EMC STANDARDS

Another EMC resource
from EMC Standards

EMC for Systems and Installations Part 4 Filtering and shielding

Helping you solve your EMC problems

1 Brassey Road, Old Potts Way, Shrewsbury, SY3 7FA T:+44 (0) 1785 660 247 E:info@emcstandards.co.uk

EMC STANDARDS

Another EMC resource from EMC Standards

EMC, systems & installations, 2000, Part 4, Filtering

Helping you solve your EMC problems

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

emc STANDARDS

Another EMC resource
from EMC Standards

EMC, systems & installations, 2000, Part 4, Filtering

Helping you solve your EMC problems

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

EMC for Systems and Installations

Part 4 – Filtering and shielding

As published in the EMC Compliance Journal in 2000, www.compliance-club.com

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

This is the fourth of six bi-monthly articles on EMC techniques for system integrators and installers, which should also interest designers of electronic units and equipment. The material in this series is based on the new book "EMC for Systems and Installations", reference [1], which I co-wrote with Tim Williams of Elmac Services. This series addresses the practical issues of controlling interference, which would be commercially necessary even if the EMC Directive did not exist. EMC management, testing, legal issues (e.g. compliance with the EMC Directive), and theoretical background are not covered – although they are in [1]. For more information, read the references at the end.

The topics which will be covered in these six articles are:

0) General Introduction – the commercial need for EMC in systems and installations

1) Earth? what earth? (The relevance of what is usually called 'earth' or 'ground' to EMC)

2) EMC techniques for installations

3) EMC techniques for the assembly of control panels and the like

4) Filtering and shielding in installations

5) Lightning and surge protection

6) CE plus CE ≠ CE! What to do instead

These EMC techniques apply to the majority of land-based systems and installations, and will be relevant for many others. However, some special systems and installations may use some different or additional techniques, as mentioned early in the first article in this series. Some of the techniques in this series may contradict established or traditional practices, but they are all well-proven and internationally standardised modern best-practices at the time of writing, and professional engineers have an explicit duty (professional, ethical, and legal) to always apply the best knowledge and practices in their work.

Remember that safety is always paramount, and should not be compromised by any EMC technique. Where errors or malfunctions in electronic circuits could possibly have implications for functional safety (including during faults, foreseeable misuse, overload, or environmental extremes) meeting the EMC Directive and its harmonised EMC standards may not be enough to meet safety requirements. Such possibilities should always be carefully considered, and if they exist competent safety experts should be involved in the EMC decisions. EMC-related functional safety is not covered explicitly in these articles. It is hoped that we will soon be able to report the publication of an IEE Professional Guidance document on EMC and Functional Safety.

Table of contents for Part 4

4.1 What do we use filtering and shielding for?

Both techniques are used either to reduce the electromagnetic (EM) disturbances entering a zone, or to reduce the EM disturbances emitted from a zone. 'Electromagnetic disturbance' is the official catch-all term for electrical and electronic noise and interference of all kinds, from dips and dropouts in the mains supply (at the low frequency end) right through to microwave radiation from radars and satellite communications (at GHz).

Such protection zones are always volumes – we often think in terms of areas (e.g. an area of floor) but we should always remember that zones are three-dimensional. A zone could be large or small. It could even contain just a single item of equipment, such as remote touch-screen controller unit for a manufacturing process which might be interfered with by walkie-talkies used by its operators.

Where sensitive electronics such as instrumentation, computer, or telecommunication rooms could suffer due to a noisy EM environment, filters and shielding can improve their reliability by providing them with a protected zone. Where a machine that creates large amounts of EM disturbances (such as plastic welders, induction heaters, or wood gluers that use powerful RF fields, or anything that uses electrical arcs or plasma) is to be used, filters and shielding may be used to restrict its disturbances to its own zone and protect the rest of the site or its external environment.

As evidenced by the cover story in the 1st July issue of New Scientist [2] – protection from EM disturbances is becoming an important issue for banking, commerce, and security, as well as for the general public, as we all become more dependant on computers and telecommunications, and as these become more sophisticated they generally become less robust to EM disturbances.

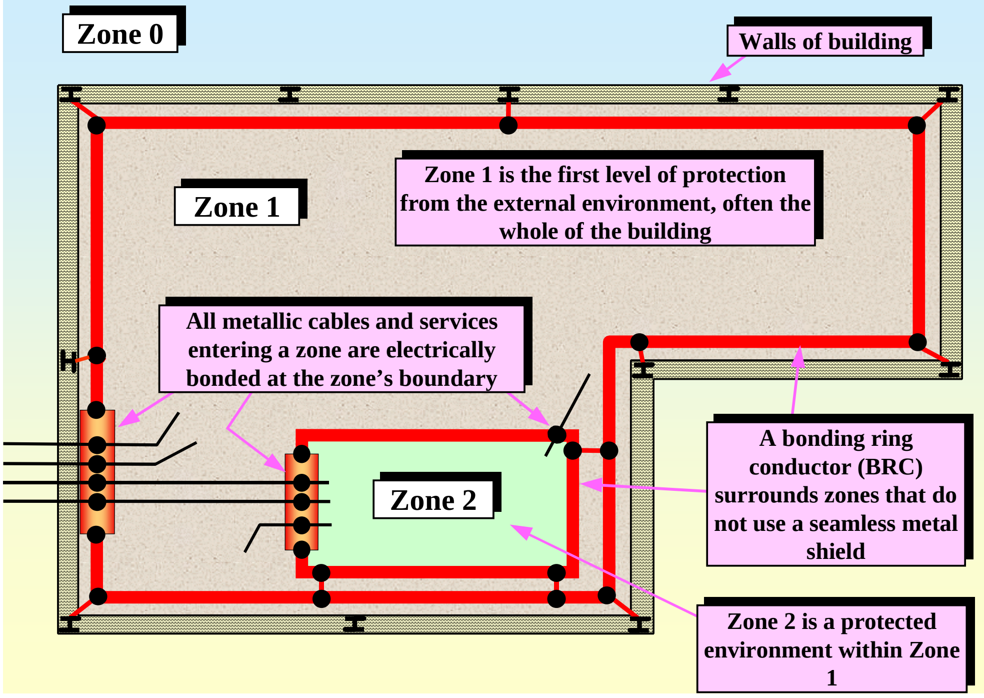
4.2 The importance of zoning in an installation

Careful zoning within a site is required to use zoning with any success. Moving existing computers and machines with all their cables can be very expensive, if only in terms of lost production. So for the best cost-effectiveness, zoning requires planning from the earliest stage of a project.

Part 2 of this series began (Section 2.2 and Figure 2A, [3]) by describing how important it was to geographically segregate certain types of apparatus and their supply and signal cables from each other, to minimise the potential for interference between them. Segregation is an essential part of zoning. Without segregation of the things to be protected (or to be protected from), the benefits of filtering and shielding can become impossible to realise.

Figure 4A shows the general zoning principle. There is no limit to the number of nested zones associated with a site, but few go beyond 2 shown by 4A. The enclosures of electronic equipment provides another zone, and within the electronic equipment there may be nested further, more protected zones (e.g. for sensitive or noisy circuitry), so a complete analysis of a 2-zone site with its electronic equipment might reveal that there are actually 4 or more nested zones involved. Equipment zones use the techniques described in my previous series of articles: "*Design techniques for EMC*" [4] and will not be described further here.

Figure 4A General zoning principles
(based on the example given in Figure 2H of part 2)



The EM coupling between all the electrical and electronic circuits within a zone and the environment outside the zone is controlled using filtering and shielding (and other techniques such as optical isolation or fibre optics) at the zone boundary. We need to consider all the ways that EM coupling could cross the zone boundary. In Part 6 of this series we will see that zoning is also very important for lightning protection, which (like electronic warfare) is an increasing worry as silicon features get smaller to make integrated circuits more powerful.

4.3 Coupling across a zone boundary

There are five types of EM coupling which may need to be controlled at zone boundaries:

- Common impedance conducted coupling
- Conducted coupling other than common-impedance
- Capacitive radiated coupling
- Inductive radiated coupling
- EM field radiated coupling

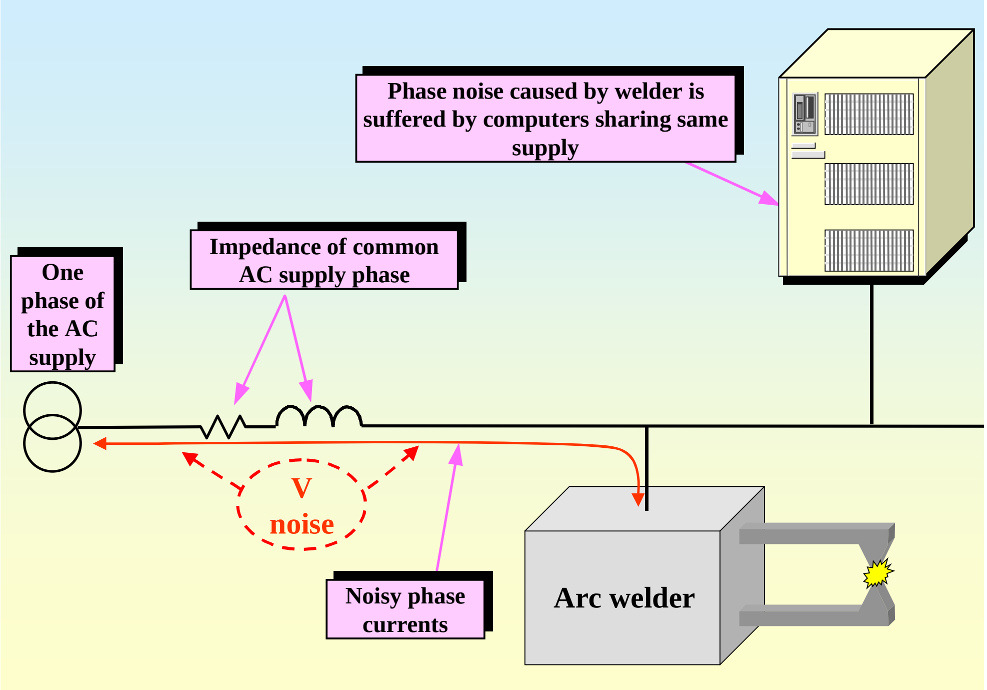
Conducted coupling can occur through anything metallic, including conductors with green/yellow striped insulation. It can also occur through conductive liquids such as impure water, some industrial solvents, and materials such as soil and human bodies. Radiated coupling travels through the air, but also travels through wood, glass, plastics, fibreglass, insulating liquids and gasses, and vacuum.

4.3.1 Common-impedance conducted coupling

Common impedance coupling is caused by the inevitable impedances in common electrical circuits, most usually 'the earth' or shared power supplies such as AC (mains) or DC. Inside a building EM coupling is not affected by earth electrodes, so instead of the word 'earth' I'll use the less misleading term 'Common Bonding Network' (CBN) for the network of protective conductors and bonded metalwork (see Part 1 of this series [5] for more on this).

Figure 4B shows how common impedance coupling occurs in a phase of the mains supply. The rapidly fluctuating currents drawn by the welder (for e.g.) from the supply cause fluctuating phase voltages due to the inevitable source impedance, which might affect the computer.

Figure 4B Common-impedance coupling



A similar situation occurs in the CBN, but the currents are less predictable as they are mostly caused by 'earth leakage' from mains filters, failing insulation, and motor leakage currents (via stray capacitance from windings to frame). In modern offices, 'earth leakage' due to the RFI filters fitted to computers can be very large indeed. In one recent building 70 Amps of leakage current due to computer RFI filters alone was found at the main earthing terminal [13].

Leakage currents due to mains filters tend to be rich in frequencies much higher than 50Hz, more so where the mains suffers from harmonic distortion, as it often does these days. Higher frequency currents cause proportionally greater common-impedance problems, because mains cables and CBNs are predominantly inductive and their impedances rise in proportion to frequency.

Some structures use a power distribution system with a single conductor for both neutral and the protective conductor (e.g. TN-C). These are very poor indeed for EMC and five conductor systems such as TN-S (three phases, neutral, protective conductor) should be used instead [7]. In some circumstances TT and IT distribution systems may be acceptable alternatives. (Many modern standards on the installation of IT and telecommunications installations make the same recommendations.)

Even where common-impedance coupling does not cause a problem in *normal* use, transient events such as switch-on surges, phase-to-earth faults, and lighting activity (not necessarily direct strikes) can cause huge currents to flow in both phase and CBN conductors, causing correspondingly large common-impedance coupled voltages.

Techniques for reducing common-impedance coupling have already been mentioned in this series – such as the use of different supply distribution transformers for different categories of equipment in Section 2.2 of [3] – and the use of MESH-CBNs and parallel earth conductors (PECs) in Sections 2.4 – 2.7 of [3].

4.3.2 Conducted coupling other than common-impedance

Other conductive coupling is usually due to metallic signal interconnections. Noise coming out of the signal connection port one unit is connected via signal cables to the signal port of a different unit. The noise can either be differential-mode (DM) like the signal itself, or common-mode (CM), and is often a mixture of both.

An important parameter for a cable is its Longitudinal Conversion Loss (LCL) – the rate at which it converts the wanted signals it carries into unwanted common-mode (CM) noise (see Part 3.4 of [4]). This is similar to the Z_T specification (surface transfer impedance) used for both cables and connectors. All metallic conductors convert wanted DM signals into unwanted CM noise (and unwanted CM noise into unwanted DM noise on the signal). See Chapter 7 of [1] for much more depth on this. CM noise travels equally on all conductors in a cable, including any screens, and generally causes the majority of EM coupling problems at frequencies above a few MHz.

The high frequency content of a DM digital or analogue signal, or the high-frequency DM noise riding on the signal, can all end up converted to CM and possibly responsible for a conducted or radiated nuisance. There is a relationship here between signal integrity and EMC, explored in greater depth in [11].

Metallic interconnections can also pick up CM noise from their environment, e.g.:

- When the equipment they are connected to has a significant CM voltage on it. (Typical of a PC or other digital processing device where an external cable has no screen, or its screen is connected to digital 0V instead of the PC's enclosure shield.)
- When the cable runs close to a noisy cable or process, 'picks up' this noise and re-radiates it. (See 'Banana Skins' No. 85 [6] for an example from the Radiocommunications Agency.)

4.3.3 Strategies for eliminating conducted coupling

Often the best way to eliminate conducted coupling is not to use conductors at all. Electronic units with built-in power sources communicating by wireless (radio), infra-red, laser, or optical fibres (metal-free types!) and having no metallic conductors attached to them at all clearly can't suffer conducted coupling. Some products are designed this way already, such as cellphones, personal organisers, and some types of medical patient-connected instrumentation.

Wireless or fibre-optic interfaces are often not considered in the early part of a project due to their higher material costs. But it can only take a day's delay in commissioning a system to add much more to the overall project costs than it would have cost to use fibre-optics (even when penalty clauses aren't invoked). And it can only take a few hours of downtime a year to make a customer choose a different supplier next time. So, avoiding metallic interfaces can be a very cost-effective strategy.

Even where cables are used, conducted coupling can be reduced by galvanic isolation techniques such as 1:1 transformers and opto-isolators. Some of these may need to be combined with filters to give broadband isolation. Quite a number of field service personnel now always carry optical data isolation devices with them. But this article is supposed to be about filtering and shielding, and further discussion of built-in power sources and non-metallic communications is outside its scope.

4.3.4 Radiated coupling – capacitive, inductive, and radio wave

'Parasitic' or 'stray' capacitance and mutual inductance between conductors causes capacitive and inductive coupling, traditionally known as crosstalk. Both are reduced by increasing the spacing between source and victim conductors and running them close to PECs, as described in Section 2.8 of [3], and 3.12 of [8].

When cables carry signals or noise with a wavelength comparable with the cable's length, then they start to behave as quite efficient RF transmitting antennas – launching EM plane waves (radio waves) into the air – to be picked up by other conductors behaving as RF receiving antennas. There are a number of ways of reducing cable radiating efficiency such as by using twisted pairs and/or screening (see Part 2 of [4]) – but these only affect the cable's LCL – they make no difference to a cable's efficiency as an RF antenna for CM noise.

Cables start to become very efficient RF antennas for transmitting and receiving CM noise when their length exceeds approximately one-tenth of a wavelength at the frequency concerned. At 10kHz (a typical switching frequency for a 50kW HVAC motor drive) cables up to 3km length could cause significant crosstalk into other cables but would not be considered very efficient RF field transmitters. But at 10MHz (a typical switching harmonic present in 0-10kW motor drives) cables often become significant RF transmitting/receiving antennas at lengths of over 3 metres, altering their 'crosstalk' characteristics significantly. (The one-tenth rule is somewhat arbitrary – if very high levels of protection were being aimed for even one-hundredth of a wavelength could be a problematic length.)

4.3.5 Summary of EM coupling across a zone boundary

Figure 4C sketches the various EM couplings which can occur across a zone boundary.

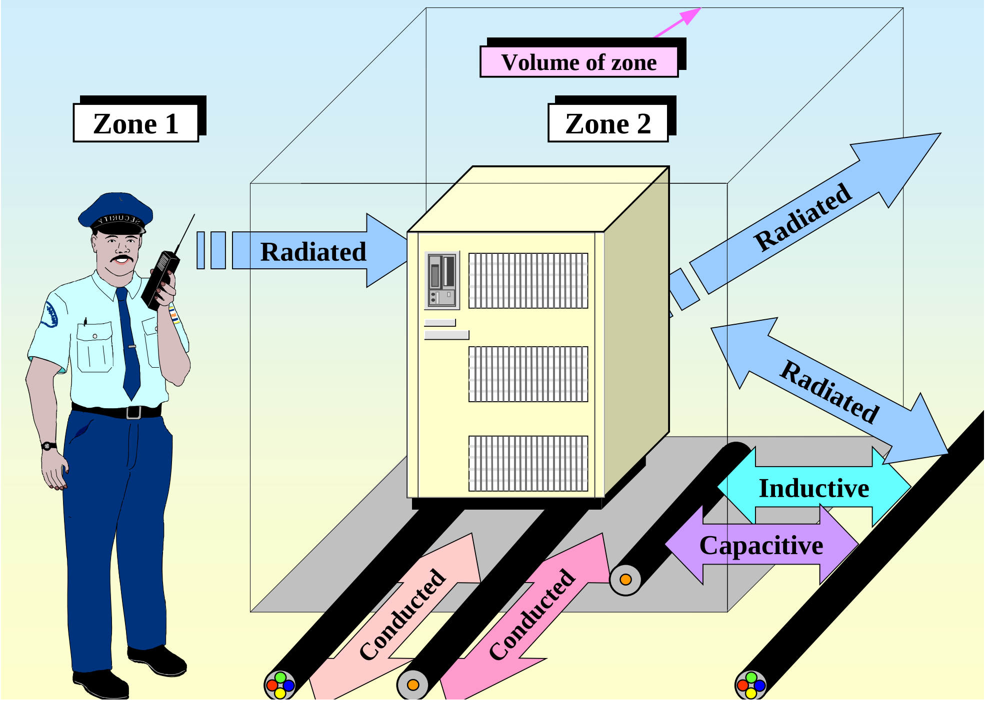
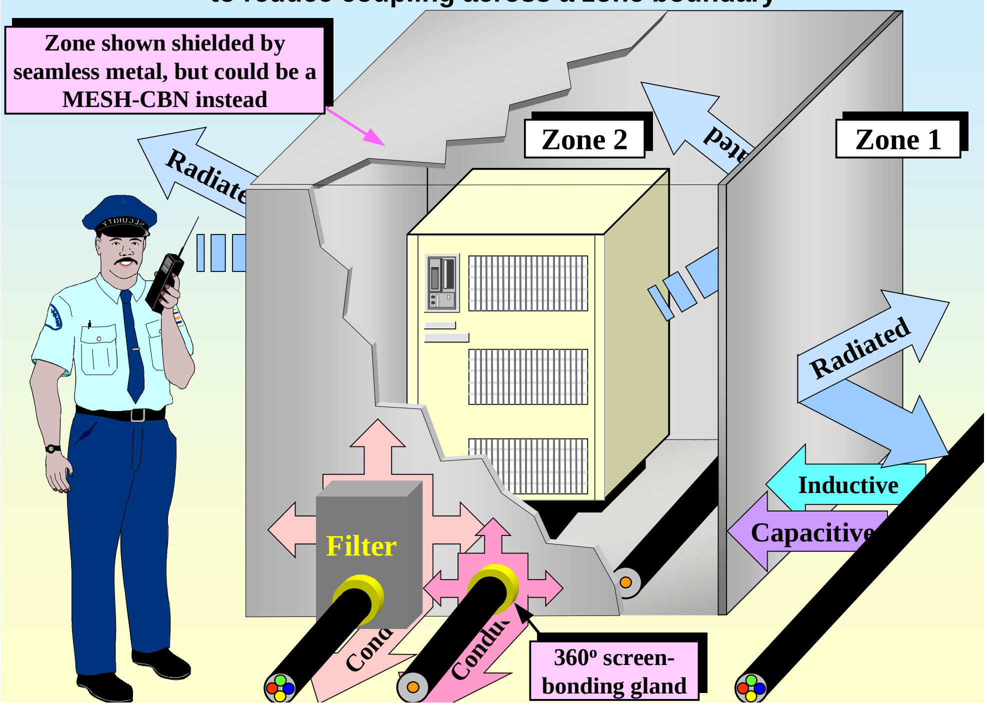


Figure 4C Coupling across a zone's boundaries

Figure 4D shows how filtering and shielding are used to reduce the coupling across a zone boundary. Notice that it is impossible to filter the CBN in the zone, but it can be made part of a 'Faraday Cage' shield if its impedance is low enough at the frequencies to be controlled.

Figure 4D Using filtering and shielding to reduce coupling across a zone boundary



4.3.6 The synergy of shielding and filtering

All electrical and radio signals and noise are EM phenomena, and all that they are capable of experiencing is changes in the characteristic impedance of the media they travel in. Filtering and shielding have the same aim - to place impedance discontinuities of the magnitudes required in all of the unwanted coupling paths. So the correct way to view filtering and shielding is as a synergy, with each one complementing the other.

Radiated fields can be picked up by cables and travel through them as conducted noise. Conducted noise in cables can then radiate into the air as a field. So it is important to understand that inadequate filtering can easily increase unwanted radiated coupling, and that poor shielding can easily increase unwanted conducted coupling.

If 40dB of shielding at 40.68MHz (say) is needed for a zone, then a cable entering via a filter that only achieves 20dB at that frequency is likely to compromise the shielding effectiveness. Similarly, where a filter needs to achieve 40dB of attenuation at 40.68MHz to protect a zone, an aperture greater than 100mm in the zone shielding near the filter could compromise the filter's performance.

4.4 Filtering in installations

4.4.1 Purpose of a filter – attenuating noise at metallic interfaces

The purpose of a filter is to prevent interference from travelling either into or out of a zone via metallic interfaces. This reduces conducted coupling directly, and also helps to reduce the radiated coupling to or from the cables.

Filter design and assembly is covered in great depth elsewhere, but when filters designed using circuit design texts or simulators are used to control EM disturbances in real systems and installations they are often found wanting. Many of these problems are caused by assembly and installation issues, also covered in [9] and [10], as well as in Chapter 8 of [1] and Section 3.9 of Part 3 of this series [8]. Rather than go through all these practical issues in detail I'll just summarise them below.

4.4.2 CM and DM attenuation

Filters should be designed to attenuate CM and DM modes, with the bandwidths and degrees of attenuation required by each. Low-pass DM filtering is often needed to strip off unnecessarily high signal frequencies or noise so that they won't get converted to troublesome CM noise by cable LCL (or Z_T).

CM filtering is often used to prevent CM noise in an electronic unit from entering a cable, or to prevent CM noise on a cable from entering an electronic unit and being converted into DM. CM filtering can be designed to give high levels of attenuation at frequencies *within* the bandwidth of the wanted DM signals.

4.4.3 Effects of source and load impedance

In real life, filters don't often see 50Ω impedances at input and output, but the performance of low-cost filters (especially those with just a single stage) depends very strongly on their termination impedances and can even lead to gain instead of attenuation.

Where a filter is a simple capacitor from a signal line to chassis, as in most D-type bulkhead filters, it is not too difficult to work out the effects of different termination impedances (not forgetting that the cable's characteristic impedance will dominate that of a remote source or load, above a frequency related to the length and velocity factor of the cable).

For a mains filter, its source impedance (the AC mains supply) can vary from 2 to 2,000Ω depending on the location and time of day (more typically from 5 to 300Ω). On its load side the impedance of an AC-DC converter is very low when the rectifiers are conducting, and very high at all other times. The overall situation is very far from being the matched 50Ω / 50Ω set-up typically used by filter manufacturers to specify attenuation.

A graphical method of dealing with mains filters is suggested in Section 3.9 of Part 3 of this series [8]. This requires getting all the matched and mismatched CM and DM curves from the filter manufacturer and drawing a new curve which is the worst-case of them all. It would be unlikely for the filter to perform worse than this new curve (see Figure 3M in [8]). This can lead to over-specification, but since the only way to be sure of getting the optimum filter is to perform conducted emissions tests on a variety of filter designs, the graphical method has advantages for custom engineering.

4.4.4 Filter gain

This is a very real problem with low-cost mains filters used in typical situations. Between 150kHz and 2MHz most single-stage mains filters, when operated with typical source and load impedances, can *amplify* emissions by up to 20dB. This problem is covered in Section 3.9 of [8] and Chapter 8 of [1] and the graphical method described above will identify it. Mains filters with two or more stages don't exhibit this problem very strongly, but may still have less attenuation than expected at lower frequencies (usually below 500kHz). Three or more stage filters can achieve even more predictable attenuation.

4.4.5 Filter frequency response

Some mains filters are only specified over the frequency range of the normal conducted emissions tests: 150kHz to 30MHz. Filter attenuation should be specified over the entire frequency range at which conducted or radiated protection is required for (or from) the zone, which in some situations could be from kHz to GHz.

4.4.6 Filter location

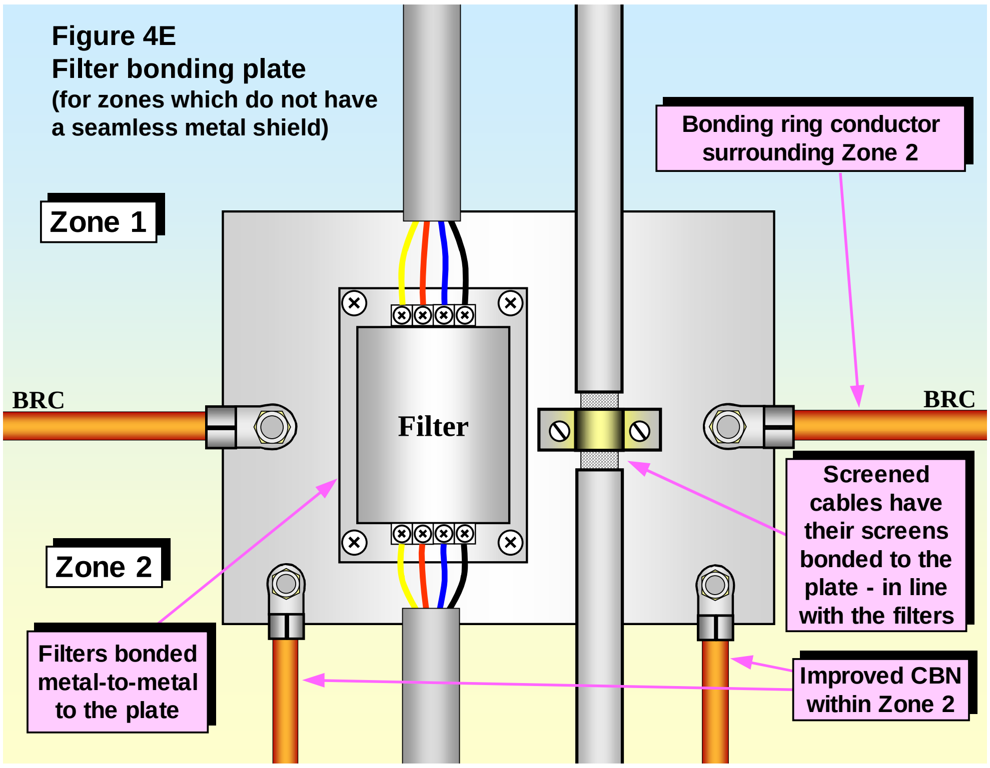
Filters should be located at a zone boundary. Locating them at any distance from the zone boundary allows coupling into its cables to breach the zone's protection. The higher the frequency, the more a filter is compromised by RF coupling from its unfiltered side to its filtered side. Many engineers have been surprised by the ease with which RF 'leaks' around a filter.

Where the zone boundary is a metal surface (e.g. a shielded cabinet, or an architecturally shielded room) that is penetrated by a cable, the filter should be bulkhead mounted at the point where the cable penetrates the metal surface. Most mains filter manufacturers make 'room filters' expressly designed for this purpose. Some bulkhead connector types (e.g. D-types) are available with built-in filters.

If lowest-cost screw-terminal filters are to be used instead of bulkhead types, the clean box/dirty box method sketched in Figure 3R of Part 3 of this series [8] helps protect the shielding integrity of the zone. Where a filter can only be positioned outside the zone it is associated with, its wiring to the zone should be twisted and run close to elements of the CBN at all times. Good attenuation at high frequencies must not be expected from such a construction, although shielding the cabling from filter to zone will improve matters (the screen must be 360° bonded at both its filter and zone ends).

4.4.7 Filter 'earthing'

Any inductance in a filter's bond to its local RF reference (see Section 3.6) can ruin its performance, so using a wire to connect a filter's body to its local RF reference is usually unacceptable. Figure 8.7 in Chapter 8 of [1] is a measurement on a single-stage mains filter and shows that increasing its 'earth' bond wire from 1cm to 15cm worsened its attenuation by 25dB at 15MHz. The greater the inductance – that is, the longer the wire – the lower the frequency at which this becomes significant. Bonding the case directly to the local RF reference is required to get anywhere near a filter's published performance. The often-provided separate earth tag on the filter's case is for safety purposes only.



Direct metal-to-metal connection of the filter body to the zone barrier, which will usually be either a shielding wall in a cabinet or chamber or the bonding ring conductor of an earthing mesh, provides the necessary high-integrity bond to the local RF reference. Where there is no existing metal wall to mount a bulkhead filter into, a large metal plate (say at least 1m x 1m) or metal cabinet should be electrically bonded to the CBN at the zone boundary at as many points as possible and used as the filter's local RF reference, as shown in Figure 4E.

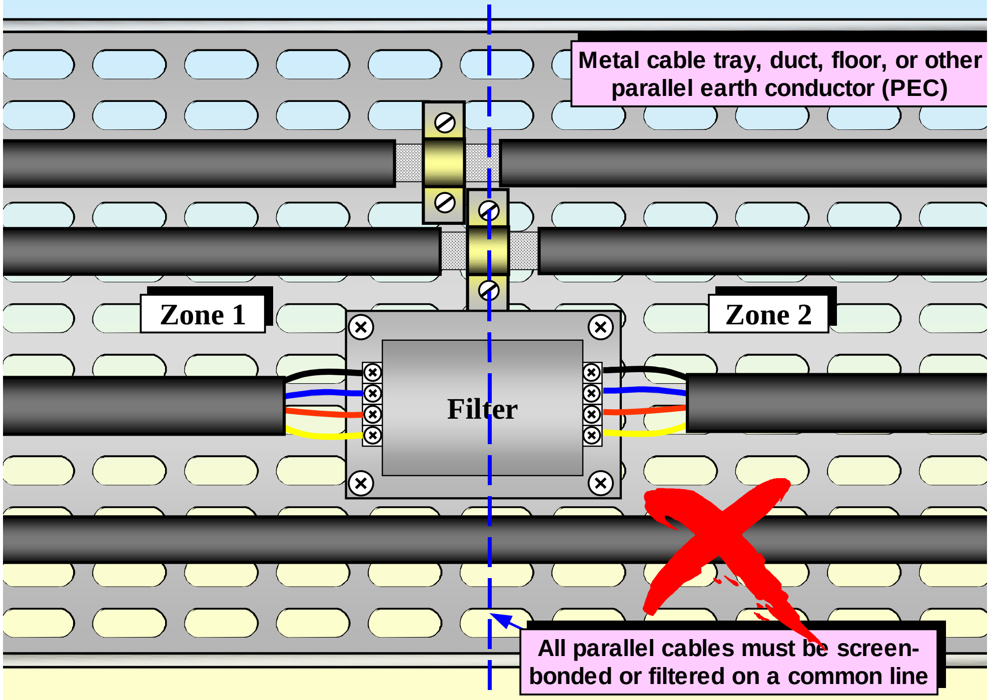
If an insulated bonding mesh or system reference potential plane is being used in the zoned area (MESH-IBN, see 2.4.5 in Part 2 of this series [3]) the plate or cabinet must be mounted at its 'single point of connection' (SPC).

4.4.8 Filter wiring

Filtered and unfiltered cables must be kept rigorously segregated. On no account should a filter's input and output wiring be loomed together. Where a zone boundary is the metal surface of a shielded enclosure or room and the filter is bulkhead mounted in that surface, the input and output cables are shielded from each other – the ideal situation. But where there is no metal shielding surface the filter's input and output cables should be carefully routed as far away from each other as possible as they leave the filter terminals. Filter performance may be improved by reducing the coupling between the input and output cables by using screened cables or screening conduit for one or both of them.

If a filter must be installed in-line in a cable tray or conduit acting as a PEC, then *all* the unscreened cables in that conduit must be filtered at the same location as shown by Figure 4F, otherwise coupling (crosstalk) to and from the unfiltered cables will compromise the high frequency attenuation of the filtered cable. Where the parallel cables are screened, their screens should be exposed and bonded to the PEC at the same location as the filter.

Figure 4F Filtering or screen-bonding parallel cables



4.4.9 Earth leakage current

Most mains filters have capacitors from phase and neutral to their metal bodies These are usually only a few nanoFarads and have a high impedance at 50/60Hz, but can still inject a significant leakage current into the local RF reference. 'Significant' refers to human galvanic response – the current required to make muscles operate involuntarily. A milliAmp or two can make a person twitch hard enough to cause damage by banging into other objects. A mere 9 mA is reputedly enough to stop a human heart (hence the safety mantra: "9 mills kills").

Achieving safety means considering the consequences of all reasonably foreseeable single faults, such as a protective conductor wire or bond being damaged allowing all the leakage current from a unit or a system to flow through a user or maintenance person. In large systems the small leakages from many small filters on individual items of equipment can create dangerously large leakage currents. Permanently wired equipment in a building is allowed by some standards to have leakage currents of up to 5% of the input current –which can be very large indeed in the case of the powerful variable-speed motors used for lifts or HVAC.

As well as safety implications, large currents in the CBN can give rise to potential differences which cause hum and/or high transient voltage levels on cables between equipments. Because the impedance of capacitors falls as frequency rises, leakage currents emphasise the high-frequency content of the mains voltage. The high inductances of some older CBNs can emphasise these high frequencies even more.

Modern best-EMC-practices require a low-inductance three-dimensional meshed bonding network (MESH-CBN). Older installations without such CBNs may benefit from the use of special low-leakage filters.

Using an isolating transformer can eliminate leakage from filters connected to its 'floating' earth-free side, to the degree allowed by primary-secondary capacitance of the transformer. Alternatively a centre-tapped transformer could be used to supply the filters in question, with its centre-tap connected to the CBN. These should only be used where the balance of all safety concerns are in their favour.

In three-phase systems, filter leakage is only as good as the phase balance at each frequency – i.e. the voltage between the neutral and the earth electrode (ignoring capacitor tolerances). These days an increasing amount of mains consumption is at harmonics of the fundamental supply frequency, and harmonics can't be balanced in the traditional way. In particular, triplen harmonics (3^{rd}, 9^{th}, 15^{th}, etc.) don't cancel, they always add constructively in the neutral. They can be blocked by a star-delta transformer, as long as the balance of the triplens on the loads of the star-connected side is good.

There are many ways of reducing harmonic pollution of the mains supply, and also therefore of reducing voltage differences due to filter leakage currents in a CBN, such as passive filtering, active harmonic cancellation, special types of uninterruptible power supply (UPS) such as motor-generator sets (most solid-state UPS's create as many mains harmonic problems as they solve). These are outside the scope of this series.

4.4.10 Filter safety approvals

Mains filters are critical for safety as well as for EMC. It is always best to use supply filters for which third-party safety approval certificates have been obtained and checked. Certificates should be checked for authenticity (ask the issuing laboratory), filter model and variant, temperature range, voltage and current ratings, and the application of the correct safety standard.

4.4.11 Filter rating

The current rating of a mains filter is principally determined by its inductor(s). Excess currents can cause three principal effects:

- Overheating, with consequences for reliability and possibly safety.
- Saturation of the choke core, causing a reduced attenuation.
- A reduced supply voltage on the filtered side.

Choosing a properly rated filter is not always simple since electronic equipment, low-energy lighting and motor drive inverters (for example) can have very non-sinusoidal waveforms with their peak current very much higher (sometimes 5–10 times) than the rated RMS value. If the peak current might exceed the filter's instantaneous current capability, consult the filter's manufacturer.

The filter manufacturer may publish a derating curve which applies to the *RMS* current and is relevant for overheating. An inductance saturation curve may also be given; this shows loss of inductance versus current and should be applied to the *peak* current, to check whether attenuation will suffer too much. When using filters on DC power, inductor saturation can also readily occur. Manufacturers should be able to provide graphs of inductance and/or filter attenuation versus DC current.

4.4.12 Filters and overvoltages

Mains filter components should (of course) be rated to withstand their nominal operating voltage, plus a safety factor and an allowance for transient overvoltages which could damage the filter. Correct filter selection assesses the transients they might experience in their environment and selects filters that will cope with the anticipated overvoltages to provide the desired reliability.

Where it is too expensive to specify filter components for transient voltages they may rarely experience, but it is important to achieve high reliability, they (and the equipment in their zone) may be protected by the lightning protection methods described in Chapter 9 of [1]. The next part of this series summarises these lightning and surge protection methods.

4.4.13 Simple soft-ferrite filters

A particularly useful type of filter is a soft-ferrite split cylinder in a plastic “clip-on” housing. These are very easy to apply as a retro-fit (and to remove when found not to do much), and are available in a wide range of shapes and sizes, including flat types for ribbon cables.

Soft ferrite materials add series inductance to the cables they are clipped onto at low frequencies, but add series resistance at high frequencies – this helps prevent unwanted resonances from occurring. When clipped around the send and return paths of a cable they only attenuate CM, and when clipped around a single conductor they attenuate DM. Beware of saturation effects, especially when using ferrites for DM suppression. Like any magnetic material, ferrite can saturate, and a thicker body to the cylinder generally indicates a greater flux-handling capacity for a given length.

Ferrite has a high permittivity, so placing a ferrite cylinder around a cable and putting the ferrite close to the local RF reference has the effect of adding a series impedance and a shunt capacitance. Part 3 of [4] has more on ferrites, with a great deal more in Chapter 8 of [1].

Most EMC engineers carry kits of split ferrites suitable for various sizes of round and flat cables, when they visit sites to investigate or fix interference problems. But in general they can only achieve between 3 and 12dB of attenuation.

4.5 Shielding in installations

4.5.1 Zone shielding

Many items of electrical and electronic equipment are supplied in metal (or metallised) enclosures. It is often most cost-effective to make the enclosure the zone boundary, and make the manufacturer of the equipment deal with all the necessary filtering and shielding (and surge suppression, optical isolation, mains harmonics, etc.). Part 3 of this series [8] covered filtering and shielding at the enclosure boundary, so these techniques won’t be described in any detail here. See Chapter 6 of [1] for more detail than is provided in either Part 3 of [8] or Part 4 of [4].

In some cases low-cost mass-produced items (such as computers and their monitors) are purchased and used in a variety of environments, installed in a protective zone. This principle is being employed with some success by the US military in their COTS (‘commercial off the shelf’) programmes [12].

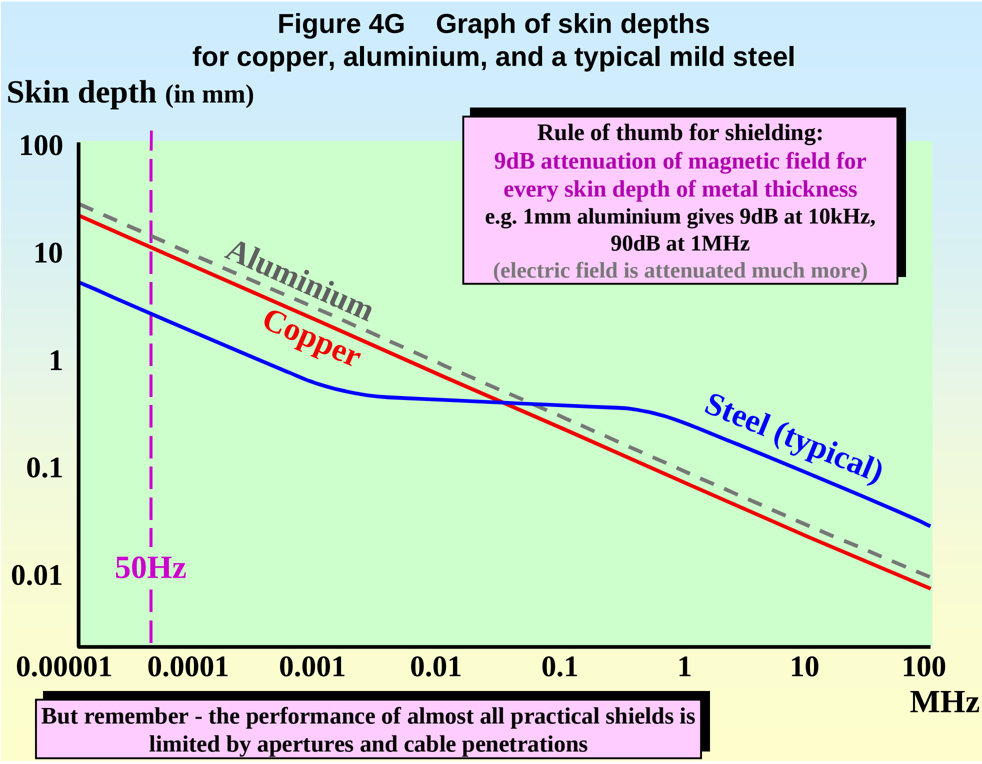
Shielding a zone or a room which is not an equipment enclosure is governed by the same physical laws of shielding as the shielding of an enclosure. Where the zone is a console or cubicle that encloses a number of equipments Part 3 of this series should be applied [8]. Where the zone to be protected is larger than this, the main techniques for shielding them are summarised below. To make a distinction with zone boundaries which are equipment or cubicle enclosures I will use the term ‘architectural shielding’.

Architectural shielding may not be easy to do, or low-cost. All shielding techniques are based upon attempting to encase the entire zone inside a seamless metal wall which has a thickness equal to many times the skin-depth at the frequencies concerned. Apertures in the wall at seams, joints, service entries, and especially at cable penetrations are weak points in the shield and need great attention to detail.

4.5.2 Shielding at very low frequencies

‘Passive’ architectural shielding against very low frequencies (say, 50Hz or 60 Hz) is generally regarded as impractical except for high-value military or scientific projects where cost is no object. But shielding against such low frequencies can sometimes be done cost-effectively with an ‘active room’ technique – which uses audio power amplifiers to drive low-frequency currents around an arrangement of electrically isolated metal conductors to drive the field sensed by local magnetometers mounted inside the zone to zero.

A three-dimensional MESH-CBN with very low resistance can attenuate external very low frequency fields within a zone. So a steel framed building under an overhead power line or near an electric tram line can reduce the 50/60Hz *electric* field to one-twentieth of the level present outside. But the low-frequency magnetic fields created by the currents in the overhead lines have a very low impedance and are difficult to reduce with shielding because the skin depth at such low frequencies would require very thick metal surfaces (see Figure 4G). Mumetal and radiometal have much smaller skin depths, but even so it has been found difficult to use them to achieve good architectural shielding against very low frequency magnetic fields.



4.5.3 Shielding above 10kHz

Since the skin depth reduces as frequency increases, practical shielding against magnetic fields (as well as electric fields) becomes possible.

The three-dimensional mesh created by a MESH-CBN is also more effective at shielding at these frequencies, with the shielding effectiveness (SE) achieved related to the size of the mesh. Mesh sizes not exceeding 3 or 4 metres are recommended for helping to protect zones against the effects of lightning (see Part 5, in the next issue). A much smaller mesh can easily be achieved by electrically bonding all the re-bars used in the concrete construction of a building, along with any metal-lined roofs or floors, at each cross-over and joint (needs to be planned early).

Cladding a room with chicken-wire mesh (as seen in the recent film “Enemy of the State” with Gene Hackman and Will Smith), welded mesh, or expanded metal can provide quite acceptable values of shielding effectiveness provided that all the seams are bonded along their lengths.

Where the zone is a subset of a room, a framework may easily be made from timber studding and clad with these materials, preferably on both sides to give two layers. Higher conductivity, higher permeability, or thicker materials are all good for improving protection against lower frequencies. Higher conductivity materials with small apertures are good for high frequencies.

4.5.4 Shielding above 1MHz

Above 1MHz good results may be had with quite thin metal shielding materials. "EMC wallpaper" is copper foil with a building paper backing, not too difficult to glue to firm flat surfaces. Metallised fabrics and expanded metal have also been successfully used, with the advantage that they allow air to pass through them to some degree. However, for the best shielding performance there is no substitute for two layers of seam-bonded metal plates, which is why this is the basic structure of most EMC test chambers.

4.5.5 Dealing with apertures

A real problem with shielding a large volume is that its SE is always compromised to some extent by necessary apertures: e.g. windows, doors, cable entries, ventilation, lighting and air conditioning. Accidental apertures, especially imperfections in the joints of the supposedly seamless metal skin, also compromise shielding.

A metal room that ought to achieve 80dB shielding effectiveness at 200MHz can be reduced to 10dB or less by the penetration of an unfiltered lighting cable, or can be reduced to 40dB by a single hole not much wider than one could put a finger through.

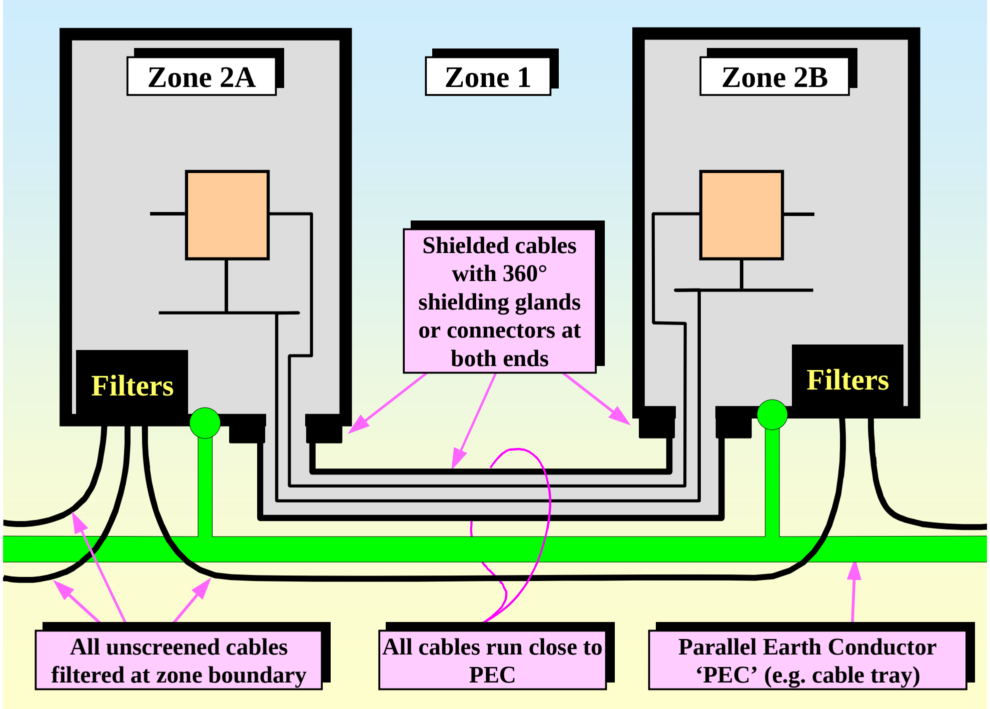
4.5.6 Doors are a problem

Other than cable penetrations, the single biggest practical problem with shielding a zone is access for people and equipment – doors. Doors often need lever-operated handles driving multiple latches on all three unhinged sides, due to the cumulative effect of gasket compression forces. It is surprisingly difficult to make a door and frame accurately and sturdily enough to compress even low-compliance conductive gaskets uniformly over the whole door aperture. Don't be tempted to use electrical latches, people have been know to be trapped in shielded rooms for hours after a power cut (especially as they often attenuate shouts for help fairly well).

4.5.7 Interconnecting shielded enclosures or rooms

Figure 4H shows how two shielded zones are connected together and to the rest of the installation, without compromising their shielding effectiveness. These enclosures could be any size: from cabinets to large rooms or even whole buildings.

Figure 4H Interconnecting zones



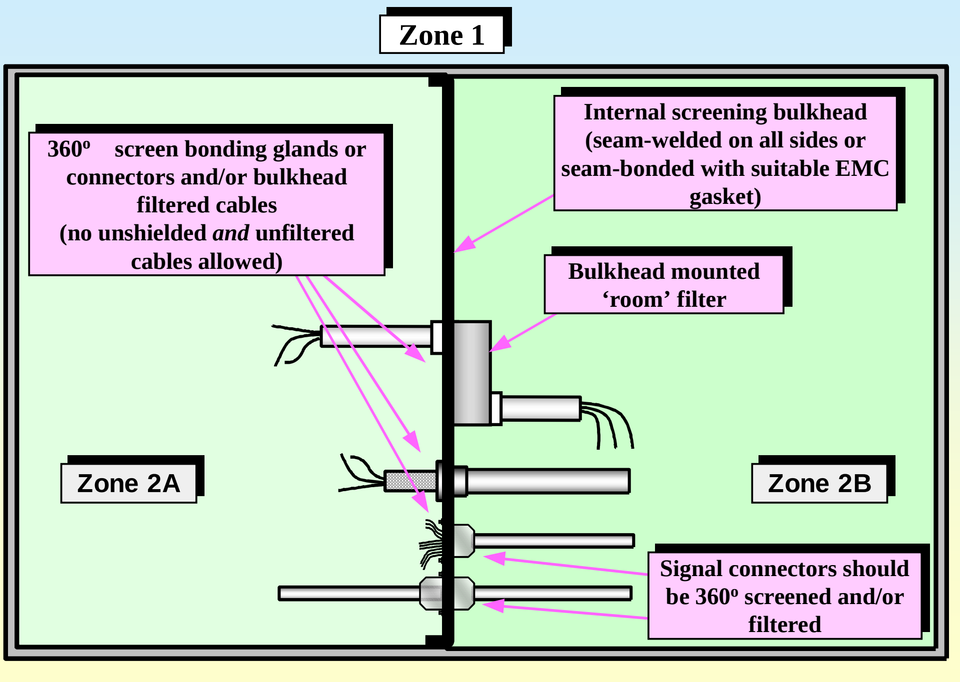
All screened cables that enter or leave shielded zones must have their screens terminated by 360° electrical contacts in shielding glands (or connectors) at the enclosure walls. Where the zone is simply defined by a MESH-CBN, high-frequencies will not be shielded against (depending on mesh size) but still the screened cables must be bonded at the zone boundary, for example by using a saddleclamp to bond them at the filter bonding plate shown in Figure 4E above.

The unscreened cables that enter or leave the zones may only enter via filters mounted at the zone boundary. Bulkhead-mounted filters (see earlier) are the best for this purpose (see earlier, and Figure 4D). A PEC (e.g. at least one metal cable tray, duct, conduit, or item of structural steelwork) is bonded to each shielded zone and runs between them, carrying all the cables between them. These cables should be segregated by their class, as described in section 2.8 of Part 2 of this series [3].

Metal-free fibre optic cables would be better than metallic conductors for such rooms, because they may enter by waveguide tubes which cause insignificant leakage (up to a critical frequency). Unfortunately it is still impossible to transfer substantial amounts of electrical power in fibre optics (above a few tens of watts) so we still need metallic cables and filters for AC mains and DC power.

Figure 4J shows the interconnection techniques for cables between a shielded zone that has been divided into two with a seam-welded metal bulkhead.

Figure 4J Example of bulkhead splitting a shielded zone into two



4.5.8 Waveguide techniques

Waveguide below cut-off is a very powerful shielding technique, discussed in more detail in Section 4.7 of Part 4 of [4]. As well as being used for fibre-optic, microwave, infra-red, and laser communications into a zone, they can be used for ventilation and lighting without compromising SE.

For the latter purposes honeycomb metal panels are often used, seam-bonded carefully around their edges to the rest of the structure. But don't forget that waveguides only provide decent amounts of shielding well below their cut-off frequency, roughly speaking for wavelengths which are longer than four times the longest dimension of the waveguide's cross-section.

4.5.9 Using a third-party

Constructing a high-specification shielded zone is not something that should be attempted by non- experts, unless they have the time and money to enjoy the learning experience. The quickest approach is to contact one of the many companies that offer to design and build shielded rooms and subcontract them to do it all. It is important for the installation's project manager to make sure that the contract specifies:

- The shielding performance for the frequency range of interest.
- The air and light quality within the zone.
- The dimensions and traffic levels for people, goods, services, equipment, and vehicles in and out of the zone.
- The electrical power and communications to be provided to the zone.
- The verification methods to be employed and the minimum results they must achieve (for instance MIL-STD-285).
- That it is the contractor's responsibility to achieve those results for the agreed price and in the agreed timescale.

Holding a substantial part (or all) of the price of the contract back until verification has been satisfactorily completed, is a powerful way to get the desired performance from an experienced contractor. Don't even think of using a contractor with no proven track record for this work, unless you have the time and money to enjoy their learning experience.

Remember that a shielded room is not shielded when any of its doors are open. It is surprising how many people will go to great lengths to wedge doors open to make life more comfortable. This is an important reason not to skimp on the air quality and HVAC to the zone.

4.6 Electronic warfare

As mentioned earlier, data security and the reliability of electronics is an increasing concern as our society comes to entirely depend upon data and electronics (see [2]). The military have a powerful zone protection programme known as TEMPEST. This is now available for civilian use to counter the increasing amount of commercial, financial, and industrial blackmail, terrorism, and espionage which relies upon the vulnerability of modern computers and their networks to EM disturbances, and their propensity to broadcast their data over large geographical areas where they may be picked up by sensitive receivers available to all.

Mains filters for TEMPEST use tend to have many more than two stages, and reliably provide several tens of dBs attenuation from 10kHz to over 1GHz. Shielding for TEMPEST tends to be similar to EMC test chambers. I understand that UK national security operatives nowadays expect to work in EMC screened rooms with only a single metallic conductor – the mains cable – which enters through a very large filter. All data in or out of the room is carried by metal-free fibre optics, presumably with sensitive devices to monitor optical signal levels for taps. I hope that they remember to shut the doors to their rooms when they are working.

Whilst the level of protection provided for the offices of spies may be excessive for most situations, merchant banks and the like that handle billions of dollars of trade ever day (or more) stand to lose many tens of millions due to a single downtime incident lasting a few hours, never mind an actual espionage or e-terrorism incident. For such enterprises, as for nuclear control rooms, financially justifying an adequate level of protection from all but the most extreme of EM threats is probably not difficult to do, especially at the planning stage where the measures required can be designed-in at much less cost than adding them after construction is complete.

4.7 References and further reading

[1] "*EMC for Systems and Installations*", Tim Williams and Keith Armstrong, Newnes, 2000, ISBN 0 7506 4167 3.

[2] "*Just a Normal Town…*", Ian Sample, cover story in New Scientist 1 July 2000 No 2245, pp 20-24.

[3] "*EMC for Systems and Installations – Part 2 EMC Techniques for Installations*", Keith Armstrong, UK EMC Journal Apr 2000, pp 8-17. Available from the article archive at www.emc-journal.co.uk.

[4] "*Design Techniques for EMC*", Keith Armstrong, UK EMC Journal Jan – Dec 1999 (six parts). Read them on-line in the article archive at www.emc-journal.co.uk.

[5] "*EMC for Systems and Installations – Part 1 Earth? What earth?*", Keith Armstrong, UK EMC Journal Jan 2000, pp 15-21. Available from the article archive at www.emc-journal.co.uk.

[6] "*Banana Skins*", No. 85 from Peter Kerry, UK EMC Journal June 2000, pp 8. Available from the article archive at www.emc-journal.co.uk.

[7] IEC 364-4-444: 1996 "*Electrical installations of buildings – Part 4:Protection for safety – Chapter 44: Protection against overvoltages – Section 444: Protection against electromagnetic interference (EMI) in installations of buildings.*"

[8] "*EMC for Systems and Installations – Part 3 EMC techniques in assembly*", Keith Armstrong, UK EMC Journal June 2000, pp 25-35. Available from the article archive at www.emc-journal.co.uk.

[9] "*Choosing and Using Filters*", Keith Armstrong, UK EMC Journal 1998, pp 6-10. Available from the article archive at www.emc-journal.co.uk.

[10] "*Choosing and Installing Mains Filters*", Tim Williams and Keith Armstrong, Compliance Engineering, pp 68-75.

[11] "*EMC and Signal Integrity*", Keith Armstrong, Compliance Engineering European Edition, March/April 1999, pp 24 – 35

[12] “*An EMC Design Approach for Integrating COTS Equipment into an Existing Military Aircraft*” Edward L Kirchner and Bruce D Salati, Proceedings of the IEEE EMC Symposium, Seattle, August 1999, pp 986-991

[13] Verbal aside during the presentation of the paper "*Protective or clean earthing* - *a potential difference*" by Peter Smith, at the "*Earthing 2000*" conference, Solihull, UK, 21-22 June 2000, proceedings available from ERA Technology Ltd, phone +44 (0)1372 376000 info@era.co.uk.