CHAPTER 5

FACILITY DESIGN

5-1. Outline. This chapter is organized as follows:

5-2. Theoretical approach to shielding.

a. Shielding theory. The shielding theory that best applies to engineering calculations is based on an analogy to transmission line theory (ref 5-1). The transmission through an electromagnetic shield where the EM wave fronts coincide with the shielding boundary configuration is mathematically modeled in a way analogous to that in which a two-wire transmission line transmits electric current and voltage. Consider an incident EM wave with a power P in watts per square meter striking a flat shield as in figure 5-1. When the wave meets the first surface of the shield, part (P_{r1}) of the incident power (P_{in}) reflects back toward the source. The rest (P_{t1}) penetrates the shield and starts to propagate through it. The ratio of reflected power to incident power (P_{r1}/P_{in}) depends on the shield material's intrinsic impedance and the wave impedance (ratio of electric field strength to magnetic field strength) of the incident wave in the same way as at the junction of two transmission lines with different characteristic impedances. Part of the power transmitted into the shield (P_{t1}) is changed into heat as the wave moves through the shield. This energy loss is called "absorption loss" and is analogous to the dissipated energy inside a lossy transmission line. Of the power propagating through the shield toward the second surface, part is reflected back into the shield and the rest (P_{out}) is transmitted through the surface and beyond the shield. If the absorption loss in the shield is small (less than 10 decibels), a significant part of the power reflected at the second surface (P_2) propagates back to the first surface, where some of it is re-reflected back into the shield. At each surface, part of the energy is reflected and part is transmitted, contributing to an increase in the total energy propagated through the shield.

b. Shielding effectiveness. A shield's effectiveness is given in terms of how much it can reduce the incident EM field strength. Shielding effectiveness (SE) is therefore defined as the ratio of the field strength without the shield to the field strength with the shield. Because of the wide ranges in this ratio, SE is commonly expressed (in decibels) as--

$$SE = 20 \log (E_1/E_2) = 20 \log (H_1/H_2) = 10 \log (P_1/P_2) \qquad \text{(eq 5-1)}$$

where E_1 is the electric field strength, H_1 is the magnetic field strength, and P_1 is the power density of the incident wave. E_2, H_2, and P_2 are corresponding values with the shield in place. The SE of a given material is a complex function with many parameters. The most notable of these are the frequency and impedance of the impinging wave and the intrinsic characteristics of the shield material. In practice, the SE of enclosures is of primary concern. Thus, the above expressions are generally used to calculate the effectiveness (in decibels) of the shield material as well as the effectiveness of shield penetration and aperture treatments.

5-3. Shield design methodology. In general, 100-decibel shields require welded steel panels, whereas 50- to 60-decibel shields can be constructed using bolt-together panels. Lower shielding levels, as may be suitable for TEMPEST, can be provided with thin metals or foils. After establishing the required shielding level, the designer must consider the shield material thickness, material properties (permeability and conductivity), apertures, penetrations, geometry, construction--including solid sheet materials or screens and seam-joining techniques (e.g., bolted or welded), and the performance requirements (shielding effectiveness versus frequency). This paragraph addresses the approach to designing a shield in qualitative terms. The rest of this chapter (paragraphs 5-4 through 5-17) presents the quantitative data and formulas for shield design.

a. Shield performance requirements. The first step in designing an enclosure shield, whether for a large facility or an equipment enclosure, is to define the SE required. An enclosure's SE is not constant with frequency and this fact is usually taken into account in the SE definition. The shield design, shield material and thickness, and aperture penetration control affect the SE frequency dependence.

(1) Overall system. To establish the shield performance requirements, the overall system (facility and associated electronic and electrical systems) must be considered. The damage and/or upset levels at the terminals of equipment housed in the facility should be known. These values can be

obtained analytically, through laboratory experiments, or in some cases, from existing data bases for the same or similar equipment.

(2) Disruptive signals. Second, the way in which disruptive voltages and currents are coupled to the sensitive equipment's terminals should be determined. For example, they may be induced by penetrating magnetic or electric fields or by currents being conducted on cables that penetrate the facility (or possibly by cable-to-cable coupling of the cables that penetrate the facility). If the disruptive signals are coupled due to fields, protection is achieved by shielding the interior cables, shielding the entire facility, providing protection at the equipment terminals, or a combination of these techniques. If the signals are the result of energy injected by a shield-penetrating conductor, then these penetrants can be controlled at the point of entry to the enclosure or at the equipment terminals.

(3) System protection concept. The overall sensitive systems' protection design concept also plays a major role. That is, the choice of shielding concept (a low-performance facility shield in combination with interior cable and equipment shields--a multi-EM barrier approach--or a single barrier, high-performance facility shield) determines how the shield should be designed. (Chapter 3 discusses shielding concepts.) In general, this decision is influenced by economics, future expansion plans, the need for flexibility in system configuration changes, and maintenance capability.

(4) Total isolation to be provided. To establish the shield performance requirements, it is necessary to know the total isolation (protection level) that must be provided. For example, low-frequency magnetic field (low impedance fields) shielding is much harder to obtain than are high-frequency plane wave and electric field (high impedance fields) shielding. However, to obtain the same overall interior system isolation, a lower SE may be required from the shield for low-frequency magnetic fields due to the way in which magnetic fields couple to cables and circuits. For magnetic field coupling, a time-varying magnetic field is required (or motion of a conductor in a stationary magnetic field which is generally not of concern). Faraday's Law states that the voltage induced in a conducting loop is directly proportional to the time rate of change of the magnetic field and the area ofthe loop (i.e., $V_{induced} = B A$, where B represents the time derivative of the magnetic field and A is the cross sectional area of the conducting loop normal to the magnetic. field). This relationship implies that if B is small (low frequency or slow rise and fall times for a transient) or A is small, the voltage induced is small. Thus, less shielding is required for the same loop-induced voltage if the frequency is low.

b. Shield material and thickness. An enclosure's SE results from losses due to both reflection and absorption. The most common theory for calculating SE is the plane wave (or transmission line) theory presented in paragraph 5-4 below. Application of this theory requires that certain conditions be met as described in paragraphs (1) and (2) below.

(1) Source to shield distance. The source-to-shield distance must be greater than wavelength/2(pi) to be considered a plane wave. At this distance, the wave front is still spherical but can be assumed to be planar with minimal error for the analysis. At distances less than this, near-field calculations must be used. For the HEMP spectrum, the lowest frequency of interest is 10 kilohertz which corresponds to a wavelength of 30 kilometers. Plane wave criteria require a source-to-object distance of approximately 5 kilometers, which is met for HEMP with HOB $\geq$ 30 kilometers. In the near-field, the electric and magnetic fields must be analyzed separately.

(2) Size of protected object. The object size must be greater than 2 to 3 wavelengths in the smallest dimension or the infinite plane shielding theory no longer directly applies. If reflection loss is neglected, the infinite plane shielding theory can be extended to objects as small as 0.1 wavelength. Neglecting reflection losses provides a conservative estimate. As can be seen from the maximum wavelength associated with HEMP, the case of an object size greater than 2 to 3 wavelengths is not met for any enclosure.

(a) Another situation in which reflection losses are ignored is when the enclosure currents are induced primarily by conducted currents collected by external cables, pipes, etc., where the cable shields and pipes are terminated on the enclosure. The field reflection losses do not enter into the calculation in this case. There is some reflection loss at the entry point, but for a worst-case analysis, this loss can be ignored. These conducted enclosure currents are obtained by analyzing the coupling of the complete system or from laboratory scale model tests.

(b) Both the reflection loss and absorption loss depend on the shield's material properties. The absorption losses increase as the square root of frequency and material properties, and directly with material thickness. Reflection losses at all frequencies for electric and plane wave fields, however, remain quite high (more than 60 decibels for iron and more than 68 decibels for copper at 10 gigahertz (see para 5-4e below). The reflection losses for magnetic fields are low (less than 50 decibels) at frequencies below 100 kilohertz for copper and aluminum and appoximately 100 megahertz for iron. The result is that any relatively good conductor (i.e., copper, aluminum, iron) will provide good SE at all frequencies for electric and plane waves. The design problem with regard to material properties and thickness, therefore, is related to obtaining the required SE for magnetic fields at frequencies below approximately 100 kilohertz.

(c) To obtain good SE for magnetic fields at low frequencies due to the enclosure size restrictions cited above, it is necessary to increase the absorption losses. This condition can be achieved by increasing either the permeability or the conductivity. Copper is one of the best conductors, but still falls short of adequate absorption loss unless excessive thicknesses are used. Therefore, the remaining option is to increase the permeability. The permeability of all materials decreases with frequency, so care must be taken in the choice of material. The conductivity of high-permeability materials is less than that of copper which reduces high-frequency SE; however, the high-frequency SE of high-permeability materials is usually adequate. The design choice is therefore to select a material and thickness for which low-frequency magnetic field absorption loss combined with the reflection loss, if possible, provide the required SE at the lowest frequency of interest (10 kilohertz for HEMP).

c. Shield considerations. The construction techniques and penetrations generally determine a shield's high-frequency performance. When openings in a shield become greater than approximately wavelength/6, significant fields can penetrate to the interior. For example, suppose a shield is composed of the reinforcement bars in concrete; even if the bars are intersection-welded, a spacing between bars of greater than wavelength/6 results in low SE. For the commonly used double exponential HEMP, the highest frequency of interest is 200 megahertz (see chap 2) and this spacing requirement is less than 0.15 meter. Bar spacing is more critical for EMI which has frequencies in the 11 to 40 gigahertz range, and relates to fields present in the entire interior volume of the enclosure. Higher fields will be present near the aperture for aperture dimensions that are small compared with a wavelength so that the penetrating fields are nonpropagating. These fields decrease in magnitude as the inverse cube of the distance from the aperture.

(1) Defective seams. Apertures resulting from seams with defects also can introduce field-coupling inside the enclosure. If these defects have openings that are nonpropagating (i.e., much smaller than the wavelength), the fields again decrease in magnitude as the inverse cube of distance from the aperture. For high shield currents and susceptible equipment located near the shield, these fields could cause potential disruption. This upset can occur even for low-frequency shield currents due to the redistribution of currents on the shield caused by the seam apertures.

(2) Apertures. Apertures for air inlets, exhausts, and similar features also must be sized and treated to maintain high-frequency SE. These openings are designed as waveguide-below-cutoff structures.

(3) Seam impedance. Seam impedance is of concern since induced currents flowing across seams can introduce potential drops over the seams, which will result in reradiation inside the shielded volume. These potential drops can also cause problems when the shield is used in the grounding system.

(4) Penetrations. Configuration control must be considered during the design phase. Conducting penetrations must be bonded carefully around the penetrant periphery (360 degrees) to the shield entry plate to prevent aperture coupling to the facility interior or to inner conductors of shielded cables. Nonconducting penetrations must be treated as apertures in the shield and given WBC treatment.

d. Design approach. In designing a facility shield, the following steps should be performed in the order listed.

(1) Shielding effectiveness required. Determine the exterior shield performance (SE) as a function of frequency and interior equipment susceptibility. Repeat this process for the interior shield (second barrier) if one will be used.

(2) Material thickness. Select the material and material thickness to obtain the necessary SE at the lowest frequency of concern and for the field impedance of interest for all shield barriers, internal and external. For small (less than 2 to 3 wavelengths) enclosures or conducted enclosure currents, the reflection loss can be ignored.

(3) Safety margin. Provide a safety margin in the SE to account for corner effects in low-performance shields (less than 60 decibels).

(4) Apertures required. Determine which apertures must be open and apply the necessary protective design techniques to achieve the same level of attenuation as that of the shielded enclosures.

(5) Aperture control. Design seams and treatment to control aperture size such that attenuation through apertures is the same or higher than that for enclosure SE.

(6) Doors. Select or design doors to achieve the same decibel attenuation as that of the enclosure. Maintenance of gaskets, spring fingers, and contact surfaces also should be considered.

(7) Seam bonding. Seam bonding must be low-impedance type.

(8) Terminal protective devices. Provide for penetrant bonding, entry plate, and entry vault to house terminal protective devices if required.

5-4. Solid shields.

a. Plane wave theory. The plane wave (or transmission line) theory is the basis for the most commonly used approach to shielding design. For a plane wave normally incident on a large plane sheet of metal, the SE is (ref 5-2)--

$$SE = A + R + B \qquad \text{(eq 5-2)}$$

where A = absorption loss of the material (decibels), R = single reflection loss (decibels), and B = re-reflection correction term (decibels).

(1) Absorption loss and frequency. For a given material, absorption loss (in decibels) at a specific frequency is a linear function of the material thickness. Characteristics of the material that influence this loss are conductivity and permeability. Absorption loss is largely independent of

wave impedance and is the same for electric, magnetic, and plane wave fields. Magnetic field shielding at low frequencies mainly depends on absorption losses since reflection losses decrease with frequency. In addition, the shield must approximate an infinite sheet. For practical cases, the smallest shield enclosure dimension must be greater than 2 to 3 wavelengths to achieve significant reflective loss. Electric fields, however, are readily stopped by metal shields because large reflection losses are easy to obtain for any good conductor.

(2) Reflection loss and impedance. The single reflection loss term depends on the degree of mismatch between the impedance of the field and that of the shield. The impedance of the impinging wave is given by the ratio of its electric to magnetic field strength in space in the vicinity of the shield. A shield's impedance is a complex function of its electrical properties, thickness, and impinging wave frequency. In general, the shield impedance is low for highly conducting shields and increases for shields with high permeability.

(3) Plane wave shielding. For the reflected wave to be as large as possible or for the reflection loss to be high, the shielding material should have an impedance much lower than the wave impedance. To shield against plane waves, any good conductor is suitable (e.g., copper, aluminum, and steel).

(4) Re-reflection. The re-reflection correction term is a complex function of material, dimensions, and frequency. The term can be ignored if the absorption loss exceeds 10 decibels. If the absorption loss is less than 10 decibels, however, the correction term should be determined.

(5) Relationships. The absorption loss, single reflection loss, and re-reflection correction terms can be approximated by relationships involving shield thickness (t), material conductivity (g), material permeability (u), and frequency (f). Since reflection loss depends on the incident wave's impedance, relationships are given for low-impedance fields (Z less than 377 ohms; magnetic fields), high-impedance fields (Z greater than 377 ohms; electric fields), and plane wave fields (Z = 377 ohms).

b. Absorption loss.

(1) For electromagnetic wave. The absorption loss for an EM wave passing through a shield of thickness t can be shown by--

$$A = K_1 t \quad f u_r g_r \quad \text{(decibels)} \qquad \text{(eq 5-3)}$$

where K_1 = 131.4 if t is expressed in meters, K_1 = 3.34 if t is expressed in inches, t = shield thickness, f = wave frequency (hertz), u_r = permeability of shield material relative to copper, and g_r = conductivity of shield material relative to copper.

(2) Proportions. The absorption loss (in decibels) is proportional to the thickness of the shield and increases with the square root of incident EM wave frequency. The absorption loss also increases with the square root of the product of the permeability and conductivity (both relative to copper) of the shield material. As noted before, absorption loss is independent of wave impedance.

(3) Calculating loss. A simple approach to calculating the required absorption loss is to--

(a) Estimate the reflection loss (if applicable, depending on the enclosure size and conducted current on the enclosure) for the type of field.

(b) Subtract the reflection loss from the SE requirement.

(c) The difference from (b) above must be obtained from the absorption loss as in (d) below. If the required absorption loss is less than 10 decibels, then the correction factor must be applied to the reflection loss in (a) above and steps (b) through (e) repeated.

(d) Calculate the absorption loss per mil thickness from equation 5-3 for the material chosen.

(e) Calculate the material thickness required by dividing the required loss by the loss per mil. If this thickness is excessive because of weight, cost, or other factors, select a new material and repeat the calculation.

(4) Example. As an example, assume the following shielding system design:

(a) Facility size = 100 by 100 by 20 meters.

(b) System sensitivity (V_{upset}) = 2 volts at equipment terminals.

(c) Maximum loop size between equipment = 2 meters squared.

(d) Incident field = HEMP; H_e = 133 amps per meter, E_e = 50 kilovolts per meter.

(e) Based on the previous discussion, since the facility size is much less than the wavelength, assume no reflection losses.

(f) Estimate $\dot{H}i_{max}$ (internal time rate of change of magnetic field). The interior loop coupling is given by Faraday's Law of Induction as (eq 5-4):

$$V = u\dot{H}_{i_{max}} A \qquad \text{(eq 5-4)}$$

where $u = u_O = 4(pi) \times 10^{-7}$ (free space or air); A = loop area; and V = maximum allowable voltage transient at equipment terminals. Thus--

$$2 = V = [4(pi) \times 10^{-7}]\ \dot{H}_{i_{max}} \quad (2)$$

$$\dot{H}_{i_{max}} = \frac{V}{uA} = 4u^2 \times 10^7 \ (2)$$

$$= 8 \times 10^5 \text{ amps/meter/second}$$

(g) Estimate $\dot{H}_{i_{max}}$:

$\dot{H}_e$ = 133 amps/meter (free field)

t_r = pulse rise time = 10 nanoseconds

$\dot{H}_{e_{surface}} = 2\dot{H}_e$ = J, the field or current density at the conducting surface.

J = 266 amps/meter

$$\dot{J} \simeq J/t_r = \frac{266}{10^8} = 2.66 \times 10^{10} \text{ amps/meter/second and--}$$

$$\dot{H}_{i_{max}} = \frac{\dot{J}}{2} = 1.33 \times 10^{10} \quad \text{amps/meter/second}$$

(h) Estimate the required SE:

$$SE = 20 \log \left(\frac{\dot{H}_{i_{max}}}{\dot{H}_{e_{surface}}} \right) = 20 \log \left(\frac{8 \times 10^5}{2.66 \times 10^{10}} \right)$$

$$= 90 \text{ decibels}$$

(i) For worst-case analysis, assume that all attenuation must be achieved through absorption and assume a lowest frequency of 10 kilohertz for HEMP.

(j) Calculate the absorption loss and material thickness:

$$A = 90 \text{ decibels (from (h) above)}$$

$$A = 3.34\ t\ (u_r g_r f)^{0.5}$$

$$f = 10^4 \text{ hertz.}$$

For steel (sheet metal)--

$$u_r = 1000$$

$$g_r = 0.17$$

Solving for t (thickness) yields--

$$t = \frac{A}{3.34\ (u_r g_r f)^{0.5}}$$

Substituting--

$$t = \frac{90}{3.34\ (1000 \times 0.17 \times 10^4)^{0.5}}$$

$$t = 20 \text{ mils.}$$

For copper--

$$u = 1,\ g_r = 1$$

$$t = 90/[3.34\ (10^4)^{0.5}]$$

$$t = 269 \text{ mils.}$$

(k) The calculation in (j) above is for a worst case since it assumes all the energy is at 10 kilohertz and no reflection losses occur. To solve the problem more rigorously, it would be necessary to obtain Hi_{max} derivative on a frequency-by-frequency basis, compare it with the spectrum $Hi_{surface}$ derivative on a point-by-point basis, and obtain the SE as a function of frequency. Since the steel result does not incur any great penalty (in fact, an even heavier material could be used since it would result in lower construction costs) it is generally not necessary to do a rigorous analysis for the envelope shield of a facility. If weight were a critical factor, the longer calculation may be justified. Further, this worst-case analysis should provide a safety margin without added SE requirements for corner effects. Although this example is greatly simplified, it represents the basic method for choosing a material and thickness.

c. Reflection loss.

(1) Approximating loss. For magnetic (low-impedance) EM fields, the low impedance reflection loss can be approximated as (eq 5-5):

$$R_m \simeq 20 \log \left[\frac{C_1}{r\,(fg_r/u_r)^{0.5}} + C_2 r\, fg_r/u_r + 0.354 \right] \qquad \text{(eq 5-5)}$$

where r = distance from the EM source to the shield and f, u_r, and g_r are as stated for equation 5-3. The constants C_1 and C_2 depend on the choice of units for the distance, r, as given in table 5-1.

(2) Limitation of approximation. For HEMP, the source region is remote enough that the waves are essentially plane waves and equation 5-5 does not apply. Equation 5-5 is for source-to-object distances (r) much less than wavelength/2(pi). The product $fr \ll 2 \times 10^9$, where r is in inches, also must be met. The source distance (r) must be less than 5000 meters at a frequency of 10 kilohertz, which is the lowest frequency of concern for HEMP. For example, the magnetic field reflection loss at r = 100 meters and f = 10 KHz is--

$$R_m = 20 \log \left[\frac{0.0117}{100\,(f)^{0.5}} + 5.35\,(100)\,f + 0.354 \right]$$

$$= 20 \log [1.2 \times 10^{-6} + 53500 + 0.354]$$

$$= 95 \text{ decibels.}$$

(3) Comparison to absorption loss. As with absorption loss, the reflection loss for low-impedance fields depends on the electrical properties (u_r, g_r) of the shield material and the EM wave frequency. In contrast, reflection loss depends on the distance from the source to the shield rather than on the shield thickness, except for very thin shields (where thickness is less than skin depth).

(4) Plane wave loss. The plane wave reflection loss for a plane wave impinging on a uniform shield is given by equation 5-6:

$$R_p \simeq 168 - 20 \log \left(\frac{fu_r}{g_r} \right) \qquad \text{(eq 5-6)}$$

where g_r, u_r, and f are as defined for equation 5-3. The plane wave reflection loss declines as the wave frequency increases and is better for shielding materials with lower u_r/g_r ratios. For example, the plane wave reflection loss for copper at a frequency of 1 megahertz is--

$$R_p = 168 - 20 \log f$$

$$= 168 - 60$$

$$= 108 \text{ decibels.}$$

(5) High-impedance field loss. For electric (high-impedance) EM fields, the high-impedance reflection loss is approximated by equation 5-7:

$$R_E \simeq C_3 - 20 \log r \frac{u_r f^3}{g_r} \qquad \text{(eq 5-7)}$$

where C_3 = 322 if r is in meters, 354 if r is in inches; r is the source-to-object distance, and g_r, u_r, are the conductivity and permeability relative to copper. High-impedance EM wave reflection loss depends on the separation distance, r, between the EM source and the shield, as does low-impedance reflection loss. This loss declines as the frequency increases and is higher when the g_r/u_r ratio is higher. For electric fields, the conditions r >> wavelength/2(pi) and fr << 2 x 10^9 should be met. For example, the electric field reflection loss for copper when r = 100 meters and f = 100 kilohertz is--

$$R_E = 322 - 20 \log 100 \quad f^3$$

$$= 322 - 190$$

$$= 132 \text{ decibels.}$$

d. Re-reflection correction term.

(1) Cause of re-reflection. For shields in which the absorption loss (A) is fairly large, say at least 10 decibels, the energy reflected back into the shield at the second surface does not contribute significantly to the wave propagated through and beyond the shield. However, when the shield's absorption loss is low, a significant amount of energy is re-reflected and

finally propagates into the area to be shielded. Thus, for shields with low absorption loss (less than 10 decibels), SE is calculated as the sum of the absorption loss (A), the reflection loss (R), and a re-reflection correction factor (B). The correction factor in decibels is--

$$B = 20 \log [1 - X10^{-A/10} (\cos 0.23A - j\sin 0.23A)] \tag{eq 5-8}$$

where A is the shield's absorption loss (from eq 5-3) and X is the two-boundary reflection coefficient. X depends on both the shield's characteristic impedance and the impinging EM wave's impedance; X is equal to 1 for all practical purposes except for low-frequency shielding against magnetic fields (fig 5-2) (ref 5-3).

(2) Graphs of relationships. The relationships for SE given in equations 5-3 through 5-8 have been plotted as graphs for ease of use. Figures 5-3 through 5-8 are nomographs and curves that permit graphical solutions of these relationships. The nomographs in figures 5-3 through 5-6 give solutions for absorption loss and magnetic field, electric field, and plane wave reflection loss, respectively. Figures 5-7 and 5-8 give solutions for the re-reflection loss in terms of the ratio of the shield impedance (Z_s) to the impedance of the incident magnetic field (Z_m). This ratio (K_w) is given by either figure 5-7 or equation 5-9:

$$K_w = \frac{Z_s}{Z_m} = \frac{1.3}{\left(\frac{g_r f}{u_r} \cdot r\right)^{0.5}} \tag{eq 5-9}$$

where g_r and u_r, are the conductivity and permeability relative to copper; f is frequency; and r is source-to-object distance (ref 5-3). Once determined, the ratio K_w is used with figure 5-8 to determine the re-reflection loss, B.

(3) Using graphs for absorption loss. As an example of how to use the figures, consider a calculation for absorption loss. On the nomograph in figure 5-3, draw a straight line between a point on the right-hand vertical scale that corresponds to the metal involved and the correct point on the thickness scale (center scale on the nomograph). Mark the point at which the straight line crosses the unlabeled pivot line and the frequency of interest (left-most vertical scale). Read the absorption loss off the compressed scale just to the left of the thickness scale. This figure shows the determination of absorption loss for a 15-mil sheet of stainless steel at 1 kilohertz. First, line 1 is drawn between stainless steel on the right-hand scale and 15 mils on the thickness scale. Then line 2 is drawn between 1 kilohertz on the left-hand scale and the crossover point. The absorption loss is 3 decibels.

(4) Using manufacturers' data. If the metal of interest is not given on the right-hand scale, calculate the product of the relative conductivity

(g_r) and the relative permeability (u_r) from figures given in the manufacturer's data sheets and use this value as the right-hand point for line 1.

(5) Using graphs for reflection loss. Since the total SE is the sum of the absorption loss and reflection loss, the procedure for determining reflection loss using the nomographs in figures 5-4 through 5-6 is similar to that described for absorption loss. The right-hand scale in these three nomographs is based on the ratio of relative conductivity to relative permeability instead of the product of the two as used in the absorption loss nomograph.

(6) Example. Except for very thin shields with little absorption loss, re-reflections are unlikely to affect SE. Re-reflection loss estimates using figures 5-7 and 5-9 are necessary only if the absorption loss is less than about 10 decibels. Figure 5-7 shows an example of computing K_w for copper at a frequency of 1 kilohertz and a source-to-shield distance of 2 inches, yielding a K_w of 2.2×10^{-2}. For a 10-mil-thick sheet of copper at this frequency, the absorption loss (from fig 5-3) will be about 1 decibel. Thus, in figure 5-6, for a K_w of 2.2×10^{-2} and an absorption loss of 1 decibel, the re-reflection loss would be about 10 decibels. This example applies to low-impedance magnetic fields which are not plane waves. The re-reflection term (B) is presented (table 5-8 in para (5) below) for electric and plane wave fields for iron and copper; or, it can be calculated using equation 5-8. HEMP fields are essentially plane wave fields.

e. Shielding effectiveness data. The data in tables 5-2 through 5-4 show the SE of common metals. In addition, quick estimates for almost any frequency can be obtained using the nomographs in figures 5-6 through 5-8. The tables and figures for these data provide an easy-to-use reference of SE when they include the shield material and frequency of interest.

(1) Using absorption loss table. Table 5-2 gives electrical properties (g_r and u_r) of common shielding materials. Since u_r is frequency-dependent for magnetic materials, it is given for a typical shielding frequency of 150 kilohertz. The relative permeability decreases with increasing frequency. A typical sample of iron, for example, has a u_r of 1000 up to 150 kilohertz. At 1 megahertz, it drops to 700 and continues to fall to a value of $u = 1$ at 10 gigahertz. Materials with very high permeability have u_r values that drop much faster. For these high-permeability materials, $u_r = 1$ should be used above 1 megahertz in most cases. For the exact values, manufacturer's data should be consulted since these values differ with each material (e.g., Mu-metal, Permalloy, etc., which are trade names). At the higher frequencies (above 1 megahertz), a large u_r value is unimportant since the reflection losses and absorption losses are high even for nonmagnetic materials. u_r is important only for low-frequency (below 100 kilohertz) magnetic shielding. The last column gives values of absorption loss in decibels per mil since a given material's absorption loss is proportional to its thickness.

(2) Variation of absorption loss. Table 5-3 shows the variation of absorption loss with frequency for copper, aluminum, and iron. Iron has a higher absorption loss than copper at low frequencies, whereas copper has the higher loss at higher frequencies. Figure 5-9 shows curves of absorption loss as a function of frequency for certain thicknesses of copper and steel shields. For example, a 50-mil steel shield provides significant absorption losses at frequencies above 1 kilohertz.

(3) Magnetic field reflection. Table 5-4 gives reflection losses for copper, aluminum, and iron for electric, magnetic, and plane wave fields. Values in this table, derived from data in table 5-3, suggest why shielding against magnetic fields is of major concern in shield design: the magnetic field reflection loss is relatively low for all three materials. The electric field and plane wave reflection losses are high enough to provide adequate shielding for most requirements, however, especially over the EMP frequency spectrum.

(4) Combined absorption and reflection. Tables 5-5 through 5-7 show the combined absorption and reflection SE for magnetic, plane wave, and electric fields, respectively, for certain frequencies. The SE values for magnetic and electric fields were derived for a source-to-shield spacing (r) of 12 inches, which represents high- or low-impedance near fields. These data again show that electric field and plane wave shielding are relatively easy. Even for magnetic fields, shields of reasonable thickness provide significant shielding (for example, 69 decibels for copper at 150 kilohertz).

(5) Re-reflection factors. Table 5-8 shows the re-reflection (B) factors for copper and iron in electric, magnetic, and plane wave fields for various frequencies and shield thicknesses. For frequencies above 10 kilohertz and shield thicknesses greater than 10 mils, re-reflection losses are negligible for both copper and iron. If the shield is electrically thin (absorption loss less than 10 decibels), the re-reflection factor must be determined to define the total SE. Figure 5-10 shows how absorption losses for copper and iron, in decibels per mil, vary with frequency.

(6) Effect of shield thickness. Tables 5-9 through 5-11 give the total SE in electric, magnetic, and plane wave fields for copper and steel shields of certain thicknesses at a source-to-shield distance of 165 feet. Figures 5-11 through 5-13 illustrate the data in these tables. Figure 5-13 suggests that, for most EM environments, including HEMP, a 50-mil shield would greatly reduce incident energy--on the order of 100 decibels or more for frequency components above 1 kilohertz.

(7) Example. As an example of how to use the above data in estimating SE, assume that the SE of a 10-mil-thick copper sheet exposed to a plane wave field is to be determined at a frequency of 150 kilohertz. From table 5-3, the absorption loss for a 10-mil thickness at this frequency is calculated as 12.9 decibels. From table 5-4, the reflection loss is 117 decibels. Since the absorption loss is greater than 10 decibels, the re-reflection loss can be

ignored; or, by consulting table 5-8, a re-reflection loss can be estimated from the 100-kilohertz column as roughly +0.5 decibels. Thus, the total SE (SE = A + R + B) would be 12.9 + 117 + 0.5 = 130.4 decibels. Table 5-12 shows other examples of SE calculations. If the above data do not include the parameters desired, the relationships for SE can be used (eqs 5-2 through 5-8).

5-5. Shielded enclosures.

a. Enclosure shielding effectiveness. The SE relationships and data in paragraph 5-4 assume a sinusoidal wave incident on a large (many wavelengths) plane surface. For other surface geometries, such as a shielded enclosure with sharp corners and small dimensions compared to a wavelength, the surface currents induced on the shield will not be uniform. Thus, the actual shielding provided by such enclosures will likely vary somewhat from that estimated using the SE relationships of paragraph 5-4. However, these plane-surface data provide a valid basis for enclosure designs and yield realistic approximations of the SE that can be achieved in practical enclosures.

(1) Low-carbon steel walls. Figure 5-14 shows the manufacturer's specified minimum SE for an enclosure made of low-carbon-steel walls. Note from this figure that for fairly thick enclosure walls (1/4 to 3/8 inch), the minimum magnetic field SE approaches 100 decibels, even for frequencies as low as 1 kilohertz. The enclosure SE values must be derated when penetrations and apertures (especially doors) are included if they are not designed to provide an SE equal to that of the shield.

(2) Layered sheet -steel walls. Typical commercial enclosures, which are acceptable for 60-decibel shields, are built with two thin layers of steel separated by plywood or other core material. Even with the fairly thin metal thicknesses and the penetrations and apertures needed for power, doors, and ventilation, these enclosures will provide significant attenuation levels to plane waves over the range of frequencies in the HEMP spectrum. Figure 5-15 shows the manufacturer's specified performance for a typical dual-wall, bolted-panel commercial enclosure. Even for an enclosure with two thin layers of 24-gauge steel, the enclosure is predicted to provide at most 60 decibels of attenuation down to 10 kilohertz.

(3) Mean shielding effectiveness. Laboratory experiments on new enclosures have shown that the seams of bolt-together laminated steel and wood shielded enclosures may have lower SE values than claimed by the manufacturers (ref 5-4). Figure 5-16 shows a measured mean value for three room types. These data represent the mean SE from 56 test points in each room tested. The standard deviation of the test data is relatively large; for example, data for one of the rooms had a standard deviation of 17 decibels (92 decibels = mean) at 200 kilohertz magnetic field testing. It should be noted that the shielded room data in reference 5-4 were taken after initial assembly of the enclosures. No efforts were made to determine the points of greatest leakage or to increase SE at those joints. Further, after aging, the bolt-together

construction would require maintenance which would greatly affect life-cycle cost.

b. Enclosure response to HEMP.

(1) Spherical enclosure and magnetic field. The exact calculation of a practical enclosed structure's SE when exposed to a transient rather than a sinusoidal waveform is extremely complex. The magnetic SE of an enclosure has been reasonably approximated by assuming an ideal enclosure geometry--a solid spherical shell. The total SE for this geometry has been derived and plotted in a nomograph to provide a rapid way to evaluate the HEMP magnetic field SE of a spherical shell enclosure (ref 5-5). Care must be taken in using the nomograph. For example, the nomograph implies that a very thin shield can provide good shielding against HEMP. However, this does not imply that thin shields are recommended because mechanical fabrication problems make them undesirable. It simply shows that, since a thin shield would provide reasonable SE, thicker shields would afford even better SE.

(2) Spherical enclosure and peak voltage. Following a similar approach, the peak voltage induced in a loop inside a 10-meter-radius spherical shield has been calculated. Three shield wall thickness (0.2, 1, and 5 millimeters) and three different wall materials (copper, aluminum, and steel) were used in the calculations. Table 5-13 shows the results. For all materials and thicknesses, the peak HEMP-induced voltages inside the shield are very small. These values were calculated usingFaraday's Law of Magnetic Induction ($V_{induced}$ = BA, where B is the time rate of magnetic flux density and A is the loop area normal to the magnetic field).

(3) Practical enclosures. The above results were obtained for an idealized spherical enclosure that had no discontinuities in its walls. Thus, the results can be seen only as approximations of the SE of practical, rectangular enclosures. However, the results do suggest that even fairly thin, solid shields will likely reduce HEMP transients to tolerable levels in ground-based facilities. It is expected that--

(a) Facility mechanical construction requirements and cost rather than HEMP shielding requirements will dictate the final type and thickness of the shield material used.

(b) The overall effectiveness of enclosure shielding will depend on shield penetration and treatment of openings rather than shield material.

5-6. Mesh and perforated type shields. Mesh screens and perforated sheets are used both in fabricating enclosures and in electromagnetic closure of apertures where ventilating air is required. Honeycomb-type panels are a form of nonsolid shield used extensively for aperture EM closure.

a. Screens and perforated metal shields. Leakage through openings (apertures) in metal shields has been studied using transmission line theory.

Based on these studies, the SE of mesh and perforated type shielding materials has been defined as--

$$SE_a = A_a + R_a + B_a + K_1 + K_2 + K_3 \qquad \text{(eq 5-10)}$$

where A_a = penetration loss for a single aperture in decibels, R_a = aperture reflection loss in decibels, B_a = correction term (in decibels) due to successive reflections, K_1 = loss term to account for the number of openings per unit square, K_2 = penetration loss correction term for penetration of the conductor at low frequencies, and K_3 = a correction term to account for closely spaced shallow holes in the material. Normally, these correction terms may be neglected.

(1) Shielding effectiveness parameters. The terms A_a, R_a, and B_a in equation 10 relate to penetration loss, reflection loss, and the re-reflection loss correction term for a single aperture. K_1 provides for multiple apertures of the same dimensions and represents the decreased SE due to multiple apertures per unit square (the "unit square" dimension unit of measure is the same as that for the aperture, i.e., inches, meters, etc.). This term applies only when the source-to-aperture distance is large compared with the aperture dimensions. K_2 is a correction term for the penetration loss (A_a) when the conductor dimensions approach the skin depth dimension, i.e., mesh wire size or conductor width between holes approaches the skin depth for the material used at the low end of the frequency spectrum of interest (10 kilohertz for HEMP). K_3 is a correction term for the penetration loss of closely spaced shallow holes. K_3 accounts for "adjacent hole coupling" between apertures since the degradation of SE for multiple, closely spaced apertures is not the linear sum of the single aperture loss over the number of apertures.

(2) Single layer wire cloth and screening calculations. Detailed expressions for the screen and perforated metal sheet SE terms are given as follows for single-layer wire cloth or screening:

A_a = aperture attenuation in decibels

$$= 27.3\ D/W \text{ for rectangular apertures} \qquad \text{(eq 5-11)}$$

$$= 32\ D/d \text{ for circular apertures} \qquad \text{(eq 5-12)}$$

where D = depth of aperture in inches, W = dimension of a rectangular aperture in inches (measured perpendicular to the E-vector), and d = diameter of a circular aperture in inches.

R_a = single aperture reflection loss in decibels

$$= 20 \log \frac{(1 + k)^2}{4k} \qquad \text{(eq 5-13)}$$

and B_a = single aperture correction factor for aperture reflection (small when A_a is greater than 10 decibels)

$$= 20 \log \left[1 - \frac{(k - 1)^2}{(k + 1)^2} \times 10^{-0.1A_a} \right] \qquad \text{(eq 5-14)}$$

(a) In equations 5-13 and 5-14:

k = ratio of aperture characteristic impedance to incident wave impedance, or

= W/3.142r for rectangular apertures and magnetic fields (eq 5-15)

= d/3.682r for circular apertures and magnetic fields (eq 5-16)

= $jfW \times 1.7 \times 10^{-4}$ for rectangular apertures and radiated fields (eq 5-17)

= $jfd \times 1.47 \times 10^{-4}$ for circular apertures and radiated fields (eq 5-18)

where f = frequency in megahertz, r = distance from signal source to shield in inches, and $j = (-1)^{0.5}$, W = largest dimension of rectangular aperture, and d = diameter of circular aperture.

K_1 = correction factor for number of openings per unit square (applies when test antennas are far from the shield compared with distance between holes in the shield)

$$= 10 \log \frac{1}{an} \qquad \text{(eq 5-19)}$$

where a = area of each hole in square inches and n = number of holes per square inch.

K_2 = correction factor for penetration of the conductor at low frequencies

$$= -20 \log \left[\left(1 + \frac{35}{p^{2.3}} \right) 705 \right] \qquad \text{(eq 5-20)}$$

where p = ratio of the wire diameter to skin depth, d:

$$d = \frac{6.61}{f} \quad \text{in centimeters, f in hertz}$$

$$d = \frac{2.60}{f} \quad \text{in inches, f in hertz} \qquad \text{(eq 5-21)}$$

K_3 = correction factor for coupling between closely spaced shallow holes

$$= 20 \log \left[\frac{1}{\tanh (A_a/8.686)} \right] \qquad \text{(eq 5-22)}$$

Figure 5-18 presents these parameters in graphic form.

(b) As an example, determine the SE of a No. 22, 15-mil copper screen when it is subjected to a magnetic field from a loop source 1.75 inches away and operating at a frequency of 1 megahertz. Such a screen has 22 meshes per linear inch. The center-of-wire to center-of-wire distance is 1/22 (0.045) inch and the opening width is smaller by an amount equal to the wire meter, 0.015 inches. The depth of the aperture is assumed to be equal to the wire diameter. Thus--

$$A_a = (27.3)D/W = (27.3)\ (0.015)\ /\ (0.045 - 0.015)$$

$$= 13.5 \text{ decibels}$$

The impedance ratio for the magnetic wave and rectangular apertures is given by--

$$k = W/(pi)r = (0.045 - 0.015)\ /\ [1.75(pi)]$$

$$= 0.00554$$

and the reflection term is--

$$R_a = 20 \log \left[\frac{(1 + k)^2}{4k} \right] = 33.2 \text{ decibels}$$

The multi-reflection correction term is--

$$B_a = 20 \log \left[1 - \frac{(k - 1)^2}{(k + 1)^2} \times 10^{-A_a/10} \right]$$

$$= -0.4 \text{ decibels}$$

The correction factor for the number of openings is--

$$K_1 = 10 \log \left(\frac{1}{an} \right)$$

$$= 10 \log \frac{1}{(0.045 - 0.015)^2 \; (22)^2}$$

$$= 3.5 \text{ decibels}$$

The skin depth correction term is--

$$K_2 = -20 \log [1 + (35/p^{2.3})]$$

$$p = \frac{0.015}{2.6 \times 10^{-3}} = 5.77$$

$$K_2 = -20 \log [1 + 35/56.3)] = -4.2 \text{ decibels}$$

Finally, the hole-coupling correction factor is given by--

$$K = 20 \log [1/\tanh (A_a/8.686)]$$

$$= 0.8 \text{ decibels}$$

The screen's SE is the sum of the six factors--

$$SE = 13.5 + 33.2 - 0.4 + 3.5 - 4.2 + 0.8$$

$$= 46.4 \text{ decibels}$$

(3) Using tables. Representative mesh and perforated sheet SE measurements are shown in tables 5-14 and 5-15. These tables provide data on a variety of material forms including meshes, perforated sheets, and cellular structures in protecting against low-impedance, high-impedance, and plane waves. Table 5-16 gives both calculated and measured values of SE for the No. 22 15-mil copper screen in the example for magnetic, plane, and electric waves for several frequencies. The SE of the screen increases with frequency for magnetic fields, declines with increasing frequency for plane waves, and is largely independent of frequency for electric fields.

(4) Shield dimensions. Screen shields usually consist of a single or double layer of copper or brass mesh of No. 16- to 22-gauge wire with openings no greater than 1/16 inch. A mesh less than 18 by 18 (wires to the inch)

should not be used. The mesh wire diameter should be a minimum of 0.025 inch (No. 22 AWG). If more than a nominal 50 decibels of attenuation is required, the screen should have holes no larger than those in a 22-by-22 mesh made of 15-mil copper wires.

(5) Galvanized hardware cloth. A mesh construction in which individual strands are permanently joined at points of intersection by a fusing process that provides good, fixed electrical contact affords strong SE and is not degraded by wires oxidizing and eliminating electrical contact. An example of this type of construction is galvanized hardware cloth. These screens are very effective for shielding against electric (high-impedance) fields at low frequencies because the losses will be mainly caused by reflection. Screens of this type are commercially available for EM closing of open apertures to allow for ventilation. They usually are not used to construct enclosures. Installation for aperture control is done by connecting a screen around the edge of the opening.

b. Honeycomb. Honeycomb panels are formed as a series of cylindrical, rectangular, or hexagonal tubular openings. Each opening acts as a waveguide-below-cutoff attenuator. The depth of the aperture determines the amount of attenuation realized and the diameter of each opening determines the cutoff frequency. For a rectangular waveguide attenuator, the cutoff frequency, f_o, is given by (ref 5-6)--

$$f_o = \frac{6920}{W} \text{ megahertz.} \qquad \text{(eq 5-23)}$$

For a circular guide--

$$f_o = \frac{5900}{W} \text{ megahertz} \qquad \text{(eq 5-24)}$$

where f_o = cutoff frequency for the dominant mode in megahertz and W = inside diameter of a circular waveguide in inches, or the greatest dimension of a rectangular waveguide in inches.

(1) Attenuation. At any frequency, f_a, the waveguide attenuation is a function of the ratio L/W, where L is the depth of the guide. For f_a much less than cutoff (that is, $f_a < 0.1f_c$), the attenuation in decibels per inch for cylindrical waveguides is approximated by the relation--

$$a = \frac{32}{W} \qquad \text{(eq 5-25)}$$

where W is in inches. For rectangular waveguides, the attenuation in decibels per inch is--

$$a = \frac{27.3}{W} \quad \text{(eq 5-26)}$$

Equations 5-23 through 5-26 are valid for air-filled waveguides with length-to-width or length-to-diameter ratios of three or more.

(2) Rectangular and circular waveguides. The attenuation of a waveguide for frequencies below cutoff is shown in figure 5-22 for a rectangular waveguide and in figure 5-23 for a circular waveguide, both for an L/W ratio of 1. For ratios other than 1, the value in decibels obtained from the curve must be multiplied by L/W to obtain the correct attenuation value. For example, an SE of over 100 decibels can be obtained at 10,000 megahertz with a 0.25-inch-diameter tube, 1 inch long, or a 1/2-inch-diameter tube, 2.25 inches long.

(3) Maintaining airflow through honeycomb. Metal honeycomb is usually used to provide EM closure of open apertures required for ventilation and/or cooling, although screening and perforated metal sheets can also be used. These materials provide for air flow through an enclosure while maintaining the SE. All such materials present an impedance to airflow compared with an open aperture of the same dimensions. Of the types listed, honeycomb provides the maximum EM attenuation with the least reduction in air flow. Figures 5-24 and 5-25 compare air impedance properties for honeycomb and screen materials. If these types of materials are used, it is necessary to increase the overall aperture dimensions to achieve the same air flow as with an unprotected aperture.

5-7. Layered shields. When shielding is mainly by reflection loss (high frequencies), two or more layers of metal, separated by dielectric materials and yielding multiple reflections, will provide greater shielding than a single sheet of the same material and thickness. Separation of the two metal layers is necessary to provide additional discontinuous reflection surfaces. When two metallic sheets of the same material and thickness are separated by an air space, the penetration and reflection losses increase but are not double the value (in decibels) of a single sheet. Benefits of layered shielding also have been noted with magnetic sheet material. With high permeability metal, two layers of material increase the SE by roughly 15 decibels compared with a single layer over a fairly broad frequency range.

5-8. Reinforcement steel (rebar).

a. Concepts. Many buildings are built with walls reinforced with steel bars or wire mesh. This structural arrangement will provide limited shielding to low-frequency fields, but not to high-frequency fields, if the conductors are welded or otherwise electrically bonded together at all joints and intersections to form many continuous conducting loops or paths (mesh structure). Further, the rebar structure must be continuous around the volume to be shielded. The SE obtained is not cost-effective. If rebars are intersection-welded only to provide shielding, the other approaches discussed would be more cost-effective. If the rebars must be intersection-welded for structural support, limited shielding is obtained at no additional cost. In this case, the SE obtained is proportional to the magnitude of circulating currents induced by the impinging EM field in and about the four walls, floor, and ceiling of the structure. The degree of shielding depends on the size and shape of the volume to be shielded, the diameter of the bars and spacing (the distance between bar centers which determines aperture size), the electrical and magnetic properties of the reinforcement steel materials (conductivity and relative permeability), and the frequency of the incident wave due to the aperture size.

(1) Electrical assumptions. It is much simpler to calculate shielding obtained using reinforcement steel if electrical conductivity, permeability, diameter, and spacings are within a practical range associated with reinforcement steel (rebar) used for normal construction. The following discussion assumes a conductivity of $g_r = 6.5 \times 10^6$ mho per meter and a permeability of $u_r = 50$ which is typical of rebar. The frequency assumed in these calculations was 10 kilohertz.

(2) Reinforcement dimensions. The bars' diameter and spacing depend on the building's structural design. Typical bar diameters chosen for the following calculations range from 20 to 60 millimeters and spacings range from 9 to over 50 centimeters (table 5-17 lists some typical rebar sizes). Bar diameters can vary 10 percent from nominal values without seriously affecting the accuracy of shielding data calculations.

(3) Magnetic attenuation. The family of curves shown in figure 5-27 demonstrates the magnetic attenuation for an enclosure which is 5 meters high. The curves represent the center area attenuation. The other dimensions vary over a 5-to-1 range. Figure 5-28 shows the same information for a 10-meter enclosure height. Bar diameters are 4.3 centimeters with a spacing of 35 centimeters on centers. Provisions for determining decibel correction factors to these figures for other bar diameters and spacings are as follows, based on room proportions:

(a) Height of 10 meters or greater--use curves for 10 meters.

(b) Height between 5 and 10 meters--use curves for 5 meters.

(c) For variations in width dimension (J)--use curve equal to or just less than the required value.

(4) Double-course reinforcement. The room dimensions, bar spacing, and diameters shown in figure 5-27 are typical and cover most cases found in practice. The curves in figure 5-28 can also be applied to double-course reinforcing steel construction if the single-course spacings are halved when determining attenuation corrections for double-course bar construction. In

addition, table 5-17 lists examples of corrections to be used in various cases.

(5) Degradation of shielding effectiveness. The attenuation values obtained from figures 5-27 and 5-28 (with corrections as necessary according to fig 5-29) can be obtained at the center of the room. Less shielding will be available near the edges of the room. Figure 5-30 indicates that SE can be expected to degrade by 10 decibels at a distance of about 10 centimeters from the wall. The degradation curve is valid for room heights between 7.5 and 12.5 meters and lengths ranging from 12.5 to 100 meters. It is also suited for use with solid steel plate and wire mesh constructions that have the same type of SE degradation away from the central area.

(6) Sample calculations. The sample calculations in paragraphs b and c below show how the various curves are used. To determine the center area attenuation and the attenuation near a wall for single-course and double-course reinforcement bar-type construction, assume H = 6 meters, J = 10 meters, L = 50 meters, reinforcing steel diameter = 3.5 centimeters plus 10 percent, and reinforcement steel spacing = 37 centimeters, center to center.

b. Single-course reinforcing steel construction. Since H = 6 meters, use the curve for H = 5 meters (fig 5-27). For J = 10 meters and L = 50 meters, the attenuation is 24.5 decibels. For 3.5-centimeter-diameter rebars on 37-centimeter centers, use the correction factor of minus 2 decibels from figure 5-29. Thus, the center area attenuation is 24.5 - 2 = 22.5 decibels. This will be the attenuation in the room beyond 2 meters of the shielding rebars. Assume that the bars used are near the outside of the wall so that a 45-centimeter wall thickness is between the rebar and an equipment cabinet. The attenuation at this point (from fig 5-28) would be 22.5 - 3.5 = 19 decibels.

c. Double-course reinforcing steel construction. For this calculation, consider that center area attenuation = 24.5 decibels (from fig 5-27), 37-centimeter spacing, 3.5-centimeter diameter (read from curve F, fig 5-29); 19-centimeter spacing (for double steel) = 9.2 decibels, and the total attenuation = 33.7 decibels for double rebars. For equipment against the wall, assume the inner bars are 10 centimeters from an inside wall of the room. Figure 5-28 gives -10 decibels for this distance. The net shielding at this point is 33.7 - 10 = 23.7 decibels.

(1) Effect of bar size and spacing. Figure 5-31 shows the low-frequency SE for welded reinforcement steel as a function of frequency for different mesh sizes and reinforcement steel diameters. When compared with the data in figures 5-27 and 5-28, this figure suggests that decreasing the space between bars and increasing the bar diameter will increase the SE of reinforcement steel. Generally, decreasing the space between bars increases the attenuation a few decibels, whereas increasing it does the opposite. Increasing the diameter of the bars also increases the attenuation afforded by the walls, whereas decreasing the reinforcement bar diameter lowers the protection.

(2) Welding intersections and splices. To increase the reinforcement bar's SE, all intersections must be welded to insure minimum electrical resistance at the joints. Other mechanical tying or clamping should follow standard construction practices to insure mechanical strength, but this should not replace welding for electrical purposes. Figure 5-32 shows typical welding practice for construction steel reinforcement bars. Welding can reduce the rebar's strength to some degree. When possible, a continuous electrical loop must enclose the whole wall, with all rebars welded firmly to the loop at crossings and terminations. Unavoidable splices should be welded over a length at least three times the bars' diameter. Interruptions in the bars, as at vents or doors, should be welded to heavy frames as figure 5-33 shows.

(3) Welding at corners. Reinforcement steel can be formed into continuous loops welded together at the building corners (ref 5-7). For two layers of 10-millimeter reinforcement steel bars welded to 16-millimeter bars at the corners, a 15-millimeter grid gave 35 and 39 decibels at 150 kilohertz and 1 megahertz, respectively. A 25-millimeter grid gave 26 and 27 decibels at 150 kilohertz and 1 megahertz, respectively. When the openings become an appreciable part of a wavelength, the SE decreases.

(4) Welded wire fabric. Welded wire fabric embedded in the walls of a room or building can provide attenuation if individual fabric wires are joined to form a continuous electrical loop around the perimeter of the area to be shielded. At each seam where the mesh meets, each wire must be connected by a continuous strip.

(5) Attenuation from welded wire fabric. The attenuation at the center of the enclosed room for welded wire fabric can be obtained from the same set of curves used to find values for reinforcing steel bars. An attenuation correction factor (increment) will be needed (table 5-18).

5-9. Earth cover electromagnetic wave attenuation.

a. Absorption loss. In the environment outside a facility, nonmetallic materials such as soil and rock can contribute to shielding, especially at higher frequencies (i.e., above 10 megahertz). This depends on the material's conductivity, permittivity, and permeability. Since these materials are poor conductors, their conductivity is low and is influenced strongly by water content. Typically, the conductivity in mhos per meter over the frequency range in kilohertz to megahertz varies from 3×10^{-4} to 8×10^{-3} at 1 percent water content, from 8×10^{-3} to 3×10^{-2} at 10 percent water content, and from 10^{-1} to 1.5×10^{-1} at 50 percent water content; it is 2×10^{-1} at 100 percent water content (ref 5-5). Table 5-25 shows the electrical conductivity of various soils and rocks. Soils and rocks have a wide range of water content, making their electrical conductivities vary. Table 5-20 lists the absorption loss (A) for soils with 1, 10, and 50 percent water content at selected frequencies. Even for a soil water content of 50 percent, the absorption loss becomes significant only at frequencies higher than about 10 megahertz. Thus absorption loss in soil will be effective as a shield only at the higher HEMP frequencies (above 10 megahertz).

b. Reflection loss from soils. Determining the reflection loss from soils is a complex problem due to the inherent inhomogeneity of soil and rock strata. Typically, soil impedances are relatively high, and thus, for the plane wave electromagnetic fields from HEMP, reflection losses will be low. For conservative designs, the facility designer should assume no reflection loss for the soil and rock overburdens of buried facilities.

5-10. Shield joints and seams.

a. Shield fabrication. An ideal shielded enclosure would be one of seamless construction with no openings or discontinuities. However, practical enclosures must have seams to facilitate construction. Each seam represents a potential discontinuity in the shield, and the enclosure SE may be degraded if the seams are not designed properly. Optimal seam design through the use of permanent bonds (welding, brazing) makes joints continuous. For enclosures used in an inside environment, satisfactory results may be obtained with closely spaced rivets or spot welding or with RF gaskets if care is taken when preparing the mating surfaces and installing the fasteners. However, these techniques tend to form fasteners that degrade over time, so that welding probably provides the most cost-effective method in terms of life-cycle cost. Bolted or riveted shields are not recommended for use on facility exteriors. Shields must have structural support to prevent possible degradation of the seam by distortions. Free-standing shielded enclosures are available commercially and are suitable for use as individual enclosures inside a facility for equipment calibration and low-level shielding (up to 50 decibels). For an overall shield lining, the facility's structural design must incorporate and support the shield.

b. Seam bonding. Seams or openings in enclosure or compartment walls, with proper bonding, will provide a low impedance to RF currents flowing across the seam. For high-quality shielding (60 decibels and higher), mating surfaces of metallic members in an enclosure should be bonded together by welding, brazing, sweating, swagging, or other metal flow methods. To ensure that the bonding techniques are suitable and done correctly, design principles in paragraph 5-16 should be used. The most desirable bond is achieved through a continuous butt or lap weld.

(1) Metal thickness. For welded joints, the metal chosen must be thick enough for easy welding and it must not buckle under the welding heat. Welds in steel at butt joints should have full penetration, with the minimum thickness equivalent to 3-millimeter steel as shown in figure 5-34. For a facility shield, the recommended minimum thickness is usually 14 gauge. Metal-inert gas (MIG) welding should be used to ensure good electrical conductivity. Fillers used in welding should have conductivity and permeability equal to or better than those of the shield material.

(2) Mating surfaces. All mating surfaces must be cleaned before welding. Also, all protective coatings with a conductivity less than that of the metals being bonded must be removed from contact areas of the two mating surfaces before the bond connection is made. Mating surfaces should be bonded immediately after protective coatings are removed to prevent oxidation. Refinishing after bonding is acceptable from the standpoint of SE, but can lead to problems in detecting faults by visual inspection. Seam backup plates should be used for thin sheets (16 to 12 gauge). The plates must be held in place firmly before welding to prevent buckling.

(3) Soldering. Soldering is an acceptable way to join solid metal sheets for WBCs and other areas sensitive to the high temperatures of welding. Care must be taken during soldering because joint expansion can crack the connection. Also, fluxes in the solder process can cause corrosion later, which will degrade the bond. If soldering is the only suitable way to join screens, use only nonreactive or noncorrosive inorganic flux for electrical bonding.

c. Mechanical joining (shielding reqts below 60 decibels).

(1) Mechanical seams. Rather than welding or soldering seams, it is possible to join them mechanically. Bolts, screws, rivets, and various types of clamp and slide fasteners have been used for this purpose. The same general requirements for clean, intimate contact of mating surfaces and minimized electrolytic (cathodic) effects apply to temporary bonds. Positive locking mechanisms should be used to ensure consistent contact pressure over an extended time. Figure 5-35 shows some typical overlapping, bolted joints, all of which are acceptable when a 60-decibel or less SE is required. Pressures of 25 kilograms per linear centimeter are recommended for joint overlaps of 4 to 100 centimeters to maintain metal-to-metal contact (ref 5-7). This contact can be improved by galvanizing steel panels. For thin panels, bolts should be close enough to ensure uniform panel edge contact, with stiffeners running along the joint to spread forces and maintain high pressure between the bolts and to prevent buckling. If these methods are used for exterior shields exposed to weather, the seam must be weather-sealed to prevent corrosion.

(a) Bolts, nuts, screws, and washers that must be made of material different from the surfaces to be bonded should be higher in the electromotive series (table 5-21) than the surfaces. This measure ensures that material migration will erode only replaceable components.

(b) A critical factor in nonwelded mechanical joints is the linear spacing of the fasteners or spot welds. The gaps between fasteners are slots in the shield that leak incident energy. The data in figure 5-36 show that, for fastener spacings less than 65 centimeters and frequencies less than 100 megahertz, the coupled HEMP interference increases proportionally with frequency. Figure 5-37 shows the sensitivity of this parameter for a 1.27-