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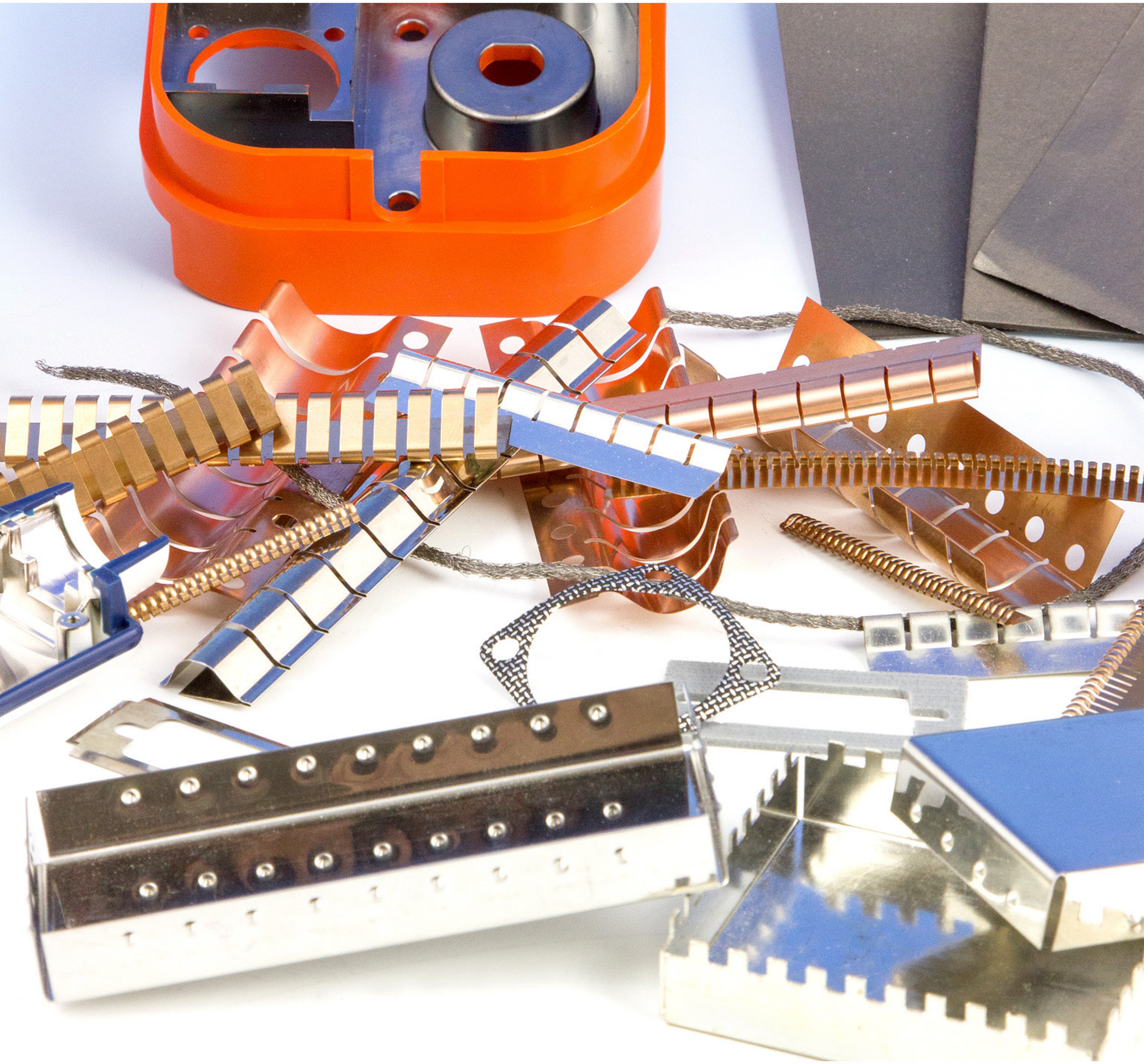
2017 EMI SHIELDING GUIDE



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INTRODUCTION

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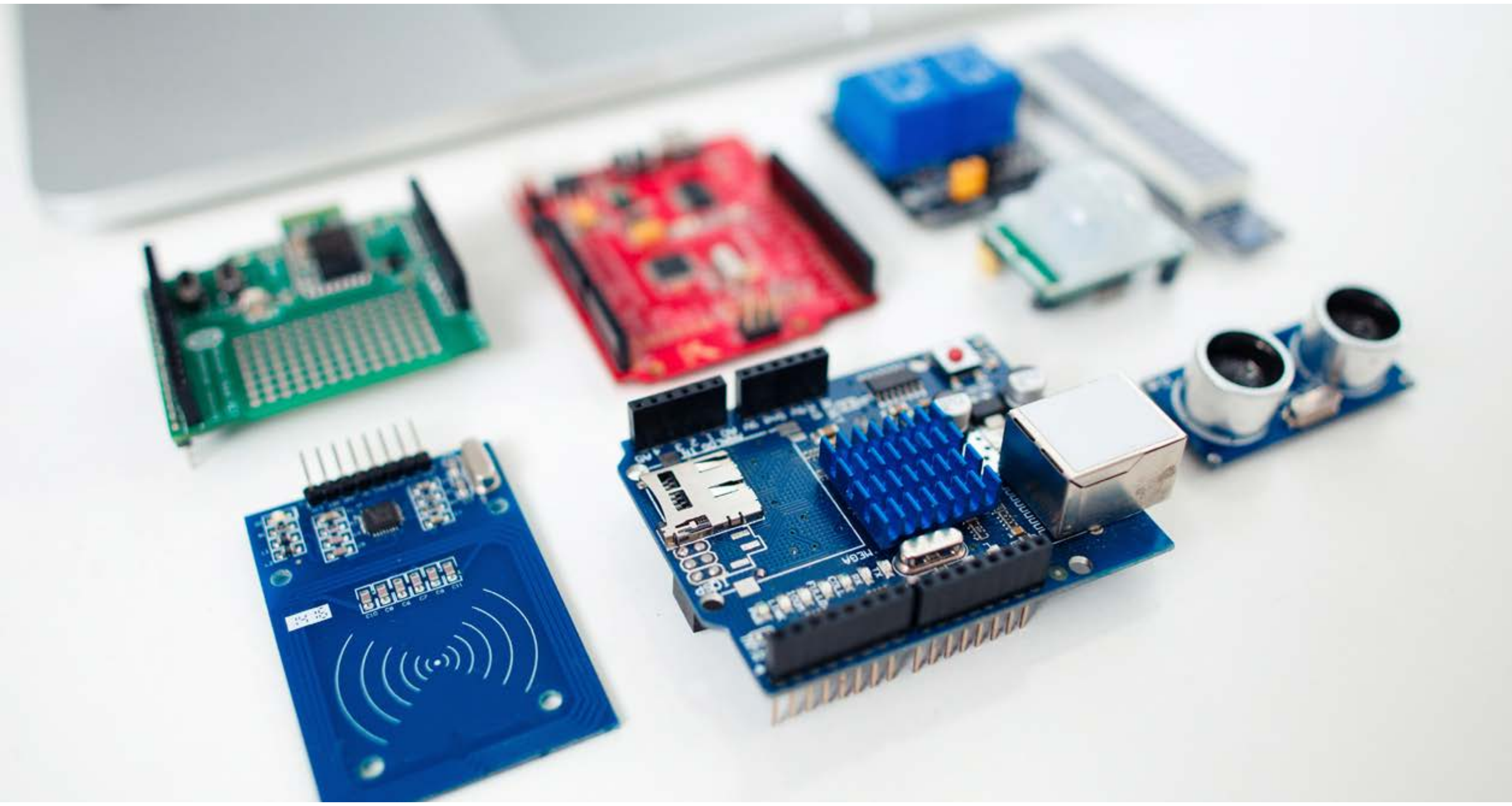
EMI shields are usually the last line of defense against EMI; both emitting from a product or system, or protecting against susceptibility of that same product or system. EMI shields come in all shapes and sizes, from large shielded rooms, to small board-level shields used for small wireless devices.

This year, we're adding an article on simulating electromagnetic shielding for aeronautical applications. George Kunkel returns with his near field shielding calculations based on circuit theory. Because the shielded enclosure for most smaller products is within the near field at most frequencies of concern - whether it be E- or H-fields, his calculations track well with the results from simple shielding effectiveness testing with near field probes - a new article from yours truly.

There are a couple articles on selecting and applying EMI gaskets and specifying and designing board level shields - a topic that is becoming much more important for mobile wireless devices.

As ever, this shielding guide also includes several new references and a chart of suppliers. I hope this information will be helpful to you this year!



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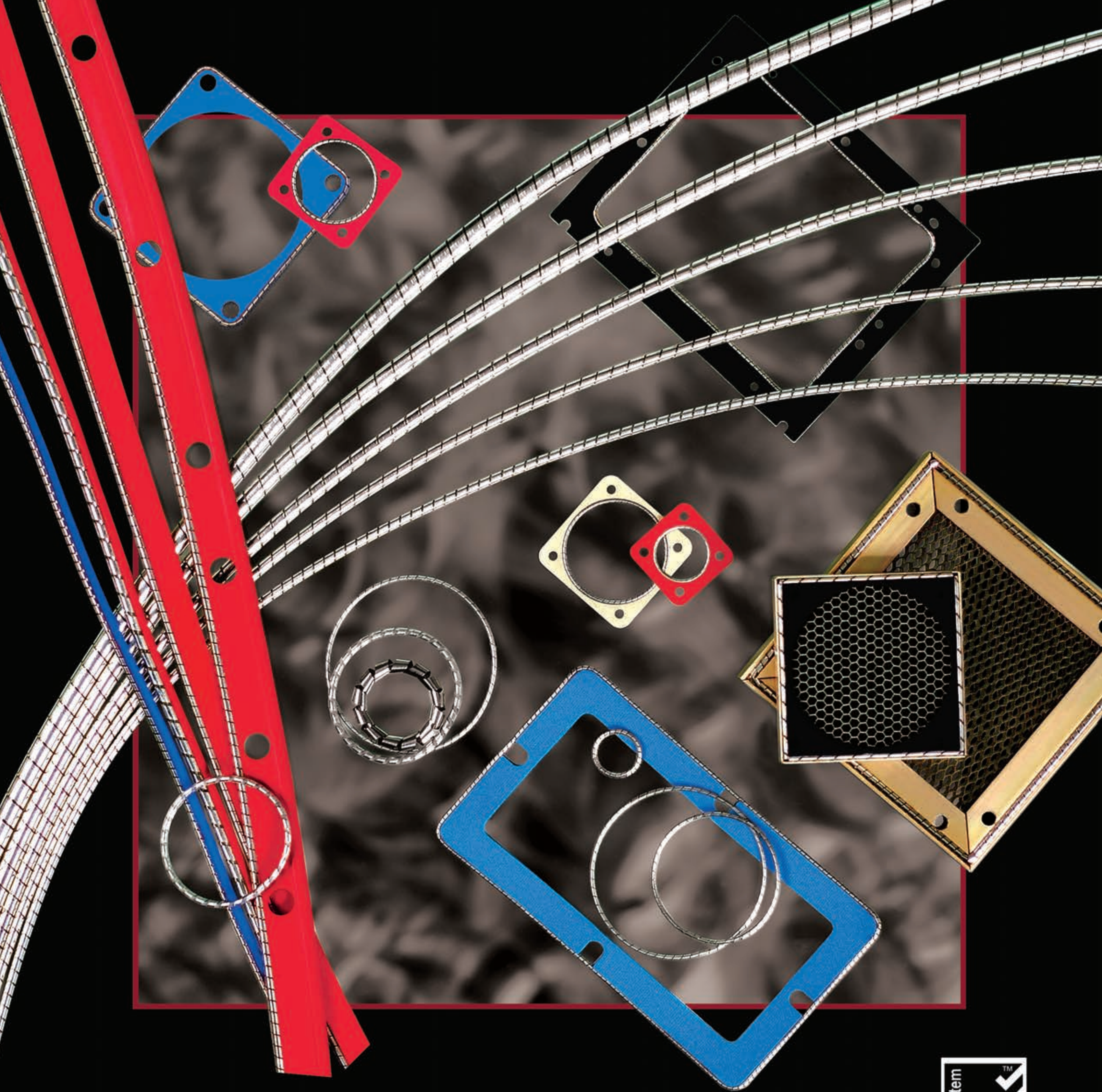
www.emc2017online.emcss.org

SHIELDING MANUFACTURERS GUIDE

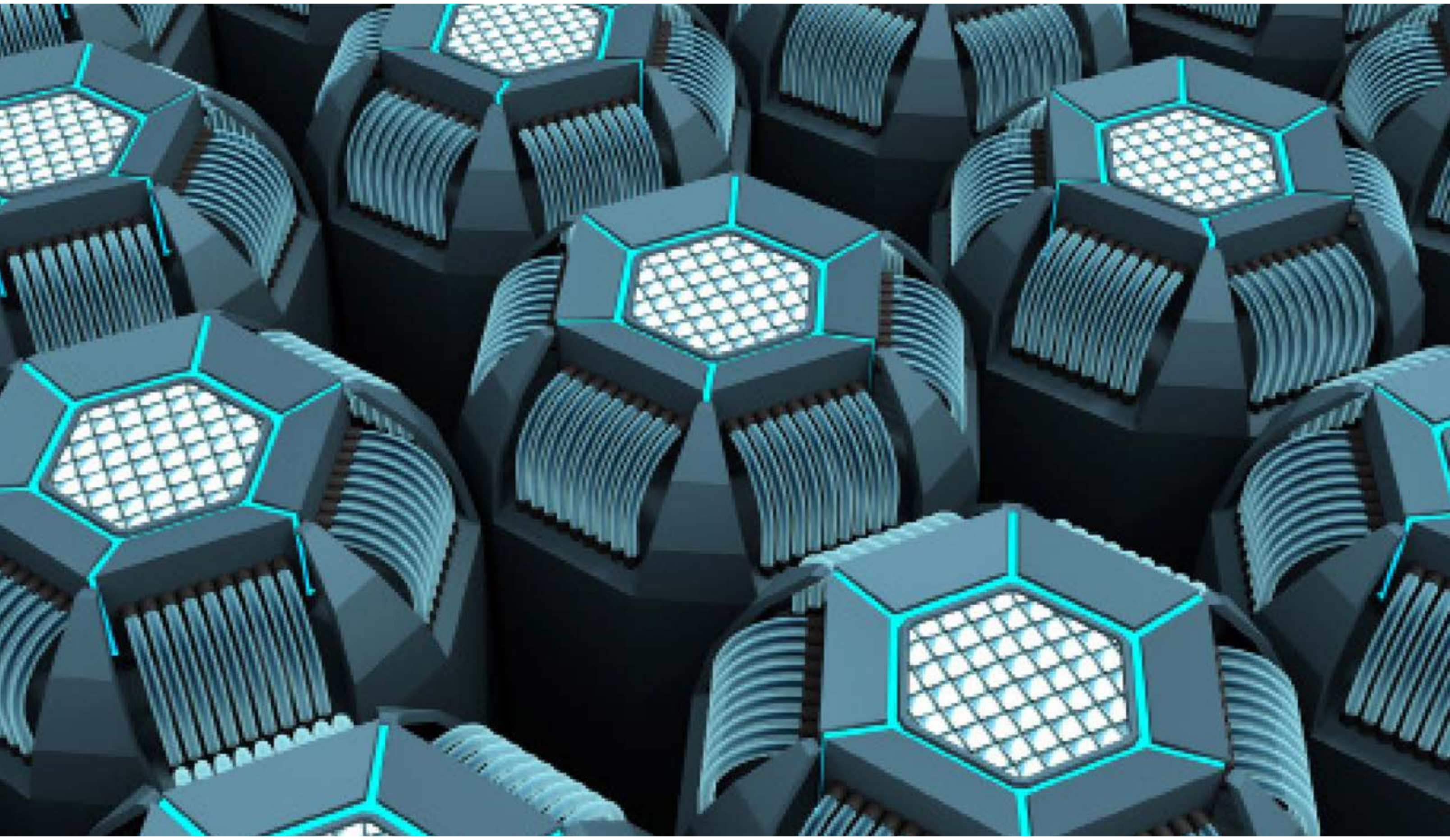
A Guide to Suppliers of EMI Shielding
Your quick reference guide to shielding manufacturers by shielding type, from absorbers to vent panels. Also includes popular gasketing materials such as silicon, form-in-place, finger stock, and various types of board level shields. Contact links are included for convenience.

Shielding Manufacturers Guide		Type of Shielding Available																									
Manufacturer	Contact Information - URL	Absorbers	Adhesives	Board Level Shields	Cable Shielding	Conductive Coatings	Coil Springs	Elastomers	Electroless Plating	Fabric over Foam	Ferrites	Fingerstock	Foams	Form in Place	Gaskets	Grease	Grounding Components	Honeycomb Filters	Knitted Wire Mesh	Laminates	Metallized Fabric	High Mu Materials	Sealants	Silicone Elastomers	Tapes	Vent Panels	Windows
3M	www.3m.com	X																							X		
Alco Technologies	www.alcotech.com				X										X				X							X	
ARC Technologies	arc-tech.com	X																									
Bal Seal Engineering Inc.	www.balseal.com						X																				
Fotofab	www.fotofab.com			X					X																		
Ja-Bar Silicone Corp.	ja-bar.com							X																	X	X	
Kemet	www.kemet.com										X																
Kemtron	www.kemtron.co.uk	X		X				X		X	X	X		X						X					X	X	X
Kitagawa Industries America, Inc.	kgs-ind.com	X			X						X				X		X								X		
Laird Technologies	www.lairdtech.com	X	X	X				X		X	X	X		X	X				X	X					X	X	
Leader Tech	leadertechinc.com	X		X	X			X		X	X	X	X	X	X		X	X	X		X	X		X	X	X	
Magnetic Shield Corp.	www.magnetic-shield.com				X																	X					
MAJR Products	majr.com	X		X				X		X	X	X		X	X					X					X	X	X
MAST Technologies	www.masttechnologies.com	X																									
Metal Textile Corp.	www.metexcorp.com	X						X		X		X			X										X	X	X
Nolato Silikonteknik	www.nolato.com					X		X						X	X		X							X			
Orbel	www.orbel.com			X								X									X						
Parker/Chomerics	www.chomerics.com	X	X	X		X										X	X			X			X		X	X	X
Photofabrication Engineering Inc.	www.photofabrication.com			X																							
Rogers Corp.	www.rogerscorp.com							X							X									X			
Schlegel Electronic Materials	www.schlegelemi.com							X		X		X	X												X	X	X
Seleco	seleco.com					X																					
Shielding Source	shieldingsource.com	X						X		X		X	X														
Spira Manufacturing Corp.	www.spira-emi.com														X											X	
SSP Inc.	www.sspinc.com							X																			
Stockwell Elastomerics	www.stockwell.com							X							X			X					X				
Swift Textile Metalizing LLC	www.swift-textile.com																				X						
Tech Etch	www.tech-etch.com			X				X		X		X			X											X	
V Technical Textiles / Shieldex US	www.vtechtextiles.com																				X						
VTI Vacuum Technologies, Inc.	www.vactecinc.com								X					X													
W.L. Gore & Associates	www.gore.com			X											X		X										
Wurth Elektronik	www.we-online.com										X																



THE FUTURE OF SHIELDING

Ed Nakauchi
EMC Consultant



THE FUTURE OF SHIELDING

The future is not all that far off. With more electronic devices that are getting smaller, more portable and with continuing faster speeds, EMI or RF issues will continue to increase. There will be more integrated system-on-chips (SoCs) where several functions will all be in one device that will need to be electromagnetically isolated. As an example, a GPS receiver working at -100 to –120 dBm will have to co-exist with a transmitter working @ 0 to +40 dBm. Automotive collision avoidance systems work at about 75 GHz and "regular" gasketing begins to degrade above 18 GHz making them ineffective at these frequencies due to skin effects and electromigration.

Here are some excerpts of quotes from David Leinwand of Hamamatsu taken from **Tech Briefs**, "Visions of Tomorrow", December 2001 issue published by NASA as "food for thought".

"…a new wireless local-area network may have to operate at 60 GHz."; "…heterojunction bipolar transistors (HBTs), a technology that is now yielding large-scale integrated (LSI) circuits packing 1000 to 10,000 transistors on a chip and operating at over 65 GHz."; " …100 Gb/s links could be in production as soon as 2010". RSFQ (Rapid Single Flux Quantum) logic is real today with speeds of 10 GHz to 800 GHz! The future is not all that far away with the very next generation logic devices having edge rates of 10-25 picoseconds (f = 40 – 100 GHz). Carbon tubes and Nanotechnology is already here and available along with RSFQ logic. These are molecular size devices. A nanocomputer could fit in a box 1/100th of a cubic micron with gigabytes of storage in a box about a micron wide (the size of a bacterium!). "Integrated circuits will be designed in three dimensions. Data will be sent by photons…Quantum computing will replace conventional computers…"

So, where does shielding go from here? At the higher frequencies, surface conductivity becomes a critical parameter. Skin effect basically means that currents will tend to crowd into the upper most layers of a conductor. So, as more current gets crowded into less thickness, the current density increases. This produces an increased voltage drop and hence, the potential for more radiation or leakage. The surface conductivity of the finishing layer or gasket material becomes critical. This is because some of the protective finishes such as zinc chromate are composed of conductive particles in a binder material. Of course, as frequencies go higher, wavelengths become shorter, openings become more significant leading to increase potential for leakage.

To demonstrate the magnitude of this EMI design criteria about keeping holes and slots small, let's go through a calculation. For a frequency of 100 GHz, the corresponding wavelength is 0.12 inches. Typically, holes should be no larger than $1/20^{th}$ to $1/50^{th}$ of a wavelength, and if anything, they may need to be smaller, so this calculates to 3 to 6 mil hole or aperture. So, at some point an alternative to enclosure shielding needs to be explored since it is impractical to completely enclose the source as any practical device will have holes and slots for antennas, cables, power cords, etc. It is becoming difficult to pursue the standard shielding approach of "containing" the noise.

Most of today's shielding theory is based upon far-field conditions and not near field conditions. This is especially critical in dealing with board level shields and the smaller size of today's devices, as different calculation methods need to be used for better results. The E or electric component and the H or magnetic field components must be analyzed separately. Current distribution and distributed parasitic impedances become involved. Also, skin depth effects can possibly be taken advantage of by having a two shielding layers separated by a low dielectric material and possibly obtain very high levels of shielding due to having "multiple layers."

With increasing use of "thin" shields like electrodeposition or vacuum metallization especially with plastic enclosures, the second boundary becomes important. When using thick metal shields/enclosures, re-reflection or multiple reflection effects could be ignored, but with thin shields, the absorption loss is negligible and hence passes through the thin shield with minimal loss. This effect is prevalent with magnetic fields. Electric fields are not affected that much since most of its losses comes from reflection at the first boundary.

Another issue with higher frequencies is resonance effect. Its coupling is a consequence of self-resonance of various structures such as reactively terminated transmission lines, slots in the PCB, slots between the PCB and metallic enclosure, etc. These structures behave as cavity resonators. A 2 inch by ½ inch enclosure resonates at a first order mode of around 12 GHz. Even weak coupling at these extremely high frequencies can induce strong oscillations than can then couple to any other point in the enclosure. To reduce this phenomenon, the "Q-factor" of the cavity must be lowered by introducing losses. So, in the future, shielding could become more of a multilevel concept. Board level shields will handle the "lower" frequencies as usual through it acting as a shielded enclosure, but then an inside layer of absorber coating will handle the much higher frequency components by reducing resonance conditions. Absorber materials are a viable option for handling these higher frequency issues. Absorbers work most efficiently at these higher frequencies (>1 GHz). Absorbers reduce radiation or "shield" by literally absorbing the energy and converting it to heat. This brings up another advantage in using absorber material in that since it converts the electromagnetic energy, it does not have to be "grounded." As long as the absorber material intercepts or is in the field path, then it will reduce the electromagnetic energy of the field.

Conductive plastics are re-emerging as a potential option to provide shielding. In the past, conductive particles (i.e. carbon, steel, etc.) were added to the plastic material to give it conductivity. However, this was without its own shortcomings in that it did not provide very effective shielding. Most conductive plastics only produced about 20-40 dB of shielding. Higher shielding levels were possible (i.e. 60-80 dB), but at the expense of harming the mechanical properties of the initial base plastic material since more conductive particles needed to be added. This also increased the weight and cost of the enclosure. Another equally important factor is that the surface of this conductive plastic was non-conductive since the conductive particles tended to settle away from the external surface. So, it is possible to have a plastic enclosure which has shielding qualities, but with major compromises in terms of processability, performance, and/or cost.

This finally leads us to today with the increasing exploration of intrinsic conductive polymers. This yields a true "conductive plastic". The main advantage in using inherently conductive polymers (ICPs) is that the user obtains the conductivity of metal such as copper, but at the fraction of the weight and with less sacrifice of losing the characteristic advantages of the main plastic material. Also, no additional processes or steps would be required to expose a conductive surface saving additional manufacturing process time and cost. Yet another advantage of conductive polymers is that they are more environmentally friendly which is especially important in today's trend.

Most shields are quantified with high levels of conductivity, but sometimes this kind of shield is not necessarily the ideal solution. It is also impossible with this kind of shield to perform frequency selective shielding. A shield where chirality, which means "handedness", has been added is called chirashield. The benefits are reduced weight for a given attenuation and, as mentioned earlier, frequency selectivity. Chirality is a geometrical concept. It is also described as handedness (i.e. left-handedness and right-handedness elements). Chirality is based upon molecules existing in two asymmetrical mirror image forms having a left-handed or right-handed structure. The structures resolve the electromagnetic field into two circularly polarized fields of opposite polarization directions and different phase velocities, so combining the structure or shield which have this relationship between their "handedness" yields an attenuation much like optical light passing (remember that light is an electromagnetic wave too!!) through polarized lenses.

How about shielding "on demand" where the material can change depending on the applied stimuli (e.g. electric or magnetic). The future of shielding is not all that far off. In fact, it is here now!!

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SIMULATING EM SHIELDING FOR AERONAUTICAL APPLICATIONS

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Introduction

The airframe of an aircraft can provide some measure of shielding against high-intensity radiated fields (HIRF), but this is compromised by doors, windows, seams, access panels and components interfaced to the airframe such as antennas used for communication and navigation. Composite materials are increasingly used in aeronautical applications due to their relatively light weight, but their unique electromagnetic properties create additional challenges for maintaining shielding integrity. This article will explore the electromagnetic simulation of shields at both the component and airframe level, while demonstrating how special modeling techniques applied in the 3D TLM method can be used to improve the efficiency of capturing the important coupling mechanisms.

SIMULATING EM SHIELDING FOR AERONAUTICAL APPLICATIONS

Introduction

Aircraft are subject to a range of environmental electromagnetic effects (E3), such as lightning strikes, electromagnetic pulses (EMP) and high-intensity radiated fields (HIRF), which can pose a risk to the safe performance of avionics. Shielding can mitigate these risks and protect electronic systems. However, shielding effectiveness may be compromised by aperture leakage or diffusion, allowing fields to penetrate.

This means that when developing shielding, the aircraft engineer has to balance several contradictory design requirements. In the name of weight reduction, material use should be minimized, but making shields thinner can increase leakage. This is made more complex by the increasing use of lightweight composite materials in the airframe, which have different electromagnetic properties to the conventionally used metals, and by the need to include doors, windows and cables in the aircraft (*Figure 1*).

Electromagnetic simulation offers an effective way to investigate these effects during the design process. Simulation allows the effect different configurations and material properties to be assessed easily and field visualization helps engineers to identify the coupling paths that lead to field penetration.

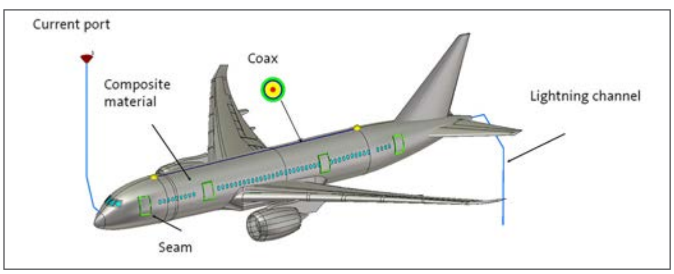

Figure 1. Simulation setup for a lightning strike on an airliner, showing some critical points in the shielding. These include cables, door seams and composite materials.

E3 Scenarios

There are a range of different scenarios that need to be considered for shielding analysis, including HIRF, EMP, lightning strike, electrostatic discharge (ESD) and radiated emissions from onboard devices. With the right simulation setup, these can all be assessed with virtual prototypes.

As these are all usually broadband or transient phenomena, a time domain approach is usually the best choice. With time domain simulation, the entire frequency spectrum of interest can be covered by a single simulation. External fields can be modeled using plane waves for external effects such as HIRF and EMP, or using near field sources drawn from simulation or measured data and placed within the aircraft. Using field sources can reduce the complexity of simulation, replacing detailed models with more efficient representations of the source of emissions.

For lightning strike analysis, lightning channels can be modeled as wires connecting the aircraft to a current source. Lightning attachment zones can first be predicted using electrostatic simulation [1].

Skin Effect and Composite Materials

The penetration of fields through solid material is limited by the skin effect. High frequency current does not flow uniformly throughout the cross-sectional area of a conductor. Instead, the current flows in a thin layer just underneath the surface, and the thickness of the conduction layer is defined by the skin depth at that frequency. The skin depth is defined as the depth at which field intensity has reduced to 1/e or 37%.

In metals, which have high conductivity and often also high permeability, the skin depth is very short. Aluminum has a conductivity of around 35 MS/m, and the skin depth at 1 MHz is around 0.085 mm. At these frequencies, any diffusion through typical metal thicknesses would be negligible.

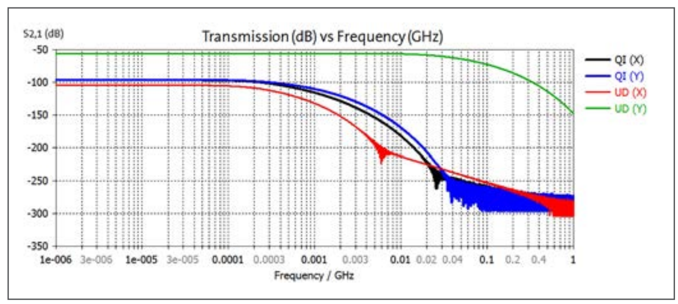

Figure 2. Simulated transmission of a diagonally-polarized plane wave incident on an 8 ply CFC laminate 1.6 mm thick.

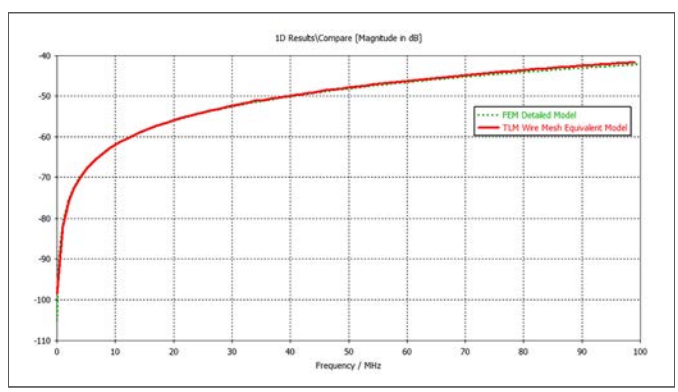

Figure 3: (left) Agreement between simulated transmission results for a detailed wire mesh model and an equivalent model. (right) Agreement between analytic transmission results for stacked graphite layers and a simulation with an equivalent model.

However, because of their light weight and strength, carbon fiber composite (CFC) materials are increasingly used in aircraft, with some modern airliners being over 50% composites. These materials are significantly less conductive, and provide less shielding. Carbon fiber has a conductivity of around 104 to 105 S/m with corresponding skin depths at 1 MHz ranging between 1.6 and 5 mm –orders of magnitude greater than aluminum. This will result in significantly greater field diffusion through the material.

An additional complication is that CFC materials often have a complex structure giving them anisotropic EM properties. Multiple layers of fibers are stacked to form a laminate, and the fiber direction can vary from ply to ply.

Figure 2 shows how this can significantly affect the shielding performance of the material. In this simulation, a broadband diagonally polarized plane wave is incident on a sheet of CFC laminate. In one variant, the fibers in each ply are all aligned in the same direction (uni-directional or UD). In the other, each layer is rotated sequentially (quasi-isotropic or QI). As the results show, the QI laminate attenuated the fields by a similar amount in both x and y directions. However, the UD laminate shows very different results, with around a 50 dB difference in field transmission between the two components.

Because CFC materials offer less shielding, especially at low frequencies, they can be supplemented with wire mesh. This creates a Faraday cage that can significantly increase shielding and lightning protection. Both CFCs and wire meshes contain fine detail, and this can be simulated much more effectively using equivalent models rather than modeling individual wires or fibers. The examples in this article were simulated using the multi-layer (stacked) thin panel material and wire mesh material in CST STUDIO SUITE®. These offer extremely close agreement to more detailed models and to the expected analytical results (*Figure 3*).

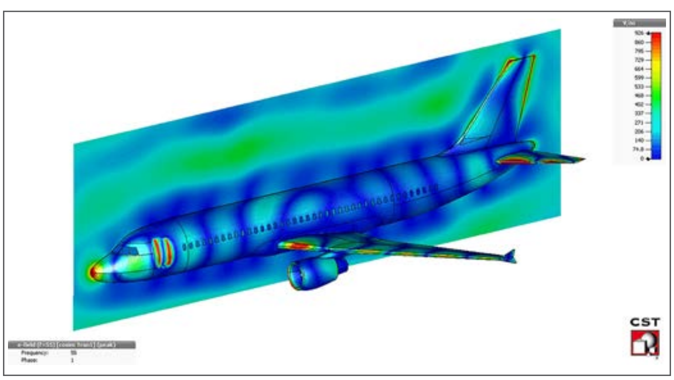

Figure 4. Induced fields and currents on an aircraft subject to HIRF at 55 MHz. There is a considerable resonance in the seam around the front door frame.

Fine Details
Any practical shield will have some gaps in it; for example, vents, windows, joints and seams. Fields can penetrate through these – even very fine seams can compromise shielding if the length of the seam corresponds to the resonant frequency of the incident radiation (*Figure 4*). This means that modeling all this fine detail is essential for the accurate simulation of shielding performance, and special simulation methods are required in order to perform these calculations in a practical length of time.

For E3 simulations, the time domain transmission line matrix (TLM) solver is often a very efficient tool. The TLM solver is broadband, and it can also model transient effects such as lightning strikes directly. In addition, the TLM solver also supports octree meshing, with a very fine mesh around small details and a sparser mesh in open space. This can significantly reduce simulation run times compared to other solver types, especially when combined with high-performance GPU computing.

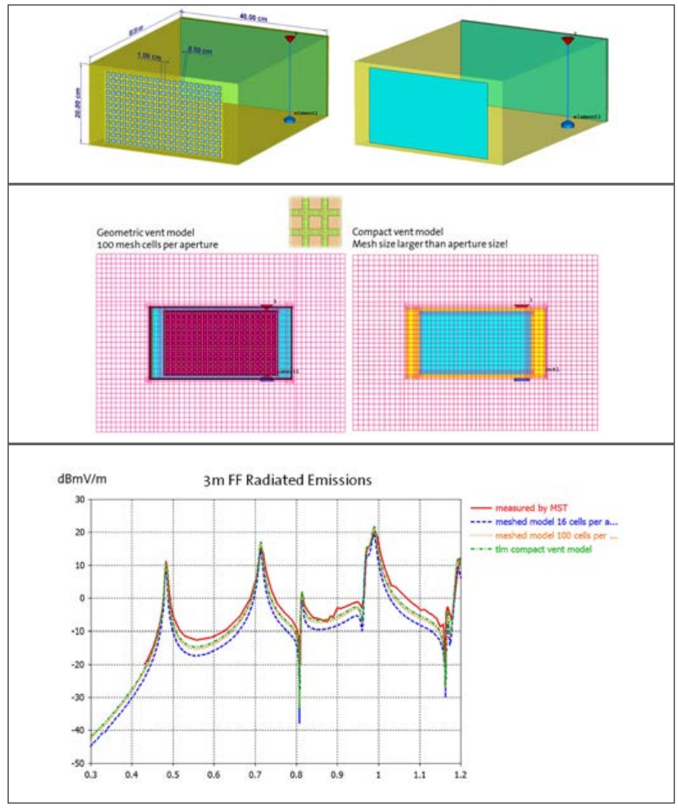

Figure 5. Detailed (top left) and compact (top right) models of a vent on an enclosure, showing the 3D model (middle) and mesh (bottom) with simulated and measured far field results at 3 m. Measured data from [3]

In addition, many fine details from the CAD data can be replaced with compact models. For example, simulating the shielding performance of an avionics box that includes a ventilation panel in 3D would mean that each individual hole needs to be modeled and meshed, increasing simulation time. The vent can therefore be replaced by a compact model containing an analytic representation of the vent's transmission properties, which is much faster to simulate – the mesh can be larger than the aperture size, which not only reduces the number of mesh cells needed but also allows a larger time step for a shorter simulation. *Figure 5* shows the implementation of a compact vent model for simulating an electronics enclosure. Using the compact model reduced simulation times by 25% compared to a 3D model with a rough mesh, and by 85% compared to a more accurate fine mesh. The simulated compact model results also agreed closely with measured results, demonstrating the viability of simulation for virtual prototyping.

Similarly, an equivalent model can be used to simulate leakage through slot/seam apertures or fasteners. This is demonstrated below where a direct electrostatic discharge (ESD) onto the front panel of a box is simulated. The ESD is simulated by modeling a laboratory ESD test setup, allowing direct comparison of measured and simulated data (*Figure 6*).

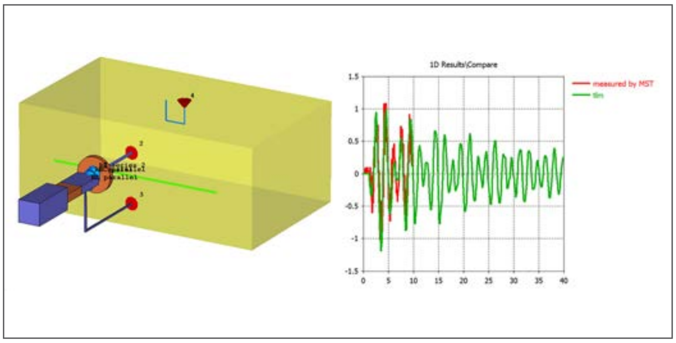

Figure 6: Comparison of simulation and measurement of an ESD shielding test scenario, showing excellent agreement between measured and simulated data [2].

Finally, an aircraft will contain many kilometers of cabling, mostly bound into complex cable harnesses. Cables are a significant factor in electromagnetic susceptibility – fields can couple into cables and cable shields and then be reradiated elsewhere. Again, the complexity and size of cables means that they are much more efficiently simulated with hybrid methods, combining full-wave 3D and analytic approaches.

Conclusion

Implementing simulation in the design process gives engineers greater capacity to analyze and optimize EM shielding at an early stage. Simulated and measured results complement each other: replicating common test scenarios with virtual prototypes allows changes to be implemented and assessed without the time and money costs associated with a physical prototype.

References

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2. F. Centola et al., “ESD Excitation Model for Susceptibility Study,” Proceedings of the IEEE International Symposium on EMC, Aug 2003
3. Li, Min; Nuebel, J.; Drewniak, James L.; Hubing, Todd H.; DuBroff, Richard E.; and Van Doren, Thomas, “EMI reduction from airflow aperture arrays using dual-perforated screens and loss“, IEEE Transactions on EMC, Aug 2000

MEASURING SHIELDING EFFECTIVENESS WITH TWO NEAR FIELD PROBES

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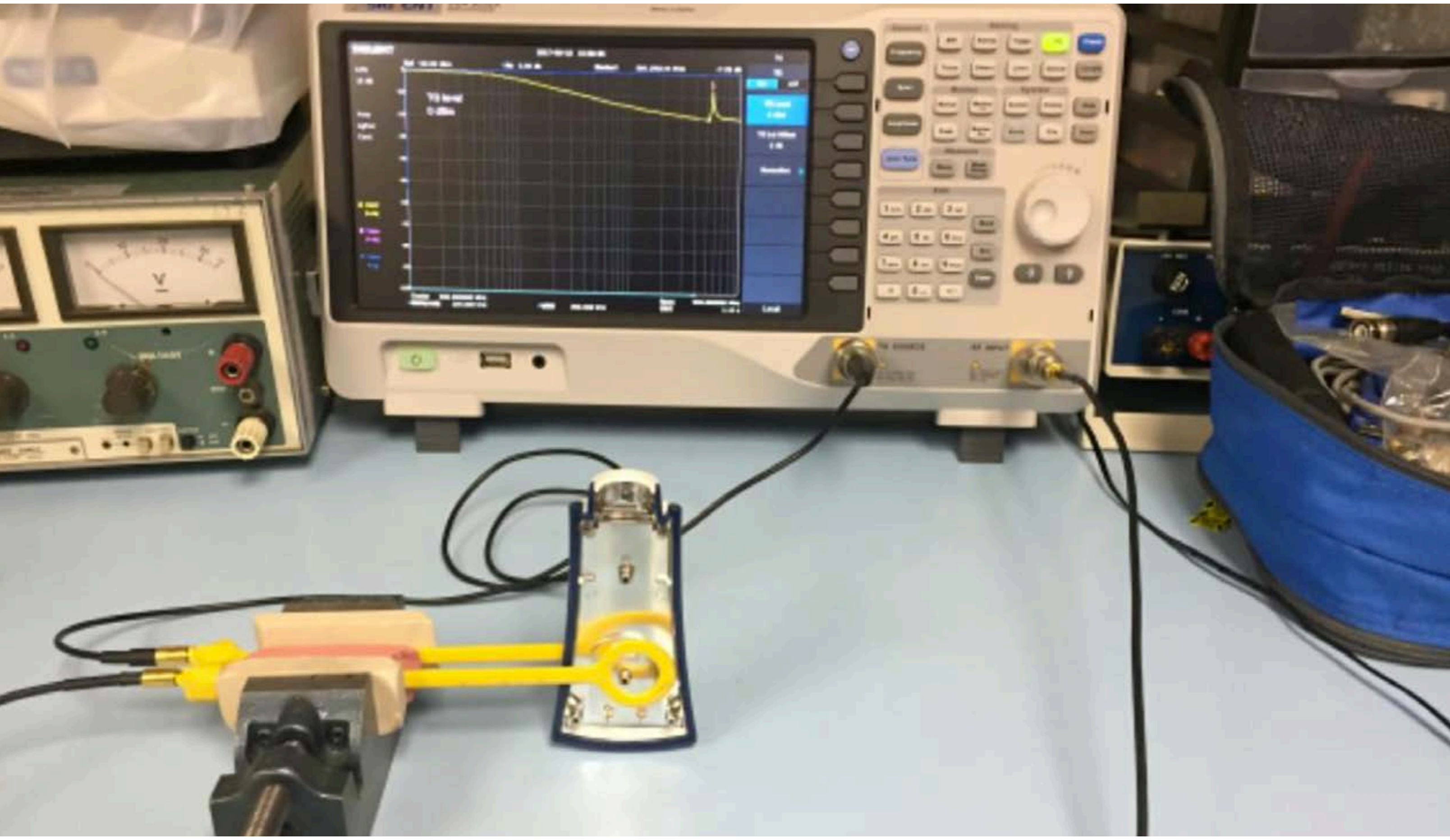
Introduction

Sometimes you may find yourself needing to make a quick check on the shielding effectiveness (SE) of a material, such as plated plastic or shield gasket material. It's possible to set up a quick measurement setup using near field probes by using a couple H-field (for magnetic field SE) or E-field (for E-field SE). You'll also need a spectrum analyzer with tracking generator or network analyzer that covers the desired frequency range.



MEASURING SHIELDING EFFECTIVENESS WITH TWO NEAR FIELD PROBES

The use of two near field probes is not unique. In fact, I used this technique in the early 1990s to measure the SE of various plated plastics we were using at the time for oscilloscope enclosures during my time with Hewlett Packard. I even tried patenting the technique, but my lawyer discovered prior art. Both my colleagues, Doug Smith (http://www.emcesd.com) and Arturo Mediano (http://www.cartoontronics.com) have promoted this technique on their web sites and public seminars.

Measuring the SE in the near field is probably more pertinent for real products, because real enclosures are usually in the near field close to circuit boards. In fact, the results you get with this method won't agree with the far field SE equations (SE = A + R + M) one generally finds in the literature. George Kunkel wrote an article recently deriving the equations for near field SE using circuit theory as the basis. This is referenced below in [1].

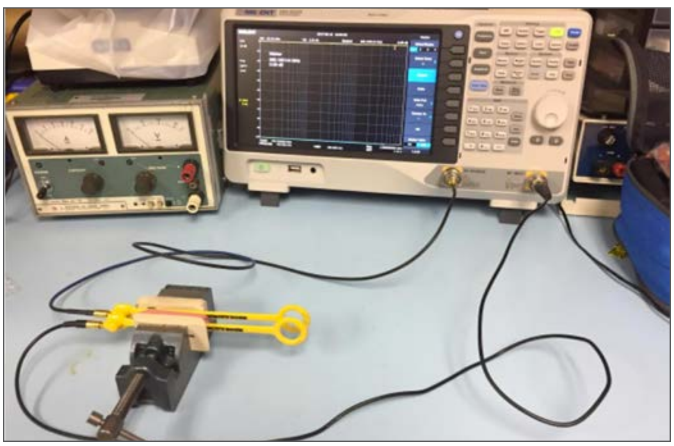


Figure 1 – The general test setup for the near field SE measurement.

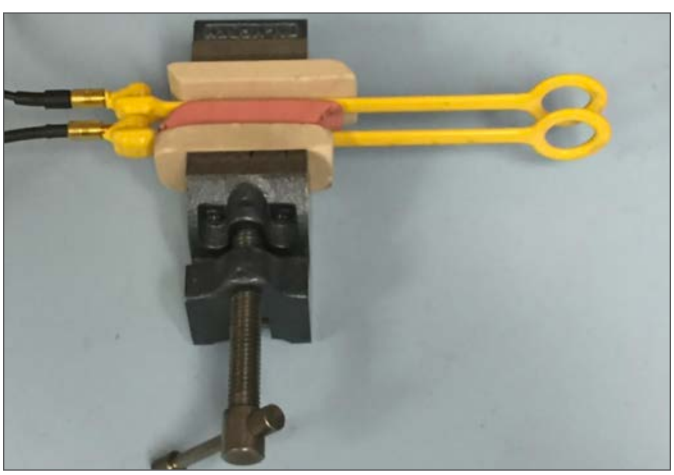


Figure 2 – Close-up of the two H-field probes in the vice. The erasers help isolate the probes from the metal of the vise.

For the purposes of this article, I'll be using a Siglent SSA3032X spectrum analyzer [2] with tracking generator and looking at frequencies in the range 1 to 1000 MHz. A pair of Beehive Electronics 100C H-field probes [3] were used. See *Figure 1* for the general test setup.

The probes were clamped between erasers in a small vise to hold them an arbitrary distance apart. The erasers helped isolate the probe shafts from the metal vise (*Figure 2*). The probe distance doesn't matter too much, except that they must be able to measure the sample without touching it and they must be close enough together to make a readable signal.

Connect one probe to the tracking generator output. Connect the other to the analyzer input. Try to separate the two coax cables to avoid coupling. Set up the spectrum analyzer as follows:

1. Start frequency = 1 MHz
2. Stop frequency = 1 GHz
3. Resolution bandwidth = 120 kHz (or 100 kHz) – not critical
4. Vertical scale = dBm
5. Reference Level = -20 dB
6. Preamp = Off
7. Attenuation = 0 dB
8. Tracking Generator (TG) = On (upper right on keyboard)
9. Tracking Generator Level = -20 dBm
10. In the TG menu, press Normalize
11. Turn TG = On

The SE response trace should appear in the top of the display and the top reference scale is now 0 dB. Placing any metallic sample between the probes will read out the SE directly versus frequency.

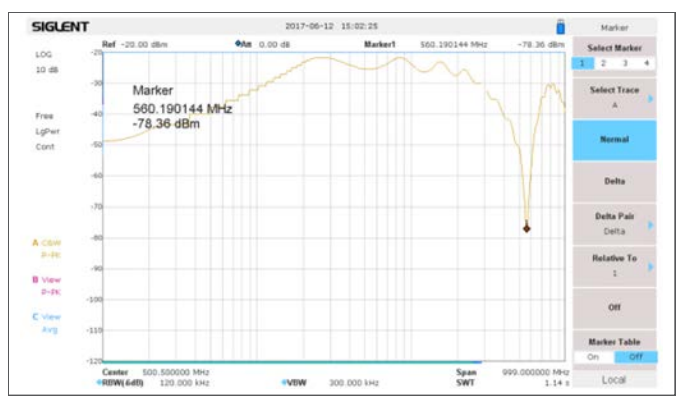


Figure 3 – A plot showing the 560 MHz resonance of the Beehive Electronics 100C probes used. While most of this is normalized out during the calibration procedure, still, some will remain and can be ignored in the displayed plots below

Note that the Beehive Electronics 100C probes I'm using have a sharp resonance about 560 MHz, which causes a spike in the response. I tried large paper clip loop probes and they exhibited a similar resonance. The use of the Beehive 100B (medium-sized) probes should move this resonance out of the displayed window. I didn't have a set of these, so had to use the larger probes as shown.

I'd just ignore the resonance and continue the SE plot straight through. See *Figure 3*.

Here are some sample measurements. See *Figures 4* through *9*.

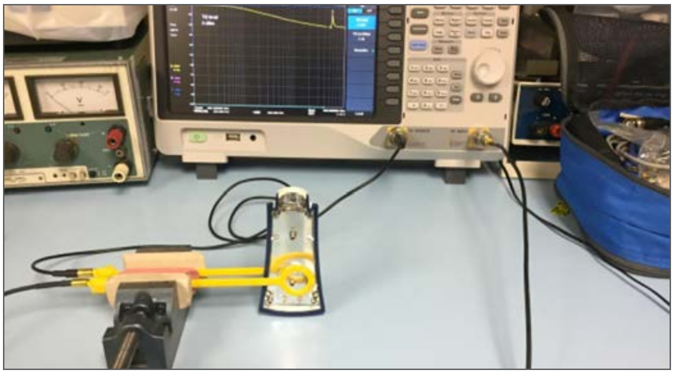


Figure 4 – A measurement of some typical plated plastic.

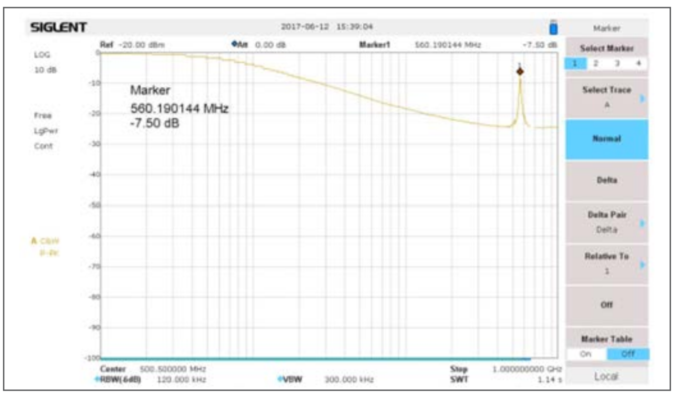


Figure 5 – Resulting plot for the plated plastic. Note it's only about 8 dB down at 20 MHz and 20 dB down at 100 MHz.

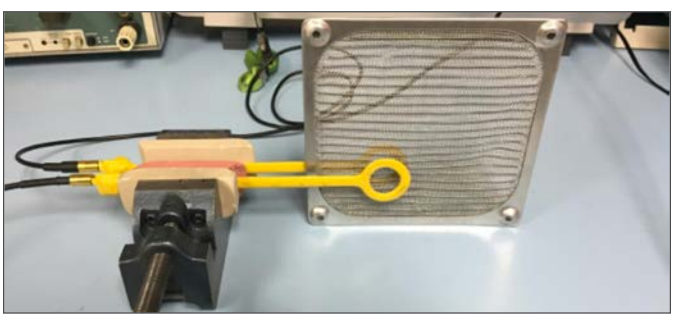


Figure 6 – A measurement of a fan EMI shield.

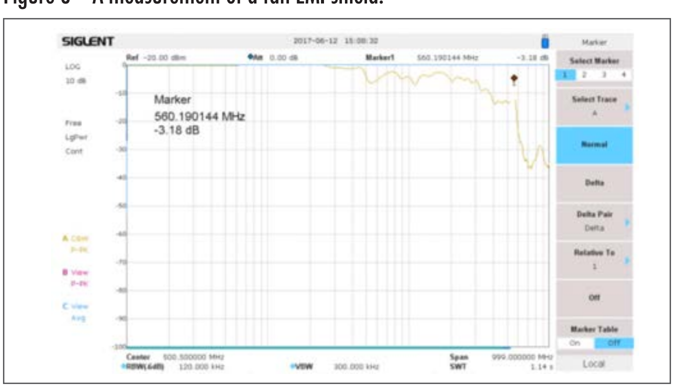


Figure 7 - Resulting plot for the plated plastic. This is a relatively poor shield for H-fields until you get above 600 MHz.

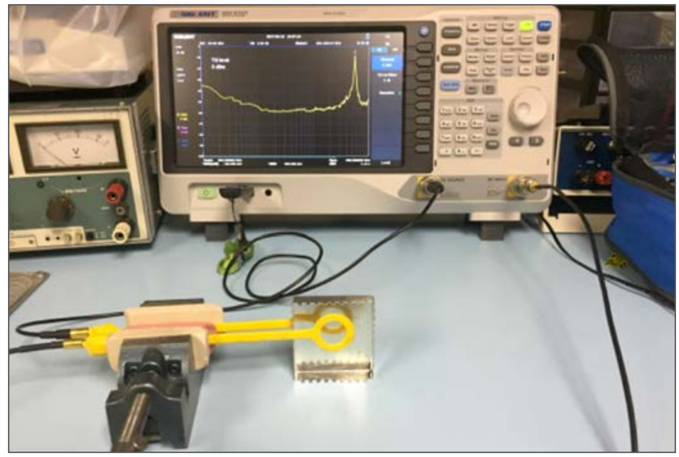


Figure 8 – A measurement of a solid steel local PC board shield.

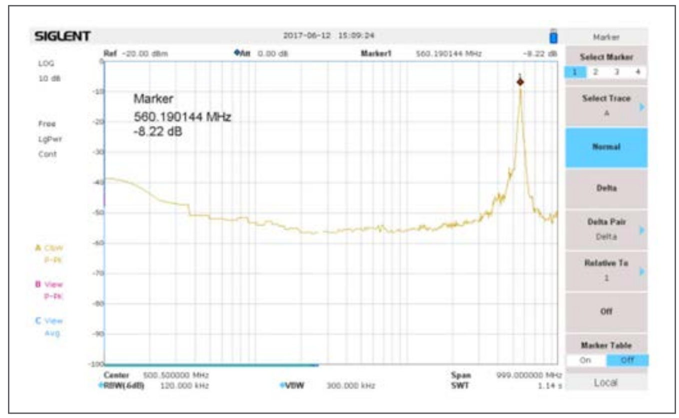


Figure 9 - Resulting plot for the plated plastic. Obviously, solid metal is much better than the thinner plated or screen shields. The SE averages about 50 dB throughout the frequency range.

Summary

Near field shielding effectiveness is easy to measure if you have a couple near field probes and either a spectrum analyzer or network analyzer. Plated plastics and most EMI gaskets or fan shields are inferior to solid metal.

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[3] Beehive Electronics 100C H-field probe, https://beehive-electronics.com/probes.html

HOW TO CHOOSE PARTICLE-FILLED SILICONES TO MEET MULTIPLE DESIGN REQUIREMENTS

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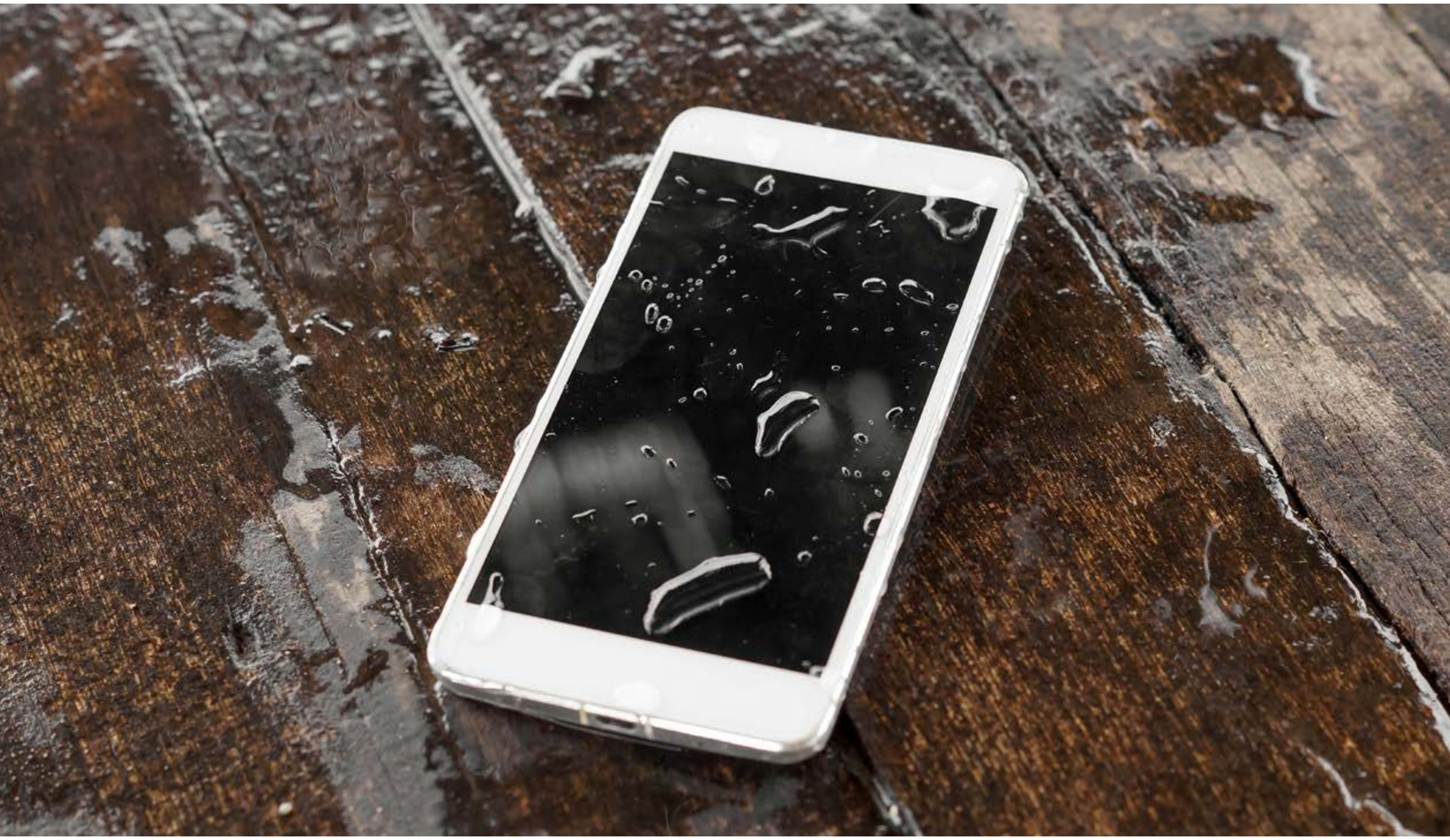

HOW TO CHOOSE PARTICLE-FILLED SILICONES TO MEET MULTIPLE DESIGN REQUIREMENTS

Many electronic designs need shielding materials that combine resistance to electromagnetic interference (EMI) with other application-specific requirements. For example, the EMI gaskets that are used in military touch-screens need to attenuate EMI emissions, provide electrical conductivity, and ensure environmental sealing. These shielding gaskets also must also cushion the unit from mechanical shock and be soft enough to avoid interfering with the display's touch function.

The EMI shielding that's used in automotive, aerospace, and medical electronics must also meet multiple requirements. For example, an EMI gasket that's used with commercial aircraft may need to resist the splash of jet fuel or cleaning agents. EMI gaskets that are used in medical devices must combine required levels of shielding with corrosion resistance. Shielding that's used with electric vehicle (EV) charging stations or robotics may require compliance with UL 94 standards for flammability.

For electronic designers, EMI shielding decisions can be complex. Particle-filled silicones are used in many demanding applications, but can they meet all of your application's requirements? Are EMI gaskets made of these materials cost-effective, and do particle-filled silicones support design for manufacturability?

Understanding Particle-Filled Silicones

Particle-filled silicones are elastomeric compounds that combine the advantages of silicone rubber with the electrical properties of metals. An inert, synthetic elastomer, silicone offers thermal stability over a wide temperature range along with resistance to ozone, water, and sunlight. When filled with tiny metal or metal-coated particles, silicone compounds combine EMI shielding and electrical conductivity with environmental sealing.

Table 1: Filler, Conductivity, and Volume Resistivity

Filler Type	Electrical Conductivity	Typical VR (ohms/cm)
Silver	Extremely Conductive	.0009
Silver-Aluminum	Super Conductive	.003
Silver-Copper	Super Conductive	.003
Silver-Glass	Very Conductive	.006
Nickel-Graphite	Conductive	.01
Carbon Black	Semi-Conductive	8.0

Table 1 shows the relationship between filler type, conductivity, and typical volume resistivity (VR) as measured in ohms per centimeter. Direct methods for measuring shielding effectiveness can be expensive and complex, so VR is a commonly used method for indicating EMI shielding effectiveness indirectly. Note the fill types for particle-filled silicones include pure silver, silver-plated materials, and nickel-coated fills.

Electrical Conductivity, Material Properties, and Cost

Silicones have many desirable properties, but loading them with a high percentage of metal particles to increase electrical conductivity can have negative tradeoffs. That's why historically; some designers have rejected particle-filled silicones as too hard or too brittle. Other designers have complained about part size limitations based on mold dimensions and long lead times for sheet materials. Some industry professionals also believe (incorrectly) that all particle-filled silicones are too thick to support thinner electronic designs.

The cost of older, particle-filled products also discouraged their use. For years, the filler of choice for shielding silicones was silver-aluminum. The U.S. military's development of the MIL-DTL-83528 specification played an important role in this particle's popularity. When silver began approaching $50 per Troy ounce in 2011, however, the fact that these elastomers were specified on thousands of gasket drawings and prints became problematic. EMI gaskets made of silicones filled were pure silver were even more expensive.

Table 2: Filler Type and Cost

Filler Type	Cost
Silver	$$$$$
Silver-Aluminum	$$$$
Silver-Copper	$$$$
Silver-Glass	$$$
Nickel-Graphite	$$
Carbon Black	$

Today's electronic designers can specify alternative particle fills. As *Table 2* shows, choices such as nickel-graphite cost significantly less. Note the difference in cost between silver, silver-aluminum, and nickel-graphite fills.

Table 3: Shielding Effectiveness Test Results

Frequency (MHz)	Reference Level (dB)	Dynamic Range (Analyzer Reading)	Test Sample (Analyzer Reading)	Dynamic Range (dB)	Nickel Graphite Gasket (Shielding Effectiveness) (dB)
20	95	-26.9	-25.1	121.9	120.1
30	100	-27.9	-24.5	129.9	124.5
40	100	-28	-24.3	128	124.3
60	100	-28.2	-25.1	128.2	125.1
80	100	-27.7	-25.5	127.7	125.5
100	100	-27.9	-25.2	127.9	125.2
200	100	-28.9	-27.7	128.9	127.2
400	100	-28.3	-26.3	128.3	126.3
601	100	-28.7	-26.1	128.7	126.1
800	100	-29.2	-27.1	129.2	127.1
1000	100	-17.8	-15.7	117.8	115.7
2000	100	-18.2	-15.5	118.2	115.5
4100	100	-17.9	-13.7	117.9	113.7
6000	100	-17.1	-13.1	117.1	113.1
8000	100	-17.2	-14.1	117.2	114.1
10000	100	-17.5	-15.7	117.5	115.7

Nickel-Graphite Silicones

Manufacturers, including Specialty Silicone Products (SSP), now supply cost-effective nickel-graphite silicones that perform at the shielding levels of silver-aluminum filled products. *Table 3* contains results from a third-party test re port. It shows how SSP's nickel-graphite silicones meet the shielding effectiveness requirements of MIL-DTL-83528, which sets a minimum shielding effectiveness of 100 dB.

Table 4: Properties of Softer Silicones				
Durometer (Shore A)	Tensile Strength (psi)	Elongation (%)	Tear B (ppi)	Maximum VR (ohm/cm)
30	100	400	N/A	0.300
45	150	200	25	0.030
55	150	200	25	0.040
65	200	200	35	0.040
75	270	250	35	0.040

Particle-filled silicones also provide other desirable material properties. For example, as *Table 4* shows, SSP 502-series SpecShield™ silicones include lower-durometer (softer) materials with good tensile strength, elongation, and tear resistance along with maximum VR levels. Durometer, a measure of harness or softness, is an important engineering property because it affects the flexibility and compressibility of an EMI gasket. With particle-filled silicones, the Shore A scale for durometer is used.

Conductive silicone gaskets can also resist salt spray and corrosion according to ASTM B 117:2003 requirements. This is an important consideration for EMI gaskets that are used in marine environments.

Silver-Aluminum and Other Silver-Filled Silicones

If necessary, electronic designers can still choose silver and silver-filled elastomers in various durometers based on their application requirements. *Table 5* lists properties for silver and silver-filled elastomers, such as SpecShield™ materials that meet the requirements of MIL-DTL-83528. Included are two silver-aluminum products from SSP with a qualified product listing (QPL) from the Defense Logistics Agency (DLA), part of the U.S. Department of Defense.

Table 5: Some Properties of Silver-Filled Silicones				
Fill Material	Base Elastomer	Durometer	Maximum VR (ohm/cm)	QPL
Silver	Silicone	65	0.002	
Silver-Aluminum	Silicone	65	0.008	Yes (Type B)
Silver-Aluminum	Fluorosilicone	70	0.012	Yes (Type D)
Silver-Aluminum	Fluorosilicone	45	0.004	
Silver-Aluminum	Fluorosilicone	70	.012	
Silver-Copper	Silicone	65	0.004	
Silver-Copper	Silicone	80	0.005	
Silver-Glass	Silicone	65	0.006	
Silver-Nickel	Silicone	75	0.005	

Some silver-filled elastomers use fluorosilicone as the base material. Fluorosilicones such as the silver-aluminum products in *Table 5* have physical and mechanical properties that are very similar to standard silicones; however, fluorosilicones also provide improved resistance to fuels, oils, and solvents.

Overcoming Design and Manufacturing Challenges

Thanks to innovations in silicone compounding, particle-filled elastomers can meet demanding shielding requirements along with other project specifications. For example, because nickel-graphite silicones such as SpecShield™ elastomers are available in 30, 40, and 45 durometer (Shore A), they're soft enough for enclosure gaskets. Other, higher-durometer shielding elastomers that use fluorosilicone as the base elastomer can resist fuels and chemicals. These fluorosilicone compounds come in 50, 60, and 80 durometers (Shore A) for applications that require EMI gaskets made of harder materials.

Unlike older shielding elastomers, newer shielding materials such as SpecShield™ products contain enough metal filler to ensure effective EMI shielding and electrical conductivity. These material are also support the cost-effective fabrication of EMI gaskets. As the only supplier of shielding elastomers that offers solid, heat-cured EMI silicones in continuous rolls, SSP can supply nickel-graphite silicones in higher durometers for applications that require harder materials. Compared to molded sheets, continuous rolls promote optimum yields for cost-effective conversion. Continuous rolls also support the use of automated equipment instead of time-consuming manual operations.

Various higher-durometer, nickel-graphite silicones are available, but some EMI gasket applications require reinforcement for added strength. For example, SSP's ArmourRFI™ is a 65-durometer SpecShield™ elastomer that's reinforced with an internal nickel-coated mesh. Lower-durometer, nickel-graphite silicones can also be reinforced with an inner layer of conductive fabric for added conductivity and material strength, which helps to prevent brittleness and tearing during EMI gasket fabrication.

During gasket cutting, particle-filled silicones won't stretch or become deformed. Connector holes align properly, and the material's structural properties support greater tear resistance – an important consideration for thinner wall gaskets. Product designers can also specify the use of an adhesive backing for ease-of-installation. For shielding applications where Z-axis conductivity is required, particle-filled silicones can support the use of electrically conductive adhesives.

Conclusion

Particle-filled silicones are good choice for meeting EMI shielding and many other application requirements. Electronic designers can choose from various types of filled elastomers, but it's important to account for all of your project requirements – including cost and manufacturability. As silicone shielding elastomers are used in a growing number of military and commercial applications, designers can expect continued advancements in nickel-graphite and silver-aluminum materials.


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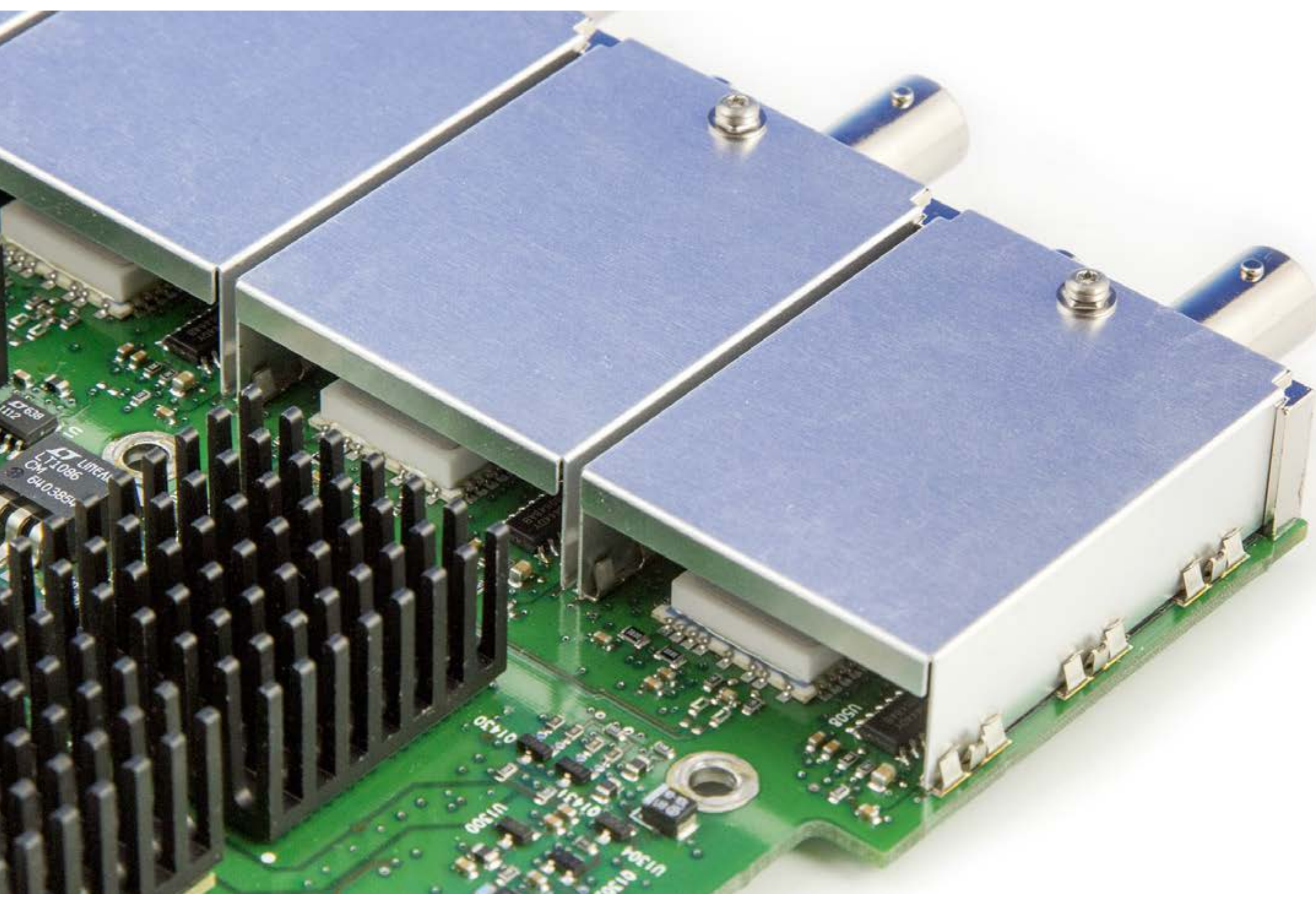
A CIRCUIT THEORY APPROACH TO CALCULATING THE ATTENUATION OF SHIELDING BARRIERS

George Kunkel, President/CEO
Spira Manufacturing Corp

EDITOR'S NOTE: *As a long time EMC engineer and working consultant, I've performed a lot of study and measurements on shielding effectiveness of real product shields. Invariably, I've noticed the measured results fail to compare with the classical Schelkunoff equations derived in the 1930s – that is, the Absorption, Reflection, and Multiple Reflection equations. It is my belief that real product shields are typically located in the near field and I suspect the Schelkunoff equations were far field derivations. George Kunkel has developed a shielding theory based on circuit theory that can accommodate "shielding quality" in both the near and far fields, for both electric and magnetic fields.*



A CIRCUIT THEORY APPROACH TO CALCULATING THE ATTENUATION OF SHIELDING BARRIERS

Abstract
There are two commonly used methods for approximating the attenuation of shielding barriers. This approximation is defined as shielding effectiveness (SE) for shielding materials used in the design of shielded enclosures. Both methods use wave theory and quasi-stationary assumptions. One of the methods uses Maxwell's equations to estimate the shielding, and the other uses the correlation between transmission lines and radiated waves. This article proposes a third method based on circuit theory (Kirchhoff's Law) as an applicable method of approximation worthy of consideration.

Introduction
The two common methods of estimating the shielding effectiveness of material used in the design of shielded enclosures require the understanding and use of wave theory and Maxwell's equations. Very few working engineers understand, and therefore properly use wave theory and Maxwell's equations. Therefore they find it difficult to evaluate the materials used in the shielding of electromagnetic waves for compliance to the various commercial and DoD EMC requirements.

A method of estimating the shielding quality (SQ) of materials used in the design of shielded enclosures using circuit theory (Kirchhoff's Law) is included in this article. The advantages of using a circuit theory analogy are: (1) the ease by which the average design engineer can understand the variables and application of the theory; (2) these advantages will greatly assist the design engineer in selecting the proper material for meeting specific shielding requirements; and (3) the approximate magnitude of both the E and H fields emanating from a shielding barrier material can be easily obtained.

The paragraphs that follow will describe:

1. The generation and propagation of an electromagnetic wave.
2. The development of the attenuation factors associated with specific shielding materials.
3. Development of equations for estimating the shielding quality of specific barrier materials for both the E and H fields of an electromagnetic wave.
4. Boundary conditions and constraints associated with the theory.
5. Comparative analysis of shielding materials using wave theory and the circuit theory contained herein.

Generation and Propagation of EM Fields
The undergraduate courses on electromagnetic theory introduce the concept of an electromagnetic (EM) field by driving a pair of parallel plates with an AC voltage source as illustrated in *Figure 1*. The current that flows through the wire comes from the top plate and is stored in the bottom plate. The over presence of the electrons on the bottom plate is illustrated by plus symbols (+) and the absence of electrons on the top plate is illustrated by minus symbols (-). This creates an electromagnetic field which is illustrated in *Figure 2*. As is illustrated, a field exists between the plates. The magnitude of the E field is equal to the voltage differential between the plates divided by the distance between the plates in meters. The resultant E field is in volts/meter (e.g., we use a set of parallel plates for performing E field susceptibility testing to MIL-STD-461/462).

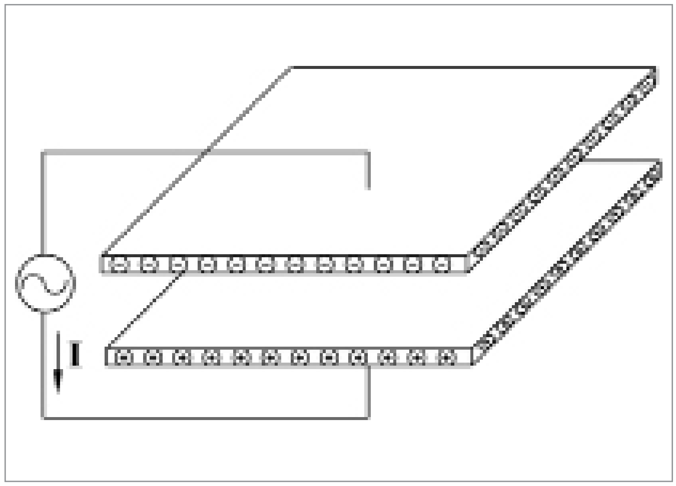


Figure 1 – Concept of an electromagnetic field resulting from an AC voltage source connected to two parallel plates.

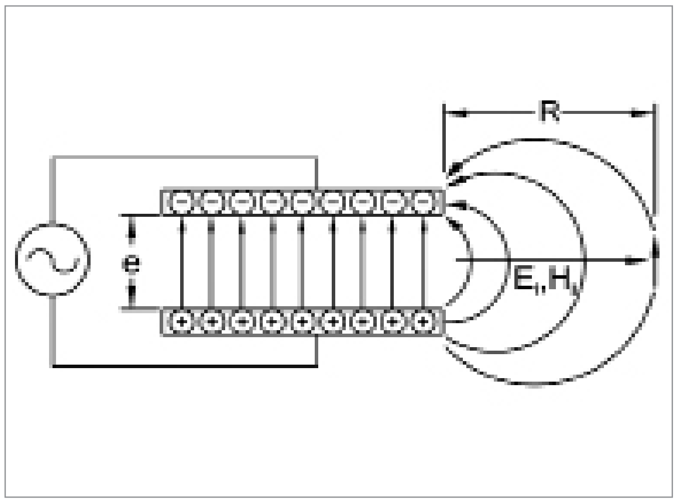


Figure 2 – The resulting electromagnetic field between two parallel plates.

As is illustrated in *Figure 2*, the lines of flux in the center of the plates are straight and flow from the bottom to the top plate. At the edges they bow out, where the fields or lines of flux repel each other, forcing the bowing. The field that bows out is an EM field where the E vector quantity is equal to the voltage divided by the length of the force line in meters (i.e., if the point of concern is one meter from the set of plates, the E field would be the voltage across the set of plates divided by the circumference of the circle or approximately E/3.1). The magnetic or H field is approximated by the following equation:

$$H_I = 2\pi R E_I / 377\lambda \qquad R \le \lambda/2\pi$$
$$= E_I/377 \qquad R \ge \lambda/2\pi \qquad (1)$$

Where R = Distance from dipole antenna to barrier (m)
λ = Wave length = c/f
c = 3 x 10^8 m/sec
f = Frequency (Hz)

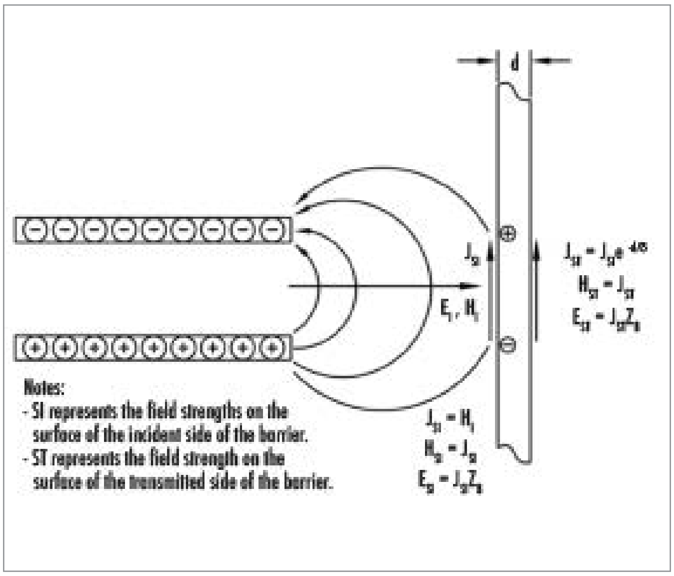


Figure 3 – Current flow in a shielding barrier in close proximity to an EM field.

Suppression (Shielding) of EM Waves
When we place a shielding barrier in the path of the EM field, the force of the field causes current to flow in the barrier. As is illustrated in *Figure 3,* the excess electrons in the bottom plate create a force on the electrons in the barrier. This force causes the electrons to flow away from the point of contact. In a similar manner, the lack of electrons on the upper plate will create an excess of electrons on the barrier at the upper point of contact. This current flow in the barrier is called the "surface current density" (Js) in amperes/meter, and is equal to the H field incident on the barrier when the field is perpendicular to the barrier. The current flowing in the barrier is attenuated by the skin effect.

The current on the transmitted side is equal to $J_{SI}e^{-d/\delta}$ (i.e., the current on the incident side attenuated by skin effect). The impedance of the field emanating from the barrier is equal to the impedance of the barrier. The values of E_T and H_T are as illustrated in *Figure 3* and are as follows:

$$H_T = J_{SI}\, e^{-d/\delta} \qquad (2)$$

$$E_T = H_T Z_B \qquad (3)$$

Where E_T = Transmitted E field (V/m)
H_T = Transmitted H field (A/m)
d = Thickness of barrier (m)
δ = Skin depth (m)
Z_B = Impedance of barrier (ohms)

$$Z_B = \frac{1+j}{\sigma\delta(1-e^{-d/\delta})}$$

Shielding Quality of Shielding Materials
The definition of shielding quality as used herein is the difference in dB between the E field and H field of the wave incident on the barrier and the wave emanating from the barrier on the opposite side, i.e.,

$$SQ_E = 20\ 1ogE_I/E_T \qquad (4)$$

$$SQ_H = 20\ 1ogH_I/H_T \qquad (5)$$

From *Figure 3* we know that the E field in the barrier on the incident side is equal to the H field (i.e., Js) times the impedance of the barrier. Therefore, we can conclude that the ratio of the E field of the incident wave to the E field in the barrier on the incident side is:

$$E_I/Z_B H_I \qquad (6)$$

We also know that the impedance of the incident wave is equal to:

$$Z_W = E_I/H_I \qquad (7)$$
and therefore $H_I = E_I/Z_W$

Substituting E_I/Z_W for H_I in *Equation 6* we can conclude that the ratio of the E fields in the incident wave and the E field in the barrier on the incident side equals:

$$Z_W/Z_B \qquad (8)$$

From *Figure 3* we also note that the E field in the barrier is attenuated by the skin effect, i.e.,

$$E_T = E_O\, e^{-d/\delta} \qquad (9)$$

Where E_T = Transmitted E field
E_O = E field in barrier on incident side
d = Thickness of barrier (m)
δ = Skin depth (m)

From *Equations 4, 8* and *9* we can conclude that the shielding quality of material used in a shielding barrier for the E field is:

$$SQ_E = 20 \log ZW \qquad (10)$$

Where $Z_w = \frac{E_I}{H_I}$
= -j377λ/2πr (r < λ/2π) Elec. dipole source
= j377 (2πr/λ) (r < λ/2π) Mag. dipole source
= 377 (r ≥ λ/2π) Both sources

$$Z_B = \frac{1+j}{\sigma\delta(1-e^{-d/\delta})}$$

$\delta = (2/\mu\sigma\delta)^{1/2}$ skin depth (m)
σ = Volume conductivity of mat'l (mohs/m)
μ = Absolute permeability of mat'l (Henrys/m)
$\lambda = c/f = 3x10^8$/frequency (m)
r = Distance from source to barrier (m)
d = Thickness of material (m)

Using the same logic and the information of *Figure 3* we can conclude that the shielding quality of a material for the H field is:

$$SQ_H = 20 \; 1og \; e^{-d/\delta} \qquad (11)$$

Comparative Analysis
A comparative analysis at 1 MHz has been performed comparing the results of the shielding effectiveness of an aluminum shield using the accepted SE = R + A + B formula derived from wave theory and the shielding quality equations derived from circuit theory (see *Appendix A* for analysis).

The conditions used for the comparative analysis are consistent with the test conditions of an earlier paper entitled "Shielding Effectiveness Test Results of Aluminized Mylar." These conditions are as follows:

1. The aluminum shield is aluminized Mylar having a dc resistance of 1.4 ohms/square. The thickness of the aluminum (based on the resistance) is 2 x 10^{-8} meters and has a theoretical impedance of 2.0 ohms.

2. The impedance of the wave at the shield radiating from the loop antenna is 4.0 ohms.

3. The impedance of the wave at the shield radiating from the electric dipole antenna is 3500 ohms.

The results of this analysis along with the results of the test contained in the earlier paper are illustrated in *Table 1.* These results are as follows:

1. Attenuation to E field. The analysis using equations derived from wave theory and circuit theory yielded a close approximation to the E field from both the electric and magnetic dipole antennas.

2. Attenuation to H field. The analysis using the equations derived from circuit theory gave a very close approximation. However, the analysis using the equations derived from wave theory resulted in an error of more than three orders of magnitude using the electric dipole antenna as the radiating source.

We can conclude from the results of the "SE=R+A+B" equations derived from wave theory that the equations were intended to predict the attenuation of only the E field through a shielding barrier.

The comparative analysis contained in the appendix contains a significant amount of information. Of particular concern are the results of the analysis contained in *Table A-I* (of the Appendix) using the wave impedance consistent with the magnetic dipole (loop) radiation source (4 ohms) and the thickness of the shield of 2 x 10^{-8} meters. From the explanation contained in the books and papers on shielding theory using R + A + B we learn that the reflection coefficient "R" represents a ratio of power reflected from the shield material to that which penetrates into the shield material. The 66.5 dB means that if 1 watt of power is incident on the shield, 2113 units are reflected for each unit that penetrates into the barrier (99.95% is reflected and .05% or .5 milliwatts penetrate the barrier). The shielding effectiveness level of 3.1 dB implies that 20% of the 1 watt (or 700 milliwatts) is observed on the secondary side of the shield material. This means that the re-reflection coefficient amplifies the energy which penetrates the shield by 140,000%. This amplification is obviously not possible and means that the explanation is faulty. It can also be noted using the equations of SE = R + A + B derived from wave theory that the impedance of the barrier Z_B is calculated to be 4 orders of magnitude less than the actual impedance using a resistance bridge when the barrier was 2 x 10^{-8} meters thick (i.e., the impedance of the barrier is the same regardless of the thickness of the barrier).

Table 1: Results of comparative analysis as compared to test results at 1 MHz with two ohm aluminized Mylar shield.

SE/SQ at 1 MHz	Radiating Source	
	Electric Dipole Antenna	Magnetic Dipole Antenna
E Field		
Test Results	66	7
Wave Theory	62	3
Circuit Theory	65	6
H Field		
Test Results	0	0
Wave Theory	62	3
Circuit Theory	0	0

Conclusion
The shielding quality equations which have been derived from circuit theory provide a close approximation of the attenuation of a wave through a barrier and are far easier to understand by the average design engineer than the presently used shielding effectiveness equations. The equations also provide information that is more appropriate to the design engineering community, i.e.,

> The voltage induced into a circuit is a function of the wave impedance and the impedance of the circuit. If a design engineer uses 377 ohms instead of the 2 ohms emanating from the aluminized Mylar shield in

performing a susceptibility analysis of a piece of electronic equipment, the calculated induced voltage can be off by more than two orders of magnitude.

Shielding quality as a measure of the attenuation characteristics of a shield is considered a more appropriate term. Shielding effectiveness is a well-defined term and possesses a specific connotation within the engineering community. However, the definition is not well understood. For example, suppose an engineer performs a susceptibility test on equipment circuits and discovers that he needs 40 dB of shielding to comply with his requirements. He selects a shield that renders 60 dB of shielding effectiveness using the shielding effectiveness equations. Upon retest after manufacturing his shield, he finds he still need 20 dB of shielding.

The term shielding effectiveness implies a level of shielding the engineer is going to obtain. In the above case the results are a level 40 dB less than is expected. There is nothing associated with the equations that can explain the results to him where the problem could easily be the distance from the shield material to the circuits being affected by the radiated field. The term of shielding quality defines the attenuation of a field by the shield material, and that definite information with regard to the field of the incident wave as well as information associated with the susceptibility of the circuits is required. Once the required information is available, a ready solution can be obtained.

The use of the shielding quality equations derived from circuit theory are more consistent with the principles associated with the engineering discipline than are the shielding effectiveness equations, especially when the shielding barrier is in close proximity to the EM source (near field).

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Appendix A
Shielding Effectiveness Versus
Shielding Quality Analysis

Included is an analysis for estimating the shielding effectiveness of aluminum shielded barriers using the equations consistent with wave theory and R + A + B technology and estimating the shielding quality of the same barriers under the same conditions using the equations contained in the body of this article.

The shielding effectiveness equations of concern associated with wave theory are:

$$SE = R + A + B$$

$$R = 20\log\frac{(K+1)^2}{4|K|} \quad \text{where } K = Z_{Wave}/Z_{Barrier}$$

$$Z_{Barrier} = \frac{1+j}{\delta\sigma}$$

$$A = 201\text{og}\ e^{-d/\delta}$$

$$B = 20\log\left(1 - \left[\frac{K-1}{K+1}\right]^2 e^{-2d/\delta}\right)$$

$\delta = \left[\frac{2}{\mu\sigma\omega}\right]^{1/2}$ skin depth (m)
d = Thickness of barrier (m)
σ = Volume conductivity of material (mohs/m)
μ = Absolute permeability of material (Henrys/m)
ω = 2πf

Table A-1: Results of Shielding Effectiveness Analysis Using Wave Theory and SE = R + A + B

Frequency (Hz)	d (meters)	Zw (ohms)	Zb** (ohms)	R (dB)	A (dB)	B (dB)	SE* (dB)
10^6	$2x10^8$	4.0	$4.72x10^4$	66.5	0.0	63.4	3.1
10^6	$2x10^8$	3500	$4.72x10^4$	125.4	0.0	63.4	62.0

The results of the analysis are shown in *Table A-l.*
The equations used for calculating the shielding quality of the shielding material using circuit theory and contained in the body of this article are:

$$SQ_E = 20\log\frac{Z_W}{Z_B}\ e^{-d/\delta}$$

$$SQ_H = 20 \text{ 1og } e^{-d/\delta}$$

$$Z_B = \frac{1+j}{\sigma\delta(1-e^{-d/\delta})}$$ with d and σ as defined above.

The results of the analysis are shown in *Table A-2*.

Table A-2: Results of Shielding Quality Analysis Using Circuit Theory

Frequency (Hz)	d (meters)	Zw (ohms)	Zb** (ohms)	SQ_E (dB)	SQ_H (dB)
10^6	$2x10^{-8}$	4.0	2.0	6.0	0.0
10^6	$2x10^{-8}$	3500	2.0	65	0.0

* This shielding effectiveness estimate is for both E and H fields (i.e., the shielding effectiveness for both fields is stated to be the same).

** The Z_B equation and value in the shielding effectiveness equations assumes the barrier is infinitely thick.

$$\text{i.e., } Z_{Barrier} = \frac{1+j}{\delta\sigma}$$

where δ thickness in meters is applicable for an infinitely thick barrier.
The equation for a barrier of any thickness is:

$$Z_B = \frac{1+j}{\sigma\delta(1-e^{-d/\delta})}$$

where $(1-e^{-d/\delta})$ is a correction factor when the thickness is finite.

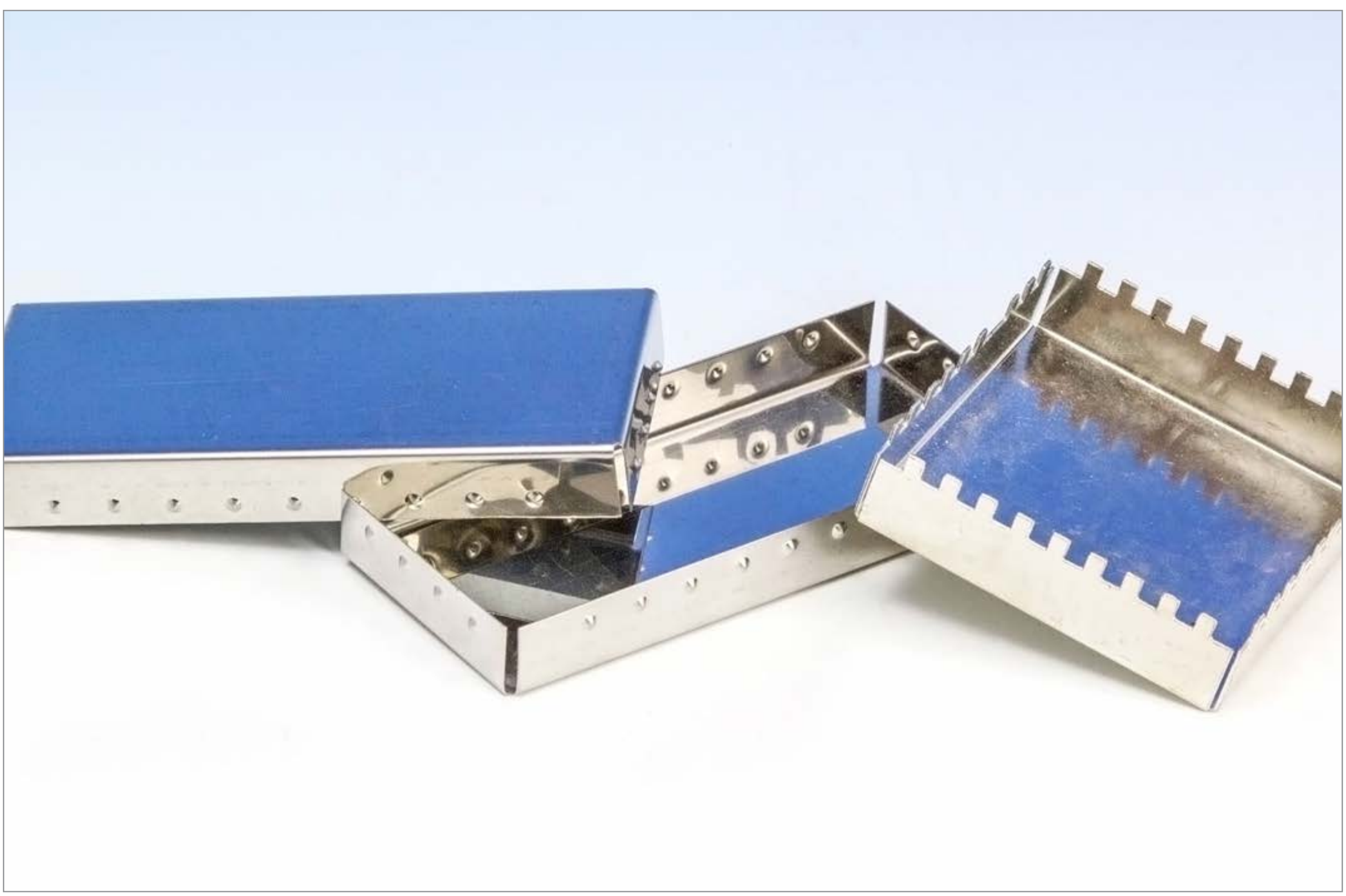
Appendix B
Shielding Effectiveness Approach to Shielding Theory

The use of Maxwell's equation to obtain the Shielding Effectiveness (SE) of a shielding material requires compliance to "Stokes Function" (the sum total of all power entering or leaving a given area must equal zero unless there is a sink or source of power). This method if properly applied will provide the engineering community with values of "SE" and the attenuation for the E and H field that are useful to the design engineer.

The wave theory approach (as presently interpreted) does not meet the requirements of "Stokes Function". The present interpretation stipulates that the power loss to an H field inside the barrier is equal to the power loss associated with an E field being reflected at the incident side of the barrier. This does not occur for the following reasons:

1. Broaddus and Kunkel did not detect an H field loss.

2. When the barrier is thick, skin effect prevents the EM wave from reaching the back side of the barrier. This fact eliminates the possibility of an H field reflection.



EMI BASICS AND BOARD LEVEL SHIELDING DESIGN

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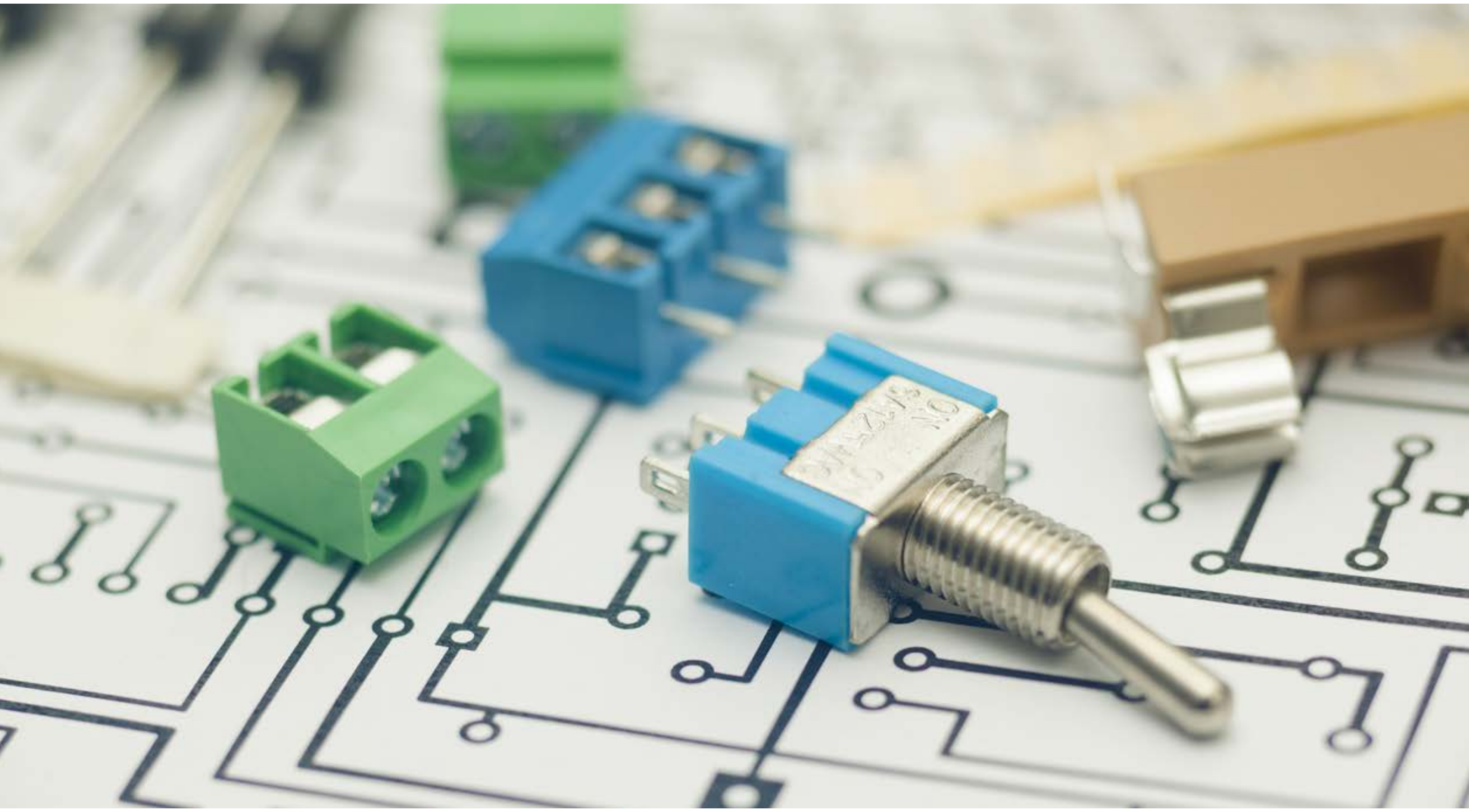
Introduction

In today's world full of digital electronic devices, electromagnetic interference (EMI) is a major concern in both military and commercial marketplaces. Electrical equipment can become susceptible to these undesirable emissions and malfunction due to their presence. The simplest and most cost-effective method for reducing EMI is to first attack it at the board level if possible. Given the increasing complexity of circuitry these days, it is rare that a printed circuit board (PCB) layout can solve EMI problems entirely; thus board level shielding has become a requirement for most PCB designers.



EMI BASICS AND BOARD LEVEL SHIELDING DESIGN

Radiated EMI occurs when an electromagnetic wave travels in the direction of an electronic device, and then disrupts the operation of that electrical component. An electromagnetic wave consists of an electric field (E) and a magnetic field (H), and the ratio of E to H (E/H) is known as the wave impedance (Z). For air or free space, Zo = 377 Ω. An electromagnetic wave with an impedance below this value is predominantly magnetic, whereas a wave with an impedance above it is mainly electric.

Using a board level shield for EMI shielding means to use a metal can, also known as a faraday cage, to enclose an electronic circuit on a PCB. This in turn will limit the amount of EMI radiation from the external environment that can disrupt PCB components, and also mitigate the amount of EMI energy generated by the circuit from escaping into the external environment.

The efficiency of a board level shield is measured in terms of shielding effectiveness (SE), which is the amount of EMI attenuation expressed in terms of decibels (dB). As depicted in *Figure 1* (Gnecco, 2000), when an electromagnetic wave comes in contact with the shield material, some of that energy is reflected, some is absorbed into the shield material, and some of it passes through the material. Thus, the total shielding effectiveness of an EMI shield is based upon the summation of the losses due to reflection and absorption.

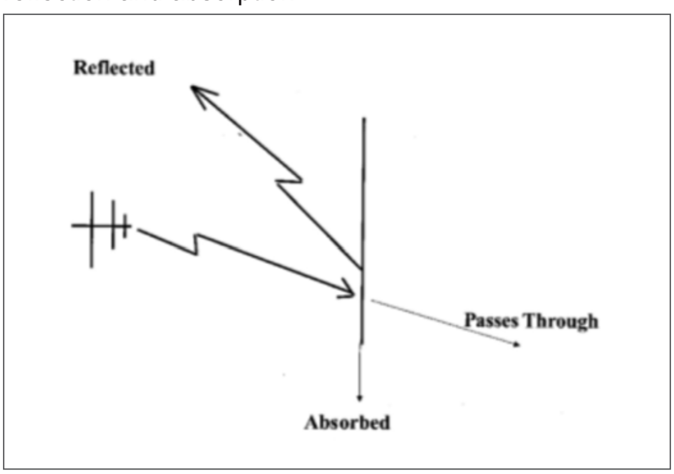


Figure 1 - Electromagnetic Wave at Shield Surface

Absorption loss is dependent upon the physical characteristics of the shield, and is directly proportional to the thickness of the shield, relative magnetic permeability and electrical conductivity of the material, and the frequency of the electromagnetic wave. Therefore, a thick walled shield with high permeability and conductivity will perform well in terms of absorption loss. Absorption loss is critical when emission suppression is needed, such as when a shield is being used to prevent electromagnetic energy from escaping an enclosure; see *Figure 2* (Tong, 2008).

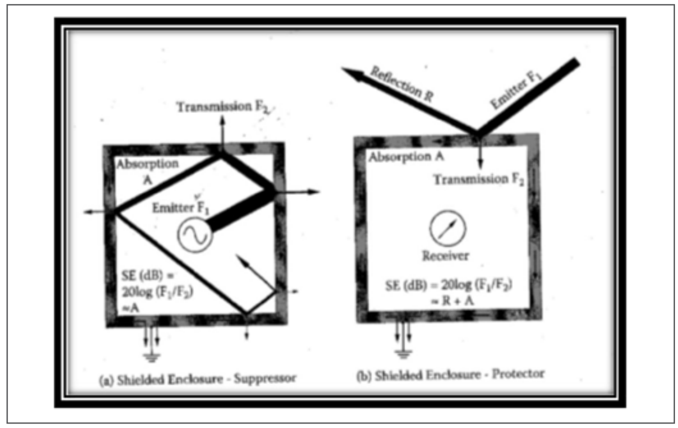


Figure 2 - EMI Protection vs. EMI Suppression (Tong, 2008)

On the other hand, reflection loss is important when a PCB component is to be protected from external sources. Reflection loss is dependent upon the relative mismatch between the impedance of the electromagnetic wave and that of the EMI shield material. If an electromagnetic wave's impedance differs from that of an EMI shield, then the wave will be partially reflected back. On the contrary, if the shield's and wave's impedance values are closely matched, then the energy will pass through the shield.

It is important to note that electrically dominant incident waves (impedance greater than 377 Ω) have high impedance, and higher conductive metals have low impedance. Thus, highly conductive metals exhibit high reflection loss for electrically dominant waves. However, for magnetically dominant incident waves that have low impedance (less than 377 Ω), the impedance mismatch between the shield & wave is minimal; hence the resulting reflection loss is very low. As a result, absorption loss is critical for shielding magnetic fields.

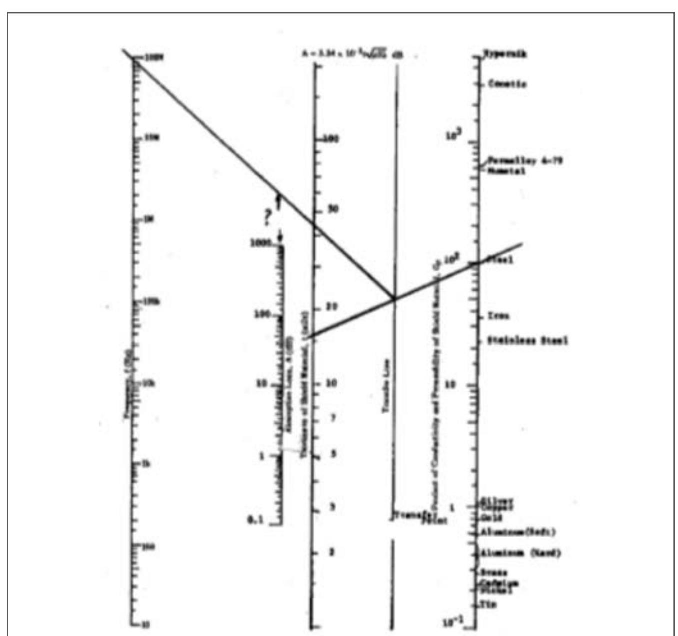


Figure 3: Absorption Loss w/ Material, Frequency & Shield Thickness

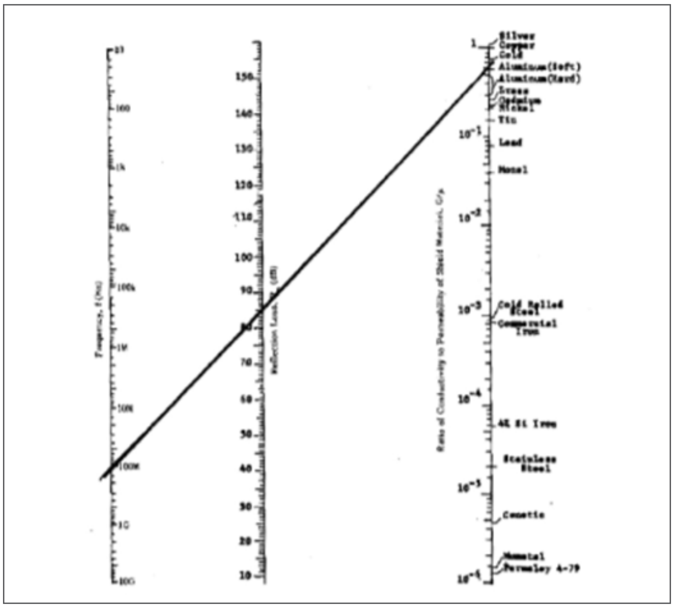


Figure 4: Reflection Loss w/ Material & Frequency (Gnecco, 2000)

Figures 3 and *4* (Gnecco, 2000) illustrate the theoretical absorption and reflection loss that can be achieved with an EMI shield using different materials, respectively. In order to make use of *Figure 3*, a line must be drawn from the known thickness of the EMI shield to the material being used, and then another line must be drawn from where it intersects the transfer line to the frequency of the incident electromagnetic wave. It is evident when viewing *Figure 3* that for a given frequency a thick walled shield with a high permeability material such as high permeability steel will outperform a thin walled highly conductive shield made of copper or brass in terms of absorption loss. On the other hand, *Figure 4* reveals that for a given frequency highly conductive materials (copper or brass) will surpass the performance of a lesser electrically conductive material (high permeability steel or stainless steel) in terms of reflection loss.

Although conceptual tools such as *Figures 3* and *4* are helpful in determining the appropriate shielding material for a given application, it is not entirely realistic as they assume that no apertures are present in the shield design. The performance of EMI shields is greatly affected by seams and penetrations, especially when dealing with electrically dominant waves at higher frequencies. The higher the frequency of an electromagnetic wave, the shorter its wavelength and the more likely it is to escape through any openings in an EMI shield. Therefore, when designing an enclosure it is critical to minimize the apertures to decrease the potential EMI leakage points, and to maximize the quality of the design near apertures for overall performance & reliability for the long term.

The frequency at which electromagnetic energy will propagate through an aperture without being attenuated is known as the cutoff frequency (fc). Frequencies above fc will propagate freely, while those below fc are attenuated.

The equations below (Weibler, 1993) demonstrate how to calculate the cutoff frequency.

$f_c = c / \lambda_c$; where c is the speed of light (m/s), λ_c is the cutoff wavelength (m), f_c is the cutoff frequency (Hz)

For:

- Circular apertures: $\lambda_c = 3.412r$; where r = radius of the aperture (m);
- Rectangular apertures: $\lambda_c = 2a$; where a = longest dimension of the aperture (m)

Besides knowing the cutoff frequency, a good rule of thumb to achieve excellent EMI shielding effectiveness in any application is to keep every aperture size no larger than 1/20 wavelength of the electromagnetic wave being attenuated, and to aim for aperture sizes as small as 1/50 wavelength (Tong, 2008). *Table 1* below is a helpful resource that lists a sampling of frequencies and their corresponding wavelengths and recommended maximum aperture size based on 1/20 and 1/50 wavelength.

Table 1: Frequency-Wavelength Chart

Frequency (GHz)	Wavelength (mm)	1/20 Wavelength (mm)	1/50 Wavelength (mm)
0.5	600	30	12
1	300	15	6
2	250	12.5	5
3	100	5	2
4	75	3.75	1.5
5	60	3	1.2
10	30	1.5	0.6
20	15	0.75	0.3
50	6	0.3	0.12
100	3	0.15	0.06

Proper design of EMI board level shielding is crucial, and if done right can even eliminate the need for overall enclosure-level shielding. Many EMI shield manufacturers have fully tooled standard, low cost off-the-shelf options readily available. Therefore, it is a good idea to plan and design for the use of board level shields during the initial PCB design to take advantage of these options.

References

1. Gnecco, Louis T. 2000. The Design of Shielded Enclosures: Cost Effective Methods to Prevent EMI. Woburn, MA: Butterworth-Heinemann.
2. Tong, Xingcun Colin. 2008. Advanced Materials and Design for Electromagnetic Interference Shielding. Boca Raton, FL: CRC Press.
3. Weibler, Joseph. 1993. Properties of Metals Used for RF Shielding, EMC Test & Design.

HOW TO SPECIFY BOARD LEVEL SHIELDING

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Orbel Engineered Solutions

HOW TO SPECIFY BOARD LEVEL SHIELDING

The Purpose of Board Level Shields

Board level shields (BLS) are generally small metallic shielded boxes mounted directly to PC board ground return layers. There are three primary purposes of board level shields:

- Isolation of sensitive circuitry from other noisy circuits on the board
- Trapping the emissions from noisy circuits on a board from propagating to the outside environment
- Keeping RF sources from the external environment from disrupting sensitive circuitry on the board.

Note that, depending on the wavelengths of the RF sources or noise, the connecting pin spacing for the attachment to ground return layer may need to be fairly close together. A good rule of thumb is no farther apart than 1/20th of a wavelength at the highest expected frequency. For critical applications, some board level shields are soldered with a continuous seam along the attachment point to the PC board.

Selecting a Shielding Manufacturer

The first step in specifying board level shielding is selecting a shielding manufacturer who can design and produce both standard and custom BLS while offering design flexibility for surface-mount and through-hole configurations. Ideally, this manufacturer will offer an array of standard shields that can be customized to any performance or application requirement, meeting today's challenging EMI/RFI shielding applications.

An extensive selection of standard BLS features (pin options, corner options, etc.) and material/design options will make it easy for you to specify board level shields that meet your product requirements. Look for the following:

- Unlimited shield sizes
- Variety of material options
- Multiple fence/cover retention methods
- Variety of pin and surface-mount styles
- Custom trace notches at no extra cost
- Standard ventilation holes
- Part number and logo identification
- Standard pick target for pick and place
- Tape-and-reel and/or tray packaging
- RoHS compliance

Choosing Your Features & Performance Specs

Whether you're in need of one-piece, two-piece, multi-cavity, or custom-configured shielding, your next step is choosing the features and performance specs that will transform your shielding concept into a high-performance reality:

Pin Options

- Alignment Pins
- Through-Hole Pins
- Through-Hole Pins with Standoffs
- Castellation Edges
- Straight Edges with No Pins

Corner Options

- Tight Corners
- Louvered Corners
- Welded Corners

Additional Options

- Trace Notches
- Pick Targets
- Ventilation Holes
- Logo or Part Number Markings

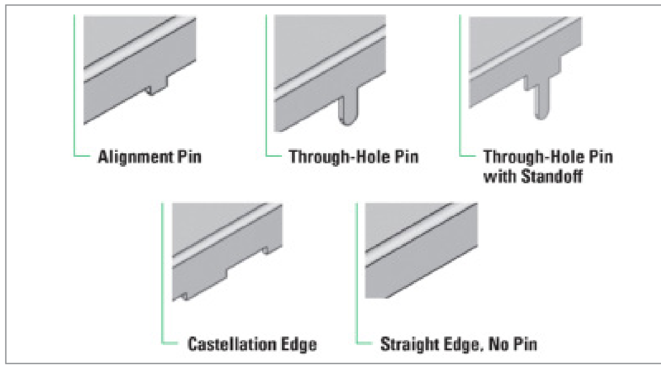

Figure 1 - Typical pin option attachments for board level shields. Figure, courtesy Orbel.

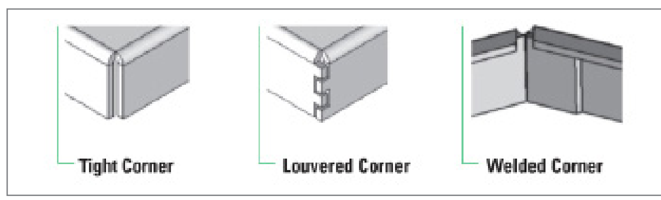

Figure 2 - Typical corner options for board level shields. Figure, courtesy Orbel.

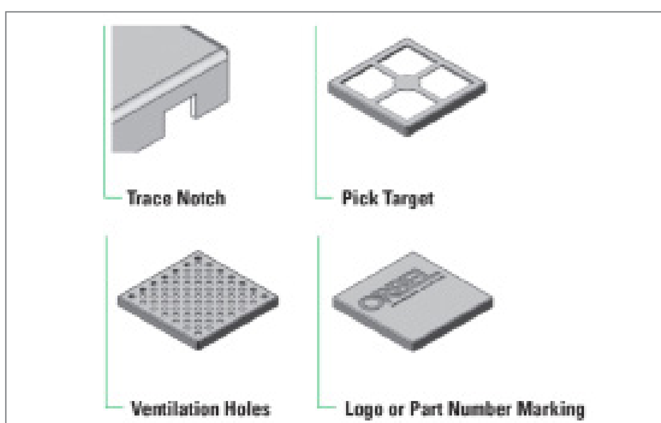

Figure 3 - Typical attachment and style options. Figure, courtesy Orbel.

When choosing performance specs, it is also important to consider your material options (nickel silver, beryllium copper, phosphorus bronze, stainless steel, etc.), co-planarity, material thickness, RoHS compliance, and shielding effectiveness.

Configuring & Ordering Your Shielding
Most BLS manufacturers utilize a part number system that both serves as a product reference guide and identifies the way a shield has been configured. In the case of Orbel Corporation, the part number codes are as follows and are described in the example shown.

For example, let's evaluate a sample Orbel part number, **B-0750 TB 1125-0250 X F-TPS**, piece by piece. Other manufacturers may have a similar part numbering system.

"B" represents the "B" in "Snap-Shield Bullzeye™," a popular board shield style. Other board shield styles include:

G = EZ-Shield **Guardian™**
M = Snap-Shield **Micro™**
L = Snap-Shield **LaZerLock™**
S = Snap-Shield **SmartFORM™**
T = Snap-Shield **TRU-View™**
V = **Vault**-Shield™
H = Snap=Shield **HEMI™**

"0750" represents the shield's frame width.

"TB" represents "Through-Hole (0.500" spacing)," the shield's mounting style. Other standard mounting styles include:

TA = Through-Hole (0.250" spacing)
TC = Through-Hole (1.000" spacing)
SA = Surface-Mount with Alignment Pins
SB = Surface-Mount with Castellations
SC = Surface-Mount with No Pins

"1125" represents the shield's frame length.
"0250" represents the shield's frame height.

"X" represents a material thickness of 0.010", which is a standard size for Orbel. Other standard material thicknesses include:

Y = 0.015"
Z = 0.008"

"F" is the shield code for "Shield Frame." Other standard shield codes include:

C = Shield Cover
A = Assembled
P = Unassembled Pair

"TPS" represents "Tin-Plated Steel." Other standard material options include:

No Code = Nickel Silver (standard)
TPB = Tin-Plated Brass
TPC = Tin-Plated Copper

Other manufacturers will offer similar coding.

Figure 4 - Designed around today's most challenging EMI shielding applications, board level shielding (BLS) from Orbel, and other manufacturers, is available in one-piece, two-piece, multi-cavity, and custom configurations.

Specifying Custom Board Level Shielding
If you are in need of a custom BLS solution, make sure you are working with a shielding manufacturer with proven engineering expertise and the advanced production techniques needed to deliver unlimited design flexibility. If your manufacturer offers custom features for both surface-mount and through-hole shield configurations, they will be able to transform your shield concept into an innovative, cost-effective solution. Look for the following custom capabilities:

- One-piece, two-piece, and multi-cavity
- Unlimited design flexibility
- Any shape or size
- Wide selection of materials
- Variety of plating finishes
- Consultative engineering services

With the right shielding manufacturer on your side, any shielding concept can be turned into a practical BLS solution. Simply convey the features you need to incorporate into your shield design, and your manufacturer can help you create a custom-configured shield that meets your needs.

Please feel free to contact the author for any questions at: kmarino@orbel.com

COST-EFFECTIVE APPLICATIONS OF EMI GASKETS

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Introduction

EMI gaskets are used extensively by the electrical/electronic industry to assist in complying with the various EMI radiated emission requirements. These requirements include compliance to DoD TEMPEST and EMI, and FCC and EU EMI test limits. As a rule of thumb the radiated emission TEMPEST requirements are about two orders of magnitude (40 dB) more stringent than the DoD EMI requirements, and the DoD EMI radiated emission requirements are about two orders of magnitude (40 dB) more stringent than the FCC and EU EMI requirements. This means that in terms of difficulty, complying to the FCC and EU requirements is relatively easy. However, the expense can be high in terms of the percentage increase in the cost of manufacturing the equipment. The FCC requires that the manufacturers of the equipment that falls under their jurisdiction be responsible for compliance throughout the life of the equipment. As such, the cost of not complying for the life span of the equipment can be very costly (i.e., redesign and retrofit can become a catastrophic cost).

COST-EFFECTIVE APPLICATIONS OF EMI GASKETS

Introduction

While many military and aerospace EMC issues may be addressed by operational changes, testing is still required to find weaknesses.

The cost of complying with the FCC (as well as DoD, EMI and TEMPEST) radiated emission requirements can be reduced to within acceptable limits by understanding the problems associated with the radiation and suppression of radiated electromagnetic waves. Because of the relatively low FCC compliance EMI radiated emission suppression levels, EMI gaskets are not always needed. However, the proper selection and use of EMI gaskets can often significantly reduce the expense associated with compliance costs. A significant aspect associated with the proper selection and use of EMI gaskets is to be prepared to use them if they are needed. If one is not prepared, then the driving force in selecting a gasket is the least cost to add the gaskets after the fact. In such cases, the cost can be, and usually is, exceedingly high. The paragraphs that follow describe the generation and propagation of electromagnetic (EM) waves from wires, the method used to shield the fields, low cost methods of implementing EMI gaskets and problems associated with obtaining reliable shielding throughout the life of the equipment.

The Generation, Propagation and Shielding of EM Waves

The equipment covered by FCC and EU requirements contains circuits, which generate RF energy that falls within the bandwidth of radios and other communication equipment. This energy travels on wires from one circuit to another, where the wires connecting the two circuits act as antennas. The energy emanating from the wires is transmitted out of the equipment in the form of electromagnetic (EM) waves. When the magnitude of the waves are a higher amplitude than is allowed by the specification limits we call it electromagnetic interference or EMI.

The fields, which radiate from wires are similar to the fields which radiate from electric dipole antennas. *Figure 1* illustrates an EM field emanating from a transmission line pair.

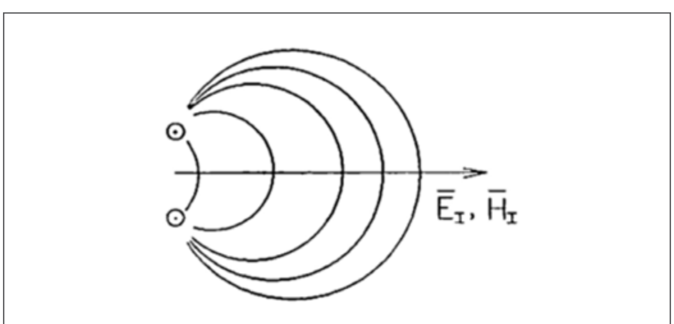

Figure 1. EM field emanating from a transmission line pair.

We know from antenna theory that the impedance of the wave is equal to Ē/H where the relationship of H to Ē is approximately equal to the following:

$$\bar{H} \cong \frac{2\pi \bar{E} R}{377\lambda}\left(R < \frac{\lambda}{2\pi}\right)$$

$$\cong \frac{\bar{E}}{377}\ (R < \frac{\lambda}{2\pi})$$

$$\text{where: } \lambda = 3\,X\frac{10^8}{f}\ \text{(meters)}$$

R = Distance from radiating wire to point in question (meters)

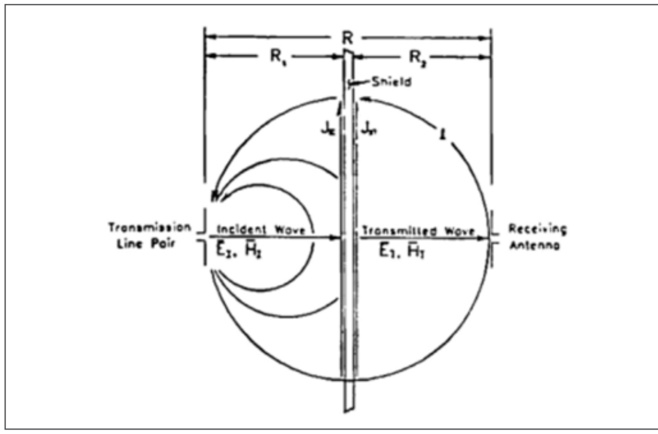

Figure 2.

When the wave of *Figure 1* strikes a shielding barrier, a current JSI (i.e., surface current density on the incident side) is generated on the shield as illustrated in *Figure 2*. The current is equal to approximately two times the value of H in amperes/meter of the incident field (the field that radiates from the wire and strikes the barrier). The current in turn is attenuated by the skin depth of the barrier where the current on the transmitted side, JST, will generate another EM field. The magnitude of the "E" field in volts/meter emanating from the barrier will be JST (current density in amperes/meter on the secondary side) times the impedance of the barrier in ohms. The secondary field is what is detected by the test antenna.

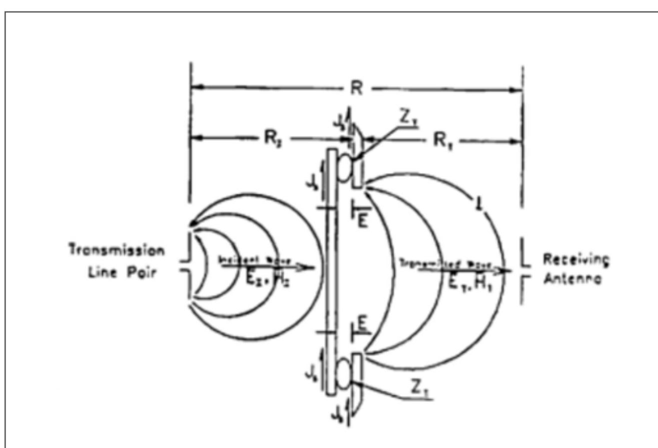

Figure 3.

If the shielding barrier has a joint in it, the current will flow across the joint creating a voltage which is equal to JSI times ZT (the current in amperes/meter times the transfer impedance of the joint in ohm-meters). A field will radiate from the joint as illustrated in *Figure 3* and is observed by the test antenna. If the field so detected is above the limits specified by the requirements we must reduce the transfer impedance (ZT) of the joint. This can be accomplished by the use of additional fasteners or by the use of EMI gasket material.

Cost Effective Use of Gaskets

Commercial electronic equipment is generally housed in non-conductive die-cast or molded plastic cabinets. The cabinets are coated with a conductive material to provide the required shielding for compliance to FCC or VDE limits. This is usually accomplished by plating the inside of the cabinet with an electroless coating (aluminum, nickel, copper, tin, etc.) or with a conductive paint. This coating will reduce the EM fields penetrating the cabinet walls to within acceptable levels. However, the joints of the cabinet provide a convenient path for the EM fields to penetrate the cabinet. These fields are reduced to acceptable levels by providing conductive paths between the joint surfaces of the cabinet. This can be performed by the use of additional fasteners or by the use of EMI gasket material. The use of EMI gasket material can be a very cost effective means of obtaining the shielding at the joint surfaces. The cost of using EMI gasket material can be significantly less than the cost of using fasteners. However, to obtain the cost effective advantage, provisions must be made in the die or mold to provide room for the gasket material and methods of holding the gasket material in place.

There are two kinds of EMI gasket material that are recommended for cost effective use. These are as illustrated in *Figures 4* and *5* and are as follows:

1. Commercial grade convoluted spring EMI gasket material. The material is made from low cost stainless steel, and can be purchased in cut-to-size lengths for pennies per inch. The material can provide an EM bond of one milli-ohm per meter length, and can be held in place by the use of pinch bosses or retaining holes.

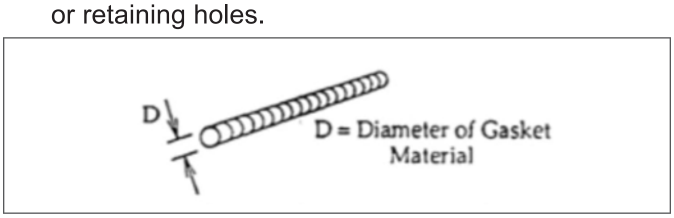

Figure 4.

2. The commercial grade convoluted spring gasket material attached to a neoprene sponge elastomer. An adhesive backed tape is supplied with the elastomer, where the purpose of the elastomer and tape is to hold the EMI bonding material in place.

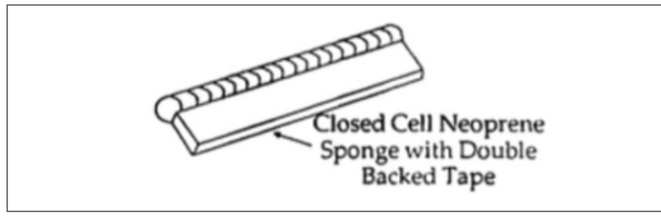

Figure 5.

In using the convoluted spring gasket material, (or any similar EMI gasket material), a groove must be provided in the die or mold to house the gasket. The recommended groove is illustrated in *Figure 6* where the width of the groove is about 35% wider than the gasket material and the depth is about 75% of the width (diameter) of the gasket material. *Figure 7* also illustrates a method, which has been effectively used to protect the gasket.

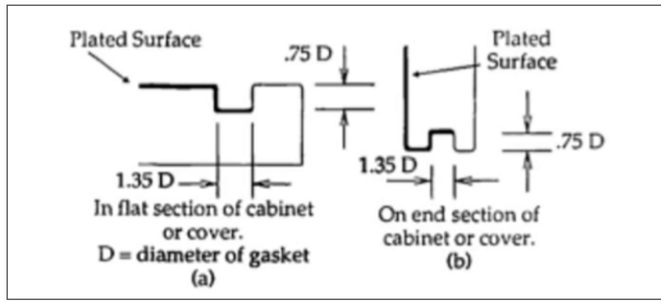

Figure 6.

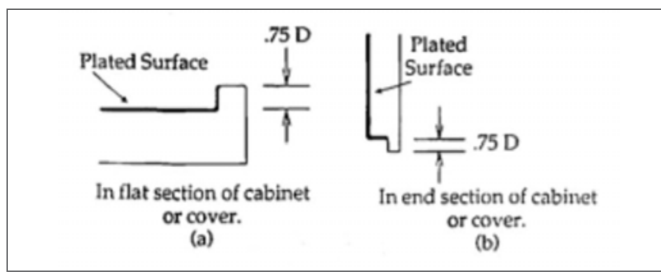

Figure 7.

The recommended diameter of the gasket material is between 0.06 and 0.15 inches (1.5 mm to 3.8 mm). Assuming a 25% maximum deflection of the gasket, this will accommodate a 0.015 to 0.037 inch gap (or unevenness) between the joint surfaces to be EM bonded. Please note! The purpose of the gasket is to provide a conductive path between the separate parts of the case. Therefore, care must be exercised to ensure that the conductive plating on the separate parts interface with the gaskets.

The grooves or configurations of *Figures 6* and *7* provide a place for the gaskets to sit. However, provisions must be made to hold the gasket materials in place. This is accomplished by providing pinch bosses or retaining holes along the groove. The pinch bosses are illustrated in *Figure 8* and retaining holes in *Figure 9*. Because the requirements are relatively easy to comply with, continuous gasketing throughout the length of the joint is not required (i.e., small segments along the length of the joint can be used effectively). The actual optimal length and number of segments of EMI gasket material will not be known until the EMI testing on a finished prototype equipment is completed. One (1) to 1-1/2 inch segments on one (1) or two (2) of the four (4) sides of a small cover is often sufficient. The grooves of *Figure 6* and *7* must be placed in the die or mold during the early design phases. The pinch bosses or retaining holes can be placed in the die or mold after the EMI testing is completed and optimal required gasketing is known.

Please note! During EMI testing, the segments of EMI gasket material can be held in place using tape or other non-destructive methods of retainment.

In applying the gasket material to the unit case the following considerations should be applied.

1. Pinch bosses

a) Cut the gasket material to the appropriate length (outside-to-outside distance between pinch bosses).

b) Push one end of the gasket material between one set of pinch bosses.

c) Stretch the gasket about 5% (to put the gasket under slight tension) and push the loose end into the other set of pinch bosses.

2. Retaining hole

a) Cut the gasket material to the appropriate length (distance between holes plus 0.4 inches).

b) Insert one end of the gasket into one hole.

c) Holding the inserted end in the hole stretch the gasket and insert the gasket into the other hole all the way to the bottom.

d) Release holding devices (i.e., fingers, etc.).

Note: A silicone RTV adhesive can be used to positively secure the two ends inside the hole.

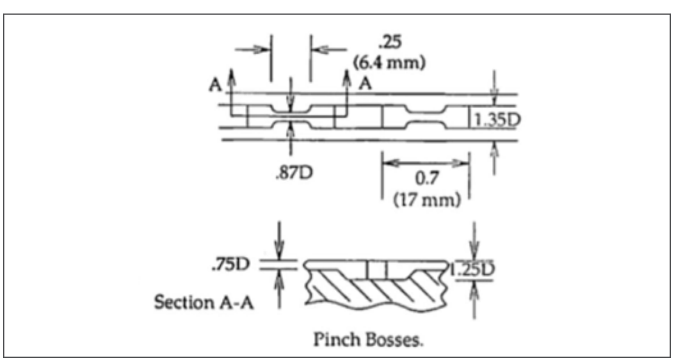

Figure 8.

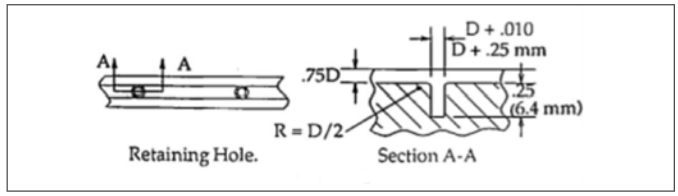

Figure 9.

The EMI gasket strip material that is attached to the neoprene sponge elastomer of *Figure 2* uses adhesive backed tape to hold it in place. The standard thickness of the material is either 1/16, 3/32 or 1/8 inch. The recommended segments or lengths of gasket material are 1 to 1 1/2 inches long. The specific placement of the gasket segments can be determined during the EU or FCC EMI testing. However, provision must be made in the design of the cabinet to provide the required space for the gasket strip. *Figures 10* and *11* illustrate two methods that have proven successful.

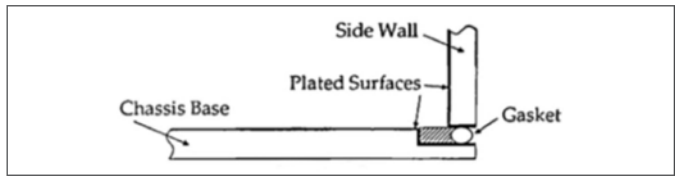

Figure 10.

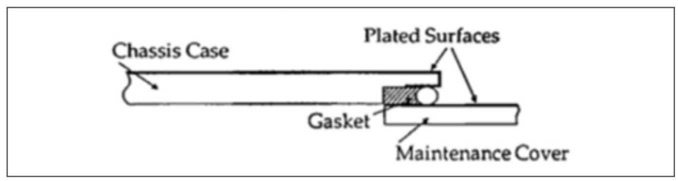

Figure 11.

Reliability of Gasketed Joint

The FCC and EU require that compliance to the specification limits be for the life of the equipment. If a problem with a piece of equipment is detected and is proven to be due to inadequate design, then redesign and retrofit of all the equipment in the field can be required. By the proper selection and use of gaskets, these problems can be circumvented to a great extent.

Two basic problems can exist. These are: (1) the initial design is marginal and proves to be ineffective with time; and (2) the impedance (resistance) of the joint or gasket increases with time. *Figures 12* and *13* illustrate work that was published by E. Grossart. The contents of *Figure 12* illustrates that the surface conductivity of many materials used for shielding can be reduced with time. This means that the surface conductivity required for compliance to the FCC and/or EU radiated emission limits can be reduced with time. This can result in non-compliance with time.

The contents of *Figure 13* illustrate: (1) common structural materials and subsequent plating; (2) materials that are commonly used in the manufacture of EMI gaskets; and (3) the compatibility of the two with each other

Corrosion due to incompatibility of the surface plating and the gasket can significantly increase the resistance of the joint. This in turn could increase the radiated EMI from the unit case with time, creating future compliance problems. It is recommended that the contents of *Figure 13* be used in selecting the joint surface plating and selection of gaskets for FCC and/or EU radiated emission EMI compliance.

Conclusion

The use of EMI gasket material can significantly reduce the cost of complying with the FCC and EU EMI radiated emission limits. The reduced cost results from using EMI gasket material in place of fasteners, where the EMI gasket material can cost as little as pennies per inch.

To use the gasket material in a cost effective means, provisions to hold and protect the gasket material must be designed into the mold or die.

These provisions consist of: (1) O-ring grooves and pinch bosses or retaining holes when using the convoluted spring gasket material; or (2) providing space between the various case sections to be EM bonded together when using the EMI strip gasket material.

Material	Finish	Initial	Resistance (Milliohms) at 400 hr 95% RH	at 1000 hr 95% RH
Alum				
2024	clad/clad	1.3	1.1	2.0
2024	clean only/clean only	0.11	5.0	30.0
6061	clean only/clean only	0.02	7.0	13.0
2024	light chromate conversion/same	0.40	14.0	51.0
6061	light chromate conversion/same	0.55	11.5	12.0
2024	heavy chromate conversion/same	1.9	82.0	100.0
6061	heavy chromate conversion/same	0.42	3.2	5.8
Stool				
1010	cadmium/cadmium	1.8	2.8	3.0
1010	cadmium-chromate/same	0.7	1.2	2.5
1010	silver/silver	0.05	1.2	1.2
1010	tin/tin	0.01	0.01	0.01
Copper	clean only/clean only	0.05	1.9	8.1
Copper	cadmium/cadmium	1.4	3.1	2.7
Copper	cadmium-chromate/same	0.02	0.4	2.0
Copper	silver/silver	0.01	0.8	1.3
Copper	tin/tin	0.01	0.01	0.01

Figure 12. Resistance Measurements of Selected Materials

MATERIALS / FINISHES

GASKET MATERIALS	Aluminum Clad, 1000 3000, 5000 6000 Series Casting 356								Aluminum 2000, 7000 Series							
	None	MIL-C-5541 Class 1A	MIL-C-5541 Class 3	Electroless Nickel	Cadmium Plated Bare	Cadmium Colored Chromate	Cadmium Clear Chromate	Chromium	MIL-C-5541 Class 1A	MIL-C-5541 Class 3	Electroless Nickel	Cadmium Bare	Cadmium Colored Chromate	Cadmium Clear Chromate	Chromium	Tin
Aluminum	A	A	A	D	A	A	A	A	A	A	D	D	A	A	A	A
Tin Plated	A	A	A	D	A	A	A	A	A	A	D	A	A	A	A	A
Monel	C	D	D	A	D	D	D	A	D	D	A	D	D	D	A	D
Silverelastomer	E	C	C	D	C	C	C	A	C	C	D	E	C	C	A	A
Stainless Steel	C	C	C	A	C	A	A	A	D	C	A	D	A	A	A	A
Beryllium Copper	C	C	C	D	C	C	C	D	C	C	D	C	C	C	D	C

GASKET MATERIALS	Carbon and Alloy Steel AISI-410									Corrosion Resistant Steels			High Nickel and PF Steels			Copper Alloys				Miscellaneous				Titanium	
	Cadmium Bare	Cadmium Colored Chromate	Cadmium Clear Chromate	Nickel	Electroless Nickel	Chromium	Tin	Lead	Silver	Passivated	Cadmium (Passivated)	Tin	Passivated	Cadmium (Passivated)	Tin	Tin	Silver	Gold	Solder (Lead-Tin)	Silver Paint	Zink Paint	Silver Adhesive	Carbon Adhesive	None	Nickel
Aluminum	A	A	A	D	D	A	A	D	X	C	A	A	C	A	A	A	X	X	A	X	X	D	D	D	D
Tin Plated	A	A	A	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	A	D	D	D	D
Monel	D	D	D	A	A	A	A	D	A	A	D	A	A	D	A	A	D	D	A	D	D	D	D	A	A
Silverelastomer	C	C	C	D	D	A	A	X	A	D	E	D	D	E	D	D	A	A	D	A	X	A	A	D	D
Stainless Steel	C	A	A	A	A	A	A	D	A	A	D	A	A	D	A	A	A	A	A	A	X	A	D	A	A
Beryllium Copper	C	C	D	D	D	C	C	D	D	C	C	D	C	C	D	C	C	C	C	D	C	C	C	C	C

LEGEND/NOTES
A - Compatible
B - Requires sealing only if exposed to salt atmopshere or high humidy. Edge priming may be satisfactory.
C - Requires sealing if exposed to humid environment.
D - Compatible in environment of controlled temperature and humidity only.
E - Requires sealing regardless of exposure.
X - Not usable.

Figure 13. Compatibility of Dissimilar Materials

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GALVANIC CHART

Mike Oliver, VP Electrical Engineering
MAJR Products Corp.

Galvanic Chart

MIL-STD 1250A (Reference)		Gold	Graphite, Rhodium	Silver	Nickel, Monel	Copper, Bronze	Nickel silver	Stainless Steel	Brass	Chromium	Tin	Tin-lead solder	Lead	Iron, Steel	Aluminum	Cadmium	Galvanized steel	Hot-dip-zinc plate	Zinc	Magnesium
	Volt	0.15	0.05	0.00	-0.15	-0.20	-0.20	-0.20	-0.30	-0.45	-0.50	-0.50	-0.55	-0.70	-0.75	-0.80	-1.05	-1.05	-1.10	-1.60
Gold	0.15																			
Graphite, Rhodium	0.05	-0.10																		
Silver	0.00	-0.15	-0.05																	
Nickel, Monel	-0.15	-0.30	-0.20	-0.15																
Copper, Bronze	-0.20	-0.35	-0.25	-0.20	-0.05															
Nickel silver	-0.20	-0.35	-0.25	-0.20	-0.05	0.00														
Stainless Steel	-0.20	-0.35	-0.25	-0.20	-0.05	0.00	0.00													
Brass	-0.30	-0.45	-0.35	-0.30	-0.15	-0.10	-0.10	-0.10												
Chromium	-0.45	-0.60	-0.50	-0.45	-0.30	-0.25	-0.25	-0.25	-0.15											
Tin	-0.50	-0.65	-0.55	-0.50	-0.35	-0.30	-0.30	-0.30	-0.20	-0.05										
Tin-lead solder	-0.50	-0.65	-0.55	-0.50	-0.35	-0.30	-0.30	-0.30	-0.20	-0.05	0.00									
Lead	-0.55	-0.70	-0.60	-0.55	-0.40	-0.35	-0.35	-0.35	-0.25	-0.10	-0.05	-0.05								
Iron, Steel	-0.70	-0.85	-0.75	-0.70	-0.55	-0.50	-0.50	-0.50	-0.40	-0.25	-0.20	-0.20	-0.15							
Aluminum	-0.75	-0.90	-0.80	-0.75	-0.60	-0.55	-0.55	-0.55	-0.45	-0.30	-0.25	-0.25	-0.20	-0.05						
Cadmium	-0.80	-0.95	-0.85	-0.80	-0.65	-0.60	-0.60	-0.60	-0.50	-0.35	-0.30	-0.30	-0.25	-0.10	-0.05					
Galvanized steel	-1.05	-1.20	-1.10	-1.05	-0.90	-0.85	-0.85	-0.85	-0.75	-0.60	-0.55	-0.55	-0.50	-0.35	-0.30	-0.25				
Hot-dip-zinc plate	-1.05	-1.20	-1.10	-1.05	-0.90	-0.85	-0.85	-0.85	-0.75	-0.60	-0.55	-0.55	-0.50	-0.35	-0.30	-0.25	0.00			
Zinc	-1.10	-1.25	-1.15	-1.10	-0.95	-0.90	-0.90	-0.90	-0.80	-0.65	-0.60	-0.60	-0.55	-0.40	-0.35	-0.30	-0.05	-0.05		
Magnesium	-1.60	-1.75	-1.65	-1.60	-1.45	-1.40	-1.40	-1.40	-1.30	-1.15	-1.10	-1.10	-1.05	-0.90	-0.85	-0.80	-0.55	-0.55	-0.50	

Cathotic metals - least suseptable to corrosion (noble to less noble - vertical to horizontal)
Anodic metals - most suseptable to corrosion (less noble to noble - horizontal to vertical)

Green - Metals in harsh or marine environments such as salt spray or salt water. Volt potential difference equal or less than 0.15V
Blue - Metals in normal environments without temperature or humidity control, warehouse storage. Volt potential difference equal or less than 0.45V
Yellow - Metals in controlled environments with temperature and humidity control. Volt potential difference equal or less than 0.95V
Red - Not recommended

REFERENCES
(STANDARDS, ARTICLES, WHITE PAPERS, BOOKS, & LINKEDIN GROUPS)

SHIELDING EFFECTIVENESS TEST STANDARDS

Standard	Description
ASTM D4935-10	Standard Test Method for Measuring the Electromagnetic S hielding Effectiveness of Planar Materials
ASTM E 1851-15	Standard Test Method for Electromagnetic Shielding Effectiveness of Durable Rigid Wall Relocatable Structures
ASTM F3057-16	Standard Test Method for Electromagnetic Shielding Effectiveness of Glazings
ASTM WK41897	Electromagnetic Transmittance Rate of Glass or Glazing (Proposed)
IEC 60096-1	Replaced with IEC 60096-0-1, Radio frequency cables - Part 0-1: Guide to the design of detail specifications - Coaxial cables
IEEE 299:2006	IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures
MIL-C-85485	Military Specification – Cable, Electric, Filter Line, Radio Frequency Absorptive
MIL-DTL-83528	Gasketing Material, Conductive, Shielding Gasket, electronic, Elastomer, EMI/RFI General specification
MIL-HDBK-1195	Military Handbook, Radio Frequency Shielded Enclosures
MIL-STD-188-125-1	DoD Interface Standard High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C4I Facilities Performing Critical, Time-Urgent Missions
MIL-STD-285	Method of Attenuation Measurements for Enclosures and Electromagnetic Shielding, for Electronic Test Purposes
NSA 73-2A	Specification for Foil RF Shielded Enclosure (Tempest Protection for Facilities)
NSA 94-106	National Security Agency Specification for Shielded Enclosures
SAE ARP1705C	Coaxial Test Procedure to Measure the RF Shielding Characteristics of EMI Gasket Materials

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3. Weston, *Electromagnetic Compatibility*, CRC Press, 2017. A good general purpose book on general EMC design, including shielding.

LINKEDIN GROUPS

- Electromagnetic Compatibility Forum
- EMC - Electromagnetic Compatibility
- EMC Experts
- EMC Testing and Compliance
- EMC Troubleshooters
- EMI and EMC Consultants
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MAJOR EMC CONFERENCES

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2018 IEEE Symposium on EMC, SI & PI
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Ray Adams, r.k.adams@ieee.org

2019 IEEE International Symposium on EMC, SI & PI
July 22-26
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Dennis Lewis, dennis.m.lewis@boeing.com

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