 10 meters for which the results follow:

The maximum peak V_{OC} for vertically polarized waves increases from about 2Mv to more than 7Mv. This change is caused by the fact that the reflection coefficient is not unity, and thus the reflected wave does not completely cancel the incident wave. The horizontal reflection coefficient does not change very much in magnitude or phase, and therefore, the cancellation of the incident wave is more like the ideal case. Table 5-1 gives peak V_{OC} , peak short circuit currents, time to peak, critical length of line and angle of incidence for maxima for both polarizations for a typical power line to meters high with $Z_c = 500$ ohms.

TABLE 5-1. Summary of EMP coupling to long lines.

Earth Conductivity σ_g mhos/m	Maximum Peak Open-Circuit Voltage (MV) Voc	Maximum Peak Short-Circuit Current (kA) Isc	Time to peak tp(ns)	Critical length of line (km)	Angle of Incidence ψ Degree
Horizontal Polarization $\theta = \psi$					
0.001	0.96	1.9	180	0.092	50
0.01	0.94	1.88	40	0.067	25
0.1	0.96	1.9	20	0.14	12
-	1.0	2.0	10	-	0
Vertical Polarization $\theta = 0$					
0.001	5.4	10.8	270	3.7	12
0.01	6.2	12.4	140	7.6	6
0.1	7.25	14.5	90	10	4
-	2.0	4.0	10	-	0

CURRENT ON A LINE

Now that an expression for the voltage induced on a long line has been found, the current flowing in the line can be determined. This is needed in order to find the voltage induced on a conductor inside a shielded cable. But first, the characteristic impedance " Z_0 " and propagation factor " γ " must be found.

$$Z_0 = (Z/Y)^{1/2}$$

$$\gamma = (ZY)^{1/2}$$

Where Z is the series impedance per unit length of line, and Y is the shunt admittance per unit length of line.

CHARACTERISTIC IMPEDANCE

As a review, remember that Z_0 relates the E and H fields both in magnitude and in phase. The higher the Z_0 , the smaller the H field for a given E.

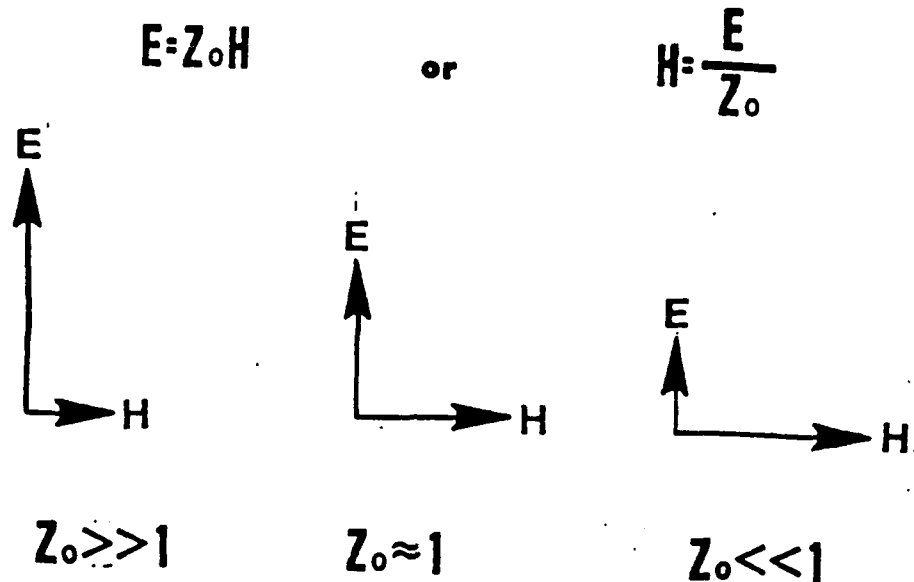


FIGURE 5-21. Relation of E to H fields.

SERIES IMPEDANCE

The first part of the characteristic impedance is the series impedance per unit length. It is composed of three components: (1) the inductive reactance, "L", associated with the magnetic field between the cable and the ground; (2) the internal impedance of the ground plane, " Z_g "; and (3) the internal impedance of the cable, " Z_i ".

The inductive reactance per unit length of a cable of radius "a" at a height "h" above a ground plane is:

$$j\omega L = j\omega(\mu_0/2\pi) \cosh^{-1}(h/a) = \frac{j\omega\mu_0}{2\pi} \ln \frac{h}{a} \left\{ 1 + [(1 - (a/h)^2)^{-1/2}] \right\}$$

If $h \gg a$ then a logarithmic function can be used.

$$j\omega L \approx j\omega(\mu_0/2\pi) \log(2h/a) \quad \text{where } \mu = 4\pi \times 10^{-7} \text{ H/M}$$

The internal impedance per unit length of the finite conducting ground plane is given approximately by:

$$Z_g = (1+j)/(4\pi h \sigma \delta) \quad \delta \ll 2h \text{ and } \sigma \gg \omega \epsilon$$

$$Z_g = [(\omega\mu)/8] + j\omega(\mu/2\pi) \log\{\delta/[2(1-\gamma_0 h)]\} \quad \delta \gg 2h$$

Where δ is skin depth and is equal to $1/(\pi f \mu \sigma)^{1/2}$ and f is frequency.

If the ground plane is earth, or another poor conductor, then the impedance of the wire is negligible in comparison. But if the ground plane is metal, the impedance of the cable and that of the ground plane are close enough that the impedance of the cable must be taken into account. For example purposes, this text will use an expression for the internal impedance with an external return as found in "Coupling to Shielded Cables," by Vance.

$$Z_i = i/(\pi a^2 \sigma) \quad \text{for } \delta \gg a$$

$$Z_i = (1+j)/(2\pi a \sigma \delta) \quad \text{for } \delta \ll a$$

SHUNT ADMITTANCE

The next part of the characteristic impedance is the shunt admittance per unit length. This term is usually dominated by the capacitive reactance between the cable and ground plane.

$$\begin{aligned} j\omega C &= j\omega[(2\pi\epsilon_0)/\cosh^{-1}(h/a)] \\ &\approx j\omega[(2\pi\epsilon_0)/\log(2h/a)] \quad (h \gg a) \end{aligned}$$

If, however, the total admittance of the ground plane must be taken into account, it can be estimated from:

$$Y_g = Y_s + Z_g$$

Where $Y_s = [j\omega\mu_0(\sigma + j\omega\epsilon)]^{1/2}$, and Z_g is the internal impedance per unit length of the ground plane.

TOTAL IMPEDANCE

The characteristic impedance of a transmission line is primarily dependent on the equivalent radius of the line, and the average height of the lines, and is as follows:

$$Z_0 = (L/c)^{1/2} \{ [1 + 1/2 \log(2h/a)] \} \log \{ [1 + (j\omega\tau_h)^{1/2}] / (j\omega\tau_h)^{1/2} \} + 1/(j\omega\tau_a)^{1/2} \}$$

$$\text{Where } \tau_h = \mu_0 \sigma_g h^2 \text{ and } \tau_a = \mu_0 \sigma_c a^2$$

This can, in most cases, be approximated by:

$$Z_0 \approx (\eta_0/2\pi) \log(2h/a)$$

Where η_0 is the impedance of free space (377 ohms) and "a" is the effective radius of the conductor. If the conductor is over a metal ground plane, the impedance of the cable, as mentioned earlier, becomes significant, compared to that of the ground plane, and must be taken into account. Taking this into account, the impedance of the cables become:

$$Z_0 = 60 \cosh^{-1}(h/a) \text{ or } Z_0 = 60 \log(2h/a) \text{ for } (h \gg a)$$

PROPAGATION CONSTANT

The propagation constant " γ " relates how the wave behaves as it travels down the cable. It is, in general, a complex number, composed of a real part " α ", and an imaginary part " β ". The real part is the attenuation constant, and the imaginary part is the phase constant.

$$\gamma = \alpha + j\beta$$

Where β is the phase constant given by:

$$\beta = \text{Im}(ZY)^{\frac{1}{2}} \text{ where Im means the imaginary part of } (ZY)^{\frac{1}{2}}$$

and

$$\alpha = 1/(2Z_0)[1/2\pi a \left(\frac{\pi f}{\sigma} c\right)^{\frac{1}{2}} + (1/4) h \left(\frac{\pi f}{\sigma}\right)^{\frac{1}{2}}]$$

Where μ_c is the permeability of the cable shield, σ_c is the conductivity of the cable shield, μ is the permeability of the ground plane, σ is the conductivity of the ground plane, and f is frequency.

The value of the attenuation constant, given above, is applicable to high frequencies such that:

$$f > 1/(\pi \mu_c \sigma_c T_c^2)$$

and

$$f > 1/(\pi \mu \sigma T_g^2)$$

Where T_c and T_g are the wall thickness of the cable shield and the ground plane, respectively.

The attenuation constant α and the phase factor β are needed for the directivity function. The equations given earlier were good approximations when $\beta = k$, and when α/k is negligible. Where " k " is the wave number and is equal to ω/c , these assumptions are safe for good conducting ground planes such as metal or aerial transmission lines when the angles of incidence are large. If the ground plane is not a good conductor, as in composite skinned aircraft, for $\cos(\theta) \cos(\psi) \approx 1$, you must take the propagation constant into account. The complete directivity functions are given by:

$$D_h(\theta, \psi) = \sin(\theta) / [(\alpha c / j\omega) + (\beta/k) - \cos(\psi) \cos(\theta)]$$

$$D_v(\theta, \psi) = \sin(\psi) \cos(\theta) / [(\alpha c / j\omega) + (\beta/k) - \cos(\psi) \cos(\theta)]$$

If we use the above equations, we can find a more exact approximation of the voltage induced on a long line. If we divide this voltage by the characteristic impedance, we will get the current flowing through the cable which may be the outer shield of a shielded cable and can be expressed as the following equation:

$$I_{SC}(\omega) = (1/Z_0) \int_{-\infty}^0 e^{(\gamma z)} E_z(z, \omega) dz$$

COUPLING TO SHIELDED CABLES

One way that EMP can be coupled to the inner conductor of a shielded cable, is by the field produced by the current which flows in the shield. Another, is by holes in the shield; i.e., braided shields. The first can be modeled as a voltage source that is equal to the current flowing in the shield, times a transfer impedance (Z_t). The second, is a current source that is equal to the voltage between the internal conductor, and the external structure, times a transfer admittance. This voltage is very close to the voltage of the shield, because the voltage between the shield, and the inner conductor is small, compared to V_0 . If $I_0 Z_t \gg V_0 Y_t Z_{1,2}$, the transfer admittance term can be neglected. $Z_{1,2}$ stands for the load impedance at either end of the line. Both ends must meet this requirement.

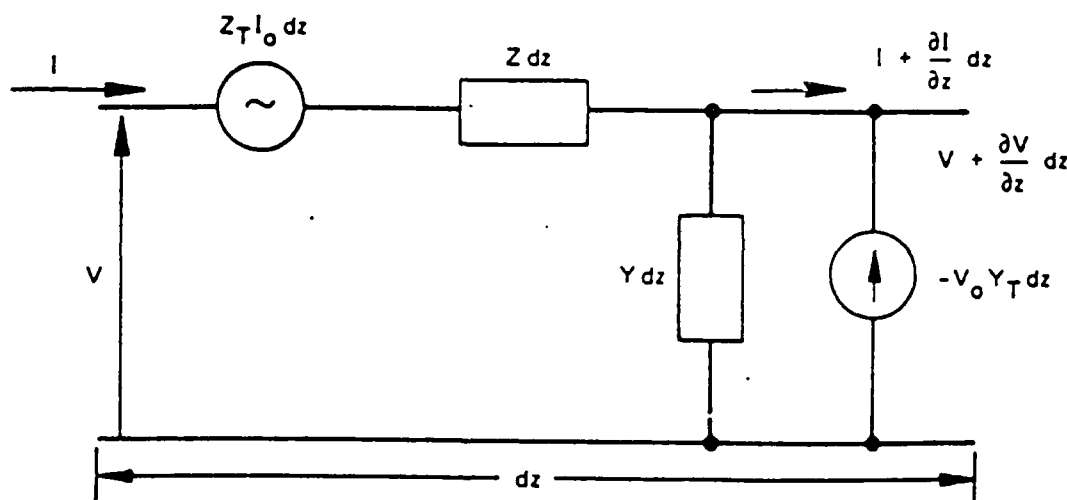


FIGURE 5-22. Equivalent circuit for the internal circuit when both the transfer impedance and the transfer admittance are included.

TYPES OF SHIELDS

The following types of shields will be discussed: Solid thin walled tube, braided wire and tape-wound or spiral shields. The use of ferromagnetic shields will then be discussed briefly.

The general form of the transfer impedance is given by:

$$Z_t = \frac{1}{I_0} \frac{dV}{dz} \quad I = 0$$

Where I_0 is the total current flowing in the cable, I is the current flowing in the conductor, and dV/dz is the voltage per unit length generated by this current flowing along the transmission line formed by the shield, and the conductors inside the shield. The transfer impedance gives the V_{oc} developed between the internal conductors, and the shield for one ampere of shield current in a cable, one meter long (at wavelengths much greater than one meter).

SOLID TUBULAR CABLE

In a solid, thin walled, tubular shield, the only way EMP can be coupled to the inner conductor, is by diffusion of the electromagnetic fields through the walls of the tube. Thus the current source can be neglected. The transfer impedance of a thin walled tubular shield is given as:

$$Z_t = [1/(2\pi a \sigma T)] [(1+j)T/\delta] / \sinh[(1+j)(T/\delta)]$$

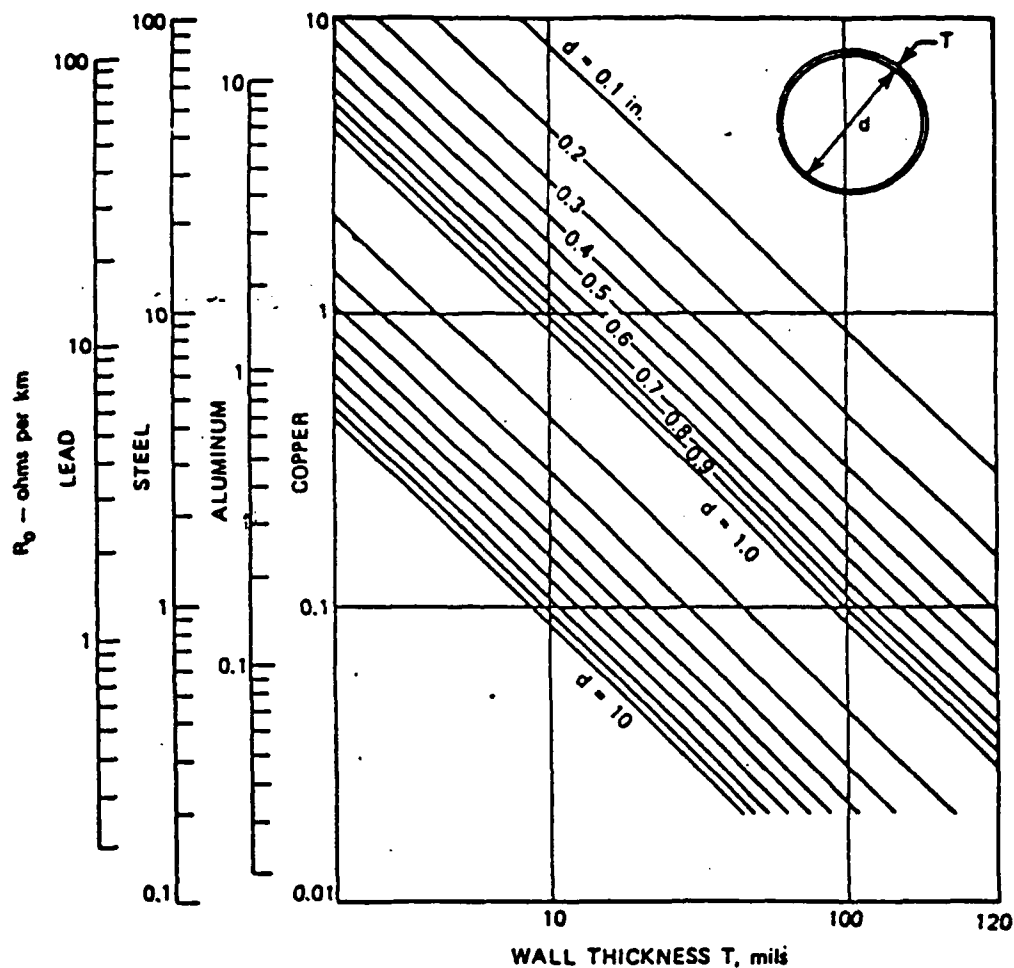
Where " a " is the radius of the shield, " T " is the thickness of the wall of the shield, σ is the conductivity of the shield, and δ is the skin depth in the shield, given by:

$$\delta = (\pi f \mu \sigma)^{-1/2}$$

It is assumed that the wall thickness T is small, compared to the radius " a " of the tube. At low frequencies, such that $T/\delta \ll 1$, the magnitude of the transfer impedance is:

$$|Z_t| \approx 1/(2\pi a \sigma T) = R_0, \quad (T/\delta \ll 1)$$

Where R_0 is the dc resistance of the tube per unit length. Some values of R_0 for typical shielding materials can be obtained from Graph 5-5.



GRAPH 5-5. Magnitude of R_0 for common shielding materials.

The magnitude of the transfer impedance at high frequencies is:

$$|Z_t| = (8)^{\frac{1}{2}} (e^{-T/\delta}) R_{hf} \quad (T/\delta) \gg 1$$

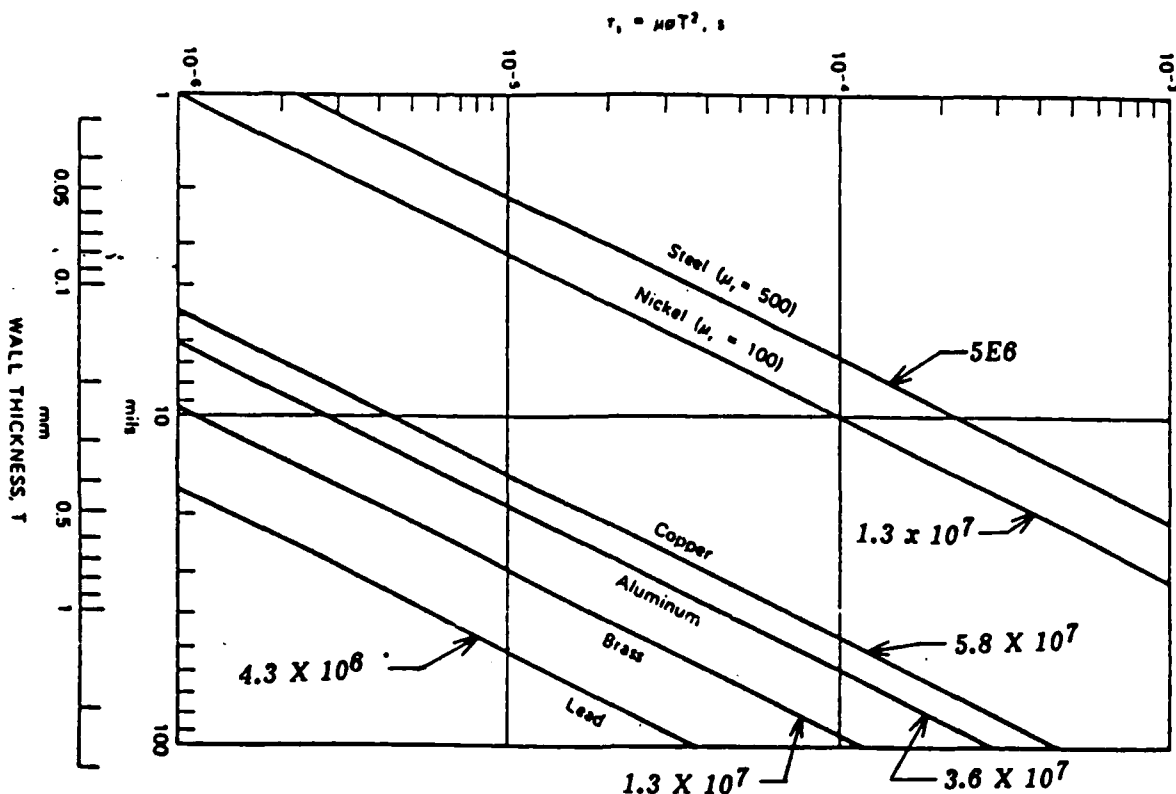
$$\text{Where } R_{hf} = 1/(2\pi a \delta \sigma)$$

If we set $(1+j)(T/\delta) = (j\omega\tau_s)^{\frac{1}{2}}$ where τ_s is the shield diffusion time constant defined by $\tau_s = \mu\sigma T^2$, the shield transfer impedance is then given by:

$$Z_t = R_0 (j\omega\tau_s)^{\frac{1}{2}} / \sinh[(j\omega\tau_s)^{\frac{1}{2}}]$$

$$\tau_s = 1/(\pi f)(T/\delta)^2 = 1/(\pi f\delta) \quad \text{where } f_\delta \text{ is the frequency where } T/\delta = 1.$$

Some values of τ_s for typical shielding materials can be obtained from Graph 5-6.



GRAPH 5-6. Diffusion time for various metals.

RESPONSE OF SHORT CABLE

The response of an electrically short cable that has a shield dc resistance per unit length R_0 , and the total shield current flowing in it is of the form $I_0 e^{-t/\tau}$, is given by:

$$V(\omega) = [(I_0 R_0 l)/2] (j\omega\tau_0)^{1/2} / [(j\omega + 1/\tau) \sinh(j\omega\tau_0)^{1/2}]$$

This equation assumes a current peak at the center conductor, which has a matched load or open at both ends.

Where I_0 is the peak current flowing in the shield. This equation gives the voltage developed between the center conductor and the shield.

The length " l ", for which the electrically short cable approximation is valid, is a function of the diffusion time constant, and the wall thickness. If $l \ll c\tau_0/(\epsilon_r)^{1/2}$, then the short cable approximation is valid.

For completeness, the current in the center conductor is found by:

$$I(\omega) = V(\omega)/Z_0$$

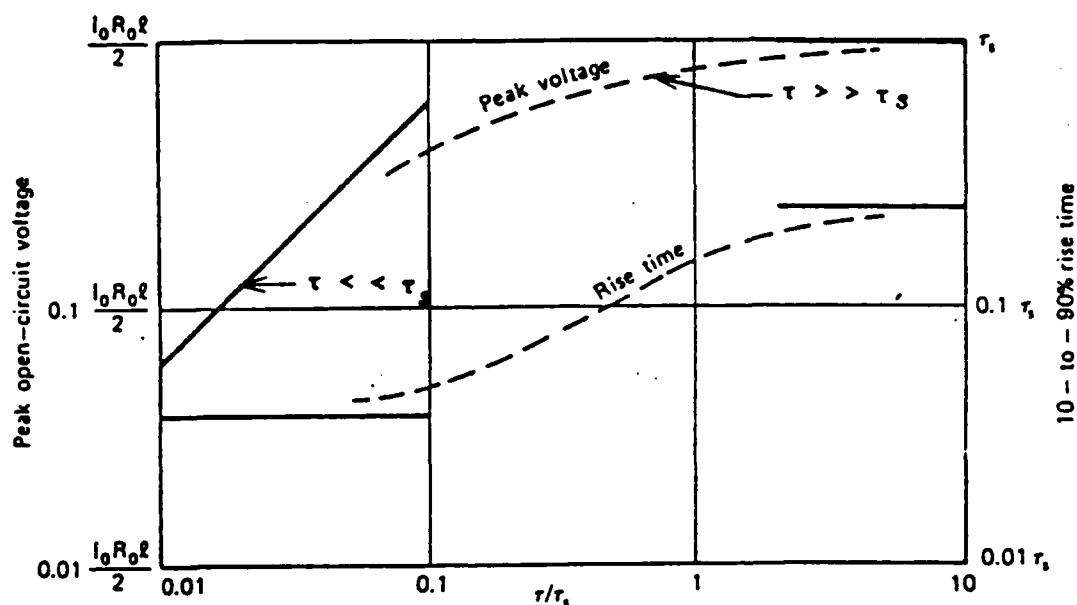
Where Z_0 is the characteristic impedance of the center conductor for a matched load at the far end and at the near end.

The time domain equations are very long and complex, and beyond the scope of this course. They can be found in "Coupling To Shielded Cables", by Vance. However, the peak voltage, and 10% to 90% rise time can be found quite easily for given regions, $\tau \gg \tau_s$, $\tau = \tau_s$, $\tau < \tau_s$. These values are given by the following:

$$\begin{aligned} V(t)_{\text{Peak}} &= (I_0 R_0 l) / 2 && \text{for } \tau \gg \tau_s \\ &= 0.77 (I_0 R_0 l) / 2 && \text{for } \tau = \tau_s \\ &= 5.9 (\tau / \tau_s) (I_0 R_0 l) / 2 && \text{for } \tau < \tau_s \end{aligned}$$

The 10% to 90% rise times are:

$$\begin{aligned} t_{10-90} &= 0.236 \tau_s && \text{for } \tau \gg \tau_s \\ &= 0.15 \tau_s && \text{for } \tau = \tau_s \\ &= 0.038 \tau_s && \text{for } \tau < \tau_s \end{aligned}$$



GRAPH 5-6a. Variation of Peak Open-Circuit Voltages and rise times.

EXAMPLE 5-2:

GIVEN:

A lead sheathed cable, 2" in diameter, with a 100-mil thick sheath is one mile (1.6km) long, and is subjected to an exponential sheath current of 1000 amps, with decay time constant " τ " of 1 micro-second.

FIND:

The peak voltage developed at the ends of the cable across the matched load impedances Z_0 .

SOLUTION:

From Graph 5-6, $\tau_s = 3.5 \times 10^{-5}$ for the lead sheath, and $\tau_{sc} = 10.5\text{km}$, so the 1.6km segment is electrically short for the penetrating frequencies, and for low dielectric constant insulation. The diffusion time constant τ_s is much larger than τ , $\tau/\tau_s = 2.86 \times 10^{-2}$. The peak voltage can be approximated by $5.9 (\tau/\tau_s)(I_0 R_0 l/2)$. From Graph 5-5, R_0 is 0.55 ohms/km. Therefore, $I_0 R_0 l/2 = 0.274 \times 1000 \times 1.6 = 440\text{v}$. Looking at Graph 5-6a, the open circuit voltage is estimated to be $V_{oc} = 0.189(440) = 74$ volts. The 10% to 90% rise time is $0.038 \tau_s = 1.33 \times 10^{-6}$. The waveform would be the form of that shown in Figure 5-23a.

Figure 5-23 shows the normalized waveforms of a short cable for the three cases given above.

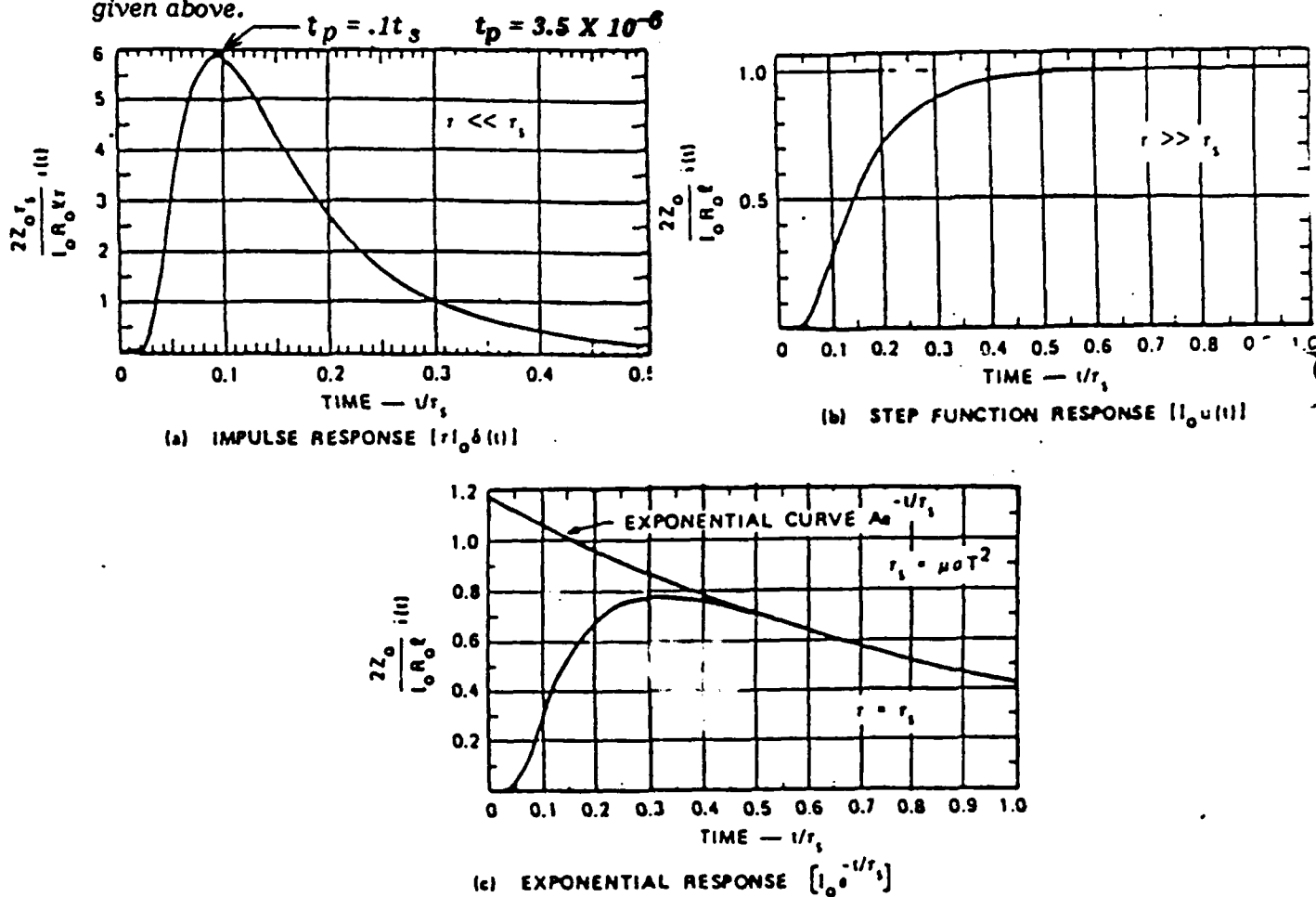


FIGURE 5-23. Normalized waveforms for a short cable.

BRAIDED-WIRE SHIELDS

The most common type of shield used, is a braided-wire type. When properly made, this type of shield is almost, but not quite, as good as the solid tubular type of shield. The weaving of the braided-wire shield is described in terms of the number of carriers (bands or groups of wires) that make up the shield, the number of ends (strands of wire) in each carrier, the number of picks (carrier crossings) per unit length, and the weave angle or angle between the carrier, and the axis of the shield.

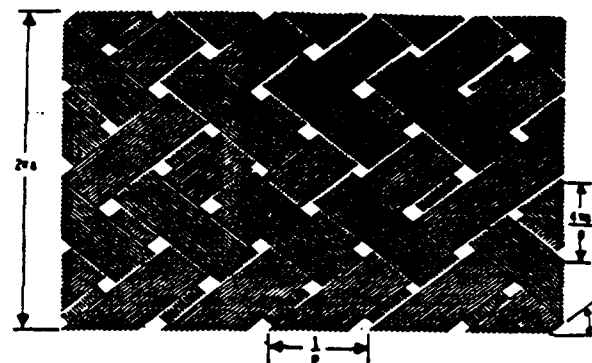
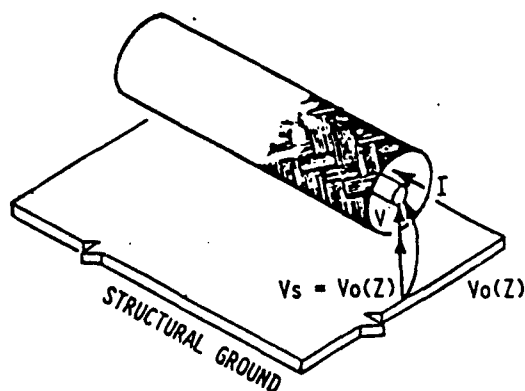


FIGURE 5-24. Sample of a typical braided-wire shield.

WEAVE CHARACTERISTICS

The five properties of a braided shield needed to define its characteristics are: (1) the radius "a" of the shield, (2) the number of carriers "C" in the braid, (3) the picks "P", (4) the ends "N", and (5) the wire diameter "d".

The principal characteristics of interest are:

$$\text{Weave angle: } \alpha = \tan^{-1} \frac{4\pi(a+d)P}{C} \quad (\text{Eqtn 5-18})$$

$$\text{Fill: } F = (PNd)/\sin(\alpha) = \frac{NdC}{4\pi(a+d)\cos(\alpha)} \quad (\text{Eqtn 5-19})$$

$$\text{Optical coverage: } K = 2F - F^2 \quad (\text{Eqtn 5-20})$$

$$\text{volume of metal: } v = \pi^2 adF \quad (\text{Eqtn 5-21})$$

In the above expressions, and all the following discussions, it is assumed that the strand diameter "d", and the aperture dimensions are small compared to the shield radius "a" and that the shield radius "a" is small, compared to the shortest wavelength of interest.

EXAMPLE 5-3:

GIVEN: The weaving data for a braided wire shield are:

Shield radius: $a = 1 \text{ cm} = 0.01 \text{ m}$
 Strand Diameter: $d = 6.3 \text{ mils} = 1.6 \times 10^{-4} \text{ meters}$
 Weave angle: $\alpha = 30^\circ$
 Number of carriers: $C = 48$
 Strands per carrier: $N = 11$

FIND: The optical coverage "K," and the Picks "P".

SOLUTION:

Solving equation (5-18) for the picks "P" results in:

$$P = \frac{\tan(\alpha)C}{4\pi(a+d)} = \frac{\tan(30)48}{4\pi(0.01+160 \times 10^{-6})} = 217.1$$

Using the value in Equation 5-19, the fill can be found by:

$$F = PNd/\sin(\alpha) = 0.7642$$

$$\text{The shield coverage is therefore } K = 2F - F^2 = 0.94$$

The result of the apertures in the shield is to allow some of the circumferential magnetic field associated with the current in the shield to penetrate and link the center-conductor which produces a mutual inductance between the shield circuit and the inner-conductor circuit. Also, some of the external electric flux, associated with the shield potential, can penetrate through the apertures and induce some charges on the conductor inside the shield.

TRANSFER IMPEDANCE

The transfer impedance of a braided-wire shield is quite a bit more complicated than that of a tubular shield. It not only contains a term for the diffusion of the field through the shield, Z_d , but also contains a term, M_{12} , for the penetration of the field through the holes in the braid.

$$Z_d = \{4/[\pi d^2 N C \cos(\alpha)]\} [(1+j)d/\delta]/\sinh[(1+j)d/\delta] \quad (\text{Eqtn 5-22})$$

$$M_{12} = \frac{\pi \mu_0}{6C} (1-K)^{3/2} \frac{e^2}{E(e)-(1-e^2)K(e)} \quad (\alpha < 45^\circ) \quad (\text{Eqtn 5-23a})$$

where

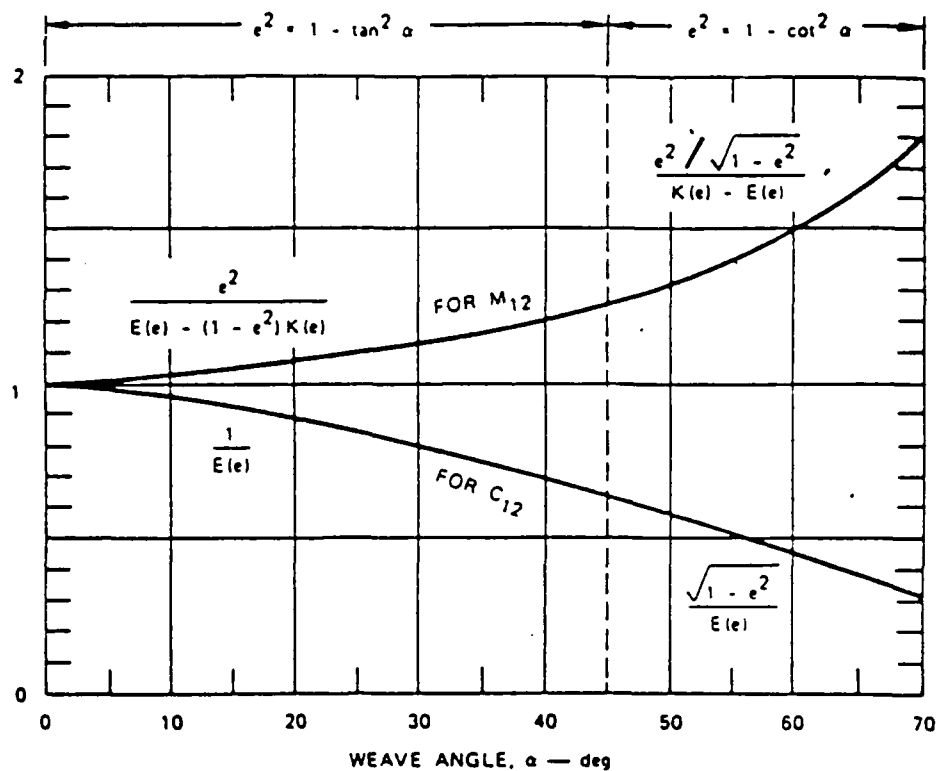
$$e = (1 - \tan^2 \alpha)^{1/2}$$

$$M_{12} = \frac{\pi \mu_0}{6C} (1-K)^{3/2} \frac{e^2/(1-e^2)^{1/2}}{K(e)-E(e)} \quad (\alpha > 45^\circ) \quad (\text{Eqtn 5-23b})$$

where

$$e = (1 - \cot^2 \alpha)^{1/2}$$

The quantities $2/(E(e)-(1-e^2)K(e))$ and $[e^2/(1-e^2)^{1/2}]/[K(e)-E(e)]$, are called eccentricity functions, and are shown in Graph 5-7, "K" is the optical coverage, "C" is the number of carriers, and $K(e)$ and $E(e)$ are the complete elliptic integrals of the first and second kinds, respectively.

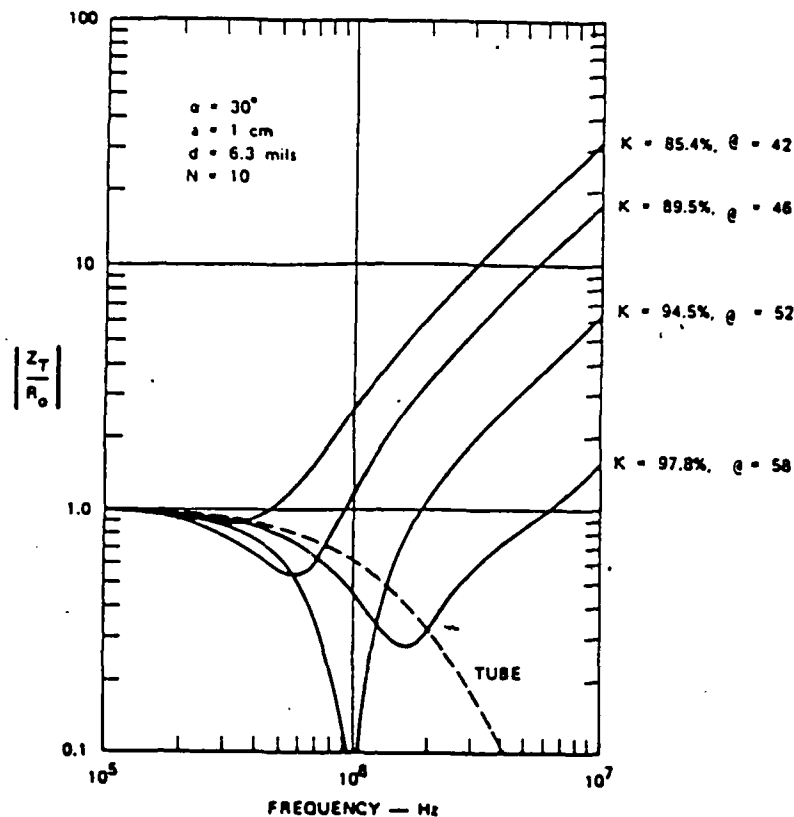


GRAPH 5-7. Eccentricity Functions for Braided-Wire Shields.

The diffusion term Z_d is based on the assumption that the shield behaves as a tubular shield with the same dc resistance per unit length as the braided shield, and the same high frequency characteristics as a tubular shield that is one wire diameter thick.

The mutual inductance term is based on the assumption that the shield behaves the same as a tubular one, with holes of the same size, shape, and placement as that made by the braided wire types.

These expressions can be considered accurate, to within a factor of 3 for high frequencies, when $\omega M_{12} \gg |Z_d|$, and very accurate at low frequencies ($d/\delta \ll 1$) (where "d" is the strand diameter and δ is the skin depth. As you probably noticed, for low frequencies, the Z_d term is just the Z_t term given previously with R_0 replaced with $4/[\pi d^2 N C \sigma \cos(\alpha)]$. You would, therefore, expect the response to be similar. Graph 5-8 shows a relation between "K" and "C" to Z_t . As you can see, the braided shield transfer impedance approaches that of a solid tubular type, as the coverage, "k", approaches 100%, and the frequency goes down. The nulls in the plot are caused by resonance in the cable.



GRAPH 5-8. Transfer impedance of a braided-wire shield.

TRANSFER ADMITTANCE

The transfer admittance relates the voltage on the shield to the current on the center conductor. It is generally given by:

$$Y_t = \frac{1}{V_o} \frac{dI}{dz} \bigg|_{v=0}$$

The transfer admittance of a braided-wire shield is:

$$Y_t = j C_{12}$$

Where:

$$C_{12} = g[\pi C_1 C_2 / (6\epsilon C)] (1-K)^{3/2} [1/E(e)] \quad (<45^\circ)$$

$$C_{12} = g[\pi C_1 C_2 / (6\epsilon C)] (1-K)^{3/2} [(1-e^2)^{1/2} / E(e)] \quad (>45^\circ)$$

C_1 is the capacitance per unit length between the internal conductor and the shield, and C_2 is the capacitance per unit length between the shield and the external circuit. The "g" is a correction factor used when the dielectrics inside the cable and

outside the cable are not the same. This is given as: $g = 2\epsilon_1/(\epsilon_1 + \epsilon_2)$. Where ϵ_1 is the dielectric of the inner insulator, and ϵ_2 is the dielectric of the outer insulator or media (the outer jacket, if it is thick). If the outer jacket is thick, and is the same as the inner insulator, $g=1$. For typical polyethylene insulated cable, this factor is 1.4. The transfer admittance can, in most cases, be omitted if an exact solution is not needed.

EXAMPLE 5-4:

GIVEN:

The cable in the preceding example is subjected to a shield current that rises exponentially to a 1KA with a time constant " τ " of 2.5ns, if the shield is woven from copper wire.

Where $I(t) = 1000e^{-t/\tau}$ and $\tau = \frac{1}{\delta}$ (fall time)

FIND:

The open-circuit voltage induced between the internal conductor and the shield for a 1 meter cable. We will neglect the mutual capacitance.

SOLUTION:

From the preceding example, the fill is 0.776, and the coverage is 95%. The dc resistance is given by $[(4/\pi d^2 NC \sigma \cos(\alpha))] = 1.87$ milli-ohms/meter, and the diffusion time constant is $\tau_s = \alpha \mu_0 d^2 = 1.87$ microseconds. From Graph 5-7, and equation 5-20, the value of the eccentricity function is 1.14, and the value of $(1-K)^{3/2} = 0.011$. Using these values in equation 5-23a, $M_{12} = 1.7 \times 10^{-10}$. The transfer impedance can now be written:

$$Z_t = 1.87 \times 10^{-3} (1.87 \times 10^{-6} j\omega)^{1/2} / \sinh[(1.87 \times 10^{-6} j\omega)^{1/2}] + j\omega(1.7 \times 10^{-10})$$

Where the first term is due to the diffusion of the field through the shield and the second term is from the inductive coupling of the field through the shield.

The responses to the two terms can be solved separately, and combined by superposition later. The V_{oc} induced by the inductance term can be obtained directly in the time domain, and is:

$$V_m(t) = \frac{M_{12}l}{2} \frac{di_o(t)}{dt} = 35e^{-t/\tau} \text{ (volts)}$$

The response to the diffusion term is:

$$V_d(t) \Big|_{\tau \gg \tau_s} = \frac{I_o R_o l}{2} = 0.94$$

TAPE-WOUND AND SPIRAL SHIELDS

Tape, or spiral shields are often used where flexibility of the shielded cable is required. However, they make a poor shield for preventing coupling of current to the inner conductor. This occurs because the shield spirals around the center conductor, creating a large mutual coupling term. For a large $di_o/dt(j\omega I_o)$ the voltage can become

large enough to arc between the turns. This will reduce the inductance and actually improve the shielding; however, the arc not only produces RF on the cable, which may be a problem, (i.e., create RF in the passband of a receiver), but may damage the cable. For a single layer tape-wound shield, in which the turns do not overlap, or even touch, the voltage produced on the internal conductor is comprised of three (3) parts:

- 1) The diffusion of the axial part of the shield current through the wall of the shield.
- 2) The azimuthal internal impedance drop produced by the axial magnetic field inside the shield.
- 3) The inductance drop, resulting from the axial magnetic flux flowing through the spiral.

The parameters of a spiral shield are given as follows:

$$\cos \alpha = \frac{W}{2\pi a} \quad \text{Where } W \text{ is shield width, } a \text{ is radius, and } \alpha \text{ is the spiral angle} \quad (\text{Eqtn 5-24})$$

$$N = \frac{\sin \alpha}{W} \quad \text{Where } N \text{ is the number of turns per unit length.} \quad (\text{Eqtn 5-25})$$



FIGURE 5-25. Important parameters of a spiral shield.

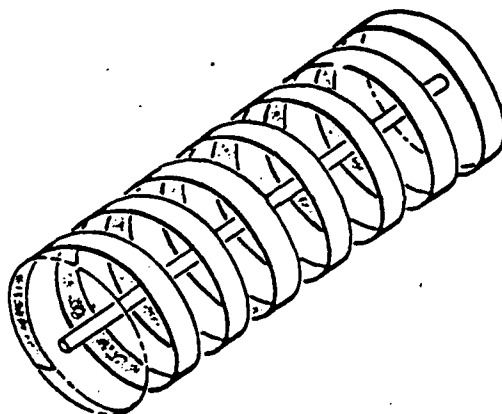


FIGURE 5-26. Spiral Shield.

The transfer impedance Z_t normalized to the dc resistance per unit length R_0 of a tubular shield of the same thickness T and radius a is:

$$\frac{Z_t}{R_0} = \frac{[(1+j)T/\delta][1 + \tan^2 \alpha]}{\sinh [(1+j)T/\delta]} + j(T/\delta_0)^2(a/T)\tan^2(\alpha) = \frac{j\omega M_{12}}{R_0}$$

Where δ is the skin depth in the shield, and δ_0 is the skin depth for an equivalent nonferrous shield ($\mu = \mu_0$).

For low frequencies, $T/\delta_0 \ll 1$, the transfer impedance increases with increasing spiral angle α . This could be expected, due to the fact that with a larger spiral angle, comes a more narrow tape width, and thus more turns per inch. At high frequencies, $(T/\delta_0) \gg 1$, the transfer impedance is dominated by the inductance term. It also increases as the spiral angle increases. **NOTE: THE CAPACITANCE BETWEEN THE TURNS HAS BEEN NEGLECTED IN DERIVING THE ABOVE EQUATION.** This capacitance is important at high frequencies, where the spiral-wound tape becomes self resonant.

EXAMPLE 5-5:

GIVEN: A tape-wound shield on a 1 cm radius cable is wound with a 10 mil thick, 1 cm wide, copper tape, without overlap.

FIND: The dc resistance and the mutual inductance per unit length for this shield.

SOLUTION: From equation 5-24, $\cos(\alpha) = w/2\pi a = 0.159$, or $\alpha = 80.8^\circ$. The dc resistance with $\tau/\delta \ll 1$ is:

$$R_{dc} = R_0[1 + \tan^2(80.8^\circ)] = 42.7 \text{ milli-ohm/m.}$$

The mutual inductance is:

$$M_{12} = (\mu_0/4\pi)\tan^2(\alpha) = 3.85 \times 10^{-6} \text{ H/m.}$$

This is four orders of magnitude greater than the value obtained for the braided-wire shield.

OVERLAPPED TAPE

The HF characteristics of a single-layer overlapped shield with an overlap width w_0 can be obtained by substituting $w-w_0$ for w in equations 5-24 and 5-25. The resultant transfer impedance will be too large at low frequencies, by a factor of $w/(w-w_0)$, and the capacitance between the overlap must be taken into account for very high frequencies because it will begin to short out the inductance so that the magnitude of the transfer impedance will reach a maximum and then begin to decrease.

TAPE WITH GAP

If the tape-wound shield has a gap between the turns, it can be treated in a similar manner as the overlapped tape. Just replace w in equations 5-24 and 5-25 with $(w+w_0)$. For low frequencies, this "fix" will produce a value that is too low, by an amount

$w/(w+w_0)$. The leakage inductance of this shield is so large that the low frequency diffusion is often of only passing interest. Since the optical coverage is less than 100%, there is a transfer admittance as well. This admittance is:

$$Y_t = j\omega C_{12}$$

with

$$C_{12} = (C_1 C_2 w_0^2) / [64 \pi \epsilon a^2 \cos(\alpha)]$$

Where C_1 and C_2 are the capacitances per unit length, as previously defined and where:

- ϵ = permittivity of insulation inside the cable
- a = shield radius
- w_0 = gap between turns
- α = spiral angle

This is good for all tape wound shields.

FERROMAGNETIC

The use of tubular shields made of ferromagnetic materials may be attractive from the viewpoint of high frequency shielding. However, the shielding is lost when the material becomes saturated. Also, ferromagnetic materials do not have the high conductivity that other materials have, therefore, they are not as good a shield as are conductive materials such as copper or aluminum. So they are not used generally as shielding material.

MULTIPLE SHIELDS

In order to improve the shielding of a cable, often times more than one shield and/or type of shield is used. One way to find the transfer impedance and admittance is to analyze each shield separately, until all shields have been accounted for. An equivalent transfer impedance and admittance can usually be obtained in this manner for two layer shields, assuming that a standing wave is not supported in the transmission line formed by the shields. In practice, this is a safe assumption if one of the following is satisfied:

- a. The frequencies that stimulate standing waves cannot penetrate the outer shield (e.g., solid tubular).
- b. The shields are in contact with each other at electrically short spacings along the cable.
- c. The shield-to-shield transmission line is very long, and terminated in its characteristic impedance, or very lossy, so that reflections from the ends do not build up standing waves.

CONNECTORS AND SPLICES

The connector or splice is also a source of EMP coupling. It can be visualized as a region in the cable that may contain cracks or splits in the shielding, allowing the external EMP to couple to the internal region. Connectors and splices form such a complex configuration that their transfer impedance and admittance are almost always found by testing. A typical connector test set-up is shown in Figure 5-27.

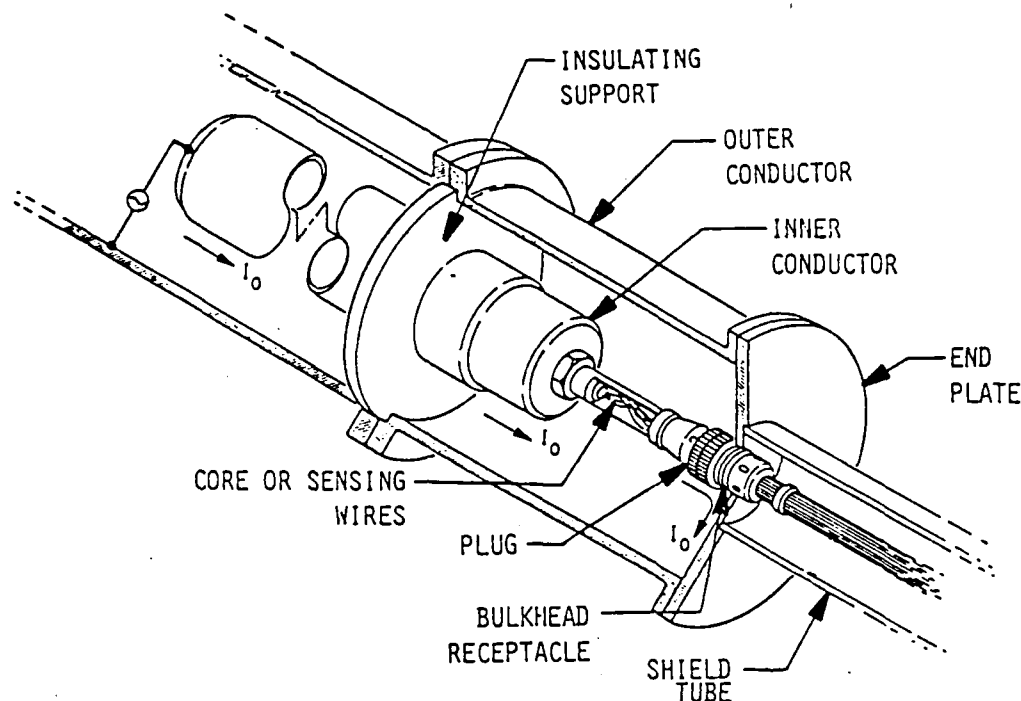


FIGURE 5-27. Connector Test Device.

MEASUREMENT OF SHIELDING

The transfer impedance of a cable shield is, as defined earlier, the V_{oc} per unit length induced on a conductor inside the shield by one ampere of shield current. The transfer admittance is the short circuit current per unit length produced by one volt of external shield potential. The most common method used to obtain these parameters, is by testing a section of the cable. One way to test a cable is to use what is called the "trough test". In this test the cable in question is suspended in a conductive trough. It is then driven in one of two ways depending on if the transfer impedance or admittance is to be obtained.

In the transfer impedance configuration, the conductive trough is connected to the shield and drives the shield with a current (I_o) negligible voltage, and the open circuit voltage (V_{oc}) induced on the center conductor is recorded. The transfer impedance is approximated by:

$$Z_t = V_{oc}/I_o l_s \quad (l_s \ll \lambda)$$

In the transfer admittance configuration, the conductive trough is isolated from the shield and develops a Voltage V_0 between the shield and trough. A short circuit current I_{sc} is then induced in the center conductor which has one end connected to ground. The transfer admittance can be found by:

$$Y_t = I_{sc}/V_0 l_s \quad (l_s \ll \lambda)$$

Where V_0 is the voltage difference between the shield and the test set.

In both of the test configurations, the test sample "l" must be short, compared to the wavelength of the excitation signal.

Another test currently being studied involves the use of a network analyzer such as the HP3577A. The output of the network analyzer is connected to an inductive coupling probe. This drives the cable shield. Another probe is used to measure the current induced on the shield. This current is then divided into the voltage induced on the center conductor. Figure 5-27a shows a typical set-up of the above described test.

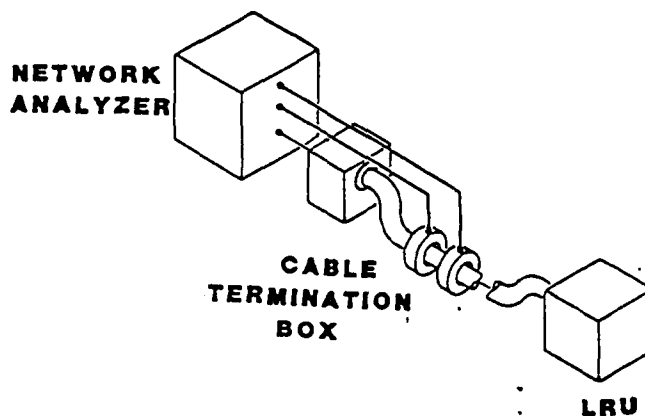


FIGURE 5-27a. Shielded cable tester setup.

A commonly used definition of the quality of a cable shield, is the shielding effectiveness, which is, for the purpose of this text, defined as:

$$S(\text{dB}) = 20 \log I_0/I$$

Where I_0 is the current in the shield, and I is the current in the conductor inside the shield.

APERTURE PENETRATION

Because the study of aperture penetration is best left to numerical methods, this section will be more informative than theoretical. It is intended to provide an insight to one method of modeling how EMP can be coupled through an aperture.

It can be shown that the electromagnetic field that penetrates through a small hole in a conducting surface can be represented approximately by the radiation from

equivalent electric and magnetic dipoles, plus a linear magnetic quadruple, located on the shadow side of the aperture. Because the quadruples contribution is negligibly small it can be ignored. Also, it is convenient to locate the other sources at the geometric center of the aperture. H. A. Bethe in his paper "Theory of Defraction by Small Holes", (Physics Review, Vol. 66, p. 163-182, Oct. 1944) has shown that the equivalent dipole moments of a small aperture in a screen are related to the specific excitation by what is called the aperture polarizabilities. If the polarizabilities of an aperture, and the field illuminating the aperture are known, then the dipole moments, and the diffraction caused by the presence of a small aperture in the screen can be found.

If the aperture is small, compared with the shortest wavelength in question, and is located in a planar conduction screen of infinite extent, then the polarizabilities are defined as follows:

$$p = E \alpha_e^{SC} E_z^{SC}(0^-)$$

for the electric, and

$$m_x = -\alpha_{m,xx} H_y^{SC}(0^-)$$

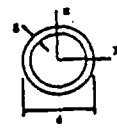
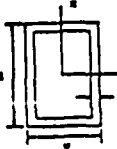

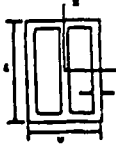
$$m_y = -\alpha_{m,yy} H_x^{SC}(0^-)$$

for the magnetic.

These equations are the equations for the dipole moments, electric and magnetic.

where E^{SC} and H^{SC} are the total field which would exist if the aperture were to be replaced by a conducting plate, and α_e and α_m are the electric and magnetic polarizabilities.

Figure 5-28 shows some polarizabilities for different types and openings.

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

$$** \Omega = 2 \ln\left(16 \frac{d}{g}\right)$$

FIGURE 5-28. Aperture polarizabilities.

The radiation from these dipoles is computed by standard methods, taking into account the presence of the screen, and its effects. After some algebra, it can be shown that the field produced by the dipole model is:

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

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

$$E_z = \frac{1}{2\pi} \frac{e^{-jkr}}{r} \left\{ \frac{p}{\epsilon} \left[\left(k^2 - j \frac{k}{r} - \frac{1}{r^2} \right) - \frac{z^2}{r^2} \left(k^2 - j \frac{3k}{r} - \frac{3}{r^2} \right) \right] + \frac{\eta}{r} \left(ym_x - xm_y \right) \left(k^2 - j \frac{k}{r} \right) \right\}$$

for the electric field; and for the magnetic:

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

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

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

Any object which scatters energy back into the aperture, further complicates the computation as it must be taken into account.

This model is good for distances far from the hole, i.e., greater than 5 to 10 times the hole size. However, caution must be used if it is applied close to the hole. Figure 5-29 gives an idea of how the model varies from an accurate numerical solution for a 1v/m incident field.

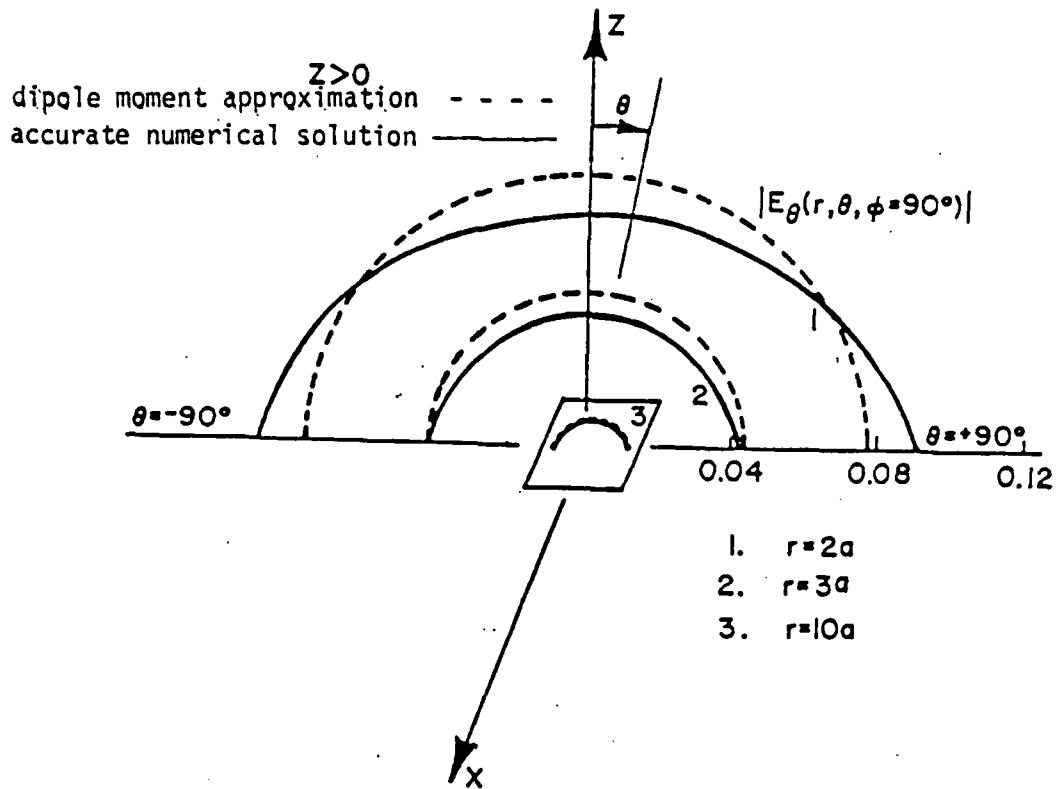


FIGURE 5-29. Electric field on shadow side of square aperture.

PROTECTIVE FEATURES

Now that we know how EMP is produced, what the waveform looks like, and how it can be coupled into a circuit, it is time to look at how to protect sensitive circuits from the large voltages and currents. One type of protection, the shielded cable, has already been covered. However, shielded cables are only one kind of protective device that are at our disposal. Other types of devices are; filters, door seals, and screens on windows, just to name a few.

All of these will be discussed, and how they are used in combination to form a complete protective barrier around the circuit.

ROOM OR CONTAINER

The room, or container, is the first line of protection against EMP penetration. It should be a perfectly conducting metal shield, completely enclosing the equipment to be protected. This type of "box" is called a Faraday Shield. There are two problems with this. First, there is no such thing as a perfect conductor. In a perfect conductor, a very thin "sheet" of metal would completely stop the EMP. In real metal, the EMP is reduced in an exponential form, $\exp(-\gamma z)$. Where γ is a complex value, and thus has an attenuation and a phase associated with it. The attenuation part is $\exp -[(\omega\mu\sigma^2/2)]$. Where μ is the permeability, σ is the conductivity, ω is the radian frequency and z is the distance the wave travels into the metal shield. Therefore, the thickness of the metal is important. It must be thick enough to stop the EMP, or at least reduce it to an amount that is acceptable, and not increase the weight more than necessary. Second, in most cases there are penetrations into the "box". Some are by conducting media

and some are by non-conducting media. Figure 5-30 illustrates some of the areas on an aircraft that will allow EMP to enter the structure.

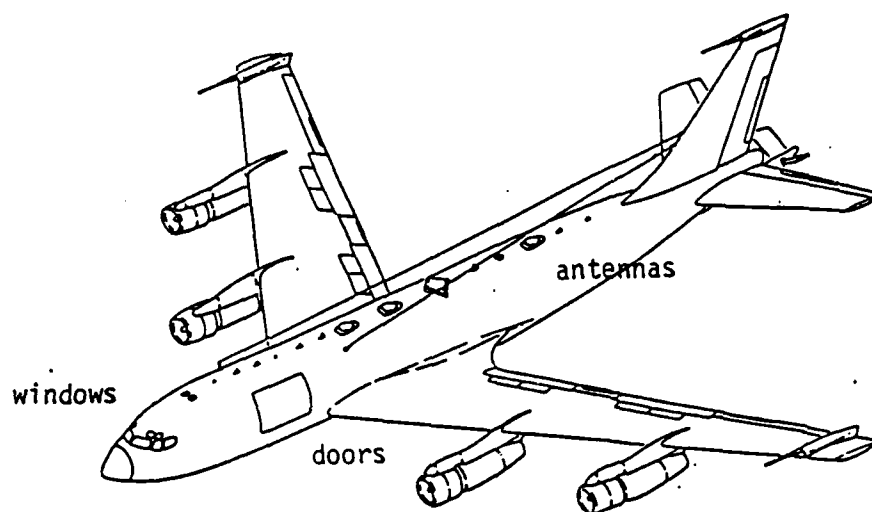


FIGURE 5-30. Aircraft penetrations.

The shielding afforded by a plane sheet of conducting material will be studied next. This will not provide an adequate model for all types of structures, but it will give a good indication of the shielding effectiveness of different materials or combinations of materials.

SHIELDING EFFECTIVENESS

The electric and magnetic shield factors η_e and η_m are defined by:

$$\eta_e = E(\omega)/E_o(\omega)$$

and

$$\eta_m = H(\omega)/H_o(\omega)$$

Where $E(\omega)$ and $H(\omega)$ are the electric and magnetic fields inside the shield, and $E_o(\omega)$ and $H_o(\omega)$ are the fields outside the shield.

The Shielding effectiveness "S" is defined by:

$$S_E = -20 \log |\eta_e|$$

$$S_m = -20 \log |\eta_m|$$

Both the shielding factors and shielding effectiveness are a combination of variables. The first is the attenuation loss due to the reduction of the wave propagating through

the metal. The second is the reflection losses caused by the impedance measurement at the interface.

ATTENUATION LOSSES

Recall from basic fields that for an electric field traveling in a good conductor ($\sigma \gg \omega \epsilon$), the field attenuates as it propagates into the conductor in an exponential form determined by the properties of the conductor. The equation for the field inside the conductor can be written as:

$$E(z) = E_s e^{-z/\delta} e^{-jz/\delta} \quad (\text{Eqn 5-26})$$

Where δ is the skin depth of the conductor and z is the distance the wave travels into the metal. A similar equation can be written for the magnetic field.

According to equation 5-26, if the wave travels a distance $z = \delta$ into the metal, it will be attenuated by an amount $1/e$ or 8.69 dB. This is referred to as the skin depth of the metal. This distance will not be the same for all materials, but can be used to give an indication of the ability of the material to attenuate EMP. Table 5-2 gives skin depth and attenuation per millimeter for three different metals, and for a range of frequencies.

Frequency in Hz	Copper		Aluminum		Iron	
	δ	A	δ	A	δ	A
1k	2.09	4.2	2.07	3.25	0.226	38.4
10k	0.660	13.2	0.845	10.30	0.072	121.0
150k	0.17	51.0	0.218	39.80	0.0185	470.0
1M	0.066	132.0	0.084	103.00	0.0072	1213.0
3M	0.038	228.0	0.049	178.00	0.0041	2102.0
10M	0.021	416.0	0.027	325.00	0.0023	3840.0

A is in dB/mm and δ is in millimeter

TABLE 5-2. Skin depth and attenuation for different metals.

Although there is an increase in shielding of a factor of almost 12, and the density increases by only a fraction of approximately 3, iron is not a good shielding metal because of the ferromagnetic properties of iron and also because iron rusts very badly.

REFLECTIVE LOSSES

The second factor mentioned earlier were the losses due to reflection. Whenever an electromagnetic wave is incident on a boundary of materials with different impedances there will be a reflected wave and a transmitted wave. This reflection is, in general, dependent on not only the material, but also the angle of incident. The maximum transmitted wave will result from a normal incident. We will, therefore, concern ourselves with this situation.

Because the transmitted wave, which is the part of primary concern, is dependent on the field at the interface, the field at the interface must be found. This field is affected by the reflected wave. Skipping the intermediate math, and going directly to the end result, the ratio of the total electric field at the surface to the incident field can be found. It is:

$$\begin{aligned} T_E \Big|_{z=0} &= \frac{E_s}{E_i} = \frac{2Z_m/Z_0}{1+Z_m/Z_0} \\ &= \frac{2Z_m}{Z_0} \quad \text{for } Z_m \ll Z_0 \end{aligned}$$

If the material is of finite thickness there is a second interface, and therefore a second reflection. Assuming a finite thickness, the overall shielding factor for a conducting sheet is:

$$e = \frac{E_t}{E_i} = \frac{(4Z_m/Z_0 e^{-z/\delta} e^{-jz/\delta})}{(1+Z_m/Z_0)^2} \quad (\text{Eqtn 5-27})$$

TOTAL LOSSES

For $|Z_m| \ll Z_0$. The shielding effectiveness can be expressed in the form:

$$S = A + R$$

Where A is the attenuation loss

$$A = 8.69z/\delta$$

and R, the reflection loss

$$R = 108 + 10 \log(\sigma_r / \mu_r f)$$

σ_r and μ_r are conductivity and permeability values relative to copper, and f is frequency in megahertz.

Equation 5-27 above is a good approximation, but only takes the first two reflections into account.

The shielding factor for a plane of conducting material when all reflections are taken into account is:

$$\eta_e = \eta_m = [\cosh(1 + j)z/\delta + (Z_0/2Z_m)\sinh(1 + j)z/\delta]^{-1}$$

BREAKS IN THE CONTAINER

If all critical circuits could be totally enclosed in a container, like that of a Faraday shield, no other protection would be necessary. However, most circuits require interface to the outside world. These interfaces will cause breaks in the container that must be protected. This is done in several different ways, depending on the requirements, and how the container was breached.

BREAKS IN THE CONTAINER BY CONDUCTING ELEMENTS

In the case of conducting media entering the "box", there must be some type of suppressor, or other form of protection to reduce the amplitude of the EMP. These devices can be simple filters, clamping devices, or a combination thereof. These suppression devices should be in a separate "isolation vault" to prevent them from radiating energy into the protected area. Sometimes the isolation vault, also called S/V box, is incorporated into the equipment. Figure 5-31 shows a typical S/V box like that used on the B-52.

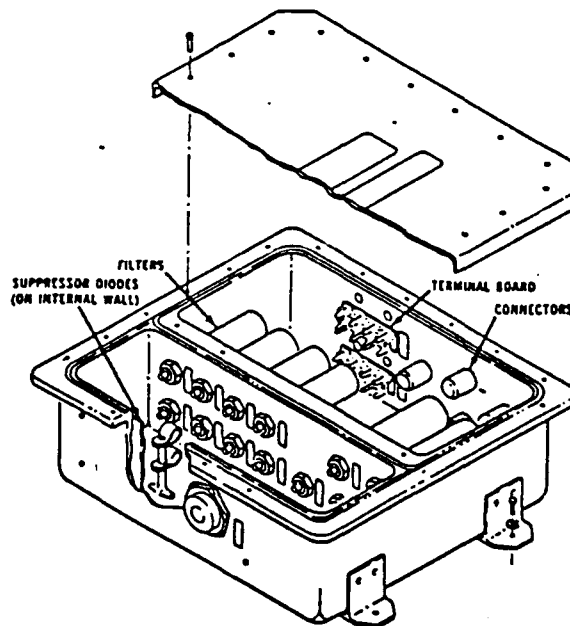


FIGURE 5-31. Typical S/V Box.

CLAMPERS

The first type of protective device to be discussed will be clampers. Devices that limit the EMP on a line, are called clampers, or limiters. Some of these devices are varistors, diodes, and spark gaps.

VARISTORS

A varistor is a semiconductor device whose resistance varies with the magnitude of the applied voltage. Varistors are composed of a polycrystalline material, made

by pressing and heating special mixtures of either silicon carbide, or oxides of zinc and bismuth. This mixture produces a resistor that has a very large resistance when small currents are flowing, and a small resistance for large currents.

These devices can respond in nanoseconds. Metal-oxide varistors have a clamping voltage, ranging from about 40 to 1500 volts, continuous power of up to 5 watts, and a peak energy of up to 160 joules. The bad thing about a varistor is that it reacts to any voltage change, and therefore is continually changing the impedance of the line. Impedance matching is very important on data, video and antenna lines. Figure 5-32 shows the symbol and V-I characteristics of two different types of varistors.

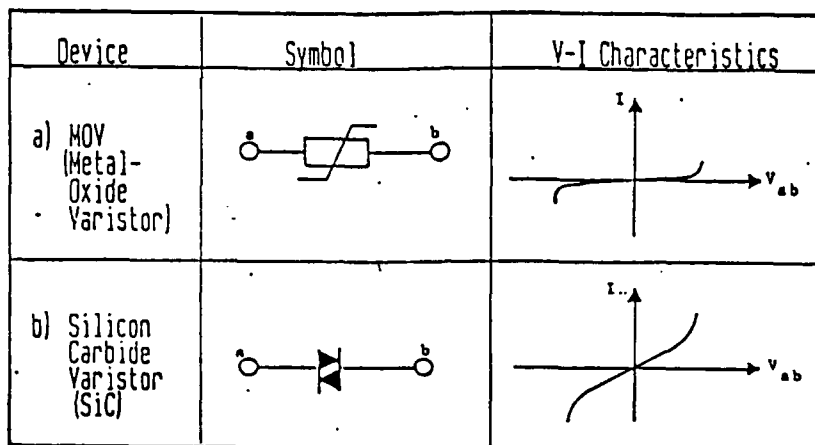


FIGURE 5-32. Symbols and V-I characteristics of some varistors.

DIODES

Diodes are also semiconductors, but they are junction devices (two or more types of materials put together) as opposed to varistors that are bulk devices (all the same type of material). Diodes perform the same function as do varistors; that of draining off the EMP energy. Diodes, however, act as switches. They do not effect the circuit until the voltage reaches a threshold value. After this value is reached, the diode turns on, and limits the voltage on the line to some value determined by the type and number of diodes in the circuit. It will also react to any voltage over the threshold, such as lightning or generator surges. The problem with diodes is that they can be damaged more easily than varistors. After a large voltage surge, holes can be made in the barrier between the two materials. This has the effect of lowering the breakdown voltage. If enough holes are punched in the junction, the diode will start to "turn on" at a voltage that is in the operation range of the circuit it is connected to. A more likely result is after sufficient holes are "punched" in the junction of the device, it will fail in a shorted mode and send all signals above the new threshold to ground. There are several different types of diodes that are used. Standard rectifiers, bipolar forward, reverse breakdown (Zeners), and bidirectional breakdown (Duel Zeners). These devices can be used individually or in combination to give the desired protection.

Figure 5-33 shows the symbol and V-I level for the four types of devices mentioned above.

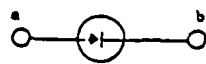


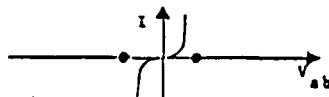

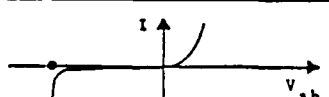


Device	Symbol	V-I Characteristics
Rectifiers		
Bipolar Forward		
Zener		
Bidirectional Zener		

FIGURE 5-33. Symbols and V-I characteristics of different types of diodes.

SPARK GAPS

A spark gap is similar to a diode, in that it is a switch that will close when a voltage larger than its threshold is reached. A spark gap consists of two pieces of conducting media separated by a gap. The gap may be filled by air or an inert gas. The type of gas placed in the gap depends on how the device is to perform. Figure 5-34 shows typical spark gap data.

A figure of merit for spark gaps is the impulse ratio. This is a ratio of the actual sparkover to static sparkover and generally increases with wave front slope. For this reason, high-speed gap switches which switch at nearly the same voltage are recommended for EMP use.

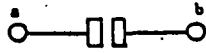





Spark Gap	Symbol	V-I Characteristics
Carbon Block		
Gas Tube		
Valve Arrestor (using Gas Tube)		

FIGURE 5-34. Symbols and V-I characteristics of different types of spark gaps.

FILTERS

Filters are used to selectively remove energy from the frequency spectrum. They are most often used after a clamping device to smooth out the signal that passes the clamping device. They also provide some EMP protection by their inherent filter properties. Some of the different types of filters used are shown in Figures 5-35a & b. The type shown in Figure 5-35a is called a "T" filter. The type in Figure 5-35b, is a "pi" filter. The type in Figure 5-35b is the type used most often.

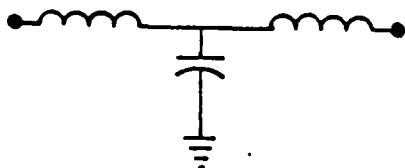


FIGURE 5-35a. T-Filter.

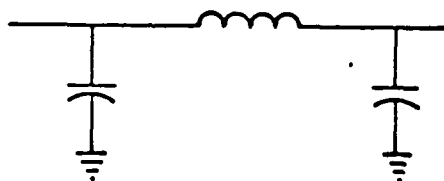


FIGURE 5-35b. Pi-Filter.

CIRCUMVENTION

Circumvention is a technique in which the circuit is removed or shut off until the danger has passed. This method is widely used in computer circuits and in transmitters/receivers. Although this method is primarily used for EMP protection, it is also used for TREE protection.

Other breaks in the container that fall into this classification are control cables and hydraulic lines. Neither of these normally carry currents, but both are capable of having EMP energy coupled onto them and then transporting this energy into a protected area.

CONTROL CABLES

There are many ways to prevent EMP from entering a protected area via control cables. The first is by the use of conducting pulleys. Figure 5-36 shows a typical placement of conducting pulleys. These were found in the Boeing 747. Another device used is a Dielectric Insertion Device (DID). The DID will isolate the inside part of the cable from the outside part. DIDs can be a problem in installation due to required mechanical clearances for the control cables. A third way is by the use of a "guard tube" on the input side of the Bulkhead. This guard tube acts as a waveguide below cutoff.

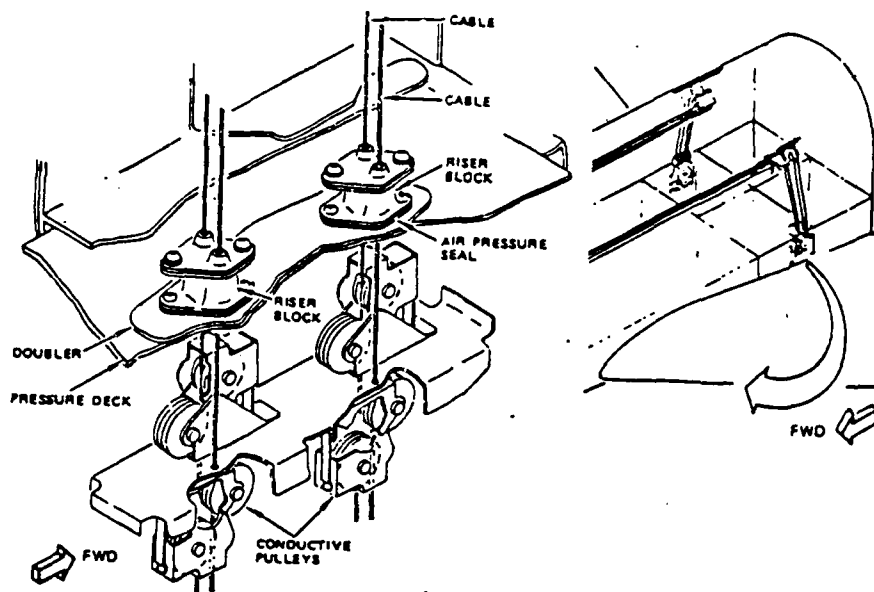


FIGURE 5-36. Landing Gear Valve.

HYDRAULIC LINES

Hydraulic lines are protected by "Bonding" them to the Bulkhead using one of several methods. These are shown in Figure 5-37.

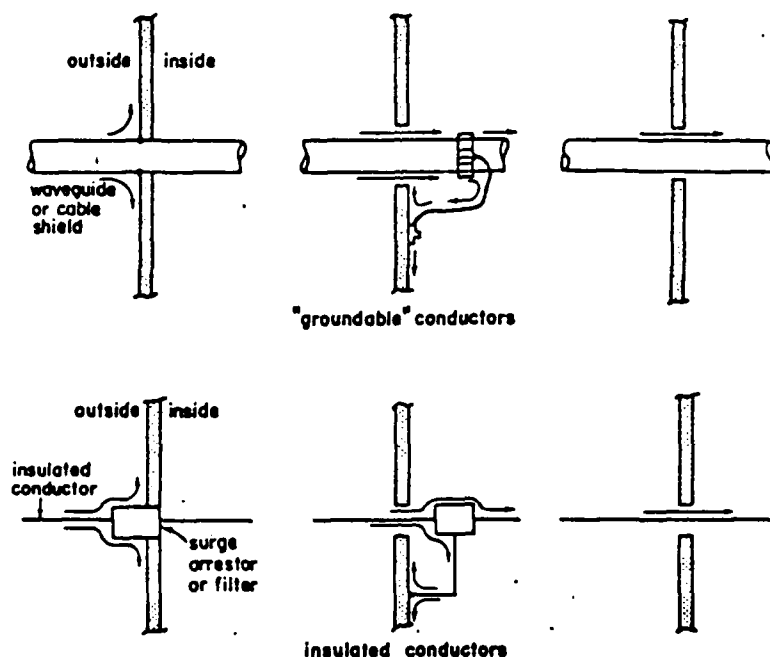


FIGURE 5-37. Hydraulic line grounding methods.

BREAKS IN THE CONTAINER BY NON-CONDUCTING ELEMENTS

Breaks in the container by non-conducting media still require some attention because any break in the shield will allow EMP to enter the container. Some of the types of breaks are: air vents, doors, access panels, and windows. Each of these will be looked at separately, as each is approached differently.

AIR VENTS

Air vents require two types of protection. They must have EMP and radiation protection. The latter will be discussed in the next sections. The most common form of EMP protection used on air vents is metal honeycomb ducting. (See Figure 5-39). This ducting acts as a waveguide below cutoff and prevents most of the energy from entering the protected areas. The length of the ducting should be at least three times the size of the hole.

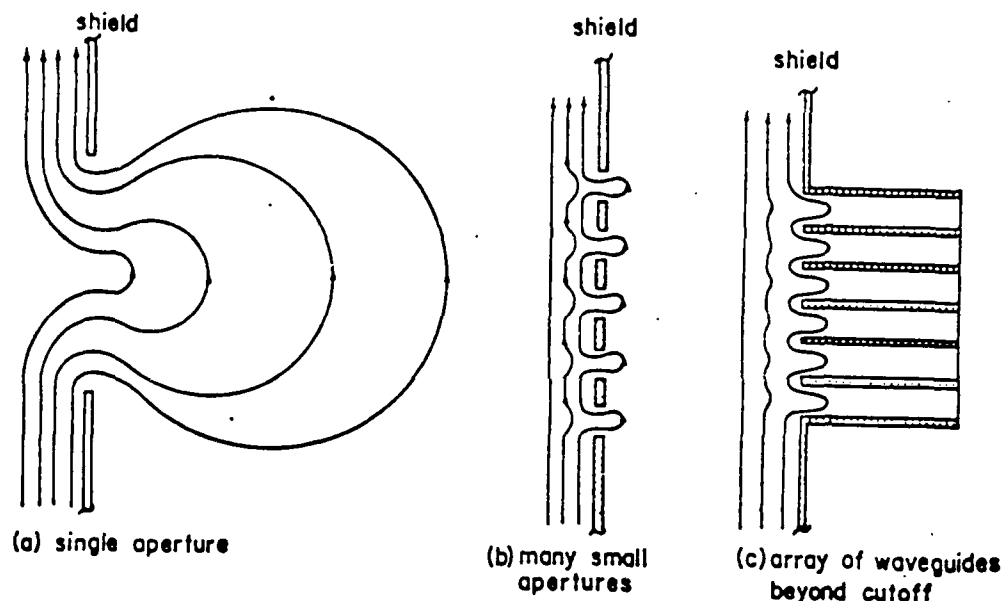


FIGURE 5-39. EMP penetration through different types of air vents.

ACCESS WAYS

Doors and access panels are another way EMP energy can penetrate a protected area. The gaps/voids between the door and door frame will allow EMP energy to enter the structure. To prevent this from occurring, an RF shield in the form of a seal or gasket is placed in this gap to attenuate the energy. Figure 5-39 shows a typical hardened and non-hardened door.

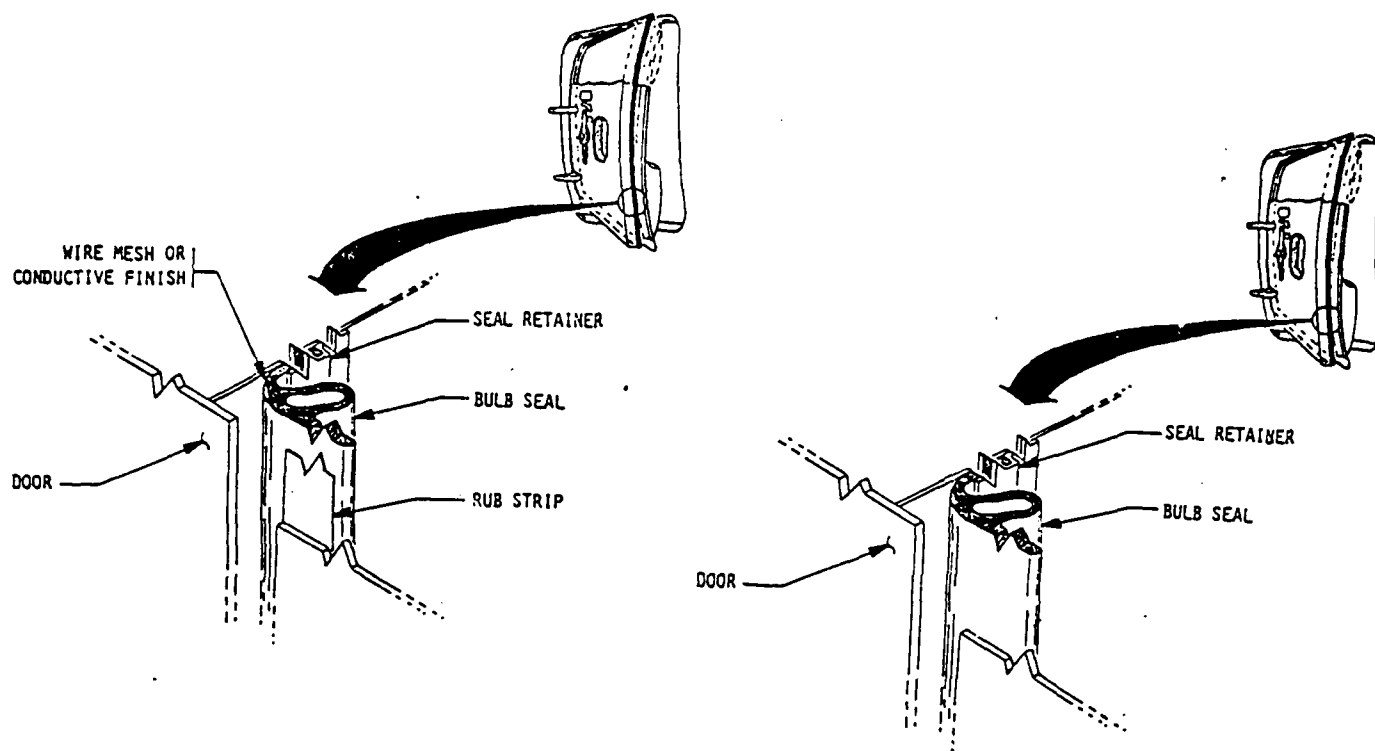
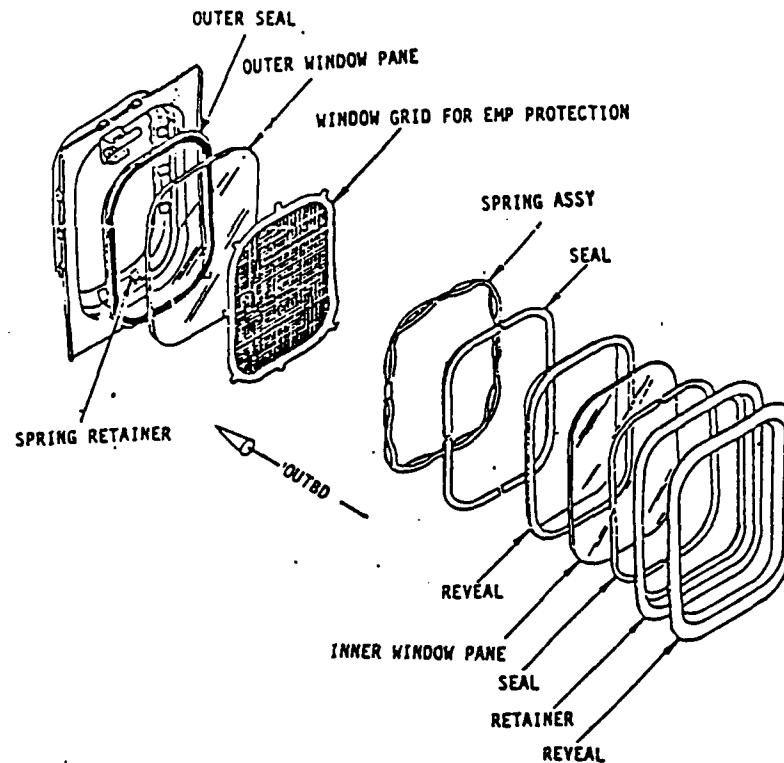


FIGURE 5-40. Hardened and non-hardened doors.

The wire mesh or conductive finish and rub strips form an EMP seal around the door or panel. If this seal is damaged or improperly installed, the hardening will be compromised. It is also very important not to paint the area of the door frame where the rubber strip makes contact with the air frame. This will cause a potential resistance build up.

WINDOWS

Windows are probably the most difficult penetration to harden. They are necessary to allow the pilot to see out, but the same opening that lets light in, will also let EMP enter. Unlike air vents, the window opening cannot be made a waveguide below cutoff. This would not allow the pilot to see out the window. Therefore, we must find another solution. One solution would be to cover the opening when the craft is in danger from EMP. However, the craft could be in danger, and the crew not know it. Therefore, this is not a good plan. The next best thing is to embed a very conductive screen in the window. This is a compromise between the ideal and a no solution. This will not completely stop the pulse, but will reduce it significantly. Figure 5-41 shows a typical hardened window. This screen should be made of as highly a conducting material as possible.



ETCHED GRIDWORK IS HELD IN PLACE AGAINST THE STANDARD 707 WINDOW, USING A STAINLESS STEEL RETAINER AROUND THE PERIPHERY. THE BRACKET CONTACTS NUTPLATES RIVETED ON THE HATCH STRUCTURE.

FIGURE 5-41. Overwing Escape Hatch Window.

SUMMARY

EMP is generated by any above ground detonation, but only a high altitude detonation will cause a pulse that extends far enough from the blast to be of concern. This HEMP is a by-product of a high energy explosion. It is a result of the Compton effect, gamma rays stripping off electrons. These Compton electrons spiral around the earth's magnetic field. The resulting current, called "Compton current", is what produces the EMP.

The EMP has, in general, a double exponential form. It has a rise time of about 10 nanoseconds and a time to one-half power of about 200 nanoseconds. This field can be as high as 50kv/m and can, if detonated high enough, cover the continental United States.

If this field encounters any conductive material, it will induce a voltage and a current. The maximum theoretical voltage can be as high as 7.25 MV. This voltage can only be obtained in a vacuum. The actual voltage and current must be obtained by numerical methods.

Protection from these large voltages and currents can be provided in a number of ways, ranging from shielded cables, to protection at the terminating end of the cable. The cables can be solid tubes, braided wire, or spiral wound. Spiral wound cables, however, are not as good protection from EMP. Other forms of protection are Faraday shields, clamps, filters, and EMP gaskets for doors and access ways.

EMP can be coupled to buried cables because they are normally less than one skin depth deep. The way EMP is coupled to buried cables will be briefly covered next.

COUPLING TO BURIED CABLES

There can be significant coupling to buried cables because they are usually buried less than one skin depth deep over a significant part of the EMP spectrum. As with overhead power lines, the longitudinal component of the field acts as a distributed (voltage) source. Using the transmission line, equation 5-6 from section "Coupling to Long Lines", and dividing by the characteristic impedance, produces a general expression for the time-harmonic short-circuit current for the semi-infinite cylinder/earth line:

$$I_{SC}(\omega) = 1/Z_C \int_{-\infty}^0 e^{\gamma z} E_z(z, \omega) dz \quad (\text{Eqtn 5-28})$$

Where γ is the propagation constant.

The illumination field in the earth and the plane wave producing it have the same z impedance dependence so that:

$$E_z(z, \omega) = E_0(\omega) e^{-\beta z} \quad (\text{Eqtn 5-29})$$

Where:

$$\beta = k_0 \cos \theta \cos \phi$$

and $k_0 = \omega/c$ is the wave number in the air. Combining equations 5-28 and 5-29 gives:

$$I_{SC}(\omega) = [E_0(\omega)/\gamma Z_C] [1/(1-j(\beta/\gamma))] \quad (\text{Eqtn 5-30})$$

The propagation constant γ is on the order of the intrinsic propagation constant of the earth γ_g where:

$$\gamma_g = (j\omega\mu_g\sigma_g)^{1/2} = \frac{1+j}{\delta}$$

and

$$\delta = \left\{ \frac{2}{\omega\mu_g\sigma_g} \right\}^{1/2}$$

With σ_g being the conductivity of the earth. The assumption that the permeability of the earth is assumed equal to that of free space is a good assumption most of the time. Therefore, the absolute value of $|\beta/\gamma|$ is on the order of $(\omega\epsilon/\sigma_g)^{1/2}$, and is negligible compared to unity. This makes equation 5-30 become:

$$I_{SC}(\omega) = \frac{E_0(\omega)}{Z} \quad (\text{Eqtn 5-31})$$

Where $Z = \gamma Z_C$ is the series impedance of the earth cylinder interface.

COATED CYLINDER

To obtain an explicit expression for the series impedance in a coated cylinder, wave scattering theory must be applied to the transmission-line formulation. The coating represents a nonmetallic protective covering, usually placed on buried cables. The cylinder, with a radius of " a_1 " and a dielectric sleeve outer radius of " a ", is assumed to be perfectly conducting. When the radius " a " is small, compared to the wavelengths in both the medium i.e., copper, aluminum, etc., and the dielectric coating, the total longitudinal current induced in the cylinder is:

$$I = E_z/Z$$

(Eqtn 5-32)

Where " Z " is a complex value given by:

$$Z = \frac{-j\omega\mu_0}{2\pi} \cos^2(\psi) \ln\left[\frac{\gamma_0 k a \cos(\psi)}{2}\right] + \frac{j\omega}{2\pi} \frac{\epsilon_c \mu_c - (k_0/\omega)^2 \sin^2(\psi)}{\epsilon_c} \ln \frac{a_0}{a_1}$$

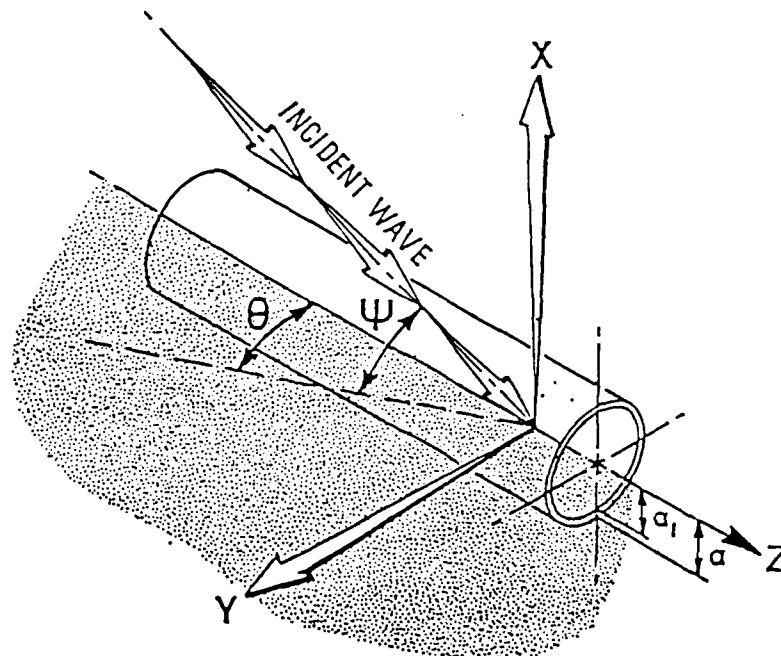


FIGURE 5-42. Coordinate systems for buried cables.

Where ϵ_c , μ_c , are the permittivity and permeability of the coating, and $k = \omega(\mu\epsilon)^{1/2}$ is the wave number in the medium. $\gamma_0 = 1.781$, and E_z is the component of the incident electric field, parallel to the cylinder. Equation 5-32 can also be applied to a cylinder that is buried in the earth, provided that the radius is small relative to the skin depth δ and that the interactions between the field scattered by the cylinder, and the interface can be neglected. E_z is the electric field that penetrates to the cylinder, and k is the wave number in earth

$$k = -j\gamma_g = (1-j)/(\delta)$$

Recalling Snell's law, $K \sin \psi = K_o \sin \phi$, and noting that $k_o/k \ll 1$ it can be shown that $\sin(\psi) = 0$ and $\cos(\psi) = 1$, therefore $I = E_z/Z$ where:

$$Z = \frac{j\omega\mu_o}{2\pi} \ln \left\{ \frac{1+j}{\gamma} \frac{\delta}{a} \right\} + \frac{j\omega}{2\pi} \frac{\epsilon_c \mu_c - \epsilon_o \mu_o \sin^2(\phi)}{c} \ln \frac{a}{a_o} \quad (\text{Eqtn 5-33})$$

or neglecting the imaginary term.

$$Z = \frac{j\omega\mu_o}{2\pi} \ln \left\{ \frac{(2)^{\frac{1}{2}}}{\gamma_o} \frac{\delta}{a} \right\} + \frac{j\omega\mu_c}{2\pi} \ln \frac{a}{a_1} - \frac{j\omega}{2\pi} \frac{\epsilon_o \mu_o}{c} \sin^2(\phi) \ln \frac{a}{a_1} \quad (\text{Eqtn 5-34})$$

The individual terms in equation 5-34 are related to network parameters as follows:

The first term of equation 5-34 represents the inductance per unit length associated with the magnetic field.

The second term is the inductance per unit length, with the magnetic field in the coating.

The last term is the distributed shunt capacitance of the coating.

Since the sheath coating is usually thin compared to the outer radius, the first term in the equation is dominant. The series impedance is then approximately that of a bare cylinder.

$$Z = [j\omega\mu_o/2\pi] \ln \frac{1.414 \delta}{\gamma_o a} \quad (\text{Eqtn 5-35})$$

To complete the equation for a buried cable, we need the E-field in the earth at the cable. This is found by first setting $h = 0$ in equations 5-10 and 5-11 to determine the field at the air/earth interface, and then multiplying by $\exp[-(1+j)h/\delta]$ to account for the effect of the earth between the interface, and the cable:

$$E_o^u = \begin{aligned} & T_H E_o(\omega) \sin(\theta) e^{-(1+j)h/\delta} && \text{for horizontal polarization} \\ & T_V E_o(\omega) \cos(\theta) \sin(\psi) e^{-(1+j)h/\delta} && \text{for vertical polarization} \end{aligned} \quad (\text{Eqtn 5-36})$$

where

$$T_H = 1 + R_H \quad 2(j\omega\epsilon_0/\sigma_g)^{\frac{1}{2}} \sin(\psi)$$

$$T_V = 1 - R_V \quad 2(j\omega\epsilon_0/\sigma_g)^{\frac{1}{2}} [1/\sin(\psi)]$$

At low frequencies, the ratio h/δ is small, therefore, the exponential function varies slowly. The losses in the earth are then negligible, and the field that penetrates to the cable is determined by the transmission coefficient (T_H , T_V) at the interface. This coefficient increases with increasing frequencies at a rate of 10 dB per decade. At high frequencies where h/δ is no longer small, the exponential factor dominates.

SHORT-CIRCUIT CURRENT

The combination of equations 5-31, 5-35 and 5-36 gives the short-circuit sheath current in a semi-infinite cable.

$$I_{sc}(\omega) = E_0(\omega) \frac{4\pi D_{h,v}(\psi, \theta)}{n_0 \gamma_g \ln \frac{(2)^{\frac{1}{2}} \delta}{\gamma_0 a}} e^{-\frac{(1+j)h}{\delta}}$$

Where $D_H(\psi, \theta) = \sin(\psi)\sin(\theta)$, and $D_V(\psi, \theta) = \cos(\theta)$ and $n_0 = 377$ ohms. To obtain the time-dependent current response to an incident pulse, the inverse transform must be evaluated (generally by numerical methods).

COUPLING TO TOWERS AND WAVEGUIDE RUNS

When a tower, or other tall conducting structure, is illuminated by an EMP, currents are induced on the structure. Most of these currents will follow the low impedance path to ground provided by the tower legs, and tower-ring ground shorting straps. Some of the current, however, will enter the building if precautions are not taken. Not only the tower, but the waveguide runs can act as collectors of the EMP. Tests run by the Bell System on a 100 meter high repeater station tower, with four waveguides and two ac conduits in Midlothian, Texas produced the following:

The measured currents were approximately damped sinusoids whose main frequency component corresponded to the quarter-wavelength resonant frequency of the tower. Higher frequencies associated with the raceway and possibly the tower base were also recorded. The test results indicate that total penetration currents from horizontal fields are about 3500 amperes peak (when scaled to 50 Kv/m incident field). Half of this current was carried by the four waveguides and half by the two ac conduits. The penetration current for vertical fields is about 11,000 amperes, peak (scaled to 50 Kv/m).

An upper bound on induced tower current can be estimated by making two assumptions; (1) The tower monopole and earth (the ground plane) are perfect conductors (no losses in either), and (2) The incident EMP electric field vector is parallel to the axis of the cylinder, producing maximum coupling. With these assumptions, we can treat a tower, or any tall metallic structure, as a simple receiving antenna.

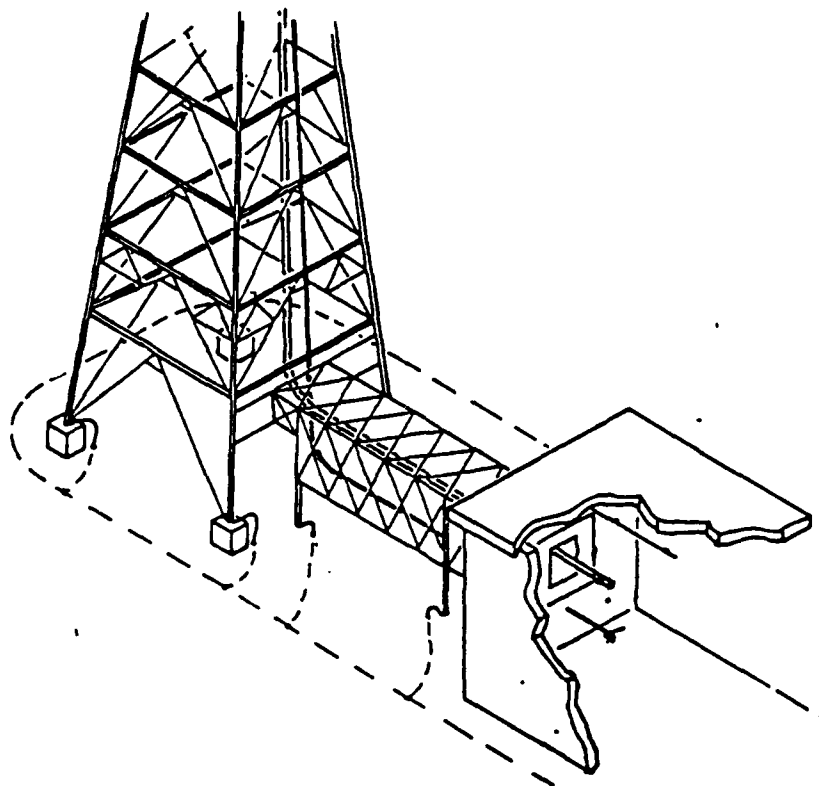


FIGURE 5-43. Typical tower insulation.

The induced dipole current in the frequency domain is: $I_D(\omega) = Y_D(\omega) E(\omega)$

Where $Y_D(\omega)$ is the dipole-system transfer function and $E(\omega)$ is the Foulter transform of the incident EMP.

$$Y_D = \frac{\pi h}{30 \Omega_T} \frac{a_0}{[(j\omega + a)^2 + \omega_0^2]}$$

$$\text{where } a_0 = \frac{2\pi C}{4h} \left[1 - \frac{0.500}{\Omega_T - 3.446} \right]$$

$$a = \frac{C}{h} \left[\frac{0.460}{\Omega_T - 3.446} \right]$$

The magnitude of the dipole transfer function is a function of the height and the radius, and is given as:

$$\Omega_T = 2 \ln(2h/a)$$

Where "h" is the height of the structure and a is the radius.

Evaluating this equation shows that it peaks sharply near the fundamental half-wavelength resonant frequency of an ideal dipole. For a fixed "h", the fundamental resonance peak, and its associated bandwidth, increase as the dipole factor decreases (physical thickness increases). In general, the fatter dipole has a greater induced current. However, the antenna Q is higher for the thinner dipole, so that the induced current oscillations do not damp out as rapidly on the thinner dipole. The induced tower current can be expressed as:

$$I_t = I_0 e^{-a_0 t} \sin(2\pi f_0 t) \quad \text{where } I_0 = \frac{\pi h}{30 \Omega_T} E_0$$

Where α_0 is the damping constant, $f_0 = \omega_0/2\pi = 1/\lambda$, c/h is the ringing frequency, and I_0 is the amplitude.

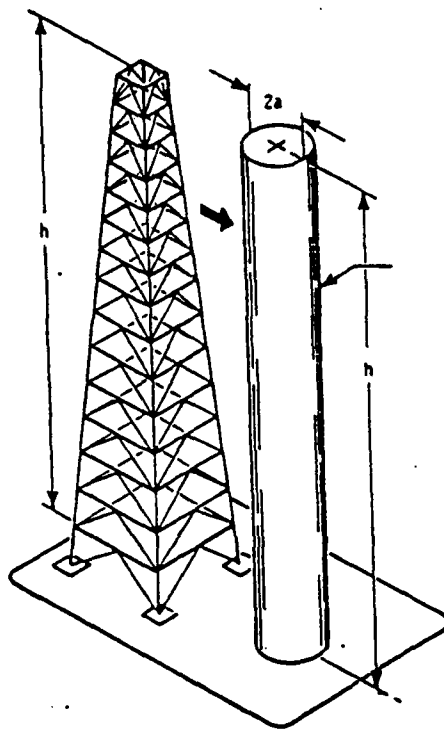


FIGURE 5-44. Comparison of tower and a monopole antenna.

SECTION 6

TRANSIENT RADIATION EFFECTS IN ELECTRONICS

With the increased use of solid state electronic devices in military aircraft, and an increasing awareness of nuclear events, the need for parts that are "hard" to radiation is becoming evident.

This section will look at how the different types of radiation produced by a nuclear detonation effects solid state devices. The first part of this section will cover how semiconductors work. Next, how radiation affects semiconductors will be covered. Lastly, hardening measures will be covered. This will demonstrate how, by device selection and design guidelines, a circuit can be made "hard" to Transient Radiation Effects in Electronics (TREE).

TREE

"Transient Radiation Effects in Electronics," commonly abbreviated TREE, refers to the effects occurring in an electronics system as a result of exposure to the transient initial radiation from a nuclear weapon explosion. (Note: transient applies to the radiation as it persists for only a short duration [1 minute], not the response which may be permanent.) The two types of radiation that are of most interest are: Gamma rays, and neutrons. Both of these can have detrimental effects on electronic devices and are present in many different energy levels. "TREE" is also the name applied to the concept of developing information and techniques for predicting the effect of radiation process in electronic materials.

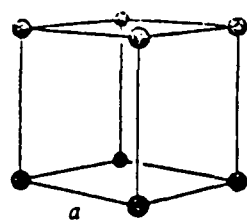
In order to perform work on radiation hardening, a knowledge of how semiconductors work is needed. To learn about how semiconductors work, a general knowledge of materials is required. This section will therefore, start with a review of electronic property of materials. After this general base has been laid, there will be a quick discussion of how semiconductors work. This ground work allows the reader to better understand how the effects of radiation on matter causes damage.

NATURE OF SOLIDS

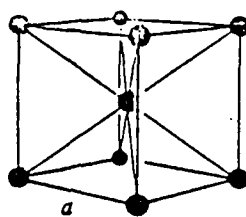
All solids can be put into one of three classes; 1) Amorphous, 2) Polycrystalline, or 3) Crystalline. Amorphous materials are solids that have no discernible periodic structures. An example of amorphous materials is sandstone. Polycrystalline materials have patches of crystalline structures in them. Crystalline materials are those which have one complete constant periodic structure. The semiconductor studied in this text will be of a crystalline type.

Although a pure crystalline structure would be ideal, this is very difficult to obtain. Companies go to great extremes to get as close as possible to a pure crystal.

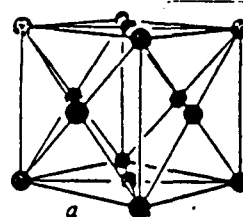
The smallest unit cell that can be repeated to form the lattice is called a primitive cell. Three of the basic forms of a primitive cell are: 1) Simple cubic, 2) Body-centered cubic, and 3) Face centered cubic. These are shown in Figure 6-1.



Simple cubic



Body-centered cubic



Face-centered cubic

FIGURES 6-1a, b & c. Different types of cubes.

Each dot in the cube represents an atom. Any disturbance in this structure will alter the electrical characteristics.

Semiconductor materials have a diamond lattice structure, which can be described as a face-centered cubic with four extra atoms at $(a/4, b/4, c/4)$ from each atom in a fcc form.

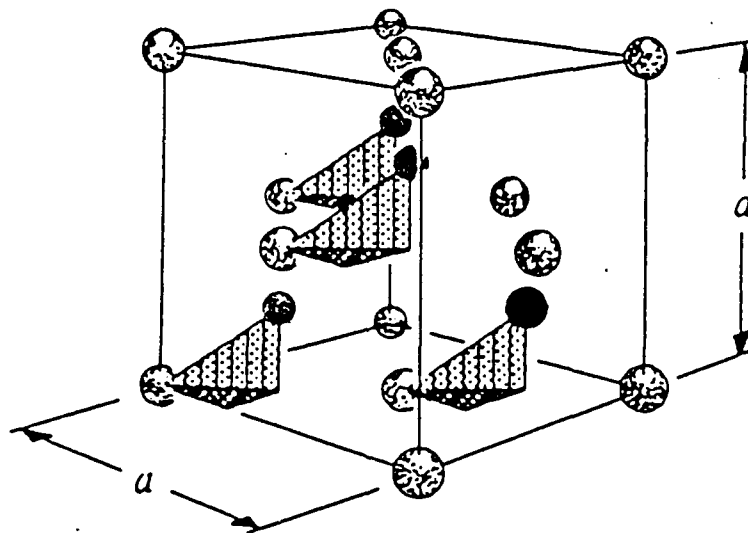


FIGURE 6-1d. Diamond Lattice Structure.

Figure 6-1d shows how a diamond lattice structure can be drawn from a face-centered cubic. The white dots stand for the atoms in an fcc unit. The black dots are the added atoms from the fcc unit to become a complete diamond unit.

HOW SEMICONDUCTORS WORK

Electrons orbiting a single atom occupy distinct energy states, and no two electrons can occupy the same energy state. As two or more atoms are brought close, these energy

states start to blur and become energy bands. Within the bands, are still distinct energy states. These electrons obey Fermi-Dirac statistics. The Fermi-Dirac distribution function gives the probability that an available energy state E will be occupied. The probability is given by equation 6-1.

$$F(E) = \frac{1}{1 + \exp(E-E_f)/KT} \quad (\text{Eqtn 6-1})$$

Where E is the energy state in question, E_f is the fermi level of the material, $K = 8.62 \times 10^{-5} \text{ eV}/^\circ\text{K} = 1.35 \times 10^{-23} \text{ J}/^\circ\text{K}$. The fermi level, E_f , is the energy level where the probability of the energy state being occupied, is 0.5. The energy bands and the fermi levels are used to explain how semiconductors work.

The fermi level is halfway between the valence band and the conduction band in intrinsic material. This is shown graphically in Figure 6-2a. In the figure, the valence band represents the energy level of valence electrons in the outermost shell of an atom. There cannot be any conduction if all valence electrons are in this band. The conduction band is the energy band where electrons will be if conduction is to take place.

An atom of a pure intrinsic semiconductor material shares it's valence electrons to four adjacent atoms to produce covalent bonds for a stable form. There are no free electrons that have an energy level in or near the conduction band, so that they can be set free at 0°K . Semiconductor materials can be given electrical characteristics to make them more useful by "doping" them with impurity atoms that create either an excess of free electrons or holes.

A semiconductor material, which is doped with atoms that have excess free electrons is n-type semiconductor, or holes, making it a p-type semiconductor. Figures 6-2b and c show the energy bands of an n-type and p-type semiconductor, respectively. For n-type material, the fermi level will be closer to the conduction band, and p-type closer to the valence band.

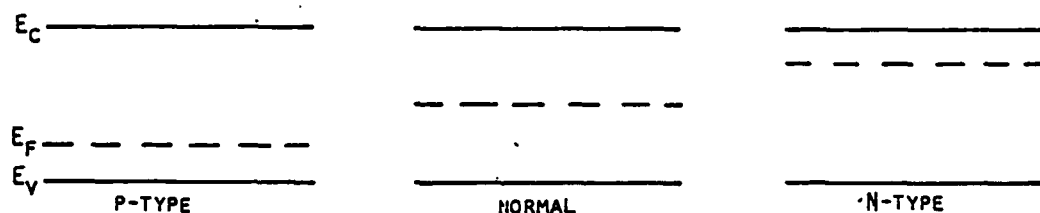


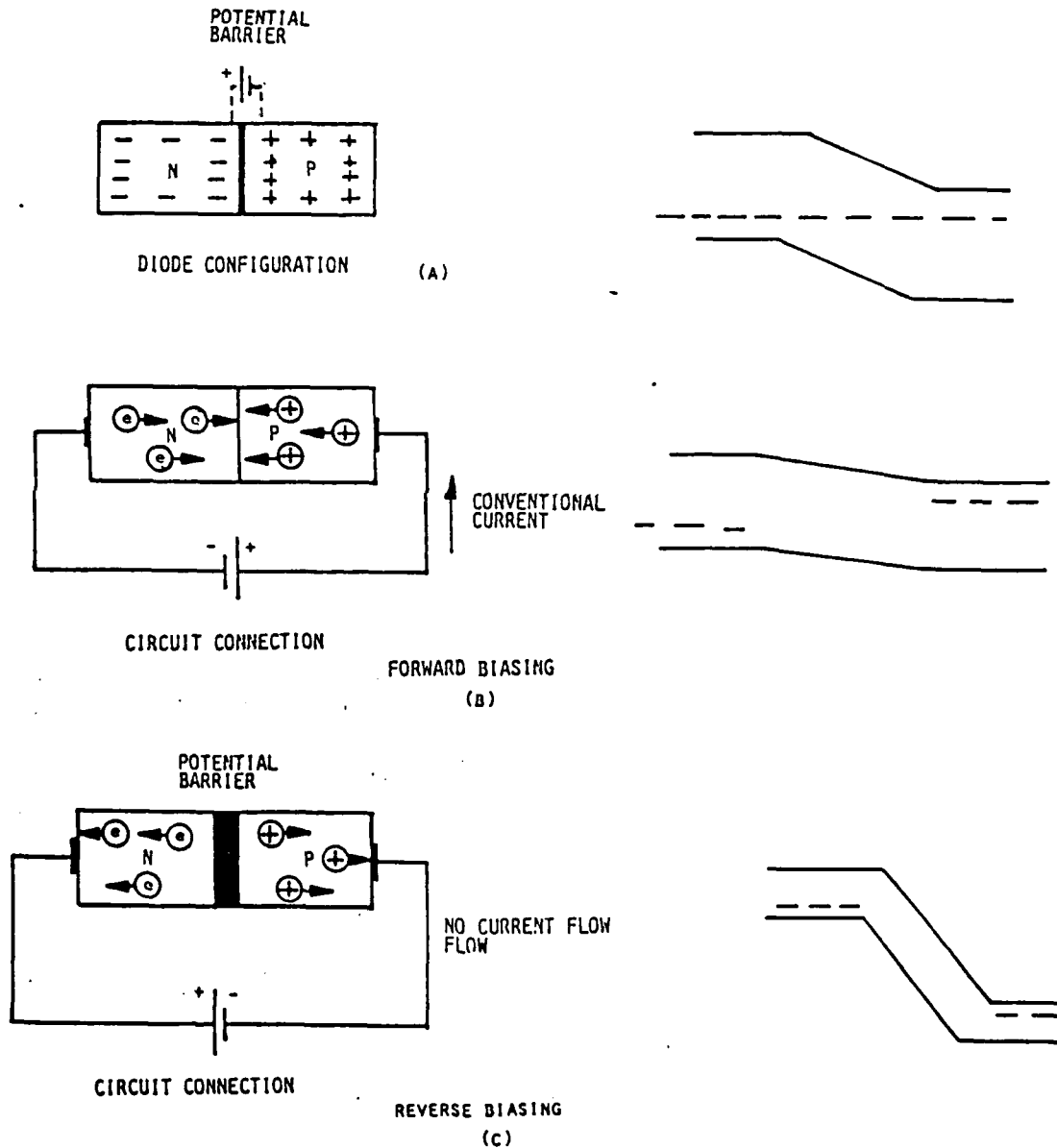
FIGURE 6-2a,b & c. Energy diagrams for different types of materials.

DIODES

A diode is made by combining an n-type and p-type semiconductor. When p-type and n-type materials are combined, the fermi levels line up and produces a "potential barrier" across the junction, as shown in Figure 6-3a.

When a sufficient voltage source is connected to the diode in a way such that the negative terminal of the source is connected to the n-type material, and positive terminal to the p-type, the majority of the carriers will overcome the "potential barrier" and produce a current. The applied voltage is called the forward bias, and is shown in Figure 6-3b.

If an external source is applied opposite to the above connection, the positive terminal of the source to n-type and negative, p-type, the barrier will become larger, and very little current will flow. This applied voltage is called the reverse bias, and is shown in Figure 6-3c.



FIGURES 6-3a, b & c. Energy diagram of a diode.

TRANSISTORS

There are two types of bipolar transistors, n-p-n, and p-n-p. All of this discussion will be over p-n-p, but the same principles apply to n-p-n.

A junction transistor is a semiconductor device composed of three adjoining, alternately doped regions. The first region, the emitter, is a heavily doped p-type. The next region, the base, is a doped n-type, but not as heavily as the emitter. The last region, the collection, is doped p-type, but not as heavily as the emitter. This produces a p-n-p configuration, or back to back diode.

This p-n-p setup is what allows a transistor to provide power gain. Figure 6-5 shows an energy diagram for a p-n-p transistor in thermal equilibrium.

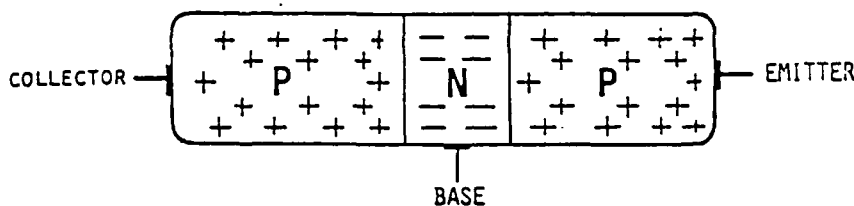


FIGURE 6-4. Transistor configuration.

As can be seen in Figure 6-5a, there is a "potential barrier" preventing the flow of either holes or electrons. If a forward bias voltage is applied to the Emitter-Base junction, and a reverse bias voltage to the Collector-Base junction, as shown in Figure 6-5b, the barrier between the base and the emitter is lowered, and the barrier between the base and the collector is increased. This will allow charge to flow in only one direction. After a charge has passed the "junction of origin", it is, for the most part, quickly swept away by the field produced in the transistor. For a very small base current, a large collector current can be contracted.

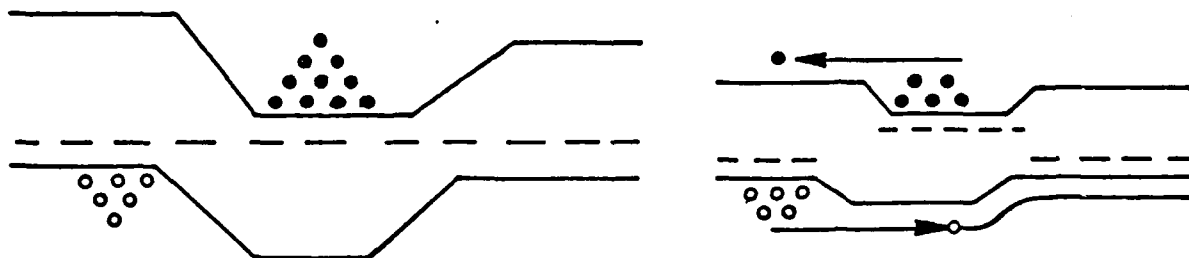


FIGURE 6-5a. Energy diagram of a transistor.

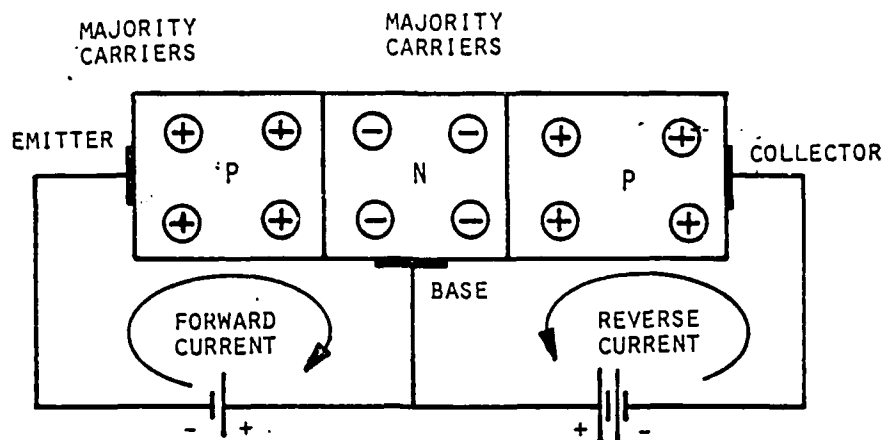
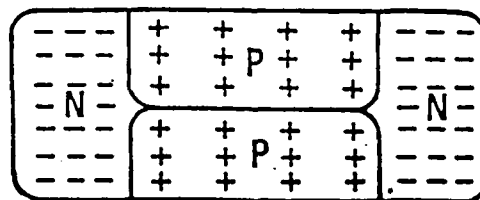
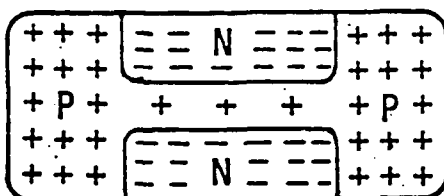


FIGURE 6-5b. Biasing a transistor.

FIELD EFFECT TRANSISTOR

A Field Effect Transistor (FET), operates on a different principle than the transistor. An FET operates by changing the width of a channel through which the charge flows. For example, look at a p-channel Field Effect Transistor (PFET), Figure 6-6a.



FIGURES 6-6a & b. Field Effect Transistors.

As the size of the N region in Figure 6-6a grows, the resistance from the source to drain goes up. Some FET's are designed to be normally conducting as shown in Figure 6-6a, and some are designed to be normally non-conducting as shown in Figure 6-6b, but they both work on the same principle.

SILICON CONTROLLED RECTIFIER

A Silicon Controlled Rectifier (SCR) is a device composed of four alternately doped layers. This arrangement produces a device which, in its off state, blocks current flow from either direction because there are two potential barriers. It can, however, be enabled to conduct in one direction by appropriate signal being applied to its gate. This signal reduces one of the barriers, and allows current to flow.

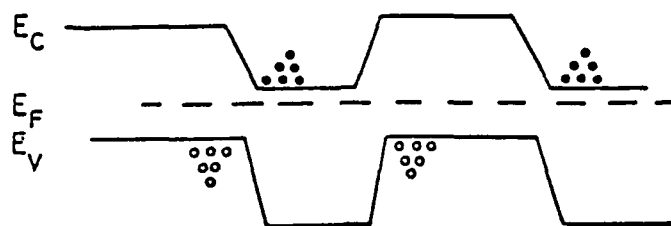


Figure 6-7. SCR Energy diagram at rest.

After the proper signal is applied to the gate and the current starts to flow, the current flow itself will, if above the hold current, keep the SCR on.

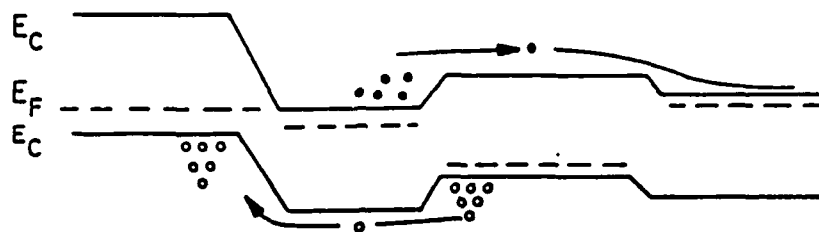


FIGURE 6-8. SCR energy diagram in "on" state.

HOW RADIATION EFFECTS SEMICONDUCTORS

Radiation can be measured in two different ways. One is the exposure level of radiation that is measured in Roentgen and defined by:

$$1 \text{ Roentgen} = 2.58 \times 10^{-4} \text{ coulomb/kg}$$

The other is by the total dose, Rad, and is equivalent to:

$$1 \text{ Rad} = 100 \text{ ergs per gram}$$

Different materials absorb this energy at different rates. Therefore, you must not only know the exposure level roentgens, but also, the way the particular material absorbs radiation, before you can discuss the total dose.

A more in-depth look into the nature of solids can be found in "Solid State Electronic Devices," by Ben G. Streetman, or in "Physical Electronics," by Ferry-Fannin.

Of all the nuclear radiation released from a burst, alpha, beta, gamma and neutrons, only the last two are of primary concern. Alpha and beta particles are stopped by a very thin piece of material, whereas gamma and neutrons are not as easily stopped. Of these two, neutrons generally cause most of the permanent structural damage. Although gammas can produce structural damage, the effects are small, so they will be ignored. Also, neutrons can produce gamma rays, but again the amount produced is small.

Neutron Fluence is defined as, "The time integral of neutron flux over total exposure time". Neutron Flux is the product of the Neutron density and average velocity (Fluence is flux times time). Since Fluence and Flux units do not indicate it's energy, the neutrons of interest must be specified. Therefore, a 1 Mev equilibrium ratio is a common reference. Table 6-1 shows some common radiation and how they compare.

Type of Radiation	Particle Size	Wavelength	Mass	Charge	Radiation Source	Depth of Penetration in Silicon	Effect on Silicon
Electron, e^-	$\sim 10^{-14}$ m	N/A	9.1×10^{-28} g	-	Hot filament	<Beta	Surface damage
Beta, β^-	Same as electron	N/A	Same as electron except for $E = mc^2$ K.E. \gg electron	-	Decay of radioactive nucleus	<10 μ	Surface damage
Proton, p^+	3×10^{-15} m	N/A	1.67×10^{-24} g	+	Ionizing hydrogen atoms	$\beta > p > \alpha$	Surface damage
Alpha, α	$\sim 4n$	N/A	6.7×10^{-24} g	++ ($2p + 2n$)	Decay of radioactive nucleus	Negligible	Negligible
Neutron, n	3×10^{-15} m	N/A	1.67×10^{-24} g	None	Nuclear reaction	Tens of microns	Bulk damage
X-Ray	N/A	10^{-8} to 10^{-12} m	No real mass	None	Electron collisions with large atom nucleus	Meters	Negligible
Gamma ray	N/A	< 10^{-11} m	No real mass	None	Collisions of nuclear particles	Meters	Negligible

TABLE 6-1. Types of Radiation.

PERMANENT EFFECT

One way that radiation can change the structure of material, is by displacement of atoms. This creates a "vacancy" in the crystal lattice and puts atoms where no atoms should be. This interaction of neutrons with atoms is in a billiard ball fashion. A larger proportion of energy will be imparted to atoms of low atomic weight, than to atoms of high atomic weight. This is why materials that contain many hydrogen atoms, such as water or paraffin, are very effective in removing some of the energy from neutrons, and slowing this down. Some of this energy is, however, converted to gamma rays. If enough atoms are displaced, the material will lose its crystal structure and become just a piece of resistive material. Following are the dynamics of how atoms are displaced.

- 1) A nuclear particle, probably a neutron, collides with a lattice atom, and imparts what is termed "recoil energy" to it.
- 2) If the particle imparts enough energy to the target atom, it will cause the atom to leave the lattice. These atoms are called, "recoil atoms."
- 3) If the particle is energetic enough, it will cause other atoms to be displaced.
- 4) Eventually, all the recoil atoms will come to thermal equilibrium in interstitial positions, except for the few that have filled vacancies. Some of the interstitials and vacancies may be isolated, but for values of " E_r ", recoil energy much greater than the displacement threshold will be associated with other defects called, "clusters."

- 5) Thermal energy of the crystal causes some of the defects and defect clusters to migrate through to the crystal.
- 6) Eventually, the mobile defects will either anneal by recombination of vacancy-interstitial pairs, become immobilized by the formation of stable clusters, or escape to a free surface.

As defect clusters are formed, the electrical characteristic of the device is degraded. After the Neutron radiation is removed, the material will start to return to the preradiated condition. It will not, however, return completely to the preradiated state.

TRANSIENT EFFECT

The other type of damage and ionization is primarily caused by gamma radiation. The primary interaction of gamma and x-rays with material occurs through the mechanics of; 1) Photoelectric Effects, 2) Compton Scattering, and 3) Pair Production. Photoelectrons are produced by Electromagnetic Waves (EMW), light, x-rays, and gamma rays striking the material. If the energy of the EMW is equal to or greater than the band gap, one or more electrons are placed into the conduction band, thus raising the conductivity of the material. Photoelectrons are produced by low level gamma rays. Gamma rays of higher energy levels interact by the Compton effect. The Compton effect, as described earlier, is where electrons are stripped off the atom. For very high energy gamma, Pair Production is the method of energy transfer. This can occur with energies of 1.02 Mev or greater, but it is a rare event and is normally neglected.

DIODES

Diodes can be affected by both displacement and ionization. Displacement effect causes degradation in crystalline structure of the diode and converts the structure to the polycrystalline form. In this structure, the fermi level will tend toward a common value and the barrier is reduced. Ionization effect generates electron-hole pairs in three regions: P, N and depletion region of a diode. Minority carriers in the bulk P and N regions diffuse to the junction, and are swept across the depletion region by the barrier potential across the junction. Carriers that are generated within the depletion region also drift by the field associated with the depletion region. Figure 6-9 shows the traveling direction of carriers in all three regions under the field across the depletion region.

The nuclear radiation effects on a diode in a particular circuit can be realized by:

1. The forward voltage of the diode is usually increased because of changes in resistivity and mobility of the semiconductor material.
2. The dynamic forward resistance will increase because of changes in resistivity and mobility modulation.
3. The reverse current increases because of increasing in carrier generation in semiconductor material.
4. Since the resistivity increases, the reverse breakdown voltage will increase.
5. The switching characteristic of the diode will be changed due to an increase in the rise time and decrease in the storage time caused by lifetime damage.

For most circuits, the changes in the forward voltage and reverse current are of most concern. Other changes are usually of secondary importance.

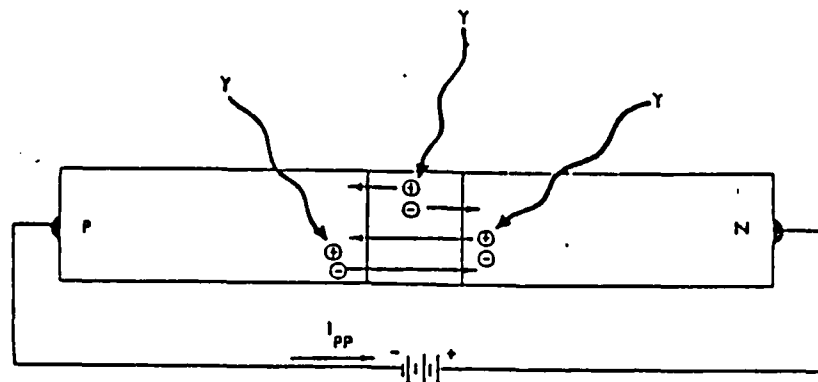


FIGURE 6-9. Effects of gamma rays on silicon diodes.

TRANSISTORS

Transistors are damaged by displacement effects just like diodes. However, the result of displacement is a reduction of the transistor gain. Ionization is also a factor to be concerned with, but it is not as important as displacement. Ionization creates photocurrents, but these currents tend to go away after the radiation is removed. Also, this current can, to some extent, be cancelled.

The nuclear radiation effects on a transistor in the circuit viewpoint can be realized by:

1. The degradation of current gain because of the lifetime damage. Usually, the gain will be degraded greatly right after a burst and rapidly recover in a quasi-state. However, the current gain recovery is too small, and can be ignored.
2. The reverse leakage current increases like diodes.
3. Since the resistivity changes in bulk material, changes occur in the punch-through voltage, base-to-emitter and collector-to-base breakdown voltage.
4. Changes in resistivity and conductivity modulation cause the increase in base-spreading resistance, collector-body resistance and saturation voltage.
5. The switching characteristics changes due to similar reasons to diode.

Table 6-2 shows the degradation of current gain of some typical transistors due to the radiation effect. The values under the head 0 rads (Si) indicate the current gain without radiation effects. Other two columns on the right show the values of under different dose rate: 10^5 rads (Si) and 10^8 rads (Si) for comparing the degree of degradation under the effect of nuclear radiation.

This loss of gain is a result of the displacement damage to the crystalline structures and a loss of the n-p-n or p-n-p configurations. The gain lost will tend to return to the preradiated level. How close it gets to the preradiated level is determined by the lifetime damage constant, and is given by:

TOTAL DOSE INDUCE β DEGRADATION IN ACTIVELY IRRADIATED TRANSISTOR

TYPE/MFG.	SAMPLE SIZE	MEASUREMENT I_C	AVERAGE ϕ		
			0 rads(Si)	10^5 rads(Si)	10^6 rads(Si)
2N2222A/MOT	10	5	103	52.8	36.9
		50	109	86.5	66.4
2N2369A/NAT	8	10	66.5	60	41.8
		50	59.5	54.5	40.5
2N2432A/TI	10	0.1	138	-	8.84
		10	201	-	68
2N2484/MOT	10	0.02	175	69.1	31.9
		1	348	221	148
2N2605/NAT	8	0.1	199	163	75
		1	206	181	103
2N2658/SOL	10	5	147	60	29
		500	225	181	138
2N2812/AP	8	10	115	65	33
		1000	136	113	86
2N2857/MOT	10	0.1	61.4	28.5	17.5
		2	80.9	51.5	35.1
2N2905A/MOT	10	10	132	131	127
		100	147	145	140
2N2907A/FC	10	0.2	112	118	81.8
		10	149	161	126
2N2920/TI	20	0.1	292	168	44.5
		1	326	235	103
2N2946A/TI	10	1	188	145	42.8
		10	146	124	56.3
2N3019/MOT	10	10	116	89.9	59.9
		50	135	123	92.9
2N3055/SEN	8	300	107.5	102.5	75
		3000	46	44	32
2N3499/MOT	8	30	205	175	117
		150	106	103	77
2N3501/MOT	10	1	93.5	52.3	30.7
		10	132	90.4	66.1
2N3506/MOT	8	100	96	85	52
		1000	107.5	104	82
2N3507/MOT	8	100	65	50.5	33
		1000	64	60	48
2N3509/MOT	5	1	59.2	34.8	28.3
		10	88.1	62.4	49.2
2N3553/RCA	10	10	20.2	15.3	9.22
		100	35	29.9	20.7
2N3700/PCH	10	1	96.3	62.4	43.8
		50	151	121	103
2N3749/AP	8	100	62	59	44.5
		500	72	67.5	50
2N3752/SOL	10	100	117	87.4	78.5
		1000	97.4	89.6	76.9
2N3810/MOT	10	0.1	217	198	140
		2	231	220	177

TABLE 6-2.

TOTAL DOSE INDUCE β DEGRADATION IN ACTIVELY IRRADIATED TRANSISTORS

TYPE/MFG.	SAMPLE SIZE	MEASUREMENT I_C	AVERAGE ϕ		
			0 rads(Si)	10^5 rads(Si)	10^6 rads(Si)
2N3866A/RCA	8	10	76	62.5	35
		100	71	63	43.5
2N3960/MOT	6	1	155	133	65
		30	122	112	82.5
2N3997/TI	8	10	118	78	46
		1000	170	148	105
2N4150/UNI	4	10	70	35	10.5
		100	86	62	32.5
2N4405/INT	8	0.1	128	90	36
		10	165	147	106
2N5003/SOL	10	10	77.2	70.1	41.7
		500	84	77.1	54.9
2N5005/SOL	10	10	77.2	70.1	41.7
2N5090/RCA	10	2	51.5	43.5	26.7
2N5108/MOT	8	1	27	15.8	4.5
		100	30.8	25.4	15
2N5152/	4	10	61	50	36
		100	75	69	57
2N5153/SOL	10	1	98.7	86.9	57.9
		100	152	143	101
2N5237/GS	8	100	83.5	78	58
		300	90	89	70
2N5250/SOL	4	200	70	44.5	25.5
		2000	78	67	48.5
2N5326/TRW	10	50	98.4	88.8	78.8
		500	116	115	108
2N5347/MOT	4	100	82	74.5	63
		500	85	79.5	71
2N5470/RCA	10	5	57.1	41	28.5
		50	53.1	45.5	35.9
2N6187/MOT	4	300	91	72	46
		3000	76	59.5	39.5
2N6266/RCA	10	50	36.8	27.5	12.9
		100	37	28.1	14.7
2N6267/RCA	10	10	49.7	35.3	13.7
		100	53.3	41.5	20.9

TABLE 6-2. continued.

$$\frac{1}{h_{fe0}} = \frac{1}{h_{fe}} + \frac{K \phi}{2 F_T}$$

Where h_{fe0} is the post-radiated gain, h_{fe} is the preradiated gain, K is the lifetime damage, ϕ is the radiated dose, and F_T is the gain-bandwidth product. The lower the life time damage constant, the harder the device.

FET'S

Although FET's operate on a different principle than transistors, the effects of displacement are basically the same. The device tends to lose it's crystalline nature, which reduces it's ability to function. However, they are not as sensitive to this type of damage as are transistors.

The effects of gamma radiation , ionization, is far more damaging in FET's than in transistors. The charge build up can counter the gate signal, or it can reinforce it. Unlike transistors, the effect of ionization has a tendency to stay in most FET's, even after the radiation is removed. This is caused by charger particles being caught in the insulating material between the gate on the channel.

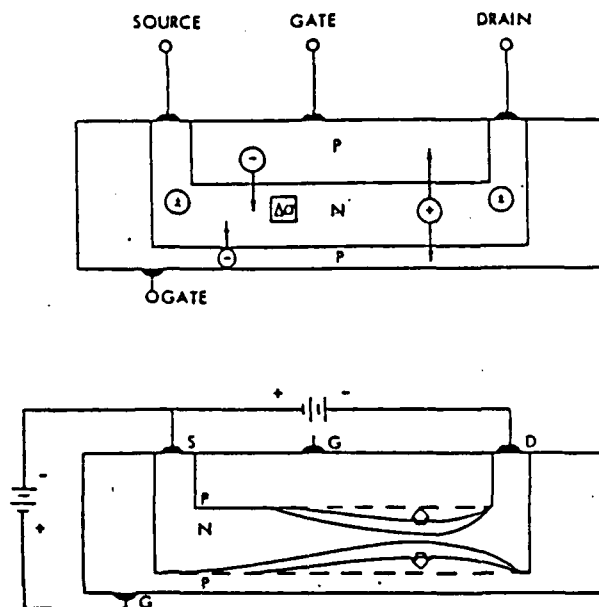


FIGURE 6-10. Ionization effects in most FET's.

SCR'S

An SCR reacts to radiation, both neutron and gammas, in much the same way as transistors, with one major exception. A transistor will tend to return to a normal mode of operation after the radiation is removed, provided the damage from displacement is not extreme. An SCR, on the other hand, will stay on if the radiation is enough to trigger it, and the current is at or above the hold level. An SCR does, however, take a longer time to turn on than do most transistors and therefore is somewhat hard to short bursts. Figure 6-11 shows an example graph of radiation levels versus time to trigger an SCR.

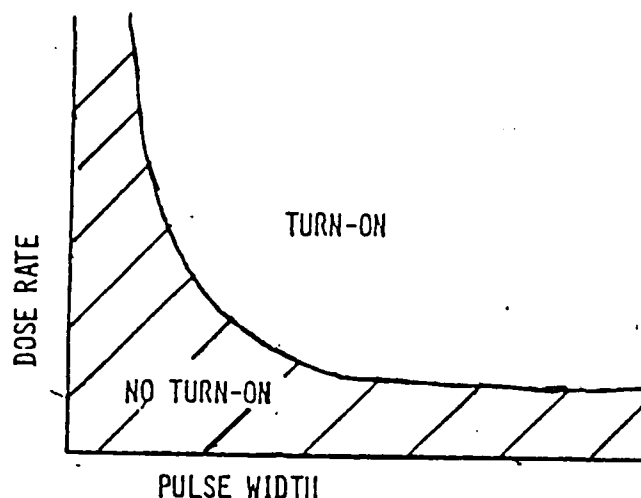


FIGURE 6-11. Typical SCR dose rate threshold characteristics.

HOW TO HARDEN AGAINST TREE

Circuit hardening can be described as any method that improves the radiation tolerance of the circuit. In order to engage in a hardening program, a knowledge of the following areas is mandatory.

- a. The anticipated radiation environment
- b. Functional requirements of the circuit including acceptable operation
- c. Component response to radiation

Without an understanding in all three areas, no worthwhile hardening program can exist. One of the problems that an S/V engineer (who is not knowledgeable in all three areas) may have is: hardening to one variable, several orders of magnitude more than another. e.g. Does it make sense to harden to an exposure rate of 10^{12} rad/sec, only to have the circuit fail due to neutron displacement?

An S/V engineer who has a good understanding of all these areas can maintain a balanced hardening program.

Radiation effects on semiconductor devices are best explained by obtaining the general admittance matrix equations containing all of the basic semiconductor properties that undergo changes when exposed to the radiated environment. This can be very hard to obtain and difficult to work out by hand for complicated circuits.

Still, hand calculations can be used for simple circuits to get a ball park figure as to how the circuit will behave. However, if "exact" solutions are needed, or if the circuit is complex, computer programs are needed. Figure 6-12 shows a typical model for a diode. This figure is intended to give an insight as to how complicated radiation models are.

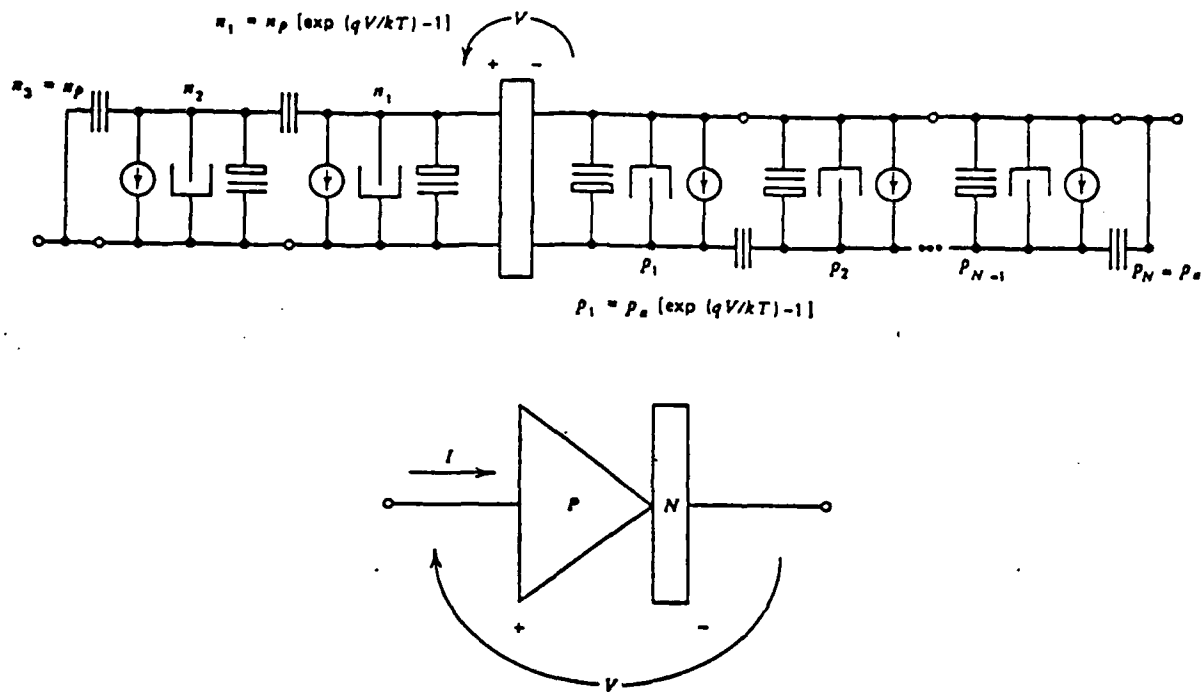


FIGURE 6-12. Diode lumped-model representation.

After the design is complete, it ideally should be tested in its operational environment. This, however, is not normally possible because some anticipated radiation levels are not attainable with present facilities. Figure 6-13 shows a typical design flow chart, starting with functional requirements and environment specifications, and taking it through to a hardened prototype.

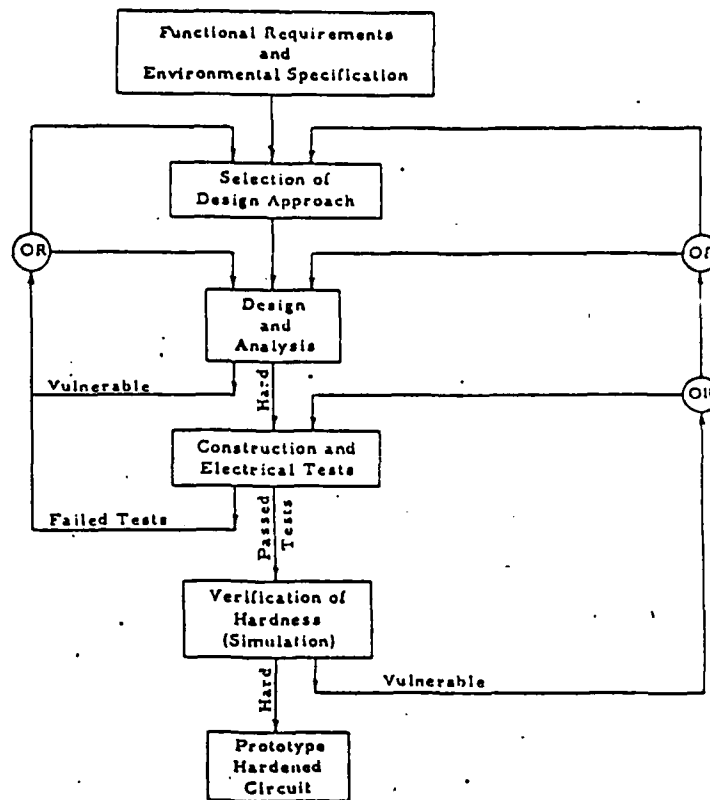


FIGURE 6-13. Typical hardening design flow chart.

The best way to harden against radiation is to prevent radiation from getting into the device. This, however is not as easy as it seems. Neutrons and gammas can penetrate relatively thick materials. As stated earlier, neutrons can be slowed down by material that contains many hydrogen atoms, but neutrons hitting these atoms produce gamma rays that may be harmful. About the only thing that can be done is to keep radioactive particles away from the equipment. This can be accomplished by placing filters on all air intake ducts. Other methods of hardening against TREE are component selection and use, circuit design techniques, and circumvention. These and others will be covered in the remainder of this section.

ELECTRONIC HARDENING METHODS

Component Selection and Use

Selection of "hard" components is the most logical hardening technique. The selection process should start with all components that meet the electrical parameters. From this group, the "non-hard" devices are eliminated. From the ones that are left, the one that has the best hardening features and electrical characteristics is chosen.

For example, after selecting transistors which meet the electrical parameters of the operating circuit or function, the one that has a high radiation tolerance is chosen.

Some factors to be compared are:

- Selecting the silicon devices, since they yield less photocurrents than Germanium devices.

- Selecting devices with high cut-off frequencies, which have a narrow bandwidth.
- Selecting transistors with low base-spreading resistance.
- Selecting transistors with small geometric parameters-junction area.
- Selecting gold-doped devices (gold doping reducing the storage time).

Device selection may mean comparing different types of devices and choosing the hardest type, if having alternate devices. For example, a tunnel diode instead of a transistor, or a zener diode used instead of a capacitor for coupling two circuits with different dc potential.

Circuit Design Techniques

There are several ways to design a circuit to be hard. One way to improve the tolerance to ionization-radiation is by the use of low impedance circuits. However, care must be taken to handle the current transients by some other method. Other methods follow.

Feedback

Feedback is good for maintaining a constant gain in an amplifier against a change in beta due to displacement. It will also stabilize the amplifier against other problems. A transistor of higher than needed gain and feedback is used to stabilize the gain at some lower levels.

Clamping

Large transients can be prevented from being passed on to the next stage by clamping. However, this method may induce other transient effects, ringing and harmonics. This method only stops the radiation induced spike from being sent on down the line.

Cancellation

Even the best semiconductor devices may suffer permanent change in characteristics or create unacceptable transients. This problem may be corrected by a second device that produces a signal that is opposite of the unacceptable transient. This method requires careful matching of devices. A problem with this technique is that it may cause another transient at another radiation level. Also, remember that no more than 90% cancellation should be anticipated on a production basis.

With respect to complementary pairs, it should be realized that matching both the radiation and the electrical characteristic of n-p-n and p-n-p is difficult, at best. Figure 6-14 shows some typical cancellation techniques.

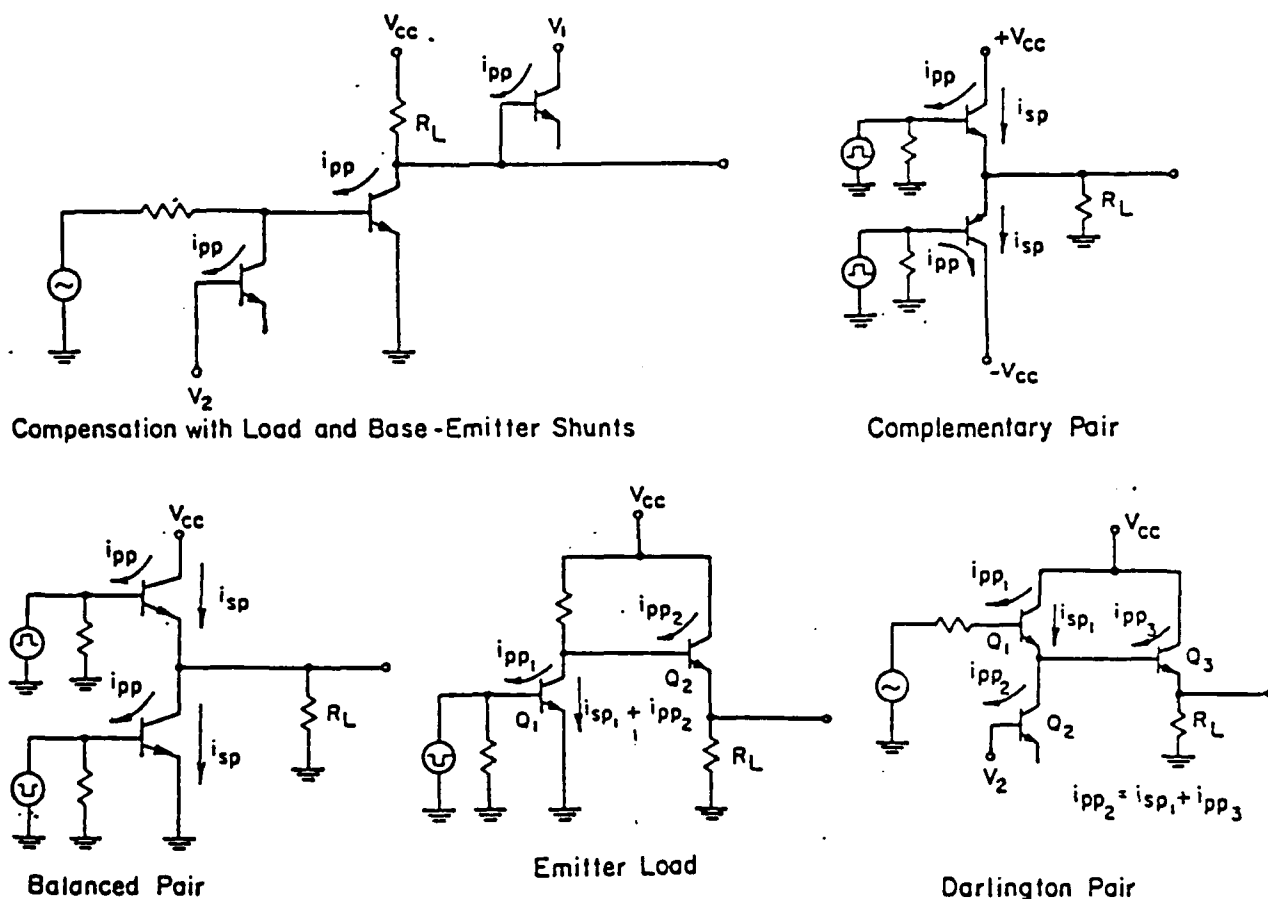


FIGURE 6-14. Typical cancellation techniques.

Circumvention

Circumvention, in its most common form, amounts to disconnection or shutting down of critical circuits during the pulse, or for some fixed time, measured from the instant of radiation arrival. Because a total loss of a circuit function may be unacceptable, there may be a second system operating in "parallel" with the primary. This second unit may be inferior in performance, but radiation hard. This will allow the system to continue at a reduced Performance level. The major problem with circumvention is "Single Event Upset" (SEU). This is when a single neutron or gamma photon strikes a transistor and changes its state. This cannot be protected against, it can only be detected after-the-fact by methods like parity check or redundancy.

CHAPTER 2: THE DEFENSE

The threat of a nuclear event (or events), such as an attack against the United States is an unpleasant thought, at best. However, the possibility is very real. The best protection against a hostile nuclear environment is prevention of its existence. Should prevention fail, the next best solution is to render the effects of that environment as harmless as possible. This portion of the text is intended to show some of the measures taken to harden against the nuclear environment, and equally important, how to retain that hardness throughout the life of the weapon system. Life Cycle Survivability (LCS) is the phrase used to describe the hardening concept. The hardening approach used on any weapon system takes into account all possible factors that have an impact on LCS. Some of those factors include: the mission requirements, cost of initial hardening, and cost of maintaining hardness level. LCS must be considered through all stages of development, production and deployment.

This chapter examines many of the areas with which the OC-ALC engineer should have familiarity. Many of the topics discussed are not unique to nuclear survivability engineering, but because this text is aimed at new-hire engineers, the coverage of some items will be slightly more descriptive than merely a study of S/V specifics.

To paraphrase AFR 80-38, any new system must be evaluated for the level of survivability required for it to be capable of fulfilling its mission when exposed to a man-made hostile environment. These survivability requirements are identified in the Statement of Operational Need (SON). Following validation of the SON, these same survivability requirements are stated in the implementing document, the "Program Management Directive," (PMD). The responsibilities for implementation of the survivability design lie with the research and development (R&D) engineers.

SECTION 7

HARDNESS CRITICAL ITEMS

After a hardened system has been put into operation, the next step is to ensure retention of the original level of survivability. This is done, in part, through close monitoring of those hardware items within a system which have been designated as "Hardness Critical Items," (HCIs). HCIs are defined by DOD-STD-100C as, "...any items at any assembly level which are mission critical and could be designed, repaired, manufactured, installed or maintained for normal operation, and yet degrade system survivability in a nuclear environment if hardness were not considered." Other definitions can be found in other documents, such as, DOD-STD-1766 and SAMSO-STD-77-8. While worded differently, they still say about the same thing.

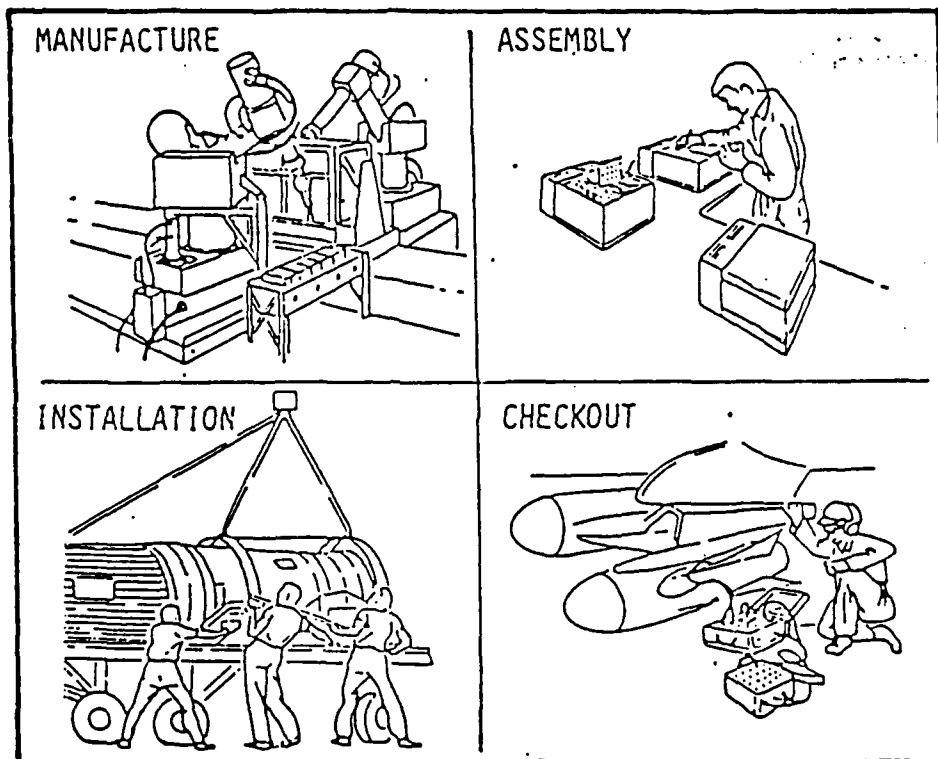


FIGURE 7-1. System nuclear survivability can be degraded during any operation which neglects consideration of hardness.

Whenever a task exists within a company (including the government) which requires that numerous persons are to perform a task, and that it be performed repetitively, there is a tendency to try to standardize the procedures for the task. Indisputably, the final results of the performance of a particular operation are more predictable if a detailed instruction set is provided and followed exclusively.

Any increase in the amount of detail, especially the addition of a magnitude and a unit of measurement as a standard against which comparisons may be made, will naturally contribute to an increase in predictability.

Unfortunately, hardness criticality is an area in which an exact quantitative reference is difficult to obtain. Whether or not a piece of hardware is classified as an HCI is left as a decision influenced by the human factor. What one individual envisions as an HCI, another may not. There have been numerous attempts to define the requirements to be levied on an item to qualify it as an HCI, but to date, human judgment is still required to specify HCIs.

The first problem encountered in defining HCIs is mission criticality. The flight crew on an aircraft might think the switch used to lower the landing gear is mission essential, where the mission essential planners might think that as long as the aircraft can get airborne and deliver the weapons, the landing gear doesn't need to come back down. But the second strike capability might be a factor. If the aircraft is going to be needed for a second sortie, it will need to land safely to take on another load. This is only one example out of many of possible controversial items. Redundancy is another questionable area. A subsystem or circuit, when it's the only one on an aircraft, may be mission essential. Does it retain that criticality when a backup subsystem or circuit exists? Also, the question arises, does the redundant system assume the same criticality? Another discrepancy in designating HCIs is that involving Hardness Dedicated Items (HDI's). An HDI is an item having as it's only function, a safeguard or protection against the nuclear environment threat. Normally, survival in a nuclear environment is not considered a mission critical function. However, any item that is solely dedicated to hardness should also be classified as an HCI.

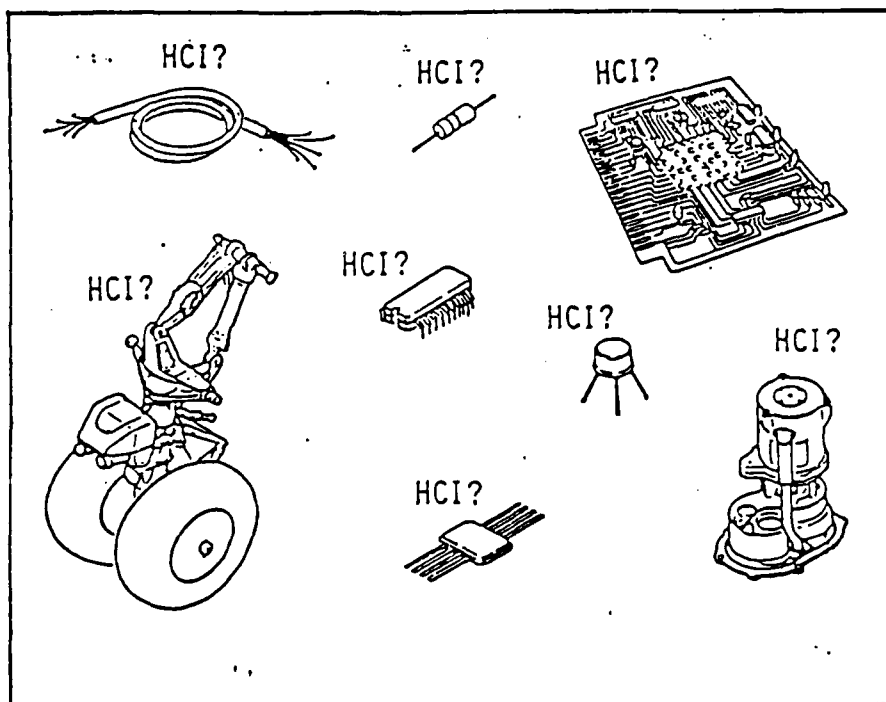


FIGURE 7-2. Classification of an item as "Hardness Critical" is complicated by many factors.

Hardness critical process (HCP's) is any process or procedure to be used during the manufacture of a hardened item which, if not followed precisely, could degrade system survivability. This differs from HCIs and HDI's in that instead of a hardware item, HCP refers to methods used in performing some task.

Identification of hardness critical items begins with initiation of system requirements and specifications. Regressing for a moment, as stated earlier, a Statement of Operational Need begins the whole process. A SON: 1) is initiated by the user (SAC, TAC, etc.), 2) identifies required capability, 3) specifies requirements in quantitative terms, and 4) states vulnerability testing results when the SON is requiring a modification to an existing weapon system.

If the SON is approved and funding provided, a Program Management Directive is written to implement the requirement. This implementing document is given to the appropriate agencies involved. For major new starts or modifications, Air Force Systems Command (AFSC) generally will be assigned the Research and Development (R&D) task. AFLC will have the acquisition role. Copies of the PMD will go to both of these major air commands with specific requirements levied on each. As in the SON, the PMD must state the survivability requirements in quantitative terms.

Having been given the quantitative requirements for the weapon system or modification, the engineering organizations involved will then write the "System Specifications." Specifications must conform to the guidelines of DOD 4120.3, the "Defense Standardization and Specification Program." As an integral part of the system specs, there are usually references made to already existing specifications or standards. An index of all of these is the "Department of Defense Index of Specifications and Standards."

In looking at the Life Cycle Survivability phases (Table 7-1.), it can be seen that the writing of the specifications is part of the validation phase.

<u>Phase</u>	<u>S/V Program</u>
Conceptual	S/V Conceptual Studies
Validation	S/V Specification and Program Plan Formulation
Full Scale Development (FSD)	S/V Design and Verification
Production	Hardness Assurance
Deployment	Hardness Maintenance and Surveillance

TABLE 7-1. The phases of Life Cycle Survivability

The next step in LCS is Full Scale Development (FSD), or sometimes referred to as Full Scale Engineering Development (FSED). Rarely are major programs done organically. The specifications will be distributed to industry in the form of a Request For Proposal (RFP). Contractors will review the specifications and submit their proposals which will include the methods they will use to incorporate the requirements, and hardness design guidelines and practices that need to be followed. The design engineers need to know the effects of a nuclear environment on electronics and

materials. They must also understand the function of the system or circuit to answer the questions: 1) must the system/circuit operate during the nuclear event?, 2) will the system/circuit be temporarily upset during the nuclear events?, and 3) how fast will the system recover to normal operation after an upset?

Hardness design practices which need to be considered include:

EMP/SGEMP DESIGN PRACTICES

- MINIMIZATION OF ELECTROMAGNETIC PICKUP
- SHIELDING AND GROUNDING TECHNOLOGY
- PACKAGE SHIELDING METHODS
- CABLE SHIELDING METHODS
- GROUNDING METHODS
- TRANSIENT SUPPRESSION
- CIRCUIT DESIGN

RADIATION DESIGN PRACTICES

- PART SELECTION
- PHOTOCURRENT LIMITING
- DERATING PARAMETERS PRIOR TO DESIGN
- CIRCUIT CONFIGURATIONS

MECHANICAL DESIGN PRACTICES

- MATERIAL SELECTION
- EQUIPMENT LOCATION
- POSITIONING OF COMPONENTS ON CARDS
- SHOCK ISOLATION
- PROTECTION AGAINST DUST PARTICLES

Quite often, a flight test program will be an integral part of an R&D effort. Even with no actual flights, some form of testing must be done prior to acceptance of a new weapon system or modification. The reference for testing is AF Regulation 80-14, "Research and Development Test and Evaluation."

During the concept phase, all analyses done regarding hardness are recorded in a series of documents called the "Hardness Assurance Design Documentation" (HADD). As the design work and development progress, all data pertaining to the nuclear hardness is incorporated in the HADD. As the weapon system goes into the acquisition phase, the HADD accompanies the hardware and is the basic document (s) for hardness management of the weapon system. Hardness Assurance (HA) is defined as: "procedures applied during the production and deployment phase to ensure the end product is in accordance with the hardness design specifications or requirements." The HADD contains an HCI listing, HCI design criteria, Vulnerability Analysis Reports (VAR) on each mission essential system, a Hardness Assurance Plan, and an HM/HS Program Plan. The HM/HS Program Plan is more or less a summary of the entire HADD. Elements of the HM/HS Program Plan are: background, hardening approach, organizational responsibilities, parts control, configuration control, repair/reprocurement, maintenance plan, and surveillance plan.

HCI/HCP SYMBOLS

Identification of HCIs and HCP's is necessary for configuration control and to flag potential degradations in hardness if proper hardness maintenance techniques are not followed. DOD-STD-100C, "Engineering Drawing Practices," has a requirement that the following statement be placed on engineering drawings having HCIs or HCP's.

"This drawing depicts Hardness Critical Items (HCI) or Hardness Critical Processes (HCP). All changes to or proposed substitutions of HCIs or HCP's must be evaluated for hardness impacts by the engineering activity responsible for survivability."

Technical Orders must also be flagged so that maintenance personnel are made aware that their maintenance actions could have an impact on nuclear hardness.

Drawings and technical orders will be labeled by having the letters "HCI" or "HCP" enclosed in a box, as shown in Figure 7-3.

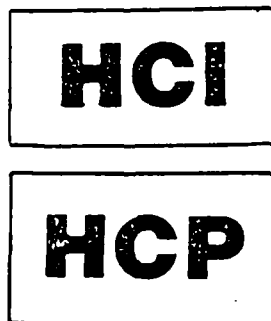


FIGURE 7-3. HCI/HCP Markings.
Engineering drawings and technical orders will have HCI's and HCP's flagged with these symbols.

Figure 7-4 is an illustration taken from a tech order page which describes the "HCP" flag and how it is used. Figure 7-5 is a sample from a tech order showing the HCP markings in an actual maintenance procedure.

1-5. NUCLEAR HARDNESS DESIGN FEATURES. The equipment documented in this T.O. contains certain nuclear hardness design features. Therefore, certain procedures/steps contained herein are hardness critical procedures (HCP). These procedures/steps are identified by use of the symbol **HCP**. This symbol is used in two ways.

CAUTION

All procedures and/or steps identified as **HCP** must be followed exactly as written. Failure to comply with this requirement will jeopardize the nuclear hardness and thus the mission integrity.

a. When the symbol **HCP** is placed between a paragraph number and title, all of that paragraph, including all subparagraphs, is considered as a nuclear HCP.

b. When the symbol **HCP** is placed between a procedure number and the text, all of that procedure is considered as a nuclear HCP.

FIGURE 7-4. HCP Marking.
A paragraph, taken from a tech order, which describes the HCP marking and how it is used.

- (3) **HCP** Check for a maximum bond resistance between ground stud assembly and box (92) of 1 milliohm as described in Section VIII.

NOTE

Install wire harness and terminations per label information and remove labels.

- (4) Install leads onto ground stud assembly by installing washer and nut.
- (5) **HCP** Install cover assembly (13) as described in 6-3.p..
- e. Install fuse holder (126, figure 3-1) as follows:
- (1) Install screws (128).
- (2) Install bus bar (130) onto fuse holder by installing screws (129).
- (3) Install leads.
- (4) **HCP** Install cover assembly (13) as described in 6-3.p..
- f. Install current limiter (127, figure 3-1) as follows:
- (1) Install current limiter in clamp to chassis with screw.
- (2) Install leads.

- h. Install relay (141, figure 3-1) as follows:

- (1) **HCP** Clean bonding surfaces as described in 4-5.a..
- (2) Insert relay into connector (148) and push until firmly seated.
- (3) Install relay and connector onto bracket (145) with washer (143) and nut (142).
- (4) **HCP** Check for a maximum bond resistance between relay and box of 1.0 milliohm as described in Section VIII.
- (5) **HCP** Install cover assembly (13) as described in 6-3.p..

- i. Install relays (157, 160, 163, 165, 167, and 183, figure 3-1) as follows:

- (1) **HCP** Clean bonding surfaces as described in 4-5.a..
- (2) Install relay onto box (92) by installing screws (26, 40, 155, and 234), washers (118, 162, 156, and 235), and nut (112).
- (3) **HCP** Check for a maximum bond resistance between relay and box of 1.0 milliohm as described in Section VIII.

FIGURE 7-5. HCP Marking.
A section, taken from a tech order page, showing the use of an HCP marking on a maintenance procedure.

CONFIGURATION MANAGEMENT

Configuration management involves configuration identification and configuration control. The first order of business is to provide some definitions. Following the definitions will be an explanation of the Air Force's configuration management approach.

Definitions (per MIL-STD-480, "Configuration Control")

Configuration

The functional and/or physical characteristics of hardware or software as set forth in technical documentation and achieved in a product.

Configuration Item (CI)

An aggregation of hardware/software, or any of its discrete portions which satisfies an end use function and is designated by the Government for configuration management.

Configuration Identification

The current approved or conditionally approved technical documentation for a configuration item as set forth in specifications, drawings and associated lists and documents referenced therein.

Configuration Control

The systematic evaluation, coordination, approval, or disapproval, and implementation of all approved changes in the configuration of a CI after formal establishment of its configuration identification.

Configuration Management

A discipline applying technical and administrative direction and surveillance to (1) identify and document the functional and physical characteristics of a configuration item, (2) control changes to those characteristics, and (3) record and report change processing and implementation status.

Critical Item

An item within a configuration item which, because of special engineering or logistic considerations, requires an approved specification to establish technical or inventory control at the component level.

Engineering Change

An alteration in the configuration of a configuration item or item delivered, to be delivered, or under development after formal establishment of its configuration identification.

Engineering Change Proposal

A term which includes both a proposed engineering change and the documentation by which the change is described and suggested.

Form, Fit and Function

That configuration comprising the physical and functional characteristics of the item as an entity but not including any characteristics of the elements making up the item.

Base Line

A configuration identification document or a set of such documents formally designated and fixed at a specific time during a CI's life cycle. Base lines, plus approved changes from those base lines, constitute the current configuration identification.

In accordance with AFR 65-3, "Configuration Management," all echelons of the Military Services and Defense Agencies and DOD Industry interfaces shall exercise configuration control.

After a baseline has been established, any change to a configuration item (CI) must take into consideration, the life cycle of that CI. Any proposed change to a CI will be evaluated by all affected activities, such as engineering, logistic support, production, quality assurance, reliability, maintenance, procurement, and operations.

Engineering changes to the configuration of a CI need to conform to one or more of the following:

Change or changes will:

- a. Correct deficiencies.
- b. Satisfy change in operational or logistics support requirements.
- c. Effect substantial life cycle cost savings.
- d. Prevent or allow desired slippage in an approved schedule.

A recommended change will be in the form of an Engineering Change Proposal (ECP) prepared and submitted in accordance with MIL-STD-480 or MIL-STD-481. The ECP will be evaluated by a Configuration Control Board (CCB). The CCB membership will consist of representatives from all affected organizations and those members will take approval/disapproval and implementation (if approved) steps required.

HCIs, a subset of configuration items, having an ECP against them, must be evaluated closely to determine whether or not the nuclear hardness is degraded as a result of the proposed change. In some cases, a change in the mission of a weapon system may result in a reduction in the hardness requirements. The changes which must be guarded against are those that inadvertently lead to a hardness degradation.

For a more detailed explanation of configuration management and the evaluation of ECPs, review AFR 65-3, "Configuration Management," MIL-STD-480, "Configuration Control," and MIL-STD-483, "Configuration Management Practices for Systems Equipment, Munitions, and Computer Software."

SECTION 8

HARDNESS MAINTENANCE/HARDNESS SURVEILLANCE

"HARDNESS:"

**"A MEASURE OF A SYSTEM'S ABILITY TO WITHSTAND EXPOSURE
TO ONE OR MORE EFFECTS OF NUCLEAR WEAPONS."**

Per AFR 80-38, Hardness Maintenance (HM) consists of "procedures applied during the operational phase to make sure that the system's operation, logistics support, and maintenance do not degrade the system's designed and fielded hardness." One of the primary difficulties in applying these "procedures", is that hardness does not readily fall into the traditional "form-fit-function" concept of maintaining a weapon system. Much of the equipment used in systems currently being built or modified, plays a dual role; one, to perform some specific function as a factor in the every day operational requirements, and two, provide for a shield against the threats of a nuclear environment. In the past, if a new part would fit where the original part fit, looked the same as the old part, and performed the same operational functions, it could be used as a suitable replacement. With nuclear hardening, the need has come for a closer look at the methods employed in the selection of substitute parts, such that a hardness criteria is included with the form-fit function requirement.

Another maintenance problem created with the inclusion of hardness is that of testing. Testing of a non-hardened system is typically accomplished by performing an operational check-out of functional requirements. Under normal circumstances, routine maintenance does not include testing of the level of hardness. How then, can there be any assurance that there has been no degradation in a system's hardness?

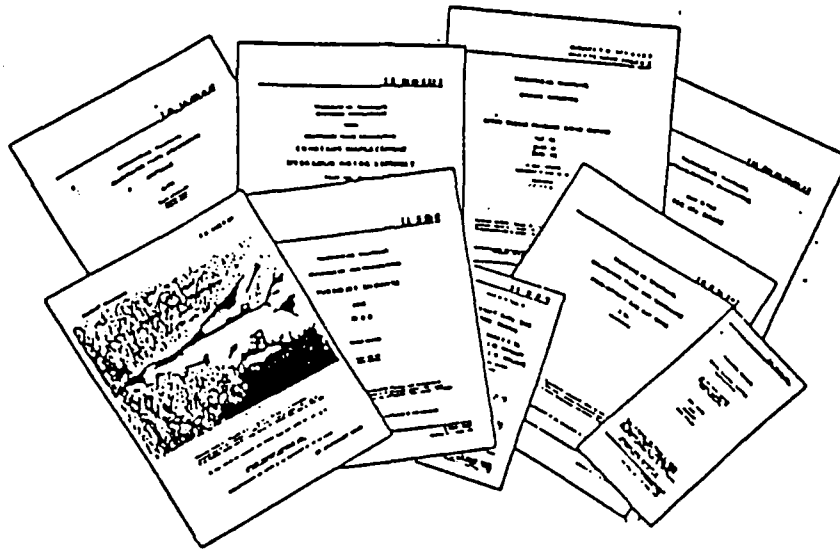
The first step is through the Hardness Surveillance Program. Hardness Surveillance (HS) is defined by AFR 80-38 as: "Scheduled tests and inspections performed during the operational phase to ensure the system's designed hardness is not degraded through operational use, logistics support, maintenance actions, or natural causes." HS is required for detection of system hardness degradation because the hardness design features are not exercised or monitored during normal system operation.

By performing surveillance on the hardness condition of a system, an 'on the spot' determination can be made and recorded in a log as to the amount of degradations experienced on the particular sample being evaluated. Additionally, with the proper documentation and record keeping, the results of surveillance testing can be accumulated into a data base to provide guidance in establishing periodic inspection schedules, based on predicted failure rates.

The success of a Hardness Maintenance/Hardness Surveillance plan is dependent upon making conscientious efforts to familiarize oneself with all aspects of the Life Cycle Survivability concept. The particular job of an engineer in the HM/HS organization is very specialized. It certainly does not require that you "work" all requirements of a total program. However, it is advantageous to be aware of the many support organizations and the "tools" available which will smooth the accomplishment of this engineering job. Some of the "tools"

are: 1) the Air Force Technical Order System, 2) specifications, 3) standards, 4) Air Force Regulations, and 5) the Maintenance Data Collection System. Each of these tools is managed and controlled by an organization or organizations having experts on the use of the tools. It is not necessary to become the expert in all aspects of a program but awareness of the different areas involved is needed to enlist the aid of those experts.

The following pages provide an introduction to some of the aforementioned "systems." It is not all inclusive but should direct the engineer in pursuit of additional knowledge.



AF TECHNICAL ORDER SYSTEM

AFR 8-2 levies a requirement for all systems and equipment to be maintained in accordance with Technical Orders (T.O.'s). Due to the large numbers of technical orders which are needed to support this requirement, a T.O. management system was established for the purpose of numbering, tracing, and controlling the T.O.s. As with any complex system, it might appear that the tech order system is difficult to use. However, armed with a few basic facts, you should be able to use the system with few difficulties.

There are two very general categories of tech orders; those which provide information and instructions for operating, installing, maintaining, inspecting, or modifying system and equipment items, and those which specify policy, procedures, and use of all T.O.s.

The Air Force Technical Order system is described in T.O. 00-5-1. In this T.O., you will find the purpose and concept of the tech order system, a description of the various types of tech orders, procedures for tech order development, and explanation of the tech order numbering system, procedures for recommending T.O. improvements or corrections, and other policies/procedures for the T.O. system. As engineers on Air Force weapon systems, it is important to be familiar with T.O. 00-5-1, and the T.O. system.

Tech orders are further divided into categories according to logically grouped subject or equipment. Figure 8-1 is an extract from T.O. 00-5-1.

TECH ORDER CATEGORY	TITLE
0	Technical Order Indices, Numerical Index, Alphabetical Indexes, and Cross Reference Table Technical Orders
00	General Technical Orders
1	Aircraft Technical Orders
2	Airborne Engines and Associated Equipment Technical Orders
3	Aircraft Propellers and Rotors Technical Orders
4	Aircraft Landing Gear Technical Orders
5	Airborne Instrument Technical Orders
6	Aircraft and Missile Fuel Systems Technical Orders
7	Airborne Engine Lubricating Systems Technical Orders
8	Airborne Electrical Equipment Technical Orders
9	Aircraft and Missile Hydraulic, Pneumatics and Vacuum Systems Technical Orders
10	Photographic Equipment Technical Orders
11	Armament Equipment Technical Orders
12	Airborne Electronic Equipment Technical Orders
13	Aircraft Firefighting, In-flight Fueling, Furnishings, Cargo Loading and Aerial Delivery Equipment Technical Orders
14	Deceleration Devices and Survival Equipment Technical Orders
15	Aircraft and Missile Temperature Control, Pressurizing, Air Conditioning, Heating, Ice Eliminating, and Oxygen Equipment Technical Orders
16	Airborne Mechanical Equipment Technical Orders
21	Guided Missile Technical Orders
22	Aerospace Vehicles Technical Orders
31	Ground Electronic Equipment Technical Orders
32	Standard and Special Tools Technical Orders
33	Test Equipment Technical Orders
34	Shop Machinery and Equipment Technical Orders
35	Ground Handling, Support and air, and Missile Base Operating Equipment Technical Orders
36	Vehicles and Construction and Material Handling Equipment Technical Orders
37	Fuel, Oil and Propellant Handling Equipment Technical Orders
38	Non-Aeronautical Engines Technical Orders
39	Watercraft Technical Orders
40	Air Conditioning, Heating, Plumbing, Refrigerating, Ventilating, and Water Treating Equipment Technical Orders
41	Subsistence and Food Service Equipment Technical Orders
42	Coating, Cleaning, and Sealing Compounds and Fuels, Gasses, Lubricants, Chemicals, and Materials Technical Orders
43	Simulator Training Devices Technical Orders

FIGURE 8-1. Technical Order Categories.

TECH ORDER
CATEGORY

TITLE

44	Common Hardware Equipment Technical Orders
45	Railroad Equipment Technical Orders
46	Office, Duplicating, Printing and Binding Equipment Technical Orders
47	Agriculture Equipment Technical Orders
49	Optical Instruments, Timekeeping, and Navigational Equipment Technical Orders
50	Special Service Equipment Technical Orders
51	Automatic Test System Technical Orders
60	Explosive Ordinance Disposal Technical Orders

FIGURE 8-1. (continued)

The least effective method for locating the appropriate T.O. for the task at hand is to go to the T.O. library and start scanning the shelves. That would be closely equivalent to searching for a particular book in a public library by merely walking up and down the aisles except that finding the T.O. would probably be more difficult. In the T.O. library, typically all that is exposed to view in passing is the T.O. number; no title, no distinguishing size, color, etc.

Even when very little information is available concerning the T.O. needed, there are systematic approaches to be taken. T.O. 0-1-01 is the "Index of Indexes." In this T.O., a listing of other indexes appears according to the category breakdown as shown in Table 8-1. By knowing the type equipment for which a tech order is needed, a category can be selected which most closely describes the equipment. Occasionally however, a piece of equipment might fit more than one category and may require a little extra investigation. Having located the index by category, that index can then be scanned for the T.O. number for the applicable volume.

T.O. 0-1-01
NUMERICAL INDEX
ALPHABETICAL INDEX
CROSS-REFERENCE TABLE

TABLE 8-1. List of Indexes for T.O.'s.

If either the part number or the National Stock Number (NSN) for the equipment is known, the task of locating the correct T.O. becomes a matter of simply looking that number up on micro-fiche available in the T.O. library and with that number, will be listed all T.O.s having pertinence.

TECH ORDER TYPES

There are five types of technical orders: 1) "Methods and Procedures," 2) "Technical Manuals," 3) "Abbreviated Technical Orders," 4) "Index," and 5) "Time Compliance Tech Orders" (TCTOs). Figure 8-2 shows a diagram of the five types as well as examples for each of the five. Preliminary Tech Orders (PTOs) are under the Air Force T.O. system, but do not fit into any of the "type" classifications. PTOs are used on a new weapon system or a modification as a means of doing the validation and verification of the equipment and also the tech order data. After the equipment has been accepted and the pertinent corrections made to the technical data, PTOs are published in the final versions which will fit into one of the five types.

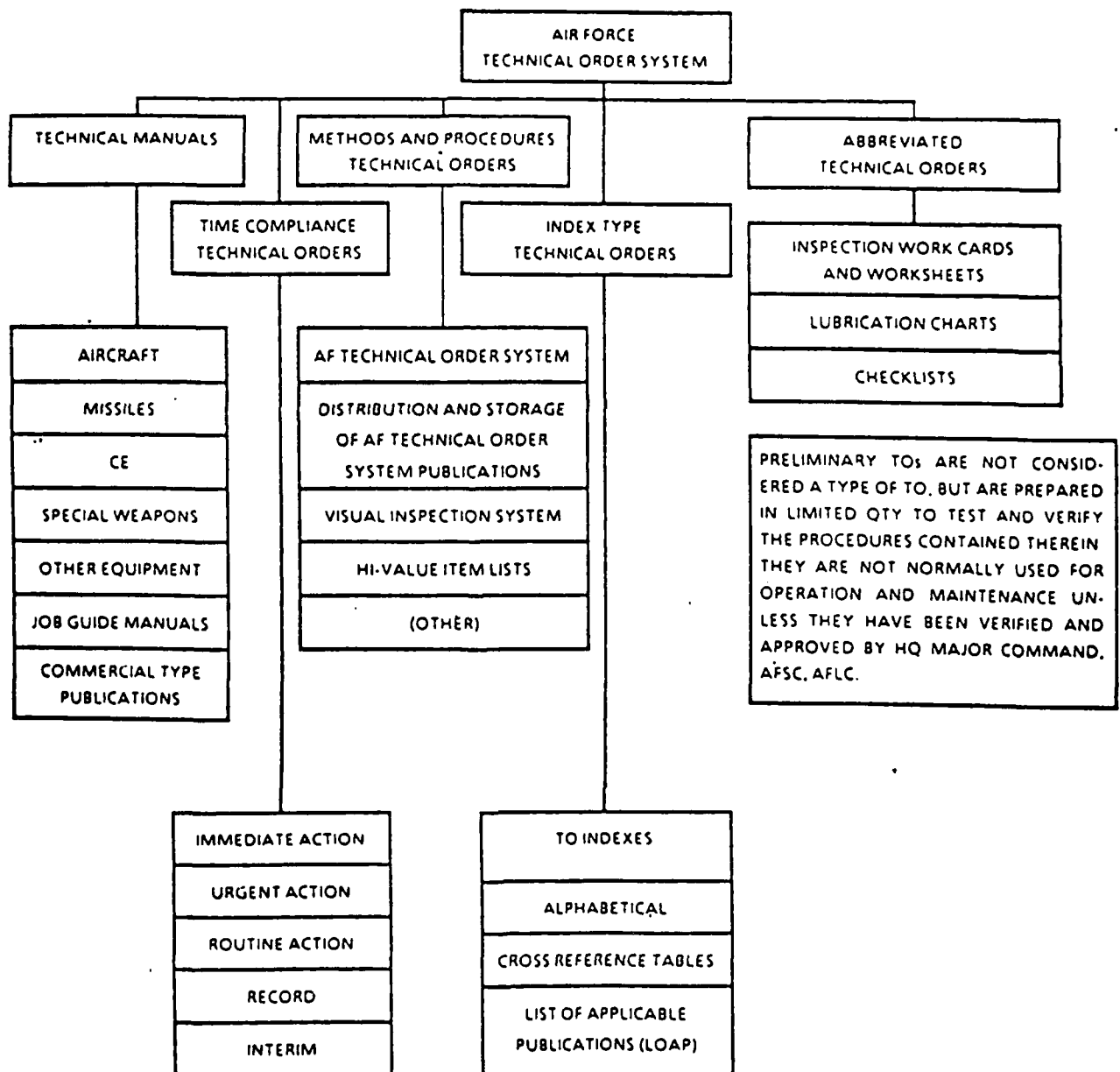


FIGURE 8-2. Types of Technical Orders.

MAINTENANCE DATA COLLECTION SYSTEM

One of the most important segments of a good Hardness Maintenance/Hardness Surveillance program is accurate documentation of maintenance actions. The Maintenance Data Collection System (MDC System) provides for a documented history of all maintenance actions, both on and off equipment. T.O. 00-20-2 is the MDC System tech order, and it states that the objectives of the MDC Systems are:

- a. Collecting base level maintenance production data.
- b. Storing base level maintenance production data.
- c. Retrieving base level maintenance production data.

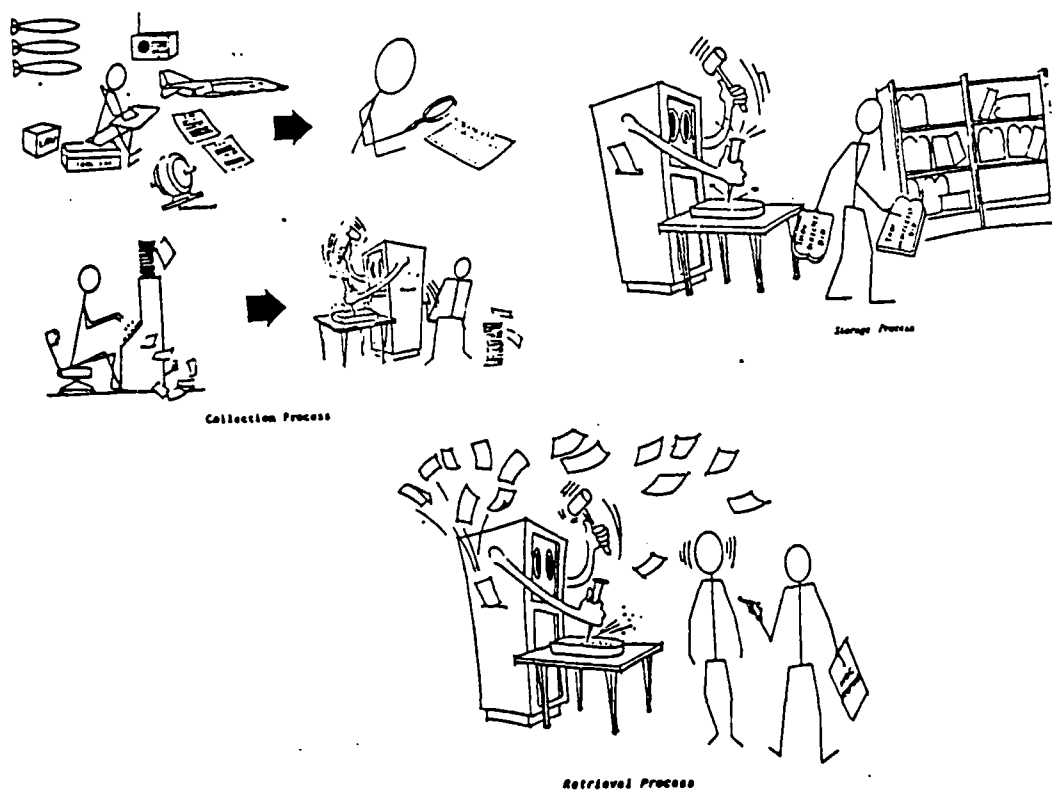


FIGURE 8-3. Maintenance Data Collection System.

Rules and procedures governing the operations of the MDC System are found in the 00-20-2-XX series of tech orders, AFM 66-267, AFM 66-278, AFM 171-267, AFM 171-278, and AFM 171-114.

The collection process involves documenting all maintenance actions on an AFTO Form 349 (see Figure 8-4) and processing that data into a computer data base.

MAINTENANCE DATA COLLECTION RECORD														ONE NO SPR 004				
1. JOB CONTROL NO.		2. WORKCENTER		3. I.D. NO./SERIAL NO.		4. NOS		5. SMO		6. TIME		7. PER		8. SORTIE NO.		9. LOCATION		
10. ENG. TIME		11. ENGINE I.D.		12. INST. ENG. TIME		13. INST. ENG. I.D.		14.		15.		16.		17. TIME OF DAY		18. JOB STD.		
19. ISC		20. PART/ST NUMBER		21. SER. NO./OPER. TIME		22. TAC NO.		23. INST. ITEM PART NO.		24. SERIAL NUMBER		25. OPER. TIME						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
LINE	TYPE	COMP	WORK	ACTION	WHEN	HOW	UNITS	START	STOP	CREW	CAT	CMD	SCN	AFSC/EMPLOYEE				
	MAINT	POS	UNIT CODE	TAKEN	DISC	MAL		HOUR	HOUR	SIZE	LAS	ACT ID	CODE	NUMBER				
1																		
2																		
3																		
4																		
5																		
26. DISCREPANCY																		
27. CORRECTIVE ACTION																		
																28. RECORDS ACTION		

AFTO FORM 349

PREVIOUS EDITIONS SHALL BE USED.

FIGURE 8-4. AFTO Form 349.

The AFTO Form 349 is filled out for each maintenance action to show codes for: action taken, when discovered, how malfunctioned, type maintenance, and varied additional information pertaining to that particular task. The codes used for documentation can be found in AFM 300-4. This manual contains all data codes used in the Air Force. More appropriately, each weapon system has what is called an "06" (oh-six) code manual. The "06" refers to a weapon system specific technical order having as the last digits in it's number, "-06." An example is T.O. 1C-135(K)A-06, which is the "Work Unit Code Manual" (WUC manual) for C/KC/EC/RC/WC-135 aircraft.

Another is the WUC manual for E-4 aircraft, T.O. 1E-4B-06. One of the sets of codes found in these T.O.s (also the source of the T.O. title) is the WUC listing. There are WUCs for systems, subsystems, Line Replaceable Units (LRU), and, in some cases Shop Replaceable Units (SRU). Also on the AFTO Form 349 are sections for a verbal description of the discrepancy or the maintenance action required and a verbal description of the corrective action or maintenance performed. Neither of these are retained in the data base, and are thus lost when the Form 349 is destroyed. The "349" file is periodically purged, and the only permanent data is in the form of the stored codes. Each base had the responsibility for putting maintenance data into a temporary storage system. The current system is the Maintenance Management Information and Control System (MMICS).

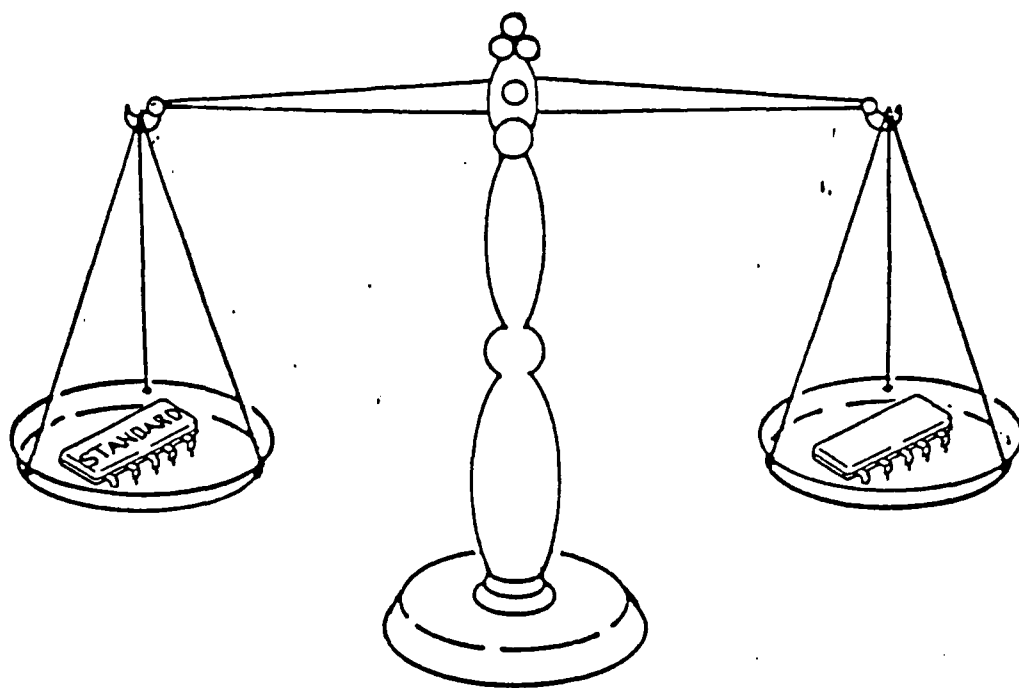


FIGURE 8-6. Standards provide a measurable guideline for the development of hardware, software and documentation.

Standardization is not limited to the government. Examples of commonly known standards in industry are ANSI (American National Standards Institute), ASTM (American Society for Testing and Materials), and IEEE (The Institute of Electrical and Electronics Engineers). Within the government, there is certainly an abundance of guidance for standardization. For anything you do, as a part of your job, you can almost be certain that one of two possibilities exists: there is some form or standard to guide you, or you are the first to do it.

The AF Tech Order System, which has already been discussed, is one form of standardization. Tech orders give step-by-step instructions for the performance of a task, they give descriptions, by assigned part numbers and National Stock Numbers (NSNs), of the acceptable replacement parts which can be used in the repair of equipment, or they specify tolerance limit for items being inspected.

There are other media used to provide standards. One of them is called a "military standard." Another is called a "military specification." The Defense Standardization and Specification Program is described in the document, Standardization Directory, (SD-1), published by the Department of Defense (DOD). Items in the Air Force inventory are assigned unique identifying numbers called National Stock Numbers (NSN) consisting of 13 digits. The first four of those digits represent the Federal Supply Classification (FSC) or a grouping of items by a class. SD-1 distributes the responsibility for standardization, by FSC, to various agencies within DOD. As an example, resistors are in the "5905" FSC. The assigned activity responsible for standardization of this FSC is the "Defense Electronics Supply Center" (DESC) in Dayton, Ohio. DESC has the responsibility for a large portion of the electronics components used by DOD. The

"Defense Nuclear Agency" (DNA) is another organization having standardization responsibilities.

Not all standardization requirements for a given FSC are handled solely by one group. In many instances, one organization will be prime with numerous other groups having secondary or support functions. All of these agencies, as well as their assigned requirements, are listed in the Standardization Directory.

Standards typically are given designations such as MIL-STD-XXXX or DODSTD-XXXX where "XXXX" is a unique number to differentiate one document from another. MIL-STD-143B is one standard. This one is titled "Order of Precedence for the Selection of Standards and Specifications." There is a standard, MIL-STD-12D, which governs the use of abbreviations on drawings and in specifications, standards, and technical documents. MIL-STD-490 is the standard for "Specification Practices."

Specifications are done similarly. Usually a specification will be designated "MIL-S-XXX, "again where "XXX" is a unique number. MIL-S-83490, "Specifications, Types and Forms, " describes the different types of specs according to Table 8-2.

- Type A - System Specification
- Type B - Development Specifications
 - Type B1 - Prime Item
 - Type B2 - Critical Item
 - Type B3 - Non-Complex Item
 - Type B4 - Facility or Ship
 - Type B5 - Computer Program
- Type C - Product Specifications
 - Type C1a - Prime Item Function
 - Type C1b - Prime Item Fabrication
 - Type C2a - Critical Item Function
 - Type C2b - Critical Item Fabrication
 - Type C3 - Non-Complex Item Fabrication
 - Type C4 - Inventory Item
 - Type C5 - Computer Program
- Type D - Process Specification
- Type E - Material Specification

TABLE 8-2. Types of Specifications.

It is not at all uncommon for a Standard or a Specification to reference other Standards or Specifications as part of the requirements. A System Specification on an electronic sub-system may reference a standard on aircraft wiring, one or more on electronic components, another one on the format for documentation, and so on.

As with tech orders, Specifications and Standards are indexed. They can be found in an alphabetical listing (Part I) see Figure 8-7. and a numerical listing (Part II) of the "Department of Defense, Index of Specifications and Standards" (DODISS).

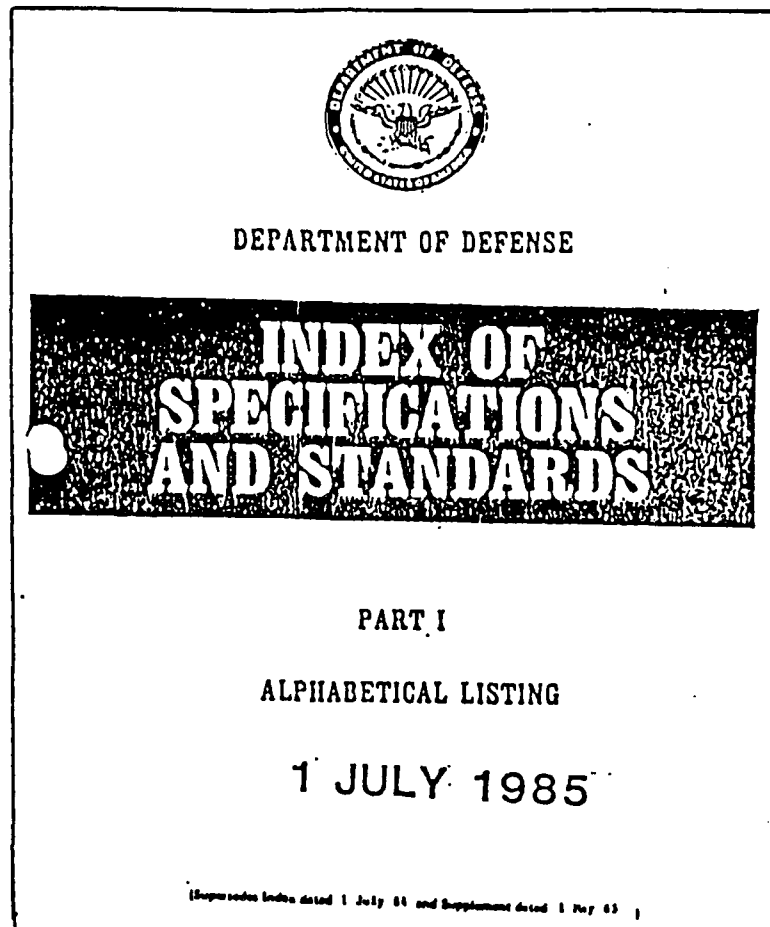


FIGURE 8-7. Index of Specifications and Standards.

DOD Manual 4120.3-M is another important document to follow in order to comply with standardization requirements. The title is "Standardization Policies, Procedures, and Instructions."

SECTION 9

TESTING

The Air Force has thousands of electronic solid state components. The complexity of the systems coupled with high maintenance cost are drivers toward EMI-EMC testing and repairing rather than replacing the item.

During the everyday operation of a hardened system, few failures of the EMP protection devices would have an adverse effect on operation. If the EMP failure did effect system operation, the effect would be "written up" and maintenance would act on the problem. Operational degradates or failures are covered by the T.O.'s.

So why add an extra work load? Obviously, the answer is "To insure that the assigned mission can be accomplished, if an EMP event should occur."

If we are going to test aircraft or systems, then the testers that are used should have outputs that resemble the EMP pulse, or, at least as a minimum, test frequencies of concern to EMP.

As stated earlier in the text, the EMP has a double exponential form. It rises, peaks, and decays in an exponential manner. The rise time is around 10 nsec., pulse width of 1 μ sec, and the amplitude is such that a voltage field of 50,000 V/m may be felt close to the earth's surface. (These are standard numbers, not classified and are used by many companies.) This type of pulse will produce a broadband of frequencies at the system or devices we want to protect.

When an EM Pulse strikes an aircraft, it radiates down the airframe, setting up a field (+ to -, or - to +), similar to the way a wave travels down a transmission line. When it reaches the end of the aircraft, a reflected wave is transmitted back up the airframe, because the "transmission line" was not terminated in it's characteristic impedance. This wave is out of phase and will cancel a portion of the forward traveling wave, thus forming a damped sine wave.

Presently, there are few EMP hardened systems which have Hardness Maintenance/Hardness Surveillance test procedures in T.O. format and as importantly, the equipment is not readily available to do the testing.

There are test facilities being used by the Air Force, which evaluate a complete airframe, or missile system. For example, Kirkland AFB has facilities, TRESTLE and the Horizontally Polarized Dipole (HPD) or the Vertically Polarized Dipole (VPD). The most prevalent use of the larger test facilities are to evaluate individual airframes or vehicles and apply the results to like airframes or vehicles.

Also, there are more portable types of equipment which allows testing in the shop, on the aircraft, or in a laboratory environment, such as; Time Domain Reflectometers, EM, Sniffers, and DITMCO to name a few. We will discuss more types further into the text.

If EMP is to be protected against, then the test facilities (fixed or portable) should generate signals that resemble the EMP pulse. As previously stated, this pulse is broadbanded or consists of many frequencies. This can be seen graphically in Figure 9-1. The varied peak amplitudes, resonant frequencies, along with pulse decay time, complicate the identifying and application of impedance matching functions, thus making

a true analysis of EMP penetrations difficult to measure accurately.

Recall from Section 5, about protective features, that the aircraft skin, if metal, provides some protection due to its conductive nature and that at frequencies above 10 KHZ, aircraft shielding further increases, due to "skin effect." In the range of 200 Hz to 20 MHz, shielding effectiveness can be expressed by:

$$S_H = 20 \log (H_1/H_2) \text{ with } H \text{ being the magnetic fields } (H_1 \text{ inside enclosure, } H_2 \text{ outside enclosure}).$$

$$S_E = 20 \log (E_1/E_2) \text{ } E_1 \text{ electric field inside, } E_2 \text{ electric field outside.}$$

Except for low frequencies, the degree of "Hardness" is controlled by defects in the shield.

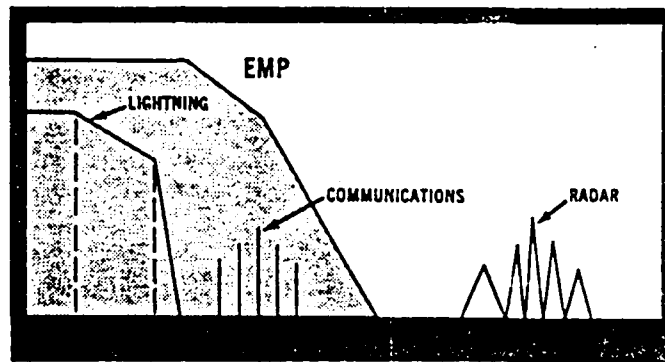


FIGURE 9-1. EMP has higher frequencies than lightning.

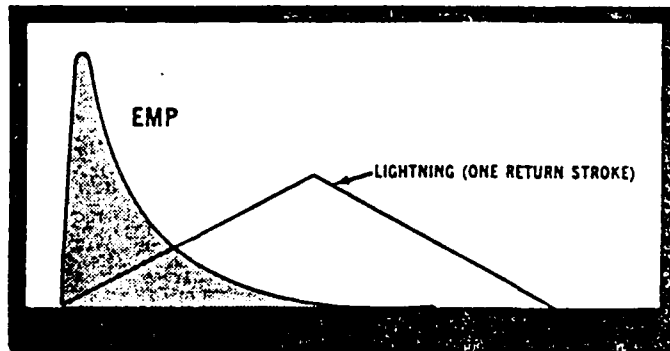


FIGURE 9-2. EMP is very intense and very rapid compared to lightning.

When any metallic structure, such as an airplane, is illuminated by an electromagnetic field, it acts like a collector, an antenna, (much like the TV antenna on your roof collects signals from the transmitter), which results in large currents flowing on the surface.

The electrical currents on the airplane's surface can reach hundreds or even thousands of amperes under certain circumstances. These currents can then enter the interior of the airplane by diffusion through the skin, through openings in the skin or

by antennas. Fields from these sources will induce currents on the wire bundles and cables located nearby. On unshielded cables, the current is induced directly onto the wires; on shielded cables, the current is induced onto the shields and then coupled to the wires at a reduced level. It is the current and voltage induced on the wires which then cause the system upsets or damage to components inside the electronic boxes or LRUs.

Hardness Verification testing will generally be done during the design and full-scale development stages. To a large extent analysis substitutes for testing this phase, particularly, when high frequency protection is the concern.

Hardness Assurance testing is performed in the production phase type of testing. i.e., to evaluate if the equipment will function as designed for its weapon system.

Hardness Surveillance and Hardness Maintenance are the two (2) categories of testing that Air Force Logistic Command and their bases are most concerned with, as they impact the day to day deployment and storage of weapon systems.

EMP TESTING

Two major concerns of EMP Testing are that personnel at the base facilities are not aware of the impact of EMP to their systems and secondly, EMP Testing is very rarely built into the purchase contract. Hardness Surveillance is currently an after-thought, but is a real concern to be addressed.

The EMP frequency range, as stated earlier, extends through the EMI range, and into the 200 MHz range. Frequencies above 100 MHz are not considered a concern, due to the rapid attenuation of signals, without a matched transmission line. We therefore, limit testing to the range of frequencies from 100 MHz down to 100 KHz.

Types of testing which will be discussed, along with their advantages and disadvantages are:

- Dipole
- Monopole
- Log periodic
- Parallel strips
- Direct Device
- Loop transmitter (small & large)
- sniffer
- cable test
- continuity checking
- TPD

TOTAL ILLUMINATION

The first type of testing to be covered will be total illumination. This is when the entire aircraft is exposed to a simulated EMP. The most talked about total illumination test device is the TRESTLE. TRESTLE testing more closely resembles an in-flight environment. The incident field is somewhat different from a plane wave, and the wooden structural members have a different dielectric constant than unity. The propagation near the TRESTLE is not the same as free space, but the overall simulation is a fair approximation of the free flight condition.

The TRESTLE test involves the use of a high power pulse network to bombard a system (KC-135R-M60 tank, etc.) with a near threat level damped sine wave pulse. Sensors are placed on the outside skin, fuselage, wing, antennas, etc. The purpose is to determine the power and frequencies that are felt at each part external to the test body. For internal sensing, probes are positioned internal to the test body at entry points, breaks in the body (door, windows, bomb bays, wheel wells, etc.). Additional inductive probes may be connected internally and externally to cables, wires, and coax, for LRUs. Sensors are also placed in air conditioning vents and conduit, inside and outside filters (mechanical and electronic) etc. The system under test has a hardness design figure. As an example only, we will use a hardness margin of 30db. If an EMP event causes a signal to be felt at the skin of our aircraft, then through the aircraft skin induced into a cable, traveling down the cable to INS LRU pin D of plug P75201, the EMP signal level must be a minimum of 30dB lower than the skin level signal.

$$> 30\text{db} = 20 \log \frac{E_{\text{out}}}{E_{\text{in}}}$$

The HPD and VPD are also total illumination tests, but do not get as close to a true inflight conductor as does the trestle. Signal ranges are from 3 KHz to 20 GHz. The dipole provides a means to illuminate a complete airframe, or a black box. The test equipment is easily obtainable, and as different frequencies are used, antenna selection is relatively easy.

The main disadvantage is susceptibility to reflections from surrounding objects. Daily atmospheric conditions also effect the wave front. Because of antenna selection, when shifting from frequency to frequency, the bandwidth is relatively narrow.

MONOPOLE

The wave impedance generated is greater than free space, lending a truer high impedance incident field test. Both monopole and dipole wave impedance are easily calculated from known formulas. As in the dipole, tests equipment is easy to obtain, and test set-ups are simple. The enclosure size is also greatly variable, and the test may be internal or external to the system being tested.

Disadvantages are a non-uniform field, and their susceptibility to reflection and bandwidth are the same as in the dipole systems.

DIRECT DRIVE INJECTION (DDI)

This is one of the more commonly used methods of testing for EMP. DDI equipment is compatible to the laboratory environment when subsystem boxes are being developed. It also works well in field testing. The test element is closely tied to the source and it is easier to deliver a more uniform and repeatable test pulse.

A damped sine or an oscillatory decaying pulse at the specified level is injected into a component by Direct Drive Injection and can be monitored by either a sensing wire inside a cable or an inductive sensor. The detected signal will be normally a damped sine. The amount of protection provided by a protective device such as a zener diode or a cable shield per meter length can be calculated in dB by:

$$\text{dB} = 20 \log \frac{E_{\text{out}}}{E_{\text{in}}} \text{ or } \text{dB} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}$$

The frequencies to be tested if a damped sine test is used should all be resonance frequencies. These will be dependent on the impedance of the device under test for an aircraft, as well as length of the airframe or antenna. The aircraft resonance frequency can be calculated using the following equation:

$$f_{\text{res}} = 150 \left(\frac{1}{h^2} + \frac{1}{l^2} \right)$$

Where "h" is the height of the aircraft, and "l" is it's length.

The other resonance frequencies for the components under test can be determined from a network analyzer that provides impedance vs frequency.

LOG PERIODIC ANTENNAS (LPA)

The elements for generating an LPA test requires the Transmitter and Receiver to be log periodic. Gain of the LP is greater than a monopole of the same type, by approximate 8db. The antenna is more broadband then the dipole or monopole antenna.

Disadvantages are that the physical size in the EMP ranges are impractically large. The matching of the antenna to the system for an acceptable VSWR is hard to achieve.

PARALLEL STRIPS

Laying transmission and receiver strips parallel to the test item allows for generation and detection of the current induced on the surface of the test item. The primary test application would be to doors, hatches, windows, seams, cables, etc.

Disadvantages are the difficulty in using and obtaining meaningful data in the EMP range 30 MHZ and above. Also, there is no way to account for reflective wave loss.

This type of testing is used by Hill AFB on the missile cables.

In the case of missile cable repair for the minute man, ALCM and SRAM missiles, Hill AFB has prime responsibility. Their facility is unique in that cable troughs have been built which require each individual cable to be laid into its test bed. Testing of the cable assembly requires a computer and signal transmission/receiving equipment. The computer controls the power and frequencies to be transmitted into the trough. At the same time, a co-program is selecting the appropriate impedance matching for both transmitter and receiver for the frequency being applied.

Each of the following frequencies covering the EMP bandwidth generated by a High Altitude Burst (HAB), 100 MHz, 75 MHz, 50 MHz, 25 MHz, 1 MHz and 100 KHz, are injected into the trough at different time intervals. The computer monitors the wires and the coaxial cables within the bundle. Missile cables are designed to give "X" protection against EMP. Any EMP signal felt at the surface of the cable, must be "X"db down at the inner conductor of the hardened cable. The computer program will monitor surface voltage levels, and compare the inner conductor voltage level together. Then, by performing the mathematics, and with the aide of a comparator program, the computer will make the determination of whether or not the shielding effectiveness is being met.

LARGE AND SMALL LOOP TRANSMITTING TO SELECTOR LOOP

Use of the large loop systems is to evaluate complete enclosures, and may be used in the 3 KHz to 1 MHz range. The small loop systems are effective in evaluating door and hatches in the 100 HZ to 10 MHZ ranges.

Large loop advantages:

- a. Total current at seams in one measurement.
- b. Uniformity of fields increase over small loop.
- c. Repeatability of tests are improved over small loops.

Small Loop Advantages

- a. Large field strength can be obtained.
- b. Impedance of field may be calculated by common formulas.
- c. Shielding Effectiveness (SE) measurements obtainable at low impedance fields.
- d. Minimize reflections, wall to wall.
- e. Placement of transmitter may be inside or outside enclosure.
- f. No special equipment required.

Large Loop Disadvantages:

- a. Complex test set-ups.
- b. As the shape of the enclosure changes, test set-up must change.
- c. Frequency range is limited.

Small Loop Disadvantages:

- a. Non-uniformity of fields.
- b. Difficult to test joints and seams with repeatability.
- c. Phase changes due to reflection effect shields.
- d. SE is not easily described from data.

SNIFFER TEST

This type of test is relatively simple. Set-ups are cheaper, and quicker to achieve than most other forms. Aids in identifying areas to be tested in more detail.

Disadvantages include:

- a. Results are a relative scale in determining leakage. No S.E. qualitative results.
- b. Credibility is not good.

SHIELDED CABLE TESTING

Recall from Section 5, under Coupling to Shielded Cables, the term called Transfer Impedance. This transfer impedance is used to indicate how well the cable shield is working. A test currently being studied by the Air Force is a method to check a shielded cable while it is on the aircraft. This test not only checks the cable, but also the connectors at each end.

The test involves use of a network analyzer and inductive coupling probes. One probe drives the shield, and the other probe measures the current. Then, the voltage on one of the inner wires is measured. The network analyzer sweeps the cable from 5 Hz to 200 MHz and graphs the transfer impedance out on the screen or to the plotter.

Different types of degrading damage are supposed to produce different transfer impedance plots.

CONTINUITY TESTING

Continuity testing is mainly an operational check. It is very important to maintain system operation, and also necessary to maintain the hardness of the system. As strands of wire break, they can become antennas. In addition, the VSWR of the cable may change, causing unwanted line reflections. DITMCO uses DC levels to test dielectric constants, and also checks continuity of the cable.

TERMINAL PROTECTION DEVICES (TPDs)

Terminal Protection Devices (TPDs), installed in S/V boxes can be easily tested on an individual basis. One such tester is the Joslyn 182 tester. This device pulses the individual circuits of an S/V box and tells the operator how good the TPDs are. It is currently under development and testing.

GLOSSARY

AIR BURST	An atmospheric detonation of a nuclear weapon where the fireball does not reach the earth's surface.
ALPHA PARTICLE	A spontaneously emitted particle from the nuclei of a radioactive element.
AMBIENT	To surround on all sides.
ATOM	The ultimate (or smallest) particle of an element still retaining the characteristics of that element.
ATOMIC BOMB	A nuclear weapon utilizing fission energy only.
ATOMIC MASS	The quantity of matter in a body, as measured in its relation to inertia. Mass is determined for a given body by dividing the weight of the body by the acceleration due to gravity.
ATOMIC NUMBER	(See nucleus)
ATOMIC WEIGHT	The relative mass of an atom of the given element.
BETA PARTICLE	A spontaneously emitted charged particle from the nuclei of certain radioactive elements.
BLAST WAVE	An air blast with sharply increased pressure at the front edge, followed by strong, but transient winds, generated by an explosion.
BLAST YIELD	The total energy that manifests itself as a shock (or blast) wave generated by a nuclear explosion.
CHAIN REACTION	A series of nuclear reactions in which the products of each reaction activate additional quantities of the reactants, thus causing new reactions. It can be started by bombardment with alpha particles from radium, etc.
CIRCUMVENTION	The disconnecting of critical circuits during the radiation pulse or for some fixed time measured from the instant of radiation arrival.
COMPTON CURRENT	The generation of electron current as a result of Compton processes.
COMPTON EFFECT	The scattering of photons (gamma or x-rays) by the orbital electrons of atoms.
COMPTON ELECTRON	The result of a Compton interaction with a photon creates an electron of increased energy ejected from an atom.

CONTAMINATION

Following a nuclear or atomic explosion, the deposits of radioactive material on the surfaces of structures, areas, objects, or personnel. This material generally consists of fallout, in which fission products and other weapon debris have become part of the particles of dirt and etc.

COSMIC RAYS

Rays at extremely short wave lengths and great penetrating power, which bombard the earth from beyond its atmosphere.

CRITICAL MASS

Under precisely specified conditions creating a minimum mass of a fissionable material that will just maintain a fission chain reaction. The system must be supercritical for an explosion to occur.

CURIE

A unit of radioactivity where the activity of a quantity of any radioactive species in which 3.700×10^{16} nuclear disintegrations occur per second.

DECAY, RADIOACTIVE

The decrease in activity of any radioactive material with the passage of time, due to the spontaneous emission from the atomic nuclei of either alpha or beta particles, accompanied by gamma radiation.

DEPLETION REGION

When p and n-type semiconductors are combined, the mobile charges around the junction in each section are attracted by the mobile charges across the junction. Since free electrons in the n-section have a higher energy than the holes, the electrons drift across the junction to fill the holes. This process neutralizes the junction between the two sections. This neutral region is called the depletion region.

DEUTERIUM

The hydrogen isotope having an atomic weight of approximately 2 units. Combined with oxygen, it forms deuterium oxide, D_2O (heavy water).

DISPLACEMENT

A permanent effect is attributed to physical property changes of the irradiated material caused by energetic particles (neutrons and secondary electrons).

DOPING

Doping is the addition of impurity materials to semiconductor substances. Doping alters the manner in which such substances conduct currents. This makes the semiconductor, such as Germanium or Silicon, into an N-type or P-type substance.

DOSE

A total quantity of ionizing or nuclear radiation.

DOSE RATE

The amount of ionizing or nuclear radiation which an individual or material would receive per unit of time, usually referred to or expressed as rads (or rems) per hour.

DOSIMETER	An instrument for measuring and registering the total accumulated doses of ionizing radiations.
DYNAMIC PRESSURE	The air pressure which results from the mass air flow behind the shock front of a blast wave.
ELASTIC SCATTERING	The neutron strikes the nucleus in its ground state, then reappears without disrupting it.
ELECTROMAGNETIC PULSE	Produced when an explosion occurs in an unsymmetrical environment by generating a sharp pulse of radio frequency (long wavelength) electromagnetic radiation. This occurs especially at or near the earth's surface or at high altitudes.
ELECTRON	A particle carrying a unit negative or positive charge of very small mass.
ELECTRON VOLT (eV)	The electron, when moved through a potential difference of 1 volt, creates imparted energy. The equivalent is 1.6×10^{-12} erg.
ELEMENT	The basic variety of matter occurring in nature which compose substances of all kinds, either individually or in combination.
EMP	(see electromagnetic pulse)
ENERGY	The capacity for doing work and overcoming resistance.
ERG	The unit of work or energy in the C.G.S. (metric) system, being the amount of work done by one dyne acting through a distance at one centimeter.
EXOATMOSPHERE	"Outside, outer, outer part" - air surrounding the earth.
EXTRINSIC SEMICONDUCTOR	An extrinsic semiconductor is a semiconductor to which an impurity has been deliberately added. N-type and P-type semiconductors are considered extrinsic semiconductors.
FALLOUT	The descent of particles, contaminated with radioactive material from the radioactive cloud, to the earth's surface. The contaminated particulate matter itself is a term also used.
FIREBALL	The result of the absorption by the surrounding medium of the thermal x-rays emitted by the extremely hot (several tens of million degrees) weapon residues creates a luminous sphere of hot gasses that form a few millionths of a second after a nuclear or atomic explosion.
FISSILE	One that can be split or easily cleft.

FISSION	The process where by the nucleus of a particular heavy element, with the release of substantial amounts of energy, generally splits into two nuclei of lighter elements.
FISSION PRODUCTS	A complex mixture of substances produced as a result of nuclear fission.
FLUENCE	The product of particle flux and time (units are particles per square centimeter per second).
FLUX	The product of particle density (particles per cubic centimeter) and particle velocity (meters per second).
FORWARD BIAS	In any diode or semiconductor junction, forward bias is a voltage applied so that current flows. EXAMPLE: For a diode, if negative voltage is applied to the cathode, and a positive voltage to the anode.
FREE AIR OVERPRESSURE	The unreflected pressure, in excess of the ambient atmospheric pressure, created in the air by the blast wave from an explosion.
FUSION	With the release of substantial amounts of energy, the nuclei of light elements, especially those of the isotopes of hydrogen, combine to form the nucleus of a heavier element.
GAMMA RAYS	Electromagnetic radiations of high photon energy originating in atomic nuclei and accompanying many nuclear reactions.
GEIGER COUNTER	An instrument for detecting and counting ionizing particles that pass through it.
GROUND ZERO	The point vertically above or below the center of a burst, or a nuclear or atomic weapon, on the surface of land.
HALF LIFE	The time required for the activity of a given radioactive species to decrease to half of its initial value, due to radioactive decay.
HARDNESS	The state or quality of being hard in various senses, specifically radiation or EMP.
HARDNESS CRITICAL ITEM	A piece of hardware which is both mission critical and is essential to maintaining system survivability.
HARDNESS CRITICAL PROCESS	Processes, specifications, and procedures which are hardness critical and which, if changed, could degrade nuclear hardness.
HARDNESS DEDICATED ITEMS	Items having no function beyond nuclear environment defense. They are also Hardness Critical Items.

HEAVY HYDROGEN	(See Deuterium)
HEAVY WATER	A compound like water, composed of oxygen and the isotope of hydrogen, with the atomic weight of two.
HIGH-ALTITUDE BURST	A detonation at an altitude of over 100,000 feet.
HYDROGEN BOMB	A nuclear weapon in which the explosive energy is obtained from both nuclear fusion and nuclear fission reactions.
INELASTIC SCATTERING	This process is identical to elastic scattering, with the exception of, the nucleus is left in an excited state.
INFRARED	Electromagnetic radiations of wave lengths between the longest red (7,000 angstroms, or 7×10^{-4} millimeter) and about 1 millimeter.
INITIAL RADIATION	Nuclear radiation, during the first minute after a nuclear or atomic explosion, emitted from the fireball and the cloud column.
INTRINSIC SEMICONDUCTOR	A pure semiconductor material containing no added impurities.
INVERSE SQUARE LAW	The law which states that where thermal or nuclear radiation from a point is emitted uniformly in all directions, the amount received per unit area at any given distance from the source, assuming no absorption, is inversely proportional to the square of that distance.
IONIZATION	The separation of a normally electrically neutral atom or molecule into electrically charged components.
IONIZING RADIATION	Electromagnetic radiation or particulate radiation capable of producing ions, i.e., electrically charged particles, directly or indirectly, in its passage through matter. (see Nuclear Radiation).
ISOTOPES	Forms of the same element having identical chemical properties, but differing in their atomic masses (due to different numbers of neutrons in their respective nuclei) and in their nuclear properties.
KILO-ELECTRON VOLT (KEV)	The amount of energy equivalent to 1,000 electron volts.
KILOTON ENERGY	Defined strictly as 10^{12} calories (or 4.2×10^{19} ergs). Approximately the amount of energy released by 1000 tons of TNT.
LATCHUP	A phenomenon associated with some types of integrated circuits wherein ionization may induce an abnormal, high current conduction state within internal elements of the circuit which in turn inhibits normal operation.

MACH STEM	Formulation of a shock front created by the merging of the incident and reflected shock fronts from an explosion.
MAJORITY CARRIER	All semiconductors carry current in two ways. Electrons transfer negative charge from the negative pole to the positive pole; holes carry positive charge from the positive pole to the negative pole. Electrons and holes are known as charge carriers. In an N-type semiconductor material, electrons are the dominant charge carriers. The dominant charge carrier is called the majority carrier.
MANHATTAN PROJECT	During World War II, the U.S. Government launched a \$2 billion effort for the purpose of producing an atomic bomb (A-Bomb).
MASS	(see Atomic Mass)
MEGATON ENERGY	Equal to the energy that would be released by the explosion of 1,000 kilotons (1,000,000 tons) of TNT, or defined strictly as 10^{15} calories (or 4.2×10^{22} ergs).
MeV	A commonly used unit of energy, equivalent to 1.6×10^{-6} erg, utilized in nuclear physics.
MICRO-	A one-millionth part of a given factor.
MILLI-	A one-thousandth part of a given factor.
MINORITY CARRIER	In an N-type semiconductor material, most of the charge is carried by electrons, and relatively little by holes. Thus, holes are called the minority carrier in N-type material. Conversely, in P-type material, the electrons are the minority carriers.
MOLECULE	The smallest particle of an element or compound that can exist in the free state, and still retain the characteristics of the element or compound.
NEGATIVE PRESSURE PHASE	The second phase of a shock wave where the pressure falls below ambient, and then returns to the ambient value.
NEUTRON	A particle with no electric charge, but with a mass approximately the same as a proton. The effect of a neutron environment is to cause permanent degradations in semiconductor devices.
NEUTRON CAPTURE	Here the neutron is captured by the nucleus, and one or more γ -rays - called capture γ -rays - are emitted. This is an exothermic interaction, and is denoted by (N, γ).

NUCLEAR RADIATION	<i>Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes.</i>
NUCLEAR WEAPON	<i>A term used to identify any weapon in which the explosion results from the energy released by reactions involving atomic nuclei, either fission or fusion.</i>
NUCLEUS	<i>The central part of an atom with the fundamental particles being the proton and neutron. It carries a positive charge and constitutes almost all of the mass of the atom.</i>
ORGANIC MAINTENANCE	<i>Maintenance performed by the Air Force using Air Force owned or controlled facilities, tools, test equipment, spares, repair parts, and personnel.</i>
OVERPRESSURE	<i>The mansient pressure exceeding the ambient pressure expressed in pounds per square inch, being manifested in the shock wave from an explosion.</i>
PEAK OVERPRESSURE	<i>The maximum value of the overpressure at a given location, and experienced at the instant the shockwave reaches that location.</i>
PLUTONIUM	<i>A radioactive chemical element formed by the transformation of neptunium.</i>
POSITIVE PRESSURE PHASE	<i>The first part of a blast wave during which the pressure rises sharply to a value that is higher than ambient, and then decreasing rapidly to the ambient pressure.</i>
PROMPT	<i>Defines particles, rays, and neutrons emitted essentially at the instant of fission.</i>
PROTON	<i>A particle of mass unity carrying a unit positive charge that is identical physically with the nucleus of the ordinary hydrogen atom.</i>
RAD	<i>A unit of absorbed dose of radiation representing the absorption of 100 ergs of nuclear or ionizing radiation per gram of absorbing material, such as body tissue.</i>
RADIATION	<i>The process in which energy in the form of rays of light, heat, etc., is sent out from atoms and molecules as they undergo internal change. (also see ionizing radiation, nuclear radiation, thermal radiation).</i>
RADIOACTIVE CAPTURE	<i>(see neutron capture)</i>
RADIOACTIVE	<i>The giving off, or capable of giving off, radiant energy in the form of particles or rays, as alpha, beta, and gamma rays, by the disintegration of atomic nuclei.</i>
RADIOACTIVITY	<i>The process or property of being radioactive.</i>

REM

A unit of biological dose of radiation; the name is derived from the initial letters of the term "Roentgen equivalent man (or mammal)."

RESIDUAL RADIATION

Nuclear radiation, chiefly beta particles and gamma-rays, which persists for some time following an atomic (or nuclear) explosion.

REVERSE BIAS

When a semiconductor P-N junction is biased in the non-conducting direction, the junction is said to be reverse biased. Under conditions of reverse bias, the P-type region has a negative voltage applied to it, with respect to the N-type region. This creates an ion-depletion region at the junction, therefore no current can flow.

ROENTGEN

The unit used in measuring radiation, as of x-rays.

SCATTERING

The diversion of radiation from its original path as a result of interactions with atoms, molecules, or larger particles in the atmosphere or other medium between the source of the radiations and a point at some distance away.

SHIELDING

Any material or obstruction which absorbs radiation, and thus tends to protect personnel or materials from the effects of a nuclear or atomic explosion.

SHOCK FRONT

The sharp boundary between the ambient atmosphere, water, or earth, respectively, and the pressure disturbance created by an explosion.

SHOCK WAVE

A continuously propagated pressure pulse or wave in the surrounding medium which may be air, water, or earth initiated by the expansion of the hot gases produced in an explosion.

SLANT RANGE

A distance from a given location to the point at which the explosion occurred.

SPECIFICATION

A specific acquisition support document which clearly and accurately describes essential technical requirements for purchased material.

SPECTRUM

The series of colored bands diffracted and arranged in the order of their respective wave lengths by the white light through a prism or other diffracting medium and shading continuously from red (produced by the longest wave visible) to violet (produced by the shortest).

STANDARD

A document establishing engineering and technical requirements for processes, procedures, practices, and methods adopted for standard use.

SUBCRITICAL

The quantity of a fissionable isotope of uranium (or plutonium) is such that the ratio of the surface area to the mass is large, the proportion of neutrons lost by escape will be so great that the propagation of a nuclear fission chain, and hence the production of an explosion, will not be possible.

SUBSURFACE BURST

The explosion of a nuclear or atomic weapon with its center beneath either ground, or surface of water.

SUPERCritical

To describe the state of a given fission system when the quantity of fissionable material is greater than the critical mass under the existing conditions.

SURFACE BURST

The explosion, at a height above the surface less than the radius of the fireball at maximum luminosity, of a nuclear or atomic weapon.

SURVEILLANCE

Scheduled tests and inspections performed during the operational phase to assure the system is not degraded through operational use, logistic support, maintenance actions, or natural causes.

SURVIVABILITY

The capability of a system to withstand an unnatural hostile environment (man-made), and not suffer abortive impairment of its ability to accomplish its designated mission.

THERMAL RADIATION

Electromagnetic radiation emitted from the fireball as a consequence of its very high temperature consisting essentially of ultraviolet, visible, and infrared radiations.

THERMONUCLEAR

An adjective referring to the process in which very high temperatures are used to bring about the fusion of light nuclei, such as those of the hydrogen isotopes, with the accompanying liberation of energy.

TNT EQUIVALENT

The mass of TNT which would release the same amount of energy when exploded as the measure of the energy released in the detonation of a nuclear or atomic weapon.

TRANSMISSION FACTOR

The ratio of the dose received behind the shield to the dose at the same location in the absence of shielding.

TREE

The effects occurring in an electronics system as a result of exposure to the transient initial radiation from a nuclear weapon explosion.

TRIPLE POINT

The intersection of the incident, reflected, and merged shock fronts accompanying an air burst.

TRITIUM

A radioactive isotope of hydrogen produced in nuclear reactors by the action of neutrons on lithium nuclei and having a mass of 3 units.

ULTRAVIOLET

An electromagnetic radiation of a wave length between the shortest visible violet (about 3,850 angstroms) and soft X-rays (about 100 angstroms).

UNDERGROUND BURST

(See subsurface burst)

UNDERPRESSURE

At some distance behind the shock front, the overpressure has a negative value. In this region, the air pressure is below that of the original atmosphere.

UNDERWATER BURST

(See subsurface burst)

URANIUM

A very hard, heavy and moderately malleable, radioactive metallic chemical element found only, in combination chiefly in pitchblend, and is important in work on atomic energy projects.

VULNERABILITY

The characteristics of a system which causes it to suffer finite degradation in its capability to perform its designated mission as a result of having been subjected to a hostile environment.

X-RAY

A non-luminous electromagnetic ray or radiation of extremely short wave length, generally less than 2 angstroms, produced by the bombardment of a substance by a stream of electrons moving at great velocity, as in a vacuum tube.

YIELD

The total effective energy released in a nuclear or atomic explosion.

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PROBLEMS

1. Determine the approximate number of fissions occurring in a 12 KT fission explosion using U238.
2. Find the reflected shock wave overpressure for a shock wave of 20 psi which hits a surface at 40°.
3. A 1 KT thermonuclear device is detonated at a height of 400 feet. The peak overpressure felt at a point on the ground is approximately 95 psi. What is the slant range between the explosion and the point on the ground?
4. An aircraft radome is built to withstand an overpressure of 2 psi. If the aircraft is on the ground, at what distance from a 25 KT blast at 11,700 feet must it be in order for the radome to survive?
5. At what distance from ground zero will 10 psi overpressure be felt from an 8 KT explosion at HOB of 1,800 feet?
6. What is the duration of the dynamic pressure of a 50 KT blast at 2,210 feet HOB and a slant range of 3,690 feet?
7. Given: Weapon yield = 1MT
 HOB: a) 8,000 feet
 b) 15,000 feet
 c) 25,000 feet
 Distance from ground zero:
 a) 500 feet
 b) 5 miles
 (A total of six combinations)
Find for each combination:
 a) Peak overpressure
 b) Horizontal component of dynamic pressure
 c) Duration of positive pressure phase
 d) Duration of dynamic pressure
 e) Arrival time on ground of blast wave
 f) Rate of thermal energy emission at 1 second
 g) Total amount of thermal energy emitted after one second
8. Name 3 differences between EMP and lightning.

9. Rank the following devices according to their degree of susceptibility to EMP, starting with the most susceptible.

Integrated circuits
Vacuum tubes
Low current switches
High current switches
Motors

10. EMP behaves locally as a:

- a) Space wave
- b) Plane wave
- c) Wave radiated from an ideal source
- d) None of the above

11. How is the EMP produced?

12. Find the propagation velocity of a wave incident on a wire at the following angles.

θ	ψ	ANSWER
0	0	
45	45	
40	33	
90	90	

13. Find the critical length of a finite line for the following.

θ	ψ	T_p	L_c
0	0	10 nS	
45	45	10 nS	
50	90	10 nS	
0	0	70 nS	
45	45	70 nS	
50	90	70 nS	

14. Which of the following could have hazardous currents induced on them by EMP?

- a) Fiber Optics
- b) Antenna coax center lead (RG58U)
- c) Fuel lines
- d) Hydraulic lines in wing
- e) Radar antenna
- f) Composite skins

15. Find the vertical and horizontal directivity values for the following:

a. $\theta = 90$ $= 90$
 $h =$ $v =$

b. $\theta = 90$ $\psi = 45$
 $h =$ $v =$

c. $\theta = 45$ $\psi = 90$
 $h =$ $v =$

d. $\theta = 45$ $\psi = 45$
 $h =$ $v =$

16. Find the clear time for the following angle and height h .

a. $\psi = 90$ $h = .75$

b. $\psi = 90$ $h = 1$

c. $\psi = 45$ $h = 0.75$

d. $\psi = 45$ $h = 1$

17. Is it possible for one burst to cover all of the continental United States? How high must the burst be?

18. What is the maximum V_{OC} theoretically obtainable and is it possible to see these voltages in real life?

19. When must the impedance of the wire of a transmission line be taken into account?

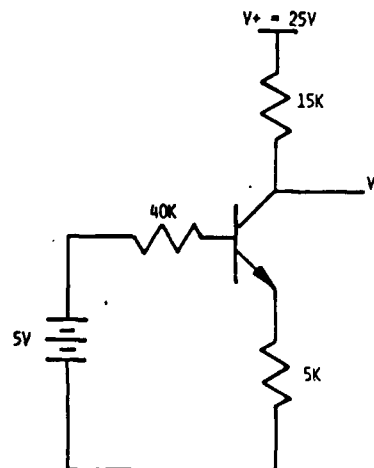
20. For a solid tubular cable 0.9 inches in diameter and a wall thickness of 10 mils, what is the D.C. resistance/KM if the shield is made of copper?

21. Find the Peak Voltage, V_{OC} per meter for a 30 mil thick .9 inch diameter aluminum tube for a pulse that has a τ of 2.5×10^{-5} sec., if the peak current I_0 is 1500A.

22. Are ferromagnetic materials good materials to use as cable shields & why or why not?

23. Find the total losses at 10 KHz and 10 MHz for a copper plate 3 mm thick, taking only the first two reflections into account.

24. A contractor wants to replace a spark gap on an antenna with a varistor.
 - a. Is this safe?
 - b. Will it effect the performance of the system?
 - c. Why or why not?
25. What is the purpose of conducting gaskets on doors and access panels?
26. Find what the skin depth is in earth at 1 MHz if the earth's conductivity $\sigma=10^{-3}$ mhos and $\mu = \mu_0$.
27. What would the main frequency component be for a tower that is 500 feet tall?
28. A transistor has an original h_{fe} of 100, a life time damage constant "K" of 3.25. This transistor is exposed to 10 rads of radiation. It has a gain-bandwidth product of 100×10^6 . What is the post radiation h_{fe0} .
29. How much: a) steel, b) concrete, c) wood; is necessary to attenuate fission product radiation by 40 dB?
 - a)
 - b)
 - c)
30. A mod will replace cmos memory with "bubble" memory. If the same hardness is to be maintained, is this a safe mod?
31. For the following circuits, the current transistor 2N3749 can no longer be obtained. Based only on the voltage gain, is a 2N3507 a suitable replacement? The output voltage must stay within $\pm 10\%$ of normal operating voltage.



SOLUTIONS

1. Determine the approximate number of fissions occurring in a 12KT fission explosion, using U²³⁸.

Using Avogadro's number, the approximation that one pound of fissionable material yields an 8KT blast, and the conversion 2.203×10^{-3} pounds per gram, an approximation of the number of fissions can be made.

First, convert 1 mole of U²³⁸ to pounds.
 One mole of U²³⁸ converted to pounds is:
 238 grams (2.205×10^{-3} lbs/gram) = 0.525 lbs.

Next, find the number of nuclei in a 12KT blast.

$$\frac{6.02 \times 10^{23}}{0.525} \frac{\text{nuclei}}{\text{lbs}} \frac{1 \text{ lb}}{8 \text{ KT}} 12 \text{ KT} = 1.72 \times 10^{24} \text{ nuclei}$$

or

1.72×10^{24} fissions if 100% fission occurs.

2. Find the reflected shock wave overpressure for a shock wave of 20 psi which hits a surface at 40°.

From the Reflected Overpressure Ratio graph (Graph 2-1), read the point of intersection for an incident overpressure of 20 psi and an angle of incidence of 40°. The ratio is approximately 2.95.

$$\begin{aligned} P_r &= 2.95 P \\ &= (2.95) (20) \text{ psi} \\ &= 59 \text{ psi} \end{aligned}$$

3. A 1KT thermonuclear device is detonated at a height of 400 feet. The peak overpressure felt at a point on the ground is approximately 95 psi. What is the slant range between the explosion and the point on the ground?

For a HOB of 400 feet, and a peak overpressure of 95 psi, from the Peak Overpressure graph (Graph 2-3), it can be seen that the distance from ground zero to the point is about 300 feet.

$$\begin{aligned} (\text{Slant Range})^2 &= (400)^2 + (300)^2 \\ \text{Slant Range} &= 500 \text{ feet} \end{aligned}$$

4. An aircraft radome is built to withstand an overpressure of 2 psi. If the aircraft is on the ground, at what distance from a 25KT blast at 11,700 feet must it be in order for the radome to survive?

Using the Peak Overpressures on Ground graph (Graph 2-5), and normalizing to 1 KT:

$$h_1 = \frac{h}{W^{1/3}} = \frac{11700}{(25)^{1/3}} = 4000 \text{ feet}$$

All distances from ground zero at 4000 feet HOB are less than 2 psi, therefore, the radome will survive at any distance.

5. At what distance from ground zero will 10 psi overpressure be felt from an 8KT explosion at a HOB of 1,800 feet?

Using Peak Overpressure Graph 2-5, and:

$$h_1 = \frac{h}{W^{1/3}} = \frac{1,800}{8^{1/3}} = 900 \text{ feet}$$

10 psi is felt at $d_1 < 930$ feet and again at $d_1 = 1250$ feet.
 $d = d_1 W^{1/3} = (930)(2) = 1860$ feet or less

and

$$d = d_w W^{1/3} = (1250)(2) = 2500 \text{ feet}$$

6. What is the duration of the dynamic pressure of a 50KT blast at 2,210 feet HOB and a slant range of 3,690 feet?

Normalizing HOB and slant range

$$h_1 = \frac{h}{W^{1/3}} = \frac{2,210}{(50)^{1/3}} = 600 \text{ feet}$$

$$SR_1 = \frac{SR}{W^{1/3}} = \frac{3,690}{(50)^{1/3}} = 1,000 \text{ feet}$$

$$r_1 = ((1,000)^2 - (600)^2)^{1/2} = 800 \text{ feet}$$

from Graph 2-7:

Scaled dynamic pressure at HOB = 600 feet and $r = 800$ feet is 0.34 sec.

$$t = t_1 W^{1/3} = .34 \times 50^{1/3} \\ = 1.25 \text{ sec.}$$

7. Given: Weapon yield = 1 MT

- HOB: a) 8,000 ft
b) 15,000 ft
c) 25,000 ft

Distance from ground zero:

- a) 500 ft
b) 5 mi

(A total of six combinations)

Find for each combination:

- a) Peak overpressure
- b) Horizontal component of dynamic pressure
- c) Duration of positive pressure phase
- d) Duration of dynamic pressure
- e) Arrival time on ground of blast wave
- f) Rate of thermal energy emission
- g) Total amount of thermal energy emitted after one second

- (1) $W = 1 \text{ MT} = 1000 \text{ KT}$
 $HOB = 8000 \text{ ft}$
 $r = 500 \text{ ft}$

$$\frac{r}{r_1} = \frac{W^{1/3}}{W_1} = \frac{1,000^{1/3}}{1} = 10$$

$$r_1 = \frac{500}{10} = 50 \text{ feet}$$

$$\frac{h}{h_1} = 10$$

$$h_1 = \frac{8,000}{10} = 800 \text{ feet}$$

- (a) Peak overpressure (from Graph 2-4) = 29 psi
(b) Horizontal component (from Graph 2-6) = <1 psi
c/d) From "pressure duration" Graph 2-7:
Positive phase duration = $0.16 W^{1/3} = 1.6 \text{ sec}$
Dynamic pressure duration = $0.33 W^{1/3} = 3.3 \text{ sec}$

(e) Arrival time (from Graph 2-9) = $0.33 W^{1/3} = 3.3 \text{ sec}$

(f) $t_{\max} = .0417 W^{0.44} \text{ sec} = .87 \text{ sec}$ (eqtn 3-6)
 $t/t_{\max} = 1/.87 = 1.15$

From "scaled fireball power" Graph 3-4:

$P/P_{\max} = .95$
 $P_{\max} = 3.18 W^{0.56} \text{ kilotons/sec}$ (eqtn 3-5)
 $= 152 \text{ KT/sec}$
 $P = .95 (152) \text{ KT/sec}$
 $= 144 \text{ KT/sec}$
 $= 144 (10^{12}) \text{ cal/sec}$ (where $1 \text{ KT} = 10^{12} \text{ cal}$)

(g) $E_{\text{tot}} = fW$
 $= 0.35 (1000) \text{ KT}$ ("f" from thermal partition Table 3-3)
 $= 350 \text{ KT}$

From "scaled fireball power" Graph 3-4:

$E/E_{\text{tot}} = 23\%$ at $t/t_{\max} = 1.15$
 $E = .23 (350) \text{ KT}$
 $= 80.5 \text{ KT}$
 $= 80.5 (10^{12}) \text{ calories}$

(2) $W = 1 \text{ MT}$
 $\text{HOB} = 8000 \text{ ft}$
 $r = 5 \text{ mi} = 26,400 \text{ ft}$
 $r_1 = \frac{26,400}{10} = 2640 \text{ ft}$

$h_1 = 800 \text{ (from \#1)}$

- (a) Peak overpressure (from graph) = 3.8 psi
- (b) Horizontal component of dynamic pressure (from graph) $< 1 \text{ psi}$
- (c) Duration of positive pressure phase = $.33 W^{1/3} = 3.3 \text{ sec}$
- (d) Duration of dynamic pressure = $.41 W^{1/3} = 4.1 \text{ sec}$
- (e) Arrival time (from graph) = $1.8 W^{1/3} = 18 \text{ sec}$
- (f) Rate of thermal energy = $P = 144 (10^{12}) \text{ cal/sec}$
- (g) Total amount of energy @ 1 sec = $80.5 (10^{12}) \text{ calories}$

NOTE: (f) and (g) are the same for part 2 of the problem as they were for part 1, because "P" and "E" are assumed to be dependent upon only weapon yield and time for explosions up to 15,000 feet.

- (3) $W = 1 \text{ MT}$
 $HOB = 15,000 \text{ ft}$
 $r = 500 \text{ ft}$

$$r_1 = \frac{500}{10} = 50 \text{ ft}$$

$$h_1 = \frac{15,000}{10} = 1500 \text{ ft}$$

- (a) Peak overpressure = 7.5 psi
- (b) Horizontal component of dynamic pressure $\ll 1$ psi (off scale of available data)
- (c) Duration of positive pressure = .30 (10) = 3 sec
- (d) Duration of dynamic pressure = .39 (10) = 3.9 sec
- (e) Arrival time = .9 (10) = 9 sec
- (f) Rate of thermal emission:
- (1) Without considering air density
 $P = 144 (10^{12}) \text{ cal/sec}$ (same as 1 and 2)
 - (2) considering air density
 $t_{\max} = .038 W^{.44} (\text{air density ratio})^{.36} \text{ sec}$
 $= .038 (20.9)(.85) \text{ sec}$ (air density ratio from chart)
 $= .68 \text{ sec}$
 $P/P_{\max} = .6$ (from Graph 3-4
 $P_{\max} = (3.56 W^{.59})/(\text{air density ratio})^{.45}$ (eqn 3-7)
 $= 210/.81$
 $= 259 \text{ KT/sec}$
 $P = .6 (259) = 155 \text{ KT/sec}$
 $= 155 (10^{12}) \text{ cal/sec}$
 (NOTE: difference = 11 (10¹²)cal/sec)
- (g) Total energy:
- (1) without considering air density: $(t/t_{\max} = 1.15)$
 $E = 80.5 (10^{12}) \text{ calories}$

(2) Considering air density: $(t/t_{\max} = 1.5)$

$$E/E_{\text{tot}} = .38$$

$$E = .38\% \text{ of } E_{\text{tot}} = 0.38(350)KT$$

$$= 133 \text{ KT}$$

$$= 133 (10^{12}) \text{ cal}$$

(NOTE: difference $\approx 52.5 (10^{12}) \text{ cal}$)

(4) $W = 1 \text{ MT}$

$$\text{HOB} = 15,000 \text{ ft}$$

$$r = 26,400 \text{ ft}$$

$$r_1 = 2,640 \text{ ft} \quad (\text{from 2})$$

$$h_1 = 1,500 \text{ ft} \quad (\text{from 3})$$

(a) Peak overpressure = 2.5 psi

(b) Horizontal component of dynamic pressure $\ll 1 \text{ psi}$

(c) Duration of positive pressure = 3.3 sec

(d) Duration of dynamic pressure = 4.1 sec

(e) Arrival time = 21 sec

(f/g) Same as #3

(5) $W = 1 \text{ MT}$

$$\text{HOB} = 25,000 \text{ ft}$$

$$r = 500 \text{ ft}$$

$$r_1 = 50 \text{ ft}$$

$$h_1 = 2500 \text{ ft}$$

(a) Peak overpressure = 3 psi

(b) Horizontal component of dynamic pressure $\ll 1 \text{ psi}$

(c) Duration of positive pressure where $3 < t < 3.5 \text{ sec}$ (this is assumption as available data is incomplete)

(d) Duration of dynamic pressure where $3.9 < t < 4.3 \text{ sec}$ (same assumption as "c")

(e) Arrival time = 17.5 sec.

(f) Rate of thermal emission:

$$t_{\max} = .038 (20.9)(.75)$$

$$= .6 \text{ and } t/t_{\max} = 1.66$$

$$P/P_{\max} = .5$$

$$\begin{aligned}
 P &= .5 (3.56 W^{.59} / .45^{.45}) KT/sec \\
 &= 150 KT/sec \\
 &= 150 (10^{12}) cal/sec
 \end{aligned}$$

(g) Total thermal energy ($t/t_{max} = 1.66$)

$$\begin{aligned}
 E/E_{tot} &= .4 \\
 E &= 0.14 FW \\
 &= 0.14 (.41)(1000) \\
 &= 164 KT \\
 &= 164 (10^{12}) calories
 \end{aligned}$$

(6) $W = 1 MT$
 $HOB = 25,000 ft$
 $r = 26,400 ft$
 $r_1 = 2640 ft$
 $h_1 = 2500 ft$

(a) Peak overpressure = 1.75 psi

(b) Horizontal component of dynamic pressure $\ll 1$ psi

(c) Duration of positive pressure = unknown

(d) Duration of dynamic pressure = unknown

(NOTE: data insufficient for "c" and "d")

(e) Arrival time = 26 sec.

(f/g) Same as #5

8. Name 3 differences between EMP and lightning.

- a) Pulse with 1 to 2 microseconds vs. 100's of microseconds.
- b) Rise time is in the nanoseconds for EMP vs. microseconds for lightning.
- c) EMP has a larger amplitude, 50K V/m vs. 100 to 1,000 V/m.
- d) area of coverage.
- e) frequency spectrum

9. Rank the following devices according to their degree of susceptibility to EMP, starting with the most susceptible.

1. Integrated circuits
5. Vacuum tubes
2. Low current switches
3. High current switches
4. Motors

10. EMP behaves locally as a:

- a) Space wave
- b) Plane wave
- c) Wave radiated from an ideal source
- d) None of the above

11. How is the EMP produced?

Gamma-rays strip off electrons by the compton effect. These electrons spiral around the earth's magnetic fields. This produces a net current.

12. Find the propagation velocity of a wave incident on a wire at the following angles.

$$V = \frac{c}{\cos \theta \cos \psi} \quad c = 3 \times 10^8 \text{ m/sec}$$

ANSWER

θ	$\cos \theta$	ψ	$\cos \psi$	
0	1	0	1	3×10^8
45	.707	45	.707	6×10^8
40	.766	33	.839	4.67×10^8
90	0	90	0	-

13. Find the critical length of a finite line for the following:

$$L_c = cT_p / [1 - \cos \theta \cos \psi] \quad c = 3 \times 10^8 \text{ m/sec}$$

θ	ψ	T_p	L_c
0	0	10 nS	(very long)
45	45	10 nS	6 METERS
50	90	10 nS	3 METERS
0	0	70 nS	(very long)
45	45	70 nS	42 METERS
50	90	70 nS	21 METERS

14. Which of the following could have hazardous currents induced on them by EMP?

- a) Fiber Optics
- b) Antenna coax center lead (Rg58u)
- c) Fuel lines
- d) Hydraulic lines in wing
- e) Radar antenna
- f) Composite skins

15. Find the vertical and horizontal directivity values for the following:

- a. $\theta = 90$ $\psi = 90$ $D_h(\theta, \psi) = \frac{\sin \theta}{1 - \cos \theta \cos \psi}$
 $D_h = 1$ $D_v = 0$
- b. $\theta = 90$ $\psi = 45$ $D_v(\theta, \psi) = \frac{\sin \psi \cos \theta}{1 - \cos \theta \cos \psi}$
 $D_h = 1$ $D_v = 0$
- c. $\theta = 45$ $\psi = 90$
 $D_h = .707$ $D_v = .707$
- d. $D_h = 1.414$ $D_v = 1$
 $\theta = 45$ $\psi = 45$

16. Find the clear time for the following angle and height h.

- a. $\psi = 90$ $h = .75$ $T_c = \frac{2h \sin \psi}{c}$
 $T_c = 5 \text{ ns}$
- b. $\psi = 90$ $h = 1$ $c = 3.0 \times 10^8$
 $T_c = 3.5 \text{ ns}$
- c. $\psi = 45$ $h = 0.75$
 $T_c = 6.6 \text{ ns}$
- d. $\psi = 45$ $h = 1$
 $T_c = 4.714 \text{ ns}$

17. Is it possible for one burst to cover all of the continental United States? How high must the burst be?

From Graph 5-26, the HOB necessary to completely cover the continental U.S. is 500 KM.

18. What is the maximum open circuit Voltage, V_{oc} , theoretically obtainable and is it possible to see these voltages in real life?

7.25 Mv, No (Table 5-1)

19. When must the impedance of the wire of a transmission line be taken into account?

When the transmission line is over a metal ground plane, or a ground plane that has an impedance that is comparable to the wire. (p. 83)

20. For a solid tubular cable 0.9 inches in diameter and a wall thickness of 10 mils, what is the D.C. resistance/KM if the shield is made of copper?

From graph 5-5, $R_o = 1 \Omega/\text{KM}$

21. Find the peak voltage, V_{oc} per meter for a 30 mil thick .9 inch diameter aluminum tube for a pulse that has a τ of 2.5×10^{-5} sec., if the peak current I_0 is 1500A.

$$V_{ocp} = 4,621 \text{ volts/m} \quad R_o \text{ from fig 5.5; } \tau \text{ from fig 5.6, } \tau = \tau_g$$

$$V_{ocp} = .77 \left\{ \frac{I_0 R_o L}{2} \right\} = 4.6.2.1 \text{ v/m}$$

22. Are ferromagnetic materials good materials to use as cable shields & why or why not?

NO. Ferromagnetic materials loose their shield effectiveness when they become saturated.

23. Find the total losses at 10 KHz and 10 MHz for a copper plate 3 mm thick, taking only the first two reflections into account.

Table 5-2 and handbook values

$$S_{10K} = A_{10K} + R_{10K} = 39.5 + 128 = 167.5 \text{ dB, Using } S = A + R = \left(\frac{8.69z}{\delta} \right) + R$$

$$S_{10M} = A_{10M} + R_{10M} = 1241.4 + 118 = 1,359.4 \text{ dB} \quad \tau_{cu} = 5.8 \times 10^7 \text{ mhos/m}$$

$$R = 108 + 10 \log \frac{\sigma_r}{\mu_r f} \quad \mu_t = \mu_{cu} \mu_o = 4\pi \times 10^{-7} \text{ henrys/m, } f \text{ in MHz}$$

24. A contractor wants to replace a spark gap on an antenna with a varistor.

- Is this safe?
 - Will it effect the performance of the system?
 - Why or why not?
- If the varistor is fast enough, yes.
 - Yes
 - It is in the line all the time and effects the impedance.

25. What is the purpose of conducting gaskets on doors and access panels?

To prevent EMP energy from entering the gap between the door and door frame.

26. Find what the skin depth is in earth at 1 MHz if the earth's conductivity (σ_g) is 10^{-3} mhos and $\mu = \mu_o$.

$$\delta = \left\{ \frac{2}{\omega \mu_o \sigma_g} \right\}^{\frac{1}{2}} = \left\{ \frac{2}{(2\pi f)(4\pi 10^{-7})(10^{-3})} \right\}^{\frac{1}{2}} = \frac{1}{2\pi 10^{-2}} = 15.915 \text{ m}$$

27. What would the main frequency component be for a tower that is 500 feet tall?

$$c = 9.84 \times 10^8 \text{ ' / sec} \quad \lambda = 4 \times 500 = 2000'$$

$$f = \frac{c}{\lambda} = \frac{9.84 \times 10^8}{2000} \text{ since antenna is } \frac{1}{4} \text{ wave length}$$

$$f = 492 \text{ KHz (using antenna constant 234, } f = \frac{234}{500} = 468 \text{ KHz)}$$

28. A transistor has an original h_{fe} of 100, a life time damage constant "K" of 3.25. This transistor is exposed to 10 rads of radiation. It has a gain-bandwidth product of 100×10^6 . What is the post radiation h_{fe} .

$$h_{fe0} = \frac{h_{fe}}{1 + \frac{h_{fe}}{F_T} \frac{K \phi}{2\pi}} = \frac{100}{1 + \frac{100}{100 \times 10^6} \frac{3.25 \times 10^6}{2\pi}} = 65.9$$

29. How much: a) steel, b) concrete, c) wood; is necessary to attenuate fission product radiation by 40 dB?

a) 6.6" using Table 4-1
b) 22"
c) 76"

30. A mod will replace cmos memory with "bubble" memory. If the same hardness is to be maintained, is this a safe mod?

NO

31. For the following circuits, the current transistor 2N3749 can no longer be obtained. Based only on the voltage gain, is a 2N3507 a suitable replacement? The output voltage must stay within $\pm 10\%$ of normal operating voltage.
using Table 6-2

2N3749

$$\theta = 0$$

$$\beta = 62$$

$$I_b = 14.27 \mu A$$

$$I_c = 14.28 \mu A$$

$$V_c = 13.29 V$$

$$\theta = 10^6 \text{ Rads}$$

$$\beta = 44.5$$

$$I_b = 18.69 \mu A$$

$$I_c = 831.78 \mu A$$

$$V_c = 12.477 V$$

$$\Delta V = .813 V$$

$$\% \text{ Dif} = 6.519$$

2N3507

$$\beta = 65$$

$$I_b = 13.514 \mu A$$

$$I_c = 878.38 \mu A$$

$$V_c = 13.176 V$$

$$\beta = 33$$

$$I_b = 23.81 \mu A$$

$$I_c = 785.7 \mu A$$

$$V_c = 11.786 V$$

$$\Delta V = 1.39 V$$

$$\% \text{ Dif} = 11.79\%$$

ACTIVE SHEET RECORD											
SHEET NO.	REV LTR	ADDED SHEETS				SHEET NO.	REV LTR	ADDED SHEETS			
		SHEET NO.	REV LTR	SHEET NO.	REV LTR			SHEET NO.	REV LTR	SHEET NO.	REV LTR
1						46					
2						47					
3						48					
4						49					
5						50					
6						51					
7						52					
8						53					
9						54					
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44						89					
45						90					

ACTIVE SHEET RECORD											
SHEET NO.	REV LTR	ADDED SHEETS				SHEET NO.	REV LTR	ADDED SHEETS			
		SHEET NO.	REV LTR	SHEET NO.	REV LTR			SHEET NO.	REV LTR	SHEET NO.	REV LTR
91						136					
92						137					
93						138					
94						139					
95						140					
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135						180					

ACTIVE SHEET RECORD											
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