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EMC techniques in electronic design Part 4 - Shielding (screening)

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Design Techniques for EMC

Part 4 — Shielding (screening)

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This is the **fourth** in a series of six articles on basic good-practice electromagnetic compatibility (EMC) techniques in electronic design, to be published during 2006-7. It is intended for designers of electronic modules, products and equipment, but to avoid having to write modules/products/equipment throughout – everything that is sold as the result of a design process will be called a 'product' here.

This series is an update of the series first published in the UK EMC Journal in 1999 [1], and includes basic good EMC practices relevant for electronic, printed-circuit-board (PCB) and mechanical designers in all applications areas (household, commercial, entertainment, industrial, medical and healthcare, automotive, railway, marine, aerospace, military, etc.). Safety risks caused by electromagnetic interference (EMI) are not covered here; see [2] for more on this issue.

These articles deal with the practical issues of what EMC techniques should generally be used and how they should generally be applied. Why they are needed or why they work is not covered (or, at least, not covered in any theoretical depth) – but they are well understood academically and well proven over decades of practice. A good understanding of the basics of EMC is a great benefit in helping to prevent under- or over-engineering, but goes beyond the scope of these articles.

The techniques covered in these six articles will be:

1) Circuit design (digital, analogue, switch-mode, communications), and choosing components
2) Cables and connectors
3) Filtering and suppressing transients
4) Shielding (screening)
5) PCB layout (including transmission lines)
6) ESD, surge, electromechanical devices, power factor correction, voltage fluctuations, supply dips and dropouts

Many textbooks and articles have been written about all of the above topics, so this magazine article format can do no more than introduce the various issues and point to the most important of the basic good-practice EMC design techniques. References are provided for further study and more in-depth EMC design techniques.

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4. Shielding (screening)

4.1 Introduction

Shielding is used to attenuate unwanted frequencies travelling through the air, or through whatever the product is immersed within (e.g. vacuum, oil, etc.) – and shields are characterised by attenuation versus frequency curves. In many ways, electromagnetic (EM) shields are the radiated-wave equivalents of EM filters, which attenuate conducted EM waves (see Part 3 of this series [3]). As will be shown later, and was discussed in section 3.3.3 of [3], shielding and filtering generally have to be used together, in order for either one to provide the EMC benefits required.

This article uses the word 'shield' instead of 'screen', because screen has some other common uses in electronics (e.g. display screen). Cable shielding was dealt with in section 2.6 of [4], so this article is concerned with other types of shields. Note that for cable shielding to function well, especially at frequencies above 100MHz, the equipment connected to either end of the shielded cable also needs to be shielded, with its shield bonded 360° to the cable shield.

Figure 4A shows the radiated EM spectrum up to 2.5GHz, and some of its commonplace civilian uses. The spectrum above 2.5GHz is being developed very quickly, as low-cost semiconductors that can operate at such frequencies are developed.

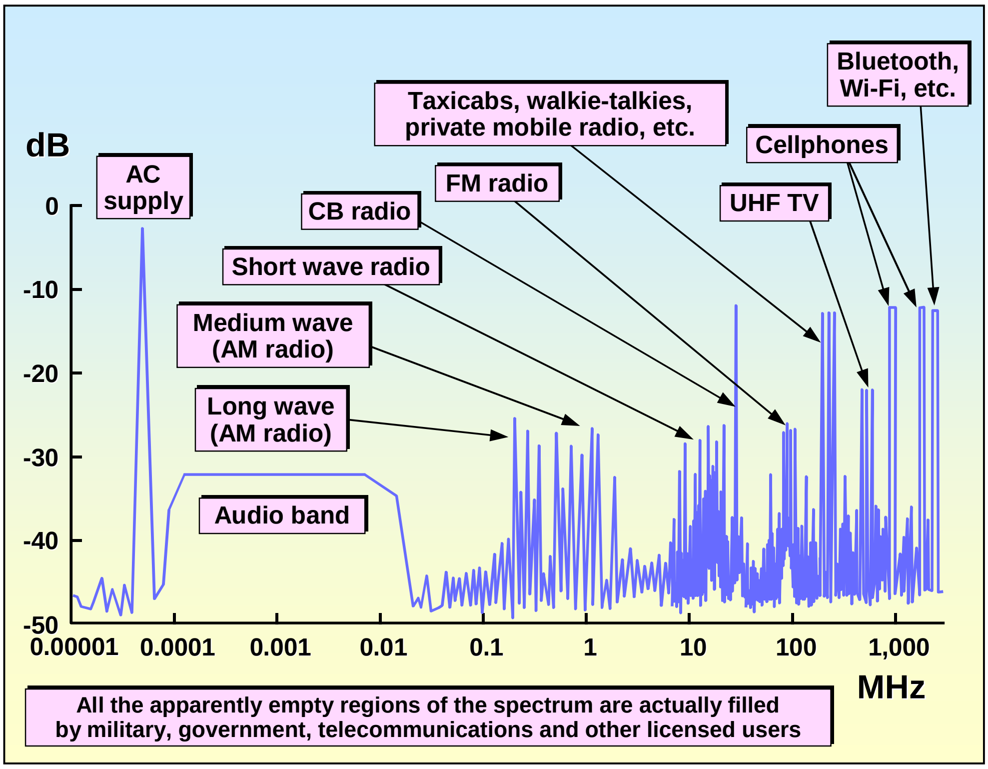


Figure 4A The radiated spectrum and its uses (only up to 2.5GHz shown)

Figure 4B shows the typical EM spectra of the noises radiated by some commonplace electronic devices, and an example of the radiated noise caused by sparking at an electrical contact. It is clear that to be able to use the radiated spectrum for broadcasting, communications, etc., we must protect it from electronic and electrical noise.

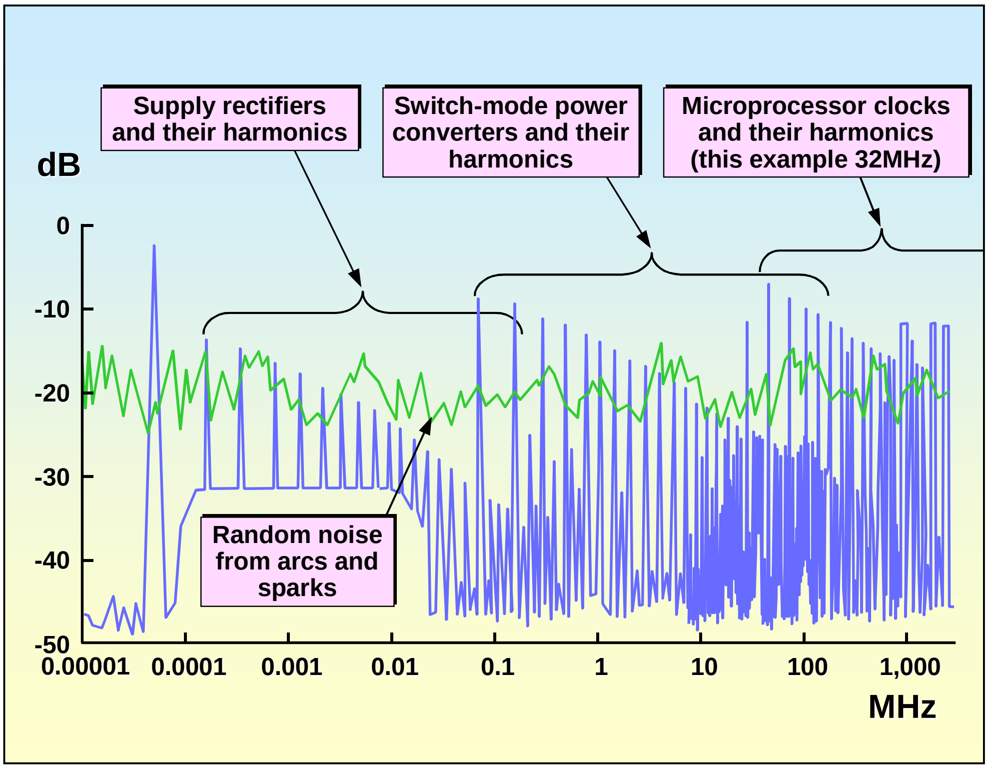


Figure 4B The spectra of noises made by electrical/electronic devices (only up to 2.5GHz shown)

For the above reasons, shielding is a technique that has been used for many years, and Figure 4C shows part of a method for testing shielding effectiveness (SE) dating from 1882 (kindly provided by Anton Kohling of Siemens EMC Test Laboratory in Erlangen).

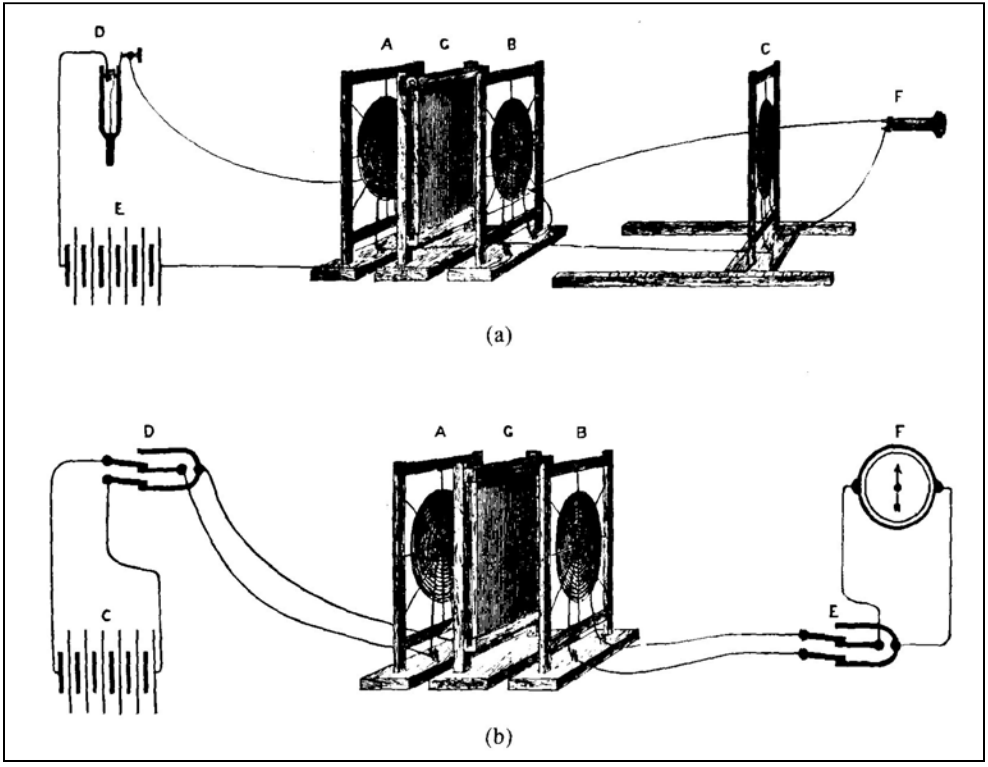


Figure 4C Shielding Effectiveness testing in 1882

Inadequately designed shielding-can make a product's emissions or immunity worse than it was without the shield. One cannot, in general, simply select a shielded enclosure from a supplier's catalogue and expect that no more work will be required – there are numerous design and assembly techniques that need to be taken into account if the purchased enclosure is to provide the shielding performance required. It is very easy to completely negate a shielded enclosure's performance by not paying sufficient attention to the issues discussed in this article.

Many textbooks and learned papers have been written on shielding and Chapter 34 of [5] includes a very comprehensive list of them. There are also now a number of simulators that run on PCs and can be used to simulate the effects of shields. This article will not go into wave equations and that sort of detail – instead it will describe the things that need to be taken into account so that shielding stands a good chance of performing as required, and to avoid unpleasant and/or costly experiences.

Shielding design or selection is not a 'black art', but nevertheless it is difficult to predict *exactly* what performance a given shield construction will achieve when installed in a product, especially at frequencies above 100MHz, so it is often necessary to experiment with different options to find the most cost-effective. Planning and designing for such flexibility from the start of a project is very worthwhile, and an example of what John R Barnes [5] calls "wiggle room" and I call "anti-Murphy design". My approach is based upon the well-known Murphy's Law – I find that designers who try to anticipate the surprises that Murphy might have in store for them reach their design targets and timescales more reliably, and the resulting products have a lower overall cost of manufacture because they have not had to have shields (or more complex shields than were hoped for) squeezed in somehow at the end of a project when compliance tests were failed.

Shields are always fitted at a boundary between two zones, one of which needs to be protected from the EM fields present in the other. This article generally considers shields that are fitted at the boundary between a product and its external EM environment – shielded overall product enclosures. Shields can also be used inside a product, for example between a switch-mode power supply and a sensitive analogue circuit, and their design will employ most, if not all, of the same design techniques.

4.2 Shielding with metal plates

The 'image plane' effect means that large metal surfaces can provide useful amounts of shielding for components and conductors that are placed close enough to them – for example, by using low-profile PCB components with an overall PCB plane, or by locating all PCBs and routing all cables close to a large metal chassis, frame, or enclosure. To be effective, the metal surface needs to have much larger dimensions than the components or conductors, and the spacing from the metal surface needs to be less than one-tenth of a wavelength ($\lambda/10$) at the highest frequency for which any shielding effectiveness is required. Closer spacings are better. When spacings are less than about $\lambda/6$, SE can become negative (i.e. provide gain), possibly worsening emissions or immunity compared with doing nothing.

Electrical bonding between the metal surface and the components or conductors helps to control and return common-mode (CM) currents, also helping to improve SE. For this to be effective, the electrical bonds must have a very low impedance (say $<1\Omega$) at the highest frequency for which improvement is required. Note that impedance does not mean resistance – at radio frequencies (RF) it is usually the inductive reactance ($2\pi fL$) that is most significant, and $<1\Omega$ at, say, 300MHz, implies an inductance of about 530pH. Ordinary thin wire has an inductance of about 1nH per millimetre length.

This technique might provide sufficient SE to eliminate the need for a shielded enclosure, or at least to reduce its SE specifications and hence its cost. Because EMC engineers work in dB, it is easy to overlook the importance of a small improvement, say 3dB. 3dB does not sound like worth bothering with, but it represents a 50% improvement in SE performance, and at frequencies above 300MHz quite possibly a 50% (or more) increase in the overall cost of manufacture of a shielded enclosure. So it is cost-effective to take every chance to improve SE by a few dB, rather than leave all the shielding to the overall enclosure.

4.3 Volumetric shielding of products

Most shields will need to be volumetric – surrounding the product to be shielded in all three dimensions – such as a six-faced rectangular box. This section discusses the design and assembly of volumetric shields applied to an entire product.

A complete volumetric shield is often known as a ‘Faraday Cage’, although this can give the impression that a box full of holes (like Mr Faraday’s original version) is acceptable, which it generally is not.

As mentioned earlier, shields can also be used inside products, to protect one zone from EM fields generated in another. The same design techniques apply to these shields as for overall enclosure shields.

4.3.1 Nested shielding and cost-of-manufacture

There is a cost hierarchy to shielding which makes it important to take shielding into account very early in the design process. Shields may be fitted around:

▪ Individual ICs or small areas on a PCB	relative cost 1
▪ Whole PCBs	relative cost 10
▪ Sub-assemblies and modules	relative cost 15
▪ Complete products	relative cost 100
▪ Assemblies (e.g. industrial control cubicles)	relative cost 1,000
▪ Rooms	relative cost 10,000
▪ Buildings	relative cost 100,000

These relative costs are only very approximate, and are only concerned with overall cost-of-manufacture. They do not cover the costs and delays of adding unanticipated shielding late in a project, which can be *very* much greater.

To save cost, devices should be chosen and circuits designed as described in Part 1 of this series [6] to reduce their need for shielding; then their PCBs should be designed so that shielding-can be applied to them (see later); then any modules and sub-assemblies designed so that shielding-can be applied to them. Finally, the overall enclosure should be designed so that shielding-can be applied.

Shielding always adds cost and weight, but the above approach will generally achieve the lowest overall costs-of manufacture whilst also considerably reducing delays and re-engineering costs if improvements in SE are found to be required late in a project, when design freedom is circumscribed and even simple changes can be very costly (see Part 0 of [6]). It can be very difficult indeed to retrofit shielding to a metal or plastic enclosure that was not originally designed to be able to be shielded, as later sections will make clear.

‘Nested’ low-cost shielding, as shown by Figure 4D, is usually not only more cost-effective than relying on a single overall enclosure shield – it is also more reliable. For example: if 60dB of shielding is required at 900MHz and is achieved solely by a shielded overall enclosure, a small defect in the enclosure or its assembly could easily reduce the SE to 20dB or less. But if three levels of lower-cost shielding are employed as shown in Figure 4D, each one giving 30dB at 900MHz, the overall cost of manufacture could be less, and the outer enclosure could suffer defects or damage, or foreseeable misuse (e.g. removing a cover) without the overall SE dropping below the required 60dB.

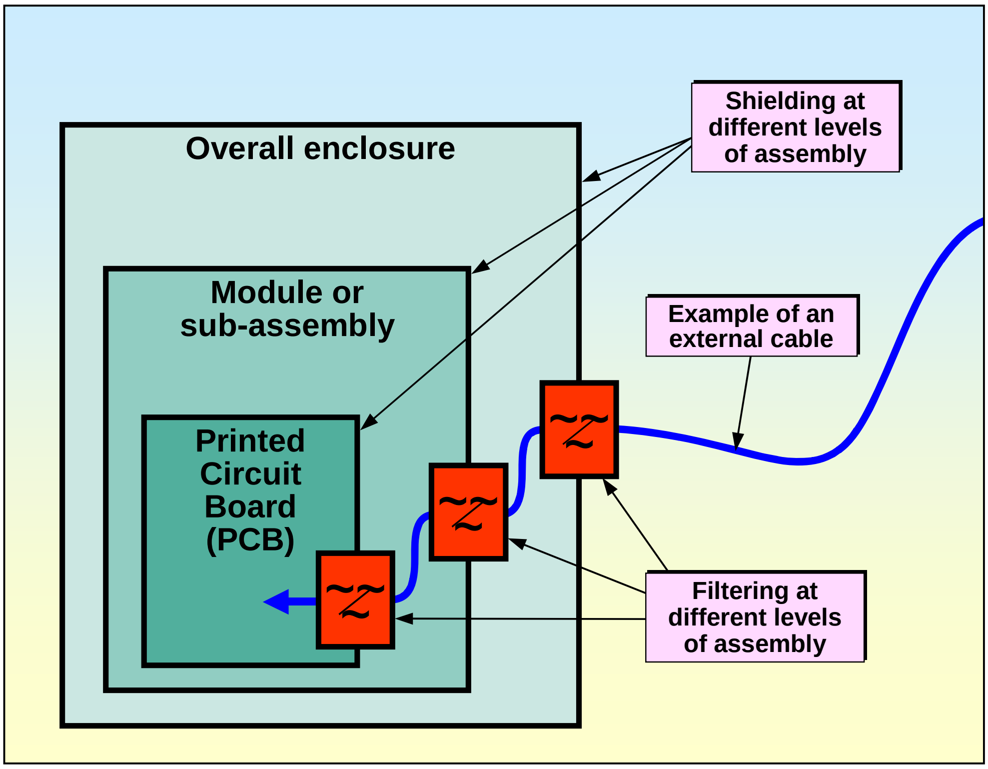


Figure 4D Example of ‘nested’ shielding and filtering

The requirements for cost-effective manufacture should always be taken into account during design. A shield design suitable for product hand-made in small volumes might not be at all appropriate for products manufactured on automated production lines in tens of thousands. The cost pressures on high-volume manufacture generally mean that shielding on the PCB is preferred to enclosure shielding [46]. Indeed, as will be shown later, above 1GHz it can be very difficult/costly to rely entirely on enclosure shielding, and PCB-level shielding is almost essential.

4.3.2 General concepts in volumetric shielding

A shield puts an impedance discontinuity in the path of a propagating radiated EM wave, reflecting it and/or absorbing it. This is conceptually very similar to the way in which filters work – they put an impedance discontinuity in the path of an unwanted *conducted* EM wave. The greater the impedance ratio between wave and shield, the greater the SE achieved.

Figure 4E shows the overall operation of a shield. Depending on its wave impedance, a proportion of the incident wave is reflected at the first ‘high-low’ impedance discontinuity (the facing surface of the conductor), and the remainder carries on inside the material as a transmitted wave, being absorbed by being turned into heat by the resistivity of the material. When the transmitted wave hits the ‘low-high’ impedance discontinuity at the other surface of the conductor, a proportion is again reflected and stays inside the conductor, while the remainder exits on the other side of the shield as an attenuated incident wave.

The transmitted waves ricochet from side to side within the shield material, each time giving rise to a wave on the outside of the shield, and gradually being absorbed. For most metals thicker than about 0.25mm we can usually ignore the reflections after the first one that gave rise to an attenuated incident wave. But when dealing with very thin metals, e.g. when shielding displays (see later) the re-reflected waves can have a significant worsening effect on the overall SE achieved.

In near-field regions, electric (E) fields generally have very high impedance, so are easily reflected by very thin metals, as long as they have a highly conductive surface and a low-impedance connection to the RF Reference Plane of the circuit being protected, at the highest frequencies to be shielded. But near-field magnetic (H) fields tend to have low impedance and so do not experience much reflection – their shielding relies more on absorption of the transmitted wave, and needs a suitable metal thickness to get a good SE (i.e. many skin depths at the frequency of concern, see below).

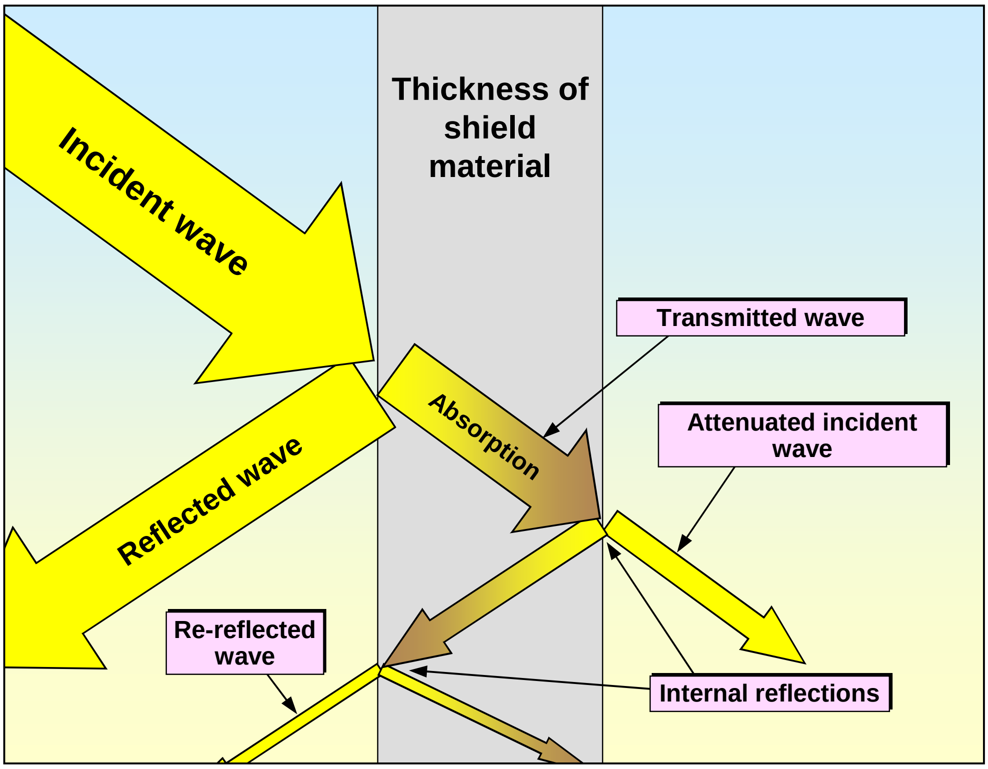


Figure 4E **Reflection and absorption by a shield**

In far-field regions, ‘plane’ waves have middling impedance. For instance, in air or vacuum the wave impedance is close to 377Ω (it will be lower in other media), so good SE depends upon both surface conductivity and thickness. Figure 4F illustrates how absorption improves the emissions and immunity of shielded electronic circuits.

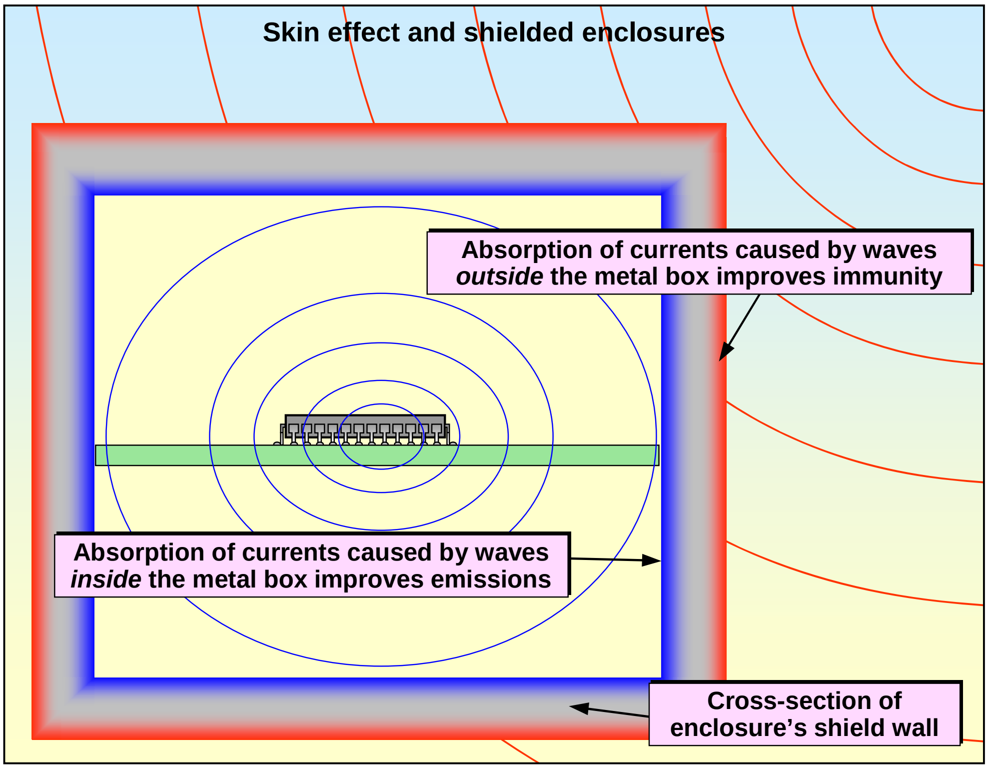


Figure 4F **Absorption and shielding**

At thicknesses of 0.75mm or over, and frequencies above 200kHz, most normal fabrication metals provide good SE, with excellent SE above 10MHz. Problems with shielded enclosure at such frequencies are mostly caused by apertures and cable penetrations, which are covered in later sections.

Many textbooks, papers, articles and free guides (e.g. [7], [47] [48]) describe how to calculate the SE of shielding materials from wave equations and first principles. This is a very interesting academic exercise, but the results only apply in the far-field of an EM source so may not be at all accurate in predicting SE when a shield is in the near-field of a source (see later). Also, they generally ignore the effects of apertures and cable penetrations, which almost always dominate real-life SE performance.

4.3.3 Skin effect and absorption

When a radiated wave impinges upon a conductive material it generates surface currents in the material. As the transmitted wave penetrates a shield it gives rise to eddy currents inside the shield's material, and these can be considered to be part of the surface currents. The finite conductivity (non-zero resistivity) of the material causes these eddy currents to lose energy as heat, governing the rate of absorption of the transmitted wave. This is called the 'skin effect' and its performance (rate of absorption) depends on frequency, and on the conductivity and permeability of the shield material.

One skin depth (δ) is the depth in the shield material at which the skin effect causes the currents caused by the impinging H field to be reduced by approximately 9dB. So a material that was just three skin depths thick would provide about 27dB of absorption to the overall SE achieved by the shield (due to the first and second reflections).

Figure 4G provides the formula for δ, and a guide graph showing copper, aluminium and a typical grade of mild steel. For copper, δ is $66/\sqrt{f}$, and f in MHz gives δ in mm.

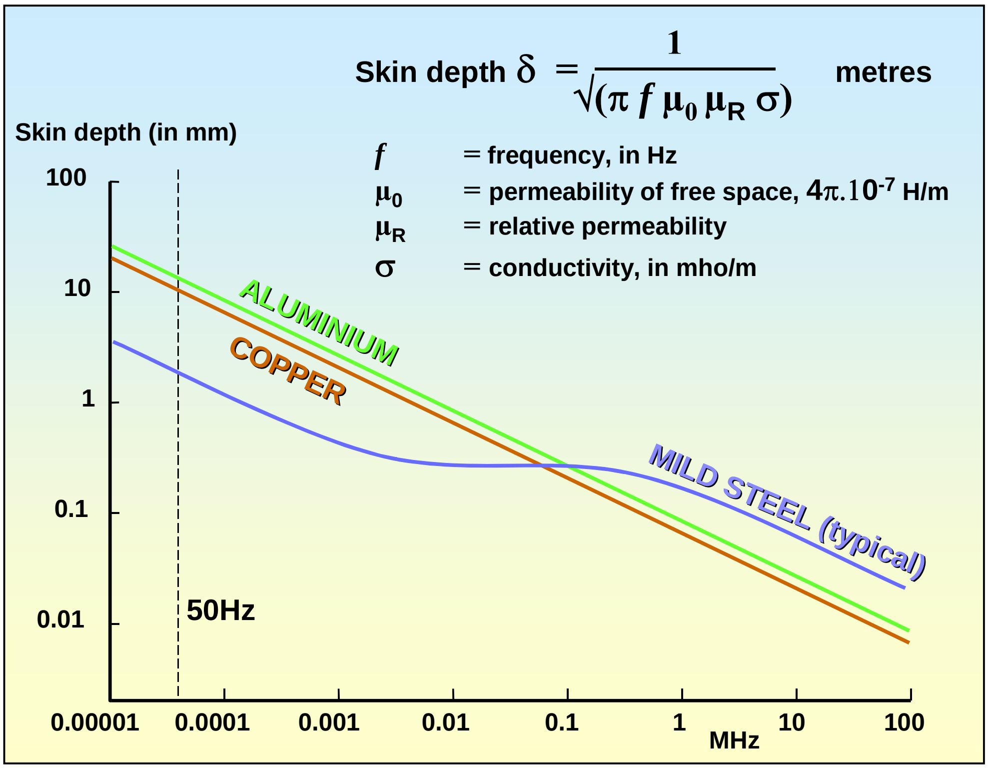


Figure 4G Skin depth formula and graph

Aluminium, copper, silver, gold, etc. have high conductivity and a relative permeability of 1 (the same as air), and in normal constructional thicknesses of 0.75-3mm are good at shielding any kinds of fields (E, H or EM) above 200kHz, because they achieve several skin-depths of absorption.

Mild steel is a ferromagnetic material with a relative permeability of about 300 at low frequencies, falling to 1 at frequencies above 1MHz, giving it a significantly smaller δ for frequencies below 10kHz, where it is often the better choice for shielding. Nickel is another commonly-used ferromagnetic metal, and like mild steel and all other ferromagnetic metals it loses its ferromagnetism above some frequency. Mild steel, nickel, and most/all other ferromagnetic metals have lower conductivity than good conductors like copper or aluminium, which means they have less reflectivity.

Mild steel or nickel that is plated heavily with tin can be good materials for a wide range of frequencies – the steel or nickel providing good absorption at low frequencies, and the tin plating providing good reflection. Different grades of steel (especially stainless) have different conductivities and permeabilities than mild steel, and might need to be substantially thicker for same SE.

For more information on skin depth, see [8], and Table 34-1 of [5].

4.3.4 Very low frequency shielding

Skin depth increases as frequency decreases, so skin depth becomes very important when shielding at low frequencies. As Figure 4G shows, at 50Hz even mild steel has a δ of about 2mm, so with normal constructional material thicknesses does not achieve very good SE.

Protection from very low frequency H fields is best achieved by segregation – placing susceptible devices and circuits in areas of low field strength – and also (where possible) by reducing the levels of the fields by modifying their sources so they emit less. Cathode ray tube (CRT) devices, such as used historically in oscilloscopes, televisions and computer monitor displays; photomultiplier tubes; electron microscopes; and some other devices are especially sensitive to H fields. The easiest solution for CRT displays these days, is simply to replace them with liquid crystal display (LCD) devices.

If it is necessary to shield from such fields, and the thicknesses of steel or nickel required would be impractical, special ferromagnetic metals with high values of μ_r, typically in the range 10,000 to 350,000 can be used, for example MuMetal®, Radiometal®, Permalloy®, etc. Designing with such metals is not about reflection and absorption, instead they are used to divert the magnetic flux away from the region to be shielded – sometimes called ‘flux-ducting’.

All ferromagnetic materials can be saturated in sufficiently intense H fields, and then they don’t work very well as shields and may even get hot. For this reason a steel or high-permeability metal box placed over a mains transformer to reduce hum fields can saturate and fail to achieve the desired benefit. Often, all that is necessary is to make the box larger so it does not experience such intense H fields.

Generally speaking, the higher the permeability of the material, the lower its saturation flux density, so a common technique is to use one or more layers of low or medium permeability material spaced away from another layer of very high-permeability material. The low or medium permeability materials must be on the side facing the field, to reduce the flux density to something that the very high-permeability material can handle without saturating.

Some companies manufacture double- or triple-layer laminated metals specifically for very low frequency H field shielding purposes, and some make large shielded enclosures out of it, for example for protecting electron microscopes.

Medium and high permeability materials are usually very sensitive to handling or machining stresses. A sharp knock can cause them to lose a great deal of their permeability, whereupon they must be annealed at high temperature in a hydrogen atmosphere. So it is best to purchase such materials already fabricated and annealed by specialist manufacturers, ready for final assembly [50].

Another shielding technique for low frequency shielding is active cancellation, and at least two companies have developed this technique specifically for stabilising the images of CRT VDUs in environments polluted by high levels of power frequency H fields. A framework of insulated conductors is placed around the region to be protected, and audio-frequency power amplifiers drive currents in each one so as to cancel most of the H fields (measured by magnetometers) inside their protected volume. Although this is becoming less used as CRT displays are replaced with LCDs, it still finds application in areas such as electron microscopy and other H-field sensitive scientific and medical measurements.

4.3.5 SE is compromised by leakage from apertures

This section is concerned with designing and assembling to control field leakage from apertures in shields. A later section covers leakages due to cable penetrations.

It is easy to get SEs of over 100dB from quite thin metals at frequencies above 10MHz, but the SEs of all *real* shields are seriously compromised by the fields that leak from even tiny apertures (gaps) at seams, joints, doors, covers, etc., and also by cable penetrations. A shielded enclosure that achieves 100dB is quite costly, and usually the sort of thing used by military and other non-commercial organisations.

Control of apertures and cable penetrations is the key to achieving good SE figures – much more important at frequencies above 100kHz – than the type or thickness of the metal a shield is made from. People will often purchase a very expensive shielded enclosure, and then completely ruin its SE by failing to design its apertures and cable ports correctly, or not taking sufficient care in assembly.

A lot of information is freely available on designing shields, for example [9], [10], [11], [12], but it tends to gloss over the actual effects of apertures and cable penetrations on SE – even though a major part of the business of many of the companies that supply this helpful information is in supplying conductive gaskets which are used to limit the effects of apertures.

It is tempting to compare EM shielding with water or gas plumbing (‘gaps mean leaks’) but the leakage from shield apertures does not work like that – the fields inside or outside the box do not ‘squirt’ through gaps like water or gas does under pressure.

Instead, as mentioned earlier, when a field impinges upon a shielding metal, currents flow in its surface (see Figure 4F). When these 'surface currents' encounter an aperture, they must divert from their preferred path in order to flow around it. Diverting a current creates an inductance and the H fields associated with that are in exactly the right orientation to pass straight through the aperture, which means straight through the shield material, causing the shield's SE to be reduced.

As the surface currents flow in the inductance created by their diversion around an aperture, voltage differences are naturally generated across this inductance, appearing across the aperture. These voltage differences generate new E fields that also reduce the SE of the enclosure.

Resonances can occur that greatly amplify the leakages through the apertures at certain frequencies. When these resonant frequencies coincide with an internal frequency, such as a clock harmonic, emissions and immunity tests are more likely to be failed at those frequencies. Baseband analogue circuits are generally sensitive to noise over very wide frequency ranges (e.g. audio circuits intended to operate over 20Hz – 20kHz are generally found to be susceptible to modulated RF fields up to 500MHz at least), so resonant apertures tend to make them more susceptible at those resonant frequencies. There are two main types of resonance that affects apertures: resonances of the apertures themselves; and resonances of the enclosure's internal cavities.

When an aperture dimension is resonant, it has a resonant gain (Q) that amplifies the E or H fields generated by the aperture's diversion of surface currents. It is effectively a perfectly-tuned 'accidental antenna'. The conductivity of most metals is such that there is little resistive loss in a resonating aperture, so its Q can be very high, maybe 40dB or even 60dB.

Enclosure internal resonances can also have quite high values of Q, and can amplify the surface currents over areas of the shield's internal surfaces. When one of these 'resonant hot spots' contains an aperture, the leakage from that aperture is considerably increased at and around the resonant frequency. Both of these resonance issues are discussed later.

Because of these resonances, the SE of a shielded enclosure generally shows some fairly sharp drops around the resonant frequencies. EMC engineers use this fact to track down the causes of poor SE, by relating the wavelengths at the frequencies of the SE's dips to the dimensions of shield apertures (e.g. seams, joints, displays, ventilation, etc.), and also to the lengths of any cables that penetrate the shield.

But SE can sometimes be seriously compromised in a non-resonant manner, over wide ranges of frequencies. I have seen dramatic levels of emissions at frequencies up to 130MHz from a hole just 4mm in diameter (intended for a plastic snap-in PCB mounting pillar) in a small PCB-mounted shield over a microcontroller. The particularly powerful near-fields associated with a certain type of microcontroller were causing significant currents to flow in the shielding-can, and it was these currents being diverted around the 4mm hole in the 0V plane that were causing the high levels of emissions. The hole was acting as an accidental antenna, but neither its diameter nor the PCB-mounted shield were anywhere near resonance at 130MHz. Soldering a small brass plate over the hole reduced the emissions dramatically, and the modification for volume manufacture was simply to move the mounting pillar a little so that it did not intrude into the shielded area of the PCB.

This understanding of the true nature of shield 'leakage' at apertures shows us that, if long narrow apertures can be aligned so that their length is aligned with the direction of the surface currents, they should leak less. Of course, this design technique requires the direction of the surface currents to be known, and for them to have one predominant direction. This can be reasonably obvious in simple situations, for example when the surface currents are mainly due to the close proximity of a current-carrying coil, but the complexity of most modern products means that computer simulations (see later) can be necessary (see later).

4.3.6 The resonant/antenna behaviour of a *single* aperture in the *far field*

All apertures in shielded enclosures behave as 'accidental slot antennas' – accidentally radiating/transmitting EM energy through the shield and worsening a product's emissions and immunity performance as a result. The lowest resonance of an aperture is the frequency at which its longest dimension, g (its maximum 'gap size': either its diameter or longest diagonal) equals half of the wavelength ($\lambda/2$). Below this first resonance the efficiency of the antenna is assumed to reduce at 20dB per decade, so for $g<\lambda/2$, we generally assume that the SE of an aperture is $20\log_{10}(\lambda/2g)$ dB.

This assumption was used to draw Figures 4H and 4J, and seems to predict SE well enough to be useful in most practical situations. At least is a design tool that is better than doing nothing. Where its predications are found to be inaccurate, it may be possible to refine it following practical experiences with the technologies and construction methods used on specific products. Figure 4H uses the plot of spectrum usages + noise from Figure 4B, but in addition plots the effectiveness of the accidental antennas caused by shield apertures.

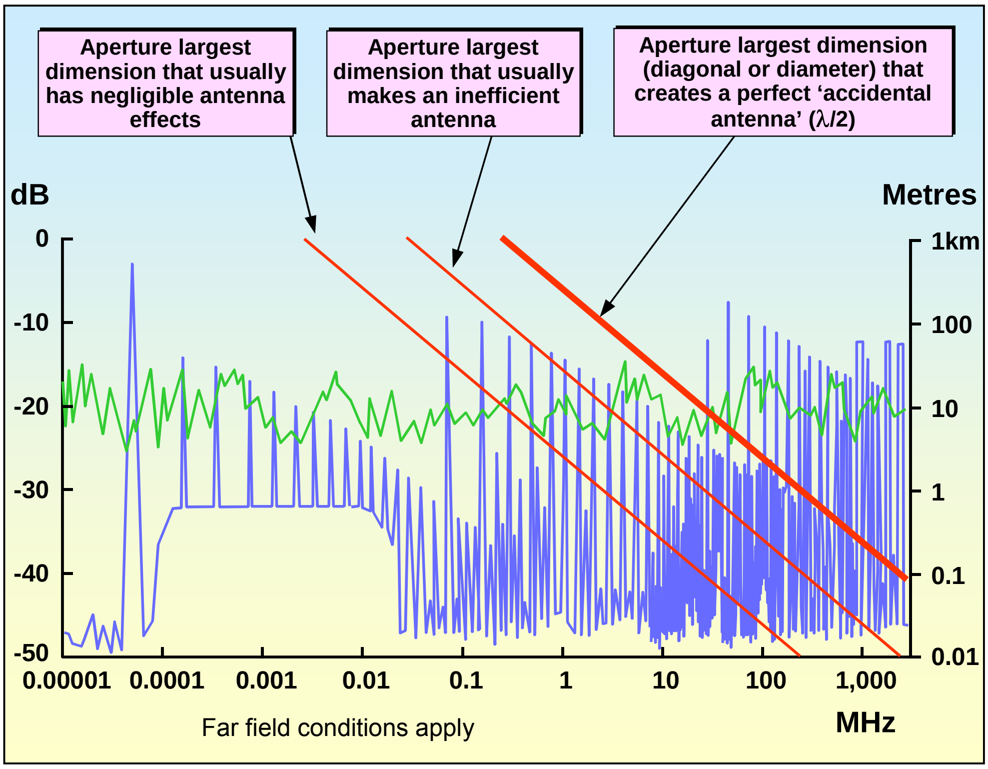


Figure 4H The accidental antenna effects of shield apertures (only up to 2.5GHz shown)

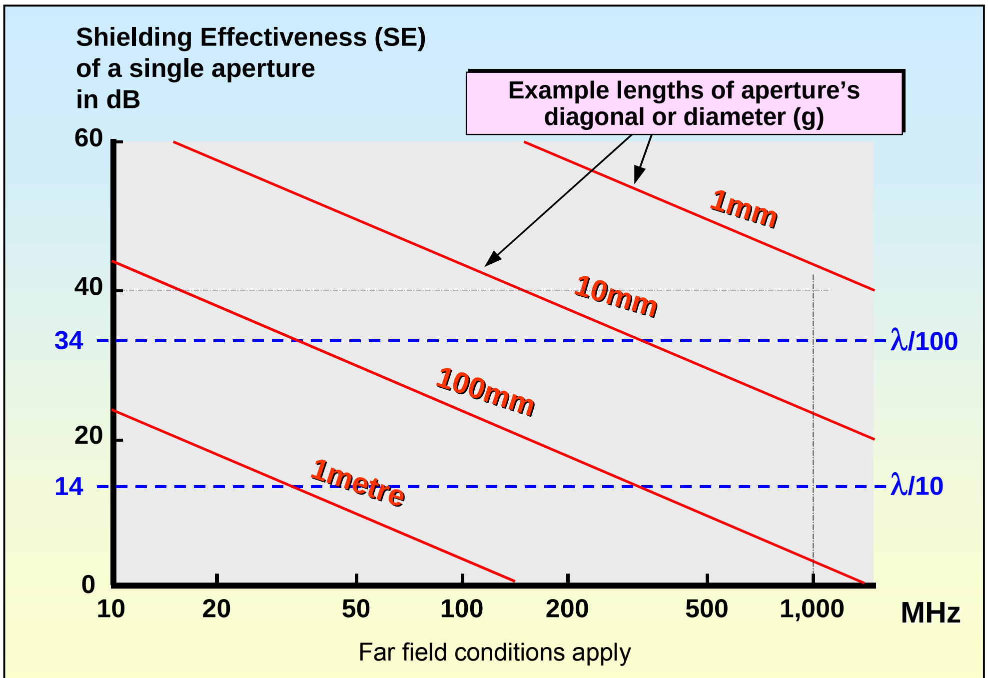
At resonance it makes little difference how wide or narrow an aperture is, or even whether there is a line-of-sight through the aperture into the enclosure. Even apertures with widths of no more than a coat of paint or film of oxide (such as are often created at joints between sheet metal parts), or that have a labyrinthine construction, still leak just as much at their resonant frequencies as similar apertures that are wide enough to poke a finger through.

Even where two surfaces that are plain metal, or have been conductively-plated are fixed together with spot-welds, screws, etc. that make good bonds at RF, it should not be assumed that they have low-resistance bonds inbetween the fixing points. All spaces between fixings should be treated as apertures, with their longest dimension, g, being (at least) the pitch spacing of the fixings. Where the quality of the RF bond at a fixing is suspect, or might degrade over the life of the product, shielding design should assume a correspondingly larger aperture.

Figure 4H is useful for getting a feel for the issue of aperture leakage, but Figure 4J is more practically useful for designing shields for far-fields. It shows, for example, that for a shielded enclosure with a single aperture, achieving an SE of 40dB at 1GHz means that the largest aperture dimension should be no larger than about 1.5mm. Note that Figure 4J only applies to a single aperture, whereas most products have several apertures, reducing SE even more (see later).

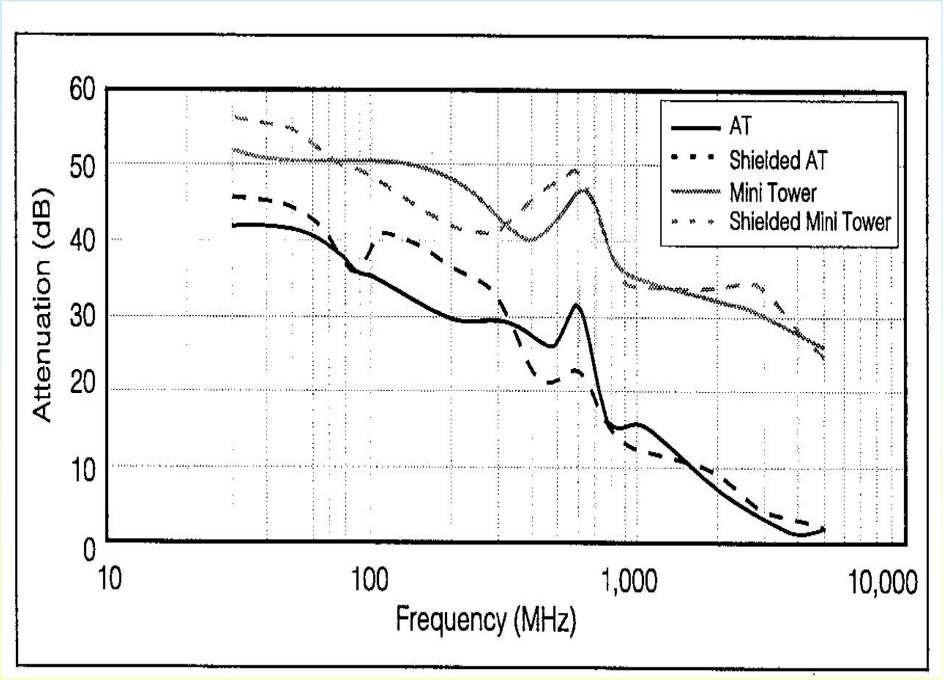
The λ/100 'rule' that is often used by EMC engineers when they want good performance only gives an SE of 34dB, and then only for a single aperture. Following the more commonplace λ/10 'rule' really only ensures that the SE will be a positive figure – that at least the shield should be better than nothing, for frequencies with wavelengths no shorter than the value of λ that was used.

Real shielding is generally constructed with numerous joints, seams, controls, displays, ventilation apertures, slots for removable storage media, etc., all of which can behave as accidentally radiating antennas unless designed accordingly. It is clearly not easy to get good SE figures even with a single aperture, and Figure 4K gives an idea of the commercial state of the art in 1997 for the enclosures for personal computers (PCs). Modern PC manufacturers have to achieve much greater SEs to much higher frequencies (e.g. to meet FCC requirements in the USA), and the fashion of fitting PCs with transparent enclosures is guaranteed to make them non-compliant with the EMC regulations of over 40 countries, and maybe even interfere with the neighbours or possibly even airplanes flying overhead. We just have to hope such fashionable people do not operate their pretty PCs too close to a hospital or other critical facility.



For other aperture sizes: divide frequency axis by the ratio of the diagonals (e.g. for a doubled diagonal: halve the frequency axis)

Figure 4J Guide for the SE of a single aperture in the far-field



From an article by Robert Foster in ITEM, 1997

Figure 4K Some shielding effectiveness test results for PC cases

Sometimes enclosures are required to provide good SE performance, for instance certain military equipment might need an SE of at least 80dB from 10kHz to 18GHz, and some critical commercial/industrial products might need to be protected from EM weapons that can create fields of up to 120kV/m at frequencies around 350MHz [13]. In such cases very close attention indeed is required to the design and assembly of any/all apertures and conductor penetrations.

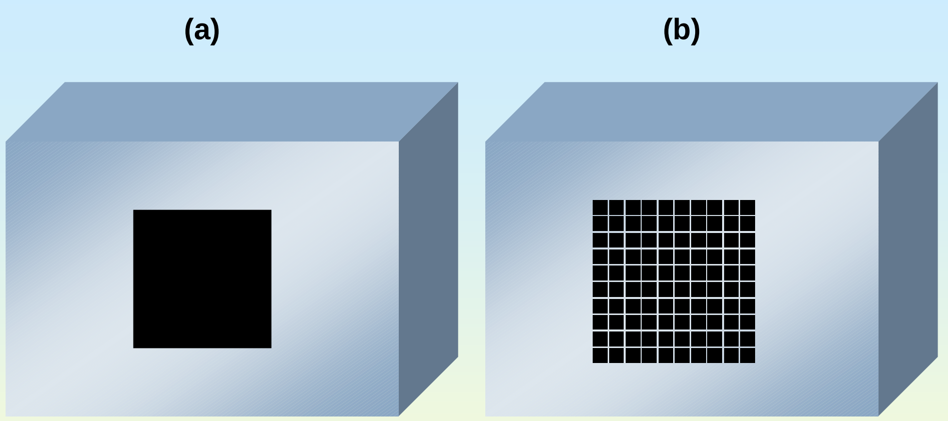
4.3.7 Multiple apertures in the *far field*

The leakages through apertures spaced $<\lambda/6$ apart add together more-or-less in-phase to reduce the SE of their shielded enclosure. It is usually assumed that N apertures with identical characteristics will reduce the SE of their enclosure by $20\log_{10}(N)$ dB, effectively causing the SE to fall by another 6dB for every doubling in the number of identical apertures, e.g. -6dB for 2 apertures, -12dB for 4, -18dB for 8, etc.

When apertures are $>\lambda/6$ apart, from some angles their leakages can phase-cancel, causing 'beaming' of the emissions. As a result, from certain angles that depend on the frequency and the locations of the apertures on the enclosure, the SE will be better than would be achieved if all the apertures were within $\lambda/6$ of each other – and (according to simplistic assumptions) it should never be worse.

So, on balance, where multiple apertures are required, it is likely to be better for SE to spread them around an enclosure so they are as far apart from each other as possible.

The simple equations used so far in this article are very crude indeed, and this becomes obvious when we try to use them to calculate the SE of an enclosure with a regular array of apertures, as shown by Figure 4L.



For a single square hole 100mm on a side at 300MHz, $20\log_{10}(\lambda/2g)$ indicates an SE of 11dB

Far field conditions apply

For a single square 10mm hole at 300MHz, $20\log_{10}(\lambda/2g)$ indicates an SE of 31dB

For 100 such holes, for same overall open area as (a), $20\log_{10}(N)$ indicates that the SE will be degraded by 40dB, i.e. -9dB !!

BUT in real life an array of small holes has *better* SE than one large one, not *worse* ***(as predicted here)***

Figure 4L Strange results from simple SE equations

Figure 4L implies that it is much better to have a single large hole, than an array of smaller holes with the same overall open area. But in real-life *the opposite is true*: a single large hole in an enclosure has a worse SE than an array of small holes with the same overall open area. In fact, replacing large apertures with many small ones is commonly used and is considered to be a good shielding practice for ventilation apertures.

This emphasises a very important issue in shielding design – simple equations are almost useless for general use. For a shielding equation to be simple, it must have been derived from Maxwell's equations via some huge simplifying assumptions – and so it is only appropriate for the very limited set of physical situations where those assumptions apply. Real-life shielding with real products is very complex indeed mathematically, and computer simulations (see later) are the only realistic way to predict SE with useful accuracy (say, ±10dB).

Lacking a computer simulator, my approach is to design so that shielding-can quickly and easily be improved, so that if the lowest-cost design that it was hoped would pass the emissions or immunity tests turns out not to be good enough in practice – the SE can be improved in minutes by fitting components (such as conductive gaskets and/or PCB shielding-cans, already designed and samples obtained) without any redesign.

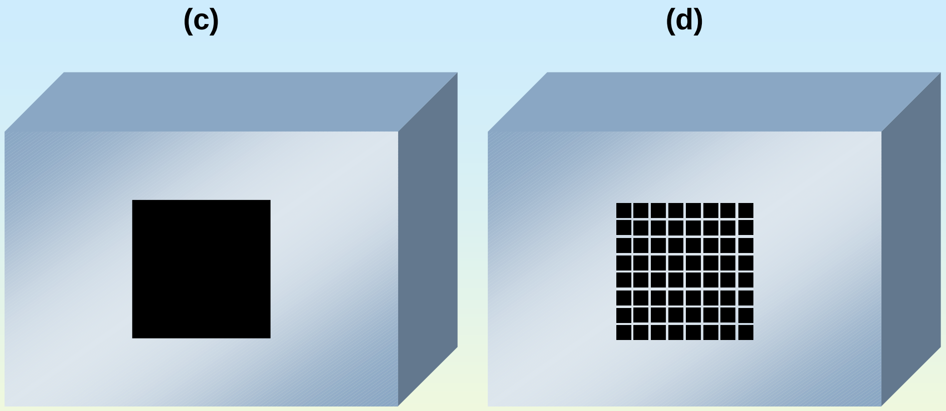
There are some simple shielding design tools freely available via the Internet, for example [14], [15] and [16], but I do not know how accurate they are at predicting real-life SE. For example, [14] uses similar simple equations to those above.

As it happens, there is a simple shielding formula that is supposed to apply specifically to the ‘array-of-small-holes’ example above. It says that where an otherwise perfectly shielded enclosure has a single square hole, replacing that hole by a grid of smaller square holes within the same outline (as shown by Figure 4M) improves the SE by S dB, where…

$$S = 20 \log_{10}\left(\frac{p^2 l}{g^3}\right) + 27\left(\frac{d}{g}\right) + 0.8 \ \text{dB}$$

– where…

l = the length of the side of the original square hole
g = the side of the smaller square holes
p = the pitch (spacing) of the smaller holes
d = the thickness of the shield material



A single square hole 100mm on a side has a certain SE

$20\log_{10}(\lambda/2g)$ indicates that it is about 11dB at 300MHz

Far field conditions apply

Replacing the 100mm square hole with an array of 10mm square holes on an 11mm pitch, within the original outline,

$$S = 20 \log_{10}\left(\frac{p^2 l}{g^3}\right) + 27\left(\frac{d}{g}\right) + 0.8 \ \text{dB}$$

…indicates that SE is improved by about 25dB, compared with (c) (for a metal thickness d of 1mm)

Figure 4M Reasonable SE predictions from an equation derived for the specific situation

This guide equation only works when $g<\lambda/6$ at the highest frequency of concern. If small round holes are used instead of square ones, g represents their diameter and S is 3dB higher. Figure 4M shows that applying this formula to an example similar to Figure 4L, the SE should be improved by about 25dB. It is difficult to say whether this will be a very accurate prediction for a real product, but at least it correlates better with real-life shielding behaviour.

The above equation only applies where the array of holes fits within the outline of the original single large hole. This means that, because of the area taken up by the metal grid between the holes, the open area of the array is less than that of the single large hole. Increasing the number of holes to achieve the same open area, e.g. for ventilation purposes, will clearly reduce the SE somewhat, but the equation does not cover this.

4.3.8 Cavity resonances and aperture leakage

As mentioned earlier, an enclosure’s internal cavity resonances can cause an aperture to leak (emit) to a much greater degree than it would normally, if the aperture lies in a region where the surface currents are being amplified by a cavity resonance inside the enclosure itself (a ‘hot spot’). These resonant frequencies are governed by the enclosure’s internal dimensions, rather than by the dimensions of the aperture.

Figure 4N shows the simple equation typically used to estimate cavity resonances. Because a shielded enclosure has a low impedance at all of its boundaries, it can only experience cavity resonances that have integer (whole) numbers of half-wavelengths, at frequencies given in MHz by

$$f = 150\sqrt{\{(l/L)^2 + (m/W)^2 + (n/H)^2\}}$$

where: l, m and n are integers (0, 1, 2, 3 etc.) representing the number of half-waves that fit between the parallel metal surfaces along any of the three axes, and L, W and H are the box's length, width, height respectively, in metres. (If the dimensions are stated in millimetres, the resonant frequencies are given in GHz.)

Only resonances with integer numbers of half-wavelengths can occur in a closed metal box, at frequencies given by:

$$f = 150\sqrt{\left\{(l/L)^2 + (m/W)^2 + (n/H)^2\right\}} \quad \text{(in MHz)}$$

l, m and n are integers (0, 1, 2, 3 etc.)

L, W and H are the box's length, width, height (in metres)

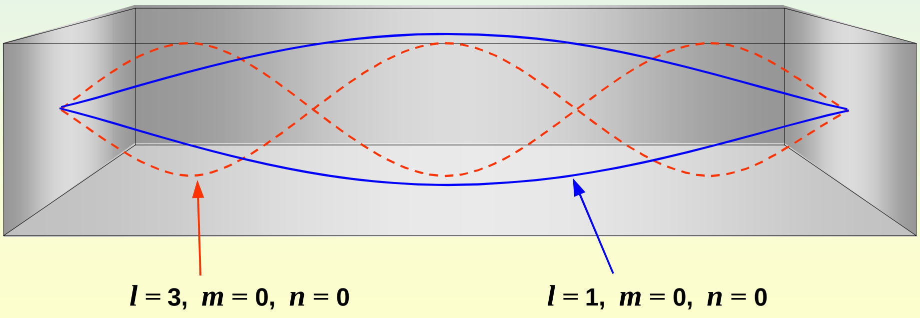


Figure 4N **Resonances and 'standing waves' caused by reflections inside a metal box**

Figure 4N sketches the field distributions for two solutions of the above equation, one for what is known as the (1,0,0) mode, in which l =1 half-wave, m = 0, and n = 0, and one for the (3,0,0) mode in which l =3 half-waves, m = 0, and n = 0. These examples show the 'standing wave' patterns for the E field distributions at these resonant frequencies. The waves are not really stationary, they are actually ricocheting back and forth between the two metal sides of the box at the speed of light, but unless we have very fast instruments we see them as if they are stationary.

It is possible to imagine very complex modes, such as (27,13,19), but in the main we are interested in simple resonant modes such as (x,0,0), which is side-to-side, (0,x,0), which is half-wave front-to-back and (0,0,x), which is top-to-bottom. A significant resonance is the (1,1,1) mode – which gives us the lowest internal resonant frequency, between opposing corners, along the three-dimensional diagonal.

Figure 4P shows an example of a three-dimensional field solver plotting the E field strengths inside a shielded box at one of its resonant frequencies (which appears to be its (3,0,0) mode). The field leakage through a small aperture in the box can clearly be seen.

Adding metalwork, printed circuit boards, cables, etc., inside a box affects its resonant frequencies, generally they make its resonances lower in frequency, as in the example shown in Figure 4Q. They can also add new resonant frequencies.

Resonant hot spots within the volume of an enclosure can sometimes have significant effect on signal integrity, due to the amplification of crosstalk phenomena at the resonant frequencies, between cables and/or PCBs. Careful design will ensure no especially sensitive or noisy components (or conductors associated with them) are placed near a hot spot, unless they are appropriately shielded or filtered.

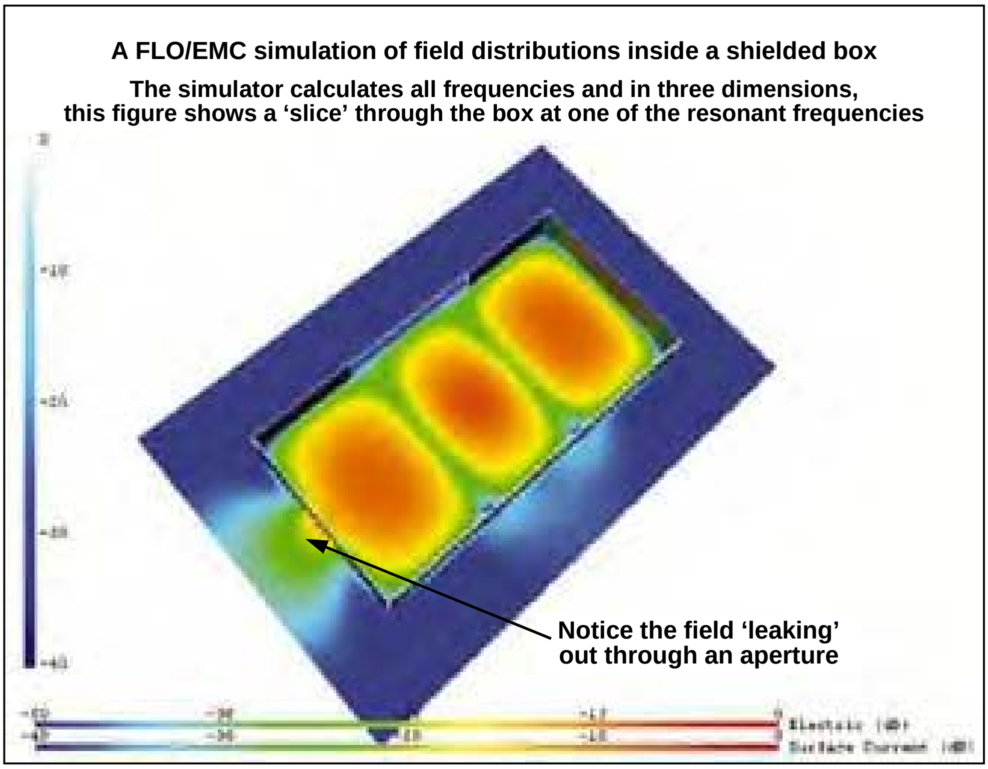


Figure 4P Examples of real-life cavity resonances

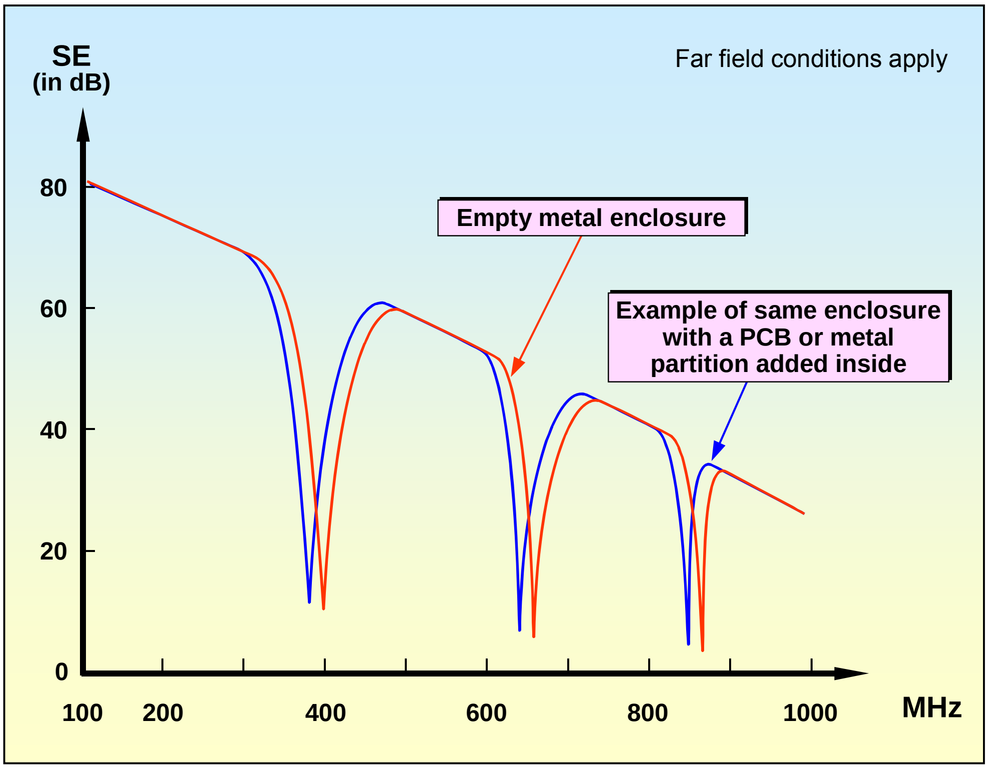


Figure 4Q Examples of cavity resonance frequencies being reduced by box contents

4.3.9 Near-field leakages through apertures

So far we have assumed that the source was so far away that its EM radiation was plane waves, i.e. the shield was in the *far-field* of the radiating source – the usual situation when trying to protect electronics from external RF sources (to improve immunity).

But when using shielding to reduce emissions from a product, the shield is usually in the *near-field* of the source – and the SE from plane wave assumptions can be very wrong indeed, especially at lower frequencies. The closer the RF source is to the apertures, the worse the SE. Very significant amounts of leakage can occur, especially at low frequencies, even through arrays of very small apertures that individually have very good SEs for plane (far-field) waves, see [17] for more detail.

Figure 4R sketches the E and H fields around an aperture, indicating that they are associated with regions of reduced SE, where it would be inadvisable to locate noisy or sensitive components or conductors.

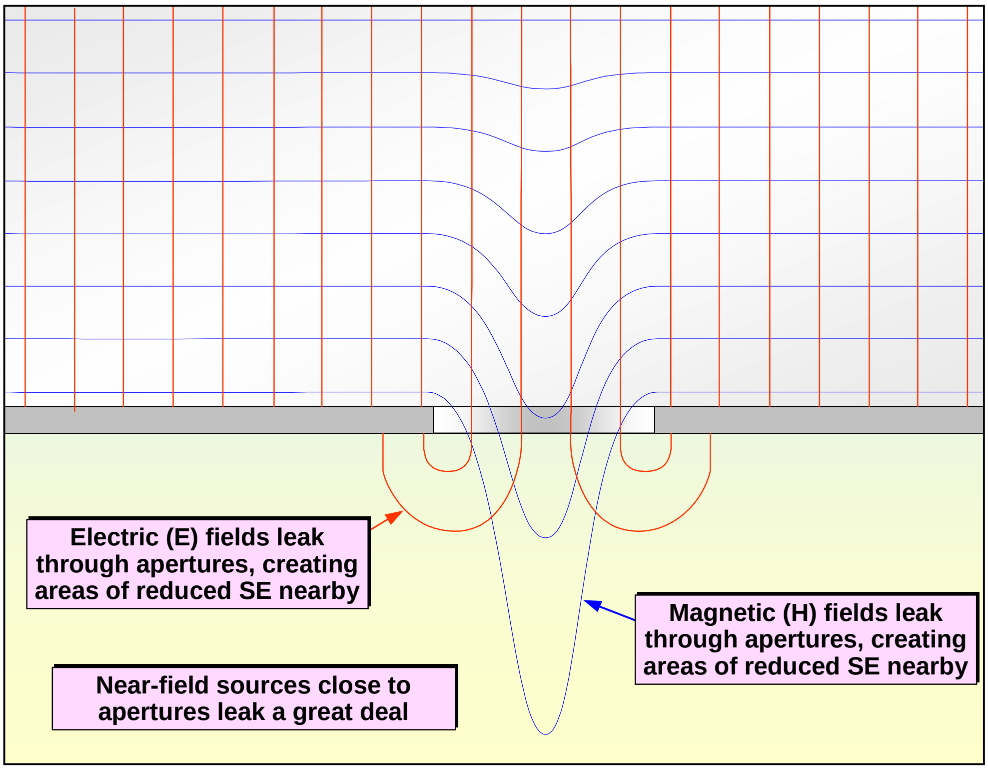


Figure 4R SE for near-fields is less when sources are near an aperture

4.3.10 Designing to reduce aperture leakages

Eliminate apertures. Only allow apertures that are necessary for the function of the product.

Reduce aperture size. Do not allow apertures to be any larger than necessary. Break any necessary apertures up into smaller ones, as shown by Figure 4M, to make their resonant frequencies much higher than the highest frequency of concern. Where there are long seams or joints between metal structures, they should be electrically connected using direct metal-to-metal bonding techniques at regular intervals along the seam or joint.

Figure 4S shows the principles of direct metal-to-metal RF-bonding, which should be used where bonds cannot be welded. It is generally bad EMC practice to rely on the fixing device (e.g. the self-tapping screw, in Figure 4N) to make the electrical bond (although this is unfortunately quite a common practice). Apart from the poorer RF performance of the bond, one of the problems with relying on the fixing device to make the bond is that company component buyers might source fixings with non-conductive plating, destroying SE completely.

Flexible conductive gaskets, often called EMC gaskets, are very valuable for reducing aperture sizes, especially where apertures must be long – for example around removable covers, doors, shielded windows, shielded ventilation panels, etc. Gaskets and gasketting methods are discussed in their own chapter, later.

Spread necessary small apertures as far apart as possible. For frequencies at which the spacing is larger than $\lambda/4$, some reduction of emissions will occur at some angles. To have any significant effect at 600MHz (where λ is 500mm), the spacing should be >125mm. It is even better if the necessary apertures can be placed on different sides of the enclosure. Don't expect large improvements from this technique.

Reduce near-field leakages. Where it is impractical to completely fill an aperture with a conductive gasket, to reduce the impact of near-field leakages from reducing the enclosure's SE, make sure that all wires, cables, PCB traces, components, etc. are not near an aperture. This is especially important for any conductors or components that are especially noisy (e.g. flyback inductors in switch-mode power supplies; microprocessors, PCB traces carrying high-rate data), and also important for any that are especially sensitive (e.g. analogue amplifiers, microprocessors, PCB traces carrying high data rate signals).

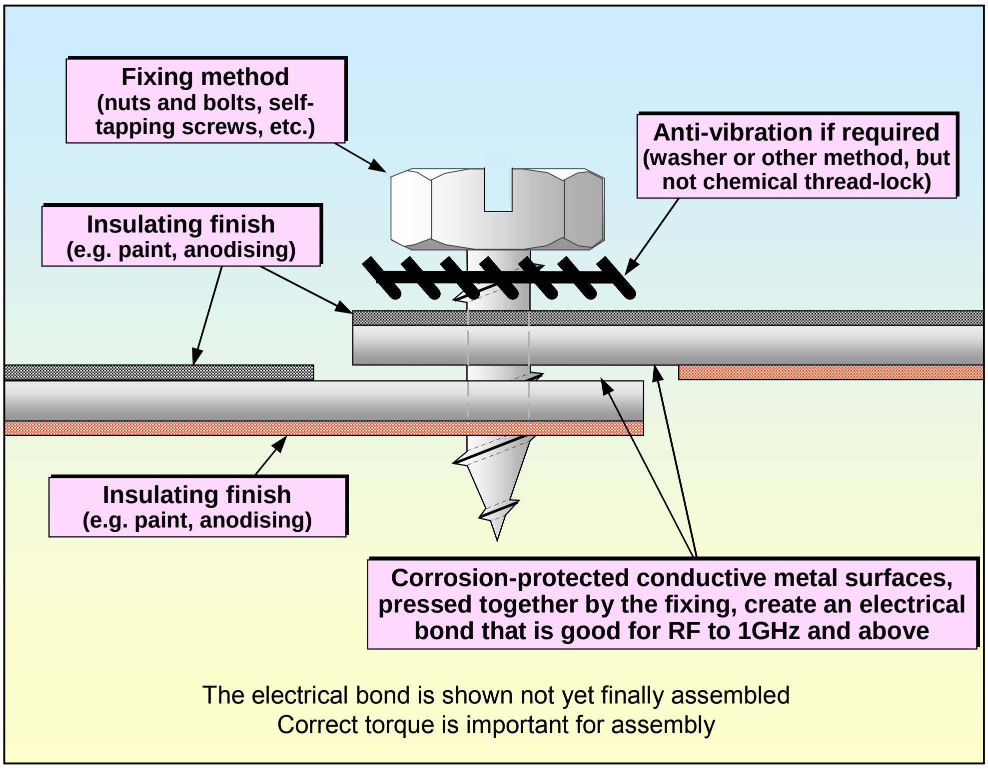


Figure 4S Principles of direct metal-to-metal RF-bonding

As far as I know there are no simple equations that can be used, but a crude guide might be that for an SE of more than 40dB at *any* frequency, the spacing between a conductor or component and an aperture should generally be at least 1.5 times the longest dimension of the aperture (i.e. its diameter or longest diagonal). Larger spacings are recommended, especially at lower frequencies. See [17] for more on this, noting that the coupling coefficient it uses could be considered to be the reciprocal of SE, which means simply reversing the sign from negative dB to positive dB.

Make shielded cavities smaller. The aim of this method is to make the cavities inside the shielded enclosure smaller, so that they each resonate at a much higher frequency than is cared about. If the highest frequency of concern was 1GHz, cavities with longest 3-D diagonals of less than 125mm are required. This is another reason why using many small shielding-cans on PCBs can be more cost-effective than an overall shielded enclosure. Often, a single large screening can is subdivided inside to create many smaller cans, to save assembly time (see the section on PCB shielding, later).

For example, Figure 4T shows one side of a shielded plastic enclosure for a telecommunications product, which has been subdivided into many smaller shielded internal volumes by ribs in the plastic moulding with form-in-place soft conductive gaskets extruded by robotic assembly machines along the ribs. Such multi-compartmented shielded enclosures can also be a great help for signal integrity – separating different circuits within a product more effectively from each other and reducing the crosstalk between them.

Damp cavity resonances with absorber. Where a cavity's resonances cannot be made small enough to resonate at a higher frequency than is cared about (see above), the Q of cavity can be damped to reduce emissions by a useful degree with two basic kinds of materials:

- Carbon-loaded elastomer, usually foam, which absorbs energy from the E-field and so is usually placed away from the walls of the enclosure.
- Ferrite-loaded elastomer, usually solid, which absorbs energy from the H-field and so is usually placed close to the walls of the enclosure.

These materials come in various thicknesses, with various proportions of carbon or ferrite filler. The types that provide more damping and/or operate at lower frequencies, are generally heavier and more expensive. Typically they only provide useful amounts of damping at frequencies above a few hundred MHz. These materials are available in sheet form, with or without self-adhesive backing, and also available in die-cut preforms as shown in Figure 4U.

Some manufacturers (e.g. Laird Technologies) offer 'absorber cans' as standard parts for shielding on PCBs, supplied with absorber already fitted to an inside surface.

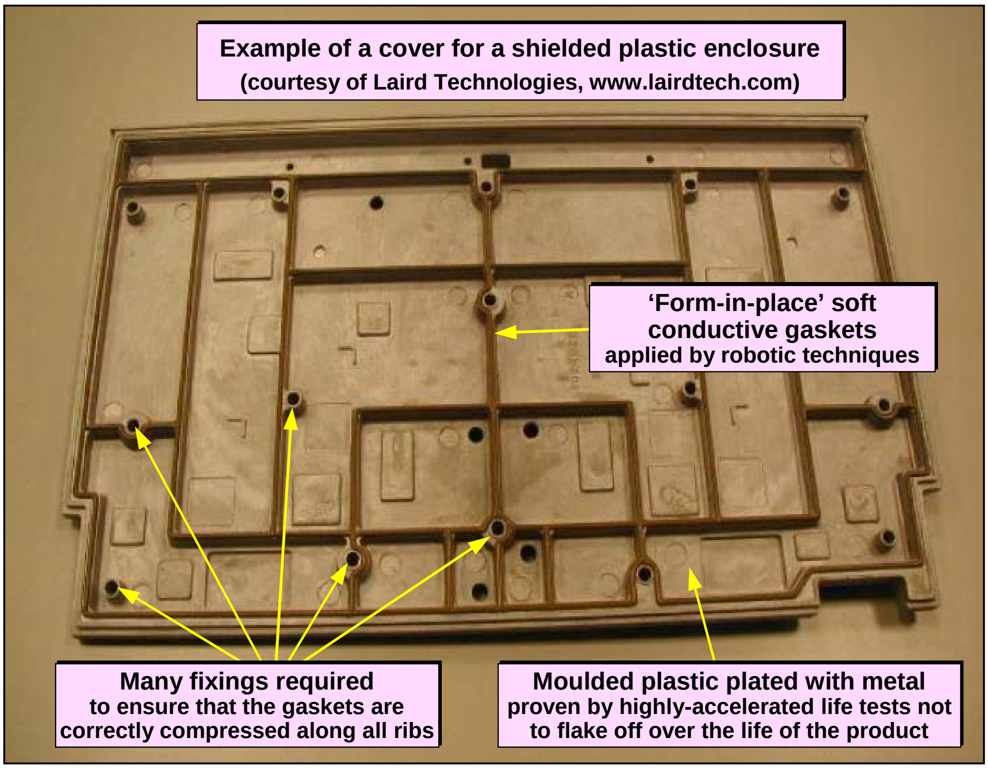


Figure 4T Example of a multi-compartmented shielded enclosure

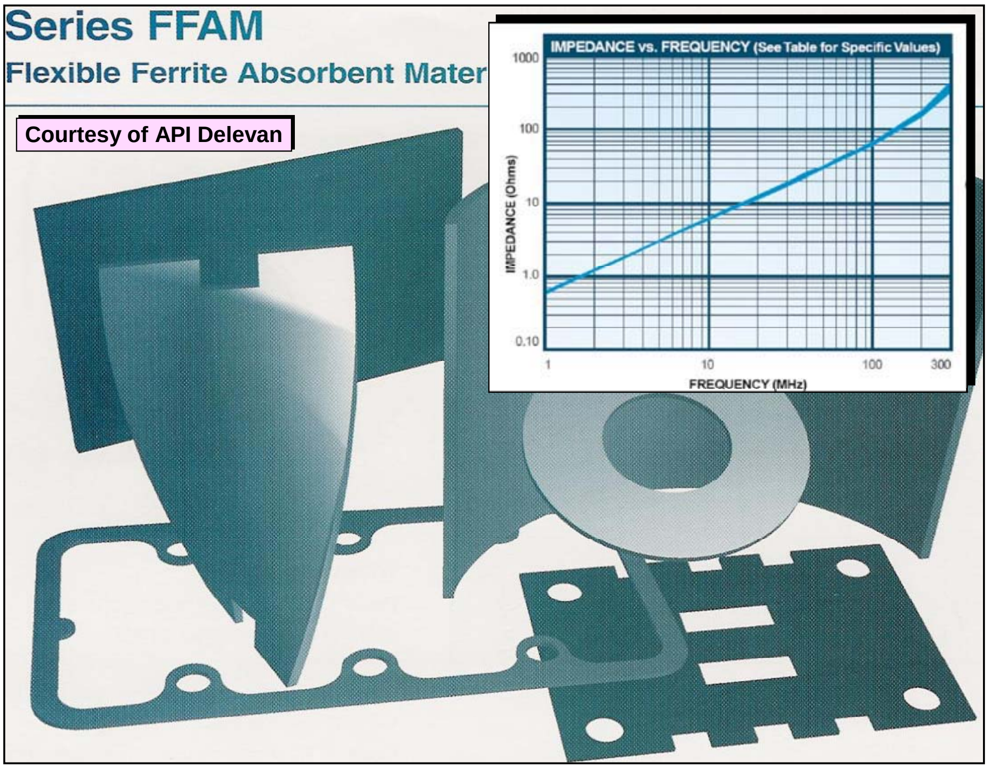


Figure 4U Examples of die-cut RF absorber materials

Randomise the cavity resonances. Where a cavity's resonances cannot be made small enough to resonate at a higher frequency than is cared about (see above), SE can be improved by careful design of enclosure shape, and aperture shape and location. Regular shapes have modes that resonate at the same frequencies, making the overall Q at those frequencies even higher.

For example, if a metal box is 1m long, 0.5m wide and 0.25m high, all of its three dimensions will resonate at 600MHz: four half-wavelengths along its length, two half-wavelengths across its width, and one half-wavelength between its top and its bottom. So at 600MHz (and also at 1.2, 1.8, 2.4, etc. GHz) the Q of the cavity will be much larger than is usual for a cavity resonance and aperture leakages can be expected to be higher as a result.

The solution is to avoid regular shapes. A common approach is to arrange the length, width and depth in the ratio 3:4:5, which is not bad but could be improved upon, for example by using irrational numbers for the ratios, avoiding numbers that are too close to simple ratios such as 1.5 or 2 – especially if the lowest-cost product is required. There is an infinite number of irrational numbers to choose from, such as √2, but the 'golden mean' (1.618…) may be a good choice because it gives a pleasing aspect to the human eye, as architects and artists have known for thousands of years. If using circular shapes, avoid shapes with a single radius of curvature such as cylinders or spheres.

Another useful method is to avoid parallel metal surfaces. In the days when mechanical designs were made using drawing boards, setsquares and compasses, and metal parts were cut from sheet and folded by hand, it was hard to avoid regular shapes such as rectangles and circles. But these days we have much more flexibility and can more easily design, manufacture and assemble enclosures using shapes based on non-parallel planes and curved sections with smoothly-varying radii.

Even where the external structure must be rectilinear with parallel sides, or (worse still) have a square cross-section or be a cube, this does not necessarily mean that the internal metal structures forming the shield(s) must be as regular.

It is important to remember that internal resonances are modified by internal conductive and dielectric structures, so to reliably obtain benefits from this approach requires early-stage design simulation of the shielded enclosure, based upon its likely apertures (e.g. seams, joints, doors, displays, ventilation, etc.) and the shapes, sizes and locations of the objects it is likely to be contain (e.g. trays, shelves, brackets, PCBs, heatsinks, cables, etc.).

Careful design of an enclosure can help achieve the lowest-cost product that still complies with EMC regulations and is sufficiently reliable in real-life use – by helping to reduce the cost and weight of the shielding and filtering measures required. But, as is usually the case where lowest-cost products are required, this requires more design resources, in both expertise and time. The use of computer simulators (see later) is an excellent way to add field-solving expertise without having to learn field theory, and commercially available computer simulators running on desktop PCs can easily predict field distributions for real-life products that even the most egg-headed EM field theory expert would not attempt.

The 'dirty box' technique. Where a hole must be cut in a shield, for example for panel-mounting a control, lamp indicator, etc. – but the component to be thus mounted does not need to be shielded – a secondary shielding box can be used, often called a 'dirty box' (the 'clean box' is the inside of the shielded enclosure). Figure 4V shows the important points of this versatile technique.

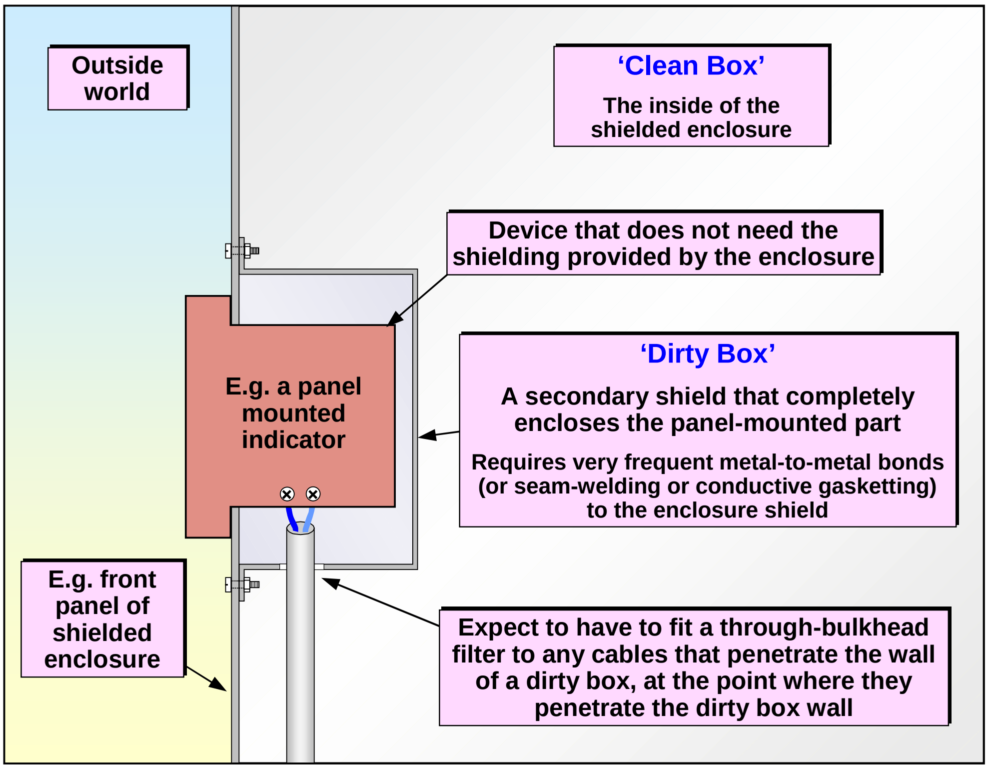


Figure 4V Example of the use of the 'dirty box' method

Notice especially that the dirty box must be treated like any other shielded enclosure – with careful design of its apertures (see above) and cable penetrations (see below). Bulkhead filters may be needed for all cables penetrating the dirty box walls, and should be allowed for in the design in case they turn out to be needed ('anti-

Murphy' design techniques, see earlier). These filters often only need high attenuation above 100MHz, so can be small, and may even be able to be replaced with ferrite chokes (such as those shown in Figure 3G of [18]) mounted on the cable very close to the point where they penetrate the dirty box.

Techniques for large apertures. Where apertures must be large, for example for doors, covers, display screens, etc., and the 'dirty box' technique is not appropriate, there are a number of techniques that have been developed to help achieve good SE…

- Waveguides below cutoff
- Shielded windows for displays
- Shielding membrane switch panels
- Shielding ventilation
- Gasketting with conductive gaskets

The first three in the above list are described in the next three sections, but conductive gasketting is a fundamental technique that can be used with all of the other aperture-control techniques, so it is given its own chapter towards the end of this article.

4.3.11 Waveguide-below-cutoff techniques

Waveguides have a cut-off frequency below which they cannot be used to 'pipe' EM waves from one place to another. In fact, their attenuation factor for frequencies below about 60% of their cut-off frequency can be very much higher than for a comparable aperture in a shielded enclosure, and this principle is sketched in Figure 4W.

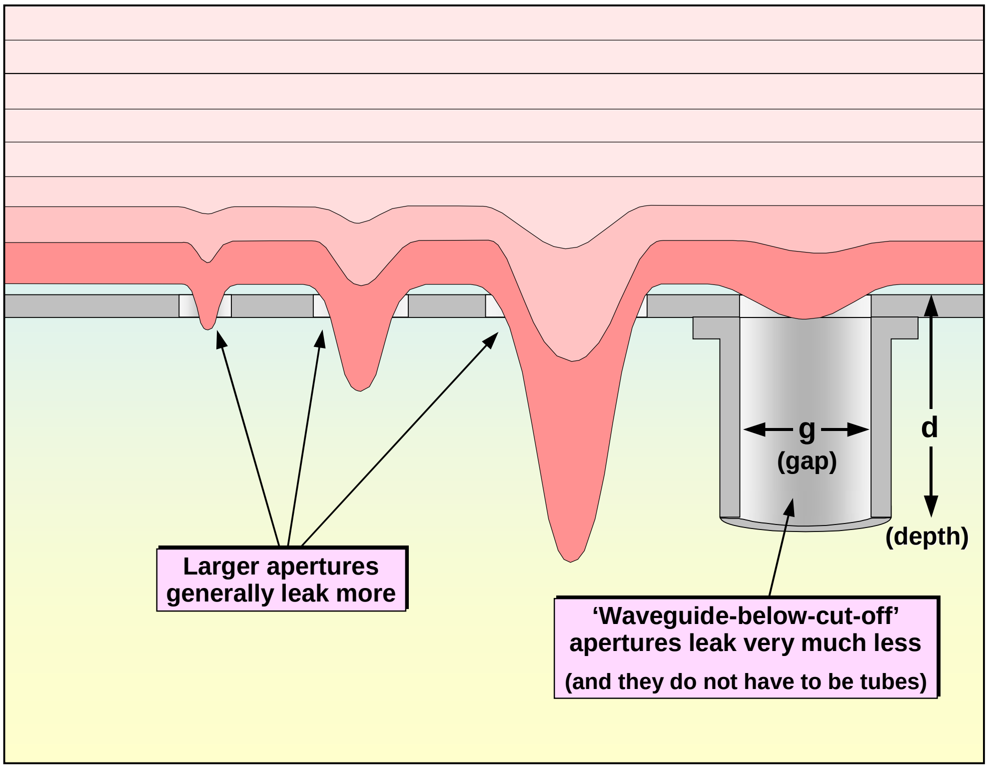


Figure 4W Waveguides used below cutoff leak much less than comparable apertures

The cut-off frequency of a waveguide occurs when its maximum aperture dimension, g (its diameter or longest diagonal, as before) is half a wavelength, so in air or vacuum: $f_{\text{cutoff}} = 150/g$ MHz when g is specified in metres. If g is given in millimetres instead, this formula gives the cutoff frequency in GHz.

Below its cutoff frequency, the attenuation of a single waveguide depends on its ratio of depth (d) to longest aperture dimension (g). For frequencies that are less than about 0.6 of the cutoff frequency, a waveguide has a constant attenuation of approximately {27 d/g} dB, so…

- $d/g = 2$ gives SE = 54 dB
- $d/g = 3$ gives SE = 81 dB
- $d/g = 4$ gives SE = 108 dB

These figures indicate very much lower leakages, and therefore much higher SEs, than apertures with the same dimensions but a negligible value of d, as shown by the examples in Figure 4X.

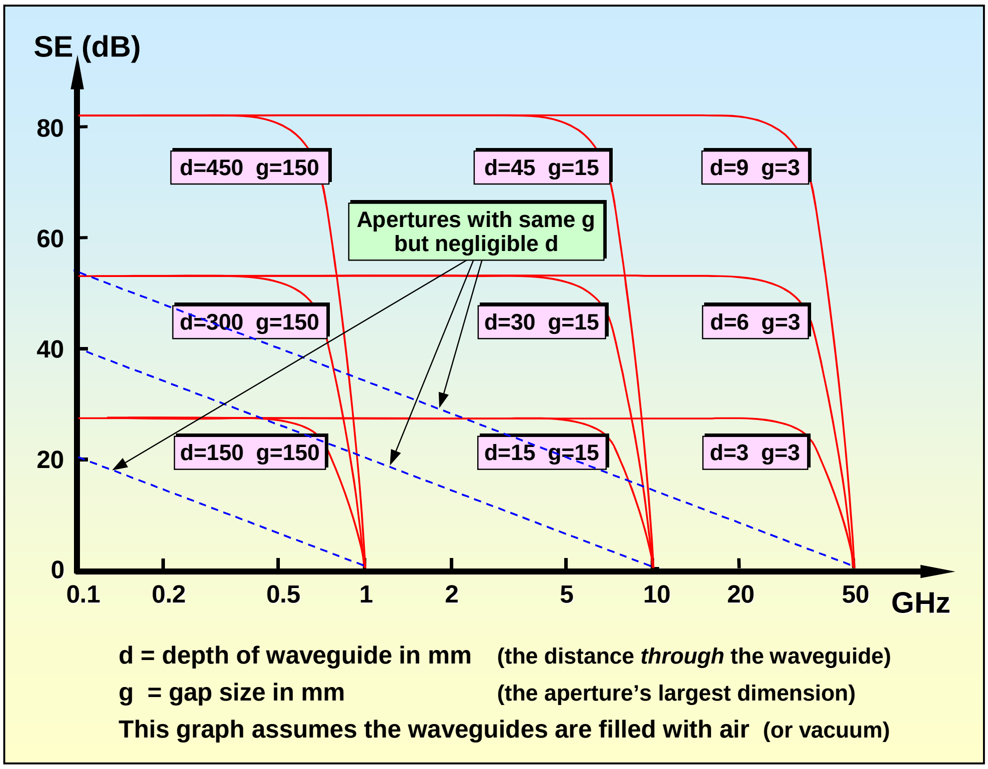


Figure 4X **Estimated SEs for some example waveguides-below-cutoff**

Designing any necessary apertures in a shielded enclosure as waveguides-below-cutoff will very significantly reduce their impact on SE. To achieve these benefits, their cutoff frequency should ideally be at least double the highest frequency of concern.

It is important to note that, just as for any aperture, passing any conductor through a waveguide-below-cutoff will completely ruin its attenuation and therefore ruin the SE of the shielded enclosure. There are *no* exemptions to this rule, regardless of the function of the conductor (e.g. mouse or keyboard cables, draw wires in fibre-optic cables, waste water).

However, waveguides-below-cutoff are very useful indeed for passing non-conductors (dielectrics) into or out of shielded enclosures – as long as the effect of their relative permittivity (dielectric constant, ε_r) in reducing the cutoff frequency is taken into account.

So far, this discussion, and Figure 4X, has assumed that the waveguide is filled with air (or vacuum), but filling with any dielectric with an ε_r greater than unity (e.g. oil, distilled water, glass, plastic) results in a reduced cutoff frequency given by: $f_{cutoff} = 150/(g\sqrt{\varepsilon_r})$ MHz (for g in metres). For mixed dielectrics – use the average value of ε_r over the cross-sectional area to estimate the new cutoff frequency.

[4] makes the point that it is much better for EMC to use fibre-optic cables than ordinary conductive cables, and that although the component and material costs of fibre-optic interconnections may be higher than copper, the overall cost of manufacture, reduced warranty costs and increase customer satisfaction often means that they achieve an overall financial benefit. In addition to these EMC benefits, metal-free fibre-optic cables can be passed through the walls of shielded enclosures, using waveguide-below cutoff techniques to have a negligible effect on SE.

Many types of fibre-optic bulkhead connectors or couplers function as very effective waveguides-below-cutoff up to at least 10GHz. The bulkhead connector must be metal, and it must make a 360° metal-to-metal bond with the shield around the hole cut for it in the shield's wall, following the RF-bonding principles illustrated in Figure 4S. The optical fibre has a high value of ε_r so the cutoff frequency will be lower than would be expected simply from consideration of the inner diameter of the metal connector or coupler.

Waveguides-below-cutoff do not have to be tubes – their shapes are limited only by the imaginations of mechanical designers and constraints of the products. For example, Figure 4Y shows that using thicker shield materials (e.g. 3mm instead of 1mm) with apertures that have a comparable (or smaller) longest dimension, g, reduces the leakages through the apertures significantly, because they start to behave as waveguides-below-cutoff.

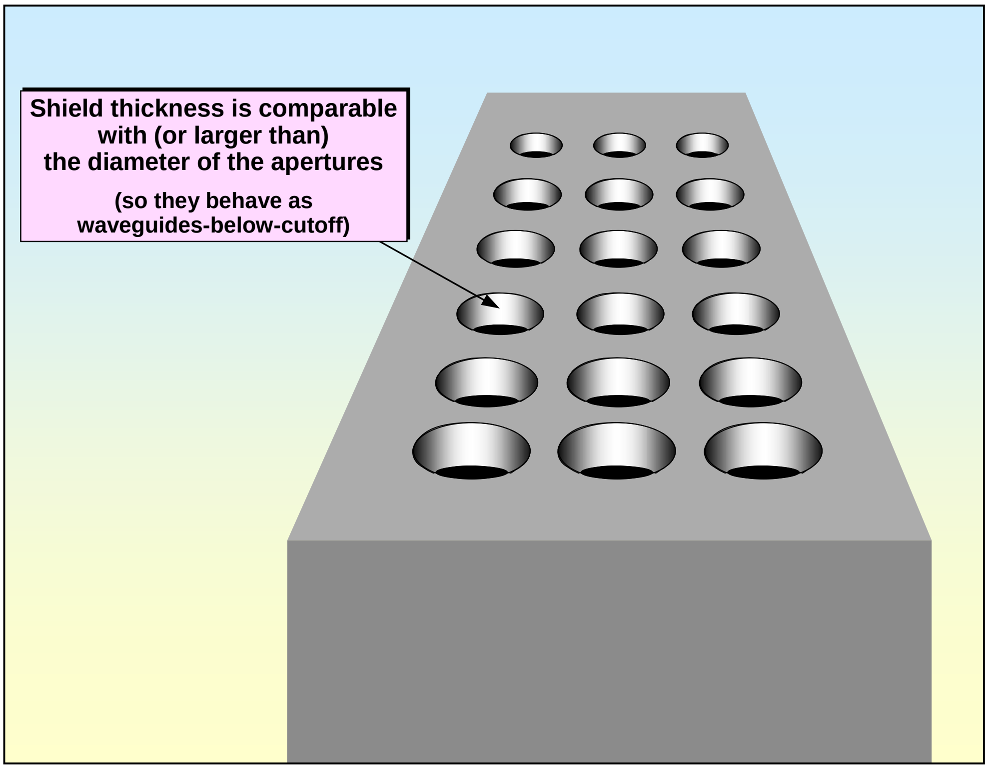


Figure 4Y **Aperture longest dimensions comparable with shield thickness**

The 27(*d/g*) term in the earlier equation for replacing a large aperture with a number of smaller ones represents the contribution from the waveguide-below-cutoff effect. For the example shown in Figure 4M it only added 2.7dB to the improvement in SE, because the shield thickness *d* was 1mm, whilst the sides *g* of the small square apertures were 10mm. But if *d* had been 3mm and *g* 5mm, its contribution to improving the SE of the enclosure would have increased from 2.7dB to a more useful 16dB.

An obvious use for this technique is for ventilating shielded enclosures, and it can be developed much further by the use of ‘honeycomb metal’. An example of honeycomb metal, and of some panels made from it, are shown in Figure 4Z. Honeycomb metal is made of small tubes with hexagonal cross-section, with a *d* (length) very much larger than their *g* (largest aperture dimension), giving a *d/g* ratio that often exceeds 6, for very low leakage indeed.

Small holes are not very efficient for ventilation, especially when made in thick plates of metal (as shown in Figure 4Y). Where ventilation is critical, achieving the same airflow rates and pressures as larger holes, often requires more ‘open area’ for the smaller holes – which tends to reduce the SE benefits of small holes in thick metal. The hexagonal tubes in honeycomb metals have very thin walls, so for ventilation they behave almost as well as a single large aperture, whereas for SE they behave like a large number of very-high-attenuation waveguides-below-cutoff.

Honeycomb metal panels can also be used to shield apertures where optical energy is emitted, (e.g. lamps, lasers, etc.) and have even been used to shield display screens – which can then only be seen from immediately in front (which can have benefits in security-conscious applications). Fibre-optic cables can also be passed through the honeycombs, as long as the cables are totally metal-free.

Metal honeycomb panels used to be costly items, with large NRE (non-recurring engineering) charges that made prototypes extremely expensive. But modern manufacturers use computer-controlled robotic manufacturing tools, so the only NRE is that needed to capture their 3-D drawings. About two years ago I was quoted around £150 for a prototype honeycomb panel about 300mm square, similar to the ones shown in Figure 4Z. Ten years ago that figure would have been about ten times larger.

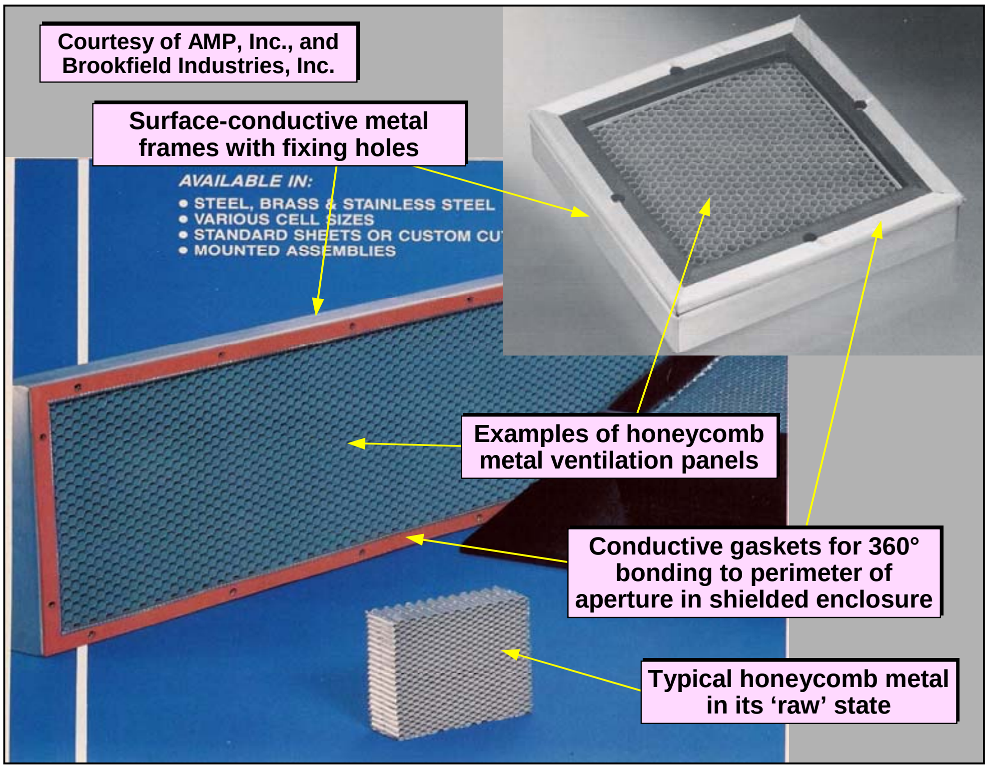


Figure 4Z **Some examples of using honeycomb metal for shielding**

To be effective in shielding applications, honeycomb metal panels must have a metal frame with good surface conductivity, with sufficient stiffness and enough fixing holes to correctly compress a conductive gasket around its entire perimeter – to avoid creating additional apertures that would degrade SE. Alternatively, they can be glued in place using conductive adhesives.

Honeycomb metal is naturally very light and stiff, which helps it to compress conductive gaskets correctly without requiring large number of fixings (see later for gasket design). The honeycomb tubes are glued together, so for the best shielding performance use panels that were overall-plated with a highly conductive finish (e.g. tin) after assembly.

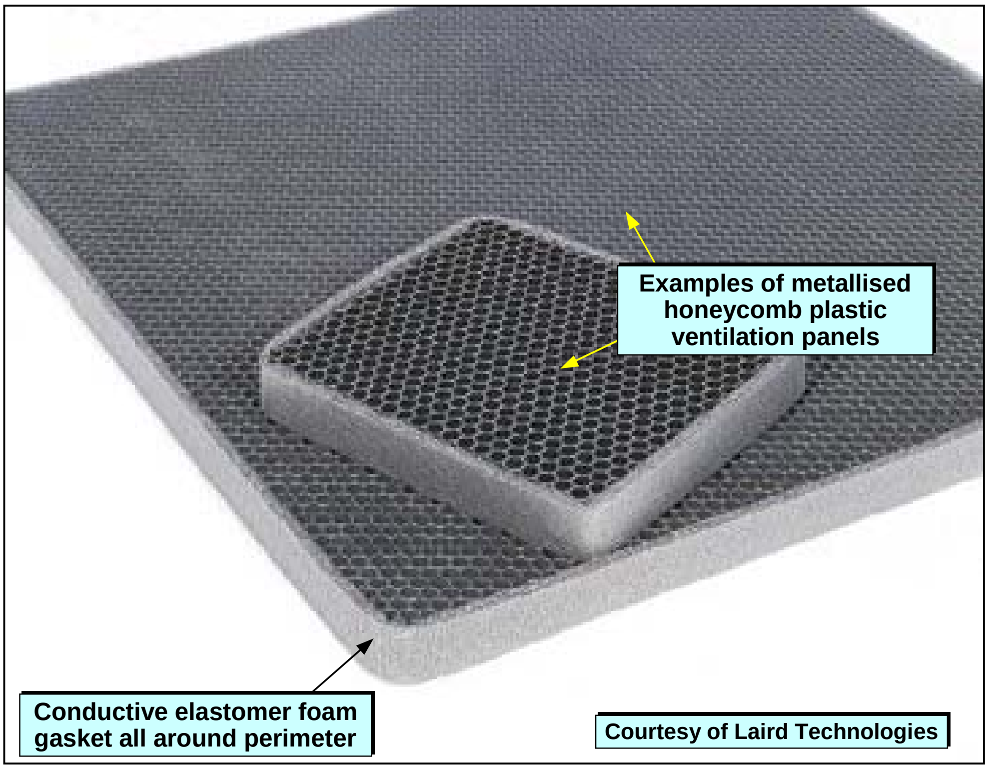


Figure 4AA **Examples of plastic honeycomb shielding material**

Figure 4AA shows a recently-developed shielding product – honeycomb plastic with an overall conductive plating, and a conductive elastomer gasket bonded around its perimeter. It doesn't have the rigidity and strength of honeycomb metal, but it weighs less and should also cost less whilst having similar attenuation characteristics to honeycomb metal.

Another application of the waveguide-below-cutoff technique is simply to provide greater overlaps at metal seams and joints, as shown in the example in Figure 4AB. This method does not *really* use waveguides, so the normal waveguide-below-cutoff theory and equations no longer apply – but in practice these forms of construction do seem to behave in a similar manner (which we might call 'pseudo-waveguide-below-cutoff'), which is why it is included in this section.

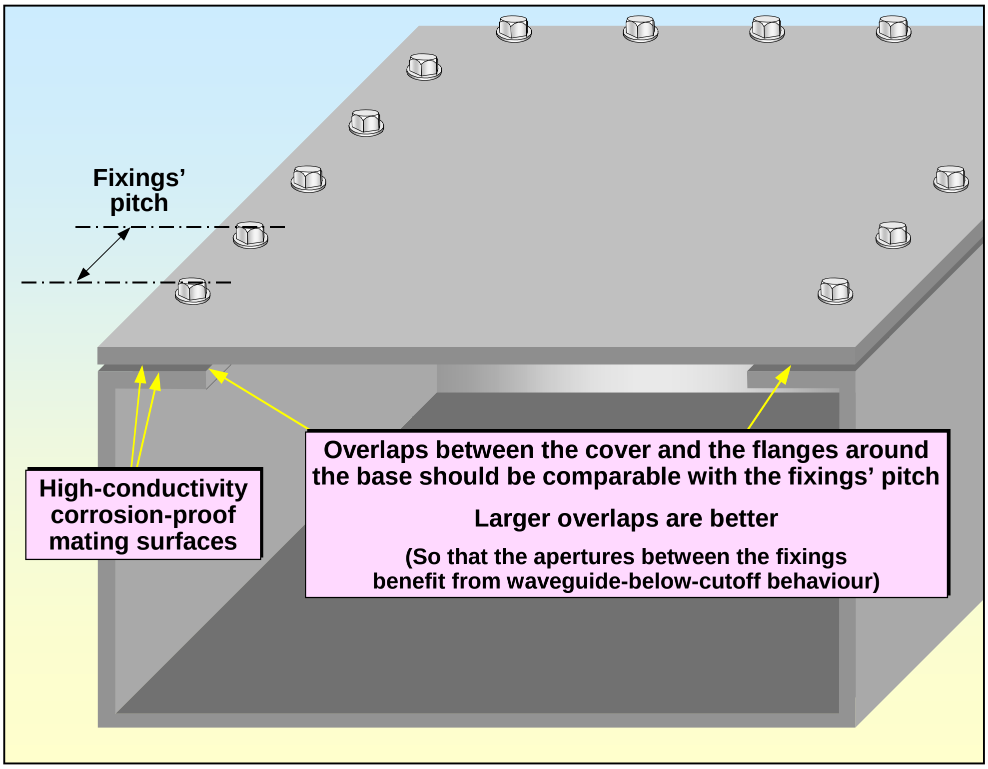


Figure 4AB Joint overlaps comparable with fixing pitch

I was once testing a product constructed rather like Figure 4AB with close-field probes to determine the cause of its enclosure's poor shielding of its internal 900MHz oscillator. The enclosure had a flat metal lid screwed onto flanges that were about 8mm wide, except along one edge where the flange was 25mm wide (for reasons that are not relevant). The lid was held down with screws located every 60mm around its perimeter. The close-field probe found uniformly high levels of emissions all around the three sides with the 8mm flanges, but 10dB lower emissions all along the edge with the 25mm flange.

Assuming the fixings and flanges create waveguides (which they do not), the simple waveguide-below-cutoff formulae above show that the cutoff frequency of the 60mm fixing pitch is 2.5GHz, so 900MHz is low enough to fall in the $27(d/g)$ dB region – which predicts that the 25mm flange should have 12dB attenuation, whilst the 8mm flange has 3.6dB. The difference between these two calculated figures is 8.4dB, much closer to the 10dB that was measured with the close-field probes than could have been hoped for (or is usually the case) when trying to compare simple EMC equations with practice, especially using close-field probing. Close-field probing is a very valuable technique for developing and fault-finding shields, and also for checking their assembly in series manufacture, for more information see Parts 1 and 2 of [19].

Reducing the longest aperture dimension, g, means adding more RF bonds, but assembling large numbers of fixings adds to assembly time and adds to the cost of manufacture. Small conductive gaskets, such as individual spring fingers, can be used instead, to make the necessary RF bonds. Sufficient mechanical fixings will still be required – to compress the pieces of gasket, if for no other reason – but because this method does not use long lengths of gasket it avoids the mechanical difficulties of providing very large amounts of pressure (see the section on gaskets, later).

Figure 4AC shows an example of the addition of individual spring finger gaskets to a cover plate, to improve the SE of the enclosure by breaking four long apertures up into 12 shorter ones (smaller values of g) to improve SE without adding more fixings. The visible surfaces of the product might be painted or anodised, but the areas that the spring fingers contact must be highly-conductive surfaces – their materials and plating selected for low corrosion in their intended operating atmosphere (see later) so that good SE is maintained for the life of the product.

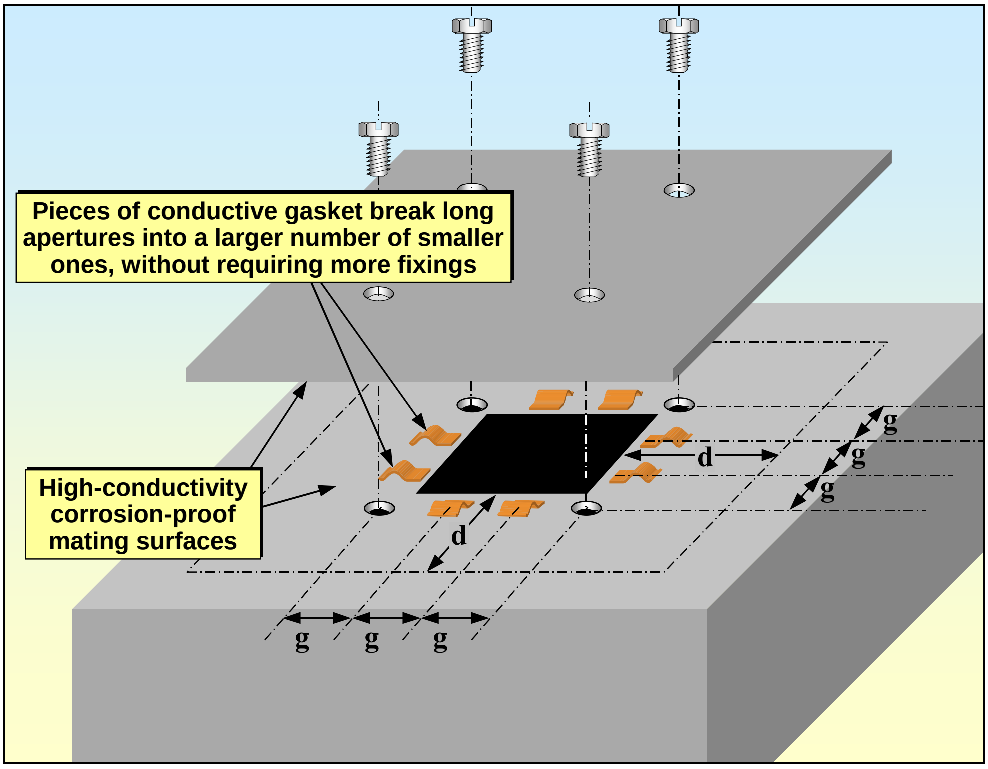


Figure 4AC **Example of reducing the aperture dimension g with conductive gaskets**

Spring fingers are generally supplied in strips, but can be purchased singly or cut off from a strip. They can sometimes be formed in the metal of the enclosure itself, for example by a 'semi-punch' process. Many other types of strip gasket can be cut with scissors to use as 'dots', but types that might shed conductive particles from cut edges should be avoided. Some EMC gasket manufacturers make products especially for the purpose shown in Figure 4AC, e.g. 'fuzz buttons' (from Teknit) or 'gasket dots'.

Where a shield's mating part is a PCB, spring fingers and many other types of RF-bonding components are available in surface-mounted styles, such as Gore-Shield SMT. Suitable components include anything that is volume- or surface-conductive, and area contacts on both sides are preferred over point contacts. However, it is very important to avoid any components that rely on a wire bond, especially if it is a spring – such components have too much inductance to make good RF bonds.

Figure 4AD shows an example of a shielded enclosure design that uses pseudo-waveguide-below-cutoff techniques like those of Figures 4AB and 4AC, with a single quarter-turn plastic fastener used to retain the cover. I know of no product like this, it is just an example to show what is possible.

The overlap at the seam between the cover and the base has been increased by making the cover a five-sided box instead of a flat plate, so that when it is assembled onto the base the (pseudo-) waveguide depth, d, comprises the flange plus most of the height of the enclosure. Spring fingers along the flanges make contact with conductive surface inside the cover, giving a value of g that is much less than d, hence very good attenuation and low field leakage. The five-sided metal cover is naturally very stiff, helping to ensure correct compression of the gasket pieces. The gap between cover and base could be used for ventilation (would probably need an air-mover).

One of the problems with covers fitted with multiple fixings, such as that shown in Figure 4AB, can be that after a year or two's use in the field most of the fixings can be missing, and the enclosure's SE sadly degraded. This is especially a problem where covers must be removed for maintenance – it is just too tedious to bother putting all the screws back in, with the correct torques. The design shown in Figure 4AD solves this by using a single quarter-turn plastic fixing that allows the cover to be removed and replaced very quickly indeed. Such plastic fasteners are also available in 'captive' styles, so that they cannot be lost (unless the cover is lost with them). And of course their positive 'snap-in' action makes it easy to ensure that the gasket pieces are optimally compressed over many years of operation.

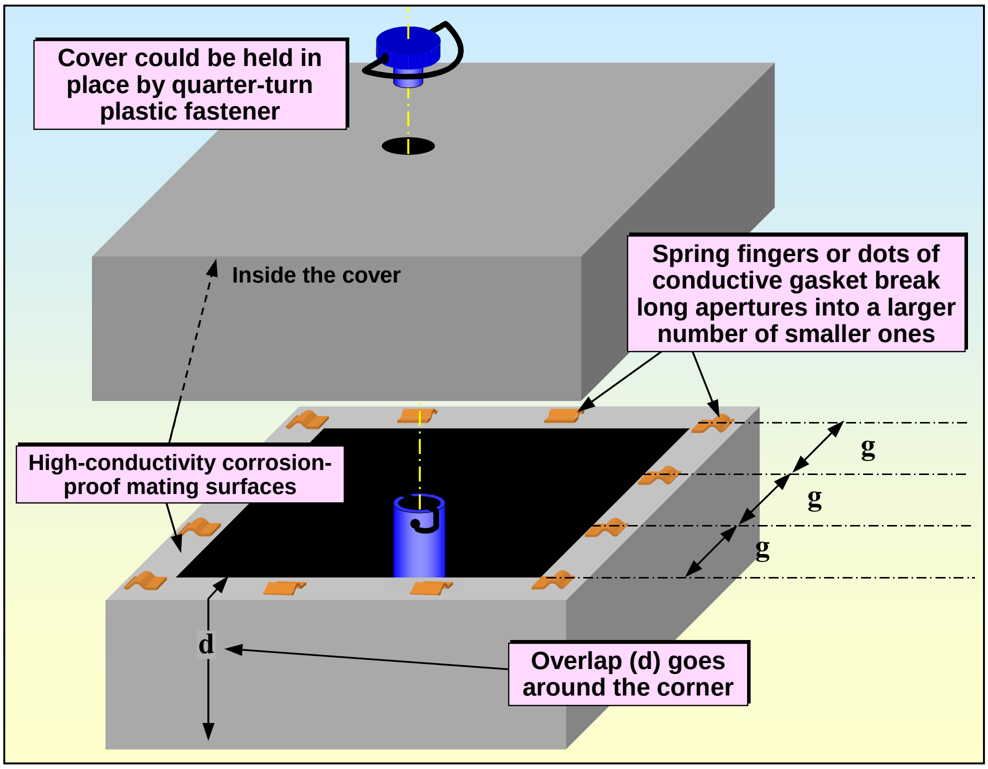


Figure 4AD Joint overlaps comparable with fixing pitch

There are many more types of design that use waveguide-below-cutoff techniques to achieve very good SE for enclosures with the lowest cost-of-manufacture – but a common thread is that *they must be designed-in from the start of the project*. It is generally impractical to try to use these techniques to 'fix' non-compliance problems late in a project, or to solve problems due to interference in the field.

Very many electronic manufacturers allow their designers to focus only on functionality and cost, ignoring all else, leaving EMC performance to the end of the project – when a pre-production prototype or early production unit are sent to an EMC test laboratory to "get their CE mark". Some project managers have even been known to *insist* that their designers behave in this financially risky manner. When the test is not passed, there is a scramble to fix the problem quickly using whatever it takes to get to market on time. Unfortunately, by that time the design freedom is very limited, and modern digital electronic technologies are increasingly making traditional post-design 'fixes' (ferrite beads, copper tape, adding capacitors, etc.,) ineffective. So it is increasingly likely that after months of trying everything, the only solution can be a complete redesign with associated huge costs and huge financial risks.

It makes much better financial sense to employ the efficient, cost-effective, and well-known EMC techniques discussed in this series of articles, such as waveguide-below-cutoff methods, right from the start of a project.

4.3.12 Shielding of displays (and the like)

Displays require apertures in enclosures, compromising shielding (see 4.3.5 in the first half of this article [20]). Individual holes for a few tiny indicator lamps or LEDs may not degrade SE too much for some types of commercial or industrial equipment, but for improved SE they can be…

- fitted with tiny metal-film or mesh shielded windows (see below)
- located behind a clear area in a shielded membrane panel (see 4.3.13)
- located at the far end of a metal tube that is swaged or otherwise 360° metal-to-metal bonded to the conductive surface of the enclosure to make a waveguide-below-cutoff (see 4.3.11 in [20]), as shown in Figure 4AE

The technique shown in Figure 4AE adds to the cost of the shielded enclosure, but allows low-cost surface-mounted LEDs to be used and does not require very close alignment of a leaded LED with a hole in a metal panel, so reduces assembly time and rework.

Pointing an infra-red or optical transmitter through a waveguide-below-cutoff as shown in Figure 4AE is a wonderful method of communicating data, up to Gb/s rates if using a laser. Microwave transmitters that operate above the waveguide's cut-off frequency can also communicate through a shield in this way without degrading the SE.

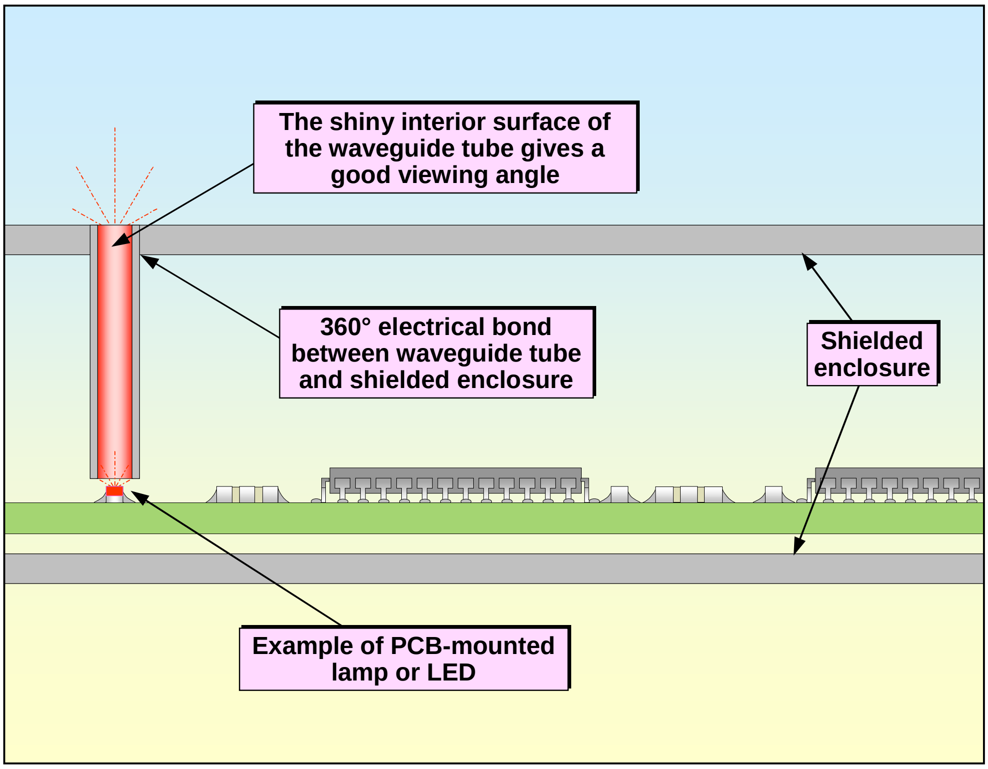


Figure 4AE Waveguide-below-cutoff techniques for indicators using LEDs or small lamps

Mounting a display outside a shielded enclosure avoids the aperture, but of course the display is no longer benefiting from the enclosure shielding, and to preserve the shielding of the enclosure the display's data and power cables must be filtered at the point where they exit the shielding enclosure (see 4.3.17 and 4.3.18).

Where an aperture large enough to compromise SE is necessary, the 'dirty box' method shown in Figure 4V of [20] can be used. The dirty box is effectively an extension of the shielding surface of the clean box. EM fields from the external EM environment are present inside the dirty box, so it does not provide shielding for any displays located inside it.

The dirty box must make a good RF bonds along all its contact areas with the inside of the clean box, to prevent the creation of apertures that could ruin the SE of the clean box. Frequent fixings around its periphery are necessary, with gaskets too if high SE values are to be achieved or frequencies of more than about 300MHz are to be shielded. Appropriate design guidance was provided in 4.3.5 - 4.3.11 of [20].

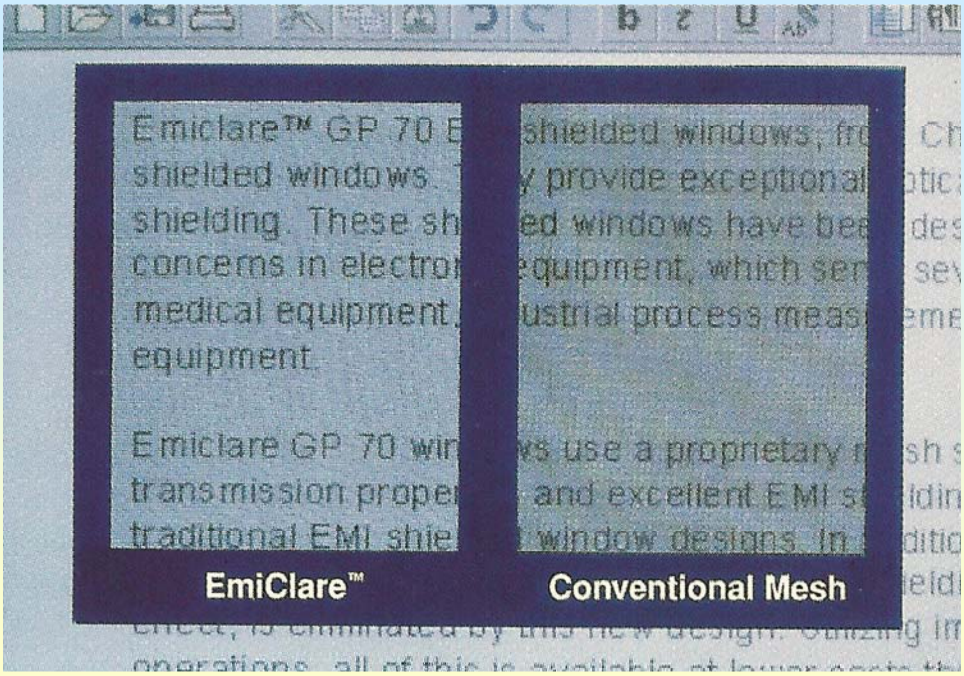
Of course, the display mounted in the dirty box is not protected by any shielding, so it must have low enough emissions and high enough immunity in its own right. The cables from the dirty box to the clean box compromise the SE of the enclosure, so a filter is usually required at the point where the cable enters the dirty box. Because the cable lengths in the dirty box are quite short they usually only create emissions or immunity problems at higher frequencies, so the filtering required can often be just an RF-suppressing ferrite cylinder fitted very close to the point of penetration of the dirty box, but a feedthrough filter fitted to the dirty box itself may be needed (see 4.3.17 and 4.3.18) to provide higher attenuation.

Where a display must be fitted inside a shielded enclosure, shielded windows are usually needed to prevent its visual aperture from degrading SE by too much. Some high-grade CRTs can provide a good shield when the metal frame around the front of their tube is electrically bonded to the front panel all around the aperture. Active matrix LCDs upgrades to products which had used high-grade CRTs have been known to be the cause of more emissions than the CRTs, and some have needed additional shielded windows where the CRTs had not.

A variety of shielded windows are available, based on two main technologies:

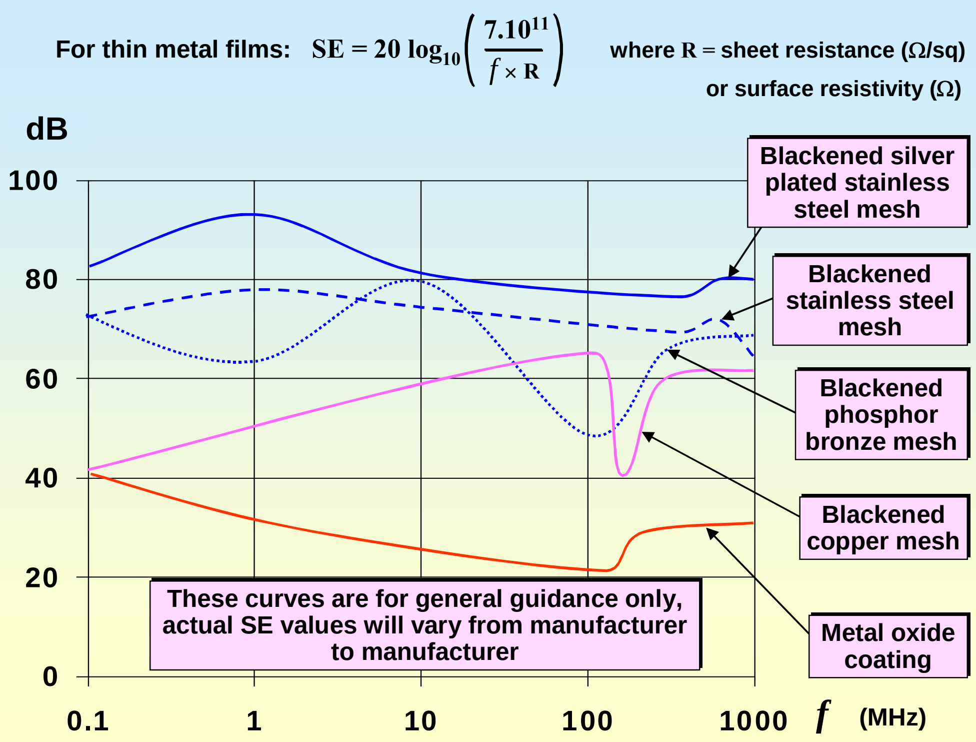
- Thin metal films, usually indium-tin-oxide (ITO), coated onto clear plastic sheets. At film thicknesses of 8μm and above, optical degradation starts to become unacceptable; and for battery-powered products the increased backlight power may prove too onerous. As Figure 4G of [20] shows, the thickness of these films may be insufficient to provide good SEs below 100MHz.
- Embedded metal meshes, usually a fine mesh of blackened copper wires. For the same optical degradation as a metal film these provide much higher SEs, but they can suffer from Moiré fringing with the display pixels if the mesh elements are not sized correctly. It can also help if the mesh is diagonally oriented with respect to the rows of pixels or dots in the display.

Figure 4AF shows an example of the visual obscuration created by two kinds of metal mesh window, and Figure 4AG shows some examples of the SE provided by metal film and metal mesh windows.



Courtesy of Chomerics
www.chomerics.com

Figure 4AF Two examples of metal mesh shielded window materials



For thin metal films: $SE = 20\log_{10}\left(\frac{7.10^{11}}{f \times R}\right)$ where R = sheet resistance (Ω/sq) or surface resistivity (Ω)

These curves are for general guidance only, actual SE values will vary from manufacturer to manufacturer

Figure 4AG Some examples of SEs provided by metal film and mesh shielded window materials

A vital issue for screened windows is that their conducting material must be RF-bonded directly to the enclosure shield's conductive surface around all the edges of the display aperture (known as 360° bonding), so conductive gaskets are generally required. This is so that the surface currents on the inside and outside of the shielded enclosure (see Figure 4F, [20]) flow relatively unimpeded across the display shield.

Film-coated plastic sheet used as a shielded window may need to be mounted in a metal frame that provides sufficient stiffness for compressing a conductive gasket (see 4.6) between its conductive surface and the conductive surface of the shielded enclosure, all around their perimeter. Where an LCD display is used, its own frame is often stiff enough. Windows with embedded films or meshes are thicker, and if thick enough might be stiff enough not to need any additional stiffening.

Figure 4AH shows an assembly method that uses conductive sealants or conductive adhesives to avoid the need for mechanical fixings. The sealant or adhesive does not need to be compressed, making mechanical design much simpler. The use of UV-curable sealant or adhesive can reduce assembly times and the result for both shielding and environmental sealing can be better mechanical fixing methods, at lower cost. Conductive double-sided adhesive tape could be used instead, which has the advantage of not requiring a cure time, although unless it is die-cut (with no joints) its environmental protection will not be as good.

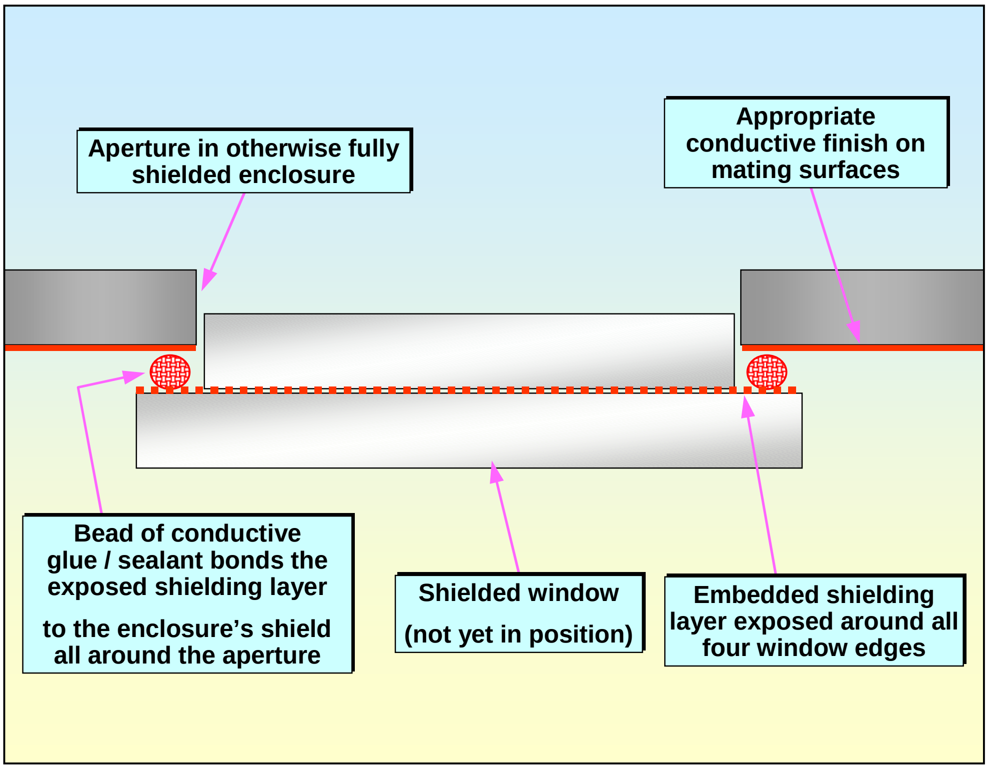


Figure 4AH **Example of RF-bonding a shielded window**

Figure 4AJ shows an example of a mesh-shielded display window with an embedded mesh (such as the one sketched in Figure 4AG) just after assembly, before the excess mesh has been trimmed off. The step around the side where the metal mesh is exposed is visible.

Metal films and meshes must be very thin if they are to be seen through at all, and this limits the amount of absorption loss they can provide (see 4.3.3 in [20]). Honeycomb metal display shielded windows, similar to the ventilation panels shown in Figure 4Z, are also available for the very highest performance. These are large numbers of waveguides-below-cutoff stacked side by side (see 4.3.11 in [20]), and are mostly used in security or military applications where their extremely narrow viewing angle means that the operator's head prevents anyone else from sneaking a look at their displays.

'Nanoscale' assembly techniques are being developed that use multiple very thin conductive films separated by very thin dielectric layers. The spacing between the layers is chosen so that a desired range of optical wavelengths passes through without significant attenuation, whereas other frequencies of radiation (such as RF) experience strong attenuation. The layer spacings can be set to pass the visible spectrum (e.g. for displays, illumination, etc.) or certain ranges of infra-red or ultra-violet wavelengths appropriate for optical data communications or certain kinds of measuring instruments.

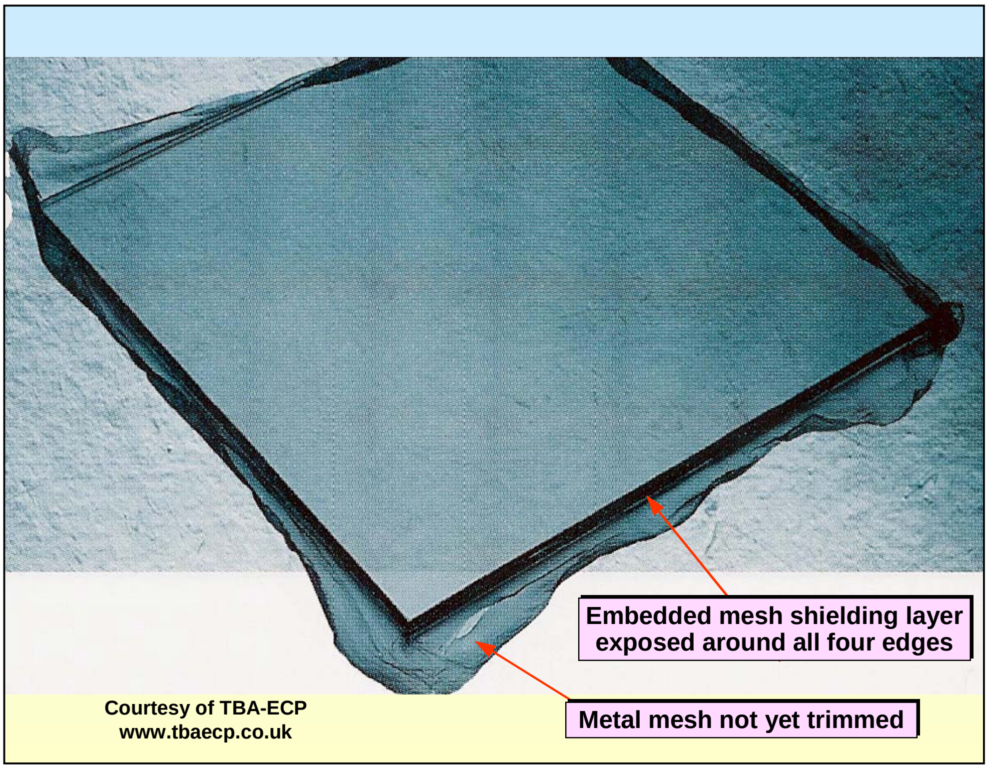


Figure 4AJ Example of a mesh-shielded window, before assembly

4.3.13 Shielding membrane switch panels

Membrane panels are laminated plastic constructions with embedded pushbuttons, clear areas for LEDs and displays to be seen through, etc. They often cause problems for enclosure SE, because of the apertures cut out for them in the enclosure. They usually have an aluminium backplate, with a fixing point (mounting) at each corner. Even when the fixings make a good RF bond (which they often do not) they create four long apertures around its edges of the membrane panel.

The solutions are similar to those already described for displays in 4.3.12:

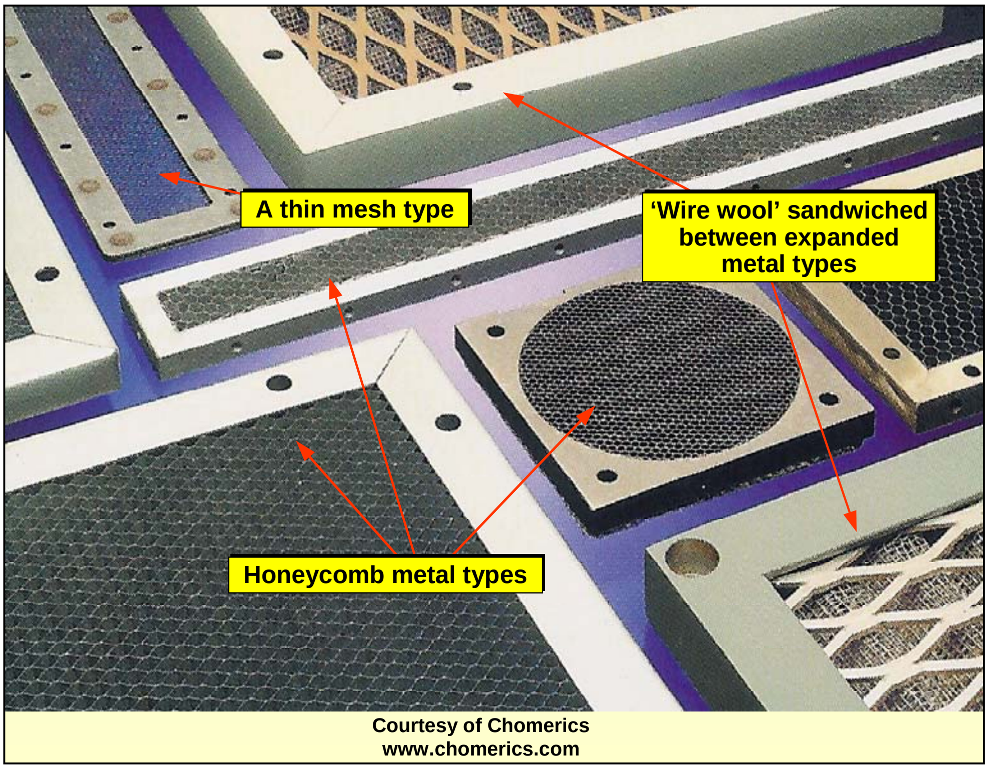
- Mount entirely outside the enclosure and filter the cable from the panel at the point where it enters the enclosure, with at least an RF-suppressing ferrite cylinder (but feedthrough filters may be required)
- Use the dirty box technique (see Figure 4V in [20])
- Fit a shielded window layer (metal film or mesh) in the panel and RF-bond it to the conductive surface of the metal enclosure all around the edges of the aperture. In this scheme the membrane panel becomes the shielded window for any displays.

4.3.14 Shielding ventilation apertures

Methods of shielding ventilation apertures are similar to those used for mesh-shielded windows, except that the mesh size can be much larger to present less impedance to the airflow. Expanded or perforated metal is often used, and because they are thin their SE is mostly given by reflection rather than by absorption, so they are good for screening low frequency E fields but poor for low frequency H fields. Shielding of plane (far field) waves is generally acceptable for most purposes providing the aperture dimensions are less than one-hundredth of the wavelength at the highest frequency of concern (see Figures 4J and 4M of [20]).

Round, square or hexagonal holes/mesh shapes are much better than rectangular or slot apertures with the same area. The perpendicular elements of a mesh must make reliable electrical contact at all crossing points (e.g. by welding). High levels of SE may need much smaller apertures, or a different technique such as the ‘wire wool’ sandwich shown in Figure 4AK.

Waveguide-below-cutoff techniques (see 4.3.11 in [20]) are often used for shielding ventilation apertures, see Figure 4Y, Figure 4Z and Figure 4AA all of [20], and Figure 4AK. Many honeycomb metals have cells that are glued together, in which case their SE can be improved if the honeycomb and its frame is plated with metal after assembly.



Courtesy of Chomerics
www.chomerics.com

Figure 4AK Some types of ventilation shields

Like shielding windows, all vent shields must make electrical contact around their periphery to the aperture in their shielded enclosures. For low values of SE or low frequencies, a metal fixing every 100mm may be adequate, but for high values of SE or frequencies of 1GHz or more conductive gaskets will probably be needed, clamped between the vent and the enclosure shield.

At least one manufacturer of highly shielded 19" rack cabinets uses a waveguide-below-cutoff technique for its top and bottom ventilation apertures, similar to Figure 4AC of [20] but with metal spacers instead of spring fingers to give a gap about 10mm tall for good airflow.

Ventilation shielding is complicated by the need to clean the shield of the dirt deposited on it from the air that passes through. Adding removable air filters can allow the ventilation shielding to be fixed permanently fixed in place.

4.3.15 Shielding rotating metal shafts that penetrate an enclosure

Rotating metal shafts can enter/exit shielded enclosures for power transmission, or for control (e.g. potentiometer shafts). These are conductors and therefore can be just as bad for SE as a cable which is neither filtered nor shielded (see 4.3.17 and 4.3.18), so may need to be fitted with conductive gaskets.

Special types of gaskets are required to avoid friction and wear when shafts rotate, whilst still maintaining good electrical contact. Conductive grease can be used, usually filled with silver or carbon particles. Metal bearings do not make electrical contact between a shaft and its frame, because they always ride on a film of grease, so they will probably require conductive grease.

A better method is to use plastic shafts. Where low values of SE are required below 1GHz their apertures might be small enough to be acceptable, but for high SE and/or >1GHz the shaft should pass through a waveguide-below-cutoff (see in 4.3.11 in [20] and Figure 4AE), remembering that the plastic shaft will reduce the waveguide's cutoff frequency.

Similar methods can be used for other metal or non-conductive items that must penetrate a shielded enclosure and be free to move physically.

4.3.16 Combining heatsinking with enclosure shielding

Figure 4AL shows one way in which shielding and heatsinking can be combined, in this case for power devices. The devices use the rear wall of the shielded enclosure as their heatsink, and a finned heatsink could be attached to the outer surface of the wall (with a suitable thermal grease to aid conduction from the wall).

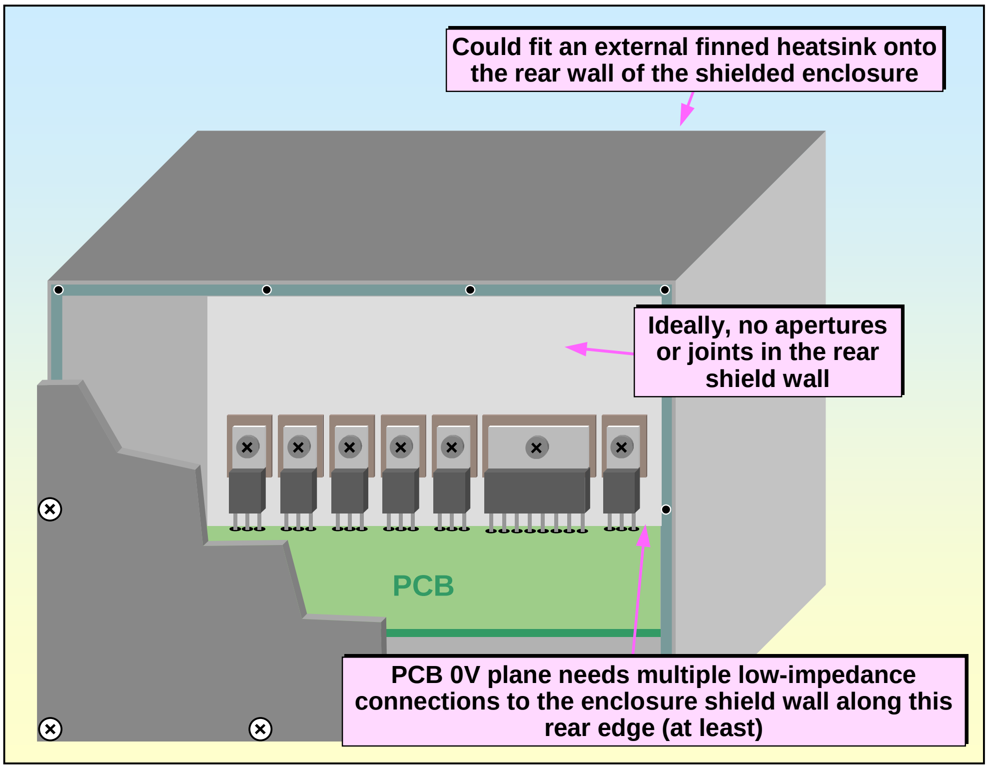


Figure 4AL An example of combining shielding and heatsinking

The stray capacitances from the devices inject high levels of RF currents into the shield wall, which for good EMC (and reduced internal crosstalk) must be returned to the circuits on the PCB with the smallest loop area. This is achieved by RF-bonding the PCB's 0V plane to the rear wall, using (for example) a number of spring fingers soldered along the rear edge of the PCB. Another method is to extend the 0V plane into an edge-plated strip along the rear edge of the PCB, and pressing that edge against a strip of conductive gasket on the rear wall when the PCB is assembled in the enclosure.

Where the 0V plane is not the optimum path for the returning currents, RF-bond the correct PCB conductor to the rear wall in a similar manner, via a number of series capacitors spread along the edge. Where safety is an issue – the values, ratings and safety approvals of the capacitors will be important.

4.3.17 Preventing shield degradation from conductor penetrations

It was mentioned in 4.3.2 of [20] that the SEs of all real shields are compromised by apertures (seams, gaps, joints, displays, etc.) and cable penetrations. Section 4.3.5 and subsequent text in [20] covered the design techniques for apertures, and this section is concerned with design techniques for conductor penetrations. Figure 4AM shows the general philosophy – all conductors that penetrate a shielded enclosure must be RF-bonded to the shield wall at their point of penetration using one of the following methods…

- RF-bonded directly (i.e. metal-to-metal) to the shield wall at the point of penetration (for the earth/ground connection and other conductors that can be earthed/grounded)
- Filtered, with the metal body of the filter RF-bonded (metal-to-metal at multiple points, or 360° using a gasket) to the shield wall at the point of penetration (for unshielded signal, data, control or power conductors). Feedthrough or through-bulkhead filters are necessary where high attenuation is required above 100MHz.
- Shielded, with the cable shield 360° bonded metal-to-metal to the shield wall at point of penetration (for any signal, data, control or power conductors)

Section 4.3.15 discusses techniques appropriate for conductors (such as rotary shafts) that penetrate shields, but are not wires or cables carrying signals, data, control or power.

Details of the correct design techniques for filters that penetrate shield walls are covered in 3.3 of [3]. Details of the correct design techniques for shielded cables that penetrate shield walls are covered in 2.6.5 to 2.6.7 of [4]. Notice that it is best to use the cable shield only for the control of interference – not for carrying signal or power return currents, so coaxial cables are not recommended for EMC (see 2.6.2 and 2.6.3 of [4]).

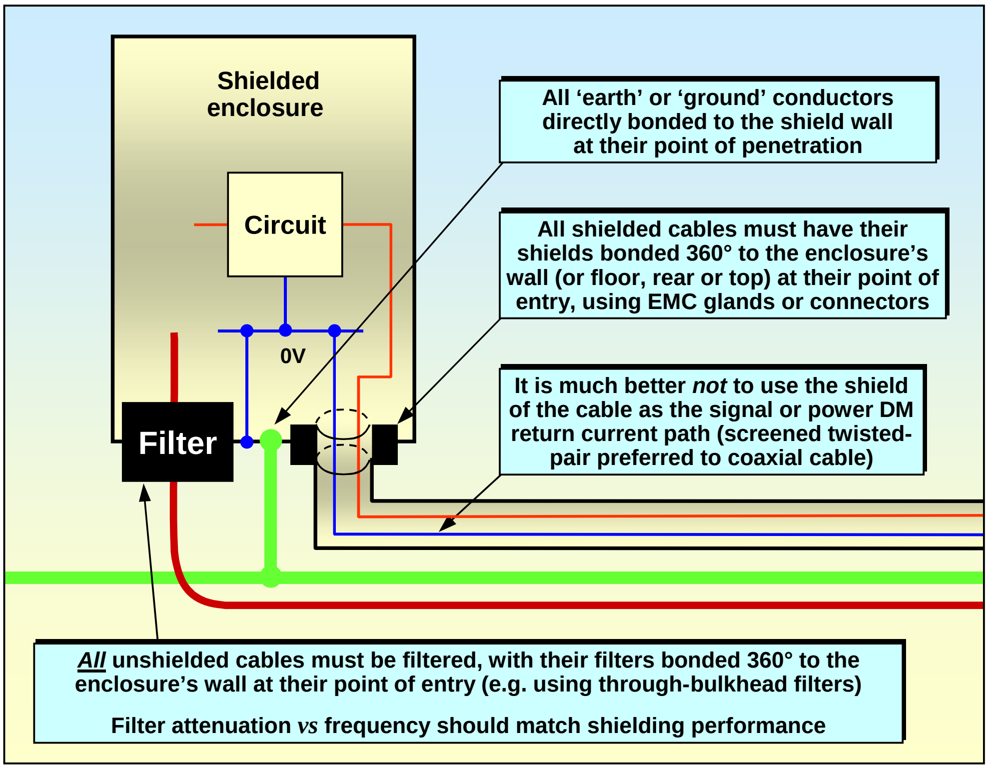


Figure 4AM Bonding, filtering or shielding all conductors that enter/exit a shielded enclosure

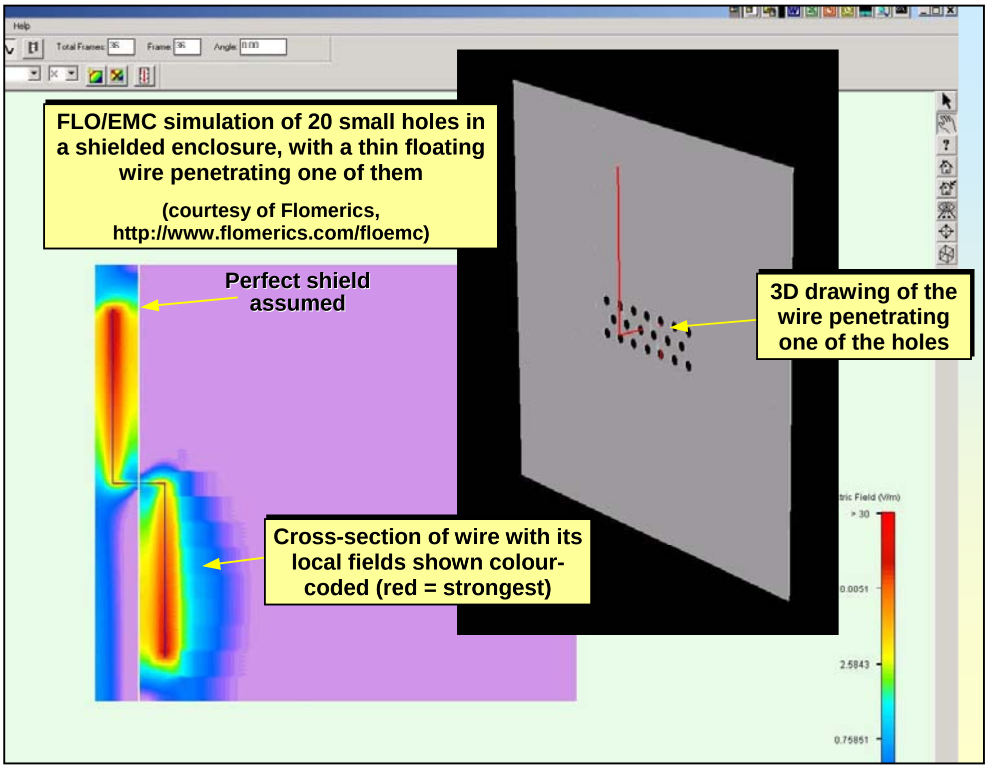
It is very important indeed to make sure that *no conductors of any type* enter a shielded enclosure without being treated by one of the methods above. It doesn't matter what the purpose of the conductor is. It is also very important to realise that at RF, and especially above 100MHz, even a very short piece of wire has too much impedance to be used as an RF bond. In the above bulleted list, where it says 'metal-to-metal' – that is *exactly* what is required. No pigtails or connections via connector pins are acceptable.

In multiconductor cables with an overall shield it is common to find some or all of the internal conductors fitted with their own shields. These internal shields are mainly to reduce crosstalk between the internal conductors, so if they have their shields pigtailed or passed through connector pins it is not usually an important issue for EMC – as long as the overall cable shield is of sufficient shielding quality and terminated 360° at the point of penetration of the shield.

I have often been asked to solve emissions/immunity problems where people had spent a lot of money on a shielded enclosure, and had done an excellent job of bonding, filtering or shield-bonding most of the cables that entered or exited the enclosure, but they hadn't bothered to do anything with the mouse or keyboard cables, because they weren't carrying high-speed signals – but of course this was the cause of their problems.

What matters is the CM noise, not the DM signals, and any conductor will behave like an 'accidental antenna' for CM noise (see 2.2. of [4]), picking it up by conducted and/or radiated means on one side of the shielding barrier, and coupling it to the other side, compromising the shielding.

Field solvers discover this sort of problem very quickly. Figure 4AN shows a simulation of a floating wire that penetrates through a small ventilation hole in a shielded enclosure, and shows how it behaves like an antenna, coupling radiated fields from one side of the metal barrier to the other.



Total Frames: 36 Frame: 36 Angle: 0.00

FLO/EMC simulation of 20 small holes in a shielded enclosure, with a thin floating wire penetrating one of them

(courtesy of Flomerics, http://www.flomerics.com/floemc)

Perfect shield assumed

3D drawing of the wire penetrating one of the holes

Cross-section of wire with its local fields shown colour-coded (red = strongest)

Figure 4AN Field solver simulation of a thin wire penetrating a shielded enclosure

4.4 Shielding at PCB level

Returning to the earlier theme of applying shielding at as low a level of assembly as possible to save costs (see 4.3.1 in [20]), this section discusses shielding at the level of the PCB, and is adapted from [21].

Shielding at enclosure level is unable to deal (on its own) with the increasing problems of interference between devices within products, due to continuing shrinking of the silicon feature sizes in integrated circuits (ICs) and the increasing packing density of modern surface-mounted printed circuit board (PCB) assemblies. The increasing use of embedded wireless communications, with its ‘noisy’ transmitters and ‘sensitive’ receivers exacerbates this problem.

As radio communications move into the microwave bands, and as ICs emit ever-higher levels at ever-higher frequencies, emissions regulations will soon be setting limits up to 2.7GHz (in Europe). But enclosure shielding is unsuitable for achieving significant levels of attenuation at such frequencies, without using costly, heavy and unattractive military design techniques.

PCB-level shielding is capable of dealing with problems of internal interference and regulatory emissions control at low-cost, providing a few basic design rules are followed. There are many interesting developments in PCB-level shielding technology, providing improved shielding performance with low-cost materials and ease of assembly.

Upcoming environmental legislation in Europe adds an extra dimension, with the need to employ shielding techniques that have low environmental and recycling costs.

4.4.1 Reasons for shielding at PCB level

There are many good reasons for using shielding techniques at PCB level. The most obvious one is that shielding always adds cost and weight but these disadvantages are minimised by shielding at the lowest level of assembly – the PCB.

The continued miniaturisation of surface-mounted devices (SMDs) and the increasing density of PCBs, are making it more necessary to shield different areas of a product from each other, to achieve the desired levels of functional performance in the product.

The continued shrinking of the silicon features in ICs is making them more susceptible to signal degradation. PCB-level shielding is a low-cost way to enable modern ICs to operate reliably in the noisy environment inside a typical modern electronic product.

When integrating wireless (radio) communications with a product, the close proximity of very ‘noisy’ transmitting antennae tends to cause interference with sensitive circuits elsewhere in the product (analogue and digital devices can both be susceptible). The close proximity of very sensitive receiving antennae to ‘noisy’ circuits such as switch-mode converters and digital processing can reduce the range over which the wireless communication will work. PCB-level shielding is a valuable technique for wireless communications.

Many modern portable computing devices are equipped with a variety of wireless data communications (such as Bluetooth, IEEE 802.11) but have no visible antennas because they are mounted inside the product's enclosure. The enclosure clearly cannot be shielded, and so PCB shielding techniques must be used instead.

Regulatory issues are also significant. As ICs' silicon feature sizes decrease, digital and switch-mode power devices switch faster. Digital processing speeds are also continually increasing. The result is that modern electronic products are increasingly emitting significant levels at frequencies exceeding 1GHz. But the spectrum above 1GHz is increasingly being employed for personal communications, so regulatory emissions standards are moving to protect the radio spectrum up to 2.7GHz (in Europe), and beyond.

Modern product enclosures are perforated with increasingly large visual displays, connectors for numerous kinds of cables, slots for a wide variety of removable storage media, apertures for ventilation, and must be constructed with a number of joints for ease of assembly. At higher frequencies, constructional issues that were once negligible can seriously compromise shielding effectiveness (SE). PCB-level shielding-can be used to reduce the SE requirements for the overall enclosure, possibly even completely removing the need for enclosure-level shielding.

4.4.2 Overview of techniques for PCB level shielding

Figure 4AP provides an overview of the issues associated with PCB shielding. A five-sided conductive 'shielding-can' is placed over an area of circuit on a PCB, and electrically bonded by via holes in the PCB at multiple points around its perimeter to a plane layer inside the PCB (or on its bottom layer). The result is a six-sided conductive enclosure, part of which is embedded in the PCB itself. Figure 4AQ sketches a cross-section of a similar PCB structure.

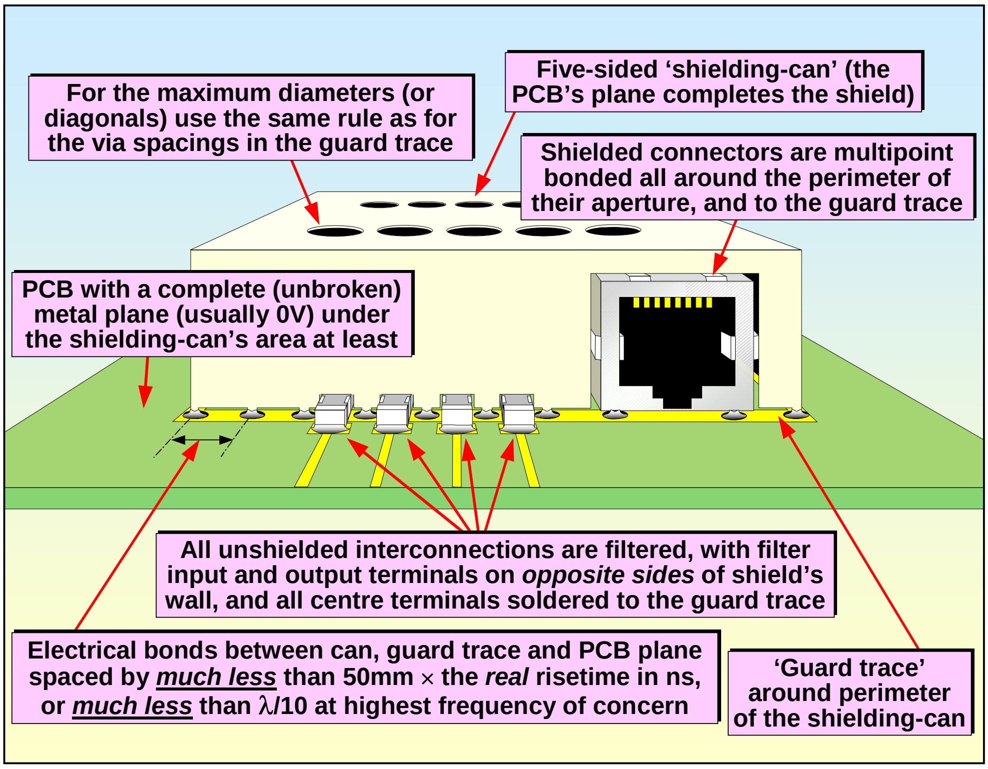


Figure 4AP Overview of PCB shielding and filtering

The plane layer used is usually at 0V potential, but could be at any potential. Traces that enter or leave the shielding-can must be either shielded or filtered (Figure 4AP only shows filtered traces). If the plane is on an inner layer of the PCB, the traces and devices on the other side from the shielding-can are not shielded. If a circuit to be shielded has devices fitted on both the top and bottom of a PCB, both sides can be fitted with shielding-cans (and PCB plane layer may not always be required). But double-sided shielding-cans are more awkward for automated assembly.

Where the devices on the top and bottom of a PCB are associated with different circuits, they can be isolated from each other (to some degree) by using an internal PCB plane layer. It is also possible to fit shielding-cans over both of these circuit areas, each one using the same plane layer as its sixth side.

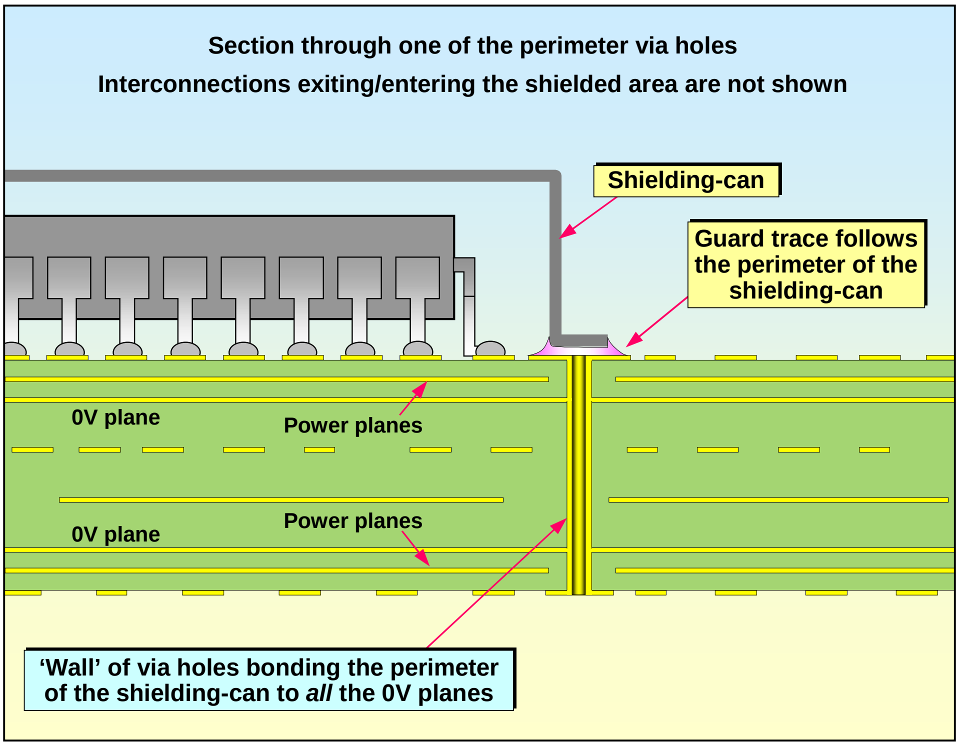


Figure 4AQ **Cross-section of a PCB fitted with a shielding-can**

For more details on the PCB design techniques associated with shielding-cans, see 3.3 of [3], and Chapter 2.2 of [22].

Unfortunately, when using through-hole-plate (THP) PCB construction, the plated-through holes associated with the circuits on one side of the plane layer will protrude into the shielded volume on the other side of the plane layer, where they will 'crosstalk' into its circuits. Also, the perforations in the common plane layer due to the clearance holes around the through-holes will reduce the SE between the top and bottom shielded volumes.

Microvia (HDI) PCB technology (see Chapter 7 of [22]) allows the achievement of much better isolation between two shielded volumes on opposite sides of a PCB, because it uses 'blind' and 'buried' plated holes that do not pass completely through the PCB. The use of microvia PCB construction (also known as high density interconnect [23], or sequential build-up) makes it possible for plane layers not to be perforated at all. Figure 4AR sketches the general principle, which should be compared with Figure 4AQ

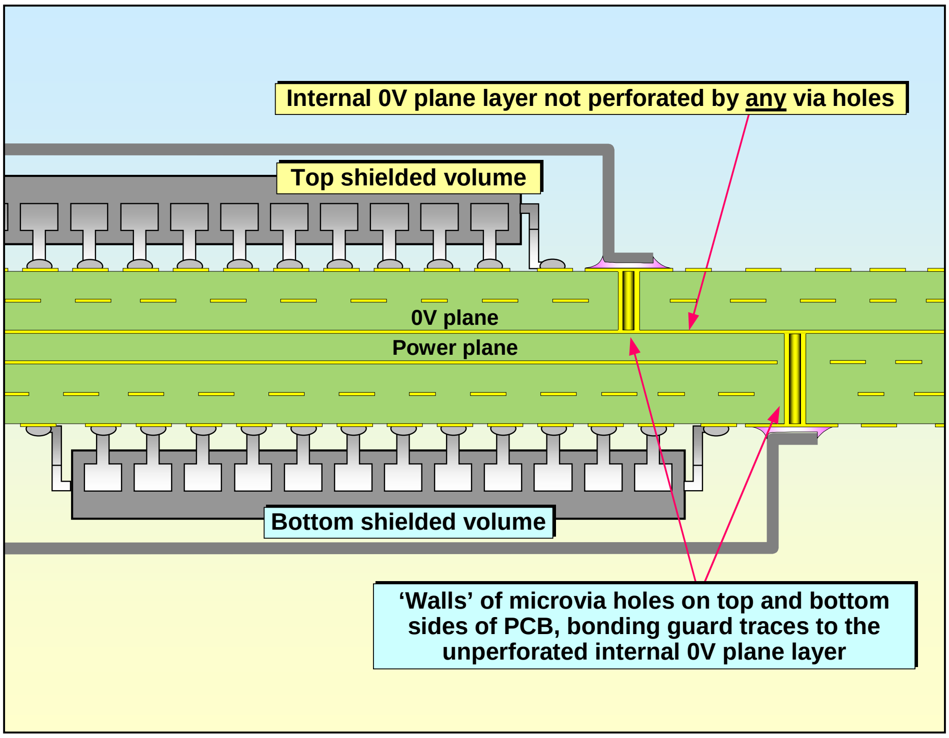


Figure 4AR **Example of double-sided shielding using microvia (HDI) PCB technology**

PCBs constructed using microvia technology can achieve very high levels of isolation between circuits assembled on opposite sides of a PCB with an unbroken internal plane layer between them.

4.4.3 Types of PCB shielding-can

Traditionally, PCB shielding-cans have been made of sheet metal, such as tin-plated steel, brass or beryllium copper. They had multiple pins around their perimeter for soldering into plated through-holes, and they usually had clip-on lids so that the devices inside could be accessed. The clip-on lids used multiple spring fingers around their perimeters to help minimise the resulting ‘leaky’ shield gaps. They were also available with internal dividers that could shield two or more areas of circuitry from each other. Figure 4AQ shows some examples of PCB shielding-cans.

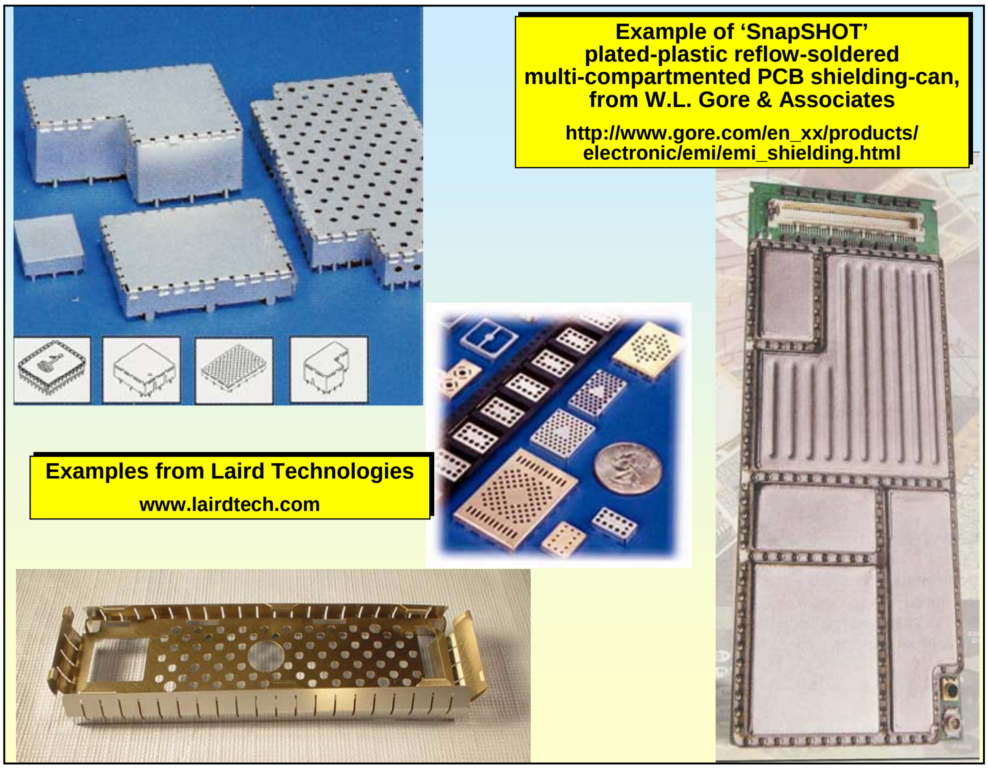


Figure 4AS Some examples of PCB-mounted shielding-cans

Surface-mounted metal shielding-cans have become readily available in recent years, and cans of up to 50mm square are successfully assembled automatically at the same time as other SMD parts. A number of alternative designs are now available (or are being developed) to reduce weight and cost. Also, shielding-cans with reduced ‘environmental impact’ are becoming available.

Metal shielding-cans without removable lids cost and weigh less, and have better SE because they have fewer apertures. Laird Technologies has a design that allows the top of the shielding-can to be removed with a ‘key’, just like opening a traditional oblong tin of sardines. To repair the shielding-can, a new metal lid with conductive adhesive is pressed onto its body.

A variation on the shielding-can made from sheet metal is the die-cast metal ‘maze’ base that is soldered or press-fitted to the PCB and has metal spikes along its top edge. A flat metal lid with holes at appropriate places is pressed onto the base. An example of a PCB using this technique is shown in Figure 4AT.

Plastic moulding techniques have recently become a vigorous area for research and development. Formed plastic shielding-cans have for years been painted with conductive adhesive, or had metal layers applied by vacuum deposition (such as sputtering) or electro-plating. But the tooling costs for the automated conductive coating of such parts can be high, or they can require costly manual processing.

One alternative is to print a flat sheet of plastic with a mesh or solid layer of conductive ink, usually silver [24], [25], or to plate it with metal [26], [27]. The conductively coated sheet is then cut and thermo-formed into the desired shape. The difficulty is in designing the ink or metal film so that it can stretch enough to make a wide range of PCB-level shielding shapes without cracking, since this creates apertures and reduces the SE.

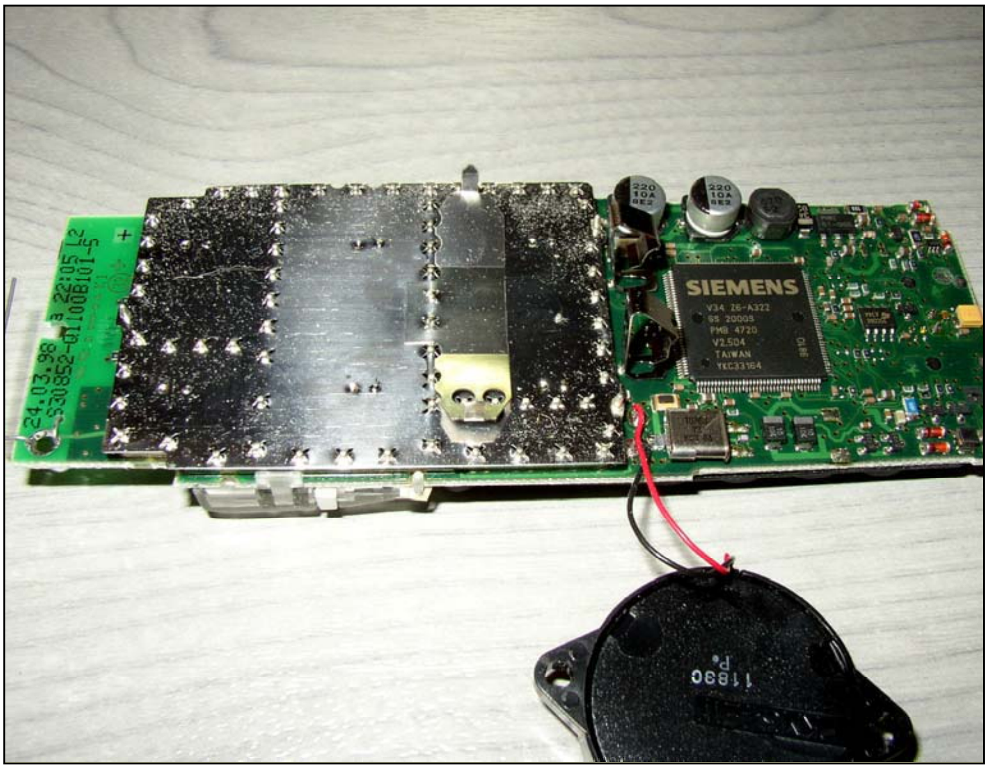


Figure 4AT Example of a DECT phone with a circuit area shielded by a die-cast ‘maze’ with a pressed-on sheet metal lid

Conductively coated plastic parts can be used just as they are, if stiff enough, but some types will need mechanical assistance, such as being clipped into a plastic or metal support (often created by the internal shaping of the product’s enclosure). An alternative is to use the thermo-forms made from the conductively coated plastic sheets as ‘preforms’ for a plastic moulding process. This is sometimes called ‘in-mould shielding’, with the shielding preform being moulded into the finished component, thereby avoiding the need for manual assembly.

Instead of using conductively coated plastic sheets as preforms, some companies [28] are using metal plated carbon fibres in in-mould shielding processes. (Note that loading the plastic material used for the injection moulding process with conductive material is not very successful, as the resulting parts have non-conductive resin-rich surfaces, see 4.7.6.)

4.4.4 Methods for bonding shielding-cans to PCB planes

Traditional through-hole metal shielding-cans are often soldered to their ‘sixth side’ plane in the PCB using manual methods. Wave soldering can be used in volume manufacture, but the thermal inertia of the metal shielding-cans add to the difficulties of setting up the process.

Surface-mounted metal shielding-cans are intended for automated assembly using reflow soldering methods, and usually have patterns of small holes to aid temperature equalisation [29].

High-performance metal shielding-cans are often required to be ‘seam-soldered’ to a plane layer (or guard trace) on the top of the PCB [30]. Like other types of surface-mounted shielding-cans, larger sizes would usually employ two or more pins to locate them, with appropriate through-holes in the PCB.

Soldered metal cans require holes to prevent ‘popcorning’ – thermally induced changes in their shape that weaken the solder joints. But these holes affect the SE that can be achieved, so there are performance benefits to be had by not using soldered-in metal shielding boxes.

Conductive gaskets can be used with metal or shielded plastic shielding-cans. Die-cut gaskets with double-sided conductive adhesive, or formed-in-place conductive gasket glue (usually based on silicones or epoxy resin), can be used to retain shielding-cans to the PCB – as well as electrically bonding them to the PCB plane layer used for their sixth side.

Non-adhesive conductive gaskets require some other means of retaining the shielding-can, such as a plastic clip. Some PCB shields are held in place by features in the product’s enclosure (either base or cover), and fall off when the enclosure is removed. Of course, gaskets do not always need to provide a continuous bond around the perimeter of a shielding-can wall, and dots of gasket can often be used instead.

An interesting recent development in conductive gaskets is the “Gore-Shield GS5200 thermal and electrical grounding pads” [31]. These are surface-mounted soldered components with a compliant layer of thermally and electrically conductive gasket material on their upper side. Arranged around the perimeter of a shielding-can, they not only provide electrical bonding to the ‘sixth side’ plane layer, they also help remove heat from devices inside the shielding-can.

Another method of electrically bonding plastic shielding-cans to a PCB is to design the plastic part so that it has ‘bumps’ in its conductive surface that are individually compliant enough to ensure that each one will reliably press against appropriate traces and pads on the surface of the PCB [32]. The bumps could be the sites for form-in-place gasket dots, or they could be designed as ‘spring fingers’ requiring no gaskets. This technique needs no soldering or conductive gaskets, but requires some means of holding the part in place, as for the non-adhesive gaskets described earlier.

By using plastic materials that will withstand soldering temperatures, plastic shielding-cans can be soldered onto PCBs just like surface-mounted metal cans. They have the advantage of not requiring ‘anti-popcorning’ holes; so can be designed to provide higher SE levels.

Gore have developed what they call the “snapSHOT shield™”, see [33], [34] and Figure 4AS, that uses a thermoformed plastic part post-metallised on its outside. Where it meets the PCB it has a small flange with holes in it. To assemble it to the PCB, standard ball-grid-array (BGA) solder balls are deposited on the PCB at the locations of the holes, and during soldering capillary action makes the balls ‘snap’ through the holes and make contact with the outer metal layer, whilst also retaining the shield in place. The advantage of this over regular surface mounting appears to be that since the inside of the shielding-can is insulating, it is less likely to short out components and traces by accident.

4.4.5 Suitable materials for PCB shielding-cans

PCB shielding-cans have traditionally been made from stamped, drawn or folded sheet metal, but a wide variety of alternative materials are now available (or are being developed) to reduce costs, ease assembly, or reduce environmental impact. Shielding-cans can now also be made using conductive ink printed onto a variety of substrates (e.g. plastic), meshed patterns of conductive ink on substrates, metal meshes (with or without substrates), metal films deposited onto plastic substrates, etc.

Where meshes are employed the SE will degrade above a frequency governed by the size of the apertures in the mesh. There is a complex relationship between mesh size and shape, SE and frequency [35], with larger mesh sizes giving poorer SE. Meshes for GHz shielding will almost always be less than 3mm on a side.

At frequencies above 100MHz, even metal films 1 micron thick can give high values of shielding [36], so the conductive material used is usually not important for SE. However, all practical shielding-cans have their SE limited by apertures and interconnections. These issues are described below.

4.4.6 Apertures in PCB shielding-cans

Apertures in shielding-cans include seams in folded metal constructions; holes for adjusting components; holes that help prevent ‘popcorning’ during automated soldering (that would weaken the soldered joints); and the spacings between the electrical bonds between the main body of the can and the PCB plane layer on its sixth side. The apertures in the plane layer caused by the clearance holes around plated through-holes have already been mentioned.

Apertures in shields must be much smaller than the wavelength of the highest frequency for which shielding performance is required. A shield with a single aperture, that has a diagonal size of one-hundredth of a wavelength, can be expected to achieve an SE of no more than 34dB, as shown by Figure 4AU.

The wavelength (λ) in air of a frequency, f, is $300/f$ mm (when f is in GHz). The wavelength inside a PCB is about half of this, due to the dielectric constant of the PCB substrate (e.g. FR4) slowing the velocity of electromagnetic propagation to about half that of free space, within the PCB itself.

Every time the number of apertures on one face of a shielding doubles, the SE in the direction perpendicular to that face falls by up to 6dB. So if there were 8 identical apertures on one face of a shielding-can, each one having its longest dimension equal to $\lambda/100$ at the highest frequency of concern, the SE perpendicular to that face, at that frequency, should not be expected to be any higher than 16dB.

The apertures created in the shielding-can by its electrical bonds to the inner plane layer partly lie in the air above the surface of the PCB, and partly lie inside the PCB, where the wavelength at a given frequency is about half of what it is in air. So to determine the spacing of these bonds, it is best to assume that the whole of each aperture is in the PCB material, and use a bond spacing that is half of what we would assume for apertures that were wholly in the air.

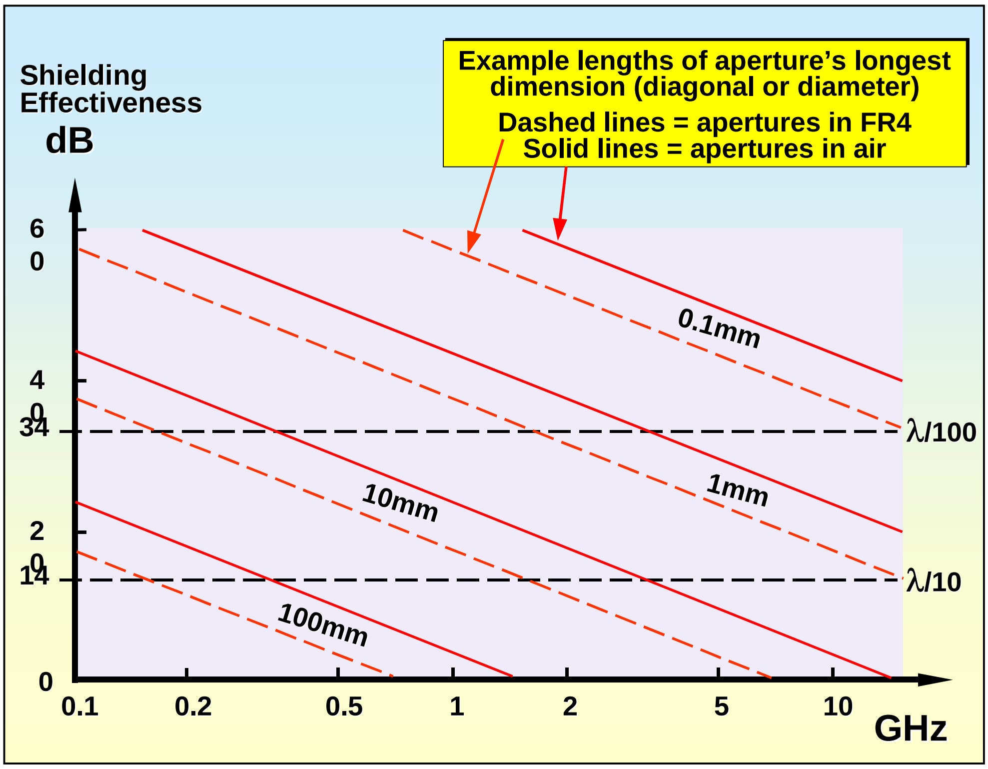


Figure 4AU **Estimating the SE of a single aperture**

For example, if it were required to achieve 20dB of SE at 3GHz in any direction around a 50mm square shielding-can, we would firstly note that the wavelength at this frequency is 100mm in air and 50mm inside the PCB material. A single aperture of 1mm diameter in air, or 0.5mm inside the PCB, would limit the maximum achievable SE of one face of the shielding-can to 34dB, so 7 apertures should result in 20dB.

Since the shielding-can is 50mm along each side, using an electrical bond spacing to the plane layer of 0.5mm would result in 100 apertures along that edge – many more than the maximum of 7 permitted by our 20dB specification. This situation is dealt with by using a plane layer (or wide 'guard trace') on the same surface of the PCB that the shielding-can is to be fitted, and electrically bonding the wall of the shielding-can to that layer (or trace) along its whole length. Seam-soldering is the traditional way of doing this for metal cans, but conductive gaskets or conductive glue can be just as good.

Now the electrical bonds to the inner plane layer do not create apertures in the air above the surface of the PCB. But we still have a problem with the apertures created by the spacings of the via holes between the guard trace and the plane layer inside the PCB. Using normal THP PCB techniques it is difficult to space them much closer than 1mm, but waveguide-below-cutoff techniques (see below) can be used to improve their SE considerably.

4.4.7 Waveguide-below-cutoff methods in PCB-level shielding

So far, the apertures that have been discussed were assumed to be of negligible material thickness compared with their length or width. But where an aperture's length or width is less than one-tenth of a wavelength, increasing its thickness will reduce its 'leakage', improving the SE of its shielding-can.

Real benefits for SE begin to occur when the waveguide-below-cutoff effects start to become effective, when the thickness of the aperture (the distance the electromagnetic fields must travel to get from the inside of the shielding-can to the outside) is comparable with the diagonal or diameter of the aperture. 4.3.11 in [20] discusses waveguide-below-cutoff design techniques. Figure 4AV gives a few examples, for when the material in the waveguide is air and also when the waveguide is created inside the PCB and filled with FR4.

When the frequency to be shielded is above 1GHz, the apertures in the shield will usually need to be less than 3mm in air, or 1.5mm inside the PCB, and waveguide-below-cutoff techniques can be used without sacrificing too much PCB area.

In the pervious example of a shielding-can with an SE specification of 20dB at 3GHz, we had a problem with the spacing of the through-holes that provide the electrical bonds between the plane layer (or guard trace) on the top surface of the PCB and the plane layer that provides the sixth side of the shielding-can. If the vertical spacing between the planes (or guard trace and plane) was 1.6mm and we used a 1mm spacing laterally between the via holes, the diagonal of the resulting apertures would be about 2mm, giving a cutoff frequency around 37.5GHz (assuming a 50% velocity of propagation inside the PCB) – well beyond the 3GHz we are concerned about.

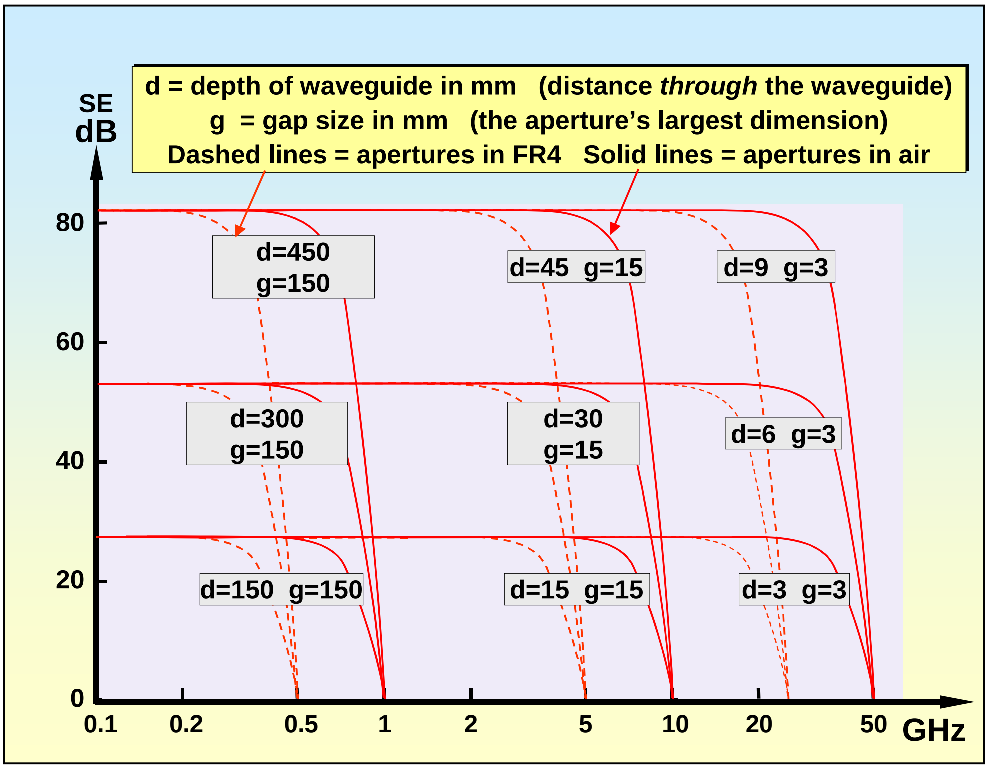


Figure 4AV Some estimated waveguides-below-cutoff, in air and FR4

A 6mm overlap between the top plane (or guard trace) and the inner plane would achieve an SE of about 81dB for each aperture at 3GHz. The 50mm side of the shielding-can requires 50 of these 1mm wide apertures, and this quantity would reduce their overall SE by about 34dB to about 47dB. Compared with the 20dB SE specification this is a very good figure, showing how effective the waveguide-below-cutoff technique can be.

Note that the waveguide-below-cutoff created by the plane (or guard trace) on the top surface plus the layer providing the sixth side of the shielding-can, can extend inside or outside its wall, or lie partially inside or outside.

As well as the waveguide-below-cutoff technique being used inside the PCB, it can be used to reduce the effects of apertures in the rest of the shield can. It is important to note that no conductor should be routed through a waveguide-below-cutoff aperture – to do so would reduce its SE to zero.

4.4.8 Cavity resonances in PCB shielding-cans

Resonances (standing waves) can occur within the cavity formed by a shielding-can at frequencies at which whole numbers of half-wavelengths will fit between its sides. They can be calculated (in GHz) by:

$$f = 150 \sqrt{\{(l/L)^2 + (m/W)^2 + (n/H)^2\}}$$

– where: l, m, n are integers (0, 1, 2, 3, etc.) and L, W, H are the shielding-can's length, width, height (in millimetres). Usually we are most interested in the lowest resonant frequency of the longest dimension, its '3-D diagonal', when: $l = 1$, $m = 1$, and $n = 1$ (the '1,1,1 mode'), when a 50 by 30 by 5mm shielding-can will resonate at its lowest resonant frequency at 2.56GHz. The 1,0,0 (lengthwise) and 0,1,0 (widthwise) modes for the same can occur at 3GHz and 5GHz.

Resonances inside shielding-cans cause local amplification of their internal E and H fields at 'hot spots' within the shielding-can, and these increase the coupling between circuits covered by the same shielding-can. Figure 4AW shows the coupling measured inside one shielding-can [33] [34].

Also, the SE of a shielding-can is reduced at its internal resonant frequencies, with 20dB reduction being recorded by [33] [34]. This reduction in SE appears to be due to locally intense fields (hot spots) being near to apertures and conductor penetrations, causing them to leak more. Figure 4AX shows the SE of the same shielding-can that was measured for Figure 4AW.

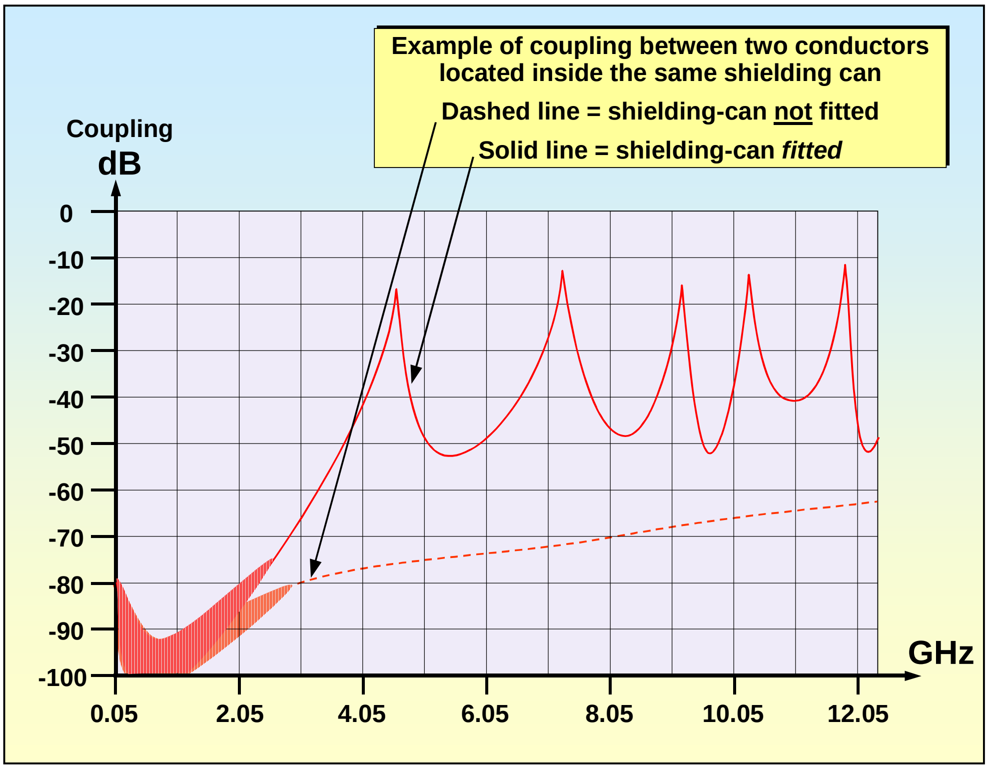


Figure 4AW Effects of cavity resonances on crosstalk inside a PCB shielding-can, from [33] and [34]

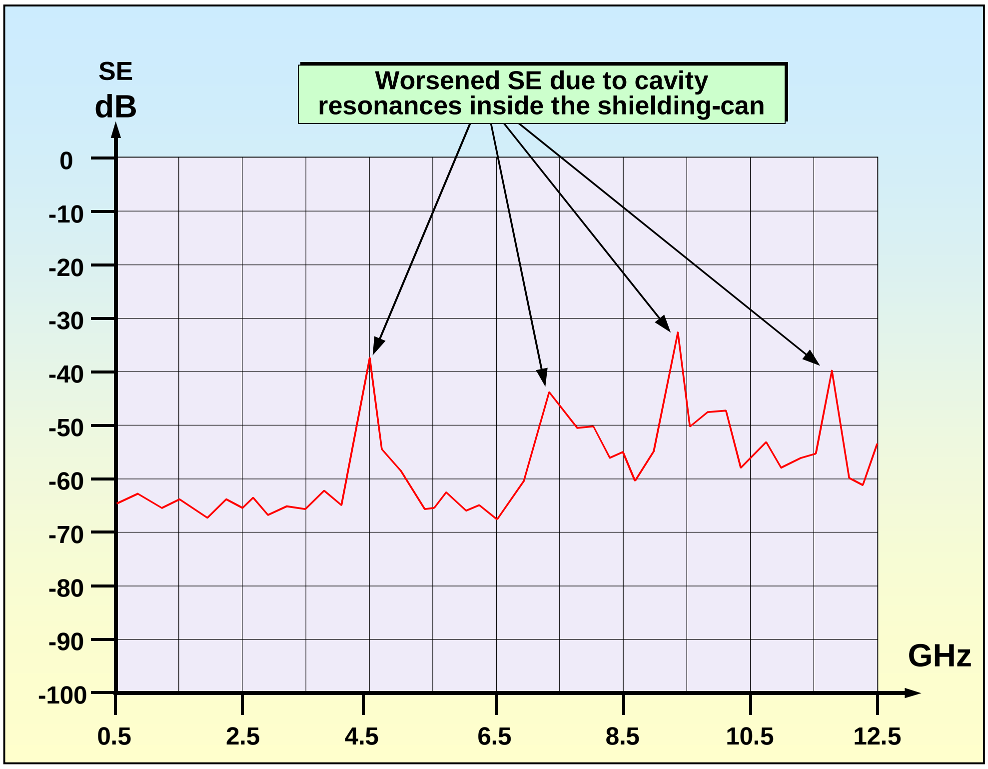


Figure 4AX Effects of cavity resonances on the SE of a PCB shielding-can, from [33] and [34]

So it is best to use shielding-cans that have length and width dimensions much smaller than half a wavelength at the highest frequency of concern, to prevent internal resonances from occurring in the frequency range concerned. Multiple shielding compartments can be formed in one shielding-can component to increase the resonant frequencies in each compartment to well beyond the highest frequency of concern, and also to help reduce interaction (crosstalk) between circuits [34].

Figure 4AS shows an example of a multi-compartmented PCB shielding-can, and Figure 4AY shows some more. Laird Technologies have developed a 'mold-in-place' elastomer rib that they claim makes PCB-mounted shields much more effective and easy to assemble. The left hand side of Figure 4AY shows an example of a double-sided shielding-can assembly for a cellphone (using microvia technology as shown in Figure 4AR but without soldering the cans to the PCB).

The PCB of the cellphone shown in exploded view has a number of guard traces on each side, which align with the perimeter of the multi-compartmented shielding-cans and also with their internal metal dividers. The shielding-cans are located in moulded features in the plastic case halves, as is the PCB. When the case halves are clipped together everything automatically aligns and the 'mold-in-place' conductive elastomer ribs make contact with the guard traces. Very easy assembly, and very easy to dismantle for recycling too.

The right hand side of Figure 4AY shows a similar multi-compartmented PCB shielding-can and a PCB with perimeter guard traces following the internal and external walls of the can, and 'mold-in-place' gaskets on the can walls, but this one is clipped onto the PCB by means of its protruding metal fingers. These fingers clip into small slots routed in the PCB, but do not make any electrical connections. As for the cellphone on Figure 4AY, assembly is simply a question of pressing the parts together, and disassembly is easy.

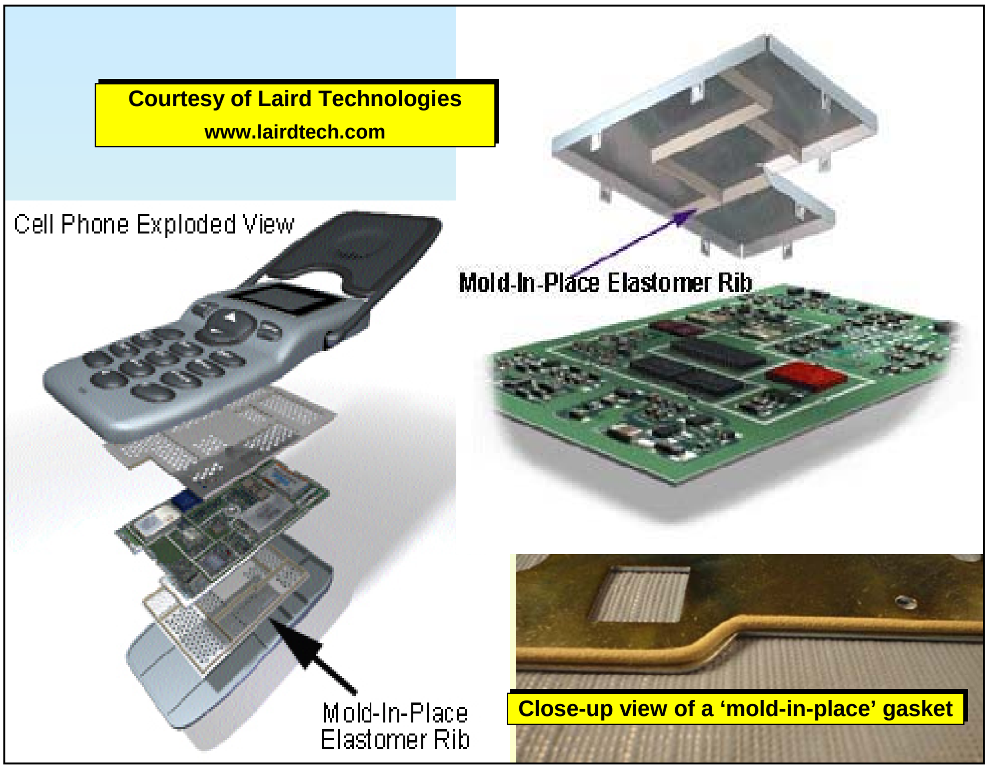


Figure 4AY Examples of multi-compartmented shielding-cans that are simply clipped into place

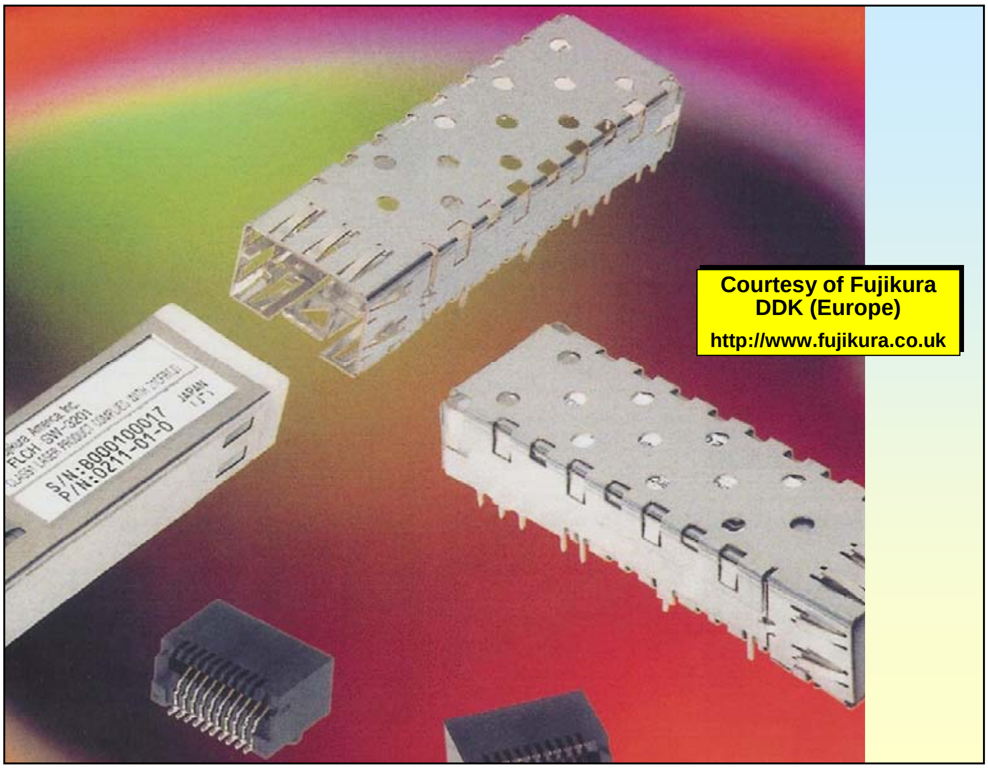
If it is not practical to avoid shielding-cans that are resonant within the frequency range of concern, then square (and cube) shaped structures should be avoided – as should structures with simple relationships between length, width and height (for example: 3:2:1). This is because at some frequencies such shapes will suffer from resonances due to their length and width together (or any two or three of the dimensions L, W and H). The amplification of internal fields at hot spots at these frequencies will be especially intense, and more likely to lead to undesirable results.

Ratios between L, W and H should ideally be irrational numbers, such as $\sqrt{2}$ (1.414….etc.) or the 'Golden Mean' (1.618….etc.), to help prevent coincidence of resonances. It will also help if the opposing sides of the shielding-cans are not parallel, but this technique is not often used, maybe because it does not result in a very pleasing appearance for a PCB assembly.

Another useful technique where cavity resonances in a shielding-can are potential problems is to use microwave-absorbing materials, such as Q-Zorb from Laird Technologies [36]. These are elastomers loaded with ferrite particles, usually a millimetre or two thick, glued to the inside of the lid of a shielding-can. These convert H fields into heat, thereby damping down both the E and H field resonances within the shielding-can.

4.4.9 Shielded cables and traces entering/exiting PCB shielding-cans

As discussed in 2.2.2 of [4], fibre-optics can be much more cost-effective, overall, than conductive interconnections when EMC issues are taken into account. Their transmitters and receivers need to be shielded, but they are only small components, as shown in Figure 4AZ.



Courtesy of Fujikura DDK (Europe)
http://www.fujikura.co.uk

Figure 4AZ Fibre-optic transmitter/receivers with integrated PCB shielding-cans

But if conductors are used to connect to a circuit under a PCB shielding-can – for the can's SE not to be degraded, all of the conductors penetrating its boundaries must either be RF-bonded, filtered or shielded, according to the principles discussed in 4.3.17 above.

Where shielded PCB *traces* enter or exit a shielded area of PCB, they must be routed as striplines between two plane layers that bond to all of the via holes in the guard trace around the perimeter of the shielding-can. The two plane layers must be electrically bonded together with plated-through via holes, and it is recommended that these vias should be no more than $\lambda/30$ apart (for example, no more than 10mm for frequencies less than 1GHz), preferably much closer.

Where a shielded *cable* enters or exits a PCB shielding-can, its connector or gland must make a direct electrical connection all around the perimeter of its aperture in the shielding-can, and also all around the perimeter of the cable's shield. This is often called 360° shield bonding, and is best done using circular connectors, or rectangular connectors with conductive gaskets, as discussed in 2.6.5 – 2.6.7 of [4].

Unfortunately, many of the connectors associated with 'modern' digital data interconnections, such as RJ11, RJ45 (see Figure 4AP), USB2.0, Firewire, etc., use cheap folded metal bodies which have seams in them, so are not as good as deep-drawn types. They are also rectangular types but instead of conductive gaskets they most often use multi-point bonding with a few little bits of bent metal. As a result of their generally cheap (and nasty) design their effect on the SE of an enclosure, whether at product or PCB-level, is generally quite poor. However, a few manufacturers offer types with improved SE characteristics, and they are well worth buying.

A very interesting result of all the above is that it is easy to make a fully shielded PCB assembly, using plane layers on the top and bottom of the PCB, stitched together with a 'via wall' all around the perimeter of the PCB, with shielding-cans fitted over all of the exposed devices and traces. An example is shown in Figure 4BA.

If you were to look at the component side of the assembly shown in Figure 4BA, you would only see metal – either the metal of the tops of the shielding-cans, or the metal of the top-side 0V plane. The top-side 0V planes are actually extensions of the guard traces, so are RF-bonded to the perimeter of each can using solder, conductive gaskets (see Figure 4AZ), or multipoint spring fingers.

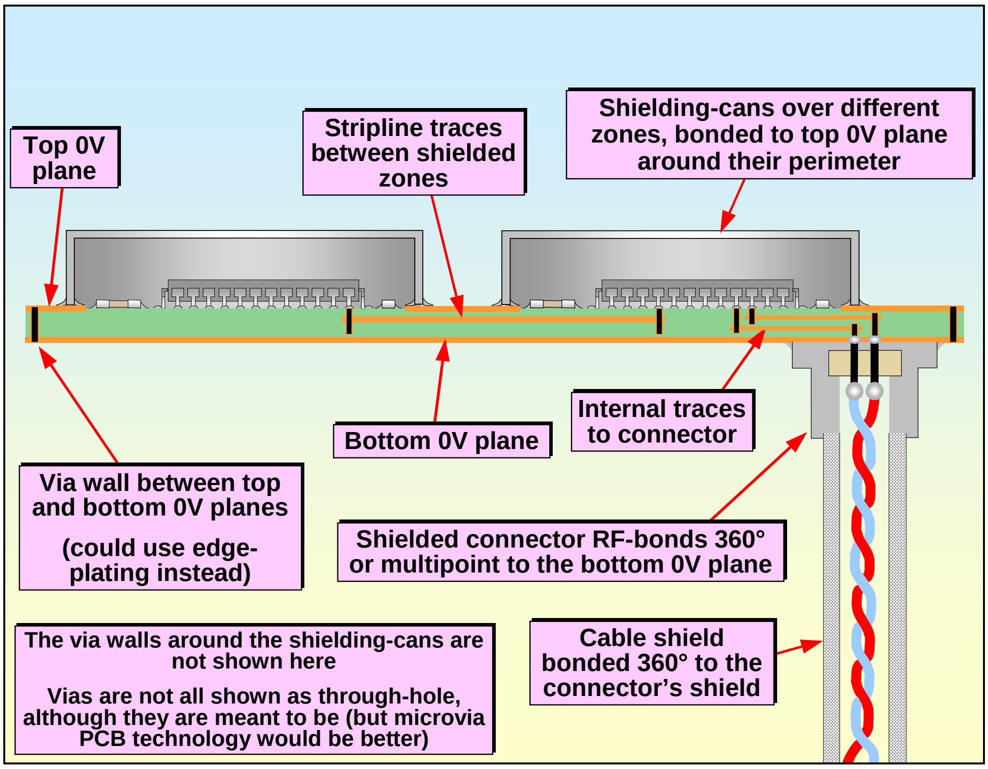


Figure 4BA Example of a fully-shielded PCB assembly

4.4.10 Combining filtering with shielding at PCB level

Where a conductor entering or exiting a PCB shielding-can is filtered, the best performance is achieved with feedthrough filters. To avoid the high cost of their manual assembly and wiring, three-terminal surface-mounted filters are used instead, and their performance is optimised by locating them on the PCB so that their centre terminals align with – and are soldered to – the guard trace that is routed around the perimeter of the shielding-can. In this way, their input and output terminals lie either side of the shield – and are shielded from each other.

Leaded feedthrough filters are screwed or soldered into appropriately dimensioned holes in the shielding-can. But SMD types lie flat on the PCB and protrude through small apertures in the bottom edge of the shielding-can's wall, as shown in Figure 4AP. The holes cut into the walls of the can for the three-terminal SMD filters to pass through are known as 'mouseholes' (for reasons that should be obvious to anyone familiar with 'Tom and Jerry' cartoons). The performance of the three-terminal SMD filters will be improved if the 0V plane via holes and shielding-can connection points to the guard trace are symmetrically placed with respect to the body of the filter component.

For more detail on using filtering in conjunction with shielding, including an example PCB pad pattern and graph showing how the performance of PCB-mounted filters is improved dramatically at frequencies above 100MHz, see 3.3.3 and 3,3,4 in [3].

Figure 4BB sketches the construction of a PCB assembly that is shielded and filtered. In some circumstances such an assembly might not need any further EMC measures, apart from a plastic box or other means to prevent electrostatic discharges occurring directly to its unshielded components.

Sometimes adequate EMC performance can be achieved solely by the use of the filters or shielding-cans. It may be worthwhile experimenting, during EMC testing [37], with lower-cost three-terminal filters, feedthrough capacitors, ferrite beads, or even zero-ohm links – so it helps to ensure that the pad patterns for the filters will accommodate a variety of such devices.

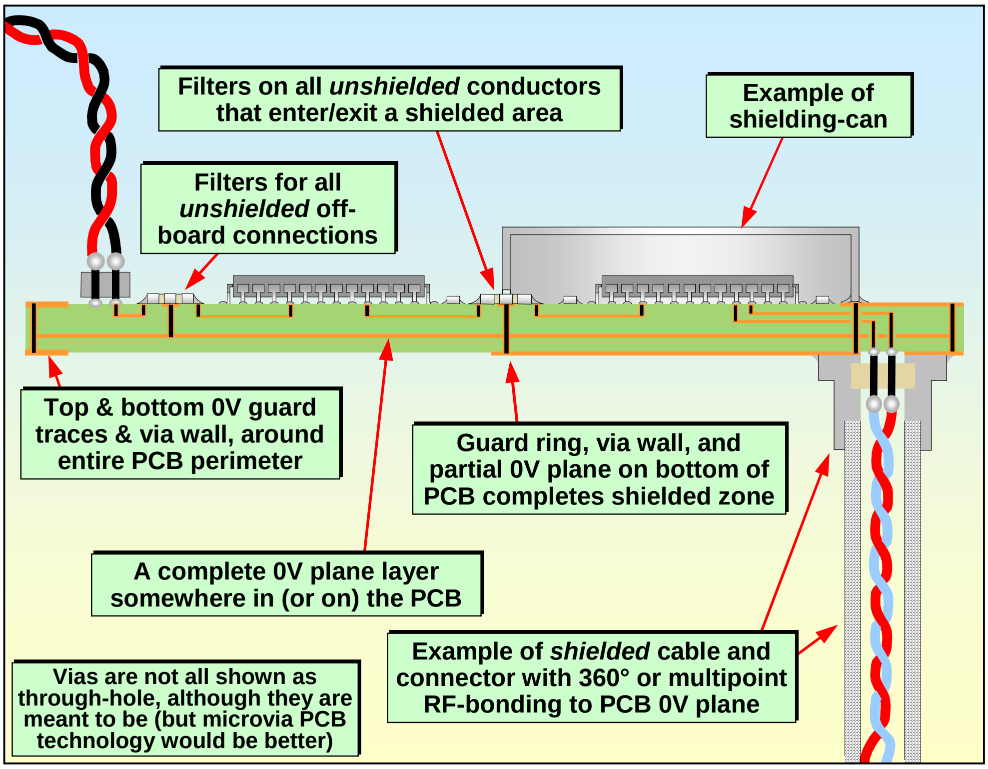


Figure 4BB Example of a partially-shielded PCB assembly, with filtering of traces and cables

4.4.11 Combing heatsinking with shielding at PCB level

Some modern ICs dissipate significant amounts of heat and so require heatsinking. Where PCB-level shielding is also required, shielding-cans are combined with heatsinks. The metal base of the heatsink becomes the lid of the shielding-can, so the shielding-can on its own is little more than a four-sided shielding wall – with its bottom face completed by a PCB plane layer – and its top face completed by the base of the heatsink. Figure 4BC sketches an example.

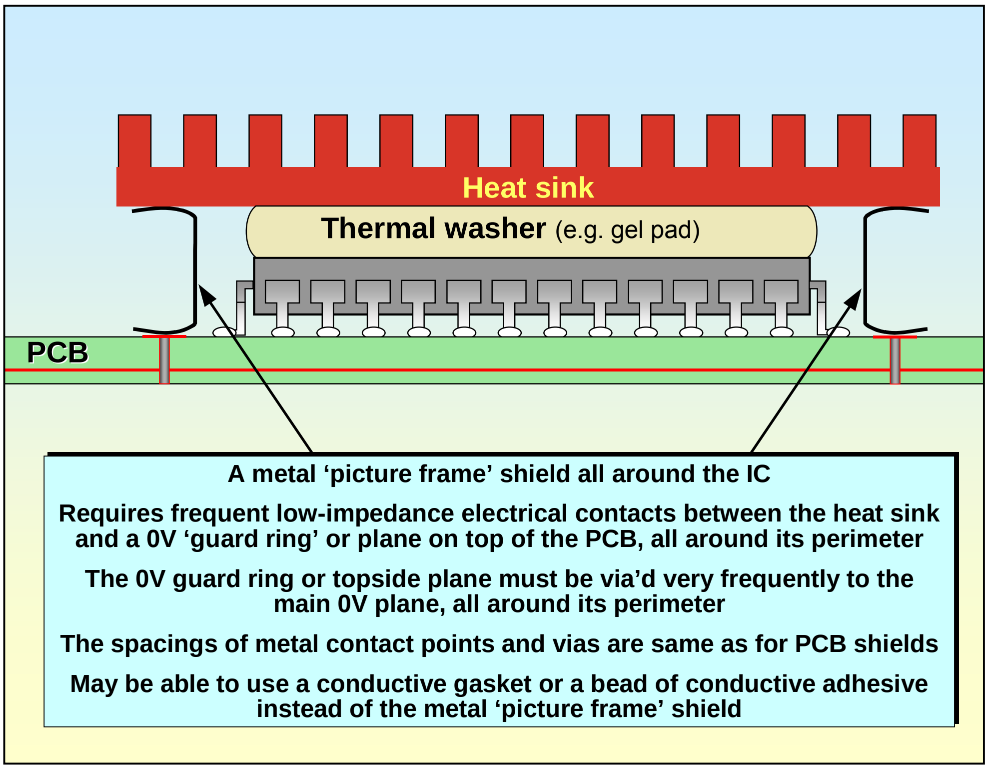
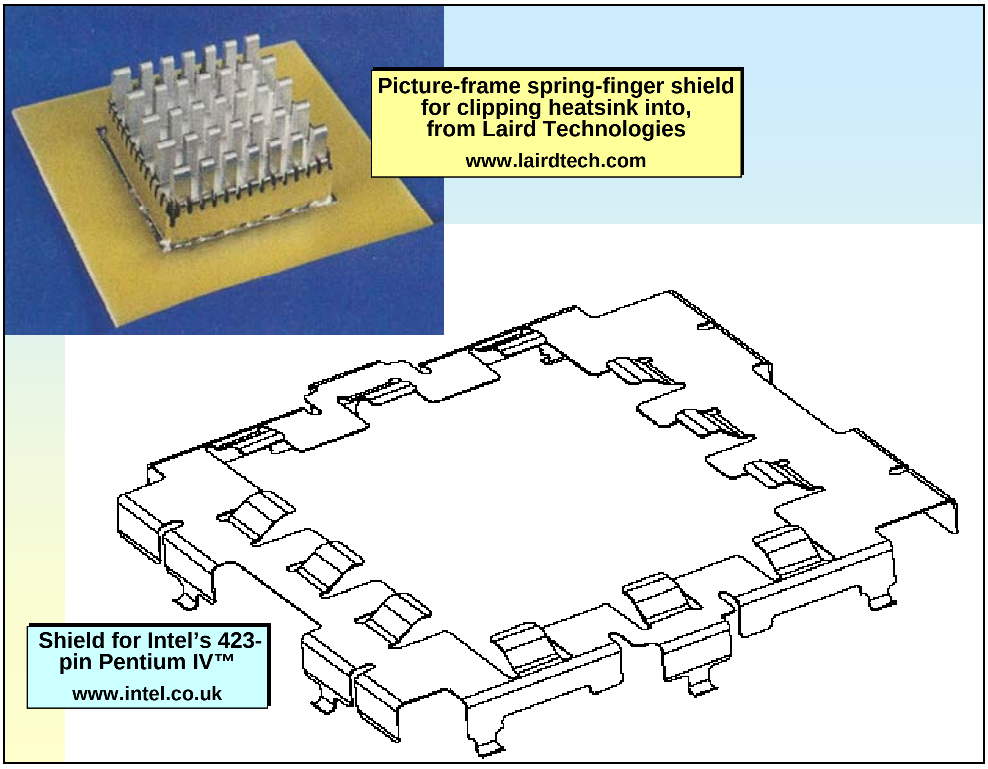


Figure 4BC Example of combining heatsinking and shielding for an IC

The base of the heatsink must have a highly conductive surface using metals chosen so that they will not corrode after years of contact with the shielding wall. The heatsink is usually not soldered to the shielding wall (although this could be done under certain circumstances). Normally, all the various ‘pressure sensitive’ techniques that can be used for attaching shielding-can walls to PCBs can also be used to electrically bond the walls to the base of the heatsink. The spacing rules for the electrical bonds to the heatsink are the same as those (above) for bonds to PCB planes.

Figure 4BD shows an example of an Intel-designed shield for one of their ICs. It has metal tabs for soldering to the PCB’s guard trace, and spring fingers on its top surface for multipoint RF-bonding to the base of the heatsink. The same figure also shows a spring-finger style ‘picture frame’ shield into which can be clipped a heatsink.



Picture-frame spring-finger shield for clipping heatsink into, from Laird Technologies
www.lairdtech.com

Shield for Intel’s 423-pin Pentium IV™
www.intel.co.uk

Figure 4BD Examples of commercially-available parts for combining shielding with heatsinks

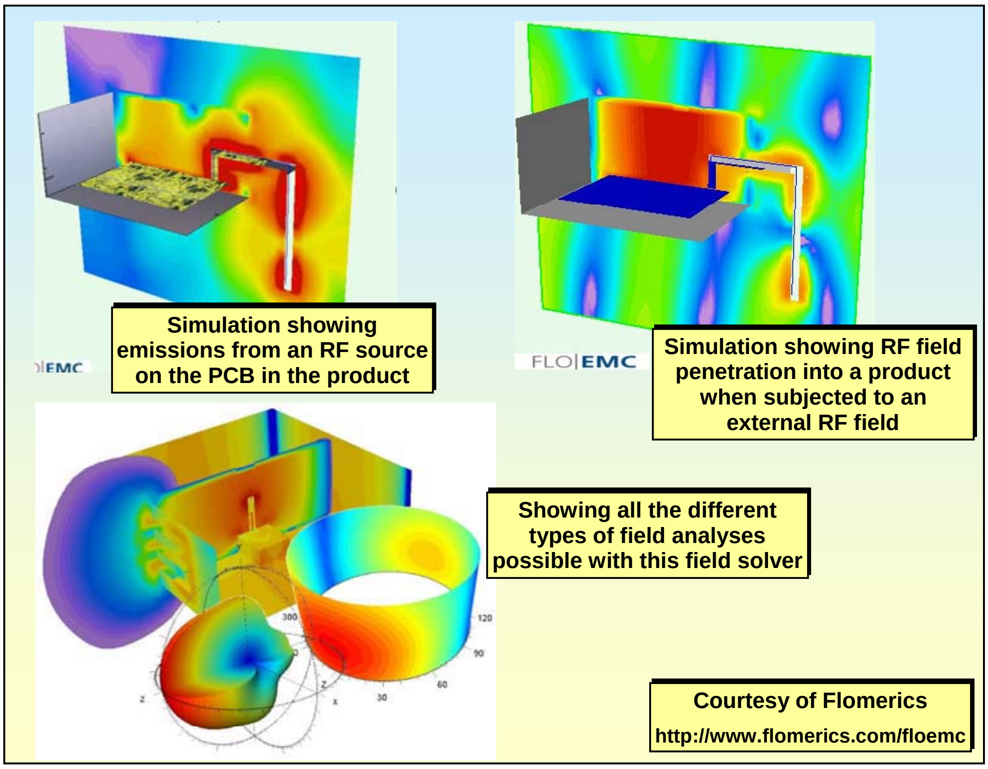
4.5 Estimating shielding effectiveness with PC-based simulators

The only really sensible way to discover the SE of any complex enclosure with apertures is to model the structure, along with any PCBs and conductors (especially those that might be near any apertures) with a 3-dimensional field solver. Software packages that can do this now have more user-friendly interfaces and run on desktop PCs, alternatively there are some bureau services and universities that have the necessary software (and the skills to drive it so as to get reasonably accurate results).

There are some free SE calculators on the Internet that can help estimate the effects of a few apertures on the far-field SE of simple rectangular enclosures, for example [15] and [16]. But PC-based 3-D field solvers are necessary for reasonably accurate predictions of SE, for multiple apertures, dissimilar aperture shapes/sizes, aperture spacings $>\lambda/4$, complex enclosure shapes and conductor penetrations, in both the near-field and far-field, for example FLO/EMC from Flomerics.

Without field-solving, the best bet for any reasonable accuracy is to mock-up the actual construction as well as can be done, plus the internal electronics or whatever, and test its SE in an EMC test laboratory at the earliest stage in a project to avoid unpleasant surprises later on. Various methods exist for SE testing of enclosures, although few of them are standardised. It is possible to do tests without using an EMC test laboratory, for instance using close-field probes you can make yourself (see Parts 1, 2 and 4 of [19]), or desk-top strip-line testers such as those made by Richard Marshall Ltd (www.design-emc.co.uk).

Since SE will vary strongly with the method and quality of assembly, materials, and internal PCBs and cables, it is always best to allow an SE 'safety margin' of 20dB, or at least design-in features that will allow SE to be improved by at least 20dB if emissions/immunity problems are experienced during EMC testing of the final design. The small amount of extra time required during the early design stages will be more than amply rewarded by the reduction in financial risk at a later stage in the project (see Chapter 1 of [22]).



Simulation showing emissions from an RF source on the PCB in the product

Simulation showing RF field penetration into a product when subjected to an external RF field

Showing all the different types of field analyses possible with this field solver

Courtesy of Flomerics
http://www.flomerics.com/floemc

Figure 4BE Examples of shielding simulations using FLO/EMC

4.6 EMC gaskets

EMC gaskets are conductive and compressible, and used to prevent apertures at joints, seams, doors and removable panels from compromising SE. They are also used for ensuring correct RF-bonding for connectors and filters. To function as intended they require a good electrical contact all along both sides of the seam, door, joint, etc., so metal contact surfaces usually need a conductive plating.

Gaskets must meet a number of often-conflicting mechanical and electrical requirements, not to mention chemical (e.g. to prevent corrosion). Shielding gaskets are sometimes required to be environmental seals too, adding to the compromise. Where a gasket does not return to its original shape when the pressure is removed, it is suffering from ‘compression-set’, so is not suitable for doors and removable panels. Considerations when designing or selecting gaskets are described in [49], and include:

- Mechanical compliance
- Compression-set
- Impedance over a wide range of frequencies
- Resistance to corrosion (galvanic compatibility with its mating surfaces, appropriate for the intended environment, see 4.7.9)
- Ability to withstand the expected rigours of normal use
- Shape and preparation of mounting surface
- Ease of assembly and disassembly
- Environmental sealing, smoke and fire characteristics

There are many types of EMC gaskets, and the main types are discussed below.

4.6.1 Volume-conductive elastomers

These are elastomers with metal particles in them (usually tiny metal-plated glass spheres), available in tape (extruded) form or as cast or die-cut materials, in a very wide variety of shapes and sizes, see Figure 4BF. Solid elastomers can require quite large pressures to compress adequately, making them difficult to use in manually-opened doors without power assistance or levers. Extruded types are available with hollow cross-sections, making them much ‘squashier’. If compressed overmuch they can also suffer from compression-set.

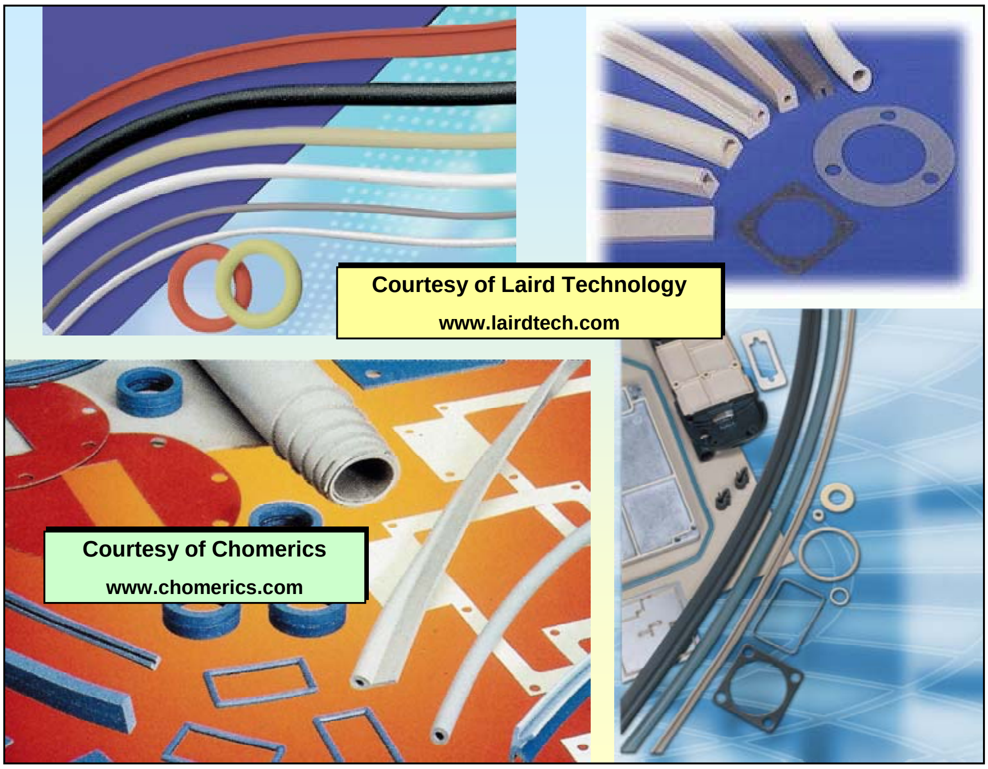

Courtesy of Laird Technology
www.lairdtech.com
Courtesy of Chomerics
www.chomerics.com

Figure 4BF Examples of some volume-conductive elastomeric EMC gaskets

They have environmental sealing properties, and can suffer from compression-set if over-compressed. Compression-set is generally prevented by designing a groove which helps to retain the gasket during assembly, and has mechanical features (like 'bump stops') which prevent over-compression. (See later for groove design).

The conductivity of these gaskets is not very high, even when they are compressed to their optimum, so the SE they can achieve is not as good as metal mesh or spring finger types. Hollow-core extruded elastomers are more suitable for gasketting plastic or sheet metal enclosures where high compressive forces might distort the mounting areas and degrade the SE of the enclosure, but they have even lower conductivity than solid types.

PTFE (Teflon) foam types filled with carbon particles are available (e.g. from W. L. Gore) and may be useful in combining EMC shielding with environmental sealing in especially aggressive environments.

A special type of volume-conductive gasket is supplied as a liquid and cured after being applied, often called 'form-in-place' gasketting. Application can be manual (e.g. with a glue gun) but in high-volume manufacture it is usually robotically applied, as shown in Figure 4BG.

Some of these liquid gaskets can also be used as adhesives, for applications such as that shown in Figure 4AH, and many of us are familiar with the use of 'conductive epoxy' to repair connections to the rear screen heaters in motorcars.

The elastomer is usually silicone, which is quite stiff – making it quite difficult to achieve adequate compression along its length, especially with plastic parts. Recently, types that foam-up after application have been developed, making much softer and more compliant gaskets that are easier to design with. These are the types of materials used in the 'mold-in-place' gaskets shown in Figure 4AY.

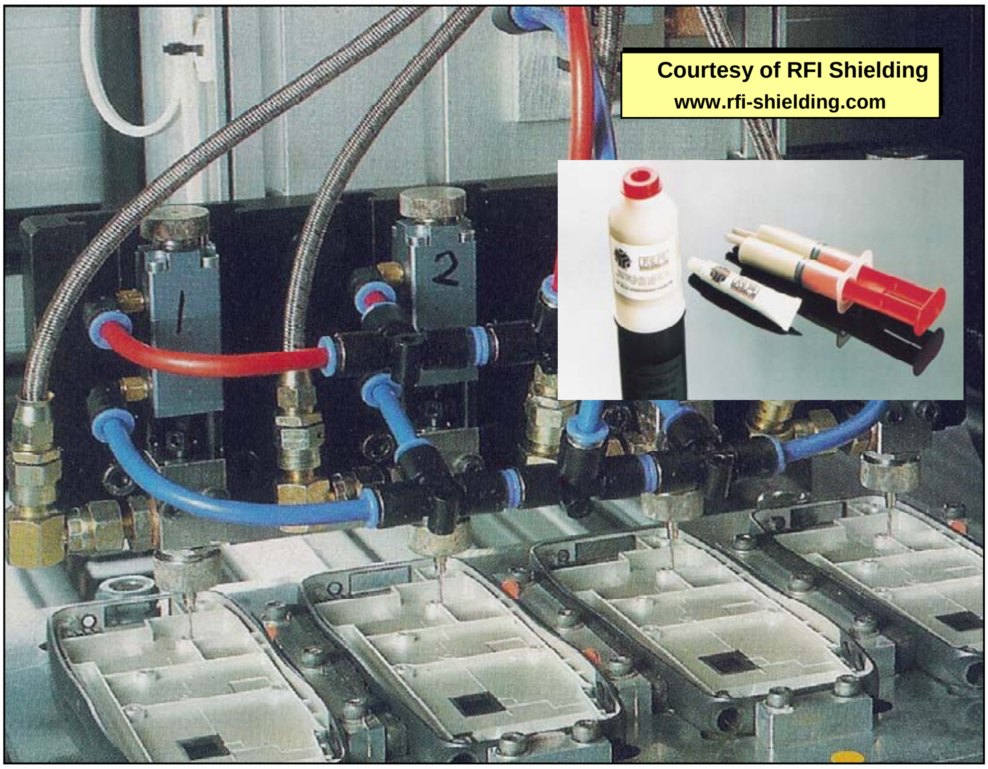


Figure 4BG Example of Form-In-Place (FIP) gaskets being robotically applied

4.6.2 Conductively coated or wrapped elastomers, see Figure 4BH

These are elastomer foams or tubes with conductive outer coatings or coverings of metallised fabric, with a low compression-set in general. The elastomer is not conductive, and merely provides a support function for its conductive covering. They can have hollow cross-sections or be foam, and can be very soft and flexible and only require low compressive forces. However, they do not – in general – make the best environmental seals, and their conductive layers may be vulnerable to wear.

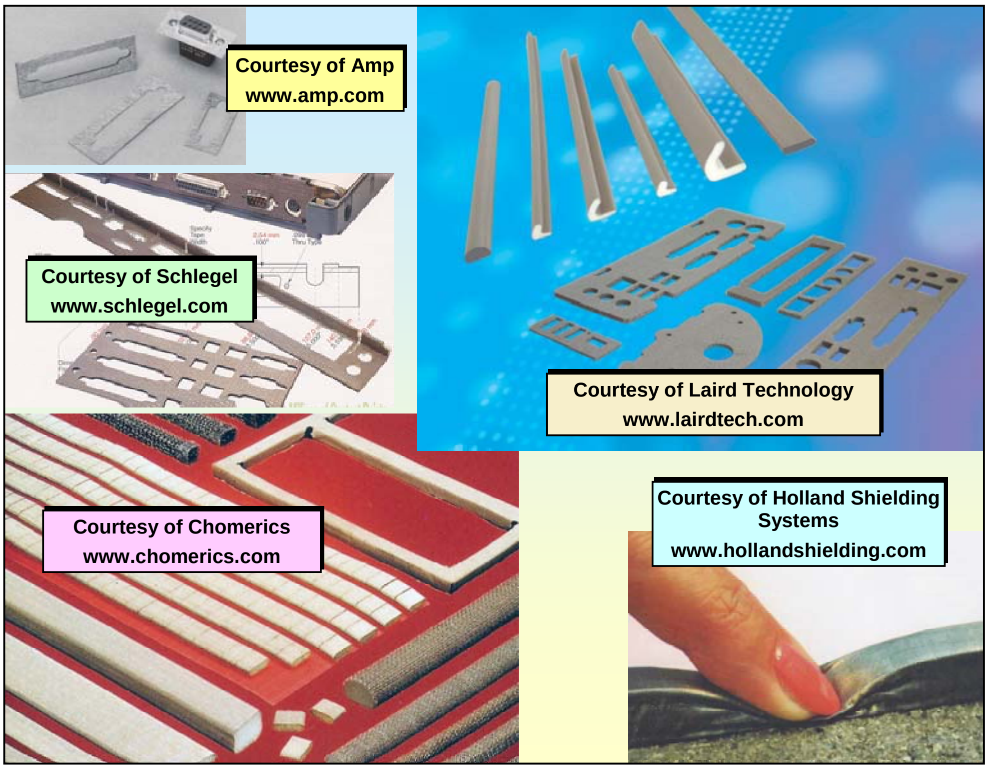


Figure 4BH Examples of some conductively-coated or wrapped polymer EMC gaskets

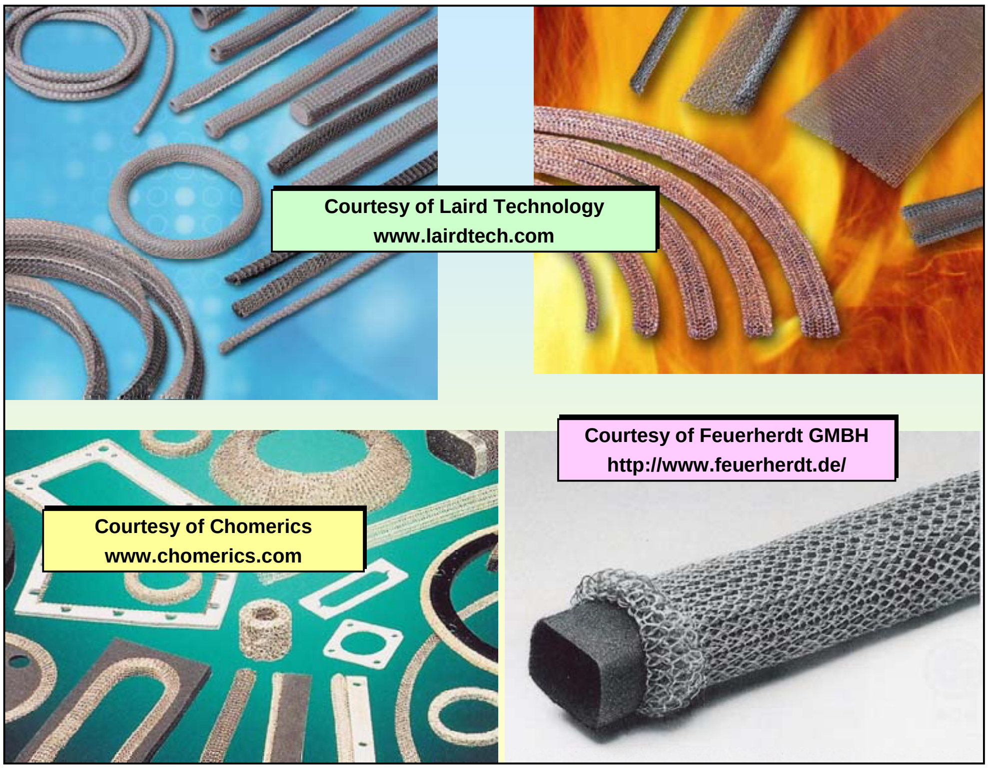
Coatings and wrappings for these gaskets include:

- metal films
- knitted wire mesh ‘stockings’
- metallised fabrics
- metallised foils

4.6.3 Metal (wire) meshes, see Figure 4BJ

These can be random meshes or knitted types. They are generally very stiff but match the impedance of metal enclosures better and so provide better SEs than the above types. Some types of gaskets use a thin knitted mesh ‘stocking’ over a foam core (see later) to reduce the force required.

They have poor environmental sealing performance, but some types are available bonded to an environmental seal, so that two types of gasket may be applied in one operation. Also, some types are available filled with an uncured silicone, which provide good environmental sealing.



Courtesy of Laird Technology
www.lairdtech.com

Courtesy of Feuerherdt GMBH
http://www.feuerherdt.de/

Courtesy of Chomerics
www.chomerics.com

Figure 4BJ Examples of some metal mesh EMC gaskets

Commonly used mesh materials include:

- Phosphor Bronze
- Tin-coated Copper Clad Steel
- Silver plated Brass
- Monel

Wire mesh gaskets are available in tape, round or rectangular cross-section gaskets. Because they generally require high compressive forces they are best mounted in a slot or a flange of a stiff enclosure (see later). They tend to suffer from compression-set, so are not the best choice where a joint may be repeatedly opened and closed, but they are a good choice for sturdy metal parts that are permanently fastened, or where replacement of the gasket each time the joint is opened would not be a problem.

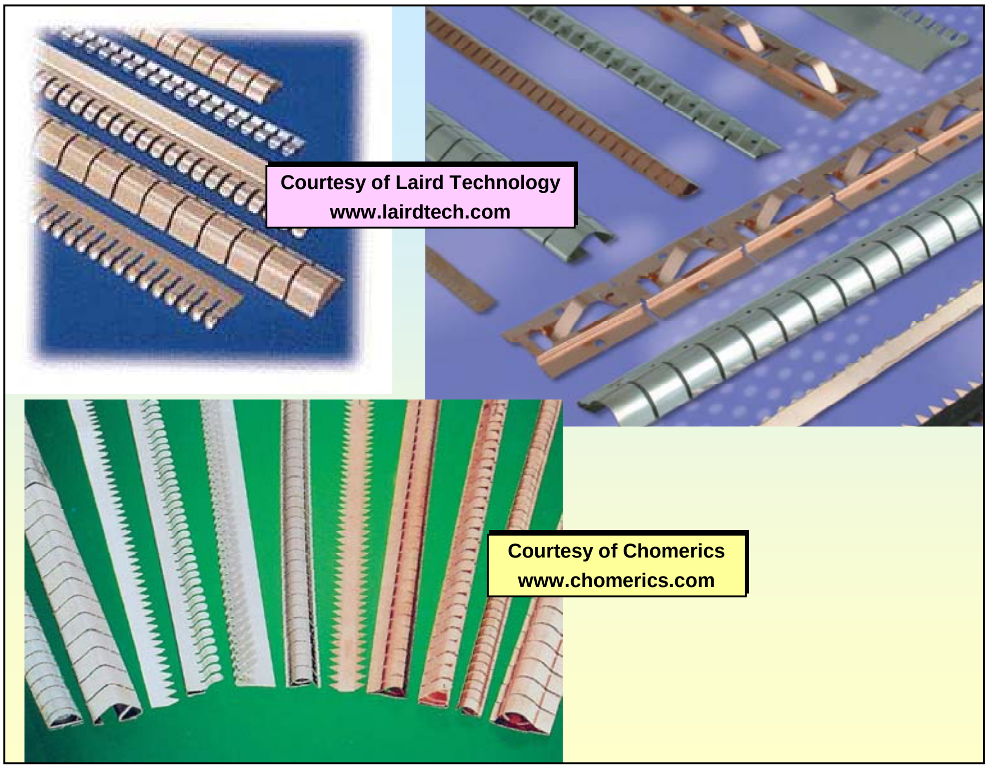
4.6.4 Spring fingers (‘finger stock’), see Figure 4BK

These are traditionally made from beryllium-copper or stainless steel and can be very compliant. Because some people are becoming concerned about the possible health hazards of beryllium, other materials are being developed, such as Laird Technology’s ‘clean copper’.

Spring fingers have very low compressive forces and no compression-set, even if squashed flat for years, so are very suitable for modules, doors and panels, that must be easy to manually insert/extract and open, and which have a high level of use. Their wiping contact action helps to maintain a good RF bond by removing oxide and corrosion films and dirt, and they have a good impedance match with metal surfaces.

Spring fingers are quite vulnerable to accidental damage, such as snapping off by getting caught in a coat sleeve. The dimensions of spring fingers and the gaps between them causes inductance, so for high frequencies or critical use a double row may be required, such as is often seen on the doors of most EMC or RF test chambers.

For shielded rooms with spring-finger door gaskets, the usual instructions are to smear them with petroleum jelly once every year, but this is rarely a requirement in equipment user instructions.



Courtesy of Laird Technology
www.lairdtech.com

Courtesy of Chomerics
www.chomerics.com

Figure 4BK Examples of some spring finger EMC gaskets

Spring fingers can be mounted by a variety of methods:

- gluing (often with a self-adhesive strip)
- riveting
- soldering
- welding
- clipping onto a mechanical feature like an edge or a flange-on, or into a slot in the metalwork.

They need a flat contact area on both sides, plated with a highly-conductive material that is galvanically compatible with the plating of the fingerstock to help prevent corrosion. Materials with tough oxide skins (like plain aluminium) or polymer passivation are unsuitable. Although the best RF-bonds require area contact rather than sharp points, there are types of spring fingers with sharp points that can give better results with less-than-perfect contact areas.

Like some other types of gaskets, spring fingers can be made circular, for use in RF-bonding the mating halves of circular shielded connectors together (e.g. as in Figure 2T of [4]). Some examples are shown in Figure 4BL, which also shows some spring-finger gaskets for D-Type connectors, and for the expansion card slots of PCs.

It can be easy to design spring finger gaskets into the metalwork of a product, so that they do not require an additional assembly step. Figure 4BM shows the example of a Sun Microsystems server, where the attractive plastic cover was fitted with a plain springy-steel sheet underneath, with spring fingers around the edges to make connection with the metal box in which the server electronics was housed. Metal sheets like this can be cut and bent from plain sheet in one stamping operation, and are usually tinned to provide a lower resistance contact.

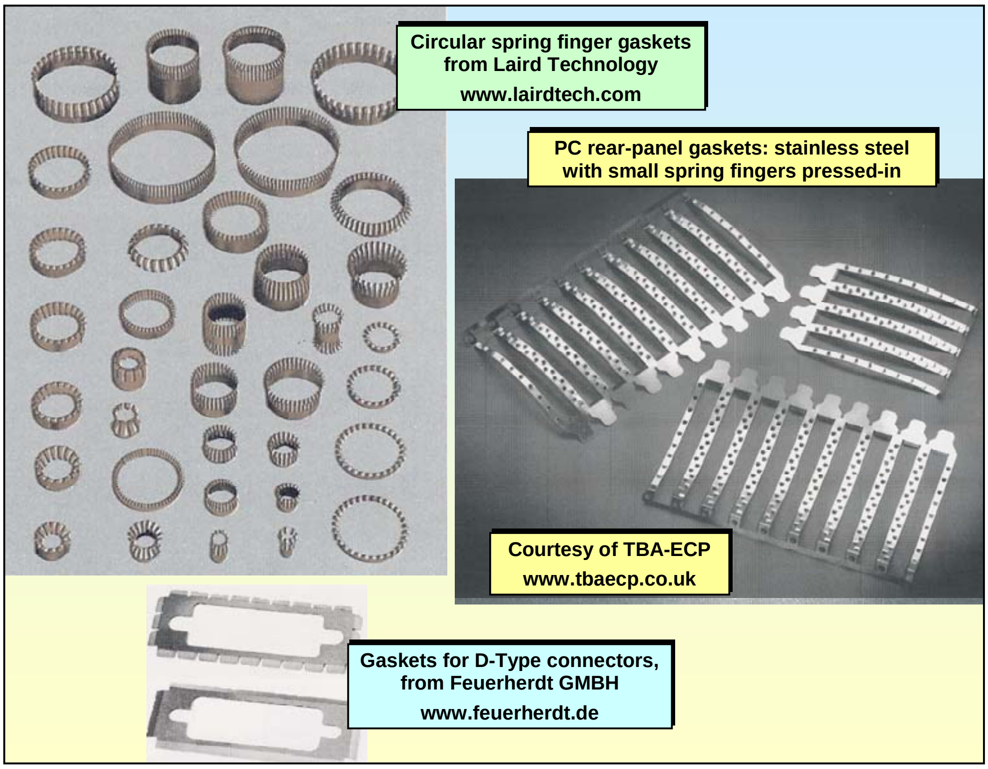


Figure 4BL Examples of some special types of spring finger EMC gaskets

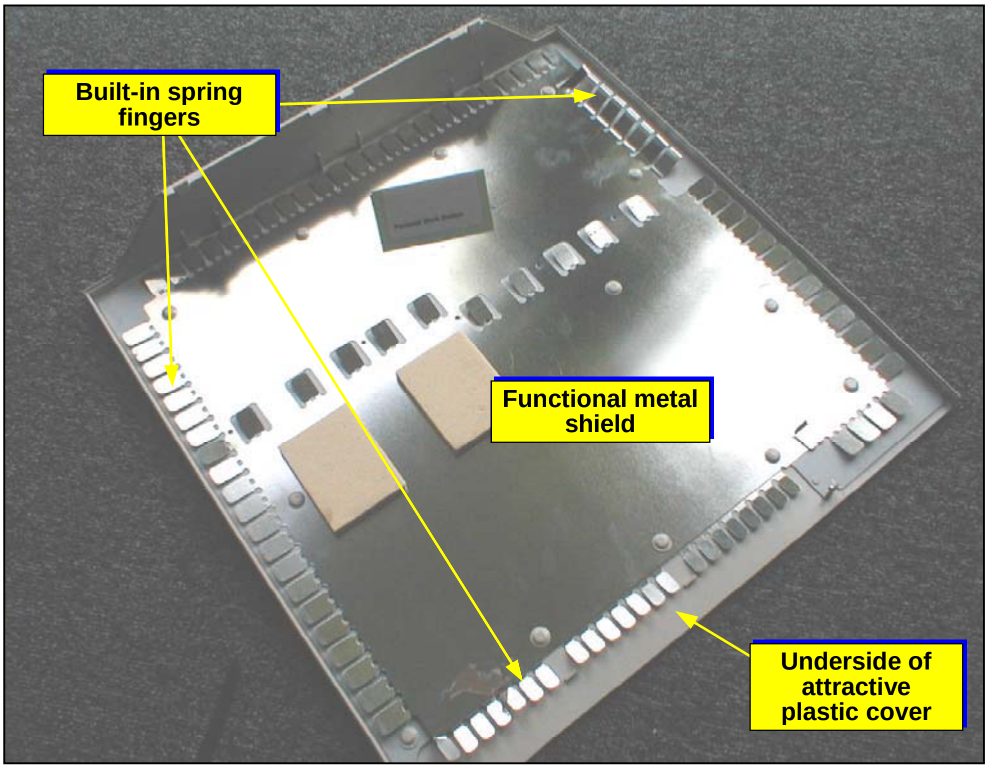


Figure 4BM Example of D-I-Y spring fingers

4.6.5 Some other types of gaskets

The four main types of gaskets have been described above, but there are many other types, some of which are shown in Figure 4BN, for example…

- Graphite (best used under very high compression, between machined surfaces)
- Oriented wires in silicone (good results with poor surfaces, but require high pressure)
- Spiral foil (can be combined with cured or uncured silicone to provide an environmental seal)
- Canted coil spring gaskets (often used in connectors and glands, see Figures 2T, 2V of [4])

- Metal fibre gaskets, using woven metal wire, sintered metal fibre or expanded metal (used on flanged mating surfaces where compressive forces are very high)
- Metal or metallised ‘velcro’ (mostly used for RF-bonding seams in metallised fabrics)

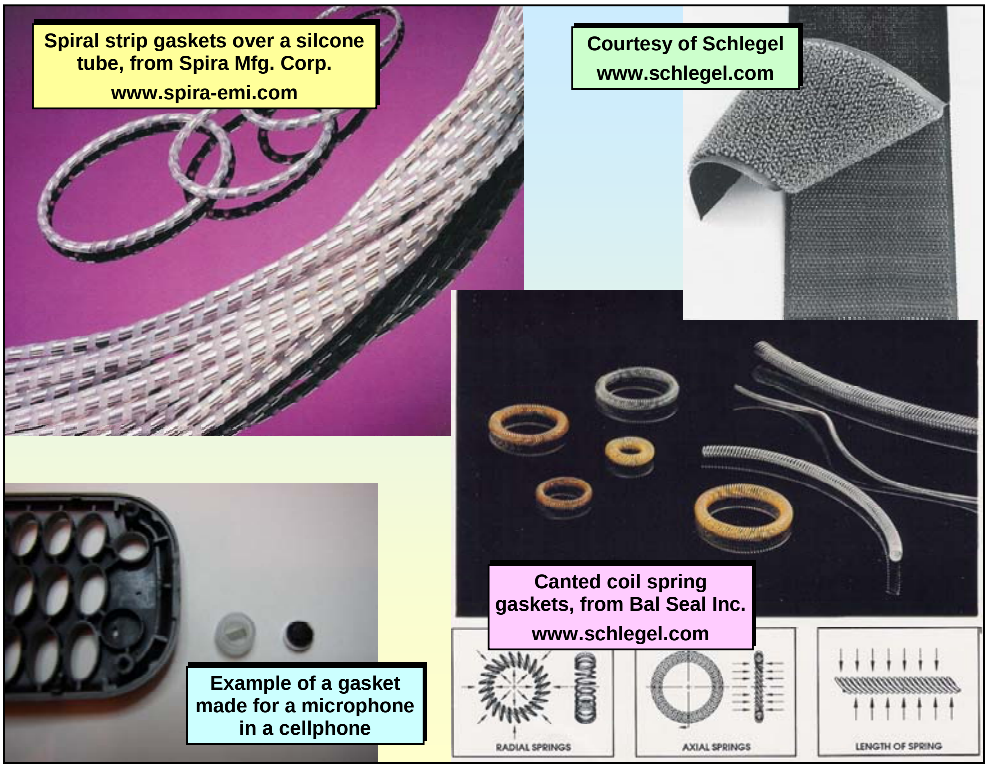


Figure 4BN Some examples of other types of conductive gasket

4.6.6 Mechanical design techniques for gaskets

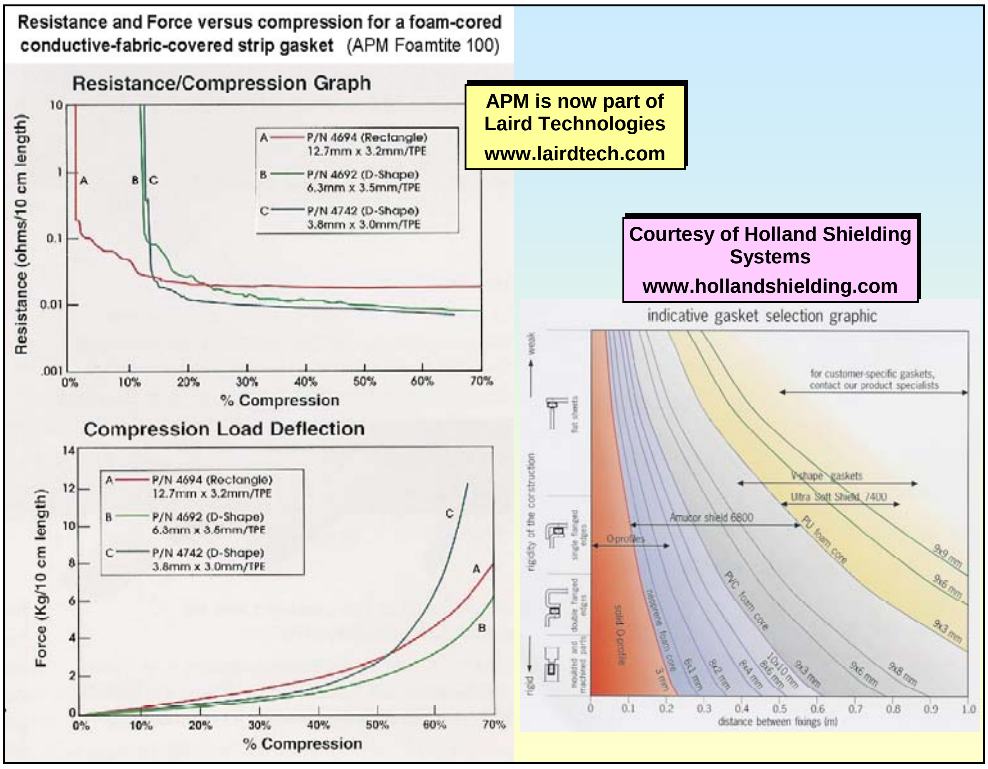
Some gaskets require a low compression force, some a medium force and others a high force. But even very soft gaskets can require a surprising amount of pressure overall, sufficient to bend quite sturdy items of metalwork, so careful mechanical design is always required. The shielded enclosure must be capable of achieving sufficient pressure to achieve the required contact resistance, all along the length of the gasket. Some gaskets need up to 0.7MPa (100 psi) to achieve a low-enough contact resistance. Hollow elastomers generally need less than 180kg/metre (10 pounds/inch), whilst foam cored and spring finger types might only need 20kg/metre (1 pound/inch).

Designing lids, covers, doors, etc, so that they have sufficient stiffness and fixings to compress the chosen type of gasket is not easy (see 4.6.7) and is beyond the scope of this article. Some gasket manufacturers supply very useful application notes that provide a great deal of technical assistance with mechanical design, such as the advice on using gaskets in a sheet metal enclosure.

Figures 4BP and 4BQ show examples of the data and other design information provided by gasket manufacturers to help shielded enclosures be designed to compress their conductive gaskets correctly. For more information, see [11], [12], [39], [40], [41] and [42].

Softer gaskets ease mechanical design, but are less likely to break through films or oxide, corrosion or dirt to achieve good electrical contact over the life of the equipment, so they need high-quality corrosion-protected conductive surfaces for their contacts on both sides.

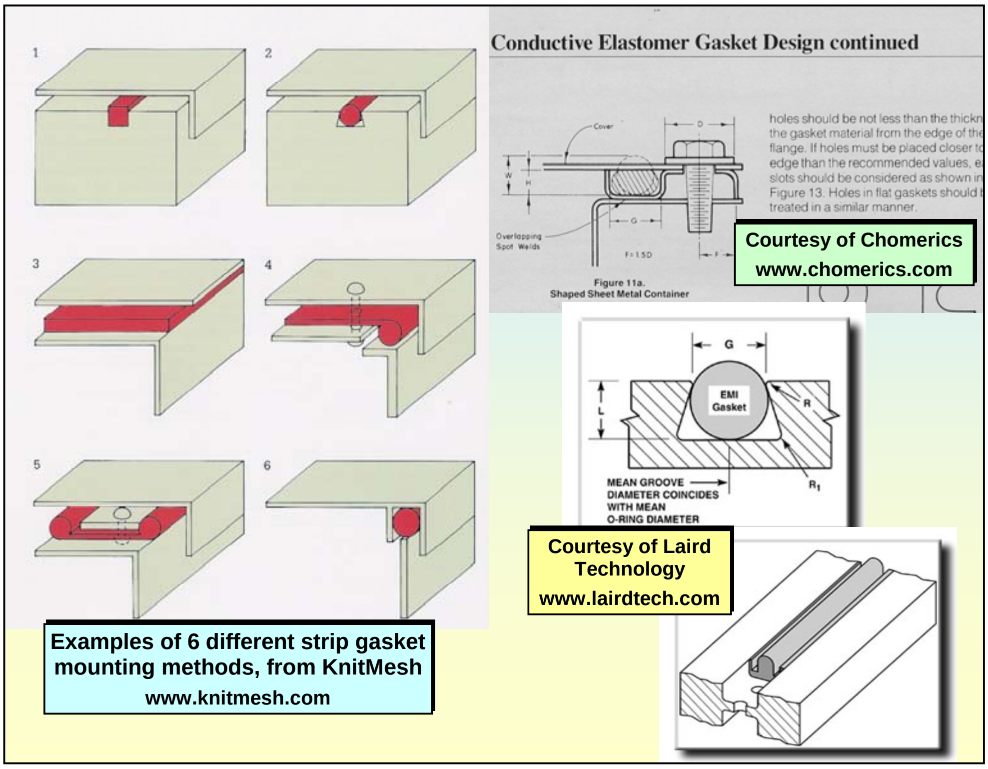
Figure 4BR shows a typical gasket design for the door of an industrial cabinet, using a conductive rubber or silicone compound to provide an environmental seal as well as an EMC shield. Spring fingers are also often used in such applications, but in this case are fixed to the side so that they wipe when being closed or opened, as the photograph of the stainless-steel cabinet in Figure 4BR shows.



APM is now part of Laird Technologies
www.lairdtech.com

Courtesy of Holland Shielding Systems
www.hollandshielding.com

Figure 4BP Some examples of gasket mechanical design information



Courtesy of Chomerics
www.chomerics.com

Courtesy of Laird Technology
www.lairdtech.com

Examples of 6 different strip gasket mounting methods, from KnitMesh
www.knitmesh.com

Figure 4BQ More examples of gasket mechanical design information

It is worth noting in passing that the green/yellow wire used for safety earthing of a door or panel has no benefits for EMC, above a few hundred kHz. This might be extended to a few MHz if a number of short wide earthing straps are used, spread along a hinge, instead of a single wire.

Gaskets need appropriate mechanical provisions to be easy to assemble whilst also effective at maintaining SE. If they are simply stuck on to a surface and squashed between mating parts they may not work as well as was hoped – the more the fixing screws are tightened in an effort to compress the gasket the more the gaps between the fixings can bow, opening up leaky gaps.

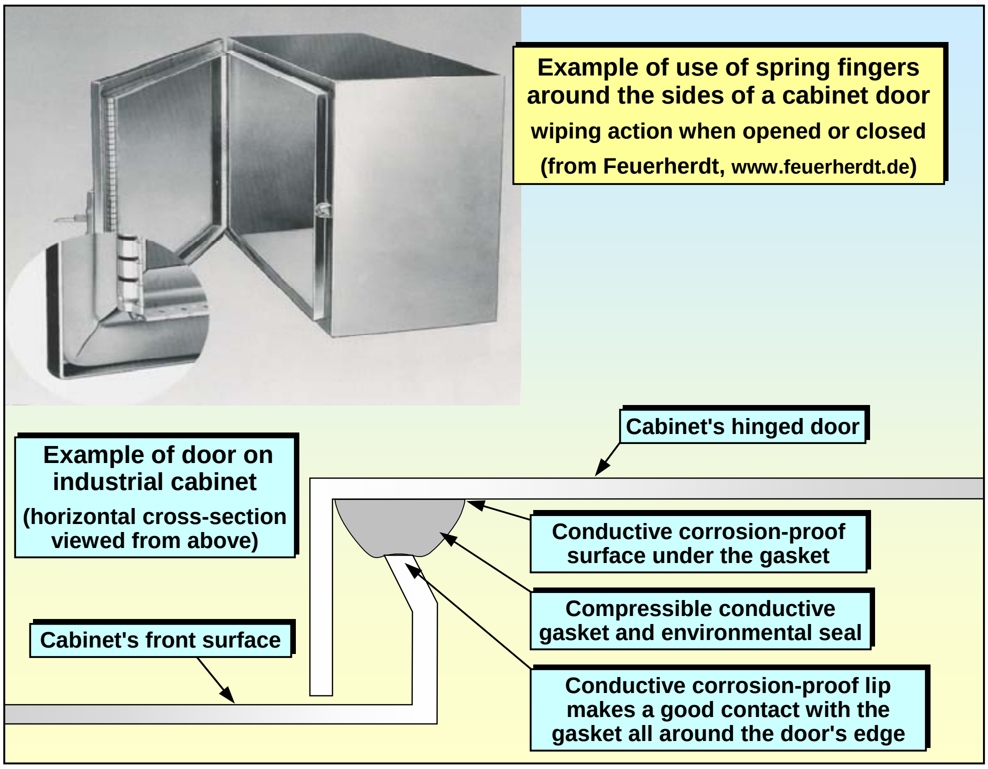


Figure 4BR Examples of gaskets on industrial cabinet doors

This is because of inadequate stiffness in the mating parts of the enclosure, but it is difficult to make the mating parts rigid enough without a groove for the gasket to be squashed into. This groove also helps correctly position and retain the gasket during assembly. The dimensions of the groove ensure that the gasket is compressed optimally to give a low contact resistance when the mating half is correctly fitted.

The groove should be designed so that so that if the fastenings are over-tightened, the gasket will not be compressed so much as to suffer compression-set or other damage, and the mating half will not become distorted. Where grooves are not used, bump-stops and similar mechanical features should be used. Figure 4BS sketches this type of design, and some partial examples of manufacturer's design information is shown in Figure 4BQ.

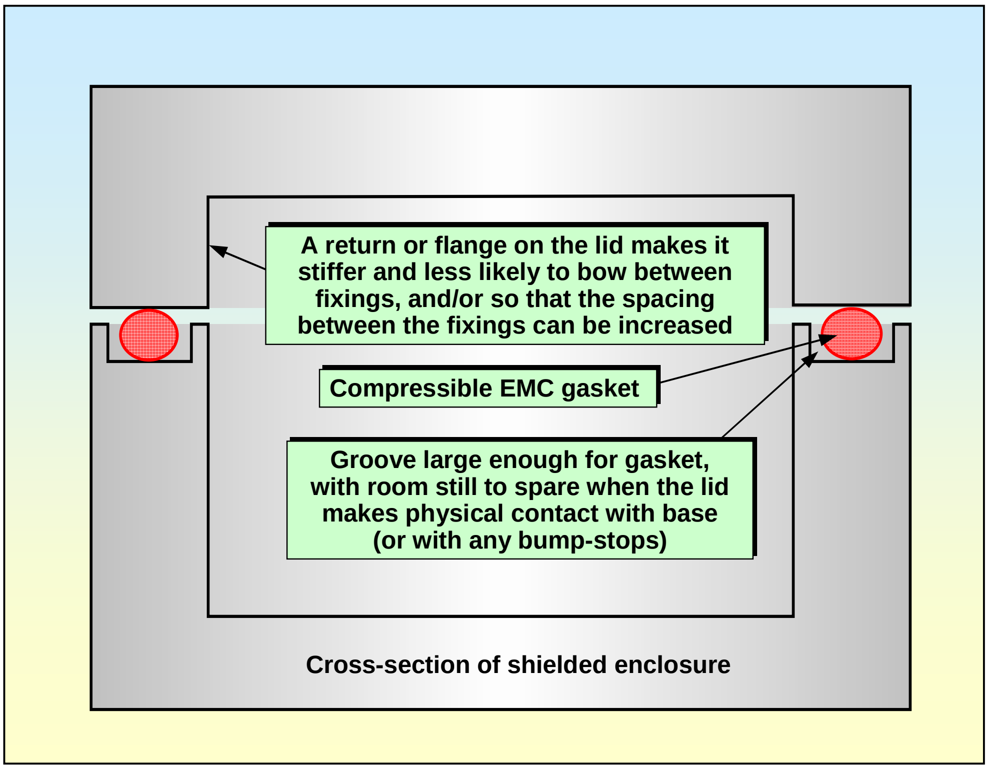


Figure 4BS Example of gasket groove design

Figure 4BS sketches an enclosure that is either die-cast or milled from solid, but gasket manufacturers' application notes describe how to design sheet-metal enclosures for gasket retention and optimal compression, as (partially) shown in Figure 4BR.

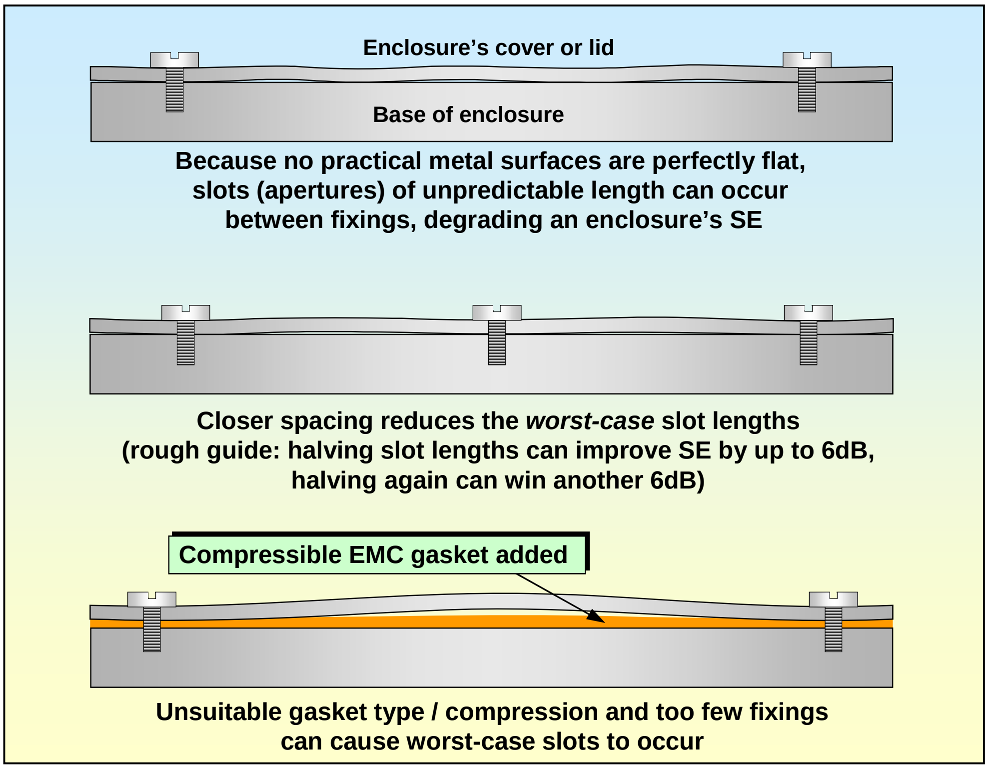
All gasket details and measures must be shown on manufacturing drawings, and all proposed changes to them assessed for their impact on shielding and EMC. It is not uncommon, when painting work is transferred to a different supplier, for gaskets to be made useless because masking information was not put on the drawings. Changes in the painting processes used can also have a deleterious effect (as can different painting operatives) due to varying degrees of overspray into gasket mounting areas which are not masked off. The use of special conductive tapes with a masking layer is discussed in 4.7.4.

4.6.7 Gasket clamping

For high values of SE when using a metal enclosure that has stiff flanges at its joints (e.g. cast metal box and lid, see Figure 4BS) – the fixing pitch should not generally exceed 50mm (2 inches). When using sheet metal enclosures, high values of SE will generally require a fixing pitch not more than 19mm (0.75 inch). Lower values of SE allow larger spacings between fixings.

The force required per fixing is determined by dividing the total compressive force required to compress the gasket optimally (see Figure 4BP), and of course the fixings chosen should be rated for at least their maximum tension. Where groove design is inadequate for gasket protection, and bump-stops are not used, assembly should be carried out with torque-controlled tools to ensure that gaskets are compressed correctly.

Thinner or more flexible materials will require the fixing pitch to be reduced to prevent distortion, which generally takes the form of bowing, creating apertures which can reduce SE as shown in Figure 4BT. This problem is not uncommon when trying to add gaskets to enclosures that were not designed to take them. Distortion becomes very obvious when, during emissions testing, fixings are tightened to try to improve SE – but beyond a certain torque the SE is worsened instead.



Because no practical metal surfaces are perfectly flat, slots (apertures) of unpredictable length can occur between fixings, degrading an enclosure's SE

Closer spacing reduces the *worst-case* slot lengths (rough guide: halving slot lengths can improve SE by up to 6dB, halving again can win another 6dB)

Unsuitable gasket type / compression and too few fixings can cause worst-case slots to occur

Figure 4BT Fixings, bowings, and SE

4.7 Materials useful for shielding

4.7.1 Metals and their surface finishes

Steel and aluminium are often used to construct enclosures, because they are relatively cheap and easy to cut, machine, bend and join. Aluminium has a high conductivity but is very reactive so its surfaces are always oxidised, and the oxide is a good insulator and very tough, making it difficult to RF-bond to. The thickness of the oxide grows with time, so the reflectivity of plain aluminium decreases and RF-bonding becomes more difficult.

Anodising is a very common surface treatment for aluminium, but works by increasing the thickness of the oxide layer, creating an insulating surface. It is not an appropriate surface treatment for a shielded enclosure, but I have seen products in which an anodised front panel was considered essential for its scratch resistance, so at all the shield bonding points it was removed by machining.

Alochrom, Alodine, Iridite and Oakite® Chromicoat are all types of commercial conductive passivating finishes for aluminium. These have good reflectivity, and help achieve good RF bonds, helping to achieve good SE, although some may require moderate contact pressures to be applied achieve useful conductivity at joints. Some of these methods rely on hexavalent chromium, which is being outlawed in the European Union by the Restriction on Hazardous Substances directive (2002/95/EC) so alternatives based on trivalent chromium and other chemicals are being developed (see 4.7.8).

Aluminium can also be tin-plated, although this is not a simple process. Reasons for tin-plating are to make it solderable, or to reduce galvanic potentials at metal contacts (e.g. with tin-plated steel or copper) and so reduce corrosion (see 4.7.9).

Mild steel has a reasonable conductivity and also has significant relative permeability that helps shield low-frequency magnetic fields (see 4.3.4 and Figure 4G of [20]). Steel surfaces also oxidise (rust) so for good RF bonds in shielded enclosures steel is usually plated with zinc or tin. Zinc can be plated as a metal, or as ‘galvanising’, and the metal is better for EMC purposes. Tin can also be plated in two forms, dull (matt) or bright – and the dull finish is better for EMC as it is easier to make RF bonds and solder to. Zinc and tin have higher conductivity than steel, so plating with them improves reflectivity.

Sheet steel that is galvanised or already zinc plated (e.g. ‘Zintec’) helps prevent rusting, but it will still rust at its cut edges. Another problem with plated sheet metals such as Zintec is that they are often supplied already passivated with a polymer coating, which is an insulator, making it impossible to create the RF-bonds required for good SE without using high-compressive-force conductive gaskets with all their mechanical design difficulties. So it is best to fabricate the metal parts from plain metals, and only then plate them with zinc or tin.

Stainless steel has lower conductivity and permeability than mild steel, is harder to work and more expensive, so is generally only used in specialised areas such as in food preparation and other areas which are subject to regular wetting. But stainless steel cabinets are usually made of metal that is quite thick, and seam welded to a high quality (for hygiene purposes), so they often make excellent shielded enclosures (see the one photographed in Figure 4BR).

Copper, brass, tin and similar metals have a high conductivity and are easily worked but their high cost means they are generally only used for small enclosures, such as PCB shielding-cans, and even then tin-plated steel is more common.

Zinc metal plating can suffer from a heavy white ‘bloom’ in high humidity. A chromate conversion process can passivate the zinc surface to prevent this, leaving a conductive surface (unlike polymer passivation). As discussed above, chromate passivation processes are currently being modified to replace hexavalent chromium with its trivalent form, but not all metals can be passivated as successfully so some further development is required.

Where metal or metal parts are for use in constructing a shielded enclosure, it is very important to specify ‘no passivation’ or ‘chromate passivation only’ on metal drawings. And even so, a surface resistance test (using very smooth probes and low pressure) is always recommended before accepting *any* batches of sheet metal or metal parts into a manufacturer’s stores.

Enclosures made from cast or ‘machined-from-solid’ metal have some advantages over those made from folded sheet metal, including...

- fewer joints and seams (apertures) to degrade SE
- easier to include grooves for EMC gaskets
- stiffer, making it easier to compress lengths of gasket

Castings often use aluminium/zinc alloys, but magnesium alloys are increasingly popular. Aluminium/zinc casting alloys can often be polished to a high gloss, and if their zinc content is high they can retain a good surface conductivity for many years – but they do scratch easily. Chromate (trivalent) passivation or similar is generally required, and always required for magnesium alloys.

Apart from the EMC benefits (which make cast or machined enclosures almost mandatory in some high-performance applications), suitable design of cast or machined enclosures can make them quicker and easier to assemble than sheet metal, helping offset their generally higher material and tooling costs.

4.7.2 The problems of polymer passivation

Beware of ‘automatic’ passivation with polymers. Many buyers, suppliers and metal platers assume that polymer passivation is always required – even when not specified on the drawing – and it is no good specifying the surface conductivity to be achieved as some metal platers do not seem to understand the concept and apply polymer passivation regardless.

If the traditional ‘yellow passivation’ is applied it is obvious that the plater has done something to the metal parts – but if they use a clear polymer it is impossible to tell it from bare metal by eye or touch.

Many product manufacturers suffer shielding problems until they discover that their shiny metal parts actually have an invisible insulating passivation layer. Sometimes, although metal parts have been supplied with a perfectly good surface-conductive finish for years, they can suddenly and without any warning start to arrive with polymer passivation layer – this may be because the company buyer has changed suppliers, or the supplier has unilaterally decided to make the change.

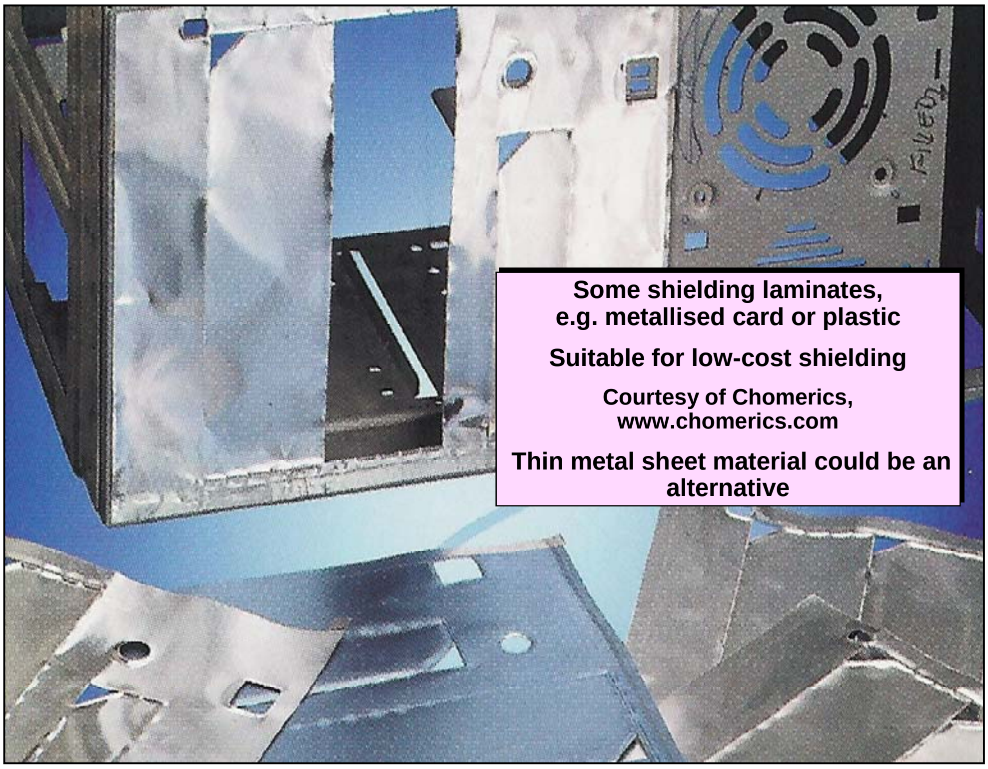
Based on the costly experiences of numerous manufacturers, I now always recommend employing a surface conductivity test at goods-in, and including this test and its specifications in the manufacturing drawings and purchasing order. It is best to have an agreement with the supplier that any deliveries that do not pass this test will be rejected back to the supplier at his own cost, who must then replace them within a specified time with parts that pass the test.

It is easy to make a suitable test device with a low-voltage electronic buzzer mounted in a hand-held device fitted with two spring-loaded contacts that press smooth conductive pads onto the metal surface to be tested. For the best sensitivity to surface conductivity, the conductive pads can be made of tin-plated copper onto which are stuck some soft conductive gaskets, such as the conductive-fabric-over-foam types (see below). The soft gaskets press against the sample, and apply a uniform low pressure – helping to avoid the possibility that any sharp edges, grit or swarf would cause an erroneously low reading.

Because an alochromed aluminium surface looks much like an anodised one, and because anodising is the more common treatment, it is easy for errors to be made in the design and purchasing process. A product that had good SE when made with alochromed aluminium can suddenly become non-compliant when constructed with anodised aluminium that looks just the same. The solution is to check all parts that are supposed to be conductive, before they are accepted into a manufacturer’s stores, as discussed for polymer passivation above.

4.7.3 Metallised papers and fabrics

Short fibres of polyester and similar materials can be metallised and bonded into a paper-like material with a random alignment of fibres. The coating on the individual fibres is very thin but the paper can be made to various thicknesses to improve its absorption. It is a low-cost material that makes good RF-bonds, and is easy to cut and glue. It can even be pasted onto walls to construct a shielded room, when it is often called ‘EMC wallpaper’. Figure 4BU shows some examples of metallised paper materials being used to shield a product.



Some shielding laminates, e.g. metallised card or plastic

Suitable for low-cost shielding

Courtesy of Chomerics, www.chomerics.com

Thin metal sheet material could be an alternative

Figure 4BU Example of the use of metallised paper

Conductive fabrics are made in a similar way, except that the metallised fibres are longer and are twisted into threads and then woven to create a fabric. Conductive fabrics are often used to make shielded tents, as shown in Figure 4BV, which have the advantage of light weight and portability because they can be folded for transport. Where a product needs to be shielded and the appearance of the shielding does not matter, for example a missile during transport, or a mobile phone that has been seized by police or security forces, metallised fabrics are often very appropriate materials.

Figure 4BV Example of a shielded tent made from metallised fabrics

Compared with metal, metallised papers and fabrics have lower conductivity, and so have lower values of reflectivity and absorption.

4.7.4 Paints and lacquers

Non-conductive paints and lacquers do not reduce the reflectivity of a metal surface. But they can create SE problems by overspraying onto areas where they increase the impedance of RF-bonds. Painting is often a manual process, so overspray can vary as can the degree of skill used to mask off critical areas. Changes in painting methods or technology can affect overspray, so where masking was not previously required, new painting techniques might make it essential, to maintain the desired SE.

One solution that avoids having to control the painting process is to use special metal tapes with a masking tape layer on top, that affix to the metal surface with a conductive pressure-sensitive adhesive, available from 3M and others. Before the metal is painted, the tape is stuck onto the areas where the gaskets must make contact. After painting, the masking tape layer is peeled off to reveal the bright shiny metal tape. The metal under the tape is protected from oxidation and corrosion by the conductive glue.

Conductive paints and epoxies consist of a binding agent and conductive filler. They have a lower conductivity than metal, so have lower reflectivity. Silver-loaded epoxy is sometimes used to reduce corrosion, and although its reflectivity is not as good as the metal when it is new, it will probably be better than if it was allowed to corrode.

4.7.5 Painted or plated plastics

Plastics can be conductively coated by painting with conductive paints (see 4.7.4); flame spraying; thermo spraying; plasma flame spraying; or electroless plating (a chemical deposition process). Suitable materials include graphite; silver; copper; and nickel, but they do not usually achieve the same conductivity as their bulk materials. Conductive paints require much thicker layers for their SE to compare with metallised finishes, because they are mostly binding agent so have low conductivity.

The most important issue with conductively-coating plastics is to ensure that the coating remains firmly stuck to the plastic over at least the intended operational lifetime. Different types of plastics require different coating materials and coating processes, and flaking or peeling conductive films can compromise reliability, and even increase safety risks. Accelerated lifecycle tests are strongly recommended to ensure that the conductive coatings don’t crack or flake off over the anticipated life of the product despite its environmental exposure (temperature, condensation, salt spray, etc.).

A problem with some conductive coatings, especially paints, is that they can flake off if sufficient mechanical pressure is applied, or rub off due to friction.

Metallised coatings are very thin, so have poor absorption at frequencies below a few hundred MHz, Nickel is often used to improve absorption at low frequencies, because it is ferromagnetic. But despite the shortcomings of painting or plating plastics, the SE of an enclosure made from such materials is usually limited by apertures and conductor penetrations, just as for enclosure made of solid metals.

See 4.3 in [20] for the basic issues of shielding, which apply equally to the conductive coatings on shielded plastic enclosures.

It can be difficult to get good RF bonds between the conductive surfaces of a plated or conductively-painted plastic enclosure – especially if the coating was a retro-fit to an existing enclosure that was not originally designed to be shielded. Figure 4BW shows the typical problem. The parts to be RF-bonded have been conductively coated on their inside surfaces, but these do not come into contact when assembled – creating an aperture in the shield.

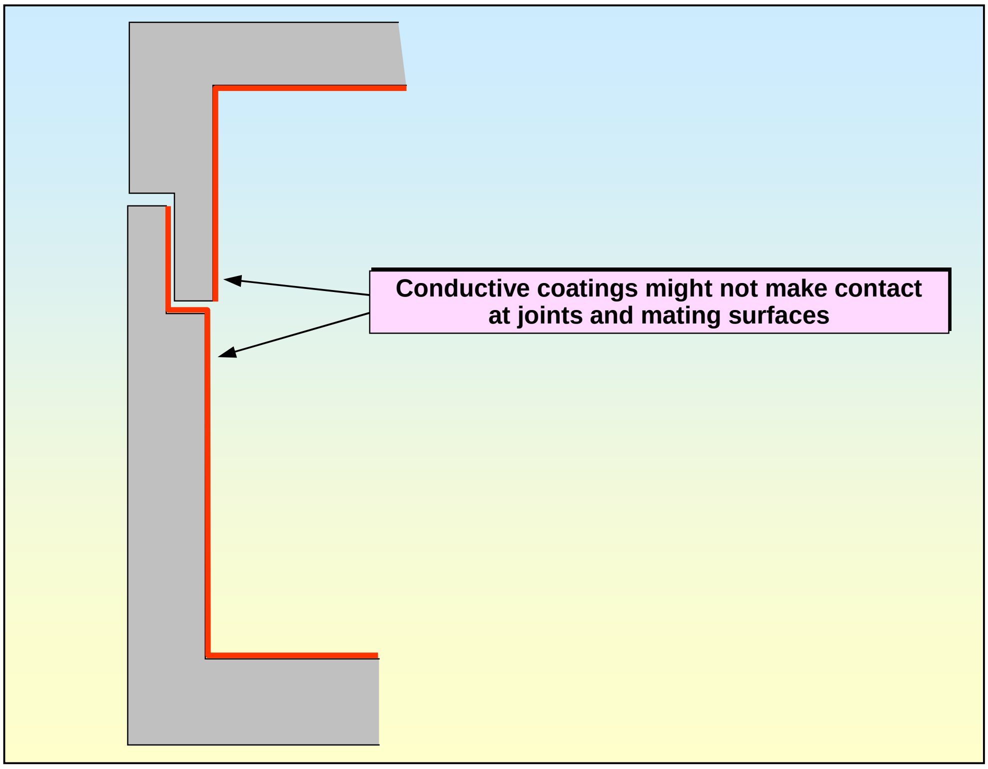


Figure 4BW A typical problem with RF-bonding coated plastic enclosures

Even where the conductive coatings wrap around the joints, contact never occurs along the full length of the seam – just as with metal parts, contact only occurs at a few 'high spots'. Temperature variations could even cause the contact points to move, changing the size of the shield apertures and making enclosure SE unpredictable.

One way of dealing with this problem is to design shielded plastic enclosures with 'built-in' plastic spring fingers. When conductively-coated, these can make good RF-bonds to their mating part's shielding surface.

Conductive gaskets can be used at seams and joints, as described for metal enclosures above – but the lower Young's modulus of plastics means that achieving the compressive forces they require, without causing mechanical distortion, is more difficult. However, it is possible to design so that gaskets can be used successfully – although it may be very costly to retrofit such design characteristics. So – where it is possible that a plastic enclosure might need to be shielded using a conductive coating – it is strongly recommended to design it from the first with the necessary 'built-in' spring fingers or fixings suitable for conductive gaskets.

Prototypes usually use conductive coatings that are hand-applied, and their quality and thickness will vary depending on the skill of the operator. Where manual application is used in serial manufacture, less care might be used, and the SE suffer. Automatic coating processes should give better repeatability, but where it is used the final EMC testing should be done on products that have used the automatic process, because the results can be very different from the hand-applied coatings on prototypes.

As well as an internal conductive coating, an additional external conductive coating can improve the SE of a plastic enclosure. Conductively coating all sides of plastic parts can also help overcome the problems with RF-bonding sketched in Figure 4BW. The external coating could be overpainted with something more aesthetically pleasing, as long as overspray did not compromise any RF bonds.

Care should be taken, when retrofitting shielding to a plastic enclosure by adding conductive coatings, not to increase safety risks by decreasing creepage distances and clearances. It often happens that immunity to electrostatic discharge (ESD) is compromised, because air-discharge can be more likely to occur due to the conductive coatings.

4.7.6 Shielding with volume-conductive plastics

Volume-conductive plastics or resins generally use distributed conductive particles or threads in an insulating binder that provides the mechanical strength. Typical conductive fillers include: carbon fibres; carbon black; metal-coated glass beads; nickel coated carbon fibres; and stainless steel fibres.

They often suffer from a ‘skin’ of the basic plastic or resin that forms over the surfaces, making it difficult to achieve good RF bonds without machining the surface, using helicoil inserts or similar methods. This insulating skin makes it difficult to prevent long apertures being created at joints, and also makes it difficult to provide good bonds to the bodies of connectors, glands, and filters.

Other problems include the consistency of mixing the conductive particles in the polymer or resin, which can make enclosures weak in some areas (too much conductive filler), and lacking in shielding in others (too little conductive filler). This is especially a problem at corners, which tend to suffer form too little filler.

Materials based on carbon fibres (which are themselves conductive) and self-conductive polymers are starting to become available, but they do not have the high conductivity of metal and so do not give as good an SE for a given thickness.

The conductivity of conductive plastics is generally much lower than that of bulk material of the filler, so reflectivity and absorption are both reduced.

The low conductivity of many conductive plastic coatings, and volume-conductive plastics, prevents them from being able to handle high fault currents or high levels of surge currents from lightning. These high current events generate significant heat, which damages the materials.

4.7.7 Alternatives to shielding plastic enclosures

Because of the Waste Electrical and Electronic Equipment in the Environment directive (2002/96/EC) conductively-coated or volume-conductive plastic parts are falling out of favour, because they are so difficult to recycle. Instead, products are increasingly being designed using PCB-level shielding (see 4.4).

Another alterative technique that is often employed is to fit a thin metal (or metallised card or plastic) shielding box within the plastic box, but around all the electronics. This metal box does not have to look nice, or provide any mechanical support – so it can be low-cost. Retrofitting such a box to an existing design is often very difficult indeed, if it is even possible. If such an internal shielding box might possibly be required – it is strongly recommended to design the product so that the box can be fitted later in the project, if found to be necessary.

Magnesium (or zinc) alloy castings can be used instead of plastic mouldings, and of course are much easier to use as shields and more easily recycled. Magnesium alloys can be as light as plastic for greater strength, or thinner and lighter for the same strength, but they cost more – so tend to be used for improving ruggedness, reducing size and weight, or for fashionable items.

4.7.8 Environmental considerations

Two European Directives concerning the protection of the environment (known as WEEE and RoHS) are now in force in the European Union. These directives will influence the type of shielding used, and the materials used in their construction, as has already been mentioned in 4.7.7 and other sections above. The volatile chemicals used in some conductive coating and electro-plating processes have a negative environmental impact, and these processes tend to make the coated materials difficult to recycle [38].

Chromate passivation using hexavalent chromium (‘Chrome 6’ or ‘Hex-Cr’) has been a marvellous technique for decades, but when Hex-Cr gets into water supplies very serious cancer outbreaks can occur. There are no direct replacements for surface treatment with Hex-Cr that provide all of its good properties on all metals (but without the cancer risks), but for specific applications/metals there are replacement coatings that can be as good, maybe even better on some tests [43]. The US Military has developed a trivalent chromium coating called TCP for aluminium, which is also effective on some other metals, and is available commercially. TCP applied to zinc-plated steel also looks promising.

Vacuum metallisation is ‘eco-friendly’, and tin and aluminium are non-toxic and easy to recycle - so vacuum-metallised plastic shielding-cans that are pressed, clipped or soldered into place may have fewer environmental disadvantages than conductively-coating the plastic enclosures themselves, or using volume-conductive plastics. [25] describes how thermo-formed shielding inserts can aid the recycling of plastic enclosures, and [29] describes how surface-mounted metal cans are easy to remove and recycle.

4.7.9 Preventing corrosion

Corrosion replaces metals with oxides, sulphides, chlorides, etc., increasing the resistance at RF bonds and reducing SE. Corrosion products are bulkier than their original metal, so tend to force joints apart, opening up apertures and reducing SE.

Some corrosion products behave as semi-conductors (non-linear resistance), which can generate harmonics of any AC flowing through them. They can also demodulate RF waveforms, and can intermodulate two or more AC signals creating new frequencies at their sum and difference frequencies. These can add to emissions, or cause immunity problems. Corrosion in connectors, antennas and grounding structures is especially a problem for RF transmitters, which have tight specifications on their harmonic and spurious emissions so as not to interfere with other radio frequencies.

Gases such as oxygen, sulphur dioxide or similar pollutants are usually dealt with by plating with a less reactive metal (e.g. zinc plating on steel) or a number of other surface treatments, discussed earlier. Multipoint RF-bonding using small, hard, contact points can generate pressures that are so high that cold-welding occurs, creating a small but gas-tight bond that is less susceptible to corrosion from gasses. Star washers are often used for this purpose, but – as mentioned in the section on spring fingers - RF bonds at higher frequencies benefit from area contacts instead of points.

Liquids that bridge joints between dissimilar metals can cause very rapid corrosion due to the galvanic effect. Environmental sealing gaskets can help keep certain gases and liquids away from a joint, but it is also good practice to use similar metals in contact, because condensation can occur inside an equipment (unless anti-condensation heaters are used).

Corrosion is most likely when dissimilar metals are in close proximity, or in contact, in the presence of electrolytes such as water (e.g. condensation), beer, food and drink, jet fuel, blood or tissue fluids, or a variety of other liquids. Two different metals plus an electrolyte creates an ‘accidental battery’, and current will flow from the cathode to the anode all the time the liquid bridges between the two metals. The anodic end of the accidental battery (the most positive in galvanic potential) has its metal turned into corrosion products, whereas the cathodic end (the most negative) is hardly affected at all.

Metals can be divided into a number of groups according to their galvanic potential, and five typical groups, with approximately 0.3V range within each group, are shown below….

Group 1	*(Most anodic)* magnesium, and magnesium alloys
Group 2	Aluminium and its alloys, cadmium, galvanised steel, and zinc
Group 3	Tin, tin-lead solder, lead, duralumin alloys, iron, and low alloy steels
Group 4	Nickel, monel, copper, brass, bronze, stainless steels, chromium, chrome steels
Group 5	*(Most cathodic)* silver, gold, platinum, graphite, and titanium

Monel (in Group 4) is often claimed to be a metal that does not corrode, and is often used in conductive gaskets. It does not oxidise readily in the air, but has no special resistance to galvanic corrosion.

Figure 4BX shows the recommended relationships in [41] between the groups the joint metals come from, the environment the joint is in, and the additional protective measures (like grease or painting). ‘Protected’ means indoors, inside a housing, not exposed to liquids and free from condensation almost all of the time.

Dissimilar metals can be plated to reduce their galvanic effect, for example tin-plated copper is a better partner for aluminium than copper would be. When plated, the dissimilar metal joint is protected from any liquids, so will not experience galvanic corrosion. However, scratches or pinholes in the plating can expose the underlying metal so the plating must be thick enough for the expected mechanical stresses, and also of sufficient quality.

AC or DC current through a dissimilar metal joint hastens galvanic corrosion, even when a liquid is not present to act as an electrolyte (this is why car battery terminals are always kept very heavily greased). So it is best to use metals that are in the same group, or the same metal, where currents could be significant. Plating dissimilar metals with the same metal is a good way to prevent galvanic corrosion, for example tin-plated aluminium with tin-plated copper, as long as the plated surfaces are robust enough and don’t have pinholes.

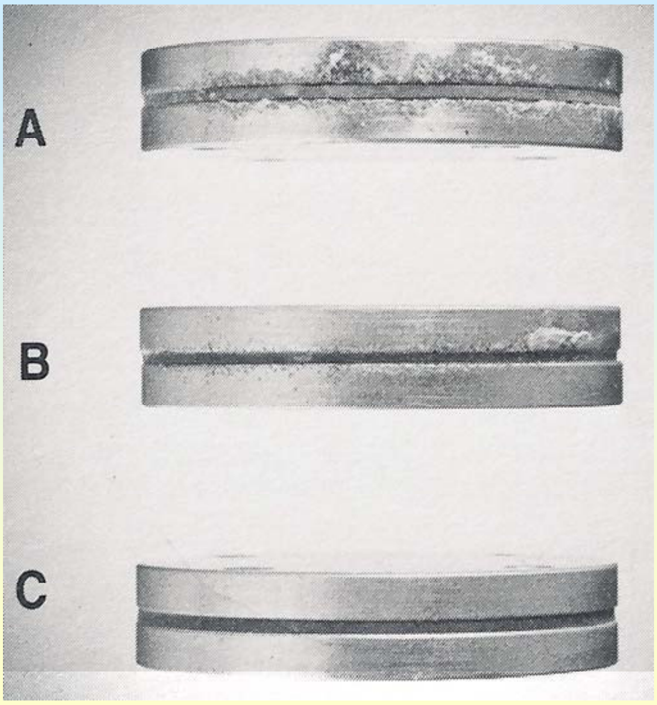
Appendix E of [45] has a great deal of useful information and design guides on preventing corrosion, and a wealth of references for further study.

Exposure situation	Anodic end (most heavily corroded)				Cathodic end
	Group 1	Group 2	Group 3	Group 4	
Exposed	**B**	**A**	**n/a**	**n/a**	**Group 2**
Sheltered	**A**	**A**	**n/a**	**n/a**	**Group 2**
Protected	**A**	**A**	**n/a**	**n/a**	**Group 2**
Exposed	**C**	**B**	**A**	**n/a**	**Group 3**
Sheltered	**C**	**A**	**A**	**n/a**	**Group 3**
Protected	**B**	**A**	**A**	**n/a**	**Group 3**
Exposed	**No**	**C**	**B**	**A**	**Group 4**
Sheltered	**C**	**B**	**A**	**A**	**Group 4**
Protected	**C**	**A**	**A**	**A**	**Group 4**
Exposed	**No**	**No**	**C**	**B**	**Group 5**
Sheltered	**No**	**B**	**B**	**A**	**Group 5**
Protected	**C**	**B**	**A**	**A**	**Group 5**

KEY: No = Do not use this combination
A = Metal may be exposed at junction surfaces
B = Coating *must* prevent any possibility of liquid bridging the join
C = Protective coatings mandatory, but joint may still have a short life

Figure 4BX Corrosion prevention guidance from NAVAIR AD 115 [44]

As mentioned in 4.6, conductive gaskets must also be galvanically compatible with the material they are in contact with, for enclosure SE to be maintained reasonably well over the life of the equipment. Figure 4BY shows the effect of a standard 144 hour salt spray test on two aluminium discs separated by three different kinds of gasket. The least suitable gasket was sample A, whilst the best was sample C. Even though a joint might not have to weather salt spray, 144 hours is not a long time, so this test is an indication of how well a joint might last in more normal environments over a period of years.



After a 144-hour salt spray accelerated life test…

Gasket material A had very poor shielding effectiveness (SE)

B had poor SE

But gasket material C had almost no change in its SE

Courtesy of Chomerics
www.chomerics.com

Figure 4BY Example of a corrosion test on three different gaskets

Good gasket manufacturers should be able to supply a wealth of test data on the compatibility of their products with different metals.

There are modern corrosion protection materials that might prove useful, such as ‘vapour-phase corrosion inhibition’ (visit www.cortecVpCI.com). I have no experience of this technique, but understand that this is based on pellets of a solid material that slowly sublime, coating everything nearby with a molecular layer that is a barrier to gasses and liquids, but is easily displaced by mechanical pressure, for example at an RF bond.

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