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Good EMC Engineering Practices in the Design and Construction of Industrial Cabinets

Helping you solve your EMC problems

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1 Introduction and background

1.1 The financial need for these good EMC engineering practices

Because of the complexity of modern industrial instrumentation and control products and systems, it is necessary, for commercial and financial reasons, to control electromagnetic interference (EMI). Added to this is the regulatory requirement for the suppliers of products and systems, and owners of premises and sites in the European Union, to comply with the electromagnetic compatibility (EMC) Directive [1], especially the very specific requirements in the new EMC Directive [1] for the use of good EMC engineering practices [2].

This guide addresses the *practical* issues of designing and assembling industrial cabinets to better control EMI, and to help achieve EMC Directive compliance. For information on other EMI and EMC issues, such as management, testing, legal, and theoretical background see [2], [3], [4] and [5].

Some of the techniques described here might contradict established or traditional practices, but they are all well-proven and internationally standardised good modern EMC engineering practices at the time of writing. EMC is a rapidly developing field, because of the rapid pace of progress in electronics, computing, software, power control (e.g. variable speed AC motor drives), radiocommunications and wired/wireless data communications. The rapidly increasing use of these technologies in industry means that some EMC techniques that might have been perfectly adequate in the 1960s (such as single-point earthing, and bonding cable shields at only one end) are now very bad EMC practice indeed. All professional engineers have a duty (professional, ethical, and legal) to apply the latest and best knowledge and practices in their work.

Remember that safety is always paramount, and should not be compromised by any EMC techniques.
A typical example of such a compromise is fitting EMI filters that cause high earth-leakage currents that increase safety risks.

However, it is very important to understand that – where errors or malfunctions in electronic circuits could possibly have implications for *functional* safety (including during faults, foreseeable misuse, overload, or environmental extremes) – merely meeting the EMC Directive and its harmonised EMC standards will almost certainly not be sufficient to achieve adequate safety risk levels. Such an approach would also almost certainly not achieve compliance with the basic standard on functional safety [6] or the industry standards derived from it (such as [7] and [8]), or with safety regulations such as the Low Voltage Directive [9] and Machinery Directive [10]. Although the design and assembly techniques described here are often used to help achieve 'EMC for Functional Safety', a lot more is involved that is not covered by this guide – for more information on this, visit [11].

1.2 These techniques suit a wide range of applications

This guide is concerned with industrial instrumentation and control, but the laws of physics (hence EMC) apply to all electrical and electronic assemblies and systems, regardless of their application, in *exactly* the same way as they do to industrial cabinets. An Amp is still an

Amp, a microvolt still a microvolt, and a MHz is still a MHz regardless of function or application. I hope that the way I have written and illustrated this guide makes the techniques it describes easy to apply wherever electrical and electronic assemblies are being designed and constructed.

1.3 EM phenomena and test standards

REO (UK) Ltd have published a series of 17 EMC Guides [4], which describe how the various electromagnetic (EM) phenomena arise, and how they can cause problems for electrical and electronic devices and circuits and the applications they are used in. They then go on to describe the European EMC test standards, which are based on International standards developed by the IEC, and how to test using them.

Many companies do their own EMC testing according to European or International standards. There are many easier, quicker and less costly ways to do EMC testing, but they are less accurate and not as useful for proving legal compliance. However, they still have value in assessing the suitability of supplier's products, design and development, fault-finding and problem-solving, checking workmanship standards and other QA activities. For more on low-cost testing, see [12].

On-site test methods exist for testing equipment outside of an EMC test laboratory, with its carefully-controlled EM environments, and can be used to save time/cost or where equipment is too large to be tested in the normal way. Examples of on-site methods that can be good enough to support a claim of EMC compliance are given in [13].

1.4 Some basic EMC theory (with almost no maths)

This guide focuses on practical tips and techniques, and does not try to explain *why* they work. This approach can leave engineers vulnerable to special situations where an unusual approach may be needed, but trying to convey the theoretical understanding required to devise special techniques is outside the scope of this guide, and many practicing engineers would find it very tedious anyway. So I suggest reading the references at the end of this article, and then reading *their* references if you still need more background. But here are a few of the reasons why these EMC techniques are needed:

- *All* modern electronics – especially digital, switch-mode, and wireless – employ a wide band of frequencies from audio up to at least 100 MHz, maybe even up to several GHz (thousands of MHz). For them to operate correctly and to achieve EMC it may be necessary to control some or all of their frequency range by using EMC techniques in their cabling and assemblies, and in the cabinets that house them.
- *All* conductors have significant impedance at frequencies above a few MHz, caused by skin effect (which increases their resistance) and inductance. Inductance (L) is typically 1μH/metre for an ordinary wire (e.g. a green/yellow insulated wire), giving a reactance of $2\pi fL$ ohms at frequency f (e.g. 63 Ω/m at 10MHz). As a result, wires (even ones with green/yellow coloured insulation) cannot be used to provide an effective circuit reference voltage at frequencies above a few MHz (usually much less), and so can't provide any EMI control.
- *All* conductors – such as metalwork, wires and cables – make good accidental antennas', and so leak a proportion of the power and/or signals they carry into their external environment. This is especially the case where the conductors are longer than one-tenth of a wavelength ($\lambda/10$) at the highest frequency of concern. The wavelength $\lambda = 300/f$ when f is given in MHz. This is a common cause of EM emissions problems. Shielding can be used to reduce this effect, but it is never 100% effective and if done incorrectly (e.g. shield bonded at only one end) can make the problem worse.
- *All* conductors – such as metalwork, wires and cables – make good 'accidental antennas', and so pick-up a proportion of the EM energy in their external environment and so add voltage and current noise into the signals and power they are carrying. This is especially the case where the conductors are longer than $\lambda/10$ at the highest frequency of concern. This is a common cause of EM susceptibility (immunity) problems. Shielding can be used to reduce this effect, but it is never 100% effective and if done incorrectly (e.g. shield bonded at only one end) can make the problem worse.
- *All* conductive structures – typically called 'earths' or 'grounds' – become ineffective above some frequency related to their dimensions and method of construction. Above this frequency they no longer provide a stable or effective circuit reference voltage – in fact, they become accidental antennas instead of 'grounds'. At such frequencies they cannot provide EMI control – and may even add to EMI problems.

The problems caused by 'accidental antennas' are illustrated in Figures 1 – 3, which show how the typical wire and cable lengths inside cabinets (0.5 to 3 metres) can cause the electrical energies they carry (whether as signals or power) to interfere with the radio spectrum that is vital for broadcasting and communications.

The words 'earth' and 'ground' are very much misused in electrical and electronic engineering, leading directly to a great deal of confusion, delay and unnecessary extra costs. I strongly recommend that these words are never used, except when referring to an actual earth or ground electrode that is buried in the soil under or around a site. This guide will try to take its own advice and use more accurate and explicit terms such as: chassis or frame; shielded (screened) enclosure; protective bonding conductor (the green/yellow wire in mains cables, used for safety purposes); protective bonding network (for a cabinet); common bonding network (CBN, for a site); and of course, Reference.

As has been implied above, correct circuit operation and good control of EMI and the achievement of EMC requires that we understand how to design and create a Reference that is effective over the full range of frequencies we need to control, especially radio frequencies (RF) – frequencies above 150kHz. In some other publications the Reference is sometimes called the RF Reference, Reference Plane, RF Common, or other terms such as 'EMC Earth' or 'EMC Ground'.

The RF Reference itself must have very low impedance over the frequency range to be controlled, much lower than the impedance of the capacitors in any EMI filters. The only kind of structure that can achieve a low enough impedance is a metal mesh, ideally a metal sheet, which is why RF References are often called Reference Planes.

Fig 1

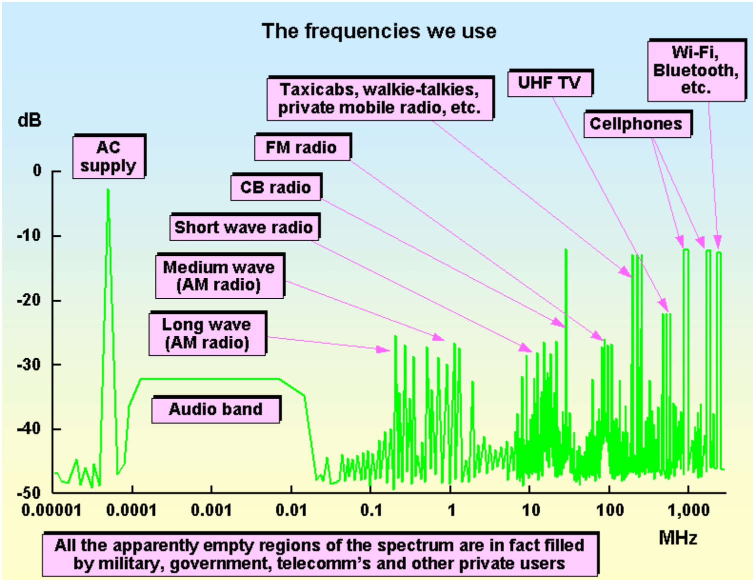


Fig 2

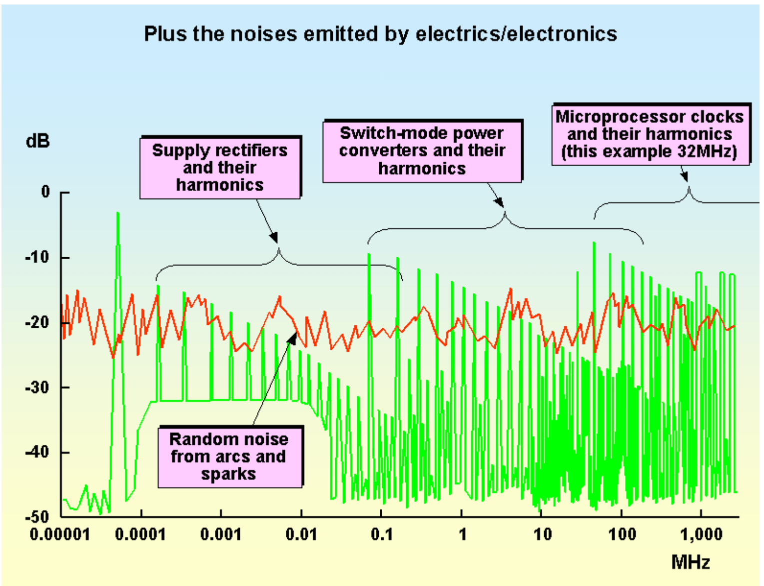
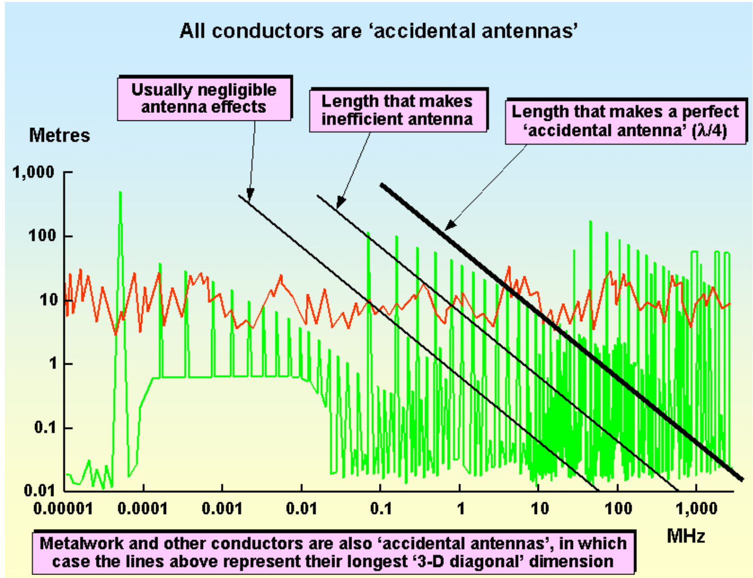


Fig 3



A circuit's RF Reference must always be physically close to the circuit that relies upon it for operation or EMC – *much* closer than λ/10 at the highest frequency to be controlled (ideally λ/100 or even less, e.g. < 30mm for frequencies up to 100MHz). This is because of all of the conductors, including large pieces of metal with negligible resistance, that might be used to connect the circuit to the RF Reference suffer from inductance and 'accidental antenna' effects at longer distances.

A metal box of whatever size can be used to shield a circuit from its external EM environment, but it can only be used as the RF Reference for that circuit if the circuit is close enough – *much* closer than λ/10 – to one of its metal surfaces.

1.5 Don't rely solely on CE-marked electronics

Don't rely solely on using CE-marked components to assemble a cabinet. The 'CE + CE = CE' approach – which assumes that as long as the components and products used in the construction of a cabinet are all CE marked, the cabinet as a whole will comply with all relevant Directives – has no technical or legal justification.

Experience all over the world shows that it is very rare indeed, for a cabinet constructed from CE-marked electronic items supplied by other manufacturers to actually meet the relevant harmonised EMC standards when tested. [14] goes into this issue in detail, showing how to spot many of the tricks that some manufacturers use when CE marking their products, and warning of the pitfalls that can compromise the EMC of the cabinet, or the system or installation it is used in, even when all the components used in the cabinet have excellent EMC compliance individually.

1.6 An overall EMC procedure

A procedure that will manage EMC to achieve reliable performance and legal compliance for industrial cabinets and similar will generally require:

- Assessing the intended operational environment for any EM disturbances, whether conducted or radiated, that might threaten the operation of the new cabinet. See [15] for more information on doing this.
- Assessing the intended application for the sensitivity of other electronic equipment that might be present, to the EM emissions from the new cabinet and its cables.
- Understanding all of the EMC regulatory requirements, for both emissions and immunity, see [2] [4] and [5].
- Deriving an EMC specification for the cabinet and its cables (usually based around the basic IEC EMC test standards for emissions, such as CISPR 22, and immunity, such as the IEC 61000-4 series, see [4]).
- Choosing third-party electrical and electronic units that are known to have the EMC performance required to meet specifications derived from the above steps. This means checking their test reports and QA systems, as discussed in [14].
- Following the electronic unit suppliers' reasonable EMC instructions.
- Applying the EMC techniques described in this guide.
- Checking that the EMC techniques have been correctly applied in assembly by inspection and simple tests (see the low-cost EMC test techniques in [12]).
- Applying the appropriate compliance procedures under the old or new EMC Directives [1] [2]. EMC testing techniques are described in [4] and [12].

Useful information on the above procedures can be found in [16], which, despite its title, is of general relevance to systems and installations of all types and the products used in them.

1.7 Following good EMC practices

In the kind of EM environments covered by the generic industrial EMC test standards EN 61000-6-2 and -4, most EMC problems can be solved by:

- Taking care to only utilise electrical/electronic that have proven good EMC performance [14] when tested to those standards or tougher ones
- Obtaining and fully applying their supplier's EMC instructions in design and construction
- Taking account of the build-up of emissions caused by having multiple units [17]

Even so, it is still advisable to employ good EMC practices wherever the units' suppliers provide no EMC instructions, or to help resolve conflicts between different units' EMC instructions.

However, most normal EM environments are worse than the ones described by any of the IEC or EN EMC test standards, because they specifically do not cover the situation where portable radio transmitters are used nearby – which is now commonplace in all environments (including industrial), and cannot be controlled without very stringent security measures. The standards also ignore a number of other EM environmental situations that can easily occur. So in almost all real-life industrial situations, and especially where the EM environment is more extreme than usual, the use of good EMC practices can be very important indeed for preventing costly lost production due to interference problems.

Good EMC practices in the construction of electrical and electronic assemblies have been known for decades, and are continually evolving to cope with the increasing frequencies being generated by modern electronic technologies, especially digital processing, switch-mode power conversion, and wireless voice and data communications. Relevant standards and public-domain documents on good EMC practices include [18] [19] [20] [21] and [22], and there are a number of guides to good practices produced by companies that sell industrial components, such as [23] [24] and [25].

Good EMC practices are often different from traditional electrical assembly and installation practices, and in some long-established industries large amounts of money and time are still needlessly wasted by fixing EMC problems with systems and installations arising during operation, instead of by design, because of an apparent reluctance to learn about EMC or modern techniques. It is often the case that operational problems aren't recognised as being EMC-related for some time, and even then take a long time to fix.

Part of good EMC practice is to follow the EMC instructions provided by the manufacturers of the electronic units that are to be used – but only where these are reasonable and don't conflict with what is written in this guide, or with each other. Where manufacturers' instructions differ or conflict, EMC expertise is needed. For example, some suppliers of industrial components and modules specify that shielded cables must have their shields bonded to 'earth' at only one end, and they often provide a screw-terminal for that purpose. While this may *sometimes* be acceptable these days in some special cases, it will generally prevent typical industrial cabinets from passing their emissions and/or immunity tests and will therefore generally lead to inaccurate or unreliable operation as well as non-compliance with legal requirements.

Such poor EMC instructions are mostly due to a lack of knowledge and/or poor design of the electronic circuits used for the inputs and outputs. They are usually written by companies who have not tested emissions and immunity, or not tested them properly, or tested them using unrealistic set-ups. They slavishly repeat the bad instructions in their manuals, believing them to be good EMC practice because they were told so 30 years or more ago.

Good EMC practices should generally be followed for all industrial cabinets, to help the purchased electrical and electronic items achieve the EM performance they are capable of, and to help EM mitigation measures like filtering, shielding and transient overvoltage suppression, function correctly. These techniques require additional effort and skill in design, but generally cost little and add very little time in assembly.

1.8 Communicating good EMC techniques within a company

Many companies have problems in turning the intentions of their designers into the constructions assembled by their assembly staff. Nowhere is this more evident than in EMC, where apparently small variations in cable length or route, or component placement, can make huge differences.

Whereas in serial manufacture there is (hopefully) time allowed for what is constructed to be compared with what was designed and any differences iterated out – in custom engineering, designs need to be translated into products and systems without errors *at the first attempt* if a company is to maximise its profits and be successful.

So it is important – to save time and money – that companies find ways to communicate the necessary EMC assembly techniques to their assembly personnel. This generally means that the various construction techniques need to be documented as Work Instructions under a QA system, and then referenced by the designers on their drawings wherever they need to be applied. A number of industrial cabinet manufacturers have used the graphics used in this guide as part of their Work Instructions, and the author will be pleased to provide any such company with these graphics for such purposes, on request [26].

2 Creating an RF Reference

2.1 Introduction to RF References

All industrial cabinets that contain two or more items of interconnected electronics (e.g. a variable-speed motor drive and its separate EMI filter, a PLC and a 24VDC power supply) should use an RF Reference to help control EMC, which can usually be created using the existing cabinet metalwork. This section describes techniques for creating RF References with useful EM performance from ordinary (unshielded) cabinet metalwork. A later section will describe the good EMC practices associated with shielded cabinets.

At frequencies above a few MHz, only a highly conductive area or volume can achieve a reliable RF Reference. But an RF Reference is only of any use if it is a *local* one. 'Local' in this context means that the cables, devices and circuits should remain close to the surface of the Reference at all times, with a spacing that is less than $\lambda/10$ at the highest frequency of concern (e.g. closer than 75mm at 400MHz, a typical walkie-talkie transmitting frequency). Much closer spacing gives much improved EM performance.

Where a metal chassis (ideally free from joints and perforations), metal cabinet, or metal enclosure is used the walls, rear, top, bottom, or door could be used as local RF References. Industrial cabinets often mount their electrical, electronic and other units on a metal backplate, or in a frame or cage for plug-in modules or printed-circuit cards. The metal support structures nearest to the electronics, such as backplates or card cages, should always form part of their local RF References and have multiple metal-to-metal bonds to adjoining metal structures.

2.2 Ineffectiveness of wires, straps and braids

As was discussed earlier, green/yellow wires or braid straps to a single point (sometimes called a 'star point') are ineffective at providing an RF Reference at frequencies above a few hundred kHz or so, depending on their length.

Even where electronic units (such as low-frequency analogue processing) do not employ or emit RF frequencies, the semiconductors in it will happily demodulate and intermodulate any RF noise in their circuits, causing immunity problems, unless their manufacturers have taken great care in their EMC design. Even DC and low-frequency analogue electronics need to employ good EMC practices.

2.3 Highly-conductive metal plating required, with no polymer passivation

It is easiest to use metal structures as local RF References if they are finished with a highly conductive metal plating that is suitable for the physical environment and lifecycle of the cabinet (see section 6). Only metal surface-to-metal surface bonds have any chance of working effectively at the highest frequencies in common use today. Non-conductive paint, plastic coatings, or anodising, increase the inductance of bonds and reduce their effectiveness at high frequencies. Where painted or plastic-coated surfaces are to be bonded to, care must be taken to achieve a good bond at RF (usually involving local removal of paint or plastic), and then to prevent the corrosion that can occur because the protective coating has been removed.

In the case of industrial cabinets fitted with backplates, zinc-plated backplates have become the standard for almost all cabinet manufacturers in recent years, to help with RF-bonding and EMC. Heavy zinc or tin plating is the best conductive finish for mild steel, but sometimes thinner plating is used with an additional polymer passivation layer. Unfortunately, the passivation is a thin plastic coating and can ruin RF-bonding properties. It is often claimed that polymer passivation is easily punctured by modest pressure from metal parts such as the nuts and bolts typically used in electronic assembly. However, it might prove necessary to use EMC gaskets, and since they would not apply sufficient contact pressure to break through the polymer film it is much better to standardise on metalwork that relies on good metal plating to prevent corrosion, and avoid polymer passivation completely.

Some industrial cabinets are seam-welded, such as the stainless-steel cabinets used in the food, pharmaceutical and other industries where hygiene is important. These make excellent RF References, but most industrial cabinets consist of frames to which metal cladding (skin) is applied. These may be fitted with shelves for mounting large items of equipment (for example the traditional 19-inch rack-mounting system), or backplates for mounting DIN rails and/or 'chassis-mounted' units or modules. These cabinets consist of many metal parts all screwed together, and to make them function usefully as an RF Reference we must RF-bond them together all over the cabinet. Any metal part in a cabinet that is not RF-bonded to form part of the RF Reference, including hinged doors, is a potential 'accidental antenna' as shown in Figure 3.

2.4 Making effective RF bonds

Figures 4 and 5 show the principles of RF-bonding between two sheets of metal, the important issues being the achievement of sufficiently low RF impedances in the bonds themselves, and the maximum spacing between the bonding points.

Although Figures 4 and 5 show two metal sheets being bonded to form a larger RF Reference, the same techniques apply to any metal parts, and in three dimensions. Where a metal mesh is being used instead of a metal sheet or other solid metal part, it can only be relied upon to act as a moderately effective RF Reference up to a frequency of $15/l$ MHz (l in metres). Closer mesh spacing gives the Reference a better RF performance at any frequency up to $15/l$ MHz.

Figures 6 and 7 show details of metal-to-metal bonds used to connect metal parts together to create RF Reference planes. Any other kinds of bonds, including short wide braid straps, are very inferior to metal-to-metal bonds – although of course it depends upon the frequency, and braid straps or even bond wires may be able to provide a sufficiently low-impedance RF Reference, if the highest frequency that is to be controlled is no more than a few hundred kHz.

Figure 6 shows the use of aggressive 'spiky' washers and screw threads for RF-bonding two metal items that have an insulating finish, such as paint, anodising or even a polymer passivation coating. When trying to improve the EM performance of an existing cabinet, this might be all that can be achieved – but it is not an ideal method (although it is much better than using wires or braid bonds).

Fig 4

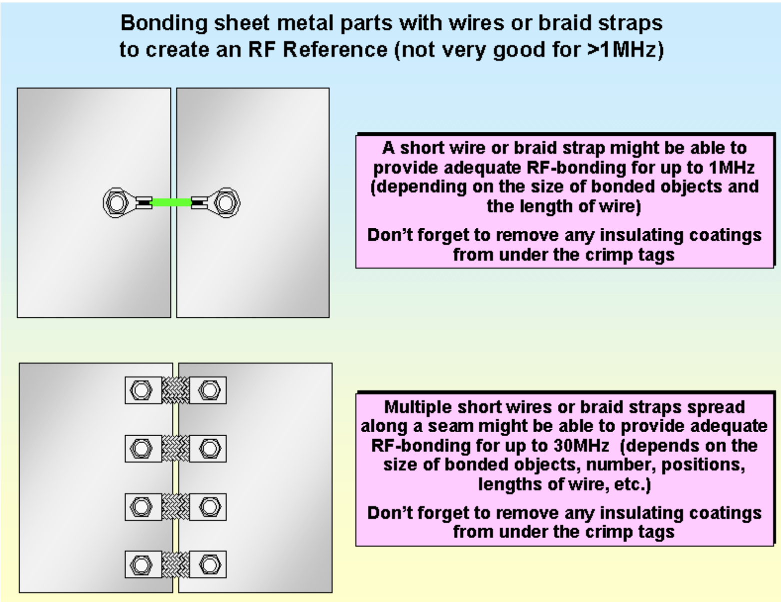


Fig 5

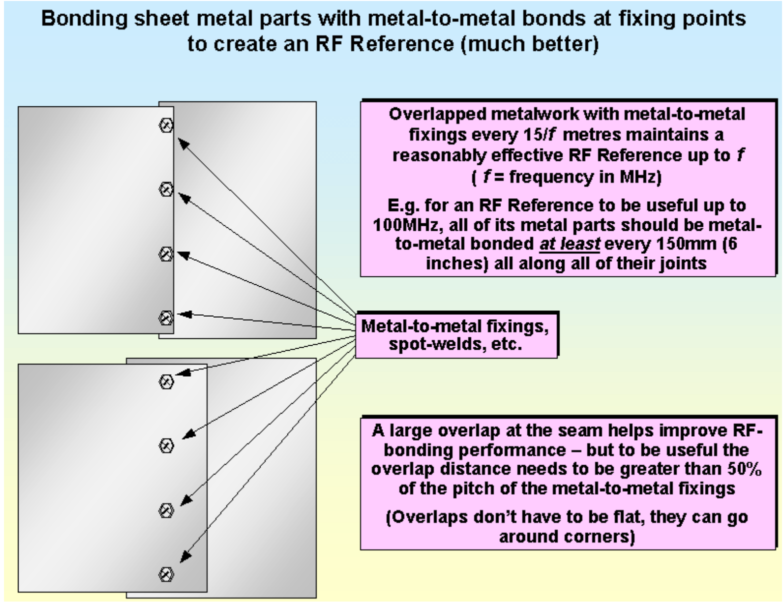
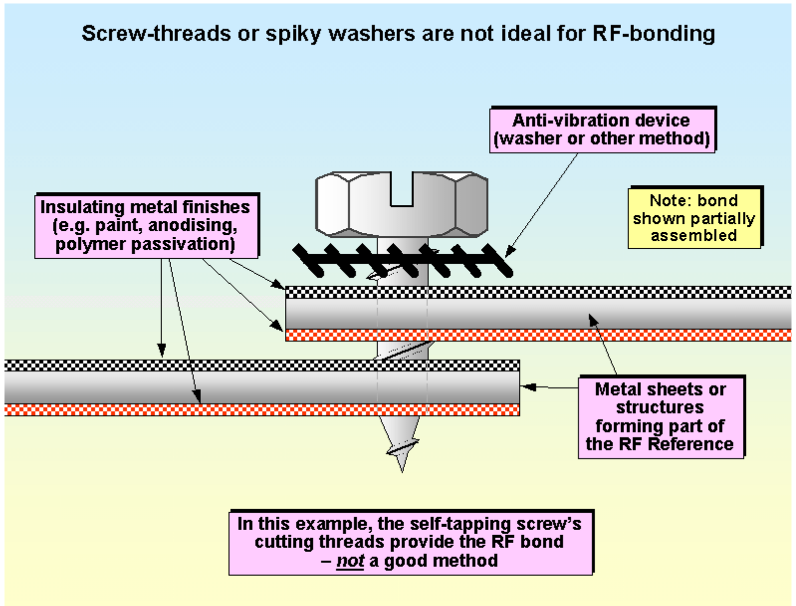


Fig 6

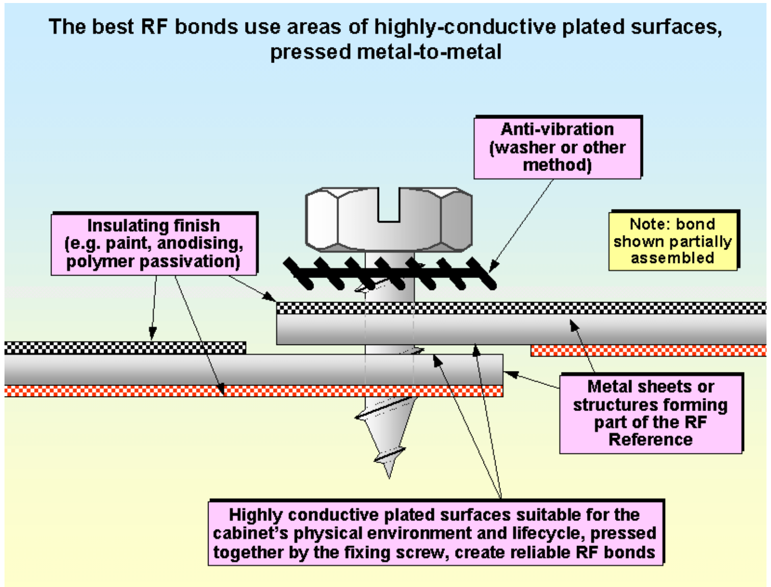


As mentioned earlier, it is much better to design cabinets in the first place to use conductively-plated metal parts throughout, with no paint or insulating finishes applied. Then the very best and most reliable RF bonds can be achieved by using the fixing screws to press the conducting metal surfaces together. Steel (apart from stainless) and aluminium are unsuitable materials on their own, they always develop a high resistance surface through oxidation, so always need to be tin plated or alochromed, or some other low resistance corrosion-proof finish.

The RF Reference in '19 inch' rack - mounting cabinets can be improved by making sure that the front panels of all the racked equipment make metal-to-metal bonds to the cabinet frame at their mounting points (sometimes called rack mounting ears). Typical mounting ears are made of anodised aluminium, and because anodising is a very tough insulator they provide no RF-bonding. It is much better to use ears with highly conductive plating, screwed into caged nuts in a frame that also has highly conductive plating. The 19 inch spacing between the bonds at both sides of the front panels means that the RF Reference thus created has a low impedance up to about 20MHz – to control higher frequencies more effectively it would help to create RF bonds along the long edges of the front panels, to the shelves above and below.

A variety of special EMC tapes are available from companies such as 3M, which can be used to provide a good high-conductivity bonding surface (usually tin) instead of relying on plating. Some types have a top layer of masking tape so that the metal parts can be painted, then the masking tape removed to reveal the metal surface where the bonding is to take place.

Fig 7



Spot-welding is as good or better than pressing metal-to-metal at fixing points, remembering to space them closer together to allow for the ones that don't work. Seam-welding (or brazing or seam-soldering) along all joints is even better, and is used where the highest RF performance is required.

An alternative to seam welding/brazing/soldering in the creation of an RF Reference is to use conductive gaskets, often called EMC gaskets, to provide low-impedance bonding all along a metal joint. Such gaskets are mostly used to create EMC shielded cabinets, and the way in which they are used to help create RF References is no different. Using gaskets instead of multiple screw fixings and/or welding helps speed the assembly, and disassembly of cabinets.

2.5 Using gaskets effectively

There are many suppliers of such gaskets, and each one offers very many different gasket materials in many different styles (see Figures 8 and 9 for some examples of just two types of gasket materials) because no one type of gasket is suitable for all applications. This guide will not discuss gaskets and their use in any detail, except to say that when assembled they should be compressed to an amount within their manufacturers recommended range – and this can require considerable pressure. Good EMC gasket manufacturers provide a wealth of data and application assistance (for example [27]), covering the correct choice of gasket materials and styles for particular applications, and the data required for correct mechanical design.

Even gaskets that are easily squashed flat between two fingers can require very large compression forces when used in long strips, so the effective use of gaskets requires careful mechanical and fixing design to prevent metal parts from bending too much. It is not unusual to fit strips of very soft conductive gaskets to the door of an industrial cabinet, only to find that it becomes almost impossible to close, and once closed it bends like a banana opening up large gaps that defeat the purpose of the gasketting.

Fig 8

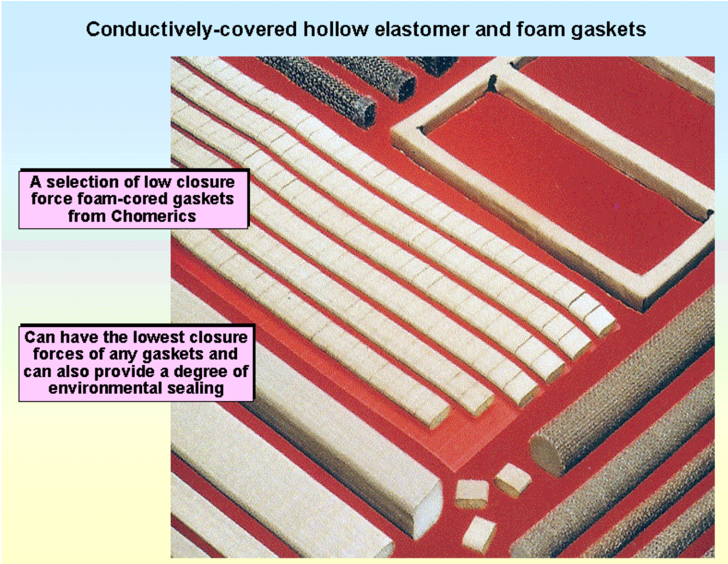
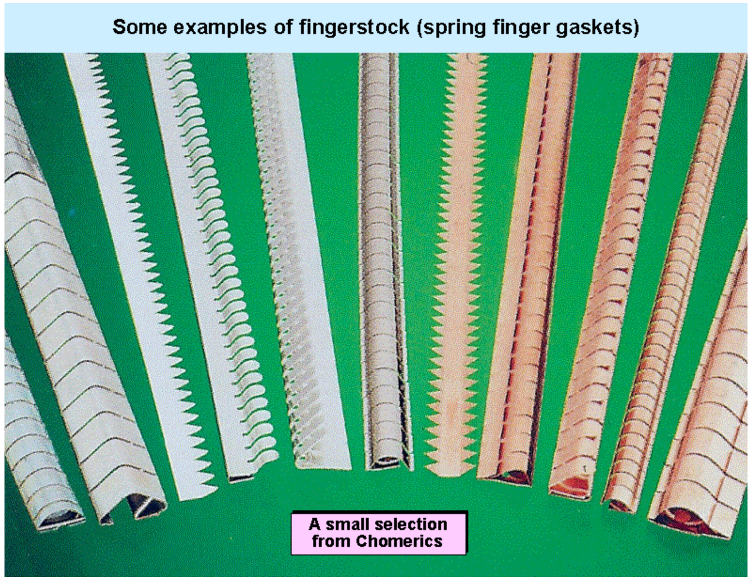


Fig 9



3.1 Routing send and return paths close together

All electrical and electronic power (AC or DC) and signals (whether data, control, analogue, inputs, outputs, etc.) have a current that flows in a loop from the source to the load (driver to receiver) and back again. It is *vital* for EMC that the area enclosed by this loop is as small as possible, which means that we must provide a wire for the send current path, and a conductor for the return current path, and route them together in the closest possible proximity over their whole route, as shown in Figure 10.

It is best to twist the send and return conductors together, to make a twisted-pair cable (sometimes twisted triples or quads are required instead, for instance for three-phase AC with either three or four wires). Shielded (screened) twisted-pairs can also be used and are very good indeed for EMC, but coaxial cables are not as good, and ribbon cables and bundles of individual wires can cause big problems for EMC.

Figures 11 and 12 show some methods for improving the EMC of unshielded wires. For more information on getting the best EMC performance from wire bundles and cables (unshielded or shielded), see the 2006 version of [28].

Fig 10

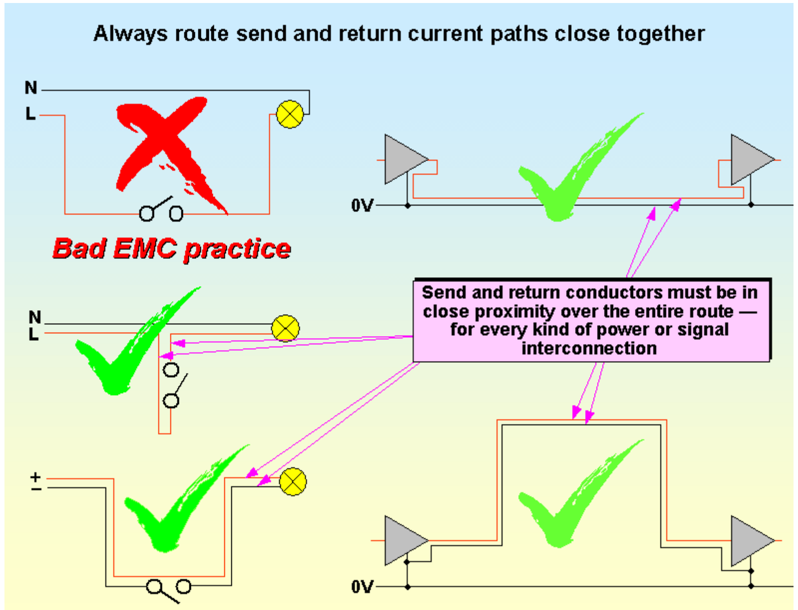


Fig 11

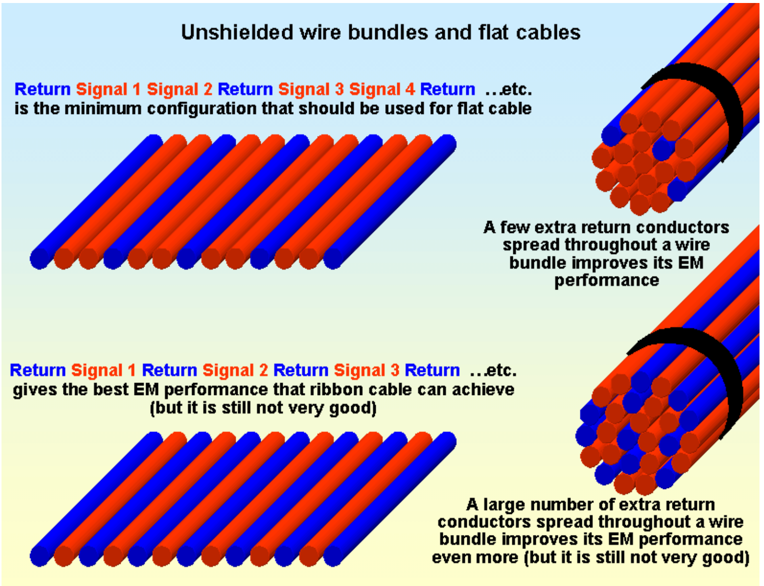
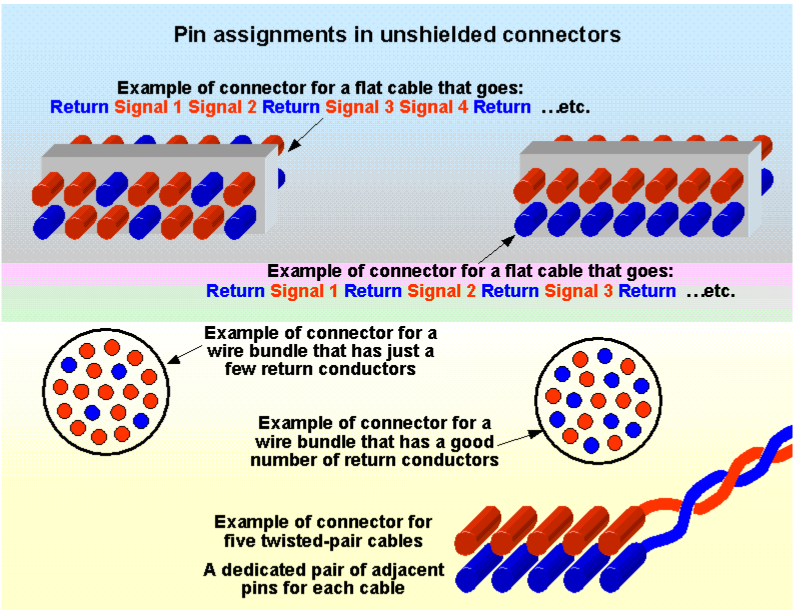


Fig 12



Where thousands of amps of current are involved, twisting the send and return conductors can cause insulation damage due to the electromechanical forces on the conductors – but inside industrial cabinets such currents are carried by solid busbars anyway. Busbars cannot be twisted, and their separation means that their currents create high levels of magnetic and electric fields in their vicinity, which can be a problem for nearby electronics. Busbars can make excellent 'accidental antennas' for any RF voltages or currents they carry, so filtering may be needed to reduce their levels of RF, or else the cabinet may need to be shielded.

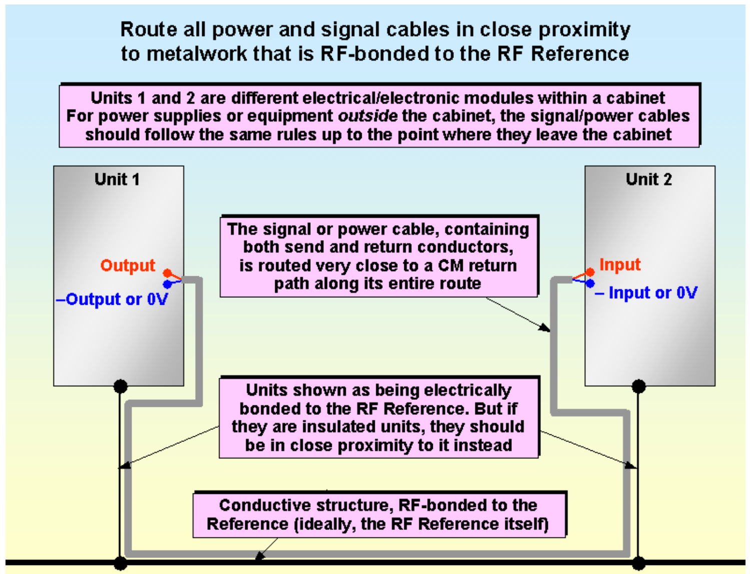
The best busbars for EMC use solid insulation (instead of air) and very close spacing between bars carrying send and return currents. In three-phase mains supplies, or three-phase motor drive cables, each of the phases is the return for the others.

3.2 Routing cables close to the RF-bonded metalwork

As discussed in 1.4, an RF Reference is only useful for assisting or improving the EM performance of a circuit if it is local – meaning closer than $\lambda/10$ at the highest frequency to be controlled (e.g. closer 30mm to control up to 100MHz) – much closer spacing means better EMC. This section discusses techniques for achieving the appropriate spacing for wire bundles and cables. Section 4 discusses the spacing and bonding of electronic units with respect to the RF Reference.

Wires and cables, and bundles of wires and cables, should never fly through the air. They should instead be routed along their *entire* lengths as close as possible to metalwork that has a continuous conductive path with a low RF impedance, all the way back to the RF Reference plane, as shown in Figure 13.

Fig 13



This metalwork creates a preferential return path for the common-mode (CM) currents that leak from all wires and cables (even shielded ones), reducing the accidental antenna effects shown in Figure 3, and further improves EMC by providing the wires and cables with what is known as an 'image plane'. The wider the metal, the lower the RF impedance and the better the image plane, so the better the EMC. If the metal structure is a part of the RF Reference, bonded to other parts of the Reference as described in section 2 – above that would be ideal for EMC.

Industrial cabinets that use backplates generally use plastic trunking for their wires and cables, and the tendency is to simply stuff all the wires and cables inside the trunking and clip its lid on. But where the send and return conductors are single wires it would be better to twist them or at least tie them together in a bundle (see Figure 11) before placing them in the trunking, so that they cannot lie too far from each other.

Plastic trunking helps to keep conductors reasonably close to the backplate (which is always the RF Reference) but some of the wires and cables might lie as much as 50 or even 75mm above it, which does not give the best EM performance. It would be better for EMC to use 'shorter' trunking, that keeps conductors closer to the backplate, at least for the more EMC-critical cables (Classes 1 and 4, see 3.3 below), or else tie these cables directly to the backplate.

Figures 14 and 15 show how to deal with the routing of wires and cables in corners and across joints in the RF Reference.

Fig 14

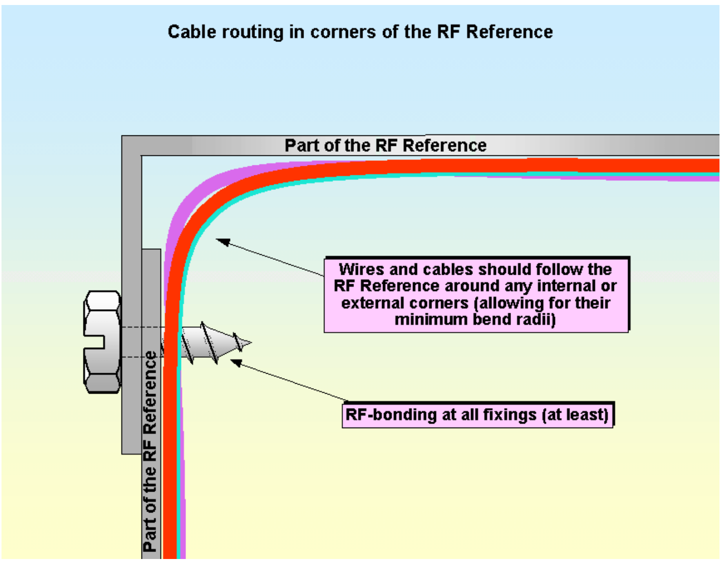
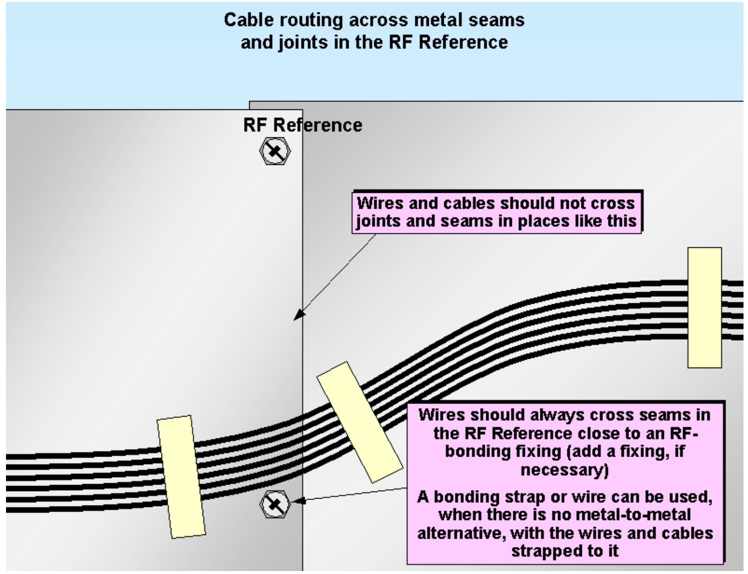


Fig 15



Conductors carrying power or signals should not go too close to the edge of the metal structures they are routed close to. Where practical their distance from the edge of the metal should be at least three times their height above it, and this is especially important for Classes 1 and 4 (see 3.3).

Where conductors connect to electronic printed circuit boards (PCBs), units, modules or other products, they should be routed very close to the RF Reference as much as is possible along their entire length. Ideally, the PCBs, units, etc., will also be RF-bonded to the Reference (see section 4), and if they have a metal body the conductors should be routed close to that until reaching their connectors or terminals.

Figure 16 illustrates this for a packaged unit, while Figure 17 shows a flat cable to a PCB. Shielded cables should have their shields bonded to the RF Reference at their ends, or as close to their ends as possible, and this is discussed in section 3.7.

Fig 16

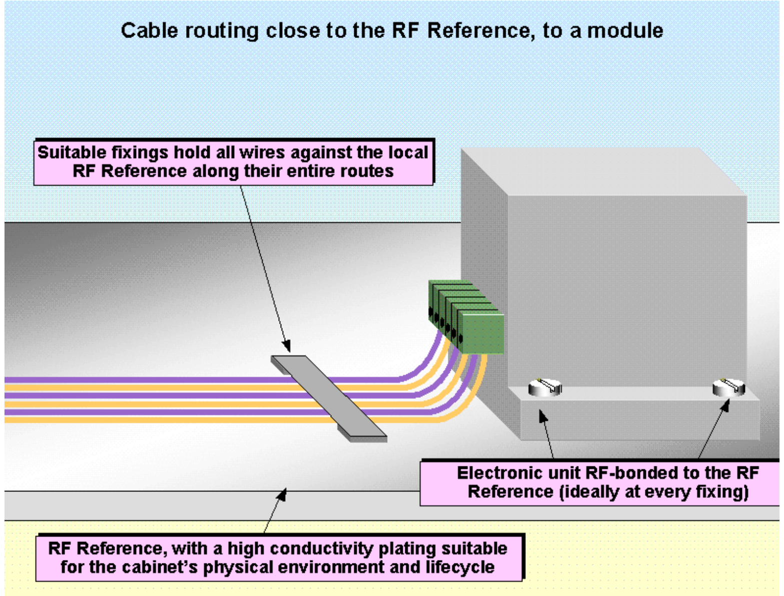
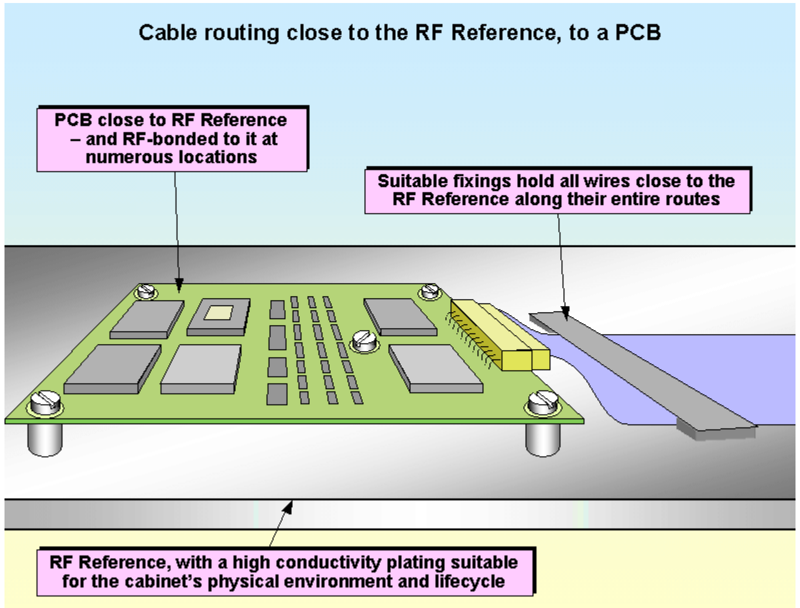


Fig 17



3.3 Segregating different Classes of conductors

Cables inside a cabinet should be split into at least 4 classes, based on the guidance in [18], as follows:

Class 1 is for conductors carrying very sensitive power or signals. Low-level analogue signals such as milliVolt output transducers and radio receiver antennae are in Class 1A. High-rate digital communications such as Ethernet are in Class 1B. Classes 1A and 1B should not be bundled together, although their bundles may be run adjacent to each other.

All Class 1 cables should use fully shielded cables and connectors over their entire path, with 360° shielding maintained throughout, from end-to-end (see [28]). Unshielded twisted-pairs are commonly used for Ethernets and similar data cables, but they are generally not as good for achieving the full data rate or EMC as shielded twisted pairs of otherwise identical specification.

Class 2 is for conductors carrying slightly sensitive power or signals, such as ordinary analogue (e.g. 4-20mA, 0-10V, and signals under 1MHz), low-rate digital communications (e.g. RS422, RS485), and digital inputs or outputs (i.e. on/off signals, not serial or parallel datacommunications; for example signals from limit switches, encoders, pushbuttons, etc.).

Class 3 is for slightly interfering power or signals, such as low voltage AC distribution (< 1kV) or DC power (e.g. 48V telecommunications power), where these do not also power noisy apparatus. Power distribution that also feeds noisy equipment may be converted from Class 4 to Class 3 by the correct application of filtering (not a trivial exercise, see [29]).

Class 3 also embraces control circuits with resistive and inductive loads, where the inductive loads are suppressed at the load (e.g. the electrical coils of relays, contactors, solenoids, actuators, valves, etc.); direct-on-line (DOL) AC motors, and so-called 'sparkless' or 'pancake' DC motors.

Class 4 is reserved for strongly interfering power or signals. This includes all the power inputs or outputs (to or from) variable-speed AC motor drives; frequency converters; AC-AC and AC-DC power converters and their DC links, and DC-DC power converters. Class 4 also applies to the cables associated with electrical welders; RF equipment (e.g. plastic welders, wood gluers, diathermic apparatus, microwave dryers and ovens); DC motors or sliprings; and similar 'noisy' apparatus. Cables to RF transmitting antennae and unsuppressed inductive loads are also Class 4. All Class 4 cables should use shielded cables and connectors with 360° shielding maintained throughout, from end-to-end (see [28]).

The switch-mode power electronic circuits used in variable-speed AC motor drives; frequency converters; AC-AC and AC-DC power converters; DC-DC power converters and the like (including most types of uninterruptible power supply) produce very high levels of RF noise on their power inputs and outputs, which is why they should be assumed to be Class 4 in the absence of any EMC test data. However, their inputs and outputs can be filtered to reduce their cables to Class 3, or even to Class 2.

For example, most chassis-mounted and modular DC power supplies contain input and output filters and are claimed by their suppliers to comply with the relevant emissions standards (usually CISPR 22, EN 55022, EN/IEC 61000-6-3 or EN/IEC 61000-6-4). Filters are available from numerous suppliers for the mains inputs of all switch-mode power converters, and responsible manufacturers of converters should at least recommend which makes/models should be used to be sure of complying with relevant conducted mains emissions standards – if they are not already incorporated in their unit. A few filter manufacturers also make filters suitable for fitting at the output of switch-mode power converters, either to remove the worst of the RF noise, or to convert the output waveform into a sinewave or DC (as appropriate) with varying degrees of purity.

Most variable-speed AC motor drive manufacturers specify the use of a shielded cable 360° bonded at both ends, for their motor cables, but when fitted with a suitable 'sinusoidal output filter' their motor cables can be treated as Class 3 instead. The cost of such filters appears to discourage many industrial cabinet designers from using them, but overall there are usually significant financial and EMC benefits to be had in using them to eliminate Class 4 shielded cables and their segregated routes from the final installation.

These four classes should be physically segregated within the cabinet at all times, and as Figure 18 shows, long parallel runs should not be any closer than 100mm, if possible, as well as being run as close as possible to the RF Reference. If cables of different classes must cross over each other, they should only do so at right angles. Greater spacings are required for parallel routes outside the cabinet, as shown by the lower part of Figure 18, but good EMC engineering techniques for systems and installations are not the subject of this guide (see [3] instead).

The above classification is based on the power and signals that are *intended* to be in the conductors, but it might be necessary to increase the classification of a conductor depending on other factors. For example, many modern electronic devices have I/O signals that would appear to be relatively benign in EMC terms (e.g. audio outputs, inputs from pushbuttons, thermocouple inputs, indicator lamp outputs). What is often not realised is that where there is digital processing or switch-mode power conversion within a unit, these I/Os can carry high levels of unrelated CM noise that can have a very significant RF content. Harmonics of digital clocks and data busses are usually the chief culprits, often causing emissions in the hundreds of MHz from conductors ostensibly carrying very innocuous signals.

Home-made close-field probes and low-cost portable spectrum analysers, such as those shown in Figure 19, can be used as described in Parts 1 and 2 of [12], to identify such problems early in a project. They help choose industrial components that have fewer EMC problems, and/or help choose the appropriate type of shielded cables and connectors (see [28]) and/or choose appropriate filters, such as clip-on ferrite suppression chokes (see [29]) – so that cables can be bundled with others of the same Classes without causing interference.

Fig 18

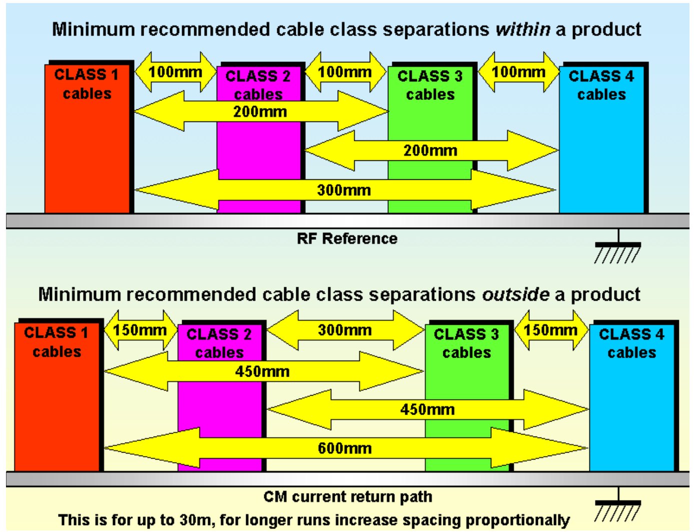
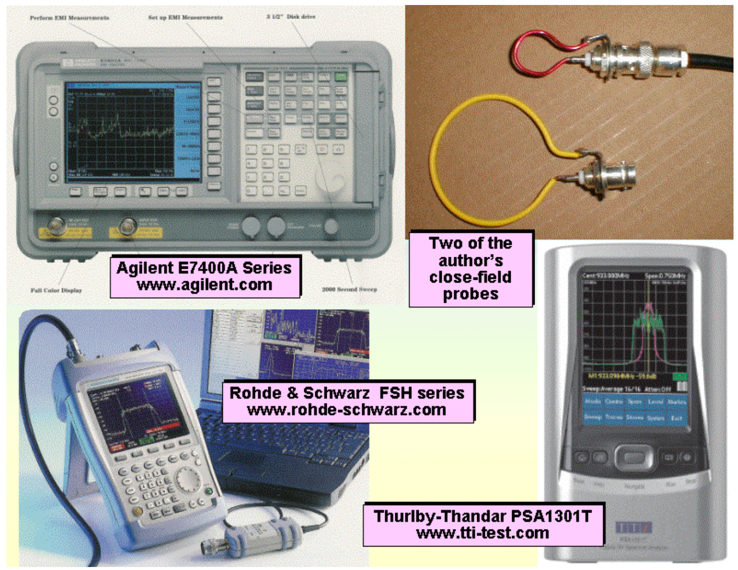


Fig 19



Another problem arises with cables exposed to the strong RF fields near the antennas of radio transmitters such as GSM, GPRS, Wi-Fi, Bluetooth, 3G or other radio transmitting devices often incorporated into industrial systems these days, or where cables are exposed to powerful RF fields from radio or TV broadcasting stations, hand-held walkie-talkies, vehicle mobiles, and RF production equipment such as induction furnaces, dielectric heaters, plastic welders or sealers, microwave dryers, etc. This is especially a problem for cables that leave or enter a cabinet, so are exposed to the external EM environment. This issue is dealt with by assessing the external EM environment as described in [15], then choosing the appropriate types of cables and connectors, and/or filtering – so that cables exposed to such fields can be bundled with others of the same classes without causing interference.

The recommended spacings between cable classes, as shown in Figure 18, are based upon a number of assumptions about the types of cables and the circuits in the electrical/electronic units connected to the cables, and real-life experience, and so they are at best a very rough guide and cannot be expected to be adequate in all cases. Increasing the number of cable classes used to five six or more; increasing the spacing between parallel routes, and routing closer to the RF Reference are all ways of improving EM performance more than would be achieved by the above guide.

Actually testing cables (when they are operating with their intended power/signals and loads) with close-field probes and spectrum analysers, as discussed above, is a very big help in removing the guesswork from this whole issue, and is generally recommended no matter what EM specifications suppliers claim their products meet.

3.4 Reducing Class spacings

Where wires and cables cannot be routed close enough to the RF Reference, the spacings between parallel routed cables of different classes should be significantly increased beyond the recommendations in Figure 18.

Where practical considerations prevent the achievement of the ideal spacings between classes, using conductors with improved EM performance will reduce the spacings required. This technique involves…

- Adding more return conductors in wire bundles, see Figures 11, 12 and the 2006 version of [28]
- Replacing straight send/return wires in bundles with twisted pairs, triples or quads as appropriate
- Replacing unshielded (unscreened) cables by shielded types using correct shield terminations at both ends, see [28]
- Replacing shielded (screened) cables by types with a higher shielding specifications and/or higher-quality terminations at both ends, see [28].

It is possible to improve the EM performance of conductors by so much, that all the classes can be bundled together. The limiting factor is usually the connectors provided by the manufacturers of the electrical/electronic units used in the cabinet. For example, screw-terminal or plastic-bodied connectors make it difficult to terminate cable shields correctly (this requires 360° bonds – not pigtails – see [28]).

Even where D-type connectors with metal bodies are provided – if the manufacturer of the unit has not correctly bonded the D-type to his units internal RF Reference, the EM performance available from 360° terminating the cable shield will be wasted. It makes good sense to consider such aspects of equipment before purchasing them.

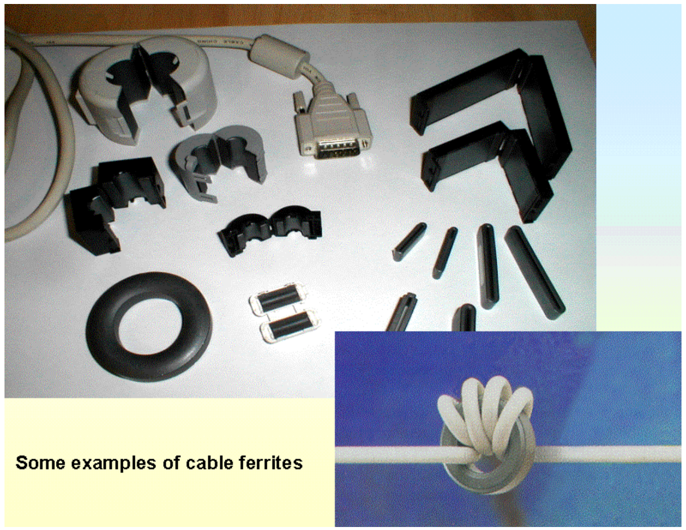
It is also possible to improve the EM performance and reduce the spacings between classes by improving the *filtering* applied to the electrical/electronic units at one or both ends of the conductors. It is impractical to open up purchased units to improve their internal filtering, so it is more usual to add external filters to the cables at the point where they enter/exit the units.

The easiest types of filters to add to cables are ferrite chokes, a wide range of which are available from many manufacturers to suit round or flat cables, many of them available in split form with plastic clips that make it easy to clip them onto existing cables, as shown in Figure 20.

Cable-mounted ferrites are available in different materials, to suppress different ranges of frequencies, so it obviously helps to choose the appropriate type. If the problem frequencies are unknown, they can be found with a close-field probe and spectrum analyser such as shown in Figure 19, or with the CM cable-current probe shown in Figure 5 of Part 1 of [12].

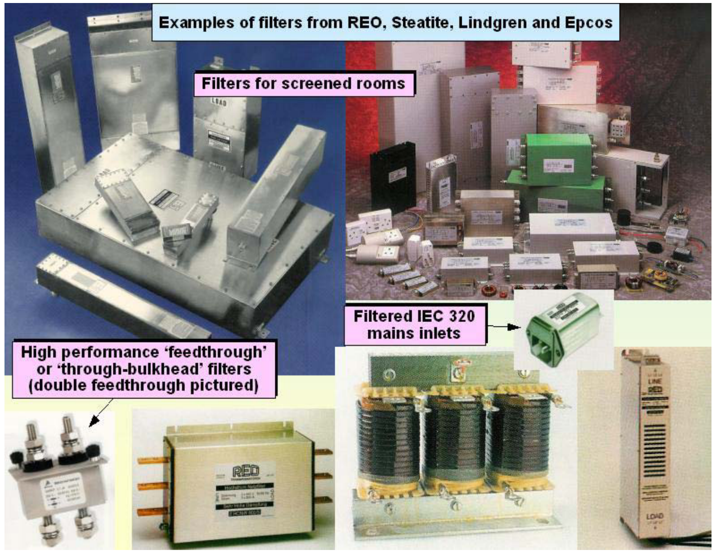
It is also possible to connect filters such as those shown in Figure 21 in series with cables, to improve their EM performance, reduce cable Class spacings, or even to change a cable from one Class to a lower. Whereas adding ferrite chokes such as those in Figure 20 is quite straightforward, there are a number of detailed issues surrounding the effective use of filters that contain capacitors, such as those in Figure 21. Some of these issues are discussed in sections 4.7 and 5.2, but for more detail please read [29].

Fig 20



Some examples of cable ferrites

Fig 21



Sometimes filtering and shielding can be effectively applied together. For instance, where a shielded cable can only achieve a poor shield termination (e.g. a pigtail, see section 3.7.6), a ferrite clamped over the cable at that end can improve matters.

3.5 Segregating cables in industrial cabinets that use backplates

The various electronic, electrical, pneumatic, hydraulic, etc., units should be located to keep sensitive units such as transducer amplifiers or programmable logic controllers (PLCs) well away from electrically noisy units such as relays and contactors or variable-speed AC motor drives ('inverters'), to help prevent them from interfering with each other. They should also be located so as to aid the segregation of the cable classes. Figure 22 is a sketch of a real-life industrial control panel, using an ordinary unshielded cabinet, which was designed according to this guide and successfully tested for EMC compliance.

Notice that the Class 1 and 2 cables in Figure 22 are run in the same trunking – this was a compromise that was felt to be acceptable because this panel was quite small, and also because there were very few Class 1 signals and they were not very sensitive. There is nothing wrong with compromise, it is the life-blood of engineering after all, but it is very important that people competent in the disciplines involved (EMC in this case) determine such compromises, case-by-case.

As in Figure 22, it is best to try to have no internal Class 4 cables at all, or at least minimise their internal lengths as much as possible. This means fitting units such as inverter motor drives near to the wall of the cabinet so that their motor drive cables (Class 4) can exit directly, and filtering any Class 4 incoming cables (e.g. very noisy mains supplies) as close as possible to their point of entry to make them Class 3 or 2. Figure 23 shows more detail of the motor drive area of the cabinet from Figure 22. The manufacturer's EMC instructions

Fig 22

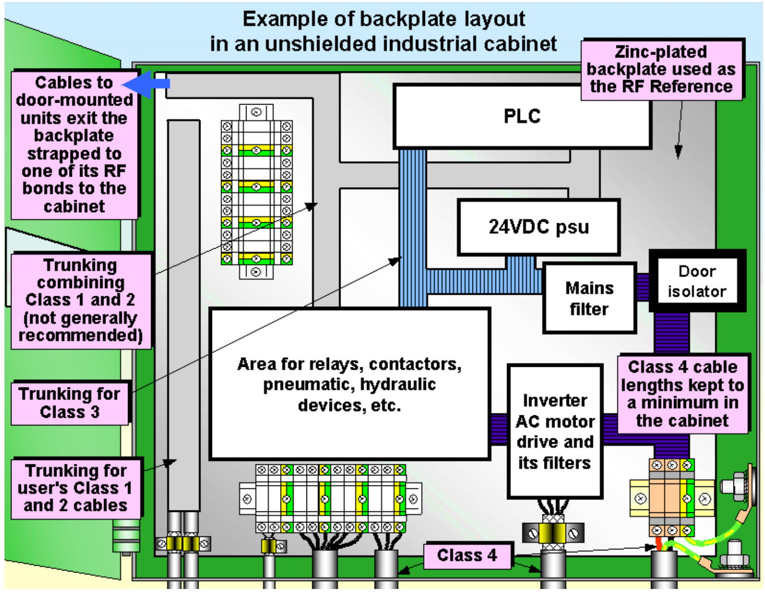


Fig 23

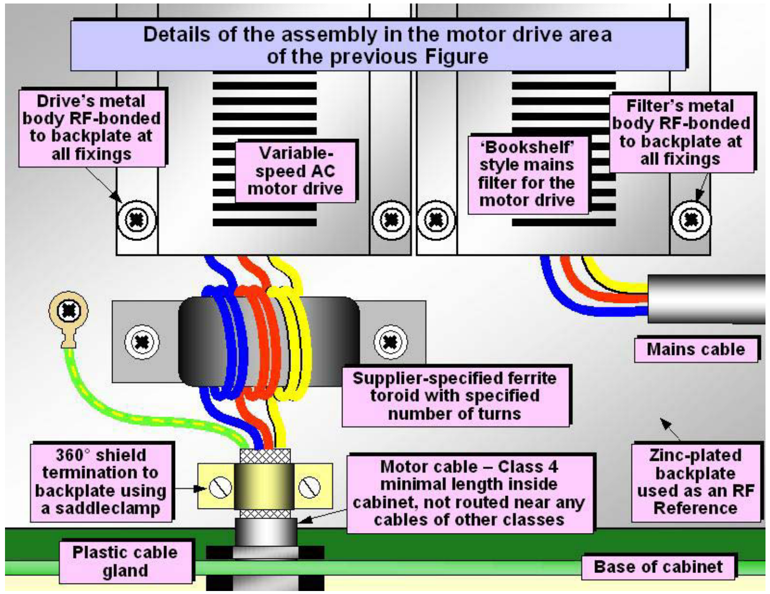
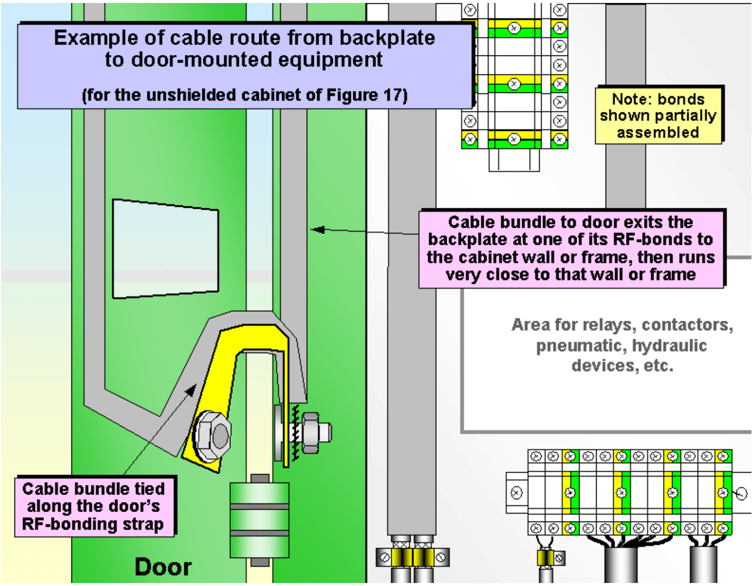


Fig 24



for this variable-speed AC motor drive required the use of a specified ferrite toroid with a specified number of turns on it, plus the use of shielded motor cable with the shield terminated 360° (see [28]) to the motor drive's metal chassis, and also at the motors metal terminal box (a typical requirement for inverter drives that do not have 'sinusoidal output' filters fitted to their motor cables very close to the drive).

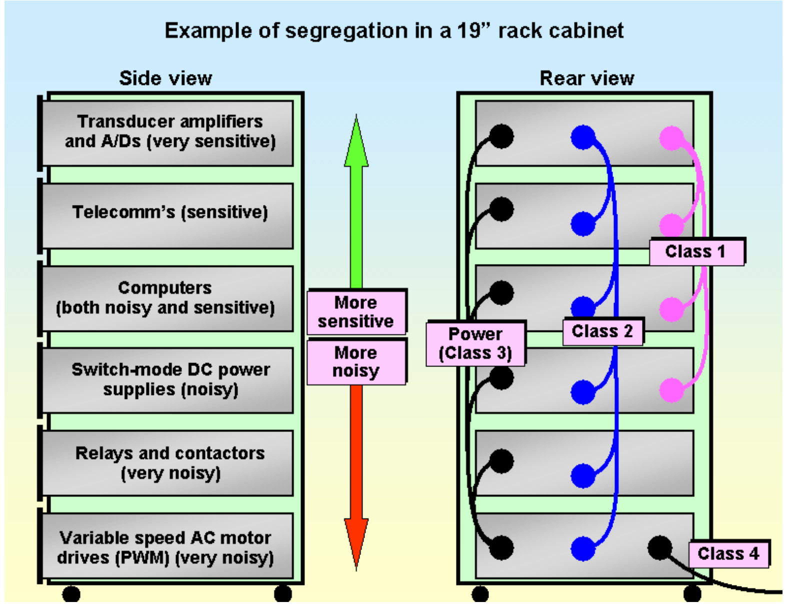
Figure 24 shows the remainder of the route of the bundle of cables in the top left-hand-corner of Figure 22, which are leaving the backplate area to connect to electronic units mounted on the door of this ordinary unshielded industrial cabinet. The cables are run close to the local RF Reference over their whole length, which means exiting the backplate at one of the points where it is RF-bonded to the cabinet wall or frame, actually tied down in such a way that it follows the route of the RF bond as near as possible. It is then routed along the wall or frame until it crosses to the door strapped to a short braid that RF-bonds the door to the cabinet wall. Hinges cannot be relied upon to electrically bond doors to cabinets, as they usually contain grease or plastic inserts. In a well-shielded cabinet the door will be bonded all around by a conductive gasket, so it does not matter where the cables cross the hinge area.

3.6 Segregating cables in rack-mounted equipment

Where the design of the rack-mounted units can be controlled, for example when they are made by the same company, they should segregate their rear-panel connectors to facilitate the segregation of cable classes within the cabinet, as shown in outline in Figure 25.

Notice also that Figure 25 shows how the racked units should be organised to place

Fig 25



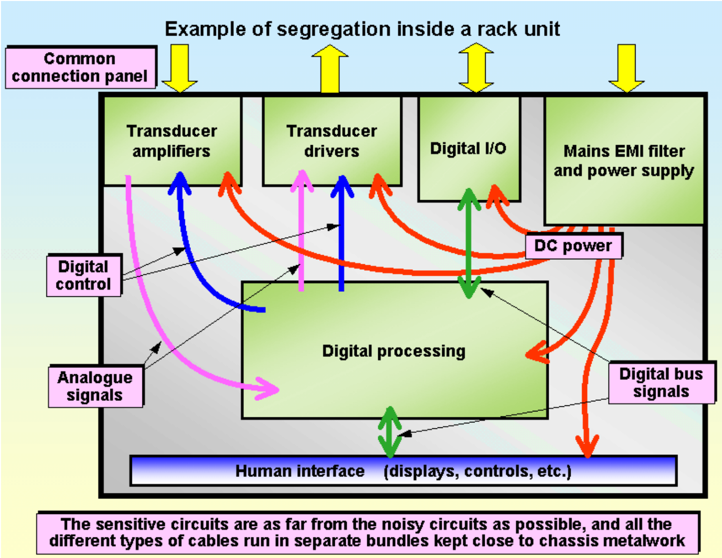
the ones with the highest levels of RF noise (relays, contactors, switch-mode power converters such as variable-speed AC motor drives and the like, etc.) far away from the units that are the most sensitive (computers, PLCs, displays, transducer amplifiers, telecommunications, etc.).

Where the rack-mounted units are purchased from a variety of suppliers there will probably be no consistency at all between their rear-panel connector layouts, and often no segregation between different cable classes either. In such cases it is important to determine which cables belong to which Class, and segregate them as close as possible to the rack units so that they can be bundled with their own Class for routing within the cabinet.

Creating an RF Reference for conductors to be routed against is not as easy when using a rack cabinet, as it is for a backplate-type industrial cabinet. Generally, it requires providing horizontal shelves for the rack unit to stand upon (as well as the units being bonded to the frame via their rack-mount 'ears'). These shelves should extend well beyond the rear panels of the units, and be RF-bonded to vertical metal sheets at the sides of the cabinet. Cables entering/exiting the rear panels of the racked units can then be routed close to their units shelves, where they will be sorted out into their Class bundles, then those bundles routed to the side sheets to run vertically between the shelves.

Of course, all the shelves and vertical sheets should be RF-bonded to each other and to the frame and other metal parts of the cabinet, as shown in Figures 4 – 7, to help create a good RF Reference as described in section 2, and the cables or cable bundles should be routed as shown in Figures 14 and 15.

Fig 26



Some industrial cabinet manufacturers make their own rack chassis units, usually where they need functions not available as a standard product, or where they hope to reduce cost. Figure 26 shows an example providing general guidance for the placement of electronic units and routing of interconnecting cables within a unit. It shows the sensitive units kept far away from the ones that create the most RF noise (the digital processing and the switch-mode power supply), and the cables routed close to the metal chassis and segregated by function in a similar manner to the Class structure discussed earlier.

This guide is not intended for the manufacturers of electrical/electronic units – it is meant for industrial cabinet manufacturers who purchase such units from third-party suppliers. Companies that wish to know more about the good EMC practices in the design and assembly of electrical/electronic units are recommended to read and apply all of the series that includes [28] [29] [30] and [31], and they will also find [12] useful.

3.7 Bonding cable shields (screens) to the RF Reference

3.7.1 Bonding cable shields at both ends is good EMC engineering practice

Cable shields should generally be bonded to their local RF References at *both* ends. This is because a shielded cable that is only bonded at one end can only provide good shielding performance up to a frequency at which its length becomes a significant fraction of the wavelength. The higher the shielding effectiveness required for the cable, the smaller the fraction of a wavelength permitted. To put some rough guidelines to this: for shielding of around 20dB at a given frequency with the shield only bonded at one end – the cable length should be less than one-twentieth of the wavelength at that frequency.

For example, at 400MHz (close to a typical transmitting frequency for walkie-talkies used in industrial premises) one wavelength in air is 0.75m, and one-twentieth of that is 37.5mm. This means that shielded cables which have their shields bonded at one end only, should be no longer than 37.5mm to maintain a shielding effectiveness of at least 20dB at up to 400MHz (to help prevent close proximity of walkie-talkies resulting in interference). If cables need to be longer than this (and most will be) they will need to have their shields terminated at both ends.

Of course, nothing is as simple as this, and most types of flexible shielded cables will be losing their shielding effectiveness by 400MHz. Braided cables generally give better shielding performance than wrapped foil types, and are easier to terminate in 360° fittings in connectors and glands. The better braid-shielded cables generally have good optical braid coverage, and double-braid or braid-and-foil may be used to give even better performance at higher frequencies. The very best flexible shielded cables are the (expensive) 'superscreened' cable types, which employ multiple shielding braids as well as at least one layer of 'MuMetal' tape.

Another problem with bonding a cable's shield at only one end, is that it then cannot provide any shielding at all from some orientations of magnetic fields. Shielding from these requires a current to flow in the shield from one end to the other, which can't happen if the shield is only bonded to the Reference at one end.

In some more extreme industrial environments there can be significant potential differences between the local RF References of items of equipment located in different areas of the site. These voltages are usually at the frequency of the AC power supply, typically either 50 or 60Hz. Bonding both ends of the shields of cables that interconnect these items can cause high levels of shield current to flow. This is a problem for the installation rather than the internal assembly of a product, and is dealt with by the use of techniques such as the meshed common bonding network (MESH-CBN) and the parallel earthing conductor (PEC) both of which are described in more detail in [3] and [18]. However, cabinets should be designed to allow their installation to use good EMC engineering practices, so should provide fixings suitable for the connections of the external PECs (which could be wires, ducts, armour, trays, etc.) – see [3] and [18].

With properly designed electronics, the only significant consequences of shield currents is heating of the cables – so-called 'hum loop' or 'ground loop' noise are a consequence of poor electronics design, which allows cable shield noise currents to flow directly into electronic circuits (usually by connecting the cable shield directly to the circuit's 0V). This issue is outside the scope of this article, but is dealt with in more detail in section 2.6.8 of the 2006 version of [28].

Of course, industrial cabinet manufacturers usually rely on third-party suppliers for their electronic units, which is why it is best for them to carefully check the EMC installation instructions for any unit, module or product they are considering, to find out if they *require* any cable shields to be bonded at only one end (there are other things to discover too, see [14]). This is typically an indication of poor design for EMC, although in some equipment intended for use in explosive atmospheres, it might sometimes be necessary for safety reasons.

3.7.2 Capacitive and hybrid shield bonding

If, for some reason, bonding the shield at both ends is impractical, it may prove acceptable to connect a short-leaded ceramic capacitor from one end of the of the cable's shield to its local RF Reference (instead of directly bonding it 360° metal-to-metal). This method is sometimes called hybrid shield bonding, because one end has a direct bond to its local RF Reference, while the other has a capacitive bond. (If both ends use capacitors in series with their shield terminations this is known as capacitive shield bonding.)

The frequencies and frequency ranges over which capacitive and hybrid bonding are effective depend upon the types of capacitors used and their values. The lengths of the capacitors' leads and any wires or conductors attached to them should *always* be minimised.

The capacitors should be rated for the voltages they have to withstand, and in the case of cables external to the cabinet and longer than about 10 metres they should be rated to withstand overvoltage surges and transients of at least 500V, and maybe as much as 10kV, depending on the installation. These surges are typically caused by lightning electromagnetic pulse (LEMP) and also by induced coupling from mains cables or lightning conductors carrying lightning surges that might be routed nearby. There may also be other sources of surge or transient overvoltages in some types of installation, such as large AC or DC motors controlled by electromechanical contactors, capacitor banks (e.g. for power factor correction), or superconducting magnets.

Where safety is a concern, the capacitors used may need to be safety-rated (and it is recommended that they are purchased as safety-approved and their approval certificates checked with their issuing bodies to make sure they are not forgeries.)

Unfortunately, without using special (and expensive) annular capacitors it is difficult to make capacitive shield bonding work well at the higher frequencies being used by modern electronic equipment, or work well over a wide range of frequencies. So hybrid shield bonding is a technique best kept in reserve to deal with special situations, such as where 360° bonding at both ends is not possible for some reason – and the frequencies for which the cable needs to have good shielding are grouped into a fairly narrow range.

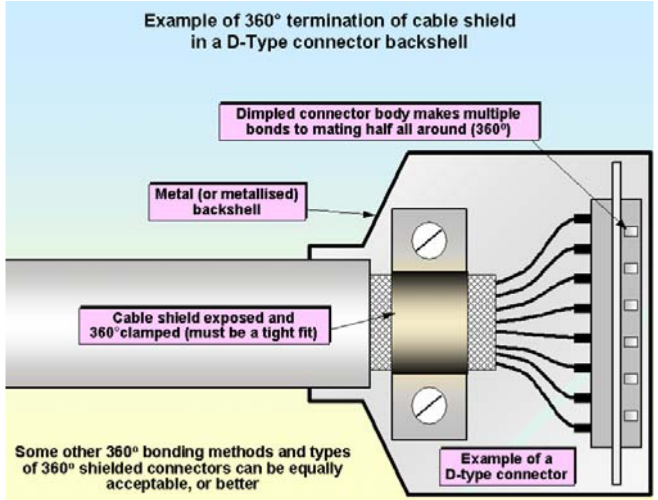
Where a cabinet provides for cable shield bonding at both ends, on-site replacement of direct bonds by capacitors is not too difficult, and removing the bonds altogether (should it prove necessary) is very easy. However, if the cabinet was designed to have its cable shields bonded at only one end only – attempting to fit capacitors or 360° bonds at the other ends to solve EMC problems on-site or during compliance testing can be very difficult and time-consuming.

3.7.3 It is best not to use a cable's shield to carry the return current

Wherever possible, never use the shield of a cable as the return conductor for the electronic signals (digital, control or analogue) or electrical power carried by its conductors – always use a twisted pair, or twisted triple, or twist whatever number of conductors it takes to fully embrace all the send and return current paths for a given power or signal connection.

Coaxial cables are often thought to be the best for controlling RF, because of their widespread use in RF and EMC test equipment – but in such applications the cables are always used as matched transmission lines, rarely the case in the industrial world. When not used as matched transmission lines in a controlled-characteristic-impedance interconnection system, coaxial cables are not as good for EMC as shielded twisted pairs, because they carry their return current in their shield, instead of in a dedicated conductor. [28] goes into this issue in more detail.

Fig 27



3.7.4 Techniques for bonding cable shields to the RF Reference

External cables entering a cabinet should have their shields RF-bonded to the cabinet's local RF Reference as soon as they cross its boundary. This applies even though they may also be bonded internally to the same Reference at another place, for instance at an electronic unit (see section 4).

An obvious way to bond a shield to the RF Reference is with a shield-bonding connector, such as the types shown in Figure 27 (a D-type) and Figure 30 (a bayonet-locking circular connector), with the chassis-mounted mating connectors themselves bonded metal-to-metal to the RF Reference at the edge where the cables enter or exit the cabinet.

The D-type in Figure 27 shows the cable shield bonded using a saddleclamp, which does not really provide a 360° shield termination but nevertheless is often an acceptable alternative. Some D-types require the assembler to make a pigtail from the braid or the drain wire of a foil-wrapped shield, and trap it under a spring clip or screw head or solder it to the body of the connector, like the connector shown in Figure 28. These types are all noticeably inferior to the saddleclamp method shown in Figure 27. D-type backshells are also available that provide a proper 360° shield termination, and these are generally preferred.

Many shielded D-type connector backshells do not provide a strain relief clamp for the cable jacket. In such situations, where the

Fig 28

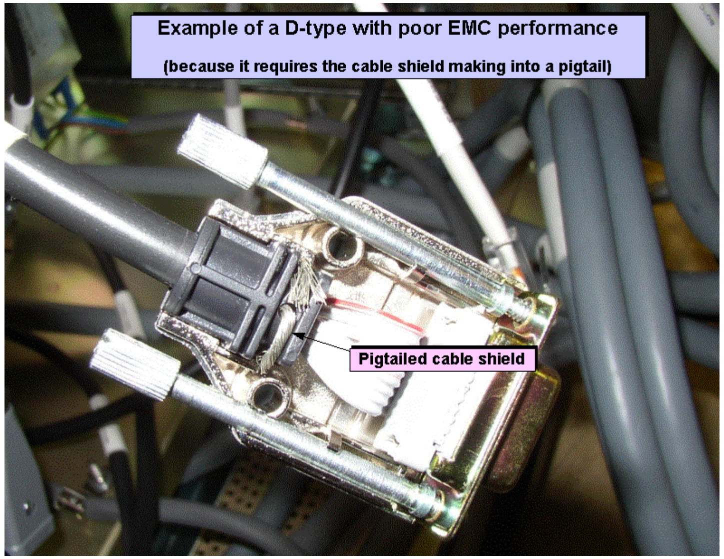
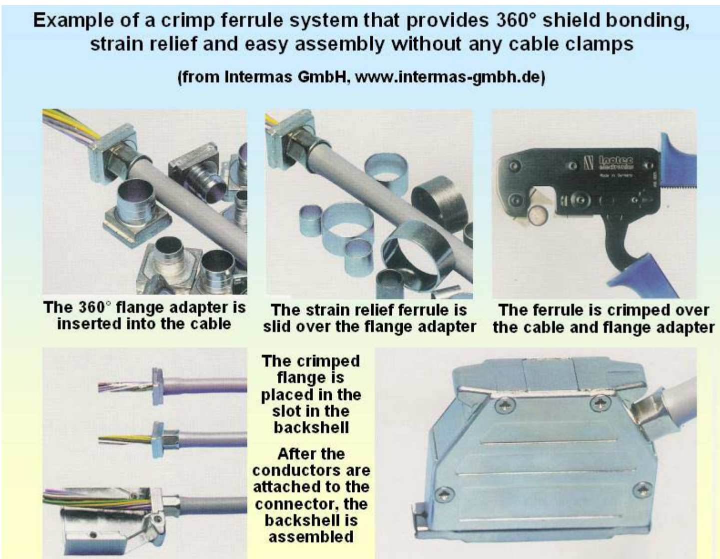


Fig 29



very best EMC performance is not required, it is usual to fold the shield back over the outer jacket and clamp both the shield and jacket at the same time. But this makes the EMC performance depend greatly on workmanship, so where the best EMC performance is required as well as strain relief, a D-Type (or any other type of connector) should provide 360° bonding of the *undisturbed* shield plus a strain relief clamp for the cable's overall jacket.

Some connector manufacturers offer shielding backshell systems for D-Type and other multiway rectangular connectors that combine both shield-bonding and strain relief functions in a crimp accessory that attaches a metal flange to the cable – the flange being clamped by the backshell when the connector is finally assembled, as shown in Figure 29.

Shielded industrial connectors are available in round and rectangular styles that will take very large number of pins, and carry signals or power up to high currents. Figure 30 shows a cross-section of a circular connector that achieves a very high quality of 360° bond between cable shield and connector body, and also provides a strain relief and environmental seal.

Many other types of connector and shield termination exist, but only those that make a 360° electrical bond between the cable's shield, the connector's backshell, and the mating connector's backshell (or the mounting panel of the mating connector) work well for EMC. Any connector bonding technique that involves disturbing the lay of the foil or braid of the cable shield, or extending it with wires (see the section on 'pigtails' below) will compromise the shielding performance of the cable and/or the connector.

Shielded cable glands can be used instead of connectors; to bond shields to the RF Reference as a cable enters/exits an RF Reference, as shown in Figure 31. Glands that bond with uniform pressure all around an undisturbed cable shield (e.g. a 360° bonding 'iris' spring or 'knitmesh' gasket) generally give the best RF performance, and an example of this type

Fig 30

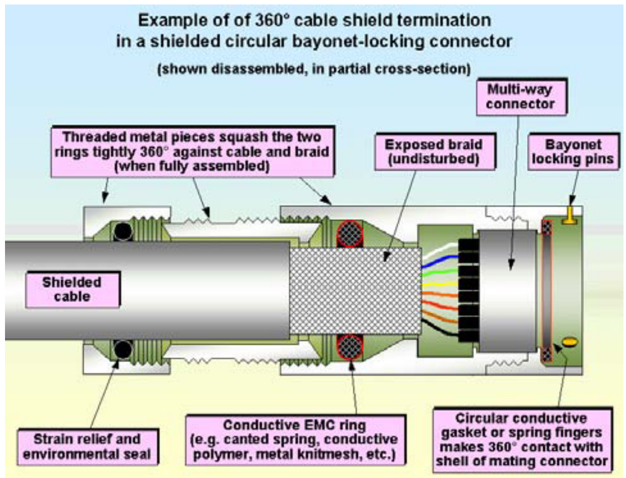
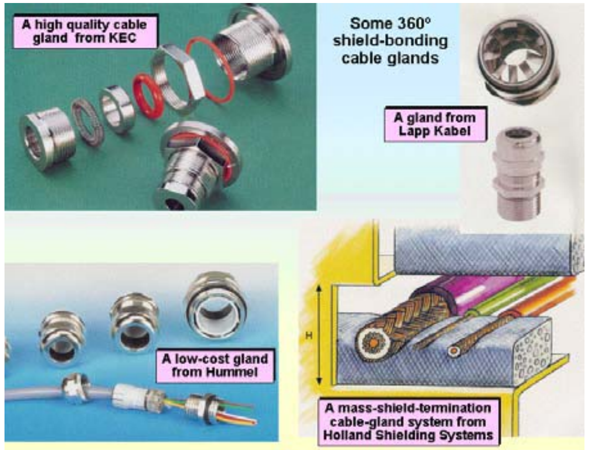


Fig 31



is shown in the top left of Figure 31. This type of gland uses the same design principles as the circular connector sketched in Figure 30, and is generally the best type to use for good EMC performance.

The type shown at the bottom-right of Figure 31 relies upon the assembler cutting the braid and spreading it over a plastic part before assembling it to the metal part that bonds to the RF Reference. Although this type of gland has a lower cost, the extra work required to assemble it costs more, and there is also the possibility that the assembler will not spread the cut braid evenly, or make other mistakes that degrade EMC performance.

Some manufacturers of cabinets or terminals sell their own cable shield bonding accessories. As long as they provide 360° (full circle) bonding *directly* between the cable shields and the *surface* of the local RF Reference they will give good performance. But beware – some of these attach the cables' shields to metal bars that have appreciable inductance, and these then usually connect to the local RF Reference by a wire or braid strap – adding even more inductance.

Mass shield termination as shown in the bottom-right of Figure 31 is a low-cost technique relying on clamping a number of exposed shields between conductive gaskets. It is quite easy to design similar shield bonding methods into, say, the base of cabinet, using simple metalwork and standard gasket types, as shown in Figure 32. This type of design easily outperforms many of the proprietary shield-bonding accessories offered by cabinet or terminal manufacturers.

Another method of mass-terminating cable shields is shown in Figure 33. Like Figure 32, this method can be easily adapted to suit a variety of situations.

Figure 34 shows two examples of terminating cable shields as they enter or exit the RF Reference plane in an industrial cabinet that uses a backplate. The saddleclamp method can also use P-clips, which do not provide as good a shield termination as a saddleclamp, which in turn is not as good as a proper 360° shield bond. But P-clips may be perfectly acceptable where the EMC performance is not required to be the highest. Saddleclamps and P-clips used to

Fig 32

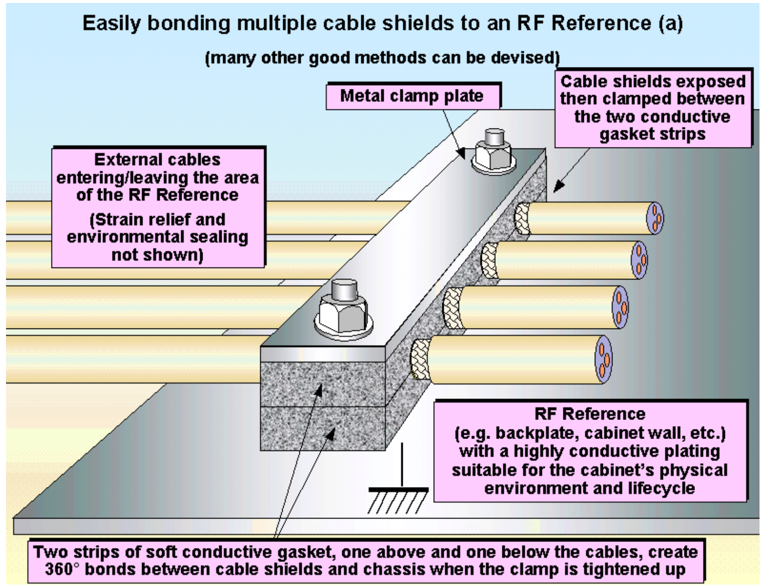


Fig 33

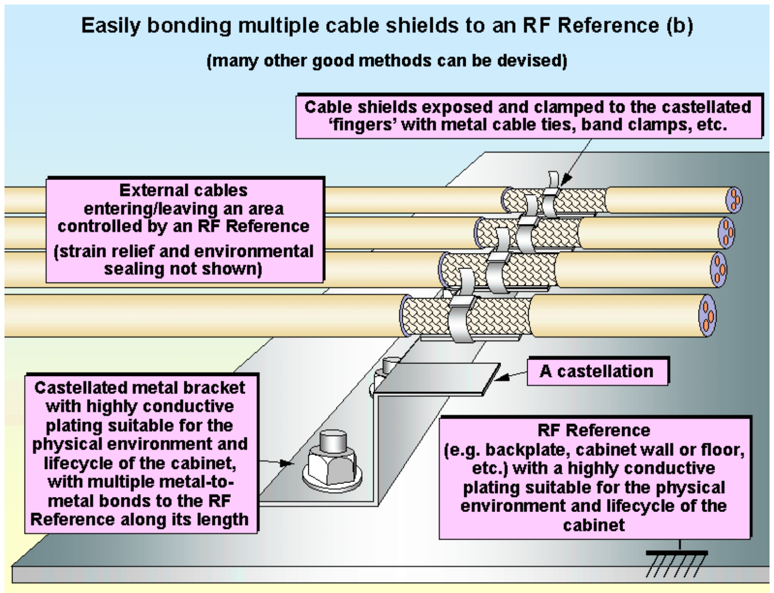
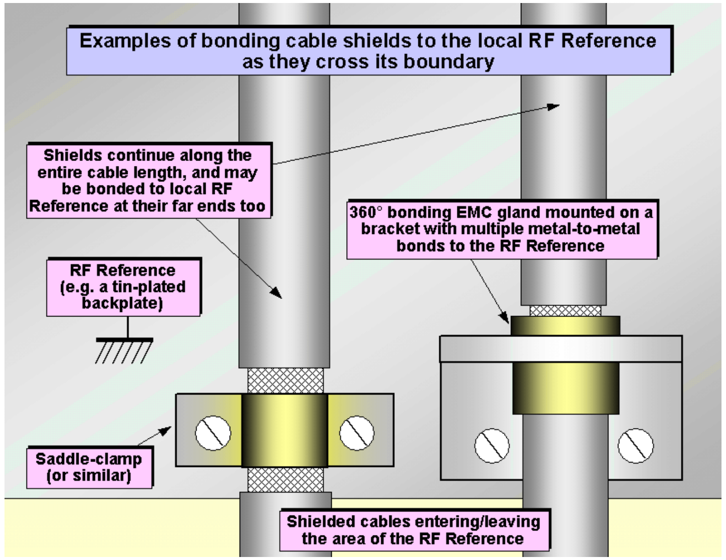


Fig 34



have to be obtained from plumbing, pneumatic or hydraulic component suppliers, maybe because the parts were too low-cost to be of interest to other manufacturers. However, there are now some EMC component suppliers who offer saddleclamps and P-clips for cable shield bonding.

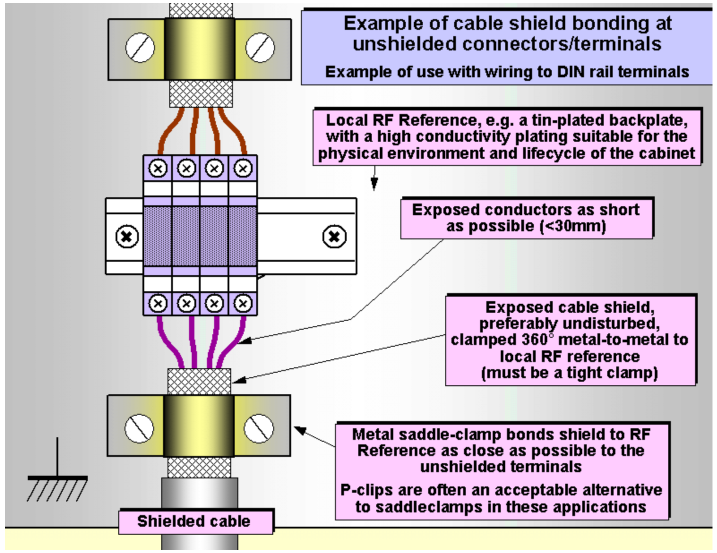
Where shielded cables don't employ shielded connectors at their ends or at junctions, and use unshielded connectors such as DIN rail terminals instead, their unshielded conductors degrade their EMC performance. Figure 35 shows how to use metal saddle-clamps (or P-clips) to bond the cable shields to RF Reference as close as possible to the unshielded terminals. The minimum length of conductors should be exposed, all the same length, as short as possible and routed as close as possible to the RF Reference.

Figure 35 shows DIN rail mounted terminals, but they could instead be screw or solder terminals or unshielded connectors on an electronics unit. Where the unshielded connector is mounted on an electronic unit, the best place to bond the shield is to the metal (or metallised) body of the electronics unit itself, close to the connector, but if this is not possible the nearest local RF Reference should be used instead – generally the metal surface the electronic unit is mounted on.

A number of practical alternatives to saddle-clamps exist, and the inventive designer will have no trouble in creating new constructions to ease assembly of his cabinets. The EMC performance of the unshielded connectors and exposed cable conductors will not be very good, but this design technique aims to make it as good as possible without changing to a shielded connector.

The EM performance of a shield bonded with a P-clip will generally not be as good as one bonded to its RF Reference by a saddleclamp, but because the EM performance of the unshielded connectors

Fig 35



is so poor, using P-clips might not make it very much worse. Figure 36 shows an example of an industrial panel using P-clips to bond the shields.

Where shielded cables are routed to unshielded terminals or connectors that are not very close to the RF Reference, the height of the bracket in Figure 33 can be increased to 'extend' the RF Reference closer to the terminals and provide a means for bonding the shields nearby. Although the metal bracket adds inductance and so has a deleterious effect at higher frequencies, it is orders of magnitude better than pigtailing the shields (see below).

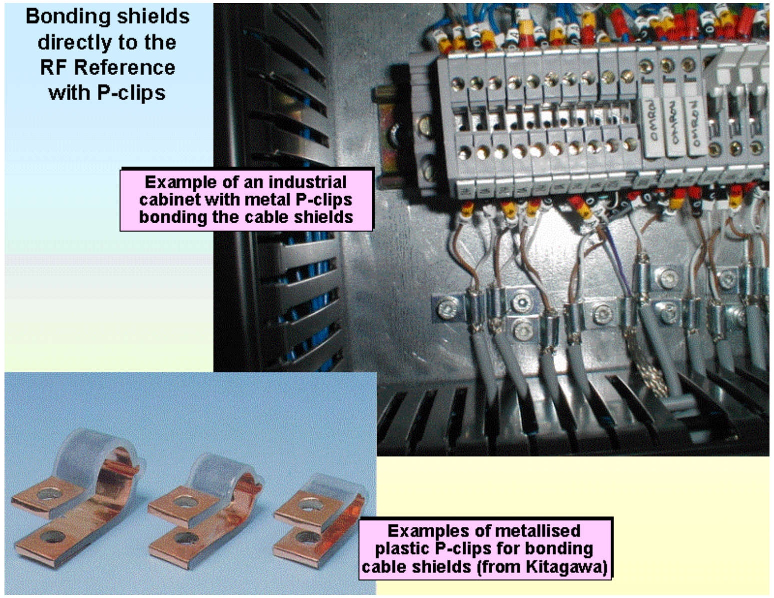
Similarly, a tall bracket could be used to support a conductive gasket clamp such as that illustrated in Figure 32, or a P-clip or saddleclamp as shown in Figures 34 – 36, close to the terminals or connectors. A tall thin metal bracket is not very much better than a pigtail (see below) at terminating a shield – such brackets should be *at least* three times as wide as they are tall, and have multiple metal-to-metal bonds to the RF Reference all along their length, spaced no further apart than 100mm.

If it is not practical to make a good RF bond at the end of a shielded cable using the methods described above (or similar techniques), make a good RF bond to the RF Reference as close as possible to the end of the cable, then continue the shield after this bond right up to the end of the cable – including the shielded connector backshell where one can be fitted.

3.7.5 Some additional shield bonding techniques

All cable shield bonding methods should make a tight fit all around the periphery of their cable's shield (but without crushing the cable), and this tight fit must not become loose with age, wear and tear. It is always best not to disturb the lay of a

Fig 36



cables' shield when 360° bonding to it, but where lower shielding performance is acceptable a longer length of braid shield can be 'scrunched up' to make a tight fit in a slightly loose saddle-clamp or connector backshell shield clamp.

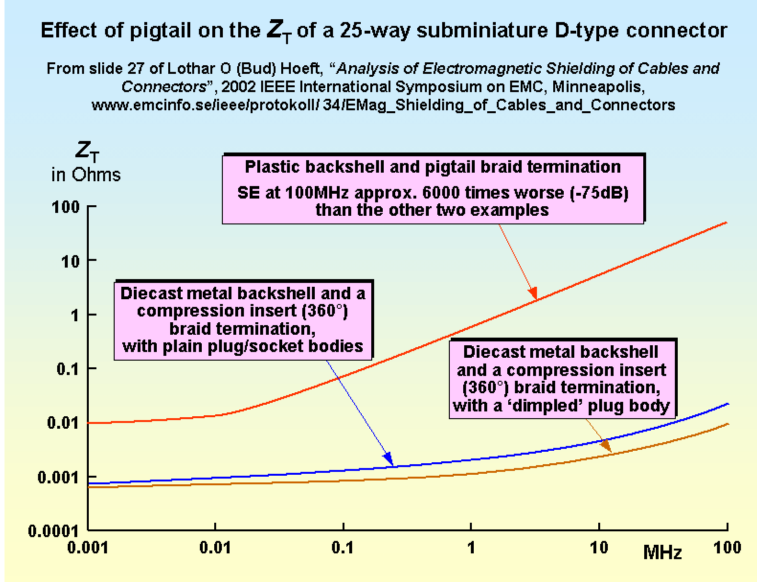
With foil shielded cables it is important to make sure that the metal surface of the foil makes a 360° contact with the connector backshell or other shield bonding method. One side of the foil is non-conductive plastic, and of course is not suitable for shield bonding. Where it is the internal surface of the foil that is conductive, the foil will need to be folded back, and with a spiral-wrapped foil cable this is difficult to do neatly and ensure a 360° bond. It is also important for any drain wires in the foil-shielded cable to be bonded along with the metallised foil surface. Where a foil shielded cable is a little loose in a shield clamp, it might be possible to wrap the drain wire over the exposed metallised foil surface a few times to make a more reliable clamp.

It has been common practice for many years to use the drain wire as the sole means of bonding foil-shielded cables, but this creates a 'pigtail' (see below) and ruins the EM performance of the cable. Because of the difficulties associated with making a 360° bond to metallised-foil shield materials, and the resulting susceptibility to variations in workmanship, braid rather than foil-shielded cables are generally preferred.

3.7.6 Pigtails – making the best of a very poor EMC technique

It has been common practice for decades to bond cable shields using short lengths of twisted braid, or the drain wires in foil-shielded cables, or by soldering a wire to

Fig 37



either of these to reach a distant shield bonding point. These days, and for the future, this is a terribly bad practice that effectively ruins the shielding performance of the cable.

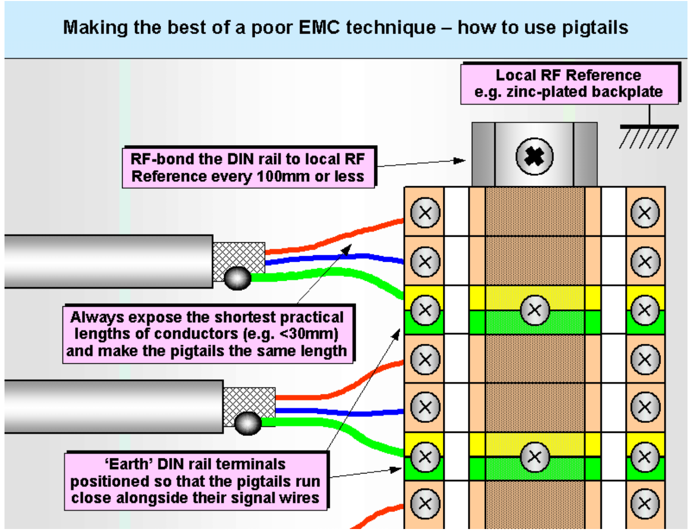
The author has measured emissions from industrial cabinets that failed the radiated tests around 70MHz because a single cable from the volt-free contacts of a PLC had a 25mm long pigtail to the RF Reference plane (the cabinet's backplate in that case). Replacing that very short pigtail with a metal saddleclamp that pressed the shield against the backplate reduced the emissions around 70MHz by over 20dB and the test was passed.

Figure 37 shows the effect of a pigtail on the surface transfer impedance (Z_T) of a 25-way subminiature D-type connector. Z_T is a measure of how well a cable or connector will function as a shield – lower Z_T at a given frequency means higher shielding at that frequency. A Z_T of around 10 milliohms is generally adequate for average levels of shielding, but high levels of shielding require 1 milliohm or less.

Figure 37 shows that the shielding effectiveness (SE) of a subminiature D-Type using a pigtail for its cable shield bond is average at frequencies up to about 20kHz, but above that frequency progressively reduces until by 1MHz the SE is unacceptably bad. Comparing this with the proper 360° shield bonding shows that at 100MHz the 360° shield termination is 75dB better than the pigtail.

It has been a common practice among the people who wire industrial cabinets to strip about 300mm of shield from the conductors at the ends of shielded wires and solder a long length of green/yellow insulated wire to the braid or drain wire. The (now unshielded) conductors are connected to the DIN rail or other terminal,

Fig 38



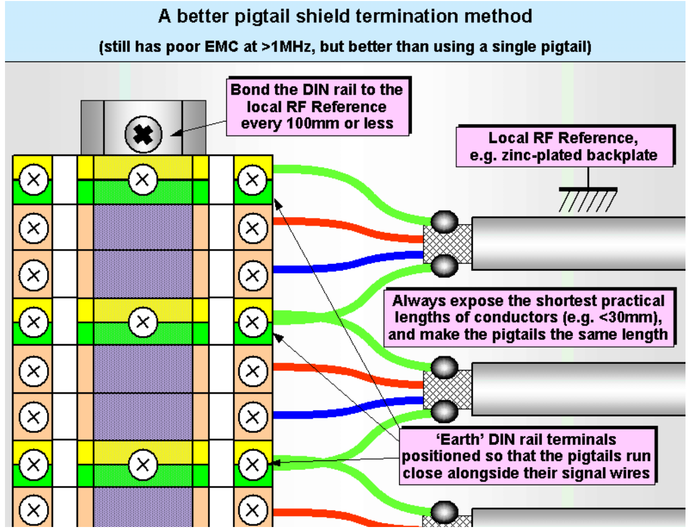
and the green/yellow wire taken to an 'earth' terminal that might be up to 1.5 metres away (a substantial copper bonding bar, usually called the 'main earthing bar', is a common choice). All the spare conductors are hidden in the plastic trunking, so that the conductors that exit the trunking appear short neat and tidy. This practice should no longer be permitted under any circumstances, for the reasons described below.

The pigtail used in the tests summarised in Figure 37 was about 30mm long – and that was long enough to completely ruin the cable's Z_T (and hence its SE) above 1MHz. Longer pigtails, even if they are green/yellow insulated or even braid straps, will have even worse SE. Also, the bundling of all of the excess lengths of unshielded conductors in the plastic trunking helps ensure lots of crosstalk between the signals on those wires and other cables – quite possibly what the cable shielding was supposed to be preventing in the first place.

Sometimes all that is needed is an average level of SE up to about 100kHz, for instance to reduce the coupling of 50/60Hz electric and magnetic fields from mains power cables and devices into sensitive transducer signals such as those from thermocouples, strain gauges and the like. Also, variable-speed motor drives and other switch-mode power converters rated at 1kW or more create high levels of electric and magnetic fields below 1MHz, so in some cases shielding may only be required for frequencies below 1MHz. And where unshielded terminals such as DIN rails are used, it may prove difficult to achieve good SE at frequencies much above 1MHz in any case.

So we need a method of using pigtails as effectively as possible, and Figure 38, using the example of DIN-rail terminals, shows this. A similar arrangement may be used at the unshielded terminals of electronic units. To get the best EM performance from a pigtail, the exposed conductors and the pigtail from a cable

Fig 39

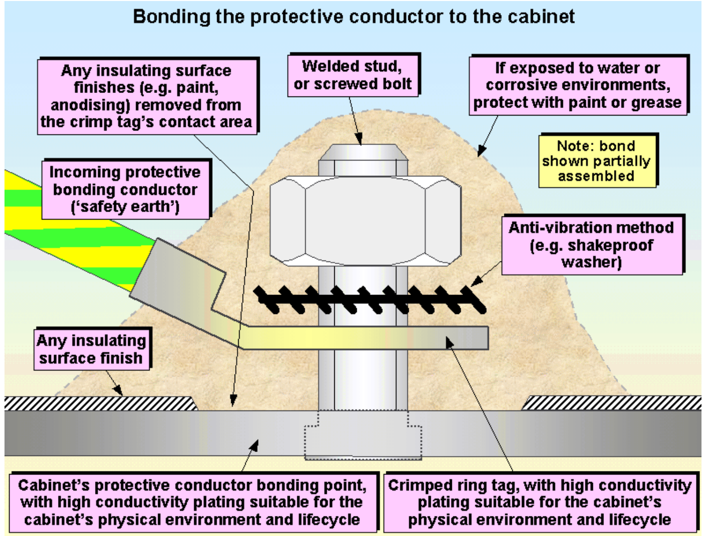


should be as short as is possible, consistent with the practical needs of assembly (say, around 30 mm), and where possible they should be kept close together by interleaving the shield bonding terminals with the signal terminals as shown in Figure 38. But remember that pigtailed shields are never going to be much use for EMC above 1MHz.

When using DIN rail terminals to connect pigtails to the local RF Reference, the metal DIN rail itself should be bonded metal-to-metal directly to the Reference at both ends, and at other positions along its length, preferably every 100mm or less. Placing shield-bonding terminals (usually coloured green/yellow to indicate they are bonded to the DIN rail and so are at 'earth' potential) either side of the signal/power terminals also helps provide a little shielding for them, although this cannot be expected to have any significant effect above about 10MHz. On *no account* should the green/yellow terminals used for bonding cable shields ever be grouped together at one end of a DIN rail, for 'neatness'.

The RF performance of pigtails can be usefully improved by using two pigtails for each cable. They should be soldered to either side of the cable, and connect to terminals either side of those used by the cable's conductors, as shown by Figure 39.

Fig 40



As discussed in section 2, an RF Reference is only useful for assisting or improving the EM performance of a circuit if it is local – meaning closer than $\lambda/10$ at the highest frequency to be controlled (e.g. closer than 30mm, to control up to 100MHz) – much closer spacing means better EMC. Section 3 described how best to route and bond cables with respect to the RF Reference; this section discusses techniques for bonding electrical/electronic circuits, units, modules, products, etc., to the Reference.

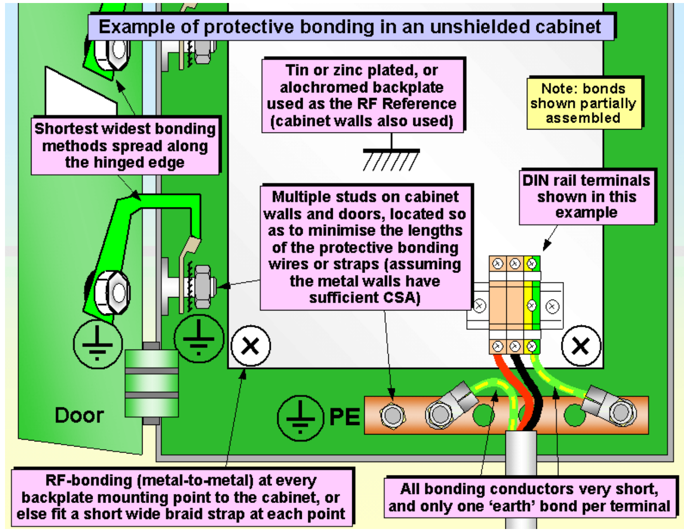
This section assumes the use of plain unshielded low-cost metal cabinets, and the techniques described are intended to get the best EMC performance from them without adding much (if anything) to cost. Section 5 discusses the good EMC engineering practices associated with the use of shielded cabinets.

4.1 Protective bonding (safety) conductors

Figure 40 shows the connection of the incoming protective conductor (often called the protective or safety earth; the green or green/yellow conductor in the mains supply cable) to the protective earthing (PE) point of a cabinet. Although this bond is primarily a safety concern, it helps to achieve the best EMC performance from the cabinet if the amount of protective conductor exposed within the cabinet is 150mm or less.

Bonding it to the *outside* of the cabinet would be the best for EMC, but for safety reasons it needs to be located close to the mains terminals. Its bonding terminal is preferably welded to the cabinet side or rear, although it could be screwed. For safety reasons the best type of welded stud is one that penetrates the cabinet from the other side, so that if the weld fails it is still retained in place and doesn't just pull free.

Fig 41



For industrial motor control cabinets, the safety standard EN 60204-1 requires no more than one protective conductor per terminal. This requirement appears to be widely ignored, for example with cabinets being wired using several ring tags 'starred' to a single stud, or with two or more green/yellow wires connected into individual DIN rail 'earth' terminals, making many industrial motor control cabinets non-compliant with safety regulations. A single 'earth' protective bonding wire per terminal is good advice for any industrial cabinet, so that if a panel (say) is removed and its protective bonding wire disconnected, this does not remove the protective bonding for anything else.

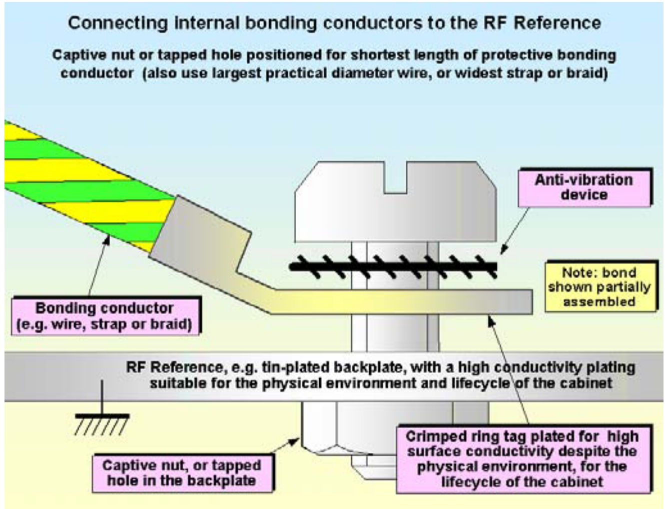
So to bond the backplate to the protective conductor I recommend a separate welded or screwed stud terminal near to the incoming 'safety earth' terminal (plus a sufficient cross-sectional area of metal between the two, see section 4.6), as shown in Figure 22.

Many control panel builders instead use a solid metal terminal block (usually called the 'main earthing bar') bonded reliably to the cabinet wall as their 'safety earth' star point, as shown in Figure 41. When using such bars, a stud that bonds the bar to the cabinet's metal wall should be located immediately adjacent to the place where the incoming protective conductor is connected.

It is always best to seam-weld all the parts of a cabinet's structure together, or else spot-weld them at multiple points along their joins, or fix them together with multiple screws or rivets that provide metal-to-metal bonding as discussed in section 2 – to help create the best possible RF Reference for the cabinet. But where it is necessary to bond them using wires, straps or braids, Figure 41 shows the basic principles *for a cabinet in which safety and RF-bonding can be safely combined* (see section 4.6).

Figures 22 and 41 are examples of protective bonding in typical industrial cabinets fitted with a backplate, and

Fig 42



assume that the cross-sectional-area (CSA) of the cabinet wall is sufficient to handle the earth-fault currents associated with the type of mains supply and incoming mains cables, according to the requirements of the relevant safety standard (typically either EN/IEC 61010-1 or EN/IEC 60204-1, making sure to use the current edition), taking the material (e.g. mild steel) and maximum cabinet temperature into account. Safety is more important than EMC, so must never be compromised for EMC reasons.

Given that the above CSA requirement is met, Figure 41 shows that doors, removable panels (and anything else associated with the cabinet structure that requires 'safety earthing') should make their protective bonding to their nearest cabinet walls using their own studs or terminals with the shortest and widest practicable conductors, e.g. metal straps or braids. In general, the shorter the length of the protective bonding wire, strap or braid, the higher the frequency at which a metal cabinet provides some shielding benefits.

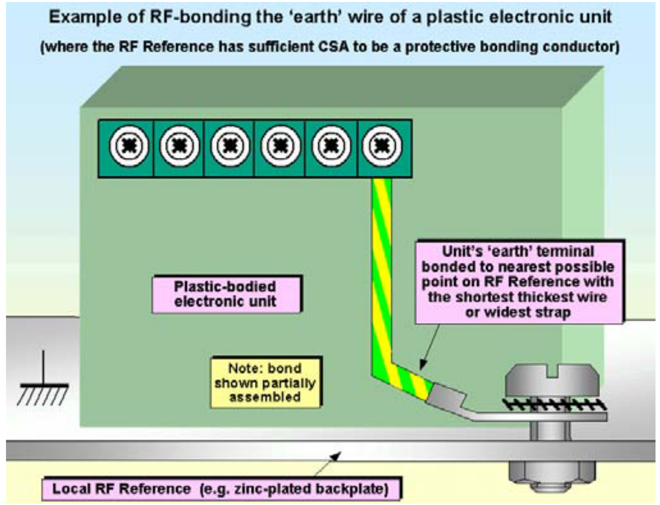
Also in general, better EMC will be achieved by having more than one short protective bonding wire, strap or braid to the part concerned – spreading them out as uniformly as practical along the length, height or width concerned, preferably spaced 150mm or less apart, as shown in Figures 4 and 5.

Figure 42 shows the details of connecting a protective bonding conductor to the RF Reference (the backplate in this example) and should be compared with Figures 6 and 7.

At frequencies for which the longest cabinet dimension exceeds one-twentieth of the wavelength (depending on the SE required for the cabinet) such straps or braids provide few EMC benefits, no matter how short they are, and a shielded cabinet using conductive gaskets around doors and removable panels may be required instead (see section 5).

To help create a larger local RF Reference and get the benefit of whatever shielding is available from a basic metal cabinet, the backplate should be RF-bonded metal-to-metal to the metal cabinet at every one of its fixing points. Some cabinets are made using plastic backplate mounting brackets, and wherever the regular fixings don't provide the required RF-bonding methods (see section 2) short wide straps or braids, or metal brackets, should be fitted between the backplate and the cabinet to provide RF bonds. Similar RF bonds should connect the backplate to the cabinet wall wherever cables enter or exit the backplate.

Fig 43



4.2 RF-bonding insulated electrical/electronic items to the RF Reference

Some insulated items of equipment, such as 'Double-Insulated' types (according to the safety standards), require no safety earth connections for their mains supply – but even so they might have a 'functional earth' that needs to be connected to the cabinet's RF Reference. Insulated items can only be connected to the RF Reference using wires, straps or braids, as shown by Figure 42, and this method – using the shortest practical wires, straps or braids – should be used to connect any protective ('earth') conductors or any functional earths to the local RF Reference. Figure 43 illustrates this practice.

It should be understood that just a few centimetres of conductor (whether round wire, wide metal strap or braid) can be completely ineffective (or even counter-productive) at frequencies above a few MHz, as shown by some of the graphs in [20], so although this method attempts to get the best RF performance from an insulated item, it cannot be relied upon to achieve good EMC where the item itself has a poor EMC performance (see [14]).

Shielded cables entering/exiting such items should have their shields bonded to the local RF Reference using one of the methods described in section 3.7 – unless specifically prohibited in the supplier's instructions – but only use pigtails when there is no practical alternative, and understand that the shield performance above 1MHz will then be very poor.

Where there are prohibitions about cable shield bonding, always check whether such suppliers really understand – in EMC terms – why they are making them, in case they are just blindly following the traditional and long-outdated practice of trying to avoid 'ground loops', see section 3.7.1 (and 2.6.8 in the 2006 version of [28]).

4.3 RF-bonding metal-bodied electrical/electronic items to the RF Reference

This section assumes the metal-bodied items have highly conductive surface platings (e.g. bright or dull tin, alochromed aluminium, etc.). Where they are painted or anodised or otherwise insulated, it is assumed that the insulating coatings are removed, and a highly-conductive corrosion-resistant paint applied (e.g. paint highly loaded with silver, zinc or aluminium specifically intended for creating conductive surfaces). If none of the above applies – or if bonding to an external metal chassis is specifically prohibited in the supplier's instructions – treat the item as an insulated item, see section 4.2 and expect similar EMC.

Where suppliers prohibit bonding the body of a unit, always check whether they understand why – in EMC terms, in case they are just blindly following the traditional and outdated practice of trying to avoid 'ground loops' (see section 3.7.1, and 2.6.8 in the 2006 version of [28]).

Items that employ conductively plated metal bodies often have better EMC performance than ones with painted, anodised or insulating bodies. They also provide more opportunities for improving their EMC by bonding their metal bodies to the RF Reference. So if there is a choice of electronic units for a particular function, and there appears to be nothing to choose between the EMC performances offered by their manufacturers, it should be best to choose the one with the conductively plated metal body.

Direct metal surface-to-metal surface electrical bonds give the best performance at radio frequencies above 1MHz or so, and should be used to bond all the metal fixings on any electronic units to their local RF Reference as shown by Figures 44 and 45 (also see Figure 7 for comparison).

Where the fixings for a metal-bodied unit are further apart than 100mm or so, adding more RF bonds between its metal case and the RF Reference will generally improve EMC. Ideally, low-profile metal brackets (with highly conductive surface plating) would be screwed between the item's metal body and the RF Reference – but this is not usually acceptable because it could damage the item or invalidate its warranty. Acceptable alternatives include making additional RF bonds with pieces of conductive gasket (see Figure 8) or metal spring fingers (see Figure 9).

Figure 46 shows an example of a 55kW variable-speed motor drive installation in a cabinet. The mains filter, DC power supply and variable speed drive are each in tin-plated boxes and each is RF-bonded to the tin-plated backplate using the method shown in Figures 44 and 45. Compare this assembly with Figure 23, and notice also that the motor cable's shield is RF-bonded with a saddleclamp type of fixing to a wide bracket extending from the drive's chassis (its RF Reference).

Modular units such as Programmable Logic Controllers (PLCs) consist of a basic chassis (or some other name) into which the modules are plugged. This chassis should be treated as described in sections 4.2 or 4.3, depending on whether its body is insulated or not.

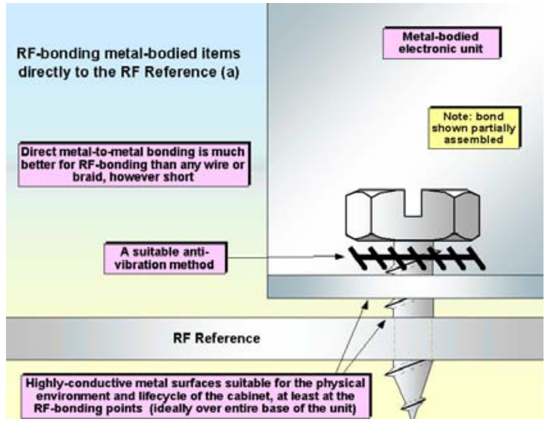


Fig 44

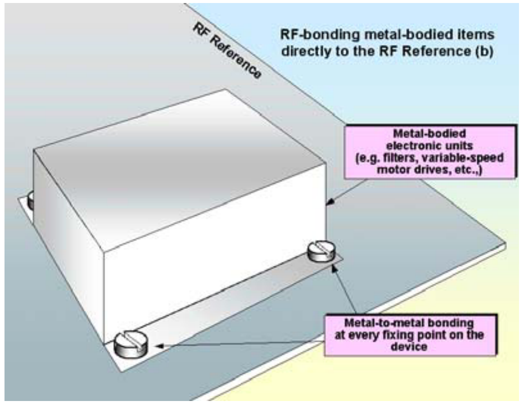


Fig 45

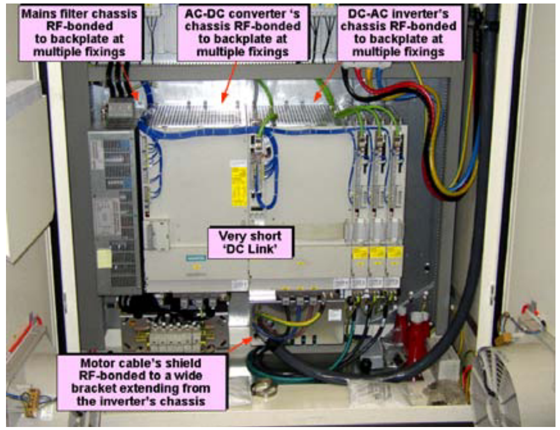
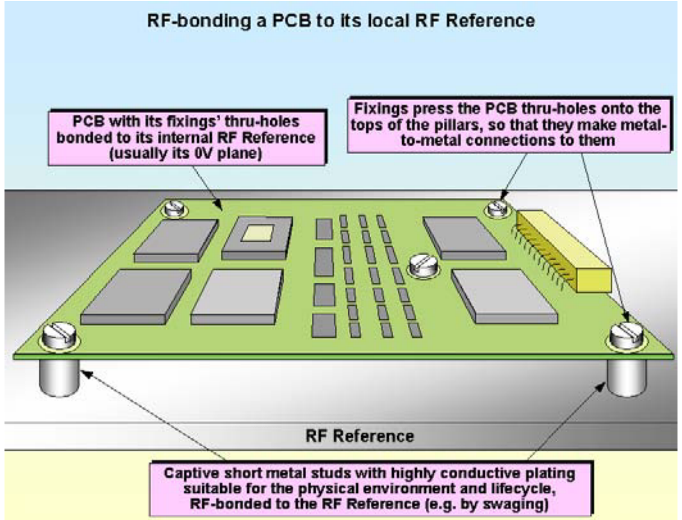


Fig 46

Fig 47



4.4 RF-bonding PCBs to the RF Reference

Ideally, PCBs would be contained within conductively-plated boxes and be treated as described in section 4.3. But sometimes cabinets use unenclosed PCBs, especially if they have been custom-designed for the cabinet manufacturer. Figure 47 shows the general principles of bonding a PCB's own RF Reference (usually its 0V plane) to the cabinet's RF Reference. The bonding points should be spread over the whole PCB area, and within it too, ideally spaced less than $\lambda/10$ apart at the highest frequency to be controlled.

Of course, this PCB bonding should not be done if specifically forbidden by the PCB supplier – but you should always check whether they really understand in EMC terms why they are making this prohibition, because they might just be blindly following the traditional and long-outdated practice of trying to avoid 'ground loops' (see section 3.7.1, and section 2.6.8 in the 2006 version of [28]).

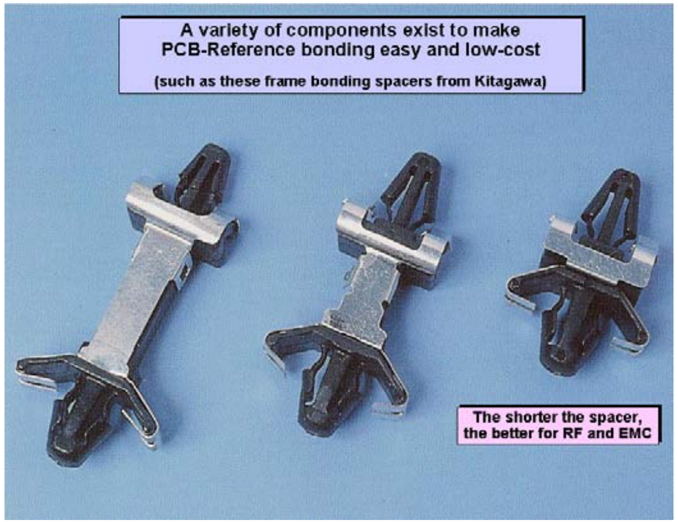
The PCB-to-Reference bonding points do not have to be fixing screws, they could use the modified clip-on mounting posts shown in Figure 48, or spring fingers such as those in Figure 9. Some manufacturers (e.g. Kitagawa) make spring fingers specifically intended for surface mounting and soldering on PCBs, for making additional RF bonds to their local RF Reference.

4.5 Capacitive and hybrid RF-bonding

Sometimes there are very good reasons why it is undesirable to make direct metal-to-metal connections between an electrical/electronic item (including PCBs) and its local RF Reference. In such cases RF-bonding can still be achieved using capacitors in series with each bond. Where there is a single direct bond, and the other bonds are capacitive, this is known as hybrid RF-bonding.

Capacitive and hybrid bonding was described in section 3.7.2, for bonding cable shields to the RF Reference, and exactly the same issues and capacitor selection issues apply when using these techniques for RF-bonding electrical/electronic items including PCBs.

Fig 48



When designing a PCB that requires capacitive or hybrid bonding, for an industrial cabinet, the series capacitors should be mounted on the board in series with the bonding points – with their traces and pads designed to minimise their inductances, to help achieve the best EMC performance.

4.6 Combining safety bonding with RF-bonding

In many industrial cabinets it is often easy to combine the safety and RF-bonding structures together, as shown in sections 4.1, 4.2 and 4.3. This saves time, improves EM performance, and also removes bundles of green/yellow wires from the plastic trunking – making more space and easing the wiring of the cabinet.

However, where 'earth-faults' could result in *very* heavy currents to a protectively bonded part, the CSA of the cabinet structure might not be sufficient to allow its use in the protective bonding system. Also, some safety inspectors might be uncomfortable if they cannot see green/yellow wires, straps or braids to a 'main earthing bar' from most/all of the protectively bonded structural parts and items of equipment.

Where the RF Reference cannot be used as the protective bonding system, both the RF Reference system and the 'traditional' protective conductor system should exist in parallel, creating a lot of 'ground loops'. In such cases we do not care how long the protective bonding conductors are, as long as RF-bonding system uses the shortest wires, straps and braids (preferably direct metal-to-metal bonds where practical). Of course, this creates a great many 'ground loops', but as was shown in section 2.6.8 of the 2006 version of [28], ground loops are generally a *good* thing for signals, EMC and safety – providing the electronics is competently designed and there are a large number of small loops and not just one or two large ones.

4.7 Choosing filters and bonding them to the RF Reference

4.7.1 Choosing filters

As Figure 21 showed, there are a great many types of mains filter, and there are also a great many types of signal filter – so it is important to choose the right ones for your applications. When choosing a mains filter, it is safest to assume that its attenuation at any frequency is no better than the worst-case derived from all of its matched 50Ω/50Ω, and its mismatched 100Ω/0.1Ω, and 0.1Ω/100Ω performance data for both common-mode and differential-mode (known instead as 'asymmetrical' and 'symmetrical' by filter manufacturers). Merely using the 50Ω/50Ω attenuation curves can result in *amplifying* an unwanted noise frequency instead of attenuating it.

Good filter manufacturers will provide all the above data as graphs covering the whole frequency range of interest, including both the conducted range (down to 150kHz or less) and the radiated frequency range (e.g. up to 1GHz or more). For more on these and other filter selection issues refer to [29] (especially its sections 3.2.8, 3.2.9 and 3.3.3) and also to [32].

It is also worth noting that the best filters for EMC have seamless metal bodies fitted with flanges or other means of directly bonding them metal-to-metal to a local RF Reference at least at two points.

4.7.2 Bonding filters to the RF Reference

Some filters rely solely on ferrites and have no need for any connection to the RF Reference. This type includes the cable chokes shown in Figure 20, and they are especially useful where a good quality RF Reference is not available at the frequency to be controlled.

However, most types of filters – and all medium or high-performance filters – contain capacitors, and it is vital for their EMC performance that their highly conductive metal bodies are bonded metal-to-metal to a local RF Reference that has lower impedance than their capacitors at the frequencies of concern. The bonds must be made *at least* at all of their fixing points, as shown in Figures 44 and 45 and described in section 4.3.

Many types of connectors are available with built-in filters, some of which are simple ferrites needing no Reference connection, some are simple capacitors, and some (more costly) types use Tee or Pi filter pins.

To help protect the electronics in a product from external EM disturbances, the filters fitted to external cables should be fitted at the point where the cable first crosses the boundary of the local RF Reference. But to help reduce interference *inside* a cabinet caused by the emissions from a noisy electrical/electronic unit, filters should be fitted to that unit's local RF Reference as close as possible to it.

Where filters must be used for both the above purposes (typical of the mains and motor drive cables associated with a variable-speed AC motor drive), their location in a cabinet can be a difficult compromise – so it is generally best to locate the noisy unit close to the edge of the RF Reference, and in the appropriate orientation, so that the filter can be mounted very close to the noisy unit and also close to the edge of the Reference where the filtered cable enters or exits.

Filters fitted to the incoming mains supply should be placed so that the length of external mains cable that enters a cabinet is minimised, preferably less than 150mm for industrial cabinets – and kept close to the RF Reference at all times. Smaller products should use a bulkhead mounted mains filter if at all possible, such as the popular IEC320 plug-inlet style, so that no external mains wires penetrate the cabinet at all. Mains filters fitted prior to on/off switches (or door isolators in industrial cabinets) will stay live even when the power is switched off at the product, so touch protection and appropriate safety warnings for their terminals must be provided (be sure to meet all the requirements in the relevant safety standards).

Filter input and output wires must never come anywhere near each other, as they are always at least one cable Class apart (see section 3.3). Cascaded mains filters can interact and make the overall EMC performance worse than that of each filter on its own, as discussed in the 2006 version of [29], so if it is necessary to cascade filters on a single cable the additional filter might have to have more stages, and be larger with a higher specification, than might seem necessary.

4.8 A single connector panel is best

It is best to provide a single connector panel for each cabinet, so that all external cables enter or exit the RF Reference in one place at one of its sides or edges.

This is so that (in conjunction with the other techniques described here) the CM RF currents (sometimes called surface currents) that can flow in long external cables, especially in some electrically noisy industrial environments or during thunderstorms, will flow from cable to cable via the connector panel or edge of the RF Reference through the shield terminations and filters mounted in that area.

The single connector panel technique gives best results when all of the external cables are either filtered or shielded at the point where they pass through the connector panel, using the techniques described in section 5.2 as if the connector panel was part of a shielded cabinet. This is because the external cables' circulating CM currents will then prefer *not* to flow through the rest of the cabinet or RF Reference, or through the internal electronics and their cables. This can significantly improve immunity to external EM threats, and it can also help contain CM currents generated *inside* the cabinet, significantly improving emissions.

4.9 RF-bonding VGA display panels to the RF Reference

VGA LCD panel displays are often used in modern industrial cabinets, but can be a significant source of emissions. If they have touchscreens, they can be a problem for immunity. The usual technique is to purchase types that have a continuous metal back cover that is electrically bonded all around its periphery to their metal 'picture frame' surround. Then the VGA panel's metal surround is RF-bonded metal-to-metal (or with a conductive gasket) to the door or wall of the metal cabinet, which should be a part of the RF Reference of the cabinet. This method can be seen as a variant of the Clean Box / Dirty Box method described in section 5.3.2.

If the VGA panels that have complete metal backs are not suitable, one should be made from thin metal (or copper tape) and RF-bonded all around its periphery to the panel's metal 'picture frame' surround, using conductive adhesive or conductive gaskets. Then the new back or the LCD panel's metal surround is bonded all around its periphery as described above.

If the above is not sufficient, a shielded window will be required – see section 5.3.2.

5.1 Introduction

Sections 2, 3 and 4 above assumed that a metal chassis, backplate, racking system, or cabinet was available and was used as a local RF Reference, but did not assume that the cabinet was designed specifically to provide any special shielding performance.

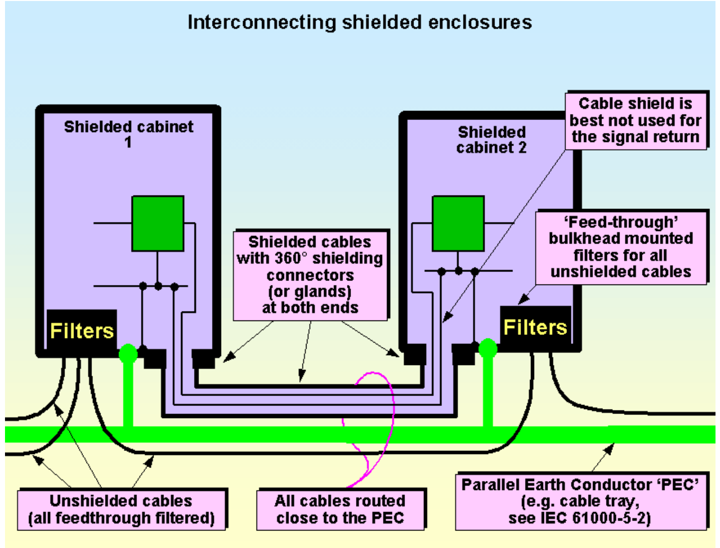
However, in some applications shielded cabinets are needed because the EM environment at the intended operational location could be too severe for the electronic units used inside the cabinet, or because the external EM environment needs to be protected from the EM emissions from the electrical or electronic units in the cabinet.

Cabinet shielding requires metal cabinets, or plastic cabinets with highly conductive metal-coated surfaces (plastic with conductive fillers is very difficult to use effectively). Very careful attention to detail in design and assembly is needed if the shielding provided by the cabinet is not to be ruined. There are two issues:

- Shielding and/or filtering of all conductors entering or exiting the cabinet, at the point of penetration of the cabinet wall, see section 5.2
- Control of all apertures, including at doors, removable panels, displays and ventilation, see section 5.3

The details associated with the design and assembly of shielded enclosures of all sizes are covered in [30].

Fig 49



5.2 Shielding and/or filtering of all conductors entering or exiting the cabinet

Shielded cabinets complete with shielded windows and ventilation with excellent EMC performance can be purchased from a number of suppliers, and *can easily be completely ruined* by cutting apertures for door-mounted units, drilling holes, poor filter mounting, poor cable shielding or shield bonding, or leaving doors open. This section covers cable penetrations, whilst section 5.3 covers apertures and gaps.

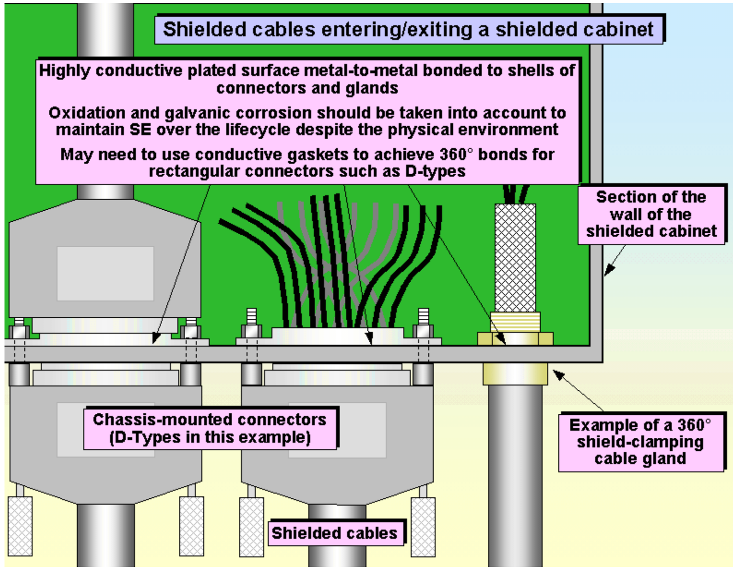
All conductors entering or exiting a cabinet must be either shielded and/or filtered with the shield and/or filter RF-bonded to the cabinet wall (or floor, rear, etc.) at the exact point of penetration of the cabinet wall. There are no exceptions to this rule for any conductors of any type, whether they are fibre-optic draw wires; metal pipes or flexible pipes with metal strengthening for hydraulics or pneumatics; cable armour, etc. The general principles of controlling cable penetrations are illustrated in Figure 49.

It is common to find the SE of a cabinet completely ruined by something as trivial as a mouse cable penetrating one of its sides. The mouse signals themselves are not generally a cause of emissions – the problem is that the mouse cable conductors are accidental antennas just like any other conductor (see section 1.4 and Figure 3). They pick-up EM noises on either side of the cabinet wall and re-radiate them on the other sides – thereby defeating the expensive shielding of the cabinet.

5.2.1 Shielded cables entering/exiting a shielded cabinet

Figure 50 shows the good EMC engineering practices required to be used when shielded cables penetrate a shielded cabinet wall.

Fig 50



The metal bodies of the chassis-mounted connectors or glands must make multiple metal-to-metal contacts with the wall of the shielded cabinet, at the point where they pass through it to connect to the cable-mounted connectors. The RF-bonding techniques for the cable shields in the cable-mounted connectors were described in 3.7.4 and Figures 27-30. It is very important to ensure that the cabinet has a highly conductive plating that is suitable for the physical environment and lifecycle of the cabinet (see section 6) at least in the areas where the connectors or glands are to be installed.

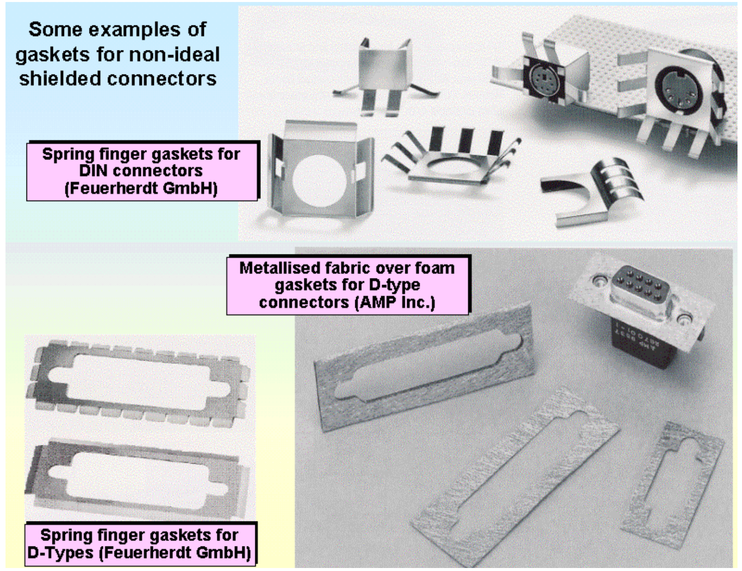
Circular connectors and glands generally make a good 360° electrical bond all around their cabinet aperture. However, rectangular connectors generally only achieve reliable RF bonds at their mounting points (two, for a D-Type) and where high values of SE are required, or where frequencies above 100MHz are to be controlled, they should be fitted with a conductive gasket during assembly to achieve a good RF-bond all around their perimeters. A number of manufacturers make EMC gaskets for different types of chassis-mounted connector, such as those shown in Figure 51.

Saddle-clamps, P-clips, pigtails and any other shield bonding method that cannot achieve a 360° electrical bond around the aperture required for the connector or gland in the cabinet wall, must not be used to bond cable shields as they enter/exit a shielded cabinet. The only exceptions to this might perhaps be in very special circumstances where the shielded cabinet is not required to shield against frequencies above, say, 100kHz (and even then, pigtails are not recommended).

5.2.2 When good shielding practices contradict supplier's instructions

It sometimes happens that two items of equipment are installed in separate shielded cabinets, and need to be

Fig 51



interconnected by a shielded cable – but one of the equipment is supplied with EMC instructions that state that its cable shield must only be connected at one end (usually at that item of equipment, and usually to a screw-terminal or connector pin). Leaving aside the issues of whether the supplier had used good EMC design, or was simply regurgitating 'traditional' instructions that are now decades obsolete – unless the supplier can be persuaded to alter his EMC instructions they should be followed or else they will disclaim all responsibility for interference.

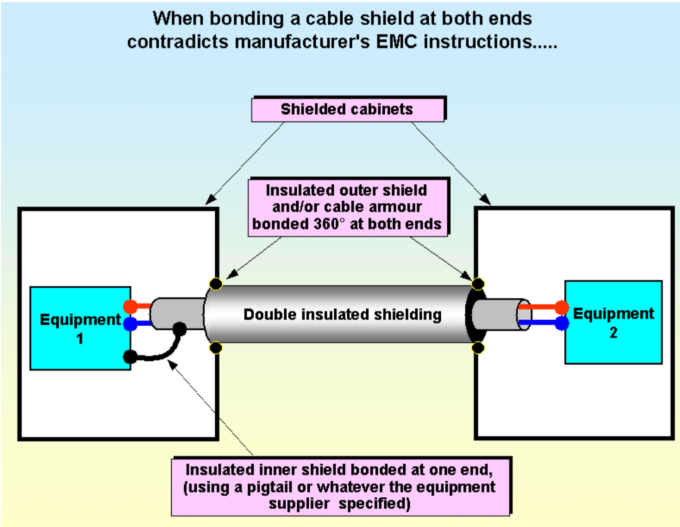
The problem is that unless the shield is RF-bonded to the walls of both shielded cabinets, following the equipment supplier's instructions to bond the shield at only one end will fatally compromise their shielding performance. Figure 52 illustrates one solution – use a double insulated shield cable and RF-bond the outermost insulated shield to both the shielded cabinets in the approved manner (see section 5.2.1). The insulated inner shield can then be terminated in accordance with the supplier's EMC instructions.

Where both equipment suppliers insist that the cable shield must only be bonded at one end, and they don't agree on which end, the method of Figure 52 will preserve the SE of the cabinets, but cannot resolve the problem of which end to bond the inner shield.

5.2.3 Unshielded cables entering/exiting a shielded cabinet

Every unshielded cable that enters or exits a shielded cabinet must be fitted with a filter that provides a similar level of RF attenuation versus frequency as the SE required for the cabinet. This filter must be mounted at the point where the cable penetrates the metal (or metallised) wall of the cabinet, and must make multiple metal-to-metal electrical bonds at that point.

Fig 52



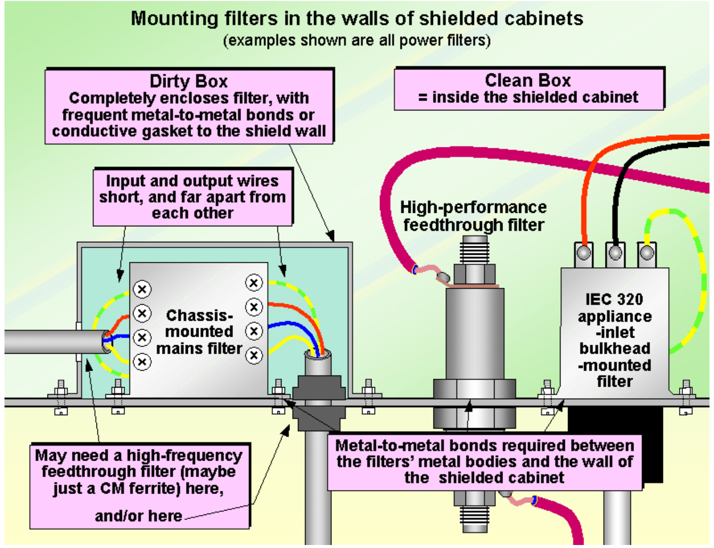
'Through-bulkhead' filters and filtered connectors cause the least degradation of a cabinet's SE, as long as their metal bodies make multiple metal-to-metal bonds to the cabinet wall all around the perimeter of their cut-outs, as illustrated in Figure 53. Many cabinets have had their SE ruined by a lack of provision of metal-to-metal bonding of IEC 320 appliance-inlet filters.

Where modest levels of SE are required from the cabinet, it may be enough to rely on the bonds provided by the fixings of the filter, but for good SE – especially at frequencies above 100MHz – a conductive gasket may be required to bond the filter's metal body to the cabinet's metal surface all around its periphery.

Note that Figure 53 does not show the protective cover that would be required for the safety of the high-performance feedthrough filter.

An alternative to is to use a lower cost chassis-mounted filter. These cannot be installed so that they penetrate the wall of a shielded cabinet, so when used on cables that enter or exit a cabinet they degrade its SE. However, they can be used with what is usually called the Clean Box / Dirty Box method, as shown in Figure 53. Attention to detail is needed to achieve high values of SE with this technique, especially minimising any gaps in the RF-bonding around the edges of the Dirty Box, and reducing the coupling of high frequencies between the input and output cables inside the Dirty Box by keeping them short and far away from each other. There will still be some coupling between the input and output cables inside the Dirty Box, especially at frequencies above 100MHz, so a high-frequency through-bulkhead filter may still need to be fitted to one of the cables. Often, this coupling can be reduced sufficiently by adding one or more soft ferrite cable suppressers (CM chokes, see Figure 20) to one or both cables close to the Dirty Box.

Fig 53



'Room filters' are chassis-mounting filters specifically designed for penetrating the walls of shielded cabinets without compromising their SE. They incorporate compartmented shields for their input and output terminals (effectively two separate Dirty Boxes), and their filtered outputs enter the shielded room through galvanised conduit with 360° bonding to the wall of the room, as shown in Figure 54.

Room filters are available from a number of manufacturers, suitable for every type of signal or electrical power. They are generally designed to achieve attenuations of at least 80dB from 100kHz to at least 1GHz, and types are available that go down to kHz and/or up to 40GHz and meet military specifications. Room filters can also be fitted to industrial cabinets, and are generally required when a shielded cabinet needs to have the highest EMC performance.

5.2.4 A segregated cabinet

Figure 55 shows a shielded cabinet that has been segregated into 'clean' and 'dirty' volumes, using the methods described above for terminating cable shields and screw-terminal filters. Instead of dividing a cabinet, some designers bring their cables into a small Dirty cabinet that is bolted (preferably seam-welded) to the side of the Clean cabinet.

5.2.5 A single connector panel is still the best

The benefits described for a single connector panel in section 4.8 also apply in the case of a shielded cabinet, because the internal and external circulating CM currents ('surface currents') do not have to cross any joints or gaps in metal surfaces, and this helps keep the internal currents inside, and the external currents outside – just what we want for good emissions and immunity respectively.

Fig 54

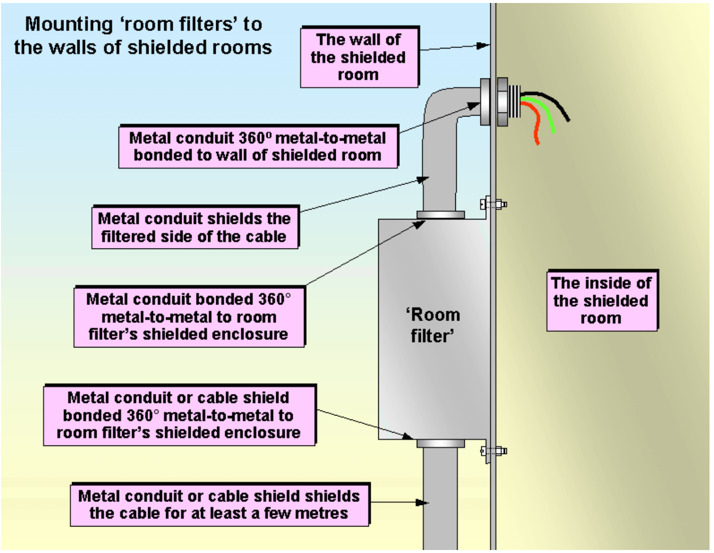


Fig 55

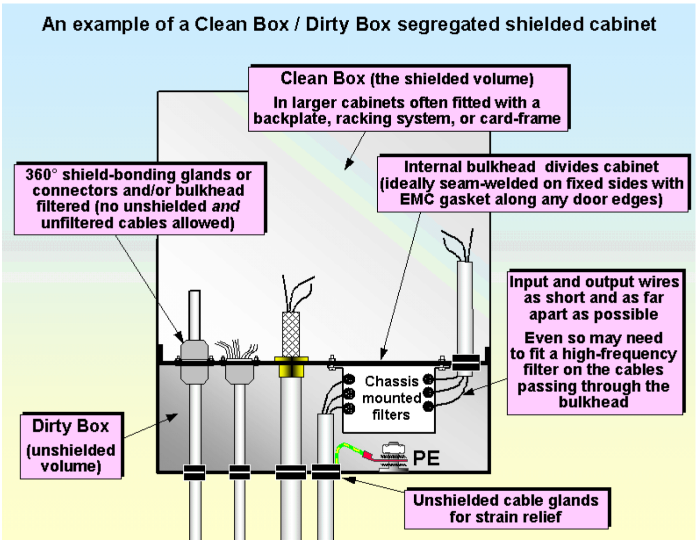
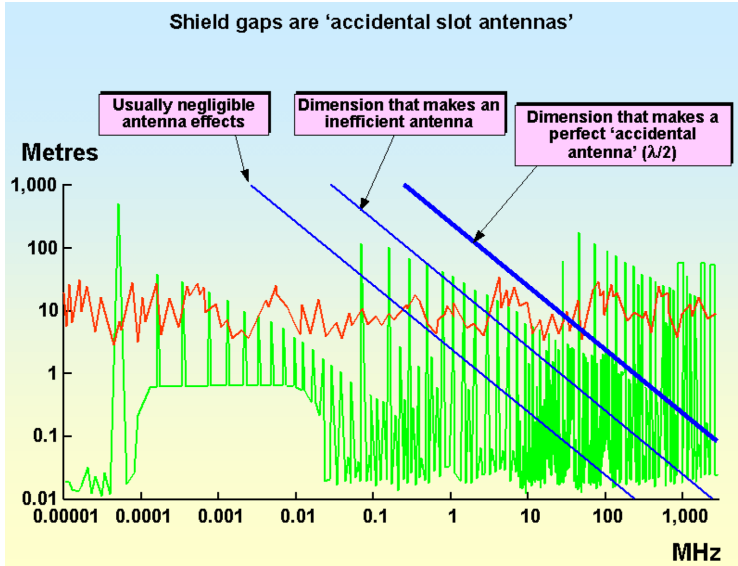


Fig 56



5.3 *Controlling apertures and gaps in shielded cabinets*

5.3.1 Introduction

Shielded cabinets complete with shielded windows and ventilation with excellent EMC performance can be purchased from a number of suppliers, and *can easily be completely ruined* by cutting apertures for door-mounted units, drilling holes, poor filter mounting, poor cable shielding or shield bonding, or leaving doors open. Section 5.2 covered the shielding and/or filtering of *all* cable penetrations, whilst this section covers apertures and gaps.

Apertures and gaps in a shielded cabinet generally act as 'accidental slot antennas' as shown by Figure 56, much as conductors act as accidental antennas as shown by Figure 3. It does not matter how narrow a gap is (even as thin as a layer of paint or anodising), or even if it is shaped like a labyrinth and there is no line of sight through it – it still leaks RF energy and degrades the cabinet's SE. Having accidental slot antennas in the wall of a shielded cabinet compromises its SE.

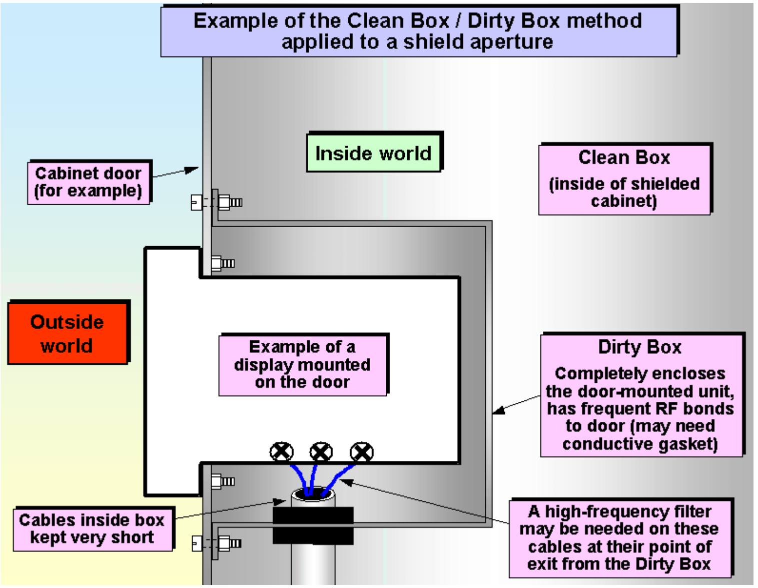
[30] describes good shielding practices for cabinets, and goes into detail on apertures and other issues that will not be repeated here.

5.3.2 Displays and controls

Figure 57 shows how to use the Clean Box / Dirty Box method where an item (such as a display, meter or control) has to penetrate the wall of a shielded cabinet. It is important to note that the item in the Dirty Box does not benefit from the shielding of the cabinet, so must have emissions and immunity performance that is adequate given the external EM environment.

Much better EMC is achieved by placing displays behind shielded windows,

Fig 57



especially with VGA-type LCD panels, and this can be important where a good SE is needed or higher frequencies are to be controlled.

Shielded windows use very fine blackened metal meshes, or conductively-plated layers (often indium tin oxide, known as ITO), sandwiched between two clear plastic panels, and the metal mesh or plated layer must be metal-to-metal bonded to the display's cut-out in the shielded wall all around the perimeter of the display. Figure 58 shows a shielded window that has just been manufactured, before the excess mesh has been removed. They are all designed so that the mesh is exposed around the four sides so that it can be 360° bonded to the shield wall.

Figure 59 shows some example figures for the SE achieved by some types of shielded window materials. Note that these are for the materials themselves, measured under ideal conditions. In practice the dominant factors for a cabinet's SE are usually the design of their assembly, and the quality of the workmanship when they are assembled in the cabinet. Metal mesh windows generally give better shielding performance than conductive coatings, for a given level of optical transmission loss and degradation of visibility, but can suffer from Moiré fringing effects if not selected carefully to suit the pixel size of the display. All shielded windows make the display look dimmer, so backlights may need to be more powerful.

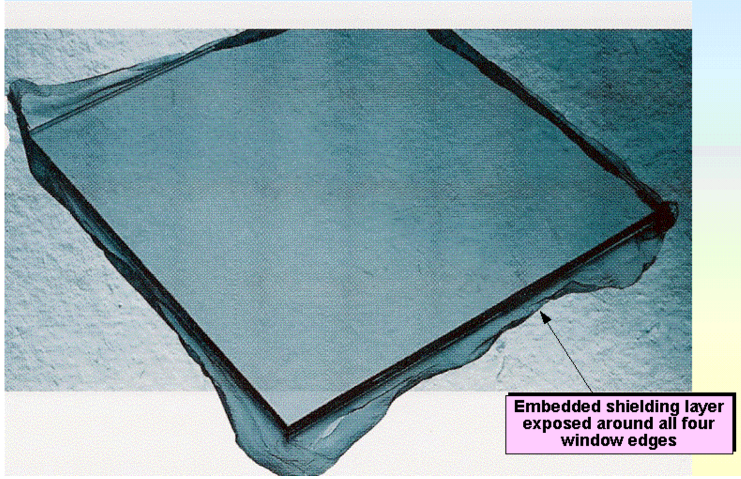
Touchscreens behind shielded windows are possibly a good EMC solution to the problem of adding human-machine interfaces to shielded cabinets, although some touchscreen technologies can be difficult to use with a shielded window.

'Honeycomb metal' can also be used for shielding displays, and has excellent SE values but has an extremely limited viewing angle. This can be very useful in security applications, because it makes it almost impossible for anyone to see a display unless they are right in front of it, but this is not a desirable feature in industrial applications.

Fig 58

Example of a mesh-shielded window, before assembly

(from TBA-ECP)



5.3.3 Ventilation

Ventilation apertures can be shielded by fitting a wire mesh (welded at each wire crossover in the mesh) over the aperture, with each wire electrically bonded metal-to-metal to the wall of the shielded cabinet all around the periphery of the cut-out in the cabinet wall. The smaller the mesh size, the better the SE. Perforating the cabinet wall with a number of small slots or holes can achieve the same SE and ventilation as fitting a wire grille over a large aperture, and avoids the need to provide RF bonding around the periphery of a wire mesh.

A number of shielding manufacturers sell pre-assembled shielding grilles that may simply be fitted with a conductive gasket all around their edges and then bolted into place on the cabinet wall (which of course must be highly conductive over the required bonding area). Some of these are based on wire mesh, and some on more exotic technologies such as wire wool or 'honeycomb metal' to give better SEs, and some examples are shown in Figure 60.

A technique known as 'waveguide below cutoff' can provide very high values of SE with very little impedance to the airflow. This technique is described in detail in [30], and honeycomb metal ventilation panels are an example of its application.

5.3.4 Doors and removable panels

To achieve useful SEs, apertures in an cabinet must be few in number and small in size, so doors and removable panels must have frequent electrical bonds all around their edges. Bonding them with

Fig 59

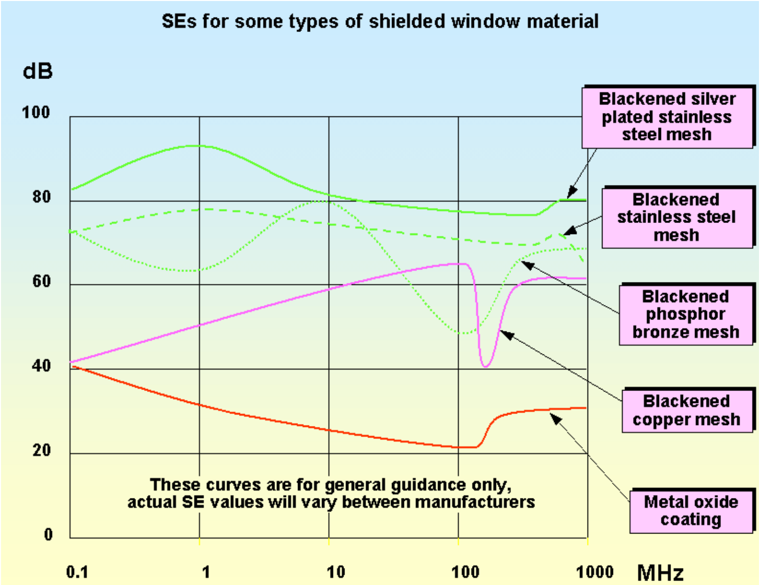


Fig 60

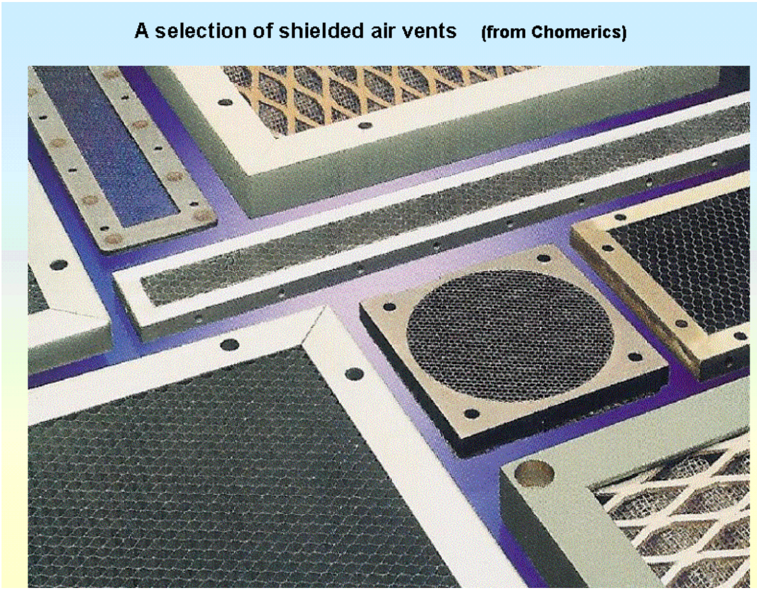
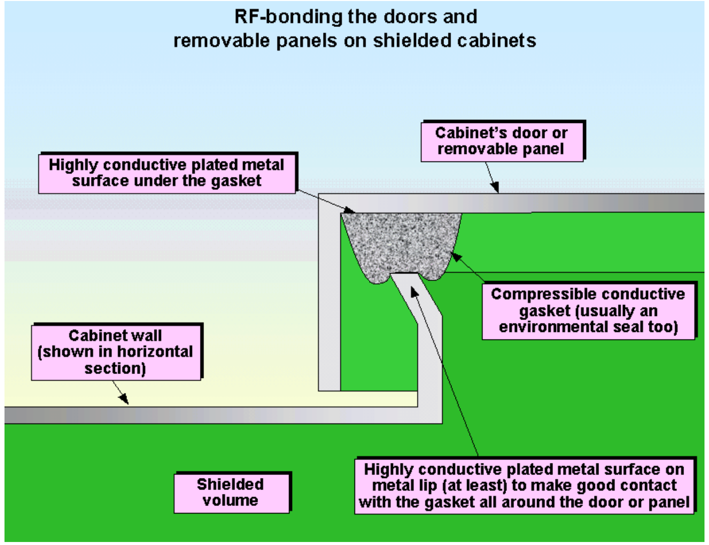


Fig 61



wires or straps is no good at all above a few MHz. Figure 61 shows details of the bonding of the doors and removable panels using a volume-conductive elastomer gasket (such as neoprene loaded with silver-plated glass beads).

EMC gaskets are available that provide environmental as well as EMC sealing. Gaskets and their contact areas must not be painted, and careful choices of materials and metal plating finishes are needed to ensure good EMC, and prevent corrosion, over the lifecycle of the cabinet (see section 6).

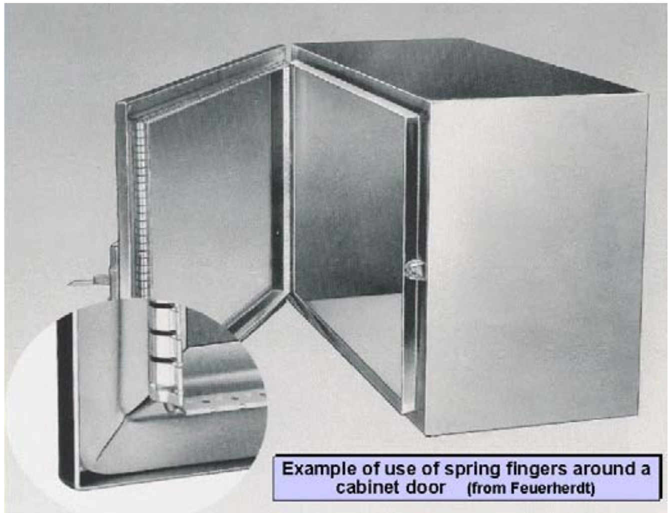
Very many different types of gaskets and spring fingers are available from a number of manufacturers. Gasket choice requires balancing many physical considerations, such as compliance, compression set, and position in the galvanic series, with electrical ones such as contact resistance. An opening door may require a soft gasket (for ease of manual closing) that always springs back to its original shape, but these are often difficult to combine with low contact resistance. Spring fingers ('finger stock') are often used around doors and removable panels, as shown in Figure 62, but are quite fragile and in some applications could easily be damaged.

5.4 The effective use of gaskets

This guide does not discuss gaskets and their use in any detail, except to say that when assembled they should be compressed to an amount within their manufacturers recommended range – and this can require considerable pressure. As mentioned in 2.5, even EMC gaskets that can easily be squashed flat between two fingers can require very large compression forces overall when used in long strips, so the effective use of gaskets requires careful mechanical and fixing design to prevent metal parts from bending too much in delivering those forces.

It is not unusual to fit strips of very soft conductive gaskets to the door of an

Fig 62



industrial cabinet, only to find that it becomes almost impossible to close, and once closed it bends like a banana – opening up large gaps that defeat the purpose of the gasketting.

It has been mentioned many times in the above text and figures that gaskets require highly-conductive metal surfaces to make connection on both of their sides. It is always recommended that metal parts are checked for the conductivity of any EMC-related surfaces when delivered by their supplier, before being accepted into store. Such tests should use very blunt, smooth probes applied with a very light pressure, to discover whether the supplier has 'accidentally' applied a polymer passivation coating – as they sometimes seem to. It is easy to design and make a probe based on a battery, buzzer and two smooth spring-loaded contacts, that can be used like a rubber stamp to de-skill metal surface conductivity checking at goods-in.

EMC gaskets must continue to be effective over the lifecylce of the cabinet despite exposure to the physical environment at the site where it is installed. This includes such issues as:

- Mechanical (e.g. shock and vibration)
- Climatic (e.g. air temperature, pressure and humidity)
- Chemical (e.g. exposure to condensation, liquids, sprays, mists, vapours and dusts of various types)
- Biological (e.g. mould growth)
- Wear and tear from normal use, cleaning, maintenance, etc.

Good EMC gasket manufacturers provide a wealth of data and application assistance (for example [27]), covering the correct choice of gasket materials and styles for particular applications, taking into account their physical environments, and the data required for mechanical design to achieve the correct compression without distortion of the cabinet or any of its parts. Galvanic corrosion of the gaskets or the plating they bond to is a real possibility, and should be avoided by following the guidance in section 6.

All of the techniques described above rely for their effectiveness on achieving very low-impedance metal-to-metal connections over the lifecycle of the cabinet, despite its physical environment. The contact resistance at each RF bond must not be permitted to increase too much over the lifecycle, either due to oxidation of the metals used, or due to galvanic corrosion – the subject of this section.

Different metals have different positions in the electro-chemical series, so when connected by an electrically-conductive liquid (called an electrolyte, for example ordinary water) they form an 'accidental battery' and a self-generated current flows in them. The most anodic of the metals gets eaten away by this current, eventually disappearing (or turning into non-conductive or semi-conductive corrosion products) altogether. If the choice of metals is poor for the environment, galvanic corrosion can completely destroy an electrical connection very quickly indeed, maybe in just a few weeks.

Fig 63

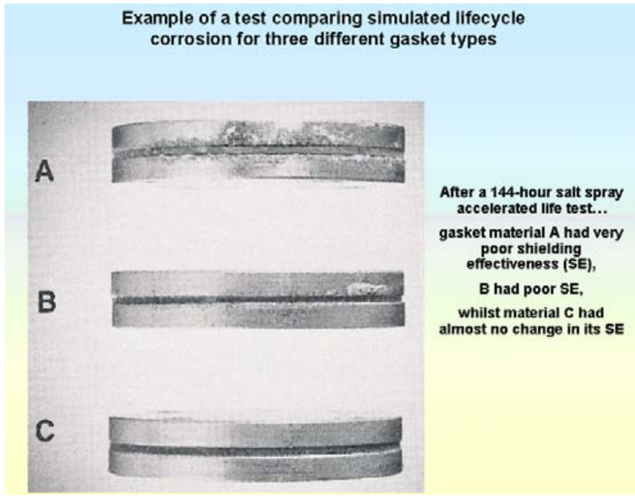


Figure 63 shows an example of a simulated lifecycle test using standard metal blanks to test the galvanic compatibility of different types of conductive EMC gasket.

[20] has a very good chapter on preventing galvanic corrosion, which is summarised very briefly below.

Classification of metals by their position in the galvanic series:

More anodic (most easily corroded) –

Group 1 Magnesium

Group 2 Aluminium and its alloys, zinc, cadmium

Group 3 Carbon steel, iron, lead, tin, tin-lead solder

Group 4 Nickel, chromium, stainless steel

Group 5 Copper, silver, gold, platinum, titanium

– more cathodic (least easily corroded)

Fig 64

Corrosion guidance (adapted from NAVAIR 115, 1988)

Exposure situation	Anode end (most heavily corroded) Group 1	Group 2	Group 3	Group 4	Cathode end
Exposed	B	A	-	-	Group 2
Sheltered	A	A	-	-	Group 2
Housed	A	A	-	-	Group 2
Exposed	C	B	A	-	Group 3
Sheltered	B	A	A	-	Group 3
Housed	B	A	A	-	Group 3
Exposed	C	B	A	A	Group 4
Sheltered	B	B	A	A	Group 4
Housed	B	A	A	A	Group 4
Exposed	C	C	C	B	Group 5
Sheltered	B	B	B	A	Group 5
Housed	B	B	A	A	Group 5

A: Metal may be exposed at junction surfaces, rest given appropriate protective coat

B: Coating must prevent any possibility of liquid bridging the join

C: Protective coatings are mandatory. Even so, only has a short life

- **Make sure the part more likely to be corroded is easily replaced.**
- **Can sometimes fit a sacrificial washer or strap (higher in the series than either side of the bond, so corrodes first) as long as regular maintenance prevents excessive deterioration**

The idea is that the galvanic voltage differences between the materials in each group are low enough to allow them to be used in contact with each other regardless of the environment. However, in very aggressive environments (such as the deck of an ocean-going vessel) it is probably best to make sure that only identical metals (or, if they are alloys, identical compositions) are used in contact.

Coating or plating mating parts with the same metal (for example, zinc, tin, or nickel) helps keep the dissimilar metals protected from the electrolyte, preventing galvanic corrosion, but depends on the quality of the plating. A pinhole or scratch in the plating can allow the metal underneath the plating to get eaten away.

Figure 64 is a useful table giving guidance on the combinations of the metals in the above five groups, depending on their environment, and was extracted from [20].

The flow of DC or AC current through an electrical bond also hastens galvanic corrosion, making it a more important consideration for industrial cabinets containing electrical/electronic circuits.

Vapour-phase corrosion inhibition is a recently developed technology [33] that claims to use small quantities of a solid material that sublimes, releasing a vapour that coats nearby metal parts with an insulating film just a few molecules thick. The film is supposed to be too weak to prevent electrical bonds from being made between different parts, but sufficient to prevent oxidation or galvanic corrosion.

7 References and further reading

[1] European Union Directive 89/336/EEC (as amended) on Electromagnetic Compatibility. The Directive's official EU homepage includes a downloadable version of the current EMC Directive and its successor; a table of all the EN standards listed under the Directive; a guidance document on how to apply the Directive; lists of appointed EMC Competent Bodies; etc., all at: http://europa.eu.int/comm/enterprise/electr_equipment/emc/index.htm.

The new European Union Directive 2004/108/EC on Electromagnetic Compatibility (2nd Edition):

http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/oj/2004/l_390/l_39020041231en00240037.pdf

See [2] for details of the transition from 89/336/EEC to 2004/108/EC.

[2] "*2004/108/EC: Systems, Installations and Good Engineering Practices*", Keith Armstrong, The EMC Journal, September 2006, available from www.compliance-club.com (search by 'Keith Armstrong')

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

[4] Seventeen EMC Guides on EM phenomena, legal compliance and EMC testing have been published by REO (UK) Ltd. They are very readable and practical, and are available via the Publications and Downloads pages at www.cherryclough.com

[5] A number of useful and practical documents on complying with the EMC Directive are available from the 'Publications and Downloads' pages at www.cherryclough.com

[6] IEC 61508: "*Functional Safety of Electrical, Electronic and Programmable Electronic Systems*" (seven parts)

[7] IEC 61511: "*Functional safety: Safety instrumented systems for the process industry sector*"

[8] IEC 62061: "*Safety of Machinery – Functional safety of electrical, electronic and programmable control systems for machinery*"

[9] The 'Low Voltage Directive': 73/23/EEC "*Council Directive of 1 February 1973 on the harmonization of the laws of Member States relating to electrical equipment designed for use within certain voltage limits*" as amended by 93/68/EEC

[10] The 'Machinery Safety Directive': "*Directive 98/37/EC of the European Parliament and of the Council of 22 June 1998 on the approximation of the laws of the Member States relating to machinery*"

The new Machinery Safety Directive: "*Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast)*"

[11] "*List of Resources on EMC and Functional Safety*", The IET, http://www.iee.org/OnComms/PN/emc/EMCandFunctionalSafety.cfm

[12] "*EMC Testing*", a series in six parts by Tim Williams and Keith Armstrong, published in the EMC Compliance Journal during 2001-2, and available via the 'Publications and Downloads' pages at www.cherryclough.com

[13] "*On-Site EMC Test Methods*", Keith Armstrong, EMC Test Labs Association (www.emctla.co.uk) Technical Guidance Note No. TGN 49, available from the 'Publications and Downloads' pages at www.cherryclough.com

[14] "*CE + CE does not equal CE – what to do instead*" available from the 'Publications and Downloads' pages at www.cherryclough.com

[15] "*Assessing an EM Environment*", Keith Armstrong, EMC Test Labs Association (www.emctla.co.uk) Technical Guidance Note No. TGN 47, available from the 'Publications and Downloads' pages at www.cherryclough.com

[16] "*Electromagnetic Compatibility in Heavy Power Installations*" IEE Colloquium, Middlesborough U.K., 23rd February 1999, IEE Colloquium Digest No. 99/0666 (ISSN 0963-3308) available from IEE Sales for around £20, sales@iee.org.uk or from the IEE Library: www.iee.org.uk/Library, libdesk@iee.org.uk

[17] "*Achieving EMC Directive Compliance with a Spreadsheet*", Keith Armstrong, Conformity, February 2006, from the archives at www.conformity.com

[18] IEC 61000-5-2:1997 "*Electromagnetic Compatibility (EMC) – Part 5: Installation and Mitigation Guidelines – Section 2: Earthing and cabling*"

[19] PD IEC TR 61000-5-6:2002 "*Electromagnetic Compatibility (EMC) – Installation and mitigation guidelines – Mitigation of external EM influences*"

[20] NAVAIR AD 115 "*Electromagnetic Compatibility Design Guide for Avionics and Related Ground Equipment*", 3rd Edition, June 1988, Naval Air Systems Command, Department of the Navy, Washington DC, USA

[21] Defence Standard 59-41, Part 6, Issue 1 26th August 1994: "*Electromagnetic Compatibility Code of Practice for Military Vehicles Installation Guidelines*", download from www.dstan.mod.uk

[22] Defence Standard 59-41, Part 7 Issue 1 10th November 1995: "*Electromagnetic Compatibility – Code of Practice for HM ships, Installation Guidelines*", download from www.dstan.mod.uk

[23] "*Electromagnetic Compatibility – Installation Guide*", Eurotherm Controls, http://download.eurotherm.co.uk/download-s/DL/EMC_025464_1.pdf

[24] "*EMC: Electromagnetic Compatibility*", Jacques Delaballe, Schneider Electric, www.schneider-electric.com/cahier_techni-que/en/pdf/ect149.pdf

[25] "*EMC-Compatible Enclosure Assembly*", Rittal, www.rittal.co.uk

[26] The author's contact details are provided at www.cherryclough.com

[27] Laird Technologies Technical Notes, visit: http://www.lairdtech.com/pages/ catalogs/emi.asp and scroll down the page.

[28] "*Design Techniques for EMC- Part 2: Cables and Connectors*", Keith Armstrong, The EMC Journal, April 1999, pages 7-16, available via the 'Publications and Downloads' pages at www.cherryclough.com. This article was updated and improved with considerably increased detail in The EMC Journal, May 2006 pages 31-41 and July 2006 pages 25-38, available from www.compliance-club.com (search by Keith Armstrong)

[29] "*Design Techniques for EMC- Part 3: Filters and surge protection devices*", Keith Armstrong, The UK EMC Journal, June 1999, pages 9-15, available via the 'Publications and Downloads' pages at www.cherryclough.com. This article was updated and improved with considerably increased detail in The EMC Journal, September and November 2006, available from www.compliance-club.com (search by 'Keith Armstrong')

[30] "*Design Techniques for EMC- Part 4: Shielding*", Keith Armstrong, The UK EMC Journal, August 1999, pages 10-20, available via the 'Publications and Downloads' pages at www.cherryclough.com. An updated, revised and augmented version will be published in The EMC Journal during 2007, and will be available from www.compliance-club.com (search by Keith Armstrong)

[31] "*Design Techniques for EMC- Part 1: Circuit Design and Choice of Components*", Keith Armstrong, The EMC Journal, February 1999, available via the 'Publications and Downloads' pages at www.cherryclough.com. This article was updated and improved with considerably increased detail in The EMC Journal, January and March 2006, available from www.compliance-club.com (search by 'Keith Armstrong')

[32] "*Choosing and Installing Mains Filters*", Keith Armstrong and Tim Williams, Compliance Engineering magazine, January/February 2000, pages 68 75. Available along with some other useful articles on choosing filters via the 'Publications and Downloads' pages at www.cherryclough.com

[33] Visit www.cortecVpCI.com for details. The author has no direct experience of this technique and makes no claims for its effectiveness.

Keith Armstrong from Cherry Clough Consultants

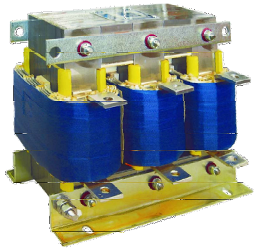
See www.reo.co.uk/ guides for lots of other practical guides, similar to this one, relating to Electromagnetic (EM) phenomena

Keith Armstrong graduated in electrical engineering with a B.Sc (Hons.) from Imperial College London in 1972, majoring in analogue circuit design and electromagnetic field theory, with a Upper Second Class Honours (Cum Laude). Much of his life since then has involved controlling real-life interference problems in high-technology products, systems, and installations, for a variety of companies and organisations in a range of industries.

Keith has been a Chartered Electrical Engineer (UK) since 1978, a Group 1 European Engineer since 1988, and has written and presented a great many papers on EMC. He is a past chairman of the IEE's Professional Group (E2) on Electromagnetic Compatibility, is a member of the IEEE's EMC Society, and chairs the IEE's Working Group on 'EMC and Functional Safety'.

Contact: Keith Armstrong by email at keith.armstrong@cherryclough.com or visit the Cherry Clough website www.cherryclough.com

Motor Choke



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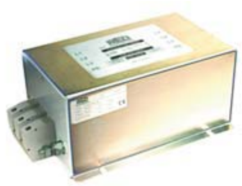

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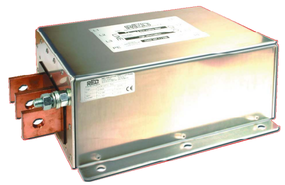
EMC Filter



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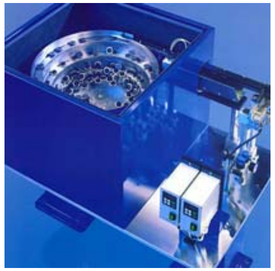

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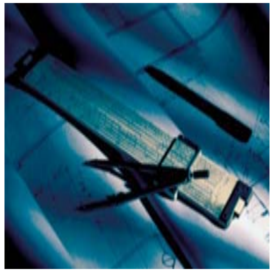

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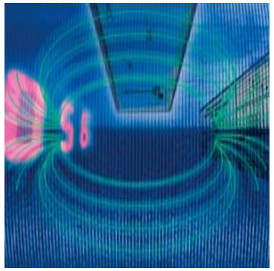
Solar transformers



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Motor Control Systems

Soft-starts

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