CHAPTER 1
INTRODUCTION

1-1. Scope.

a. Focus. The focus in this pamphlet is on electromagnetic pulse (EMP) produced by nuclear explosions at high altitudes (high-altitude EMP, or HEMP). Herein, the terms EMP and HEMP are used synonymously. In many cases facilities are not targeted for other nuclear effects and a HEMP event is the worst-case scenario for ground-based facilities. Therefore, many protective measures described herein will also protect against some other electromagnetic environments.

b. Subjects not covered. Specific protection methods for other types of EMP, such as source-region EMP and surface-burst EMP are not covered. In addition, this pamphlet does not cover protection against other effects of nuclear explosions (for example, blast overpressure &d thermal/nuclear radiation).

c. TEMPEST problem. The TEMPEST problem is nearly the inverse of the HEMP event. TEMPEST is the unclassified name for the studies and investigation of compromising emanations. Equipment within the facility can be the source of electromagnetic waves and stray currents/voltages with characteristics which are related to the information content of signals being processed. If these unintentional emissions are intercepted and studied, the analyst can reconstruct the original data and could gain access to national security information. A proper TEMPEST design, however, will preclude the presence of analyzable signals in uncontrolled areas.

d. Common treatment. Thus, HEMP and TEMPEST protective measures must each control electromagnetic energy, the former protecting system equipment from externally generated signals and the latter containing emissions from internal sources. The functional similarities imply that a common treatment can be employed for the two purposes.

1-2. Application. Information in this pamphlet is applicable to engineers responsible for the design, construction, and maintenance of mission-critical facilities, such as those supporting the command, control, communications and intelligence network. The information is relevant to new construction as well as to additions, upgrades, and retrofits to existing facilities.

1-3. References. This pamphlet is intended to stand alone and, as such, no additional references should be required to understand the material herein. However, only a small sample of the material published on HEMP and TEMPEST can be highlighted here. Because different facilities will have differing requirements for protection, supplementary sources are listed at the end of
most chapters to assist the engineer in designing protection on a case-by-case basis.

1-4. Background.

a. Reliance on electronic technology. Military facilities are becoming increasingly reliant on automated systems that take advantage of modern electrical and electronic technology. Facilities are equipped with state-of-the-art computerized systems for expeditious, reliable, and cost-effective operations. However, the electromagnetic (EM) properties of many electronic components can make entire systems susceptible to upset or permanent damage due to the environmental effects of EMP. Systems are also susceptible to the compromise of security information by the unintentional intelligence-bearing emanations of electromagnetic signals. Thus, with the benefits of automation has come an increased vulnerability.

b. Early planning. Techniques to protect a facility are usually selected during the early design phase. If it is anticipated that a facility may someday acquire equipment that must be protected, early planning can avoid costly retrofitting later. The decision to harden will be based on the interaction of mission criticality, electromagnetic environment, security requirements, and costs.

c. Far-reaching effects. HEMP is dangerous because this event has far-reaching effects at distances where other nuclear environments are either nonexistent or inconsequential and because of its high level of broad spectral energy. However, the spectrum included under HEMP does not cover all EM environments. For example, the characteristic pulse risetime and possible conducted current waveforms for lightning differ from those for HEMP; thus, hardening against HEMP does not necessarily protect against lightning.

d. Evolving technology. It is important to note that this field is relatively new and that technical expertise is still evolving. Therefore, it is the designer's responsibility to stay current with new developments to assure the most cost-effective reliable configuration for vital military fixed facilities.

1-5. Pamphlet organization. At the beginning of each subsequent chapter, there is an outline. The purpose of the outline is to provide more detail on the chapter's content than is ordinarily appropriate in a table of contents.
CHAPTER 2

EMP ENVIRONMENT

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a. HEMP generation. HEMP is caused by a nuclear burst at high altitudes. Prompt gamma rays following the nuclear detonation are the principal source of HEMP. This gamma radiation causes bursts of electron flow from the Compton effect, a photoelectric effect, and a "pair production" effect. Of these three effects, however, the primary source of HEMP is the Compton effect. Due to their low level of significance, the photoelectric and "pair production" effects are not discussed.

(1) Gamma radiation. At high altitudes (above 30 kilometers), the atmosphere is thin and thus allows gamma radiation from the nuclear burst to travel out radially for long distances (ref 2-1). Below the center of the burst, however, the atmospheric density increases as the Earth's surface is approached. The prompt gamma rays propagate toward the Earth in a thin spherical shell, moving at the speed of light away from the burst.

(2) Compton scattering. When the downward directed rays encounter the upper regions of the atmosphere, they begin to interact with the atoms (or molecules) of the atmosphere at a rate which is a function of atmospheric density and burst conditions. The dominant interaction is Compton scattering, in which the energy of a gamma ray is partially transferred to an electron of an air atom (or molecule). The electron then begins traveling in approximately the same direction as the gamma ray. The other product of collision is a gamma ray of reduced energy. Figure 2-1 illustrates this process (ref 2-1). The spherical shell of gamma rays is converted during Compton scattering into a spherical shell of accelerated electrons.

(3) Deposition region. The region in which Compton scattering occurs is called the deposition region. The thickness and surface range of the deposition region is a function of height-of-burst (HOB) and weapon size and type. A representative thickness is from 20 kilometers to 40 kilometers, but a deposition region may be as thick as 70 kilometers (10-kilometer to 80-kilometer altitude) for a 300-kilometer HOB and a 10-megaton weapon.

(4) Radiating magnetic field. In the spherical shell of Compton electrons, the electrons are charged particles that rotate spirally around the Earth's geomagnetic field lines (ref 2-2). The electrons thus have a velocity component transverse to the direction of the gamma radiation. These transverse currents give rise to a radiating magnetic field. This field propagates through the atmosphere to the Earth's surface as if it were contained in the same spherical shell as that formed by the original gamma ray shell.
b. HEMP ground coverage. Significant HEMP levels can occur at the Earth's surface out to the tangent radius (and beyond, for frequencies below 100 kilohertz). The tangent radius is where the line of sight from the burst is tangent with the Earth's surface. If one assumes a spherical Earth of radius \( R_e \), the tangent radius \( R_t \) is given by--

\[
R_t = R_e \cos^{-1} \left( \frac{R_e}{R_e + \text{HOB}} \right)
\]  

(eq 2-1)

where HOB is the height of burst. For an approximate Earth radius of 6371 kilometers, an HOB of 100 kilometers corresponds to an \( R_t \) of 1121 kilometers, an HOB of 300 kilometers corresponds to an \( R_t \) of 1920 kilometers, and an HOB of 500 kilometers corresponds to an \( R_t \) of 2450 kilometers. Thus, the HEMP generated by a nuclear explosion at an altitude of 500 kilometers would illuminate the whole continental United States. If high-yield weapons are used, the field strength will not vary much with HOB, so this large geographic area can be covered with little reduction in peak field strength.

c. Field strengths versus ground location. HEMP fields can be significant out to the tangent radius, but the exact field strength as a function of ground position depends on many factors. Burst-observer geometry is important because HEMP is produced by electron motion transverse to the Earth's magnetic field. Thus, electron moving along the field do not radiate. For a burst at high geomagnetic latitudes, as would be the case for Europe or North America, the pattern shown in figure 2-3 results. There will be a region of near-zero field strength north of the sub-burst point, where the magnetic field lines from the burst site intersect the Earth. There will also be a broad arc of maximum field strength that corresponds to electron trajectories perpendicular to the geomagnetic field. The field amplitude is an appreciable fraction of the peak amplitude (about 0.5 for most high-yield weapons) out to the tangent radius. The EMP field strength will also vary as a function of HOB, weapon yield (especially gamma yield), and geomagnetic field, which depends on geomagnetic latitude. Near the equator, the Earth's magnetic field strength is weaker and the orientation is very different, so peak HEMP fields would be smaller and the field strength pattern much different than that shown.

d. Electric field. A commonly used unclassified time waveform of a HEMP electric field \( E(t) \) in free space can be approximated by the analytical expression--

\[
E(t) = \frac{kE_p e^{a(t-t_s)}}{1+e(a+b)(t-t_s)} \quad \text{(kV/m)}
\]  

(eq 2-2)
where $E_{pk} = 50$ kV/m (peak electric field in kilovolts per meter; $k = 1.2$ (a normalization constant); $a = 5 \times 10^8$ per second (exponential decay rate); $t_s = 10^{-8}$ seconds (a time shift parameter); and $t$ is the time of interest (in seconds). This waveform is often called a "double exponential." Figure 2-4 is a graphic representation of the HEMP waveform; the frequency content of the HEMP pulse also is depicted in figure 2-4. This waveform rises from 0.1 to 0.9 times its peak amplitude in about 5 nanoseconds ($t_r$), and decays to one-half its peak amplitude in about 200 nanoseconds ($t_{1/2}$) (fig 2-4). The upper left curve shows this waveform plotted on a linear time scale. The upper right curve shows a logarithmic time scale that distorts the pulse shape but gives the risetime more clearly. The Fourier transform of this transient electric field is given by--

$$E(u) = \frac{2.47 \times 10^{13}}{(ju + 4 \times 10^6)(ju + 4.76 \times 10^8)} \text{ volt second per meter}$$

(eq 2-3)

where $j$ is the unit imaginary number and, $u$ is the radian frequency. As the lower curve shows (fig 2-4), the electric field strength stays fairly constant in the 10-kilohertz to 1-megahertz frequency range, declines by a factor of 100 in the 1- to 100-megahertz range, and continues to decrease at a more rapid rate for frequencies greater than 100 megahertz. HEMP energy generally ranges from frequencies of 0.1 to 10 megahertz, with all but 1 percent falling below 100 megahertz.

(1) Transients. The transient expected from HEMP has recently been redefined analytically. Details of this new definition are classified and thus cannot be presented here (DOD-STD-2169(C), ref 2-3).

(2) Transient definition. In DOD-STD-2169, EMP experts have divided the time representation of the HEMP event into three periods: early time, intermediate time, and late time.

(a) The early-time portion arrives at the Earth's surface quickly and lasts about 1 microsecond. This is the portion caused by the first gamma ray pulse. It is a fast spike and has its energy concentrated in the one to several hundred megahertz frequency band.

(b) Intermediate-time HEMP occurs between 1 microsecond and 0.1 second and has a frequency spectral content between 1 hertz and 100 kilohertz. It is primarily a high-impedance field.

(c) Late-time HEMP is primarily the magnetohydrodynamic (MHD) EMP occurring from 0.1 to 1000 or more seconds. MHD-EMP is discussed in paragraph f below.
(3) Qualitative characteristics. Figures 2-5 and 2-6 show unclassified qualitative HEMP characteristics.

f. Magnetohydrodynamic EMP (MHD-EMP). MHD-EMP is the late time \((t > 0.1\) second) component of EMP caused by a high-altitude nuclear burst. Two distinct physical mechanisms are thought to produce different parts of the MHD-EMP signal: an "early phase" from \(0.1\) to \(10\) seconds after the detonation, and a "late phase" lasting from \(0.1\) to \(1000\) seconds. MHD-EMP fields have low amplitudes, large spatial extent, and very low frequency. Such fields can threaten very long landlines, including telephone cables and power lines, and submarine cables.

(1) MHD-EMP early-phase generation. A nuclear burst at high altitudes gives rise to a rapidly expanding fireball of bomb debris and hot ionized gas. This plasma tends to be diamagnetic in that it acts to exclude the Earth's magnetic field from the inside of the fireball. Thus, as the fireball expands and rises in early stages, it will deform the geomagnetic field lines and thereby set up the early phases of the MHD-EMP, which can propagate worldwide. The region on the ground immediately below the burst is shielded from early-time MHD EMP by a layer of ionized gas (the X-ray patch) produced by X-rays from the nuclear burst.

(2) MHD-EMP late-phase generation. Residual ionization and the bomb-heated air under the rising fireball are mainly responsible for the late phase of the MHD-EMP. As the bomb-heated air rises, residual ionization moves across geomagnetic field lines and large current loops form in the ionosphere. The ionospheric current loops then induce earth potentials. The late phase of the MHD-EMP is seen in large sections of the Earth's surface, including regions at the magnetic conjugate points. Though amplitudes are smaller than for HEMP, the low-frequency fields can introduce damaging potential differences on long cable systems.

(3) Electronic surge arresters. The longer duration and greater energy content coupled into electrical lines in the DOD-STD-2169 environment is an important factor in the design and selection of electronic surge arresters.

2-3. Other EMP environments. Of several different kinds of EMP environments, HEMP is the one specified most often for system survivability. The discussion of HEMP applies to all systems that must survive a nuclear event, even though they are not targeted or even located close to a target. One reason is that the peak field amplitudes are large enough to damage or upset most unprotected electronic systems that use solid-state technology. Further, the frequency band is broad and thus all types of electronic/electrical systems are potentially susceptible. Third, as discussed previously, the HEMP area coverage is large. The fact that HEMP occurs when other nuclear environments are absent implies that systems with no defense against other nuclear effects may need protection against HEMP. Although HEMP is a vital concern for mission-critical systems and is the environment addressed in this manual,
other environments are briefly discussed for the sake of completeness. Table 2-1 lists some of the other EMP environments and compares their properties.

a. Surface burst EMP (SBEMP). SBEMP is produced by a nuclear burst close (less than 0.2 kilometer) to the Earth's surface (fig 2-7). The EMP is generated in the source region, which extends out to a radius of 3 to 5 kilometers from the burst. EMP environments inside the source region can affect systems such as ICBMS or command centers that have been hardened to withstand nuclear blasts, thermal energy, and radiation inside the source region. A surface burst also has fields radiating outside the source region, with those field amplitudes significant (greater than 5 kilovolts per meter) out to ranges of 10 kilometers and more. In this range, the radiated EMP is a principal threat to systems that respond to very low frequencies or have very large energy collectors such as long lines. Conducted EMP for these systems is such that special attention must be given to surge protection to ensure that the high currents can be dissipated.

(1) Source region. The generation of EMP by a surface burst starts when the gamma rays travel out radially from the burst. These rays scatter Compton electrons radially, leaving behind relatively immobile positive ions (fig 2-8). This charge separation produces radial electric fields (\(E_r\)) with amplitudes over 100 kilovolts per meter (amplitudes may approach 1 megavolt per meter) and risetimes as short as a few nanoseconds. Since the ground conducts better than the air at early times, the strong radial electric field causes a ground current to flow in a direction opposite to the radial Compton current in the air. The resulting current loops produce azimuthal magnetic fields. Magnetic fields are strongest at the Earth's surface and diffuse both upward and downward from the interface. The discontinuity due to the air Earth interface also generates strong vertical electric fields in the source region. Source region fields depend strongly on factors such as weapon yields (gammas and neutrons), HOB, and distance from the burst. The interaction with a system is very complex: besides the EM fields, the system may be exposed to nuclear radiation, in addition to being located in a region of time-varying currents and conductivity. In specifying a source region environment for a system, then, the concept of balanced survivability is useful, as it is with all EMP environments. If a facility is designed to withstand ionizing radiation and other nuclear effects at a specified range from a given burst, it should also be designed to withstand the EMP effects generated at that range.

(2) Electric and magnetic field relationship. The time-varying currents and conductivity of the surface-burst source region imply a complex relationship between electric and magnetic fields, which does not show the simple magnitude and direction relationships of a plane wave. Determination of these relationships is beyond the scope of this manual.

(3) Radiated region. Outside the source region, the most important feature of the charge distribution produced by a surface burst is the asymmetry due to the air-earth interface (fig 2-8). In an infinite uniform
The atmosphere, Compton electrons would travel out radially in all directions. However, for SBEMP, the earth interferes with down-flowing electrons, which results in a net vertical flow of Compton current. This produces a time-varying vertical dipole that radiates outside the source region. The main components of the radiated field are the vertical electric field and the azimuthal magnetic field. The field amplitude has a $1/R$ dependence with range, as is typical of electric dipole radiation. The field rises quickly to its first peak (electric field vector vertically upward), with a second peak of opposite sign following some tens of microseconds later. More of the energy occurs at lower frequencies than for HEMP. Figure 2-9 shows the calculated electric field amplitude as a function of range for a large surface burst. As the figure shows, radiated surface burst field amplitudes most often are smaller than HEMP fields outside the source region. However, field amplitudes can still be significant at ranges of 10 kilometers or more. The right portion of the curve shows the inverse relationship between amplitude and range beyond 5 kilometers. This is typical of electric dipole radiation in the far-field region. There is no standard waveform as there is for HEMP. Thus, the very concept of a standard waveform is less likely to be useful for SBEMP because of the variation in amplitude and waveform with range and weapon yield (output). Radiated SBEMP typically gives off most of its energy at lower frequencies (below 100 kilohertz). The increase in low frequency content and the vertical electric field orientation mean that the system impact of radiated SBEMP may be more important than that of HEMP for some systems, even though HEMP field magnitudes are generally larger.

b. Air-burst EMP.

(1) Source region. Air-burst EMP results from a nuclear explosion at intermediate altitudes—2 to 20 kilometers. The EMP produced by a burst at heights between 0.2 and 2 kilometers will share characteristics of air and surface bursts, and a burst between 20 and 40 kilometers will cause EMP sharing characteristics of air-burst and high-altitude EMP. The source region resembles the surface-burst source region in that weapon gammas scatter Compton electrons radially outward (fig 2-10). Positive ions are left behind, producing charge separation and radial electric fields. For air-burst EMP, there is no return path through the ground. Due to ionization, however, increased air conductivity enables a conduction current to flow opposite the Compton current in the air. Still, no significant current loops are formed, and the large azimuthal magnetic fields typical of a surface burst do not result.

(2) Radiated region. Outside the source region, the radial charge separation resulting from the Compton current will produce some radiated fields because a slight asymmetry exists. At intermediate altitudes, the atmospheric density gradient permits Compton electrons to move farther up than down. This asymmetry results in electric dipole radiation (fig 2-11). The water vapor density will also vary with height, though this variation depends on the weather. A typical decrease in water vapor density with altitude will reinforce the asymmetry produced by the atmospheric density gradient. Even
with these two effects combined, the asymmetry is much weaker than for a surface burst. The typical field strengths produced are on the order of 300 volts per meter at 5 kilometers from the burst. Pulse waveforms vary significantly with burst altitude and assumed water vapor gradient, with typical risetimes in the 1- to 5-microsecond range. The recoil Compton electrons can also produce a radiated signal by the same geomagnetic turning mechanism that gives rise to HEMP. This is called magnetic dipole radiation. At low altitudes, electron paths are short so that peak amplitudes are limited to hundreds of volts per meter, mainly to the east and west of the burst. The peak amplitude increases with burst height until it reaches tens of kilovolts per meter as the burst approaches the high-altitude region. Rise and decay times are similar to those for HEMP--on the order of tens of nanoseconds.

c. System generated EMP (SGEMP). SGEMP results from the direct interaction of nuclear weapon gammas and X-rays with the system. Because weapon gammas and X-rays are attenuated by the atmosphere at low altitudes, SGEMP has special importance for systems outside the atmosphere, such as satellites in space and missiles in flight. These can receive significant gamma and X-ray exposures at considerable distances from a nuclear burst. SGEMP involves complex modes of field and current generation that strongly depend on the system's physical and electrical configuration. As a result, there is no standard threat. The field amplitudes generated can be as large as 100 kilovolts per meter, making SGEMP a significant threat to exposed systems.

(1) Coupling modes. The initial physical process is the generation of energetic free electrons by Compton and photoelectric interactions of weapon X-rays and gammas with the system materials. Emitted electrons produce space-charge fields that turn back later electrons or, at higher gas pressures, cause appreciable ionization. Emission of the electrons from internal walls results in current generation and, hence, EM fields inside cavities. This effect is termed internal EMP (IEMP). Coupling occurs both by electric and magnetic field coupling directly onto signal cables and by induced current flow on cable shields and ground systems. The asymmetric displacement of electrons from a cable shield and from internal conductors and dielectrics inside a single cable or cable bundle produces a distributed current generator over the whole exposed region of the cable. Electron emission from the outer skin of the subject system generates whole body interaction effects that produce charge displacement and direct field coupling. These effects also can influence internal EMP if there are penetrations or openings to the inside.

(2) Transient radiation effects on electronics. The direct impingement of radiation (e.g., X-rays, gamma rays, neutrons) can also change the performance of semiconductor electronics through atomic interactions. Operating thresholds, junction voltages, and the crystalline structure of solid-state materials can be affected, thus changing the way devices and circuits using such materials operate. TREE normally is important only when modern electronics might be exposed to the nuclear detonation source region with a high in-flow of nuclear radiation.
d. Summary. Table 2-2 outlines the EMP waveforms important for critical systems. HEMP is the most difficult threat to harden against because of its large spatial extent, high amplitude, and broad frequency coverage. It is also the simplest threat to describe using the waveform definition in equation 2-2 and the plane wave approximation. The source region for an air or surface burst combines intense fields with significant time-varying conductivities and environments. Source-region EMP is important for systems that can withstand other nuclear environments present in the source region. EMP radiated from a surface burst usually has lower amplitude than HEMP and can affect systems more due to the vertical field orientation and lower frequency. Air-burst radiated fields have lower amplitudes and are less likely to be important (a system hardened to survive HEMP will survive radiated air-burst EMP). SGEMP is characterized by very high amplitudes, very fast risetimes, and importance to systems outside the atmosphere. MHD-EMP has low amplitude but can damage the interface circuits of long landlines or submarine cables.

2-4. Environment-to-facility coupling. To analyze how HEMP will affect facilities and electronic equipment, the exterior free field threats must be related to system, subsystem, and circuit responses. The functional relationship between external causes and internal effects is often called a "transfer function." The analysis involves learning how the system collects energy from the incident HEMP field. The result is usually a matrix of internal fields and transient voltages and currents that may flow in circuits and subsystems. This is called a "determination of the coupling interactions between the external threat and the system." Generally, HEMP enters shielded enclosures by three different modes: diffusion through the shield; leakage through apertures such as seams, joints, and windows; and coupling from intentional or inadvertent antennas. These different modes are shown in figure 2-12 and are discussed next.

a. Modes of HEMP entry.

1) Diffusion through the shield. HEMP fields diffuse through imperfectly conducting walls of shielded enclosures. The diffusion is greatest for magnetic fields and is a low-pass filtering event, as shown by the magnetic shielding effectiveness curve for an ideal enclosure (fig 2-13). Thus, the field that reaches the inner region of a shielded enclosure is basically a low-frequency magnetic field. This effect is greatest in an enclosure with solid metal walls. It is also seen somewhat in enclosures with metal rebar or wire mesh reinforcement. The shielding effectiveness (SE) for an enclosure with rebar is also shown in figure 2-13. The reduced SE at high frequencies for rebar and wire mesh structures allows a significant fraction of the incident HEMP environment to penetrate to electronics inside the enclosure.

2) Leakage through apertures. Openings and other shielding compromises include doors, windows, holes for adjustments and display units, seams, improperly terminated cable shields, and poorly grounded cables.
Unless properly treated, each opening is a leak through which the HEMP field can couple directly into the shielded enclosure. Leakage through an aperture depends on its size, the type of structure housing it, and its location. The aperture responds to both total magnetic and electric fields at the site of the leak. The effect of apertures on the magnetic SE of an ideal enclosure is shown in figure 2-14.

(3) Intentional and inadvertent antennas. Intentional antennas are designed to collect EM energy over specified frequency bands. However, there will also be an out-of-band response to HEMP. Because the incident HEMP field has a broad frequency spectrum and high field strength, the antenna response must be considered both in and out of band. Analytical models are available for determining the different antennas' responses to HEMP. These models, along with the incident field, yield the HEMP energy that appears at the connecting cable. This energy later reaches the electronic systems inside the enclosure at the other end of the connecting cable. Inadvertent antennas are electrically conducting, penetrating external structures, cables, and pipes that collect HEMP energy and allow its entry into the enclosure. As a rule, the larger the inadvertent antenna, the more efficient energy collector it is in producing large, transient levels in the enclosure. Figure 2-15 shows some inadvertent antennas for a ground-based structure. The coupling for inadvertent antennas can be analyzed using transmission line and simple antenna models. These analyses, however, are complex and beyond the scope of this manual. The reader is directed to references 2-2 and 2-6 for guidance on these analyses.

b. Conductive penetrations. Many factors affect the coupling of EM energy to penetrating conductors. The EMP waveform characteristics, such as magnitude, rate of rise, duration, and frequency, are each important. Further, the observer's position with respect to the burst is a factor. Because the interaction between fields and conductors is a vector process, the direction of arrival and polarization is also important. Conductor characteristics also affect HEMP coupling. These include conductor geometry (length, path, terminations, distance above or below the earth's surface), physical and electrical properties that determine series impedance per unit length (including diameter, resistivity, and configuration), and the presence and effectiveness of shielding. For overhead or buried conductors, the electrical properties of soil affect coupling. Though dielectric permittivity and magnetic permeability may be significant, soil conductivity is usually the greatest determining factor for coupling. This is because both HEMP attenuation in the ground and reflection from the ground increase with greater soil conductivity. The soil skin effect also varies. An EM wave in a conductive medium attenuates to 0.369 of its initial amplitude in a distance 

\[ d = \left( \frac{2}{\pi wc} \right)^{1/2} \]

where \( d \) is the skin depth, \( p \) is the magnetic permeability of the medium, \( \omega \) is the angular frequency, and \( c \) is the conductivity. Because the skin depth is greater at lower frequencies, lower frequency field components attenuate less and the pulse risetime increases. Many elements of a facility can act as efficient collectors and provide propagation paths for EMP energy. As shown in figure 2-16, EMP can couple to structures such as
power and telephone lines, antenna towers, buried conduits, and the facility grounding system. Actual antennas, nonelectrical penetrators such as waterpipes, and any other conducive penetration can couple EMP energy into a structure. In addition, if the structure is not shielded or is not shielded well enough, EMP can couple to the cables between equipment inside. Paragraphs (1) through (3) below briefly describe coupling mechanisms, including theory, and give rough values for the currents and voltages that can arise from a typical EMP event.

(1) Basic coupling mechanisms. Figure 2-17 shows two basic modes by which currents and voltages are induced in conductors. One mechanism shown is that for inducing voltage in conductors by electric field. The electric field exerts forces on the "mobile" electrons in the conductor, which results in a current. The voltage associated with the force is the integral of the tangential component of E along the length of the wire. This assumes the electric field is constant over the length of the wire and is parallel to it. The other mechanism by which currents are induced on conductors is through changes in the magnetic field, also shown in figure 2-17. Faraday's Law is the mathematical expression that describes this phenomenon. This law relates the time rate of change of the magnetic field to the production of an associated electric field. This electric field "curls" around the changing magnetic field and causes a voltage if a loop is present. The voltage for the loop of area A in the figure is 

\[ V = A \frac{dB}{dt} \]

where \( B \) is normal to the loop and has the same magnitude over the whole loop. This can give a good approximation with HEMP when the magnetic field can be considered uniform over the area of the loop. The fast rise rate of the magnetic field can produce large currents and voltages. A sample calculation is helpful. Assume the following--

\[ A = \text{loop area} - 0.1 \text{ meter squared} \ (m^2) \]
\[ E(t) = C e^{-t/a} \text{ where } C = 50,000 \text{ volts/meter} \]
\[ a = 0.5 \times 10^{-6} \text{ (time constant)} \]

(Note: a simple exponential is used for this example.)

\[ H = \frac{E}{377} \text{ (a plane wave)} \]
\[ = e^{-t/a} \left( \frac{C}{377} \right) \]

\( u_0 \) = loop antenna in free space

\[ u_0 = 4\pi \times 10^{-7} \text{ Webers/amp-meter} \]

Then:

\[ H = \frac{50,000}{377} e^{-t/0.5 \times 10^{-6}} \text{ amps/meter} \]
\[ = 132.6 e^{-t/0.5 \times 10^{-6}} \text{ amps/meter} \]

2-11
\[ B = u_0 H = 4(\pi) \times 10^{-7} \times 132.6 \, e^{-t/0.5} \times 10^{-6} \, \text{webers/meter}^2 \]

Loop voltage \( V_L = A \, (dB/dt) \)

\[
= 0.1 \, \text{meters}^2 \left( \frac{d(4(\pi) \times 10^{-7} \times 132.6 \, e^{-t/0.5} \times 10^{-6})}{dt} \right) \text{webers/meter}^2
\]

\[
= 0.1 \left(2 \times 10^6 \times 4(\pi) \times 10^{-7} \times 132.6 \, e^{-t/0.5} \times 10^{-6}\right) \text{webers/second}
\]

\[
= -33.3 \, e^{-t/0.5} \times 10^{-6} \, \text{volts.}
\]

(2) HEMP coupling analysis. This section describes some of the more important coupling interactions in the design and analysis of shielded facilities.

(a) Equivalent circuit for a small electric dipole. A small electric dipole is one with a short length compared with the dominant wavelengths incident on it. A HEMP contains 99 percent of its energy in wavelengths longer than 3 meters. The analysis done here using a small dipole model is significantly more accurate for dipoles less than 3 meters. The model is fairly simple and serves to show how EMP coupling calculations are done. Figure 2-18 shows a dipole and its equivalent circuit. The voltage is induced by the EMP. The capacitance is caused by the two halves of the dipole acting like two plates of a capacitor. For large resistance \( R_L \) (\( R_L \gg 1/WC_A \)), the capacitance has almost no effect and the voltage across the equipment terminals is in phase with the incident electric field. For small \( R_L \) (\( R_L \ll WC_A \)), the capacitance takes effect. Then--

\[
Q = CV_{OC} = C_A \{-hE \sin(\theta)\}
\]

(eq 2-4)

\[
V_L = IR_L = \frac{dQ}{dt} \cdot \frac{R_L}{L} = R_L \{-hC_A \cdot \frac{dE}{dt} \cdot \sin(\theta)\}
\]

(eq 2-5)

(b) Equivalent circuit for a small loop (magnetic dipole). For HEMP, a small loop is one with a radius less than 3 meters. Loop antennas can be a major source of EMP-induced currents and voltages because of the EMP’s quickly changing magnetic field. Figure 2-19 shows a loop antenna and its equivalent circuit. The voltage is induced by the EMP. The resistance, \( R_L \), is the equipment or load resistance. The inductance, \( L_A \), is due to the loop. For large \( R_L \) (\( R_L \gg WL_A \)), the inductance has almost no effect. Thus, the voltage is proportional to the area of the loop and the rate of change of the transverse magnetic field. For small \( R_L \) (\( R_L \ll WL_A \)), the inductance takes
effect and the current in the loop is proportional to the magnetic field. The current will flow in a way that makes the magnetic flux through the loop due to the current cancel the magnetic flux through the loop due to the field.

(c) Typical coupling model. In actual coupling calculations, it is often hard to depict a structure using the small dipole circuits just described. For example, the microwave tower in figure 2-20 is not small compared to a 3-meter wavelength, and it would be hard to represent it by superimposing loops of different sizes, shapes, and orientations. Instead, such a structure can be electrically approximated by a monopole of the same height and of some effective radius, $a_e$. An upper bound on the effective radius is given by the tower dimensions at the base. The effect of ground is approximated by assuming an infinitely conducting ground plane. For a worst-case vertical orientation, the equivalent fat monopole over an infinitely conducting ground plane is equal to a dipole of the same radius and twice the height in free space. Models such as this can be used to find bounds or orders of magnitude for coupling to large or complex structures. Model validity or accuracy depends on the amount and kind of approximation used and on how well results agree when compared empirically with experimental or complex analytical data.

(d) Shielded cable coupling. To analyze the transients induced on cables by EMP, two calculations usually are needed to find the coupling onto the cable sheath and the voltage and resultant currents induced on the internal wires. The calculation of coupling onto the cable sheath depends on cable construction and location, and will be discussed for some typical cases later. Figure 2-21 shows the calculated voltage induced on a wire inside a shielded cable. The transfer impedance can be found theoretically, especially for simple cable shields such as solid metallic conduits. For example, the transfer impedance of a thin-walled tubular shield is given by--

$$Z_T = \frac{1}{2(\pi rcT) \sinh(1+j)T/d} \cdot \frac{(1+j)T/d}{\sinh(1+j)T/d} \quad \text{(eq 2-6)}$$

where $r$ is the radius of the shield, $c$ is its conductivity, $T$ is the wall thickness, $j$ is the unit imaginary number, and $d$ is the skin depth. Some geometries, however, such as braided coaxial cables, are too complex for theoretical treatment. Thus, it is often preferable to determine the transfer impedance by experiment. For braided coaxial cables, the transfer impedance is typically expressed as--

$$Z_T = R_0 \frac{(1+j)s/d}{\sinh(1+j)s/d} = j\omega M_{12} \quad \text{(eq 2-7)}$$

where $R_0$ is the d.c. resistance per unit length, $j$ is the unit imaginary number, $s$ is the shield wire diameter, $d$ is the skin depth, $\omega$ is the angular frequency, and $M_{12}$ is the leakage inductance per unit length. For typical
braided coaxial cables, $R_0$ ranges from 1 to 25 milliohms per meter and $M_{l2}$ ranges from 0.1 to 1 nanohenry per meter. At low frequencies, $s/d \ll 1$ and $wM_{l2} \ll R_0$ and $Z_T$ reduces to $R_0$. For example, for an RG-58 coaxial cable at $f = 10^4$ hertz, $d = 0.24 \ll 1$ and $wM_{l2} = 0.01$ milliohms per meter $\ll R_0 = 14.2$ milliohms per meter so the transfer impedance is about equal to $R_0$. A 500-amp current on a cable length of 100 meters will therefore induce a voltage drop on the center conductor of 500 amps(100 meters)(14.2 milliohms per meter) = 710 volts.

(e) Transmission line coupling. Transmission line theory is the chief method used to calculate EMP coupling to aerial and buried conductors, simple cables, and other long penetrators (e.g., pipes, ducts). A transmission line picks up EMP from both the electric field and the changing magnetic field. The loop formed by the line, its terminations, and the ground behaves much like a loop antenna and picks up EMP from the transverse changing magnetic field. The links between the line and ground behave much like dipole antennas and pick up EMP from the vertical electrical field. The line also picks up EMP from the longitudinal electric field. Though this last source seems the most clearcut, it does not cause as much of the total current and voltage as the other two. The transmission line theory involves many points that were ignored in the analyses of small dipole and loop antennas. First, the conductor is long compared to the incident wavelengths. This means that currents and voltages will differ everywhere on the line. Also, there will be reflection from the ground plane. With all such factors taken into account, an analytical solution can be obtained, often with the help of a computer. This solution usually involves the short circuit current and the open circuit voltage at the line's termination. Figure 2-22 shows an approximate model of this EM coupling. The transmission line is broken into $N$ sections. $N$ is chosen based on the bandwidth needed in the model. One to three foot sections are typical. Each inductor and capacitor in the model is chosen such that $L = Z_0T/2$ and $C = T/Z_0$, where $Z_0$ is the characteristic impedance and $T$ is the transit time in each section. The voltage source in each section depends on the incident field. This theory also applies to transmission lines with multiple cables. In this case, a source and load impedance will exist between each cable and ground and between each cable and every other cable. Current and voltages will be induced between the cables. This is caused by the changing magnetic field component transverse to the loop formed by two cables and by the electric field component pointing between them. This kind of EMP pickup is called the differential mode. EMP pickup causing currents and voltages between each cable and ground is called the common mode. These two modes are often treated separately and both create a need for protection.

(f) Aerial conductors. Long, straight, horizontal aerial conductors include pole-mounted power distribution lines and signal-carrying cables. Figure 2-23 shows how the peak coupled current and the time-to-peak depend on the line length. The peak current and time-to-peak also depend on the line's height above ground, its size and construction, the soil conductivity, and other factors. The figure shows peak currents calculated for a pulse of the form $E_0e^{-t/\tau}$, where $E_0$ is the peak field amplitude of 50 kilovolts per meter.
and \( x \) is an exponential decay constant of 250 nanoseconds. This waveform looks much like the standard double exponential discussed earlier. It is used here to make calculations easier. Grazing, end-on incident is assumed with a polarization of about 16 degrees from the horizontal. The vertical field component for this polarization angle is 15 kilovolts per meter. The horizontal field component is much larger (about 48 kilovolts per meter), but it gives rise to a smaller induced current because of transmission line behavior. This polarization is typical of that expected at latitudes in the United States where the magnetic dip angle is more vertical than horizontal. A worst-case angle of incidence is assumed. Figure 2-23 shows how peak current as a function of the line length approaches a limiting value, in this case about 10 kiloamps. The point at which the limiting value is reached is called the critical line length. The time required for the current to reach its peak value also increases with line length until a limiting value is reached. Figure 2-23 also shows the bulk current that will be induced on the aerial conductor. If the conductor is a shielded cable, the values shown will correspond to the sheath current. The currents induced on conductors inside the shield will depend on the transfer impedance.

(g) Buried conductors. Buried conductors can be significant EMP collectors because low-frequency components of EMP fields are not greatly attenuated for typical soil conductivities and burial depths. The amplitude of the induced current varies inversely with the square root of the soil conductivity, which ranges from \( 10^{-4} \) to \( 10^{-2} \) mhos per meter. Figure 2-24 shows the variation in induced cable current with burial depth. The effect of deeper burial is both to reduce the amplitude of the induced current and to increase the risetime to peak current because of increased skin depth. (See para 2-4b above.) Figure 2-24 is for a semi-infinite cable. A finite cable will show a different response, especially near the cable ends. The differences in response are related to the cable sheath material and the way the cable is grounded. The cable's induced current also depends on the amplitude, waveform, and direction of the incident pulse. It will be proportional to the amplitude of the incident pulse \( (E_o) \). It will also be proportional to the square root of the decay time constant \( (T) \) of the incident pulse for an assumed exponential waveform \( E(t) = E_0 e^{-t/T} \). This constant is nearly the same as beta in the standard double exponential waveform. In the figure, the pulse is incident from directly overhead with the electric field parallel to the cable. This is a worst-case orientation. The current given in the figure corresponds to the total current induced on the cable, mainly sheath current, that can be related to the current on conductors inside the shield in terms of the transfer impedance.

(h) Ringing. As discussed earlier, the incident HEMP pulse is a broadband signal with a time waveform approximated by very fast risetime and exponential decay. If all coupling paths had broadband frequency responses, EMP-induced transients would show similar waveforms. However, inductance, capacitance, and resistance are inherent in any cable, cable shielding, and grounding system, and give rise to frequency dependence. Any LRC system will have characteristic resonant frequencies. EMP-induced transients thus will
tend to oscillate, or "ring," at these dominant frequencies, with the decay rate of the oscillation ruled by the width of the resonance in the frequency domain (fig 2-25). A very narrow resonance can cause a long-lived oscillation. This increased energy is added to the system and the likelihood of damage increases. Typical ringing frequencies range from 1 to 15 megahertz, depending on the physical and electrical details of the shielding and grounding systems.

(i) Conductive penetrations. Pipes and other penetrators with nonelectrical functions act very much like the shield of a shielded cable. Most often such penetrators are buried. For these buried conductors, transmission line theory can be used to calculate HEMP coupling. With the soil acting as the return path. Both nonelectric penetrators and components with an electrical function can couple EMP energy by acting in a mode other than that for which they were designed. For example, waveguides usually are designed to guide waves of a much higher frequency than HEMP; however, currents can be coupled onto the exterior of waveguides and conducted to the sensitive equipment. Conductive penetrations not only can collect HEMP energy, they also can serve as low-impedance paths to ground for currents induced elsewhere in a facility.

(3) Intrasisite cables. Intrasisite or internal cables at a structure may connect to mission-essential equipment. EMP-induced transients on these cables result partly from direct interaction with EMP fields that reach the structure's interior. These internal EMP fields couple to long, internal cable runs and internal cable loops (fig 2-26). EMP-induced transients on internal cables may also result from "cross talk." Typically, a cable that penetrates a facility will branch into many smaller cables (e.g., low-current power cables, individual telephone lines). These penetrators run alongside other internal cables so that penetrating EMP-induced transients tend to be shared. This especially occurs when cables run together in the same cable tray or conduit, but it can also happen to some degree if the cables pass within a few meters of each other. The result is that all cables linked to a piece of mission-essential equipment must be seen as potential sources of harmful voltage and currents. Figure 2-27 shows the distribution of currents at equipment leads for a typical unshielded telephone communications facility when subjected to a 50-kilovolt per meter EMP, polarized 16 degrees from the horizontal and coming from a worst-case direction. The structure has an incoming power line on which a peak current of 4 kiloamps is seen. Nineteen waveguides with a total peak current of 5 kiloamps also penetrate the structure. The waveguides come from a microwave tower and are grounded as they enter the structure.

2-5. Equipment susceptibility. System damage or upset from EMP is caused by currents and voltages induced in conductors exposed to a free-field or a horizontal polarized EMP wave. The narrow resonance results from circuits of high Q (quality factor) which have low resistive dissipation of energy.
partly attenuated EM pulse coupled to circuits. External conductors, structures, and internal conductors act as unintentional receiving antennas and "coupling" paths. They can deliver the resulting EMP-induced currents and voltages to sensitive components of electronic equipment. The HEMP-induced currents on exterior long-line penetrators, such as power and telephone lines, can have amplitudes as high as thousands of amperes. Currents induced on internal cable runs can be as high as hundreds of amperes for most structures and even higher in facilities with lower SE. It is important to note that exterior voltage transients can be in the megavolt range, and it would be normal to expect an order of thousands of volts from internal coupling. Transients of these magnitudes can be delivered to electronic circuits, such as integrated semiconductor circuits, which can be damaged by only a few tens of volts, a few amperes, or less. These circuits also operate at relatively low levels (e.g., 5 volts and tens of milliamperes) and can be upset by EMP currents of similar values. If the large exterior coupled transients were allowed to enter a structure that had no HEMP protection treatment, even relatively "hard" devices, such as relay coils and radio frequency interference (RFI) filters, would likely be damaged. Figure 2-28 shows this potential EMP interaction leading to mission degradation.

a. Equipment response. HEMP produces two distinct responses by equipment and system components: upset and damage. Upset is a nonpermanent change in system operation that is self-correcting or reversible by automatic or manual means. Damage is an unacceptable permanent change in one or more system parts. The spectrum of thresholds for some system components is shown in figure 2-29. The figure clearly shows that semiconductors are highly susceptible to HEMP and thus need protection.

(1) Upset. Transient upset has a threshold about one order of magnitude below the damage thresholds. It occurs when an induced HEMP transient exceeds the operating signal level. It has a time scale that falls within the circuit's time response. Figure 2-30 shows some examples of upset. Figure 2-30(a) shows a flip flop changing state due to a HEMP transient on the trigger input. Figure 2-30(b) shows a NAND gate with a temporary change in its output logic level from a HEMP transient on the power supply line. Figure 2-30(c) shows an amplifier driven to saturation by a HEMP transient superimposed on its signal input.

(2) Damage.

(a) Semiconductors. Damage to semiconductors due to applied transients is typically some form of thermal-related failure and therefore is related to the total energy applied to the device. For discrete devices (transistors, diodes), the predominant failure mode appears to be localized melting across the junction. The melted regions form resistive paths across the junction which short out the junction or mask any other junction action (ref 2-7). Metallization burnout resulting in open circuits has also been identified as a failure mode in integrated circuits (ref 2-8). A convenient
approach for failure analysis is the concept of the power failure threshold (P_th) (ref 2-1). The power failure threshold is defined as:

\[ P_{th} = At^{-b} \]  

(eq 2-8)

where A is the damage constant based on the device material and geometry, and b is the time-dependence constant. The constants A and b can be determined empirically for every device of interest by the least-squares curve fit to experimental pulse test data. In general, it will be more convenient to use the Wunsch model (ref 2-7) for the power failure threshold with previously determined values of the Wunsch model damage constant for any analysis. This theoretical model has a time-dependence constant of b = 1/2. Empirical data for a wide range of devices fits the model within the experimental data spread in the midrange of pulse widths, approximately 100 nanoseconds to 100 microseconds (ref 2-1). The Wunsch model theoretical equation is:

\[ P_{th} = Kt^{-1/2} \text{ Kw/cm}^2 \]  

(eq 2-9)

where t is the pulse width in microseconds and K is the Wunsch model damage constant in kW - (microsecond)^1/2. K is expressed in these units since the numerical value of K is then equal to the power necessary for failure when a 1-microsecond pulse is applied to the junction. Figures 2-31 and 2-32 show typical ranges for K for various semiconductors. Multiplication of this factor by t^{-1/2} will yield the pulse power threshold.

(b) Passive elements. The passive elements most susceptible to damage from HEMP-induced currents are those with very low voltage or power ratings and precision components for which a small change is significant. Resistor failures due to high-level pulsed currents are caused by energy-induced thermal overstress and voltage breakdown. Resistor failure threshold can be calculated from the resistor's parameters and the empirical relation given in reference 2-9. Exposure of capacitors to transient currents sets up a voltage across the capacitor that increases with time. For non-electrolytic capacitors, this voltage keeps rising until the capacitor's dielectric breakdown level is reached. That point is typically 10 times the d.c. voltage rating. For electrolytic capacitors, the voltage relationship holds until the zener level of the dielectric is reached. After that, damage can occur. The damage threshold for electrolytic capacitors in the positive direction is 3 to 10 times their d.c. voltage rating. For the negative direction, it is one-half their positive failure voltage (ref 2-10). Transformer and coil damage due to HEMP-induced currents results from electric breakdown of the insulation. The pulse-breakdown voltage is typically 5500 volts for power supply transformers and 2750 volts for small signal transformers (ref 2-11).

b. Equipment sensitivity. Localizing responses of specific circuits or components within equipment or a system often is not possible for complex equipment. Therefore, when estimating system response, it is often more
realistic to deal with the thresholds at the equipment level instead of at the circuit or component level. Using the equipment thresholds approach usually requires that the applicable systems have had their thresholds analyzed or measured. Measured thresholds for some types of communications equipment are given in table 2-3.

c. Typical damage and upset levels. Table 2-4 gives typical HEMP-induced transient levels as observed in tests and analyses at operational facilities. The largest voltage value is 2 megavolts and the largest current is 4 kiloamps. Much smaller values may also result. This is especially true for the inner conductor of the coaxial line because of the shielding protection provided by the outer conductor. The data in Table 2-4 were obtained with the equipment under test in a parallel plate EMP simulator. The simulator excitation approximated the 50-kilo-volt/meter double exponential waveform with risetime of 5 to 10 nanoseconds and e-fold of approximately 0.5 microseconds. A current probe was then used to measure the peak-to-peak current on a power supply lead. The current measured was typically a damped sinusoid with frequency dependent on equipment type and lead length.

2-6. Cited references.


2-5. EMP Awareness Course Notes, DNA 2772T (HQ, Defense Nuclear Agency, August 1971).


2-7. Uncited references.


EMP Engineering and Design Principles, Bell Laboratories, PEM-37 (Lawrence Livermore Laboratory, 1975).

MIL-STD-461C, Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference (DoD, 4 August 1986).
Table 2-1. Important features of EMP environments*

<table>
<thead>
<tr>
<th>Type</th>
<th>Features</th>
<th>Systems impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMP</td>
<td>Large extent, high amplitude, broad frequency band, plane wave</td>
<td>Most widely specified threat</td>
</tr>
<tr>
<td>Surface-burst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source region</td>
<td>Large amplitude, limited extent includes varying conductivity, currents</td>
<td>Important for systems which are hard to other nuclear effects</td>
</tr>
<tr>
<td>Radiated region</td>
<td>Large amplitude varies inversely with distance</td>
<td>Can supersede HEMP if vertical orientation or low freqs. important</td>
</tr>
<tr>
<td>Air-burst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source region</td>
<td>Similar to surface-burst</td>
<td>See surface burst</td>
</tr>
<tr>
<td>Radiated region</td>
<td>Amplitude less than HEMP</td>
<td>Superseded by HEMP</td>
</tr>
<tr>
<td>SGEMP</td>
<td>Very high amplitude and fast rise time</td>
<td>Important for exoatmospheric systems</td>
</tr>
<tr>
<td>MHD-EMP</td>
<td>Very low frequency, low amplitude, large extent</td>
<td>May affect long-land or submarine cables</td>
</tr>
</tbody>
</table>

Table 2-2. EMP waveform summary*

<table>
<thead>
<tr>
<th>Type</th>
<th>Peak amplitude</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMP</td>
<td>50 kV/m</td>
<td>Few nanosec to 200 nanosec</td>
</tr>
<tr>
<td>Surface-burst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source region</td>
<td>1 MV/m</td>
<td>Few nanosec to 1 microsec</td>
</tr>
<tr>
<td></td>
<td>10 kV/m</td>
<td>1 microsec to 0.1 sec</td>
</tr>
<tr>
<td>Radiated region</td>
<td>10 kV/m</td>
<td>1 microsec to 100 microsec</td>
</tr>
<tr>
<td>Air-burst</td>
<td>Similar to surface-burst</td>
<td></td>
</tr>
<tr>
<td>Source region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiated region</td>
<td>300 V/m at 5 km, typical (highly dependent on HOB)</td>
<td>10 nanosec to 5 microsec</td>
</tr>
<tr>
<td>SGEMP</td>
<td>100 kV/m</td>
<td>Few nanosec to 100 nanosec</td>
</tr>
<tr>
<td>MHD-EMP</td>
<td>30 V/km</td>
<td>0.1 sec to 100 sec</td>
</tr>
</tbody>
</table>

### Table 2-3. Response thresholds*

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Lead**</th>
<th>Upset level, p-p*** (A)</th>
<th>Damage level, p-p (A)</th>
<th>Max. stress level, p-p (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary frequency supply (PFS-2A)</td>
<td>-24 V</td>
<td>0.4</td>
<td>--</td>
<td>-9</td>
</tr>
<tr>
<td>A5 channel bank</td>
<td>-24 V</td>
<td>80</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>(solid state modem)</td>
<td></td>
<td>--</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>input</td>
<td></td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gain</td>
<td></td>
<td>--</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Multiplex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WELMX-1 (tube)</td>
<td>130 V</td>
<td>0.07</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>WELMX-2 (solid-state)</td>
<td>-24 V</td>
<td>0.02</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>WEMMX-1 (tube)</td>
<td>130 V</td>
<td>2</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>WEMMX-2 (solid-state)</td>
<td>-24 V</td>
<td>--</td>
<td>--</td>
<td>50</td>
</tr>
<tr>
<td>Wireline entrance link, 3A (amplifier)</td>
<td>-24 Vl</td>
<td>1</td>
<td>--</td>
<td>35</td>
</tr>
<tr>
<td>100-A protection switch (switching unit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM-1 radio-27 V</td>
<td></td>
<td>--</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>L4 cable system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger A equalizer</td>
<td>-24 V</td>
<td>8</td>
<td>--</td>
<td>110</td>
</tr>
<tr>
<td>Protection switch</td>
<td>-24 V</td>
<td>16</td>
<td>--</td>
<td>110</td>
</tr>
<tr>
<td>WE TD3 radio</td>
<td>dc power input 50</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>WE TH3 radio</td>
<td>dc power input 60</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Farinon FM 2000 radio</td>
<td>dc power input 208</td>
<td>240</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Lenkurt 778A2 radio</td>
<td>dc power input 35</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Collins MW608D radio</td>
<td>dc power input 50'</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>


**Point where induced current was measured.

***Induced peak-to-peak (damped sinusoid) on indicated lead.

+Data not measured.
Table 2-4. Typical EMP transients and equipment thresholds—
EMP threat level*

<table>
<thead>
<tr>
<th>Point of entry</th>
<th>Waveform</th>
<th>Voltage</th>
<th>Current</th>
<th>Impedance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.C. power lines, telephone cables (above-ground)</td>
<td>DE**</td>
<td>2 MV</td>
<td>4 kA</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>2 MV</td>
<td>4 kA</td>
<td>500</td>
</tr>
<tr>
<td>External antennas</td>
<td>2-30 MHz DS**</td>
<td>60 kV</td>
<td>1.2 kA</td>
<td>50</td>
</tr>
<tr>
<td>Video COAX lines (inner conductor)</td>
<td>1-5 MHz DS5</td>
<td>5 kV</td>
<td>71 A</td>
<td>70</td>
</tr>
<tr>
<td>Telephone cable (submarine sheath)</td>
<td>DE</td>
<td>60 kV</td>
<td>1.2 kA</td>
<td>50</td>
</tr>
</tbody>
</table>


**DE = double exponential; DS = damped sinusoid.
Figure 2-1. The Compton process. (Source: ref 2-1)
This page not used.
Figure 2-3. Variations in high-altitude EMP peak electric field strength as a function of direction and distance from surface zero.
(Source: ref 2-1)
Figure 2.4: HEMP waveform. (Source: ref 2-1)
Figure 2-5. Qualitative time domain example of HEMP. (Source: ref 2-1)
Figure 2-6. Qualitative frequency domain example of HEMP. (Source: ref 2-1)
SURFACE BURST EMP
- Source region fields and currents are significant for hardened systems
- Significant radiated fields extend out more than 10 km

Figure 2-7. Surface-burst EMP showing source region and radiated region.
(Source: ref 2-1)
Figure 2-8. Overview of surface-burst EMP. (Source: ref 2-1)
- Amplitude typically less than 100 μVp outside source region.
- Amplitude varies inversely with range outside source region.
- No standard waveform.
- System impact may supersede HEMP due to high low-frequency content (below 100 kHz).
- Vertical E-field orientation.
WEAPON GAMMAS
CHARGE SEPARATION
FIELO (-Efr)
NO SIGNIFICANT
FIELDS

SCATTER COMPTON ELECTRONS
ION PRODUCES RADIAL ELECTRIC
FIELD (E_r)
NO SIGNIFICANT CURRENT LOOPS OR MAGNETIC
FIELDS

Figure 2-10. Air-burst EMP--source region.
ATMOSPHERIC DENSITY GRADIENT PRODUCES WEAK VERTICAL DIPOLE

ATMOSPHERIC DENSITY GRADIENT RESULTS IN ASYMMETRIC CHARGE DISTRIBUTION.

RESULTANT VERTICAL DIPOLE PRODUCES WEAK VERTICAL ELECTRIC FIELDS.

WATER VAPOR DENSITY GRADIENT CONTRIBUTES TO ASYMMETRY AND RADIATION.

GEOMAGNETIC TURNING OF COMPTON ELECTRONS ADDS HEMP-LIKE COMPONENT.
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Figure 2-17. Two mechanisms by which EMP couples to conductors.  
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(Source: ref 2-1)
Figure 2-19. Equivalent circuit for a small loop (magnetic dipole).
(Source: ref 2-1)
Figure 2-20. Modeling example—microwave tower and equivalent fat cylindrical monopole. (Source: ref 2-1)
\[ \Delta V = I_S Z_T \Delta x \]

\( \Delta V \) = Voltage drop on center conductor of cable of length \( \Delta x \)

\( I_S \) = Sheath current

\( Z_T \) = Transfer impedance per unit length

\( \Delta x \) = Incremental length

Figure 2-21. Shielded cables and transfer impedance. (Source: ref 2-1)
Figure 2-22. Transmission line coupling. (Source: ref 2-1)

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Figure 2-23. Aerial conductors: effect of conductor length.
(Source: ref 2-1)
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(Source: ref 2-1)
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Figure 2-29. Energy level ranges, in joules, that damage various components.  
(Source: ref 2-4)
Figure 2-30. Examples of transient upset. (Source: ref 2-4)
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(Source: ref 2-5)
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CHAPTER 3
EMP HARDENING CONCEPTS FOR FACILITIES

3-1. Outline. This chapter is organized as follows:

3-1. Outline
3-2. Discussion of general concepts
   a. System functions
   b. Survival confidence
      (1) Levels of confidence
      (2) Inherent uncertainties
   c. Critical equipment sensitivities
      (1) Design margin
      (2) Coupled energy
   d. Potential HEMP coupling paths
   e. Design verifiability
      (1) Hardness validation
      (2) Retrofit designs
      (3) Designing to facilitate testing
      (4) Approaches to validation
   f. Physical environment
   g. Other factors
3-3. Description of HEMP hardening concepts
   a. Shielding
      (1) Global shielding
      (2) Tailored shielding
      (3) Zonal or topological shielding
      (4) System configuration
      (5) Cable shielding
      (6) Grounding
   b. Hardening allocation concept
   c. Shield penetration protection concepts
      (1) Large access doors
      (2) Personnel entrances
      (3) Electrical penetrations
      (4) Transient suppression devices and filters
      (5) Electromagnetic isolation
      (6) Dielectric isolation
      (7) Isolation switching
3-4. Cited references
3-5. Uncited references

3-2. Discussion of general concepts. The HEMP environment is defined by DOD-STD-2169. This definition includes the classification and specific information on field strengths, pulse characteristics, spectral content, angle of arrival, range of relative burst locations, and weapon yield.
a. System functions. Associated with the electronic and electrical systems and subsystems to be protected are support functions such as utilities, personnel housing, office space, document storage, food facilities, and others. Many aspects of a facility are not sensitive to HEMP energy or are robust enough that HEMP protection is not required. Some sensitive system elements may not be critical to the facility mission. The definition of mission-essential functions that must remain in operation will have major impact on the choice of hardening concepts.

b. Survival confidence. The issue of defining "survivability requirements" must be specifically addressed and resolved in the concept definition phase of each particular HEMP hardening effort. The system user should define the required survival confidence level, at least qualitatively, since this factor will determine how conservative the design will be. If required confidence levels are high, greater safety margins in protection levels will be required, producing a need for a high-quality overall shield and adequate validation testing.

   (1) Levels of confidence. Survivability confidence may require that a facility--

   (a) Experience no HEMP-induced stress greater than the stresses occurring in the normal operating environment.

   (b) Experience neither permanent nor operational upset as a result of the HEMP.

   (2) Inherent uncertainties. Another survivability issue concerns the inherent and analytical uncertainties in quantifying the stress level causing malfunction or the stress level experienced by the equipment.

c. Critical equipment sensitivities. The main factors in determining required protection levels are--

   (1) Design margin. The design margin required, which is related to the difference between critical equipment sensitivities and coupled transients.

   (2) Coupled energy. The energy level coupled from connected subsystems or components.

d. Potential HEMP coupling paths. Most electronic/electrical systems to be HEMP-hardened and their housing facilities will have to interface with external elements such as antennas, utilities, communications lines, and other facilities. The complexity of interfacing and possible coupling paths for HEMP energy will greatly affect the choice of topological approaches to HEMP hardening.

e. Design verifiability.
(1) Hardness validation. A key issue in HEMP hardening philosophy and associated design concepts is that of hardness validation and required confidence levels for final acceptance. (Required confidence levels are usually specified only qualitatively.) Generally, the more critical the facility is to national military security, the more politically and publicly visible it will be; for these facilities, higher confidence levels will be required. In all cases, design concepts may not be chosen if they cannot be validated with acceptable confidence levels. For example, a design concept for a large underground facility that depends on a degree of protection from the overburden and has numerous conducting penetrations through the overburden may have hardness uncertainties. Examples include questions about the homogeneity of the overburden and difficulties in protecting penetrations when no highly conductive shield is present. If the facility is too large to be practically subjected to a threat level test by an EMP simulator and no other proven validation tests exist, the uncertainties will prevail and hardness confidence will be low.

(2) Retrofit designs. In retrofit designs, another consideration in concept selection may be the ability to validate hardness without disrupting the operation of critical systems. Concepts should be chosen to allow nondisruptive validation and acceptance testing.

(3) Designing to facilitate testing. Good design validation requires a choice of design concepts that facilitate testing. HEMP hardening management must include adequate funding and scheduling for this effort. The difficulty and cost of validation will increase with--

(a) System complexity.
(b) Topology layer and zone numbers.
(c) The number of required penetrations.
(d) The protective design philosophy.

(4) Approaches to validation. In considering the validation problem for concept selection, it is helpful to review the many approaches to validation, including laboratory testing, full-scale HEMP threat level field testing, partial scale threat-level field testing, current injection testing, scale model testing, physical modeling testing, computer modeling evaluations, analyses, and radio frequency CW shielding tests.

f. Physical environment. Various aspects of the facility physical environment can greatly affect concept selection, mainly in the degree to which corrosion can accelerate aging and degradation of protection.

g. Other factors. Other factors to be considered in concept selection are--
(1) Complexity of required interactions with facilities.

(2) Design and construction costs.

(3) Constructibility.

(4) Maintenance costs.

(5) Reliability requirements.

(6) Flexibility for expansion or system changes.

(7) New construction versus retrofit.

(8) Supportability.

3-3. Description of HEMP hardening concepts.

a. Shielding. For HEMP-hardened facilities, some kind of EM shielding is essential. Shielding theory is discussed in detail in chapter 5 and is treated thoroughly in the literature. Shielding involves the use of a barrier or series of barriers to reduce the magnitude of the EM energy incident upon the electronic or electrical system to be protected. Shielding philosophy can be developed around different approaches as discussed in paragraphs (1) through (6) below and shown in figure 3-1.

(1) Global shielding. Global shielding (or hardening) is a protection concept that uses an overall shield to encompass the entire facility. In this approach, all conducting penetrations and all apertures are protected at the shield. The intent is to keep all HEMP fields and HEMP-induced transients outside the protected volume. The global shield could be placed on the entire outer walls, ceiling, and floor (surface) of the facility, or it could be reduced to a smaller volume that contains all sensitive equipment to be protected. The most common shield material for global shielding of ground-based facilities is sheet steel with welded seams, although other designs can provide adequate global HEMP shielding.

(a) Global shielding may be desirable if there is a requirement to be able to modify, reorganize, add to, or move the sensitive equipment without changing the shield or protective features.

(b) A remote, yet possible, disadvantage of global shielding that must be considered is that a single protective component or device failure may jeopardize the entire facility.

(2) Tailored shielding. Tailored shielding is a protection concept in which shielding is designed and constructed according to specific protection requirements for the equipment involved. After defining the system to be protected, its possible operating configurations, the expected HEMP
environment, coupling paths, equipment sensitivities, and subsystem/system criticalities, the required protection levels for various subsystems or groups of subsystems can be defined. Tradeoff studies may be performed for comparing various shielding arrangements to verify that they meet safety margins in protection, cost-effectiveness, maintainability, survivability, flexibility, and other requirements. The objective is to optimize protection for the specific mission-critical system. Tailored shielding options may include global shielding, zonal shielding (discussed under (3) below), shielding of cabinets or components, or combinations thereof. In a typical tailored protection design, discrete protection will be provided to eliminate specific, localized deficiencies.

(3) Zonal or topological shielding. Zonal or topological shielding (ref 3-1) is a concept in which a facility is divided into zones, with shielding barriers located topologically in a shield within a shield configuration. Figure 3-2 shows a generic topological shielding system. The outer zone is designated zone 0; zone 1 is inside shield 1 but outside shield 2. Zones and shields are assigned increasingly larger numbers as they progress toward the more deeply nested areas.

(a) Note that figure 3-2 is a simple schematic to represent the zoning concept; although not depicted, each zone could contain more sets of subzones. For example, shield 3 could contain 2 or more zones designated as zone 4. Further, figure 3-2 shows possible shield types including a site housing shield and an interior shielded room, with equipment and component housings making up the shields of the next topological orders.

(b) The zonal concept shown in figure 3-3 is a specific example of an underground facility that uses topologically zoned protection. The rock and soil overburden above the facility serves as shield 1. Zone 1 is the volume between the underground building and the excavated outline of overhead rock. In some cases, a shield of this type provides adequate protection for robust electrical or electronic equipment. Shield 2 is composed of a sheet metal building that may provide only a limited level of shielding. Inside this building (zone 2), some systems would be adequately protected. The above-ground building and connecting conduit represent an extension of zone 2. Shield 3 is then the interior shielded room which provides further protection within zone 3, where sensitive, electronic equipment may be operated.

(c) Figure 3-4 shows another specific example of a zonal or topographically shielded facility for which steel-reinforced concrete comprises shield 1. This type of shield usually does not provide adequate protection and thus the additional shields are necessary.

(4) System configuration. The term "system configuration" identifies which way the cables, wires, equipment, and subsystems are laid out in relationship to each other, as well as the relationship of these items to the topological boundaries. In some instances, the cables, connectors, and equipment casings are actually part of the topological protection. Although
"system configuration" as defined does not directly attenuate the environment, it is an important element in the topological protection concept. The system configuration influences protection design requirements since some configurations are easier to protect than others (e.g., collocation of all mission-critical equipment). Thus, the system configuration should be coordinated with the protection design and the protection topology will be optimal for a specific configuration. During the facility life cycle, the protection design may be required to accommodate some changes in configuration. To ensure that the configuration's design modifications do not compromise or defeat the protection, careful configuration management is necessary. The topology should be designed to tolerate configuration changes that are totally within a boundary. The boundary can never be violated (for example, opened)—only extended. All modifications must be subjected to review by EMP experts to ensure continual compliance with the HEMP hardening requirements.

(5) Cable shielding. Conductive or metallic cable shielding or conduit is used in the zonal/topological protection concept to extend the boundary formed by equipment enclosures and thus provide a way to interconnect elements while maintaining boundary continuity. Cable shielding is also used to protect a wire or wires as they travel from one boundary to another. This would be the case with a shielded RF signal traveling from its entrance into a building to the RF receiver. From a HEMP standpoint, the shielding attenuates coupling of radiated energy within the first boundary as the signal travels to the receiver. Of course the shield is somewhat reciprocal in that it also prevents signals from radiating out of the cable. The main feature of cable shielding stressed here is continuity of the boundary provided by the cable shield/connector combination which may require special joints.

(a) Another way to maintain this continuity and provide cable shielding is by using steel conduit to house all wires and cables. The steel conduit will provide substantially higher shielding levels than the cable shields. Chapter 5 presents conduit system design in detail.

(b) Both cable shields and conduit connected to a shielded zone must have equal or greater shielding effectiveness than the shield.

(c) Figure 3-5 shows a cable entry vault used to protect cable penetrations through a shield. Entry vaults are discussed under shield penetrations in paragraph c below.

(6) Grounding. Some form of grounding is required in any electrical or electronic system for protecting personnel from electrical shock, controlling interference, proper shunting of transient currents around sensitive electronics, and other reasons. (Grounding does not directly provide protection against EMP, but must be done properly to prevent creation of more serious EMP vulnerabilities.) Ideally, grounding would keep all system components at a common potential. In practice, because of possible inductive loops, capacitive coupling, line and bonding impedances, antenna ringing
effects, and other phenomena, large potentials may exist on grounding circuits. The choice of grounding concept is therefore important in the HEMP protection philosophy.

b. Hardening allocation concept. The shielding concepts in this chapter introduce the concept of hardening allocation in which the overall protection philosophy specifies degrees of hardening for each zone. The practicality of this concept usually depends on the complexity of the system to be protected. If it is determined that an overall SE of 80 decibels is required for the most sensitive components, but the remaining elements require only 60 decibels, then zones with different SE may be established. The cost-effectiveness of a zonal design with a hardening allocation for each barrier must be studied carefully on a facility/system specific basis to determine the practicality of this approach.

c. Shield penetration protection concepts. All shielded zones will require penetrations to allow entry of equipment, personnel, electric power, communications, and control signals, ventilation, water, fuel, and various fluids. Without protection, these penetrations compromise the shield.

(1) Large access doors. Large access doors are often necessary to provide an entry for equipment, supplies, or vehicles into EMP hardened facilities. In facilities that require blast overpressure protection, large blast doors are used. These doors generally use one or more thick steel plates to provide protection. The door's inherent shielding ability is thus high, but its large size presents a difficult gasketing problem. If blast protection is not required, it is still necessary to design the door with a high degree of structural strength. This step is to ensure that the door can provide the necessary gasket compression force and that proper mechanical alignment of closure contact surfaces is maintained.

(2) Personnel entrances. Two concepts are commonly used for personnel entrances: conventional EMP/RFI shielded doors and personnel tunnels that act as waveguides below cutoff. The shielded doors generally use metal fingerstock or EMI/RFI gaskets to provide an electromagnetic seal around the door jamp periphery. Currently available gasket and fingerstock doors require regularly scheduled maintenance and/or replacement to maintain required shielding levels. The gaskets are relatively easily damaged and also require replacement. Air-expandable doors may also be used, although they typically have more maintenance problems. These doors generally use a movable subassembly of two shielding plates on a framework that is moved on rollers in and out of a steel-framed opening. When closed, air expansion tubes cause the two shielding plates to make uniform surface contact with the frame inner surfaces.

(a) Fingerstock doors can provide over 80 decibels of shielding to magnetic fields from 100 kilohertz through 30 megahertz and greater SE to plane waves and electric fields. Air-expandable doors can provide greater than 120 decibels of magnetic field SE from 10 kilohertz to 10 gigahertz.
(b) Air-expandable doors require an air source and air controls with back-up in safety controls. They also require very strong steel frames and, as a result, are more expensive than gasketed doors. They are also more difficult and costly to maintain. The air-expandable door would thus be used only when a large safety margin of HEMP shielding is needed or when equipment to be protected is extremely sensitive to HEMP or other EM interference.

(c) The waveguide entry tunnel acts as a WBC that will typically have a cutoff frequency in the 60-megahertz region. Thus, the higher frequencies in the HEMP spectrum will penetrate it. Doors are therefore required to prevent the higher frequency signals from penetrating. Since only high frequencies can propagate through, doors have good attenuation in this range and can easily provide the required attenuation. Maintenance requirements are not as stringent as for doors that must block the entire frequency spectrum; thus, the waveguide entry tunnel for personnel access is attractive from a life-cycle cost standpoint. When the facility has a TEMPEST requirement as well as EMP shielding requirements, the tunnel is usually designed with interlocking doors, i.e., a door at each end and interlocked so that only one door can be opened at once, thus preventing any leakage of classified information during the entry of personnel. The waveguide entry tunnel also is highly useful in underground or buried facilities because the overburden attenuates the high frequencies, thus acting to complement the tunnel attenuation.

(3) Electrical penetrations. A common feature for electrical penetrations in a global protection approach is a cable entry vault to prevent large currents on external conductors from being conducted into the facility. Ideally, all penetrations should enter a single vault. In some cases, however, it may be necessary to separate the vault into two compartments or to use two vaults for penetrations by different types of lines: power, signal and control, and antenna. The vault must be connected directly to the external facility ground system. (See chapter 5 for details.) The cable entry vault serves three purposes: to insure that penetrating conductors do not cause conducted HEMP energy to enter the protected topology; to contain and divert penetrator-conducted HEMP energy to the boundary exterior; and to contain or divert radiant EM energy resulting from the activation of transient suppression devices subjected to a conducted pulse. Conductive penetrations, such as a conduit, waveguide, or shielded cable, must have a circumferential weld or other means of providing good electrical connection at the intersection with the entry vault.

*Cutoff frequency is determined by the relationship \( F_\alpha = 5900 \text{ MHz/}W \), where \( W \) is the greatest cross sectional dimension in inches. Below cutoff, the waveguide attenuation is a function of the waveguide length. In practice, the length-to-width ratio should be 5.
(4) Transient suppression devices and filters. Transient suppression devices fill a critical gap in the concept of topological protection. The necessity of supplying power to a facility and of communicating over cables or antennas are two major factors contributing to their use. Power lines entering a facility are typically connected to an unshielded power grid so that large, conducted currents must be bled off to prevent their entry into a facility. These currents are diverted to the exterior boundary of the topology. This boundary can be an overall external shield or an enclosed entrance vault. Antennas, such as for high-frequency (HF) communications, are designed to gather EM signals (at wavelengths in the EMP frequency spectrum) and to apply these signals to the center conductor of a shielded cable. The EMP transients associated with an HF antenna can be, by far, the largest single signal entering a facility. Transient suppressors often are used in conjunction with filters. Filters are frequency selective whereas surge suppressors are amplitude-selective. Filters often are used to attenuate transients associated with the nonlinear operation of surge arresters. They also are used for selectively passing (or stopping) frequency bands as in the case of antenna cable penetrations. Transient suppressors are an integral part of the EM topology, demanding specific installation techniques as will be seen later. A spark gap is a surge suppressor that provides a conducting path to ground when the voltage across the device exceeds the gap breakdown level. Spark gaps with a high current capacity do not operate quickly enough to block all HEMP energy transients entering the vault. For this reason, it may be necessary to use other protection devices in conjunction with the spark gap.

(5) Electromagnetic isolation. The electromagnetic isolation concept involves the use of elements either immune to interaction with EM radiation or that provide a current path interruption. Optical fibers are examples of elements immune to EM radiation that can be used to reduce the number of conductive penetrations. For practical purposes, optical fibers can be used for long communications links without signal interference from HEMP. Further, they can be used to enter shielded zones through waveguide below cutoff penetrations without compromising the EM shielding effectiveness, as figure 3-6 shows. Where possible, optical fibers are recommended for--

(a) Voice and data communications lines.

(b) Energy monitoring and control systems (EMCS).

(c) Intrusion detection systems.

(d) Other security systems.

(e) Control systems.

*Within a facility, inside shield 1, power lines are often routed through steel conduits to provide shielding.*
(f) Any other use where possible and practical.

(6) Dielectric isolation. Other isolation techniques include using dielectric isolators for shield penetration when external metallic EM energy collectors are involved. Examples are control rods or cables (normally metallic), piping systems for fluids, and metallic duct systems for air. Dielectric sections are installed at or near the shield to prevent the energy induced on the external metallic part from being conducted through the shield. Dielectric control rods can enter through a shield in the same way as optical fibers, that is, through a waveguide-below-cutoff section. Dielectric isolation concepts for metallic piping systems and air ducts are discussed in chapter 5.

(7) Isolation switching. Although not recommended now, isolation switching has been provided at facilities so they can use commercial electric power during routine operation, but can switch to internal generators or power systems in the event of an emergency such as nuclear attack. Since the commercial power wiring is a source of significant HEMP energy injection through a shield, switching to internally generated power is an obvious advantage when advance warning of impending nuclear attack is received and throughout the entire nuclear attack cycle. This concept applies to communications lines and control lines as well as power lines. Switching used in past facility designs has been called "alert attack" switching. Such switching must provide adequate switch contact separation to prevent arcing, and must be designed to reduce coupling interactions between wiring and switch contacts to acceptable levels. It should be noted that advance notice of a HEMP attack is not always provided.


3-5. Uncited references.


*Rods that must be mechanically rotated or pulled to control switches, valves, and other components.
Figure 3-1. Building examples showing three concepts for critical equipment protection.
Figure 3-2. Zonal shielding concept.
Figure 3-3. Underground facility with four zones.
Figure 3-4. Zonal shielding concept with steel-reinforced concrete as shield 1.
Figure 3-5. Shielded enclosure: cable entry vault.
Figure 3-6. Optical fiber shield penetration.
CHAPTER 4
SYSTEM ENGINEERING REQUIREMENTS

4-1. Outline. This chapter is organized as follows:

4-1. Outline
4-2. Standards and specifications
4-3. Electromagnetic integration
   a. Incompatible design approaches
   b. Correcting incompatibilities
   c. Electromagnetic shielding
   d. Surge protection
4-4. HEMP and lightning protection integration
   a. Lightning rise time
   b. Frequency and current levels
   c. Induced transients and injected current
   d. Voltage surges
   e. Radiated and static fields
   f. Magnetic fields
   g. Summary
4-5. HEMP/TEMPEST and electromagnetic integration
   a. Electromagnetic compatibility (EMC)
   b. Electromagnetic interference (EMI)
      (1) Natural radio noise
      (2) Purposely generated signals
      (3) Man-made noise
   c. Achieving electromagnetic compatibility
      (1) Frequency ranges
      (2) Spectra encompassed
      (3) Interference within enclosures
      (4) Exceptions
4-6. Environmental requirements
   a. Corrosion
   b. Groundwater
   c. Thermal effects
   d. Vibration and acoustics
   e. Ground shock
4-7. Cited references

4-2. Standards and specifications. Definitive standards and specifications for hardening facilities against HEMP/TEMPEST do not exist. However, efforts are underway to develop them and to integrate them with other HEMP/TEMPEST requirements and with electromagnetic compatibility (EM) standards. Results of some recent studies have been reported (refs 4-1 through 4-3). Campi et al. (ref 4-1) compiled a listing of Government and industrial standards, specifications, and handbooks related to HEMP/TEMPEST mitigation. Most of these standards pertain to EMC and TEMPEST (table 4-1). However, many of
these specifications and standards may be useful in integrating EMP hardening requirements. A comprehensive listing of EMP-related standards is available in reference 4-4.

4-3. Electromagnetic integration. Facilities often are required to be protected against several EM environments, including HEMP (or other EMP), electromagnetic interference (EMI), electromagnetic compatibility, and lightning. The facility may also have TEMPEST requirements that impose the need for communications security through control of compromising EM emanations.

a. Incompatible design approaches. Vance et al. (ref 4-2) have examined 70 related standards and specifications and tabulated areas in which the design approaches are not compatible for all EM protection requirements. Many of these incompatibilities are related to methods for grounding cable shields and allowances for penetrating conductors.

b. Correcting incompatibilities. Graf et al. (ref 4-3) have recommended ways to correct these incompatibilities. In view of these studies and other programs, unified EM specifications and standards probably will eventually become available. Meanwhile, designers will find it necessary to integrate the EM design on a site-, facility-, and system-specific basis.

c. Electromagnetic shielding. Generally, the main method used in EM protection is EM shielding. The shielding required for HEMP/TEMPEST is usually more than enough for all other EM protection. A comprehensive discussion of grounding and bonding technology for all EM protection is in MIL-HDBK-419A (ref 4-5). MIL-STD-188-124A gives specific grounding and bonding requirements (ref 4-6).

d. Surge protection. An area in which care must be taken to ensure compatibility in EM integration is surge protection. Some surge arresters used for lightning do not clamp fast enough to protect against EMP. Some ESAs used for EMP may not have great enough current carrying capacity for lightning protection in all situations. Thus, for compatible lightning and EMP protection, a carefully selected combination of protection elements will be required.

4-4. HEMP and lightning protection integration. The EM environment generated by lightning differs from that of HEMP in energy spectral distribution rise time, current levels, pulse repetition, and coverage area.

a. Lightning rise time. Many early studies indicated that the typical rise time of lightning was almost three orders of magnitude slower than that of HEMP. More recent work, however, has shown that radiation fields produced by lightning can have much faster rise times. Step leaders in the initial stroke have had measured rise times reportedly approaching 30 nanoseconds. Return strokes have been determined to have initial portions with rise time in the 40- to 200-nanosecond range. A complete lightning flash contains a first
stroke with a downward-moving step leader and usually numerous return strokes as shown in figure 4-1. The total flash time can be greater than 1 second.

b. Frequency and current levels. A comparison of lightning and HEMP in the frequency domain shows that radiated lightning energy is higher at low frequencies and lower at high frequencies as indicated in figure 4-2. The current levels of lightning return strokes average nearly 35 kiloamps, but may be less than 10 kiloamps and as high as several hundred kiloamps for so-called "superbolts."

c. Induced transients and injected current. Hazards common with both HEMP and lightning are induced transients coupled onto sensitive elements and injected current from exterior electrical conductors. Lightning also can strike directly with extreme damage potential. In rare cases, the direct strike has been known to cause structural damage as well as electrical damage, even to underground facilities. Thus, facilities need a system of lightning rods with suitable grounding to divert the extremely high currents (up to hundreds of kiloamperes peak) away.

d. Voltage surges. Lightning can produce high voltage surges on power lines without a direct strike. Figure 4-3 shows some typical surge values versus distance from the stroke.

e. Radiated and static fields. One study has identified radiated fields associated with lightning (ref 4-7). Figure 4-4 summarizes approximated typical near-field radiated E-field values. Another study has identified radiated and static fields associated with lightning (ref 4-8). Figure 4-5 shows averages for these fields.

f. Magnetic fields. Table 4-2 lists typical values of the H-field close to a stroke. The close in H-field from lightning thus has higher magnitude than the HEMP H-field (see table 4-2 for magnitudes); since it has greater energy content at low frequencies, shield thickness must be greater than for HEMP.

g. Summary. In summary, integrating HEMP and lightning protection requires--

(1) Greater shield thickness for lightning if protection from close-in strokes is required since the H-field magnitude can be greater, although this is not common practice.

(2) More robust surge arresters for lightning.

(3) Use of lightning rods.

(4) High-frequency protection for HEMP using more sophisticated transient protection and filtering.
4-5. HEMP/TEMPEST and electromagnetic integration. EMC is defined in ref 4-9 as the ability of communications-electronics equipments, subsystems, and systems to operate in their intended environments without suffering or causing unacceptable degradation because of unintentional EM radiation or response. Electromagnetic interference (EMI) results when EM energy causes unacceptable or undesirable responses, malfunctions, degrades or interrupts the intended operation of electronic equipment, subsystems, or systems. RFI is a special case of EMI for which the radio frequency transmission (usually narrow-band) causes unintentional problems in equipment operation. For commercial electronic and electrical equipment, systems, or subsystems, the Federal Communications Commission (FCC) has regulations defining allowable emission and susceptibility levels. Military equipment is regulated by MIL STD 461 and MIL STD 462 (refs 4-10 and 4-11). MIL STD 461 defines allowable emission levels, both conducted and radiated, and allowable susceptibilities, also both conducted and radiated. Other specifications exist, but they apply to specific equipment.

a. Electromagnetic compatibility (EMC). EMC requirements usually apply to individual equipment as well as to the overall system. Because of equipment level requirements, the equipment cabinets or racks often must have a degree of protection, which comprises part of the topological protection.

b. Electromagnetic interference (EMI). The EMI environment has contributors from three main classes:

(1) Natural radio noise. Natural radio noise originating mainly from atmospheric disturbances (including lightning) and partly from extraterrestrial sources.

(2) Purposely generated signals. Signals that are generated purposely to convey information but that may interfere with the operation of other equipment.

(3) Man-made noise. Man-made noise such as spectral components generated incidentally by various electrical and electronic devices, motors, generators, and other machinery.

c. Achieving electromagnetic compatibility. Achieving EMC involves the same principles as protection against HEMP/TEMPEST. Generally, a HEMP/TEMPEST-protected facility will provide EMC protection as well over most of the desired frequency range. Some exceptions are--

(1) Frequency ranges. EMC encompasses the low frequencies, including the power frequency spectrum (5 to 400 hertz), and therefore, may have shielding and filtering requirements different than those for HEMP or TEMPEST protection.

(2) Spectra encompassed. EMC includes the VHF and microwave spectra as well as system-specific radiators or susceptibilities requiring special

4-4
treatment. Examples are susceptibilities to high power radars beyond the
HEMP/TEMPEST frequency range and switching transients below the HEMP/TEMPEST
frequency range.

(3) Interference within enclosures. EMC also can include interference
between equipment within the same shielded enclosures.

d. Exceptions. Clearly, EMC integration requires that special engineering
attention be given to these stated exceptions. For further guidance, see
references 4-9 and 4-12.

4-6. Environmental requirements. HEMP/TEMPEST protection must withstand
adverse environmental conditions that may occur at the facility. The major
concern is corrosion of buried grounding or shielding system elements,
including exterior steel sheets and buried water pipe or conduit. Other
environments of concern include those with high temperatures, excessive
vibration, and potential ground shock.
a. Corrosion. Design details and the materials used for external
grounding systems and underground shielding elements will affect the corrosion
of all exterior exposed metal installed underground throughout the facility
complex. Galvanic cells are the main cause of corrosion associated with
grounding system and adjacent underground metal objects. A galvanic cell is
produced when two dissimilar metals are immersed in an electrolyte and the
potential difference between electrodes causes a current to flow in a low-
resistance path between them. For HEMP/TEMPEST-protected facilities, the many
grounding connections between steel objects, including shielding and
reinforcing bars in contact with the shield, and the external grounding system
provide a low-resistance conductive path between interconnected metals in the
soil. Current will flow from cathodic material, such as copper or concrete-
encased steel, through these connections to bare steel, such as pipes and
conduits (anodic material). The current flow carries ferrous ions into the
earth electrolyte, resulting in galvanic corrosion of the pipes and conduits.
Conventional design practice for corrosion protection is to electrically
isolate the ferrous metal to be protected from buried copper and concrete
embedded steel. The protected metal often is coated with a dielectric
material. Conventional procedures must be modified to meet the restrictions
and limitations imposed by HEMP/TEMPEST requirements for electrically
continuous and grounded pipes, conduit, and electrical equipment. Close
coordination is required between grounding system design and that for
corrosion protection. Through such coordination, it is often possible to
design grounding systems that avoid corrosion problems, reduce corrosion
protective requirements, and simultaneously improve the grounding system.
b. Groundwater. In areas with high water tables, groundwater presents a
threat to underground shielding elements. Careful design is required to
obtain water-tight penetrations of the floor, roof, and exterior walls. This
includes piping, conduit, and utility or access tunnel connections.

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c. Thermal effects. If the metallic shield is subjected to temperatures somewhat higher than adjacent concrete, the sheets will tend to buckle outward. This condition could occur during construction or during building operation. Shield buckling is undesirable because welds can be damaged, compromising the shield and possibly the steel envelope's structural integrity. To eliminate buckling, provisions for expansion, temperature control, and/or securing the plates must be included in shielding design.

d. Vibration and acoustics. Shielded rooms in which the audible noise level is high should be studied for possible acoustical treatment because of steel's low sound absorption. Likewise, shielded rooms that have vibrating equipment should be given special consideration to avoid resonant vibration of shield panels or shielding elements. Excessive panel vibration could eventually damage welded seams, thus compromising the shielding.

e. Ground shock. If the hardened facility will be in an area of high seismic activity, or if it must withstand nuclear strikes with high overpressures, requirements will be defined for ground shock resistance. Expansion joints may be required between linear plate shielded structures to protect against differential motion from ground shock. Design for ground shock protection should be delegated to structural engineers who have appropriate experience and expertise.

4-7. Cited references.


4-10. MIL-STD-461B, Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference (DOD, 1 April 1980).


Table 4-1. HEMP/TEMPEST-related standards and specifications. (Sheet 1 of 3)

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Table 4-2. Peak magnetic field values for close lightning strokes.

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<td>16</td>
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<td>20</td>
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<td>30</td>
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Figure 4-1. Processes and currents occurring in a flash to ground.
Figure 4-2. EMP and lightning comparison.
Figure 4-3. Sample power line surge voltage as a function of distance from stroke to line.
Figure 4-4. Typical spectrum of lightning radiated E-field.
Figure 4-5. Average radiated and static fields for lightning.