Electromagnetic Compatibility (EMC)

Topic 9

Shielding

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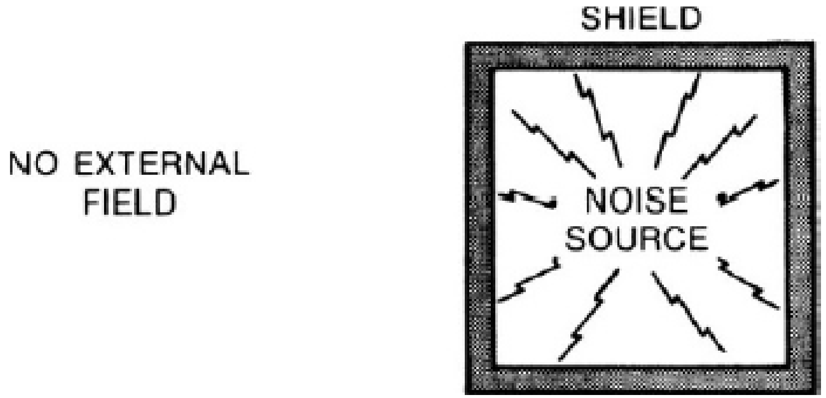
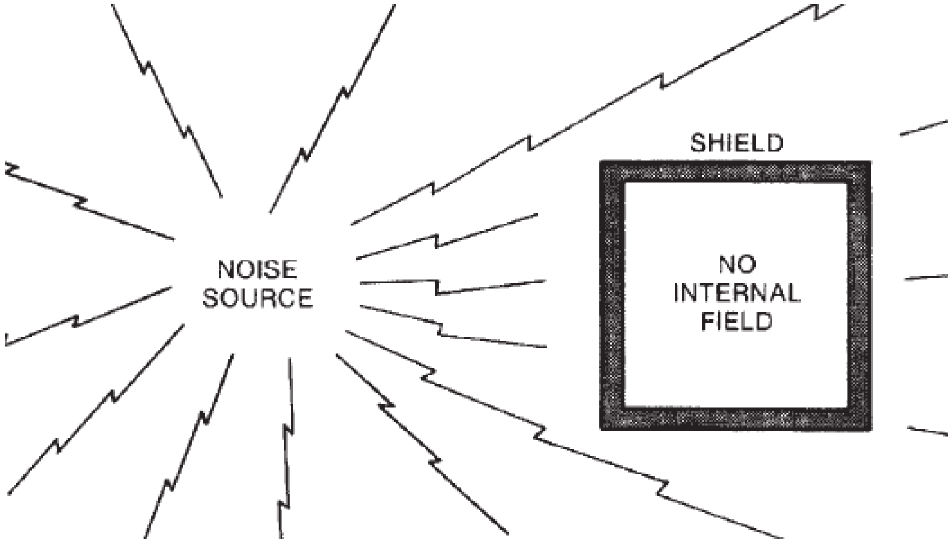
Introduction

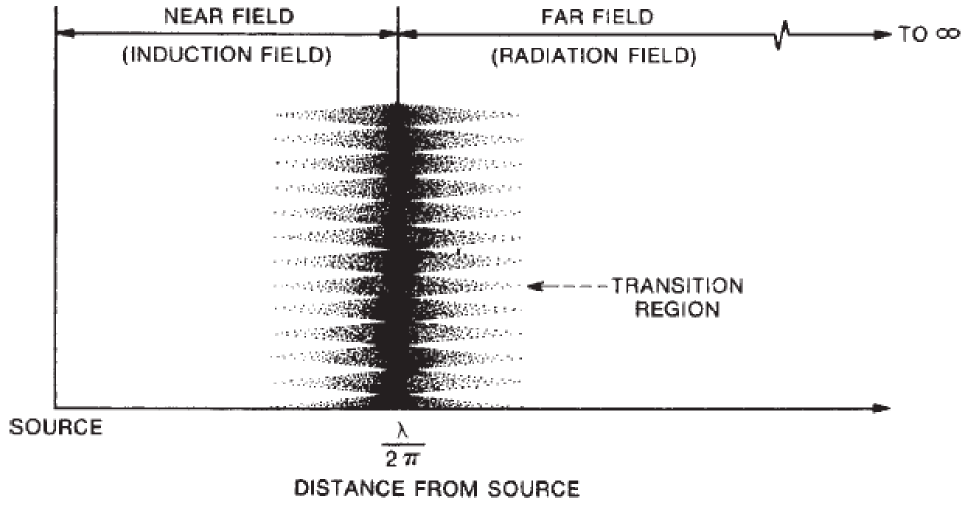
- A shield is a metallic partition separating two regions in space. It is used to control the electromagnetic (EM) wave propagation from one region to another.
- They can contain the fields within one region (to prevent radiation in space and keeps waves inside), or can prevent radiation (EM-waves) from affection the enclosed space inside.
- Noise voltages that might come for cables entering a shield should be filtered out and bonded to the enclosure to prevent noise from entering.
- We will discuss solid shields and their characteristics, then we will discuss practical shields and apertures along with their shielding effectiveness.

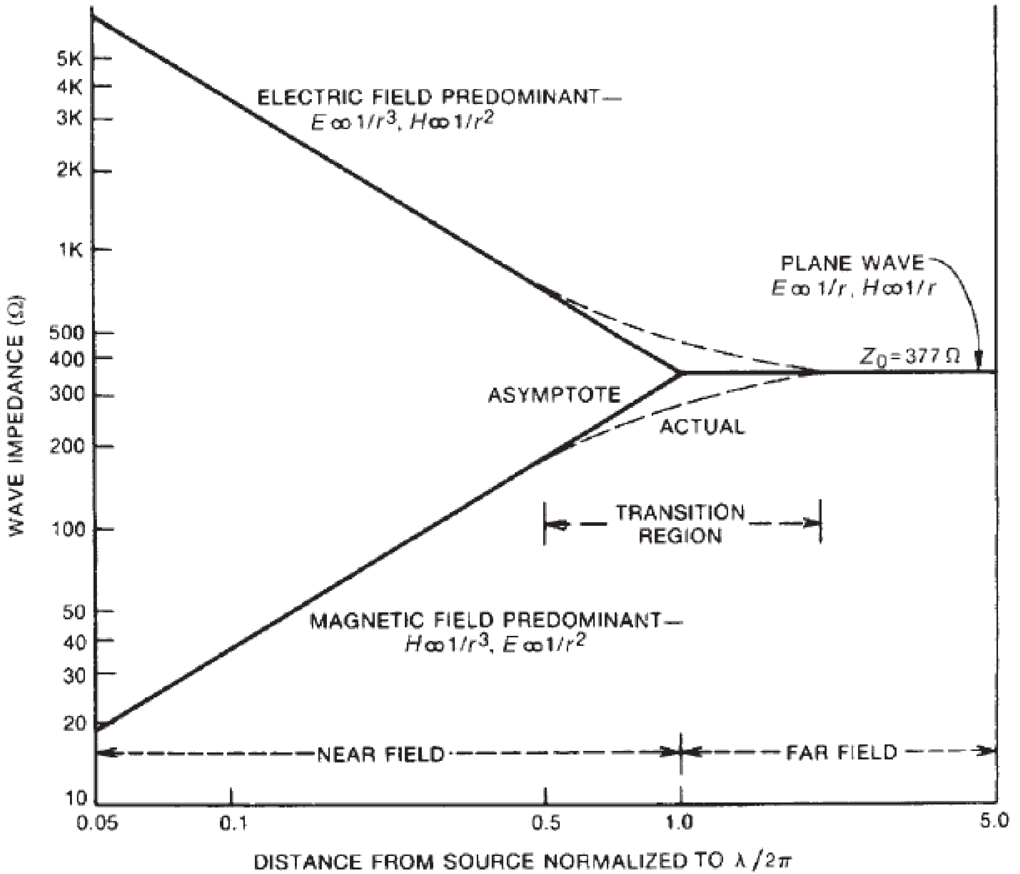




Near and Far fields

- Field characteristics depends on the source, the medium and the distance from the source and point of interest.
- If the point of interest is close to the source, the source characteristics control the field properties (near field - NF, d < $\lambda/2\pi$). Far from the source, the medium affects the properties of the fields (far fields – FF).
- The E-field to H-field ratio gives the wave impedance. In FF, $E/H = Z_0 = 377\Omega$.
- In NF, if source has high current and low voltage (loop antenna) E/H < 377Ω. If the source has low current and high voltage (wire antenna), E/H > 377Ω.
- As shown in Figure, the E and H-fields needs to be considered separately in the NF as their attenuation and characteristics are heavily dependent on distance (not constant ratio) until they asymptotically level to a ration of Z_0 beyond $\lambda/2\pi$





Wave impedance

- For any EM-wave, the wave impedance is defined as (Z_w):

$$Z_w = \frac{E}{H}$$

- The characteristic impedance of a medium is defined as (Z_0):

$$Z_0 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

- For a plane wave in the FF, $Z_w = Z_0$.
- For insulators, $\sigma << j\omega\varepsilon$, and Z_0 becomes independent of frequency, thus

$$Z_{0,insulator} = \sqrt{\frac{\mu}{\varepsilon}}$$

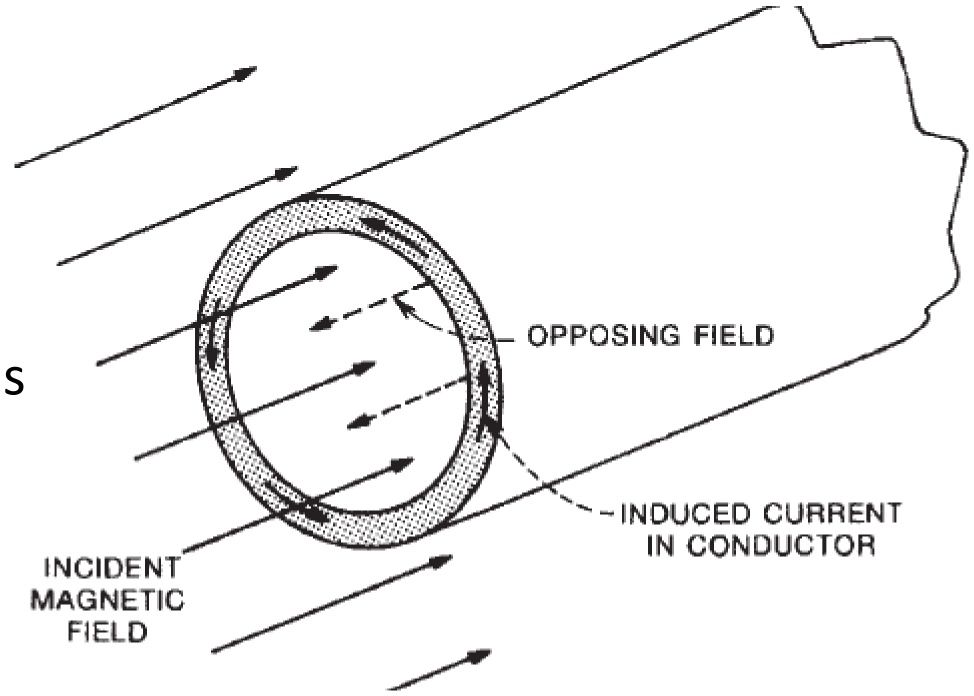
- For conductors, $\sigma >> j\omega\varepsilon$, and its shield impedance (Z_s) becomes,

$$Z_{0,conductor} = \sqrt{\frac{j\omega\mu}{\sigma}} = \sqrt{\frac{\omega\mu}{2\sigma}}(1 + j)$$

- Thus the characteristic impedance of the medium is dependent on the medium properties, and can be a complex value (magnitude and phase) in case of conducting media.
- A table of common material properties follows.
- For example, the Z_s of copper @ 1MHz is $3.68 \times 10^{-4}\ \Omega$

Material	Relative conductivity σ_r	Relative permeability μ_r
Silver	1.05	1
Copper—annealed	1.00	1
Gold	0.7	1
Chromium	0.664	1
Aluminum (soft)	0.61	1
Aluminum (tempered)	0.4	1
Zinc	0.32	1
Beryllium	0.28	1
Brass	0.26	1
Cadmium	0.23	1
Nickel	0.20	100
Bronze	0.18	1
Platinum	0.18	1
Magnesium alloy	0.17	1
Tin	0.15	1
Steel (SAE 1045)	0.10	1000
Lead	0.08	1
Monel	0.04	1
Conetic (1 kHz)	0.03	25,000
Mumetal (1 (kHz)	0.03	25,000
Stainless steel (Type 304)	0.02	500

Shielding effectiveness



- Shields will be analyzed by treating them as transmission lines with both loss (heat) and reflection (impedance mismatch). This was the method adopted by Schelkunoff (1943).
- Shielding can be used to reduce E or H fields (as we saw in the cabling section). We will describe it in dB units.
- For E-fields and H-fields, the shielding effectiveness (S) is given by:

$$S = 20\log_{10}\left(\frac{E_0}{E_1}\right) \quad , \quad S = 20\log_{10}\left(\frac{H_0}{H_1}\right)$$

Where E0/H0 are the incident fields, E1/H1 are the fields emerging from the shield (transmitted through for example)

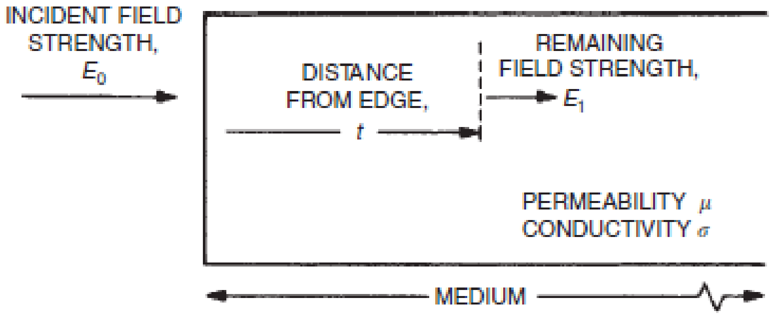
- Two considerations when designing shielding enclosures:
  (1) Shielding effectiveness of the material used
  (2) Shielding effectiveness of the discontinuities within the enclosure

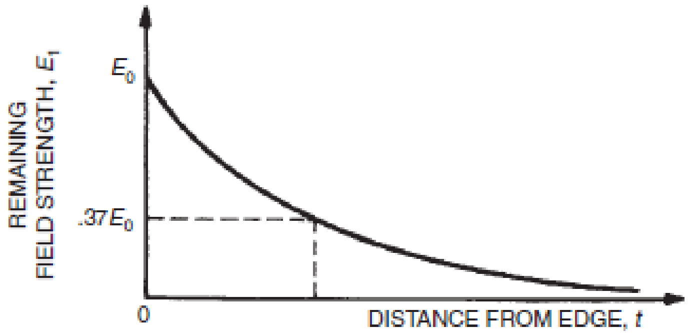
- The shielding effectiveness of the solid continuous shield is evaluated First with no holes or seams. Then, the effect of holes and other discontinuities are considered.
- At high frequencies, the holes, apertures and discontinuities will dominate the overall shielding effectiveness of the structures.
- Shielding effectiveness is a function of frequency, geometry, position, incident angle and polarization of the waves/fields.
- Two types of losses are observed when the EM wave impinges on a metallic surface:
  - Reflection loss
  - Transmission loss (absorption, or penetration loss)
- The total shielding effectiveness is given by:

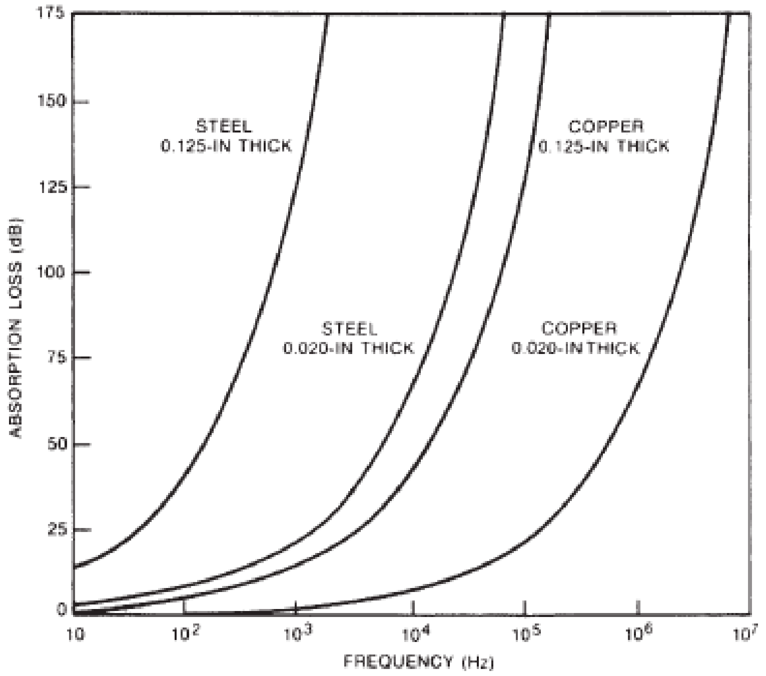
$$S = \underbrace{A}_{absorption-loss} + \underbrace{R}_{reflection-loss} + \underbrace{B}_{correcting-factor} \quad \mathrm{dB}$$

- Usually, R+B are the total reflection loss. We will ignore B if the fields are plane waves (in FF). If you are in NF, then check correcting factors.

Absorption losses







- When an EM-wave passes through a medium, its amplitude decreases exponentially because of the induced currents in the shield produce ohmic losses and heating.
- This decay in amplitude is a function of the skin depth (δ) and the distance from the edge (t)

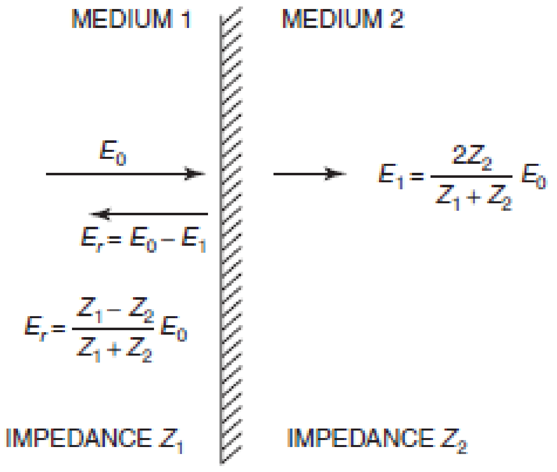
$$E_1 = E_0 e^{\frac{-t}{\delta}} \quad , \quad \mathrm{H}_1 = H_0 e^{\frac{-t}{\delta}} \qquad\qquad \delta = \sqrt{\frac{2}{\omega\mu\varepsilon}}$$

- Thus the absorption loss (**A**) becomes,

$$A = 20\log\left(\frac{E_0}{E_1}\right) = 20\log\left(e^{\frac{t}{\delta}}\right) = 20\left(\frac{t}{\delta}\right)\log(e) = 8.69\left(\frac{t}{\delta}\right) \text{ dB}$$

- Absorption after 1 skin depth thickness is about 9dB, for 2, we double it and so on.

Reflection losses



- The difference in media properties leads to differences in their impendences thus leading to reflection at the interfaces between two media
- EM Waves will follow the same behavior as we saw with voltage and current waves in transmission lines.
- At the interface, we have (check figure for H relations)

$$E_r = \Gamma E_0 = \frac{Z_1 - Z_2}{Z_1 + Z_2}E_0 \quad , \quad E_r = E_0 - E_1 \quad , \quad E_1 = \frac{2Z_2}{Z_1+Z_2}E_0$$

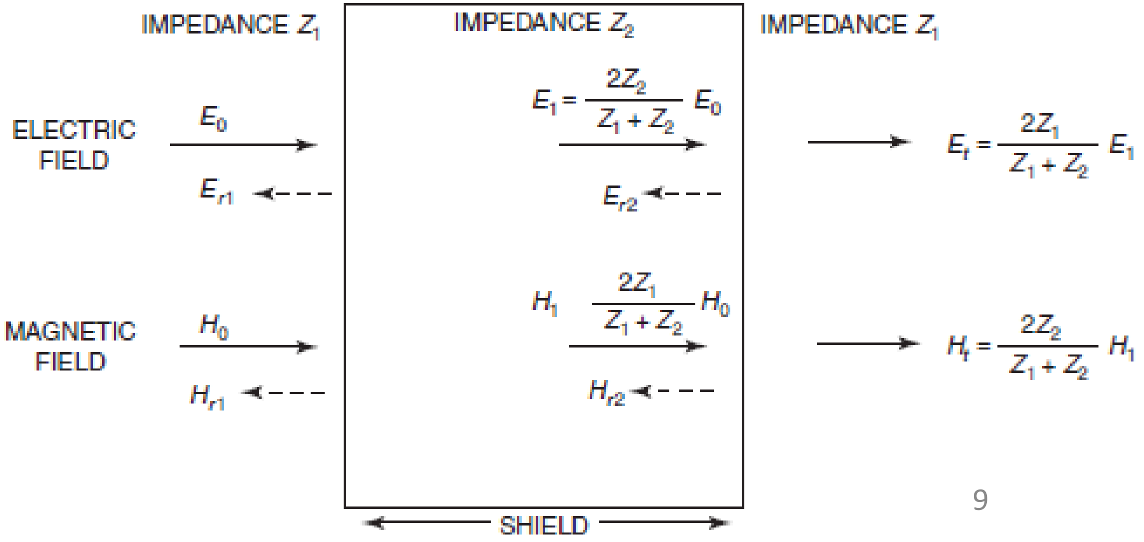
- When the wave passes through a shield, it passes two boundaries, thus we have

$$E_t = \frac{2Z_1}{Z_1+Z_2}E_1 \quad , \quad H_t = \frac{2Z_2}{Z_1+Z_2}H_1$$

- For thick shields,

$$\boxed{E_t = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}E_0 \quad , \quad H_t = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}H_0}$$

Same net effect!



- Note that even though the E and H fields are reflected differently at each interface, the net effect at the other side of the shield is the same for both fields.
- If we have a metallic shield with surrounding air, then $Z_1 >> Z_2$.
- Then, under this condition, the largest reflection (smallest transmission) of E-field happens at the first interface, while this happens at the second (exiting the metal) interface for the H-fields.
- If the protection is against E-fields, then a thin metal can do the job. For H-fields, more attention should be considered. Note that multiple reflections within the shield can degrade **S**
- When $Z_1 >> Z_2$,

$$E_t = \frac{4Z_2}{(Z_1)} E_0 \quad , \quad H_t = \frac{4Z_2}{(Z_1)} H_0$$

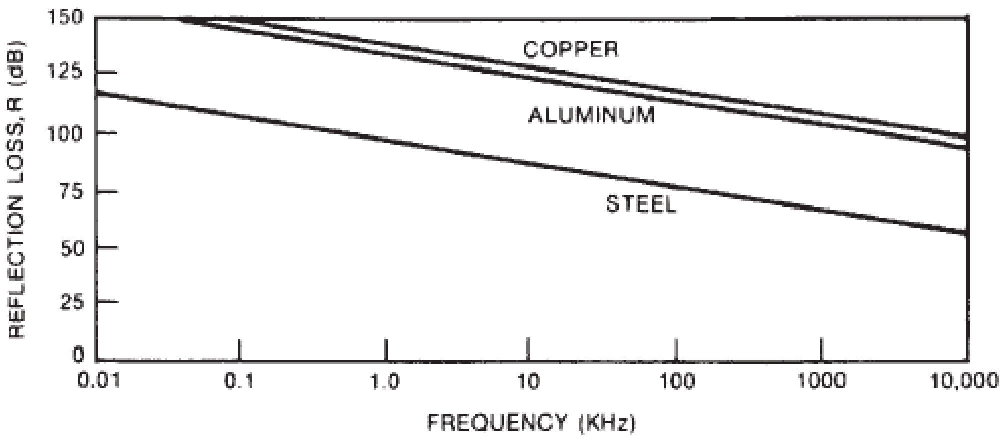
- substitute the wave impedance Z_w for Z_1 and the shield impedance Z_s for Z_2, we get,

$$\boxed{R = 20\log\frac{E_0}{E_t} = 20\log\frac{Z_1}{4Z_2} = 20\log\frac{|Z_w|}{4|Z_s|}}$$

- For a plane wave impinging on a metallic shield, Z0 = 377Ω , so,

$$R = 20\log\left(\frac{94.25}{|Z_s|}\right) \text{ dB}$$

- Thus, the lower the shield impedance, the greater the **R**.
- We can also write, $$R = 168 + 10\log\left(\frac{\sigma_r}{\mu_r f}\right) \text{ dB}$$

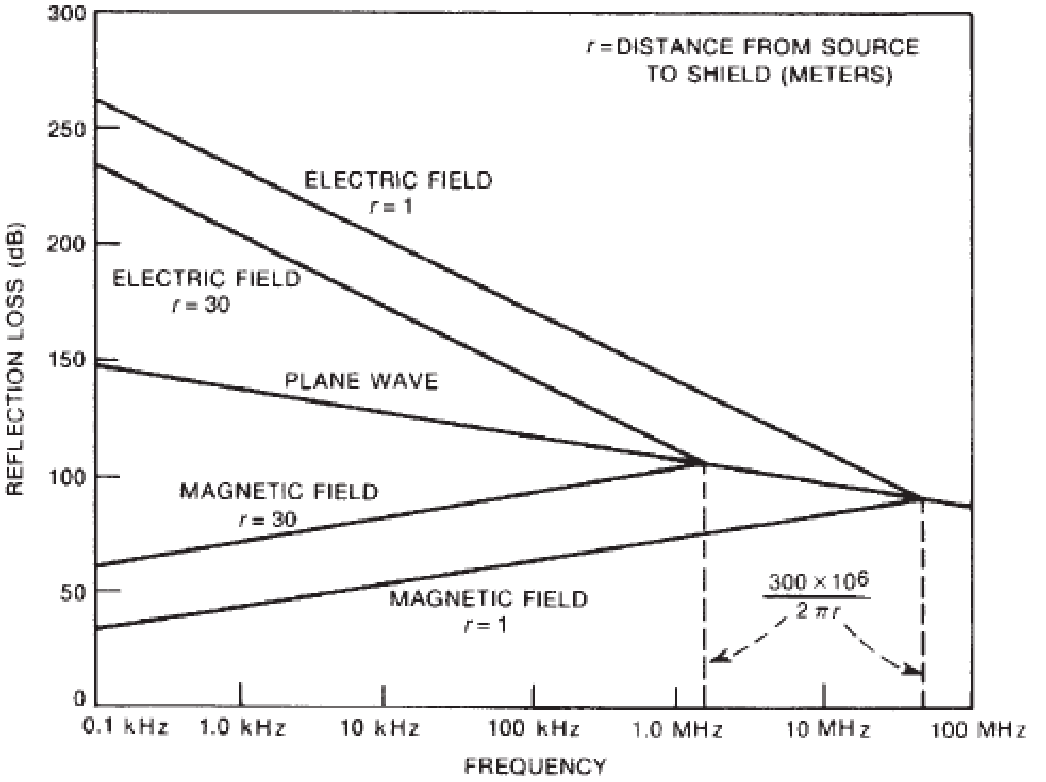


- In the NF, the ratio E/H is not a constant as in FF. So, the source type will determine if the wave impedance is > 377 or < 377Ω as indicated before. So, a high-impedance E-field has higher R than a plane wave, and a low-impedance H-field has lower R.
- Most practical sources have E and H components, so we need to evaluate their contributions for r < λ/2π.

$$|Z_w|_e = \frac{1}{2\pi f \varepsilon_r} \rightarrow \boxed{R_e = 20\log\left(\frac{1}{8\pi f \varepsilon_r |Z_s|}\right) \text{ dB}}$$

- And,

$$|Z_w|_m = 2\pi f \mu_r \rightarrow \boxed{R_m = 20\log\left(\frac{2\pi f \mu_r}{4|Z_s|}\right) \text{ dB}}$$

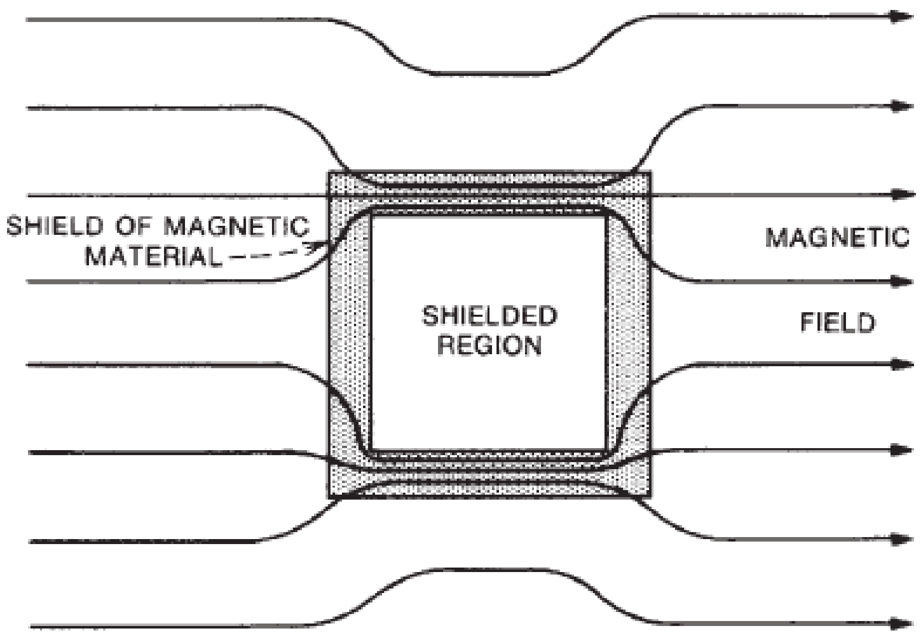


- In general, and neglecting multiple-reflections, we can write general expression for R, as,

$$\boxed{R = C + 10\log\left(\frac{\sigma_r}{\mu_r}\right)\left(\frac{1}{f^n \underbrace{r^m}_{distance-from-source}}\right)}$$

Type of Field	C	n	m
Electric field	322	3	2
Plane wave	168	1	0
Magnetic field	14.6	–1	–2

- For E-fields, **R** is the main shielding mechanism at low-frequencies, while **A** is the main one at higher ones.
- In the near fields, R is low for low-frequency H-fields. The main loss for H-fields is absorption loss. Still, at low-frequencies, **S** is small. It is therefore difficult to shield low frequency H-fields.
- We can improve S for low-frequency H-fields by using low reluctance magnetic shunt paths to divert the H-field around the circuit.

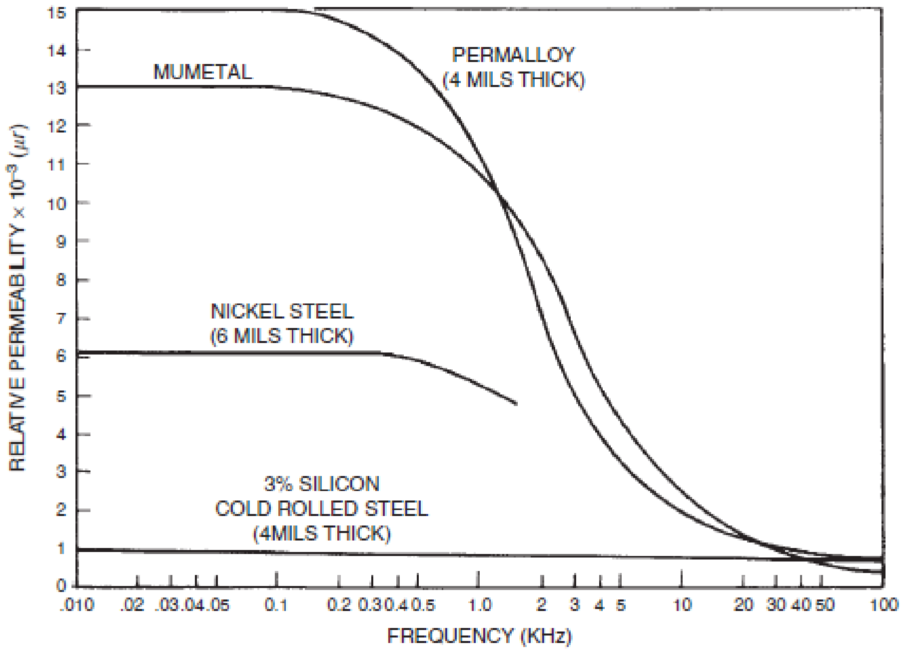


Shielding with Magnetic material

- When using a magnetic material, we will have an increase in μ and decrease in σ. This has the following consequences:
  (1) Absorption loss (A) is increased because the rate of increase of μ is higher in magnetic materials than the decrease in σ
  (2) Reflection loss (R) is decreased.
- In case of low-frequency H-fields, very little R occurs, while A is the primary shielding mechanism. Thus magnetic material is recommended.
- For low-frequency E-fields, or plane-waves, the main shielding mechanism is R, thus the use of a magnetic material will degrade S.
- Pay attention, when using magnetic material, always remember that:
  - μ decreases with frequency
  - μ depends on field strength
  - Machining may change magnetic properties

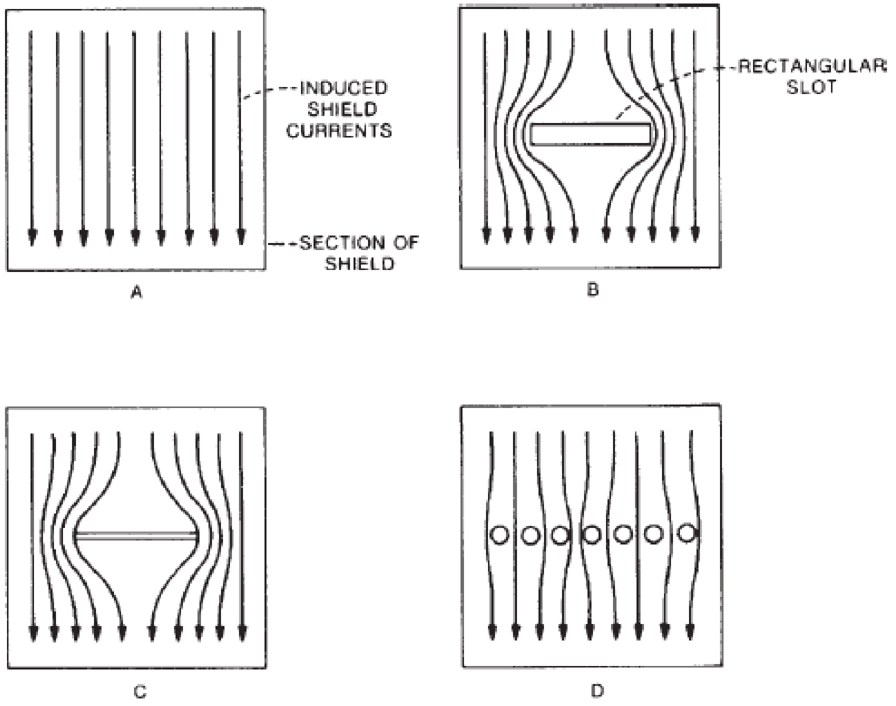
Relative Permeability of Steel versus Frequency

Frequency	Relative permeability, μ_r
100 Hz	1000
1 kHz	1000
10 kHz	1000
100 kHz	1000
1 MHz	700
10 MHz	500
100 MHz	100
1 GHz	50
1.5 GHz	10
10 GHz	1



Apertures

- Most shields are not solids, as there are doors, holes for cables, ventilation, switches, displays, joints and seams. All of these considerably reduce the shielding effectiveness of the shield.
- Leakage through apertures becomes even more problematic at high frequencies
- Apertures have more effect on H-fields compared to E-fields. Emphasis will be on H-field shielding improvement.
- The amount of leakage through an aperture depends on:
    (1) The maximum linear dimension, NOT AREA, of the aperture
    (2) The wave impedance of the EM wave
    (3) The frequency
- When an incident EM wave impinges on a shield, it induces current on it that will in return generate an opposite field that will reduce (cancel) the original one on the other side of the shield
- A slot in the shield will make a current disruption, thus reducing the opposing field generated, and reducing the shielding effectiveness.

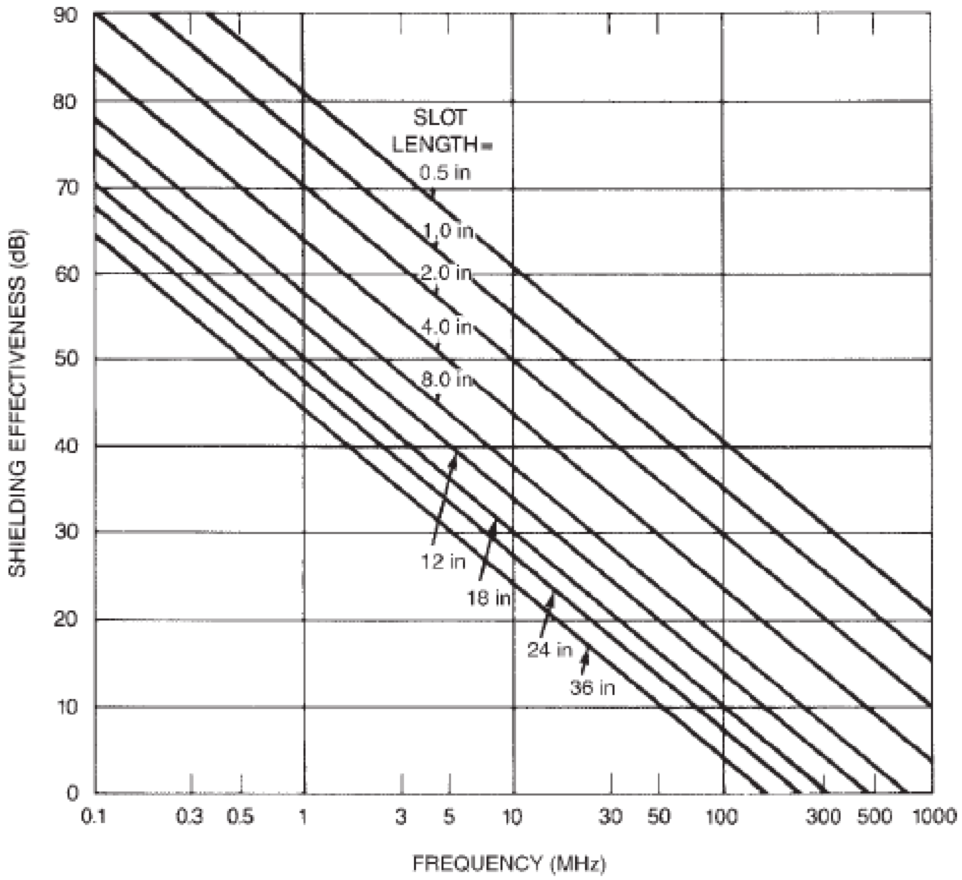


- Rectangular slots with length more than λ/10 can cause considerable leakage. Maximum radiation from a slot occurs at a length of λ/2.
- The shielding effectiveness of a slot with a length equal to or less than λ/2, is

$$S = 20\log\left(\frac{\lambda}{2\underbrace{l}_{\max-linear-length}}\right) = 20\log\left(\frac{150}{f_{MHz}l_{meters}}\right)$$

- Always try to have apertures NOT Exceeding λ/20, which will provide S = 20dB.
- Multiple apertures will reduce the S. This depends on:
    (1) Number of apertures
    (2) Frequency
    (3) Spacing between apertures
- For a **linear array** of closely spaced apertures, the reduction in S can be found using,

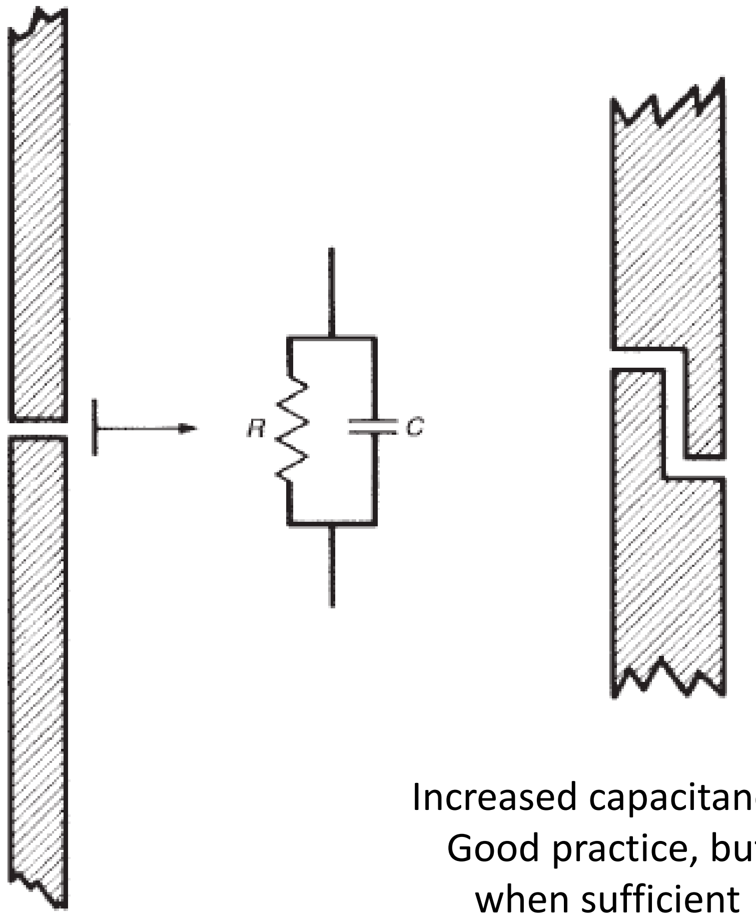
$$S = -20\log\sqrt{\underbrace{n}_{number-of-apertures}} = -10\log(n)$$



Reduction in Shielding Effectiveness Versus the Number of Apertures.

Number of Apertures	S (dB)	Number of Apertures	S (dB)
2	−3	20	−13
4	−6	30	−15
6	−8	40	−16
8	−9	50	−17
10	−10	100	−20

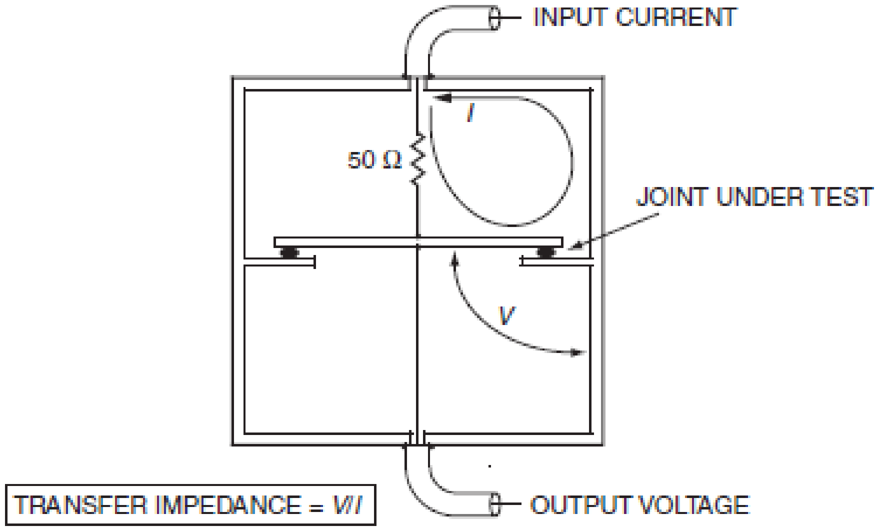
- A **seam** is a long narrow slot that may or may not make an electrical contact at various points along its length
- If the length of the seam approaches $\lambda/2$, then it will radiate. Thus make sure you increase the number of electrical contacts on a seam to reduce its length.
- Such multiple contacts can be via
  (1) Multiple fasteners
  (2) Contact buttons
  (3) Contact fingers
  (4) Conductive gaskets
- The transfer impedance of a seam should not exceed $5m\Omega$ over the frequency of operation and should not increase significantly with time or aging.
- The SAE standard ARP 1481 suggests $2.5m\Omega$
- Low contact resistance between two surfaces is a function of:
  - Having a conductive surface of finish
  - Providing adequate pressure
- Seam impedance can consist of resistive and capacitive elements



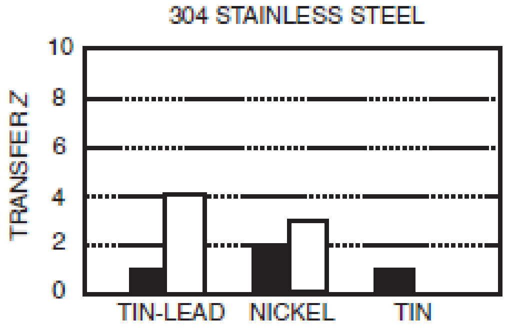
Increased capacitance, Good practice, but when sufficient pressure is applied between mating parts

- Measuring the shielding effectiveness of seams or joints is not easy to measure due to the complicated radiated mechanisms involved.
- A better, more reliable and repeatable method is to measure the quality of the electrical contact between mating parts of a shield via the measurement of its transfer impedance.
- The transfer impedance of a joint measures the voltage across it due to a known current flowing across it. The ratio between the voltage and the current is the **Transfer impedance**.
- S will be proportional to the inverse of the measured transfer impedance.
- The SAE ARP 1705 defines the shielding quality (good approximation of S) as the ratio of the incident wave impedance Z_w divided by the transfer impedance Z_T, thus,

$$S = 20\log\left(\frac{Z_w}{Z_T}\right) \quad , \text{ for a plane-wave } S = 20\log\left(\frac{377}{Z_T}\right)$$



Coaxial transfer impedance test fixture.



SCALE	TRANSFER IMPEDANCE
1	0.5–0.8 mΩ
2	0.8–1.6
3	1.6–2.8
4	2.8–5.0
5	5.0–8.9
6	8.9–15.8
7	15.8–28.1
8	28.1–50
9	50–158
10	>158

- We can have additional attenuation from the aperture if the opening is made with a depth to represent a **waveguide**.
- If the **waveguide cut-off frequency** is chosen to be higher than the frequencies of interest, all such frequencies will be attenuated as long as they are below the cut-off frequency of the waveguide.
- For a round or rectangular waveguides, the cut-off is

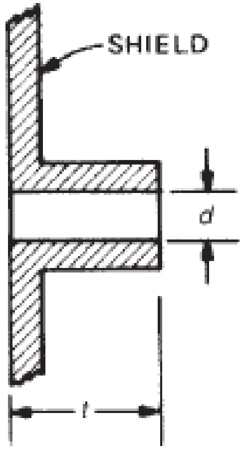
$$f_{c,round} = \frac{6.9\times10^9}{d} Hz \quad , \quad f_{c,rectangular} = \frac{5.9\times10^9}{l} Hz$$

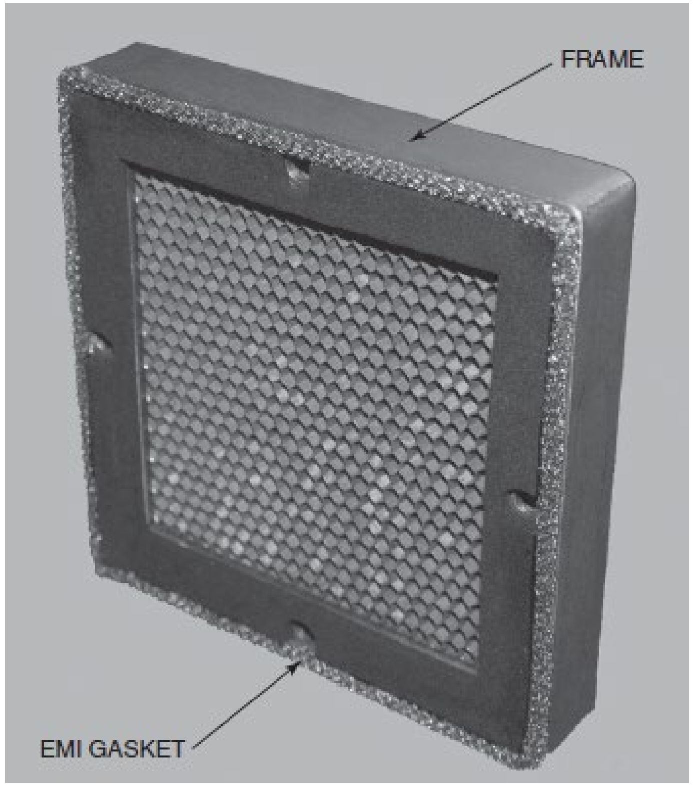
diameter (d) and length (l) are in inches.

- So, as long as the operating frequency is much less than the waveguide cut-off frequency, the magnetic field S for round and rectangular waveguides is

$$S_{round} = 32\frac{t}{d} \text{ dB} \quad , \quad S_{rectangular} = 27.2\frac{t}{l} \text{ dB}$$

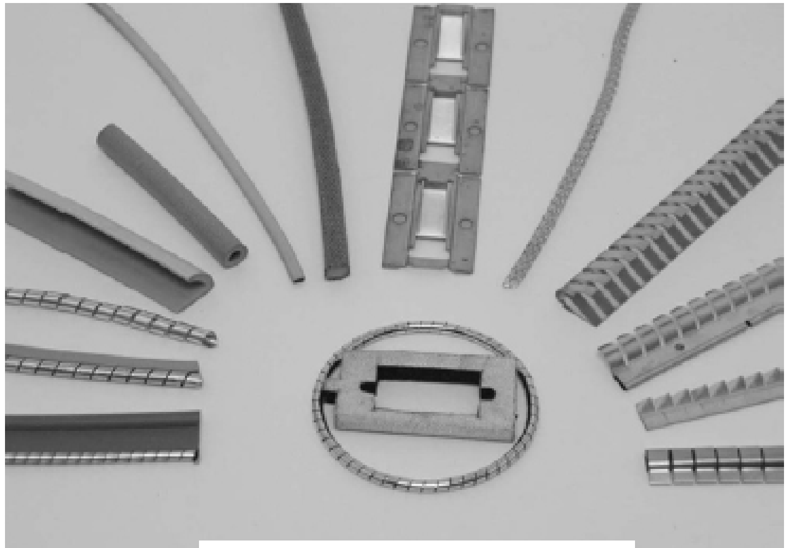
- These shielding values are in addition to the ones resulting from the aperture sizes (slide 15)
- Honeycomb EMI Gasket with 1/8 in. holes, and 1/2 in. thick, thus t/d=4, & S=128dB. (edges should be in good contact with chassis)



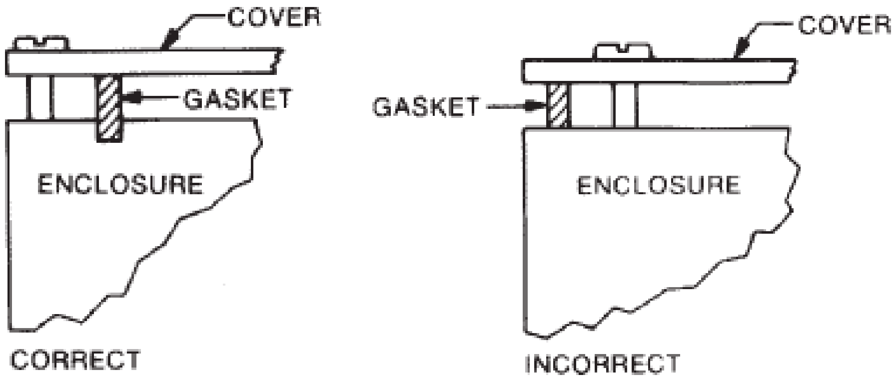


Conductive Gaskets and internal Shields

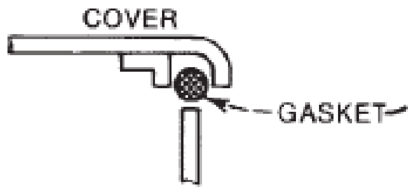
- An ideal shield is a conductive enclosure without any discontinueties or apertures (continuous), i.e. a Faraday cage.
- The main function of an EMI gasket is to provide a low-impedance conductive path between the two mating parts of a seam. The gasket with a proper surface finished enclosure will provide good electrical continuity between the mating parts, thus minimizing the joint impedance and increasing S.
- EMI gaskets can be in the form of wire meshes, metal spring fingers, spiral ribbons, wire knit, die cut, etc.
- Shielding can be done internal to the enclosure by shielding individual components or PCBs or sub-assemblies
- At the board level, a 5 sided shield can be designed to be placed on the top of a PCB where the 6th side is the ground plane. See example on slide 20.

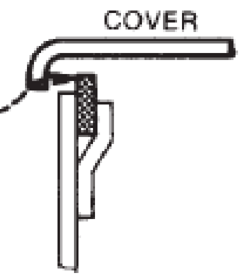


Various types of EMI gaskets.

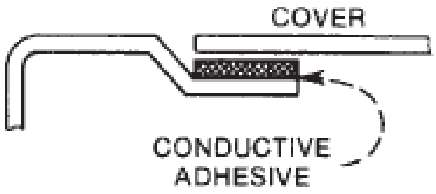


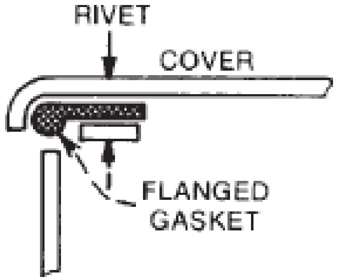
EMI gaskets, correct and incorrect installation.

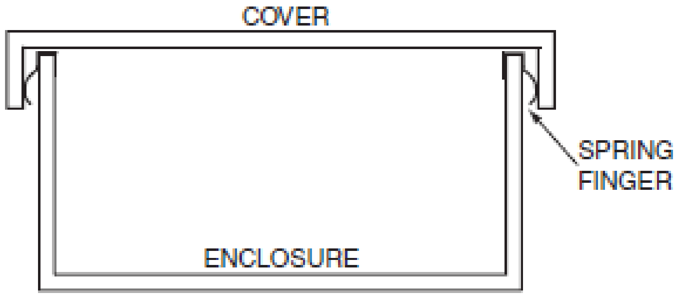


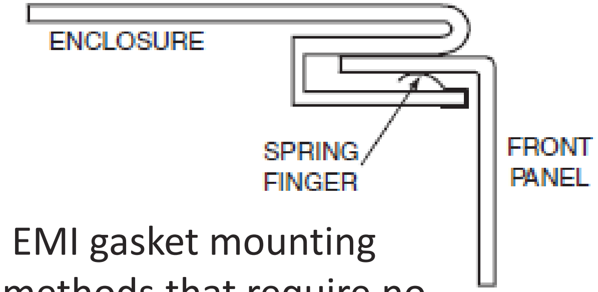


Suitable ways to install EMI gaskets in sheet metal enclosures

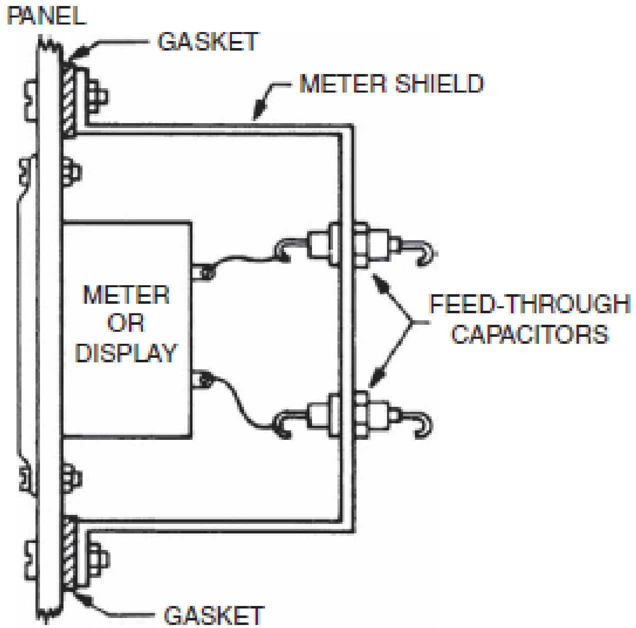




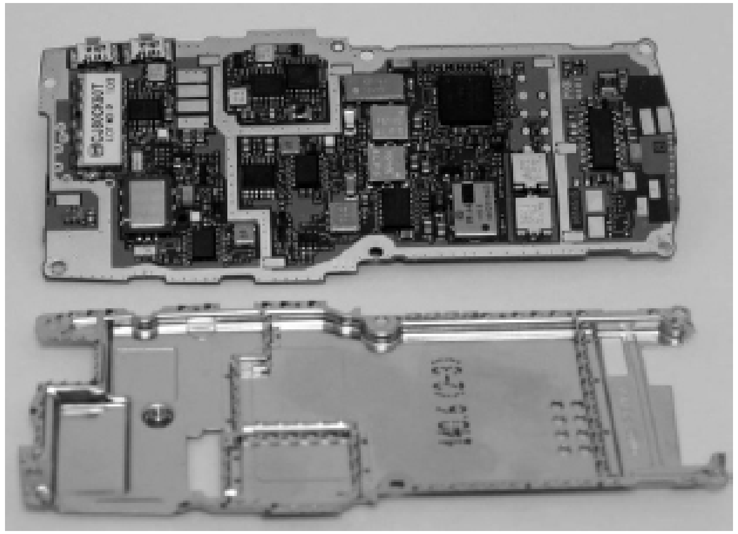




EMI gasket mounting methods that require no fasteners. Gasket is mounted in shear not compression



Method of mounting a meter or display in a shielded panel



← A PCB (top) with its board level shield (bottom).

Next time …

- More on Conducted Emissions …