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Design Techniques for EMC Part 4: Shielding

Helping you solve your EMC problems

9 Bracken View, Brocton, Stafford ST17 0TF T:+44 (0) 1785 660247 E:info@emcstandards.co.uk

Design Techniques for EMC
Part 4: Shielding

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Eur Ing Keith Armstrong CEng MIET MIEEE ACGI BSc(hons)
Partner, Cherry Clough Consultants, www.cherryclough.com, Associate of EMC-UK
Phone & fax: (+44) (0)1785 660247, Email: keith.armstrong@cherryclough.com

This is the fourth in a series of six articles on best-practice EMC techniques in electrical/electronic/mechanical hardware design. The series is intended for the designer of electronic products, from building block units such as power supplies, single-board computers, and "industrial components" such as motor drives, through to stand-alone or networked products such computers, audio/video/TV, instruments, etc.

The techniques covered in the six articles are:

1) Circuit design (digital, analogue, switch-mode, communications), and choosing components
2) Cables and connectors
3) Filters and transient suppressors
4) **Shielding**
5) PCB layout (including transmission lines)
6) ESD, electromechanical devices, and power factor correction

A textbook could be written about any one of the above topics (and many have), so this magazine article format can only introduce the various issues and point to the most important best-practice techniques. Many of the techniques described in this series are also important for improving signal integrity: reducing the number of iterations during development and reducing manufacturing costs.

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4. Shielding

4.1 Shielding and the commercial imperative

A complete volumetric shield is often known as a "Faraday Cage", although this can give the impression that a cage full of holes (like Mr Faraday's original) is acceptable, which it generally isn't.

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

- Individual ICs example cost 25p
- Segregated areas of PCB circuitry example cost £1
- Whole PCBs example cost £10
- Sub-assemblies and modules example cost £15
- Complete products example cost £100
- Assemblies (e.g. industrial control and instrumentation cubicles) example cost £1,000
- Rooms example cost £10,000
- Buildings example cost £100,000

Please don't take these example costs as more than a very rough guide to orders of magnitude for domestic, commercial and industrial products. For example the shielding used in the new MI6 building in London will have cost very much more than £100,000, and that used on a flight-critical avionics computer will cost a lot more than £100. These costs do not take account of the re-engineering costs of adding shielding late in a project, which can be very much greater. They also don't take account of the lost sales and market position that can result from delays caused by shield re-engineering late in a project.

The important point is that shielding can be very low cost if it is designed-in carefully from the start, but can be extremely expensive indeed if it has to be applied at the last minute to make a product acceptable to a customer (or to an EMC enforcement agent).

Shielding always adds cost and weight, so it is always best to use the other techniques described in this series to improve EMC and reduce the need for shielding. Even where it is hoped to avoid shielding altogether it is best to allow for Murphy's Law and design from the start so that shielding can be added later if necessary. Mr Murphy can usually be discouraged from upsetting your product rollout if you have a variety of shielding (and filtering) solutions ready to be dropped in when you first test your new product for EMC.

A degree of shielding can also be achieved by keeping all conductors and components very close to a solid metal sheet. Ground-planed PCBs populated entirely by low-profile surface mounted devices are therefore recommended for their EMC advantages. Even though such PCBs may require additional enclosure (volumetric) shielding, it should not need to have as high a shielding effectiveness (SE) and so will be easier to make and cost less.

A useful degree of shielding can be achieved in electronic assemblies by keeping their internal electronic units and cables very close to an earthed metal surface at all times, and bonding their earths directly to it instead of (or as well as) using a safety star earthing system based on green/yellow wires. This technique usually uses zinc-plated mounting plates or chassis, and can help avoid the need for high values of enclosure SE.

4.2 General concepts in shielding

Many textbooks have been written on the subject of how shields work, and it is not intended to repeat them here. However, a few broad concepts will help. A shield puts an impedance discontinuity in the path of a propagating radiated electromagnetic 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 signal. The greater the impedance ratio, the greater the SE.

At thicknesses of 0.5mm or over, most normal fabrication metals provide good SE above 1MHz and excellent SE above 100MHz. Problems with metal shields are mostly caused by thin materials, frequencies below 1MHz, and apertures, and this article focuses mainly on these.

4.3 Bigger and rectangular is better

It is generally best to allow a large distance between the circuits being shielded and the walls of their shield. The emitted fields outside the shield, and the fields that the devices are subjected to, will generally be more "diluted" the larger the shielded volume. This advice generally raises hollow laughter, since most product design seems to be about fitting a quart into a pint pot.

Where enclosures have parallel walls opposite each other standing waves can build up at resonant frequencies, and these can cause SE problems. Irregular shaped enclosures, or ones with curved or non-parallel walls (more hollow laughter) will help prevent resonances. Where opposing shield walls are parallel, try to prevent the resonances due to the width, height, or length from occurring at the same frequencies. So avoid cubic enclosures, use rectangular cross-sections instead of square, and try to avoid dimensions that are simple multiples of each other. E.g. if the length is 1.5 times the width, the second resonance of the width coincides with the third resonance of the length. Best to use irrationally ratio'd dimensions, such as that provided by the venerable Fibonacci series (which the Greeks knew as the Golden Mean). It is probably not worth worrying *too* much about this because the internal PCBs, components, and wiring alter its resonances unpredictably anyway.

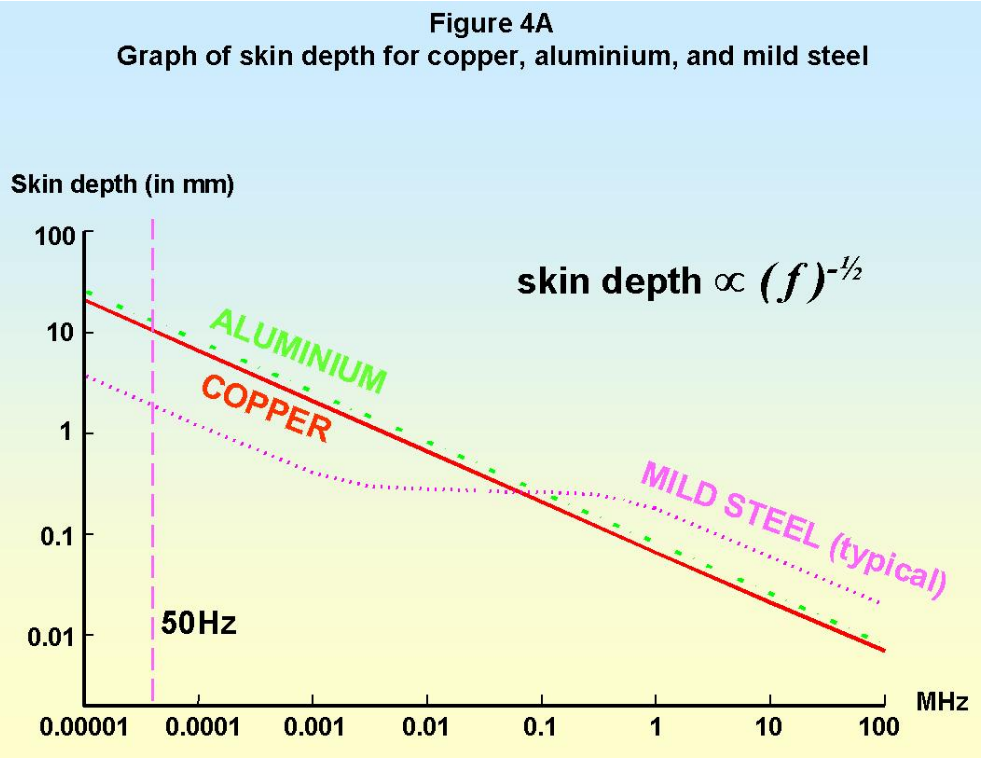
4.4 Skin effect

Fields come in two flavours: electric (E) and magnetic (M). Electromagnetic fields consist of E and M fields in a given ratio (giving a wave impedance E/M of 377Ω in air). Electric fields are easily stopped by thin metal foils, since the mechanism for electric field shielding is one of charge re-distribution at a conductive boundary, so almost anything with a high conductivity (low resistance) will present a suitably low impedance. At high frequencies quite considerable displacement currents can result from the rapid rate of charge re-distribution, but even thin aluminium can cope with this quite nicely.

However, magnetic fields are much more difficult to stop. They need to generate eddy currents inside the shield material to create magnetic fields that oppose the impinging field. Thin aluminium is not going to be very suitable for this purpose, and the depth of current penetration required for a given SE depends on the frequency of the field, and on the characteristics of the metal used for the shield, and is known as the "skin effect".

One skin depth is the depth in the shield material at which the "skin effect" causes the currents caused by the impinging magnetic field to be reduced by approximately 9dB. So a material which was as thick as 3 skin depths would have an approximately 27dB lower current on its opposite side and have an SE of approximately 27dB for that M field.

Skin effect is especially important at low frequencies, where the fields experienced are more likely to be predominantly magnetic with a lower wave impedance than 377Ω. The formula for skin depth is given in most textbooks, but requires knowledge of the shielding material's conductivity and relative permeability. Figure 4A solves this for aluminium and steel, with copper thrown in for comparison. Pure zinc will have skin depths close to those of aluminium.



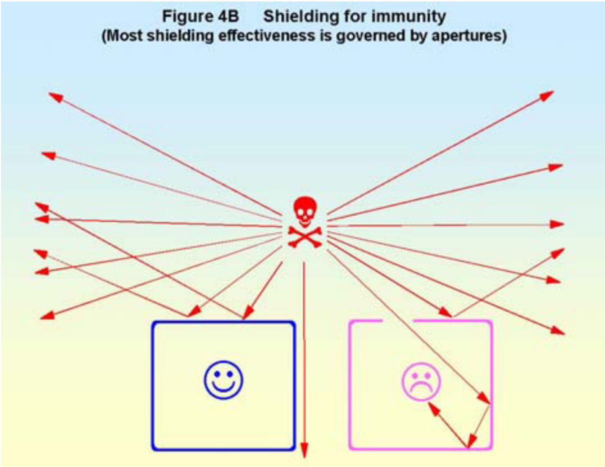
Copper and aluminium have over 5 times the conductivity of steel, so are very good at stopping electric fields, but have a relative permeability of 1 (the same as air). Typical mild steel has a relative permeability of around 300 at low frequencies, falling to 1 as frequencies increase above 100kHz, and its higher permeability gives it a reduced skin depth, making reasonable thicknesses of mild steel better than aluminium for shielding low frequencies. Different grades of steels (especially stainless) have different conductivities and permeabilities, and their skin depths will vary considerably as a result.

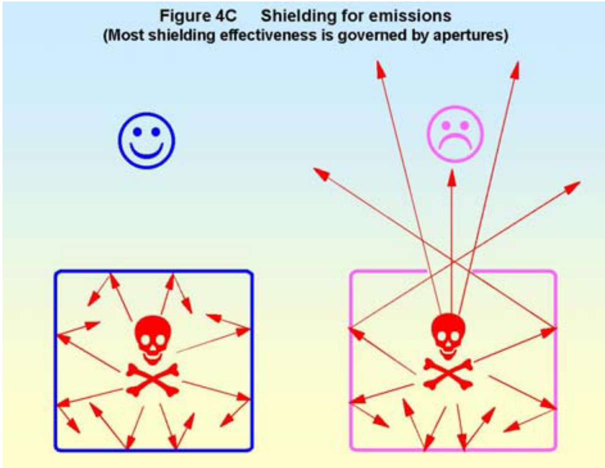
A good material for a shield will have high conductivity and high permeability, and sufficient thickness to achieve the required number of skin-depths at the lowest frequency of concern. 1mm thick mild steel plated with pure zinc (say, 10 microns or more) is just fine for many applications.

4.5 Apertures

It is easy to achieve SE figures of 100dB or more at frequencies above 30MHz with ordinary constructional metalwork. But this assumes a perfectly enclosing shield volume with no joints or gaps, which makes assembly of the product rather difficult unless you are prepared to seam-weld it all around and also have no external cables, antennae, or sensors (rather an unusual product).

In practice, whether shielding is being done to reduce emissions or improve immunity, most shield performance is limited by the apertures in it, as these two simple Figures 4B and 4C try to show.



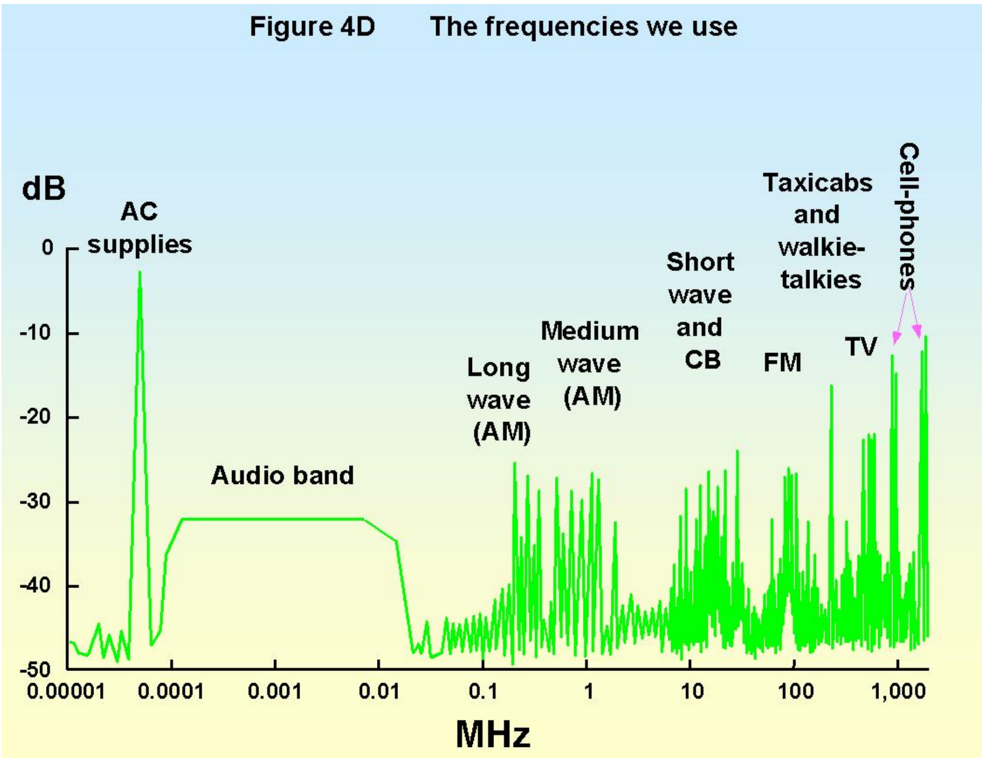


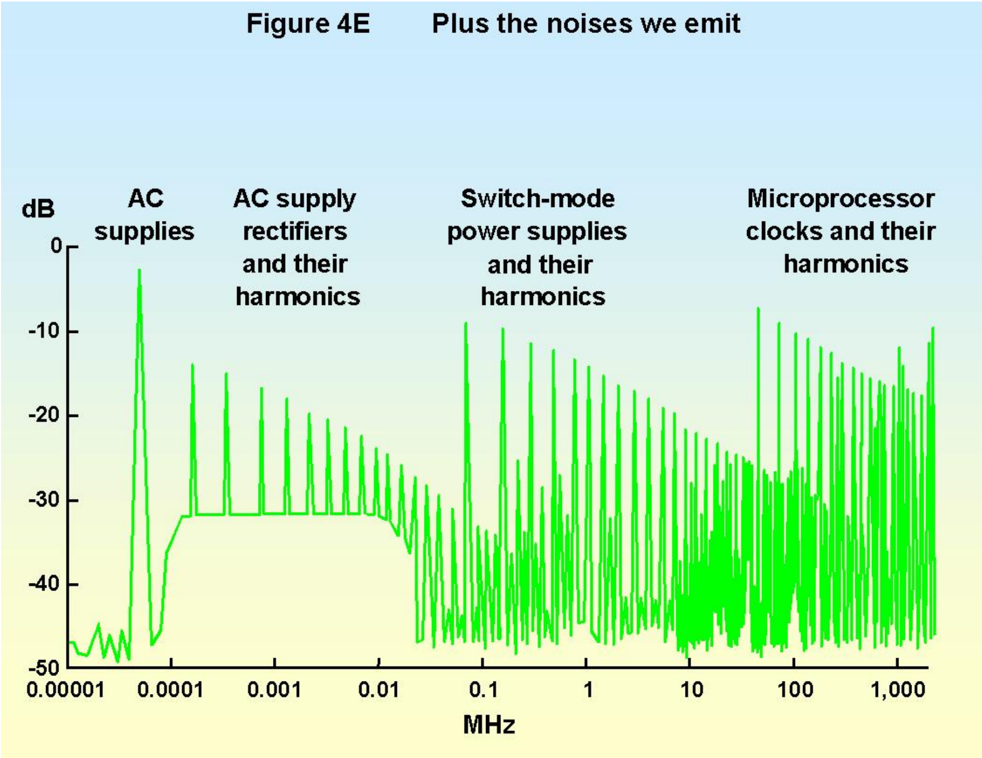
Considering apertures as holes in an otherwise perfect shield implies that they act as half-wave resonant “slot antennae”, and this allows us to make predictions about maximum aperture sizes for a given SE: for a single aperture, SE = 20log(λ/2d) where λ is the wavelength at the frequency of interest and d is the longest dimension of the aperture. In practice this assumption may not always be accurate, but it has the virtue of being an easy design tool that is better than doing nothing. Where its predications found to be are inaccurate it may be possible to refine it following practical experiences with the technologies and construction methods used on specific products.

The resonant frequency of a slot antenna is governed by its longest dimension – its diagonal. It makes little difference how wide or narrow an aperture is, or even whether there is a line-of-sight through the aperture.

Even apertures the thickness of a paint or oxide film, formed by overlapping metal sheets, still radiate (leak) at their resonant frequency as well as if they were wide enough to poke a finger through.

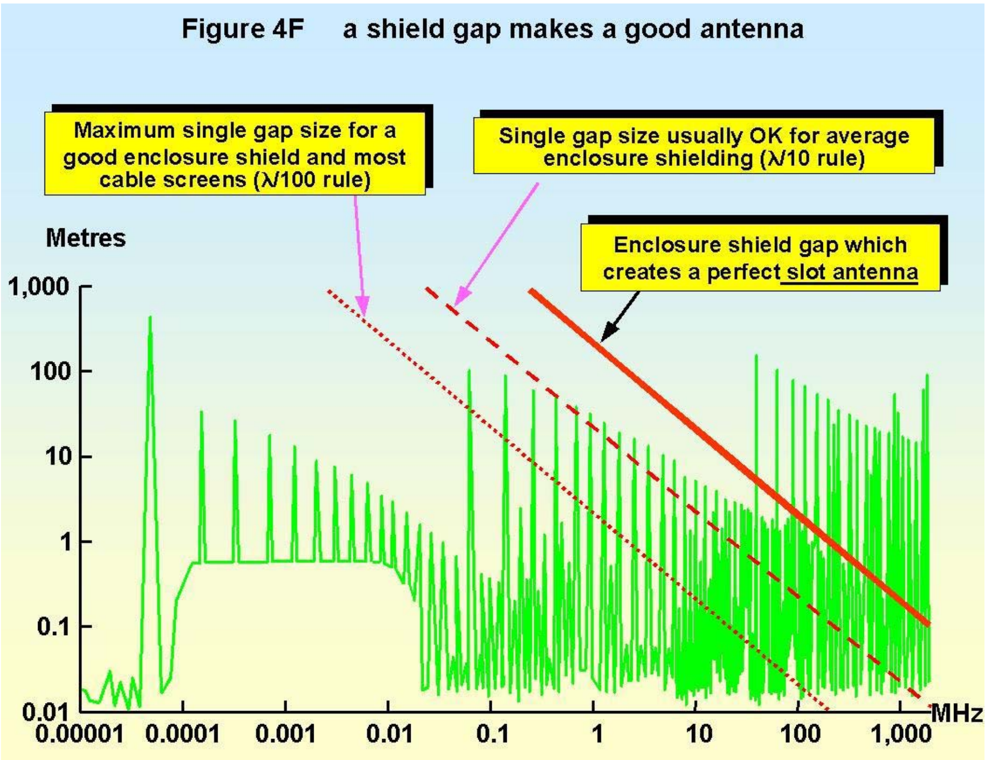
Figures 4D and 4E have been used before in this series to try to give a feel for the fact that the frequencies inside modern electronic products use the same range of frequencies as we rely on for communications and broadcasting.





One of the most important EMC issues is keeping the products' internal frequencies inside, so they don't pollute the radio spectrum outside.

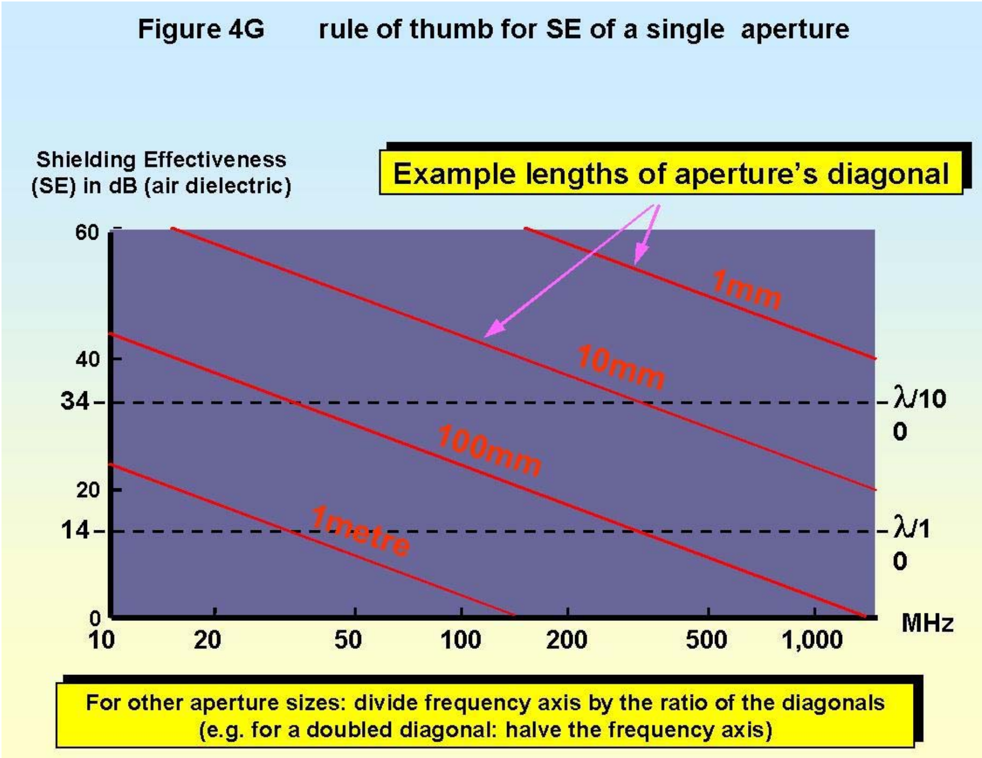
Figure 4F shows how effective apertures in shields can be at behaving like antennas and allowing the internal frequencies to disturb the radio spectrum and cause interference.



The half-wave resonance of slot antennae (expressed in the above rule of thumb: SE = 20log(λ/2d)) is the basis for the solid line in Figure 4F (and for the rule-of-thumb of Figure 4G) using the relationship $v = f\lambda$ (where v is the speed of light: 3.10^8 metres/sec, f is the frequency in Hz, and λ is the wavelength in metres).

We find that a narrow 430mm long gap along the front edge of a 19-inch rack unit's front panel will be half-wave resonant at around 350MHz. At this frequency our example 19-inch front panel is no longer providing much shielding, and removing it entirely might not make much difference.

Figure 4G is useful when estimating the maximum size of an aperture for a given SE, and may be easily scaled to suit different dimensions.



For an SE of 20dB at 1GHz (the present upper limit of testing in most standards) Figure 4G suggests an aperture no larger than around 16mm. For 40dB this would be only 1.6 mm, requiring gaskets to seal apertures and/or the use of the waveguide below cutoff techniques described later.

Actual SE in practice will depend on internal resonances between the walls of the enclosure itself, the proximity of components and conductors to apertures (keep noisy cables such as ribbon cables carrying digital busses well away from shield apertures and joints), the impedances of the fixings used to assemble the parts of the enclosure, etc.

Wherever possible, break all necessary or unavoidable apertures into a number of smaller ones. Unavoidably long apertures (covers, doors, etc) may need conductive gaskets or spring fingers (or other means of maintaining shield continuity). The SE of a number of small identical apertures nearby each other is (roughly) proportional to their number ($\Delta SE = 20\log n$, where n is the number of apertures), so two apertures will be worse by 6dB, four by 12dB, eight by 18dB, and so on. But when the wavelength at the frequency of concern starts to become comparable with the overall size of the array of small apertures, or when apertures are not near to each other (compared with the wavelength), this crude '6dB per doubling' rule breaks down because of phase cancellation effects. However, at least this simple rule errs on the side of caution.

Apertures placed more than half a wavelength apart do not in general worsen the SEs that each achieves individually, but half a wavelength at 100MHz is 1.5 metres, so at such low frequencies on typical products smaller than this an increased number of apertures will tend to worsen the enclosure's SE.

Apertures don't merely behave as slot antennae. Currents flowing in a shield and forced to divert their path around an aperture will cause it to emit magnetic fields. Voltage differences across an aperture will cause the aperture to emit electric fields. The author has seen dramatic levels of emissions at 130MHz from a hole no more than 4mm in diameter (intended for a click-in plastic mounting pillar) in a small PCB-mounted shield over a microcontroller. Figure 4G implies quite a good SE at that frequency from a 4mm hole, but the emissions from a particularly noisy microcontroller were causing significant currents to flow in the shielding can, and it appeared to be these that were causing the emissions, not the hole's antenna effect. Where long narrow apertures are concerned, it is sometimes possible to reduce such emissions by orienting the aperture's longer dimension appropriately with respect to the internal circuitry.

But be warned that the suggestions given are very very approximate and often confounded by proximity of cables, heavy loop currents flowing in the enclosure, etc., etc.

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 you will be able to find a university or design consultancy that has the necessary software and the skills to drive it.

If you don't want to do field-solving, your best bet for any reasonable accuracy is to mock-up the construction as best you can, 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.

Since SE will vary strongly with the method and quality of assembly, materials, and internal PCBs and cables, it is always best to allow yourself an SE 'safety margin' of 20dB, or at least design-in features that will allow you to improve the SE by at least 20dB if you have problems with the final design's verification/qualification testing.

4.6 Low frequency (magnetic field) shielding

The frequency of 50Hz is highlighted on Figure 4A, to show how difficult it is to achieve good SE at this frequency with any reasonable thickness of ordinary metals.

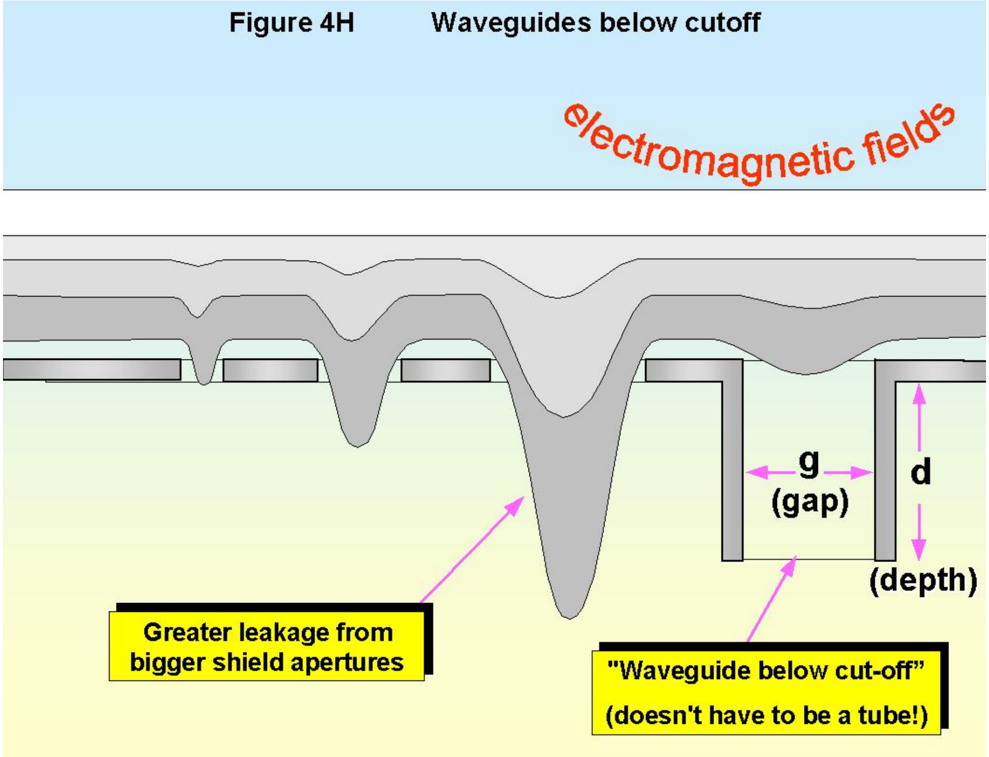
Special materials such as Mumetal and Radiometal have very high relative permeabilities, often in the region of 10,000. Their skin depth is correspondingly very small, but they are only effective up to a few tens of kHz. Care must be taken not to knock items made of these materials, as this ruins their permeability and they have to scrapped or else re-annealed in a hydrogen atmosphere. These exotic materials are used rather like channels to divert the magnetic fields away from the volume to be protected – a different concept to that used by ordinary shielding.

All metals shield materials with relative permeability greater than 1 can saturate in intense magnetic fields, and then don't work well as shields and often heat up. A steel or Mumetal shield box over a mains transformer to reduce its hum fields can saturate and fail to achieve the desired effect. Often, all that is necessary is to make the box larger so it does not experience such intense local fields.

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 magnetic fields.

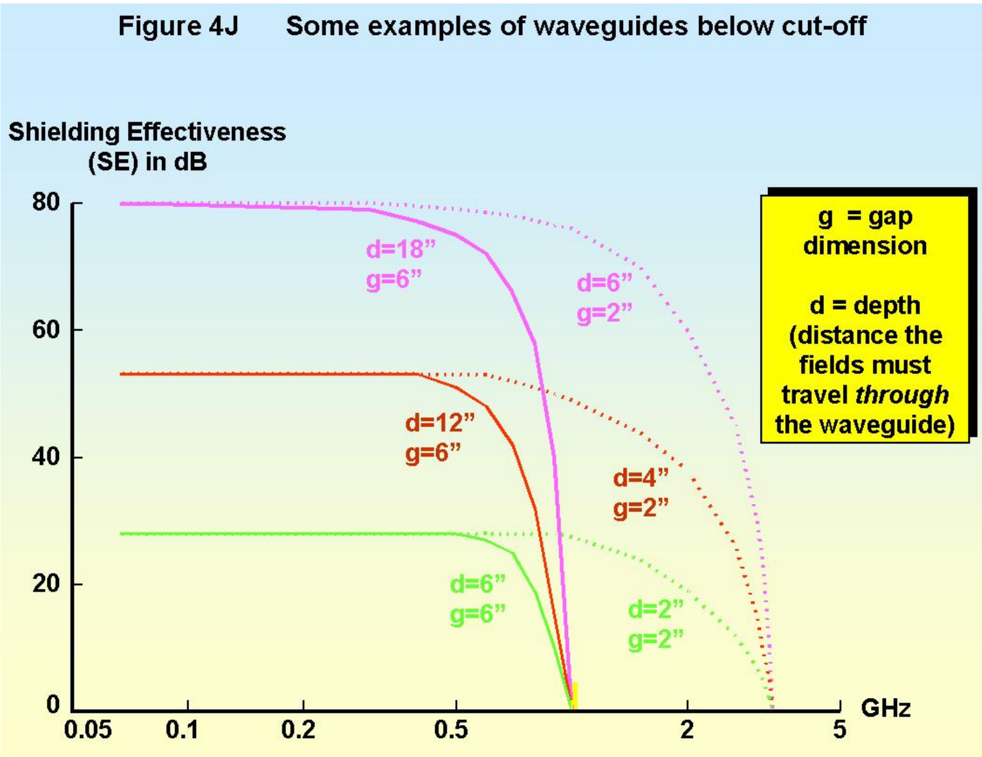
4.7 Waveguides below cutoff

Figure 4H shows that if we extend the distance that a wave leaking through an aperture has to travel between surrounding metal walls before it reaches freedom, we can achieve respectable SEs despite apertures large enough to put your fist through. This very powerful technique is called "waveguide below cutoff". Honeycomb metal constructions are really a number of waveguides below cutoff stacked side-by-side, and are often used as ventilation grilles for shielded rooms, and similar high-SE enclosures.



Like any aperture, a waveguide allows all its impinging fields to pass through when its internal diagonal (g) is half a wavelength, so the cutoff frequency of our waveguide is given by: f_{cutoff} = 150,000/g (answer in MHz when g is in mm). Below its cutoff frequency, a waveguide does not leak like an ordinary aperture (as shown by Figure 4H) and can provide a great deal of shielding: for $f < 0.5 f_{cutoff}$ SE is approximately 27d/g where d is the distance through the waveguide the wave has to travel before it is free.

Figure 4J shows examples of the SE achieved by six different sizes of waveguide below cutoff. Smaller diameter (g) results in a higher cutoff frequency, with a 50mm (2 inch) diameter achieving



full attenuation by 1GHz. Increased depth (d) results in increased SE, with very high values being readily achieved.

Waveguides below cutoff do not have to be made out of tubes, and can be realised using simple sheet metalwork which folds the depth (d) so as not to increase the size of the product by much. As a technique it is only limited by the imagination, but it must be taken into consideration early in a project as it is usually difficult to retrofit to a failing product not intended to use it.

Conductors should never be passed through waveguides below cutoff, as this compromises their effectiveness. Waveguides below cutoff can be usefully applied to plastic shafts (e.g. control knobs) so that they do not compromise SE where they exit an enclosure. The alternative is to use metal shafts with a circular conductive gasket and suffer the resulting friction and wear.

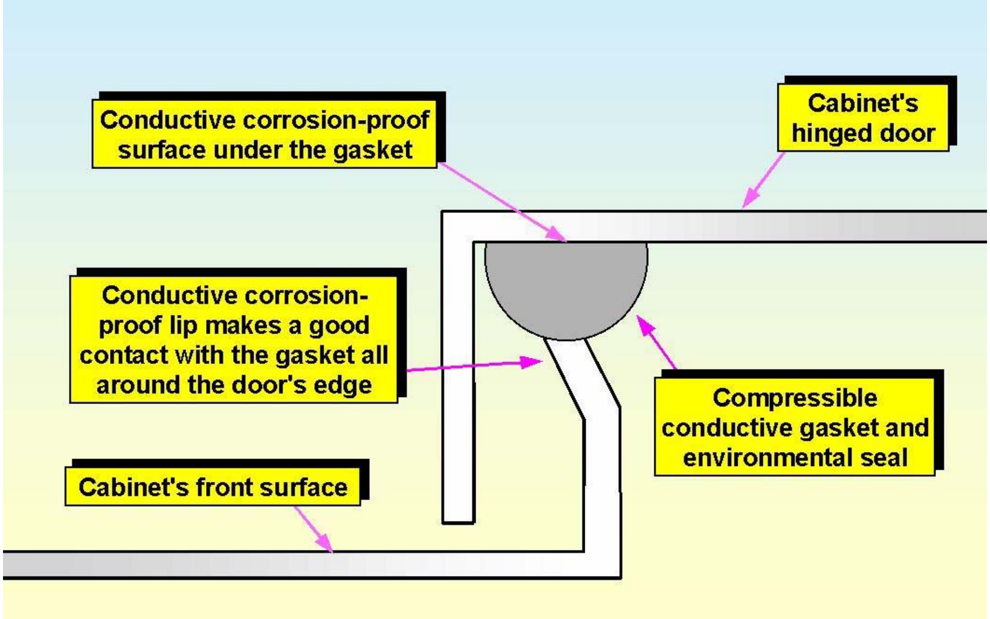
Waveguides below cutoff can avoid the need for continuous strips of gasket, and/or for multiple fixings, and thus save material costs and assembly times, but they appear to be rarely used: as a mechanical technique it is not of interest to electronic designers; and whoever saw a mechanical designer attend an EMC course?

4.8 Gasketting

Gaskets are used to prevent leaky apertures at joints, seams, doors and removable panels. For fit-and-forget assemblies gasket design is not too difficult, but doors, hatches, covers, and other removable panels create many problems for gaskets, as they must meet a number of conflicting mechanical and electrical requirements, not to mention chemical (to prevent corrosion). Shielding gaskets are sometimes required to be environmental seals too, adding to the compromise.

Figure 4K 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 often used in such applications too.

Figure 4K Bonding doors and removable panels on shielded cabinets
– example of door on industrial cabinet –
(horizontal cross-section viewed from above)



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 short wide earthing strap is used instead of a long wire.

A huge range of gasket types is available from a number of manufacturers, most of whom also offer customising services. This observation reveals that no one gasket is suitable for a wide range of applications. Considerations when designing or selecting gaskets include:

- Mechanical compliance
- Compression set
- Impedance over a wide range of frequencies
- Resistance to corrosion
  (low galvanic EMFs in relation to its mating materials, appropriate for the intended environment)
- Ability to withstand the expected rigours of normal use
- Shape and preparation of mounting surface
- Ease of assembly and dis-assembly
- Environmental sealing, smoke and fire requirements

There are four main types of shielding gaskets:

i. Conductive polymers (insulating polymers with metal particles in them). These double up as environmental seals, have low compression set but need significant contact pressure, making them difficult to use in manually opened doors without lever assistance.

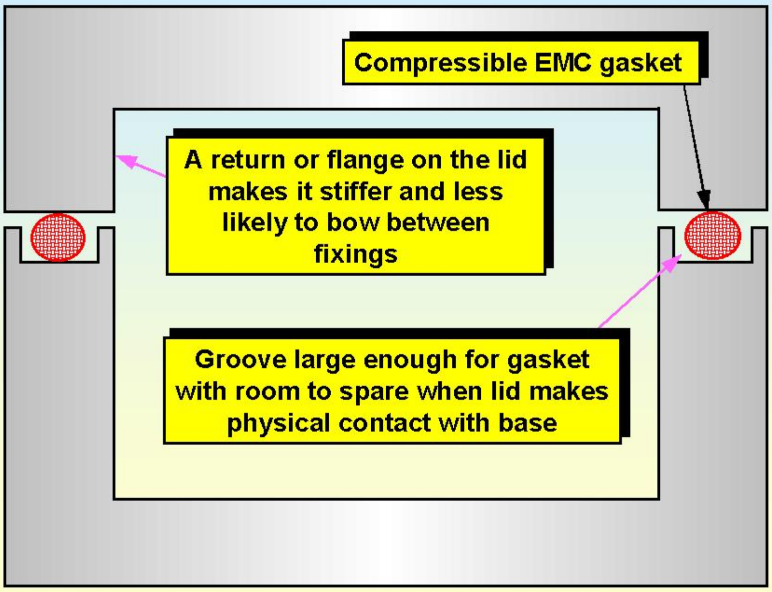
ii. Conductively wrapped polymers (polymer foam or tube with a conductive outer coating). These can be very soft and flexible, with low compression set and some only need low levels of contact pressure. However, they may not make the best environmental seals and their conductive layer may be vulnerable to wear.

iii. Metal meshes (random or knitted) are generally very stiff but match the impedance of metal enclosures better and so have better SEs than the above types. Poor environmental sealing performance, but some are now supplied bonded to an environmental seal, so that two types of gasket may be applied in one operation.

iv. Spring fingers ("finger stock"). Usually made of beryllium copper or stainless steel and can be very compliant. Their greatest use is on modules (and doors) that must be easy to manually extract (open), easy to insert (close), and which have high level of use. Their wiping contact action helps to achieve a good bond, and their impedance match to metal enclosures is good, but where they don't apply high pressures maintenance may be required (possibly a smear of petroleum jelly every few years). Spring fingers are also more vulnerable to accidental damage, such as getting caught in a coat sleeve and bending or snapping off. 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 can be seen on the doors of most EMC test chambers.

Gaskets need appropriate mechanical provisions made on the product to be effective and easy to assemble. Gaskets simply stuck on to a surface and squashed between mating parts may not work as well as was hoped – the more their assembly screws are tightened in an effort to compress the gasket and make a good seal the more the gaps between the fixings can bow, opening up leaky gaps. This is because of inadequate stiffness in the mating parts, and it is difficult to make the mating parts rigid enough without a groove for the gasket to be squashed into, as shown by Figure 4L. This groove also helps correctly position and retain the gasket during assembly.

Figure 4L Example of gasket mechanical provisions



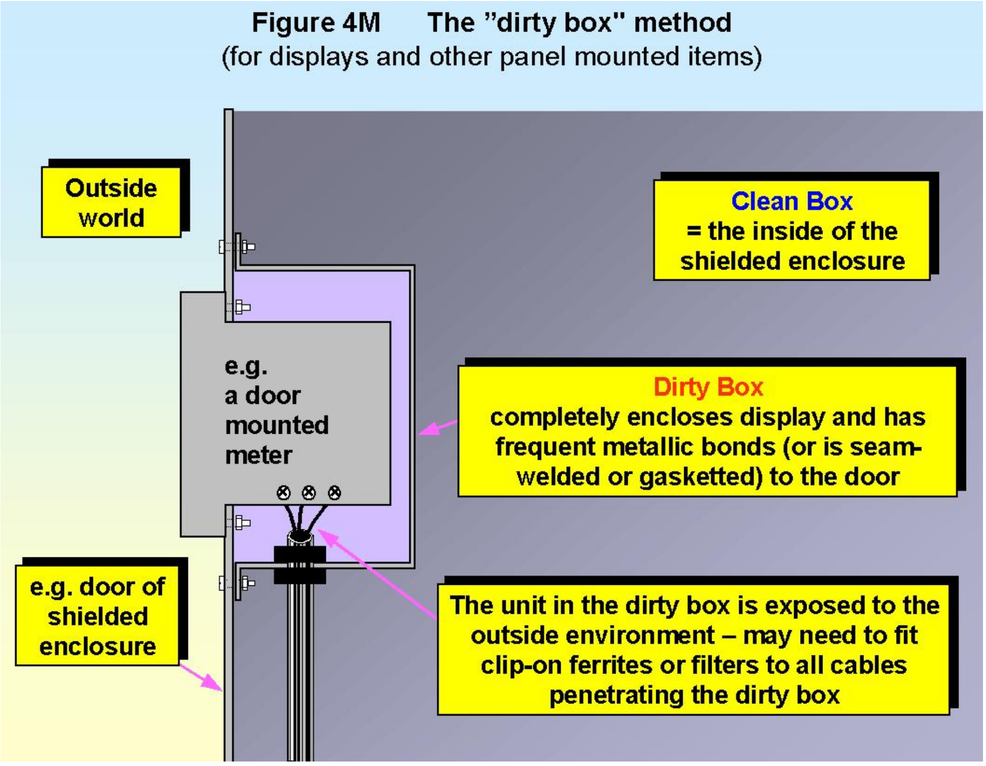
Gasket contact areas must not be painted (unless it is with conductive paint), and the materials used and their preparation and plating must be carefully considered from the point of view of galvanic corrosion.

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.

4.9 Shielding of displays (and the like)

Displays require apertures in enclosures, compromising shielding. A few small LEDs usually present few problems (although when using plastic enclosures they are often a weak spot for personnel ESD susceptibility). Mounting a display outside a shielded enclosure avoids the aperture, but removes the benefit of the shielding from the display and creates the new problem of what to do with the display's data and power cables and their penetration of the enclosure.

Figure 4M shows a display unit mounted in a large aperture in the wall of the shielded enclosure, using an internal "dirty box" to control the field leakage through the aperture. The joint between the dirty box and the inside of the enclosure wall must be treated the same as any other joint in the shield.



Shielded windows are needed where a display needs shielding by a product's enclosure. 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:

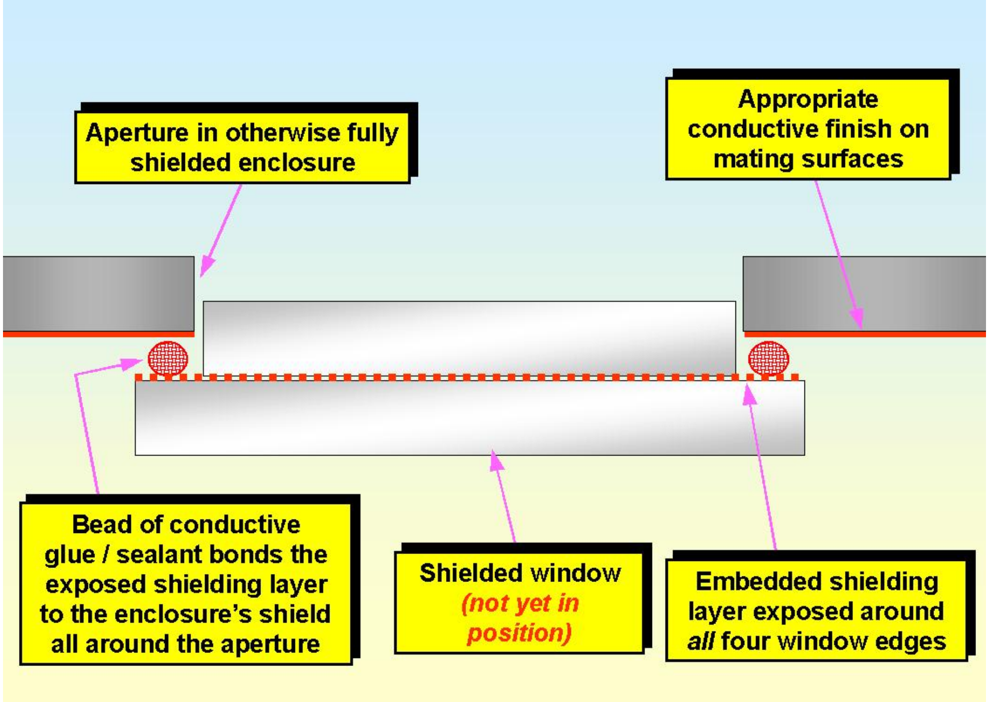
- Thin metal films on plastic sheets, usually indium-tin-oxide (ITO). At film thicknesses of 8 microns and above optical degradation starts to become unacceptable, and for battery-powered products the increased backlight power may prove too onerous. Referring to Figure 4A, we see that the thickness of 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 is not sized correctly. One trick is to orient the mesh diagonally.

Honeycomb metal display screens are also available for the very highest shielding performance. These are large numbers of waveguides below cutoff, stacked side by side, 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.

A vital issue for screened windows is that their conducting layers (mesh, film, or honeycomb metal) must be bonded directly to the enclosure shield surface around all the edges of their cut -out.

Figure 4N shows one typical assembly method, which can use a conductive sealants / glues to avoid the need for mechanical fixings. The use of UV-curable conductive adhesives can make assembly times equal or better mechanical fixing methods.

Figure 4N Bonding shielded windows



4.10 Shielding ventilation apertures

This presents similar issues to the shielding of displays, but only meshes or waveguides below cutoff can be used. As above, these must be bonded metal-to-metal (or with conductive gaskets) to the enclosure shield all around their ventilation aperture. Mesh size can of course be much coarser than for display applications, and expanded metal is sometimes used.

The mesh size must be small enough not to reduce the enclosure's SE too much. The SE of a number of small identical apertures near to each other is (roughly) proportional to their number, n, ($\Delta SE = 20\log n$), so two apertures will make SE worse by 6dB, four by 12dB, eight by 18dB, and so on. For a large number of small apertures typical of a ventilation grille, mesh size will be considerably smaller than one aperture on its own would need to be for the same SE. At higher frequencies where the size of the ventilation aperture exceeds one-quarter of the wavelength, this crude "6dB per doubling" formula can lead to over-engineering, but no simple rule of thumb exists for this situation.

Waveguides below cutoff allow high airflow rates with high values of SE, and honeycomb metal ventilation shields (consisting of many long narrow hexagonal tubes bonded side-by-side) have been used for this purpose for many years. It is believed that at least one manufacturer of highly shielded 19" rack cabinets claims to use waveguide below cutoff shielding of the top and bottom ventilation apertures using ordinary sheet metalwork techniques.

The design of shielding for ventilation apertures can be complicated by the need to clean the shield of the dirt deposited on it from the air. Careful air filter design can allow ventilation shields to be welded or otherwise permanently fixed in place.

4.11 Shielding with painted or plated plastics

Plastic enclosures are often used for a pleasing feel and appearance, but can be difficult to shield. Coating the inside of the plastic enclosure with conductive materials such as metal particles in a binder (conductive paint), or with actual metal (plating), is technically demanding and requires attention to detail during design of the mould tooling if it is to stand any chance of working.

It is often found – when it is discovered that shielding is necessary – that the design of the plastic enclosure does not permit the required SE to be achieved by coating its inner surfaces. The weak points are usually the seams between the plastic parts: they often cannot ensure a leak-tight fit, and usually cannot easily be gasketted. Expensive new mould tools are often needed, with consequent delays to market introduction and to the start of income generation from the new product.

Whenever a plastic case is required for a new product, it is *financially vital* that consideration be given to achieving the necessary SE right from the start of the design process.

Paint or plating on plastic can never be very thick, so the number of skin-depths achieved can be quite small. Some clever coatings using nickel and other metals have been developed to take advantage of nickel's reasonably high permeability to reduce skin depth and achieve better SE.

Other practical problems with painting and plating include making them stick to the plastic substrate over the life of the product, in its intended environment. Not easy to do without expert knowledge of the materials and processes. Conductive paint or plating flaking off inside a product can do a lot more than compromise EMC – it can short conductors out, causing unreliable operation and risking fires and electrocution. Painting and plating plastics must be done by experts with long experience in that specialised field.

A special problem with painting or plating plastics is voltage isolation. For Class II products (double insulated) adding a conductive layer inside their plastic cases can reduce creepage and clearance distances and compromise electrical safety. Also, for any plastic-cased product, adding a conductive layer to the internal surface of the case can encourage personnel electrostatic discharge (ESD) to occur through seams and joints, possibly replacing a problem of radiated interference with one of susceptibility to ESD. For commercial reasons it is important that careful design of the plastic enclosure occurs from the beginning of the design process, if there is any possibility that shielding might eventually be required.

Some companies box clever (pun intended) by using thin and unattractive low-cost metal shields on printed circuit boards or around assemblies, making it unnecessary for their pretty plastic case to do double duty as a shield. This can save a great deal of cost and headache, but must be considered from the start of a project or else there will be no room available (or the wrong type of room) to fit such internal metalwork.

4.12 Shielding without metal

Volume-conductive plastics or resins generally use distributed conductive particles or threads in an insulating binder which provides the mechanical strength. Sometimes these suffer from forming a "skin" of the basic plastic or resin, making it difficult to achieve good RF bonds without helicoil inserts or similar means. These insulating skins make 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. Problems with the consistency of mixing conductive particles and polymer can make enclosures weak in some areas, and lacking in shielding in others.

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.

4.13 Failing conducted tests due to inadequate shielding

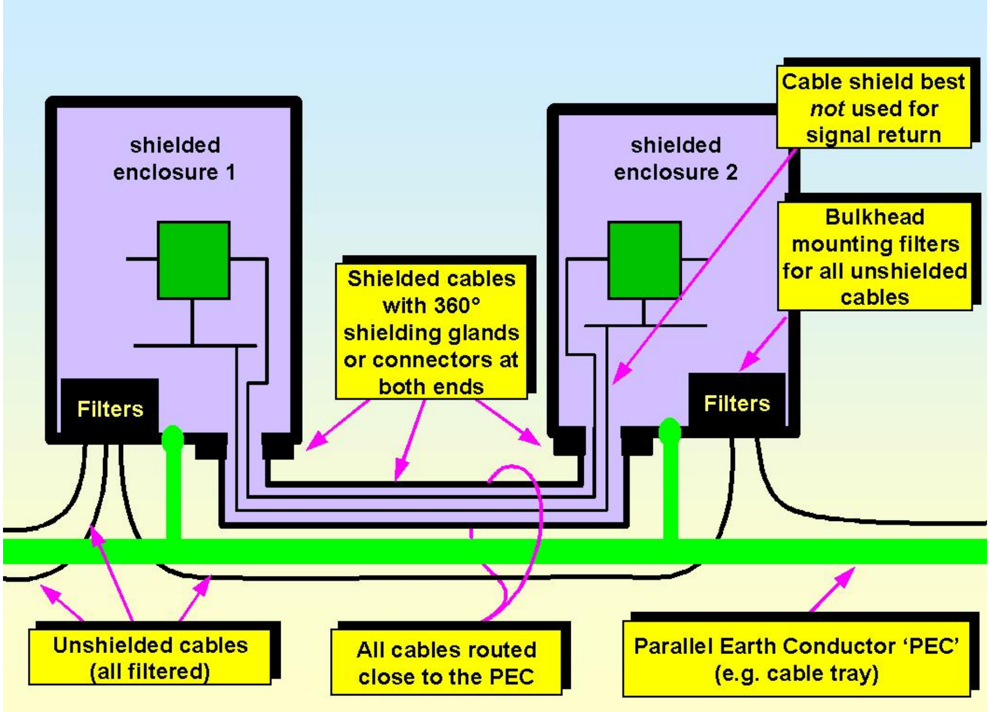
Just because radiated phenomena are generally only tested above 30MHz, does not mean that shielding is unimportant below 30MHz. An enclosure that leaks excessively at low frequencies can cause a failure on a conducted test.

Small products with dimensions less than 0.5 metres usually make relatively inefficient antenna below 30MHz, and most problems are due to leaky cable screens (cables usually being long enough to be good antennae below 30 MHz). However, even a small product might need enclosure shielding that is effective at under 30MHz if it contains a powerful source of low-frequency fields.

4.14 Installation of shielded enclosures

A wire poked through an aperture in a shielded enclosure will completely destroy any SE pretensions. Figure 4P shows the main aspects of how to install an shielded enclosure without ruining it.

Figure 4P Interconnecting shielded enclosures



The screens and connectors (or glands) of all screened cables that penetrate a shielded enclosure, and their 360° bonding, are as vital a part of any "Faraday Cage" as the enclosure metalwork itself. The thoughtful assembly and installation of filters for unshielded external cables is also vital to achieve a good SE. These points were made in Parts 2 and 3 of this series, and they are worth making again.

In passing it is worth repeating that a cable screen pigtailed to an enclosure shield (instead of being 360º bonded) will ruin the SE of that enclosure from quite low frequencies upwards (say, above 10MHz for a short pigtail, lower if it is longer).

Refer to the draft IEC1000-5-6 (95/210789 DC from BSI) for best practices in industrial cabinet shielding (and filtering) and BS IEC 61000-5-2:1998 for best practices in cabling (and earthing) – including why pigtails are best consigned to the history books along with soldering irons that had to be heated in a fire. Figure 4P shows the main points of installing shielded cabinets according to these two best-practice standards, and is repeated from part 2 of this series. Refer to Part 2 for more details on this figure as regards the installation of shielded cabling, and Part 3 for details of installing filters on unshielded cables.

4.15 Using PCB-level shielding

Returning to our original theme of applying shielding at as low a level of assembly as possible to save costs, we should consider the issues of shielding at the level of the PCB.

The ideal PCB-level shield is a totally enclosing metal box with shielded connectors and feedthrough filters mounted in its walls, really just a miniature version of a product-level shielded enclosure as described above. The result is often called a module, can provide extremely high SEs, and is very often used in the RF and microwave worlds.

Lower cost PCB shields are possible, although their SE is not usually as good as a well-designed module. All depend upon a ground plane in a PCB being used to provide one side of the shield, so that a simple five-sided box can be assembled on the PCB like any other component. Soldering this five-sided box to the ground plane at a number of points around its circumference creates a "Faraday cage" around the desired area of circuitry. A variety of standard five-sided PCB-mounted shielding boxes are readily available, and companies who specialise in this kind of precision metalwork often make custom designs. Boxes are available with snap-on lids so that adjustments may easily be made, test points accessed, or chips replaced, with the lid off. Such removable lids are usually fitted with spring-fingers all around their circumference to achieve a good SE when they are snapped in place.

Weak points in this method of shielding are obviously the apertures created by the gaps between the ground-plane soldered connections, by any apertures in the ground plane (e.g. clearances around through-leads and via holes), and any other apertures in the five-sided box (e.g. ventilation, access to adjustable components, displays, etc.). Seam-soldering the edges of a five-sided box to a component-side ground plane can remove one set of apertures, at the cost of a time-consuming manual operation.

For the lowest cost, we want to bring all our signals and power into the shielded area of our PCB as tracks, avoiding wires and cables. This means we need to use the PCB equivalents of bulkhead-mounting shielded connectors, and bulkhead-mounting filters.

The PCB track equivalent of a shielded cable is a track run between two ground planes, often called a “stripline”. Sometimes guard tracks are run on both sides of this “shielded track” on the same copper layer, these guard tracks having very frequent via holes bonding them to the top and bottom ground planes. The number of via holes per inch is the limiting factor here, as the gaps between them act as shield apertures (the guard tracks have too much inductance on their own to provide a good SE at high-frequencies). Since the dielectric constant of the PCB material is roughly four times that of air, when Figures 4F and 4G are used to determine via spacing their frequency axes should be divided by two (the square root of the PCB’s dielectric constant). Some designers don’t bother with the guard tracks and just use via holes to “channel” the track in question. It may be a good idea to randomly vary the spacings of such rows of via holes around the desired spacing, to help avoid resonances.

Where striplines enter an area of circuitry enclosed by a shielded box, it is sufficient that their upper and lower ground planes (and any guard tracks) are bonded to the screening can’s soldered joints on both sides, close to the stripline.

Track which only have a single ground plane layer in parallel, their other side being exposed to the air, are said to be of “microstrip” construction. When a microstrip enters a shielded PCB box it will suffer an impedance discontinuity due to the wall of the box. If the wavelength of the highest frequency component of the signals in the microstrip is greater than 100 times the thickness of the box wall (or the width of box mounting flange), the discontinuity may be too brief to register. But where this is not the case some degradation in performance may occur, and such signals are best routed using striplines.

All unshielded tracks must be filtered as they enter a shielded PCB area. It is often possible to get valuable improvements using PCB shielding without such filtering, but this is difficult to predict so filtering should always be designed-in (at least on prototypes, only being removed from the PCB layout after successful EMC testing).

The best filters are feedthrough types, but to save cost we need to avoid wired types. Leaded PCB-mounting types are available which can be soldered to a PCB in the usual manner and then hand-soldered to the wall of the screening box when it is fitted at a later stage. Quicker assembly can be achieved by soldering the central contact of the filter to the underlying ground plane, making sure that solder joints between the shielding box and the same ground plane layer are close by, on both sides. This latter construction also suits surface-mounted “feedthrough” filters, further reducing assembly costs.

But feedthrough filters, even surface mounted types, are still more expensive than simple ferrite beads or capacitors. To allow the most cost-effective filters to be found during development EMC testing, whilst also minimising delay and avoiding PCB layout iterations, multipurpose pad patterns can easily be created to take any of the following filter configurations:

- zero-ohm link (no filtering, often used as the starting point when EMC testing a new design)
- a resistor or ferrite bead in series with the signal

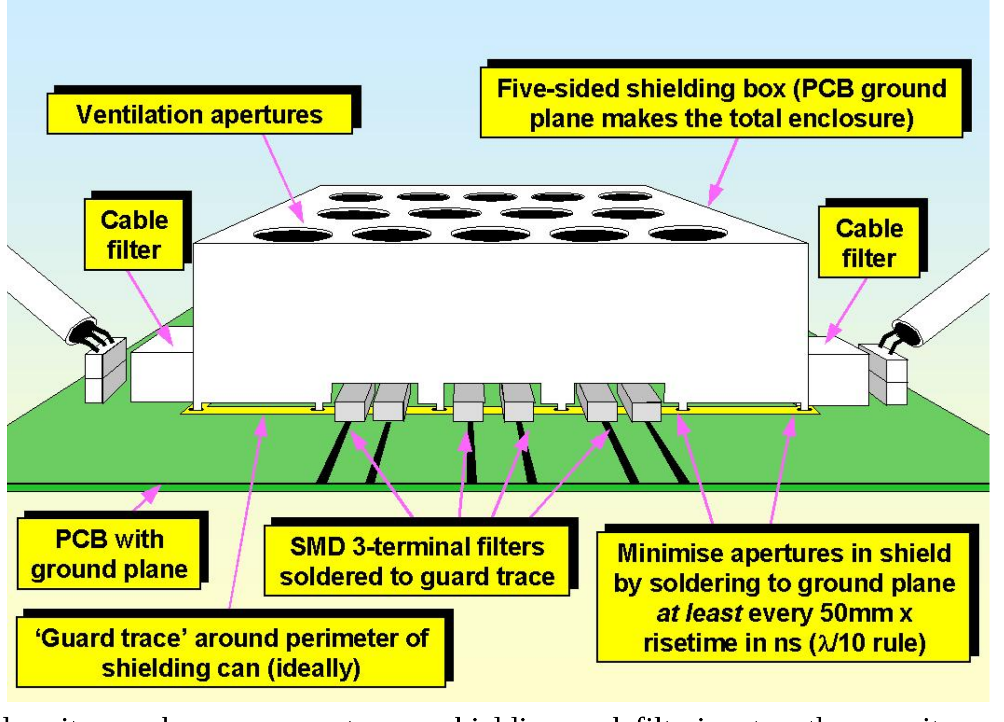
- a capacitor to the ground plane
- common-mode chokes
- resistor/ferrite/capacitor combinations (tee, π, LC, etc. see Part 3 of this series for more details)
- feedthrough capacitor (i.e. centre-pin grounded, not truly feedthrough)
- feedthrough filter (tee, π, LC, etc., centre-pin grounded, not truly feedthrough)

Multipurpose padding also means we are not restricted to proprietary filters and can cook up our own to best suit the requirements of the circuit (and the product as a whole) at the lowest cost.

By now it should go without saying that all these PCB mounted filters should ideally be lined-up with their centres along the line of the wall of the shielding box, which will probably need a little cut-out in it to accommodate the components. Using surface-mounted devices rather than leaded allows the box cut-out size to be minimised, improving SE.

Where simple lines of filters are hard to achieve, take great care not to allow any unfiltered tracks to run close to any filtered tracks. Figure 4Q attempts to sketch what low-cost PCB shielding could look like.

Figure 4Q Sketch of PCB-level filtering + shielding



As with cables, it may be necessary to use shielding and filtering together, so it may be a wise precaution to provide for multi-padded filter layouts for all the "shielded" tracks entering a shielded PCB area, or at least make provision for a ferrite bead.

4.16 Further reading

[1] Tim Williams, *EMC for Product Designers* 3rd edition, Newnes 2001, ISBN: 0-7506-4930-5, www.newnespress.com.

[2] Tim Williams and Keith Armstrong, *EMC for Systems and Installations*, Newnes 2000, ISBN 0 7506 4167 3 www.newnespress.com, RS Components Part No. 377-6463.

[3] Keith Armstrong, *EMC for Systems and Installations Part 2 – EMC techniques for installations*, EMC+Compliance Journal, April 2000, pp8 – 17. Available from the 'Publications & Downloads' page at www.cherryclough.com.