When designing a system, you need to first consider the regulatory and RF environment where the system will operate. Many systems are designed that work well in the laboratory but fail in the field. During the more than 40 years that I have worked with EMC, I have come across overhead cranes that move while unattended, nuclear power plants that accidently shut down and even ATM machines that dispense money because of the RF environment. Years ago the Wall Street Journal discussed a major toy company’s FCC emission problems that prevented their product from being shipped into the U.S.

Problems also occur when you don’t consider EMC until the product’s final stage. Finding EMC (electromagnetic compatibility) problems at this late stage can often result in wasted time and money using hit-and-miss fixes. Inefficient components and techniques become part of the final product. These fixes add cost and weight to the product. Often, over design as well as under design is done because no thought was given to EMC at the beginning of the project.

In response to the many EMC problems I have seen in products that are either failing while in the field or that fail their compliance testing while in their final stages of design, I created a three-day EMC by Your Design Seminar (Ref. 1). My goal was to help digital and analog design engineers become aware of EMC pitfalls, and more importantly, techniques they can incorporate to minimize EMC problems. At the same time, engineers must not add to a product’s cost by overdesigning their product. In this article, I will cover one small section of the seminar: Enclosure design, an important part of a system’s overall EMC performance.

**Enclosure design**

Every product must meet regulatory and procurement specifications. These specifications will define the maximum emissions allowed from a system and the maximum interference the system must withstand while still functioning properly. Therefore, a product’s enclosure must reduce both the emissions leaving the product and the interference trying to enter the product. The amount of reduction of the radio waves passing through the surface is generally referred to as enclosure’s shielding effectiveness (SE).

Shielding is one of many ways you can control a system’s emissions and minimize immunity issues. If you plan to use an existing enclosure, then you must test a prototype to confirm it will comply as part of the new design. If you design a new enclosure, it must meet EMC emissions and immunity requirements in addition to meeting aesthetic, mechanical, and cost constraints. If the product will be sold only in the U.S., it generally won’t need immunity testing. Designing for both emissions and immunity up front will avoid the possibly of having to redesign the enclosure should the product later be sold in the European Union, which requires immunity testing.
**Determine shielding effectiveness**

When designing a new enclosure, you need to know the amount of attenuation (reduction of radio waves passing into or out of the enclosure) that is required. To do this, you need to know which regulatory requirements apply to your product: FCC, European Union, Military, RTCA, etc. In general, shielding for immunity for EU or susceptibility for Military/RTCA is more difficult than shielding for emissions only.

If you have no regulatory requirements available, you may possibly need to do a site survey. Before doing so, I would recommend reading the example of a site survey found in an old medical standard, MDS 201-0004 that defines the ambient conditions found in several medical environments. (Ref. 2).

If you have a prototype available, you can test it unshielded for immunity/susceptibility. If the circuit malfunctions when subjected to electric fields of 1 V/m and the device must pass at 10 V/m, you simply need more than $20 \log_{10}(10 \text{ V/1 V})$ or $>20$ dB of shielding. For emissions, an unshielded prototype can be computed or measured without cables. Knowing the regulation and the emissions, you can again determine the amount of shielding needed. You can estimate the amount of shielding needed by calculating the emissions from a design making a few assumptions. Enclosures seldom require shielding of more than 15 dB to 30 dB for civilian (FCC and EU) emissions/immunity applications. When designing products for the military or for commercial aviation, you need shielding effectiveness (SE) of 30 to 60 dB and perhaps more.

**Plane waves and electric fields**

Plane waves can be seen as either electric or magnetic since they are related by a constant, the impedance of free space, $377 \ \Omega$. Shielding is accomplished in primarily two ways: reflected loss (R) and absorption loss (A). There is a third loss related to multiple reflections but it is generally not much of a factor. Reflection loss is the loss when a wave strikes a surface (see $E_\text{a}$ in Figure 1) due to the impedance mismatch. This can easily be imagined when you realize the impedance of a plane wave ($Z_w$) is $377 \ \Omega$ and the impedance ($Z_s$) of most conductive surfaces is in the range of $<2 \ \Omega$.

Using the $2 \ \Omega$ and the following equation will give a reflected loss of about 33 dB of attenuation which is enough attenuation for most civilian applications, for both emissions and immunity.

$$SE = 20 \log_4 \frac{Z_w}{4Z_s} \ dB \Rightarrow 20 \log_4 \frac{377}{4\times2} = 33.5 \ dB$$
The other major contributor to shield attenuation is from absorption loss, which is the dissipation of the energy in the form of heat as the wave passes through the material (Figure 1). This loss is related to a material’s resistivity as well as its permeability (its magnetic characteristic).

The reflective loss falls off with increasing frequency; this is intuitive because impedance will generally increase with frequency. As can be seen in the equation above, if the impedance of the shield increases, the shielding effectiveness decreases. The good news is that absorption loss increases with frequency and the two complement each other such that across the entire frequency spectrum, any conductive material used as a shield and strong enough to stand by itself will provide enough shielding for almost all applications, including most military enclosures. (See Figure 2 where the minimum total shielding is >140 dB.)
Figure 2. A copper shield with a thickness of 0.02 in. has a total shielding effectiveness that’s the sum of absorption and reflection.

An ideal shield would be a continuous, metal container with no apertures (penetrations) (Ref. 3). Practical shields require penetrations and are generally not made with continuous bonding between various parts of the cabinet.

Reflective loss can also be from conductive coatings. The coating can be made using paint, loaded with conductive material such as silver, nickel, copper and even silver-plated carriers. Some manufacturers use graphite but I do not recommend it because you can’t get good surface resistivity and thus not enough attenuation.

The resistance characteristic of the coating is measured using a concept called “Ohms per square.” This concept is developed in Figure 3. The size of the conductive film does not matter as long as it is square (equal length sides). This concept will be examined using a single resistor versus using four resistors. The single resistor is 2 Ω and the square is 1 in. by 1 in.. The four resistors are represented by a square 2 in. by 2 in. This 2 in. square is made up of four 1 in. squares. If two 1 inch squares are put in parallel, the total resistance is 1 Ω. Two 1-Ω resistors in series result in 2 Ω. Therefore, a 1 in. square with a resistance of 2 Ω has the same value as a 2 inch square with a resistance of 2 Ω. To use the formal concept of Ohm per square would require the film to be cut into a square rectangle, damaging the material.
Figure 3. The sample on the left is made up of a single 1-in. square which is represented by the resistor R. The sample on the right is made up of four of these 1-in. squares represented by four resistors (R) with two groups of two R’s in parallel and placed in series.

However, when I make the measurement, I don’t use a perfect square. I simply use two pennies as seen in Figure 4. I measure the resistance and expect to see < 2 Ω. Using this modified 2 Ohms per square, even though it does not meet the strictest definition, will assure about 33 dB of attenuation. The two pennies prevent breaking through any surface film, which would prevent contact with another surface when joining two sections of an enclosure. When using a conductive coating, make sure the surfaces have a smooth transition because tight corners can develop turbulence during spraying, causing a high resistance surface to develop. When checking for quality on this type of enclosure, be sure to place pennies on opposite sides of a rib, a corner, or a transition.

Figure 4. A two-penny test fixture measures less than 2 Ω.

Conductive plastics are offered today as an alternative to non-conductive plastics. They need to be
used with caution. First of all, they’re difficult to use. The conductivity of the plastic is associated with the aspect ratio of the conductive fill, the volume fraction and the conductivity of the material. The larger the aspect ratio, the better the conductivity but the harder the material is to use. One problem with fills is it changes the shrinkage of the plastic which can require new tooling. Another problem is that a resin rich surface tends to form which makes it difficult to bond two surfaces together.

**Magnetic shielding**

For low-frequency magnetic fields, use metals with magnetic properties. Magnetic shield is typically accomplished by shunting the fields away from the problem area. I was once called to an office building where a video monitor was being exposed to about 1000 mG of 60 Hz flux. We ended up putting Mu metal on the wall and floor as well as adding a special enclosure for the monitor. The walls and floor reduced the field to about 50 mG and the special enclosure reduced it to about 6 MG. See Figure 5.

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**Figure 5. Mu Metal on a wall shields a monitor from a source of magnetic flux.**

**Making the enclosure**

Figure 6 shows that even a practical box is far from ideal because it’s built from multiple pieces that may need continuous bonding. Besides these discontinuities, the box has yet to have penetrations for cables entering or leaving the enclosure, an air vent for cooling, and possibly viewing apertures.
Figure 6. In this practical, but not ideal box, holes are still needed for air in, heat out, viewing displays, power in, signals in/out, controls, Shafts, etc.

Figure 7 shows how apertures are generally the biggest source of uncontrolled energy leaving or entering an enclosure. Figure 7A shows that with no aperture, the current in the shield is uniform. In Figure 7B and 7C, an aperture distorts the current flow and thus creates a voltage drop across the slot, which can cause energy to pass through it. The distortion is virtually the same in both parts B and C because the maximum dimension, which is the diagonal distance from one corner of the aperture to the other, determines the leakage. The area of the opening doesn’t determine the leakage. Figure 7D shows that multiple openings, because of the more uniform current, create less voltage drop than across a single, larger gap. That results in less energy passing through the shield. Figure 7E stresses the point that it’s the maximum dimension of the opening that matters most.

**Effect of shield discontinuity on magnetically induced shield current.**

(A) Uniform current flow  
(B) Distorted current flow  
(C) Distorted current flow  
(D) Smoother current flow

Henry Ott, Electromagnetic Compatibility Engineering, Wiley 2009 - Used by permission

Figure 7. The maximum dimension of an opening in a shield determines how much energy can pass through.

It is the maximum dimension of the slot, not the area, that determines the field that passes through. One of the ways to reduce the slot size when bringing two pieces of material together is to use
gasket material. Figure 8 shows how gasketing comes in many different styles and some even require special consideration be made when constructing the enclosure.

Figure 8. Gaskets can reduce slot size, thus reducing the amount of energy that passes through the enclosure.

Conductive tape is often used to cover a seam, especially while testing. This helps to determine the locations of exiting or entering fields. It is generally best not to use conductive tape in production, except in special cases, because of its cost and its short lifetime. Figure 9 shows a conductive window which is transparent. Notice the edges on the right and the bottom require bonding to the enclosure.

Figure 9. Conductive window used for shielding against unwanted signals.
Cables are another major source of energy leaving or entering an enclosure. There are multiple ways that you can handle this problem.

1. Add a properly terminated shield on the cable (Ref 4).

2. Filter of the leads to remove any energy trying to enter or leave through the cable (Ref. 5).

3. Add ferrites to increase the common mode impedance of the cable.

4. Place wires properly. **Figure 10** shows the use of a commercial power line filter which can be an expensive addition. Its effect can be completely nullified by improper lead dress, as is seen in the top photo, where the noisy wires are coupled to the quiet wires by routing the wires in the same harness. In the bottom photo, by keeping the input and output of the filter separate from each other, the filter can function as it was designed.

### Use Filters to Remove Noise

Be careful about re-coupling noise. This is the most common mistake seen with power line filters.

![Wrong Wiring](image1)

![Correct Wiring](image2)

**Figure 10.** Running wires from a noisy side along with those from the filtered side can cause energy to couple into the filtered wires, thus nullifying the filter.

After the best techniques have been implemented on the internal circuit boards and wiring, the equipment housing becomes the final barrier. As previously mentioned, low frequency magnetic fields are harder to shield against than electric fields or plane waves. For magnetic shielding it is best to use a thick magnetic material.

Use a good conducting shield for electric fields, plane waves, and high-frequency magnetic fields. This good conductor gives maximum reflection loss. For almost all applications, any solid shield thick enough to be made into an enclosure will supply adequate absorption loss, giving a total attenuation sufficient for most applications.

### Conclusion

In general, shielding effectiveness is determined by seams and joints, not the material. Maximum dimension of an opening (not area) determines leakage. A large number of small holes is much better than a single larger hole. Until the last hole is treated, the best metal box might appear
When designing a metal housing “all” metal parts need to be well bonded. Avoid long seams and slots. Often finger stock or gaskets are needed to bond the metal section of an enclosure together. After the enclosure is designed, the shield integrity may need to be restored at cooling holes, viewing apertures and component holes. A honey comb filter can be used to prevent leakage from openings such as air vents and a conductive window can be added for viewing.

When designing using plastic, make sure the conductive coating is < 2 Ω /☐, and then treat the enclosure like a metal box, provided the surfaces can be bonded. Remember, use two pennies and an Ohm meter to check its quality.

Be sure to filter or treat all cables entering or leaving an enclosure. The treatment might include filtering, ferrites and/or shielded cables properly terminated.

At higher frequencies, small gaps may need to be closed between contact points with RF gaskets or finger stock. Remember a good enclosure for emissions is also a good enclosure for immunity. Reciprocity holds here. Be sure to test a prototype for EMC as soon as practical. TMW

References
1. EMC by Your Design three-day seminar, October 23-25, 2012, Northbrook, IL by Donald L. Sweeney and Roger Swanberg covers many ways to reduce EMI in addition to enclosure design. www.dlsemc.com/emcseminar.
4. Properly terminated is discussed in depth in the cable section of the EMC by Your Design Seminar and also in Mitigating Excessive Emissions dlsemc.com/tm-0812.
5. Filtering of the leads is a major topic, which is covered in depth in the EMC by Your Design Seminar.

Acknowledgements

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