Metal enclosure design for EMI and EMC protection

Engineering guidance for mechanical and electrical design teams

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Design the enclosure as a complete conductive boundary. Its protection depends on the continuity of the walls, cover joints, vents, displays and cable interfaces, together with the circuits and wiring inside. A thick metal wall cannot compensate for an untreated cable entry or an unreliable lid contact.

EMI means electromagnetic interference. EMC means electromagnetic compatibility: acceptable equipment operation in its intended electromagnetic environment without causing unacceptable interference. This guide supports the design of metal housings from small instrument boxes to cabinets. It develops the supplied aperture note into practical construction guidance, calculations, design reviews and verification, with separate treatment of low frequency magnetic fields and conditional industrial, marine and defence standards routes.

Use this guide to make design decisions

- Define the electromagnetic environment, frequency bands and required attenuation before selecting hole sizes or gasket parts.
- Give every penetration and removable joint a deliberate shielding treatment, supported by a drawing and a verification method.
- Use hand calculations to compare concepts and identify risks; use assembly measurements to establish actual shielding performance.
- Verify the operating equipment with its final cables, filters, software modes and loads. Enclosure attenuation alone does not establish EMC compliance.

Engineering basis. Numerical examples are calculated from stated idealised models. They are not test results or a released product specification. Dimensions, ratings, severity levels and acceptance limits for a particular product must be populated from its approved requirements. References distinguish technical background, manufacturer guidance and standards scope.

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Use Sections 1 to 4 to define the design basis, Sections 5 to 9 for construction details, Section 10 for a worked example, and Sections 11 and 12 for verification and release. Appendix A records corrections to the source note; Appendix B is a reusable review worksheet.

Reading equations. SE means shielding effectiveness in dB. All logarithms shown as $\log_{10}$ use base 10. Calculations use SI units unless a table states otherwise. The speed of light is rounded to 3.00×10^8 m/s for design examples. Positive attenuation means a lower field after shielding.

Requirement language. “Recommended” identifies engineering guidance. Mandatory project requirements are those in the approved product specification, drawings, adopted standards and contract. A numerical example does not become a mandatory design rule simply because it appears in this guide.

1 Design priorities

Start by drawing the shielding boundary and tracing every path across it. Assign an identifier to each connector, vent, window, shaft opening, lid joint and unused cutout. The resulting boundary schedule is the common reference for the mechanical designer, circuit designer, wiring technician and test laboratory. Treat changes to any listed feature as changes to the electromagnetic design.

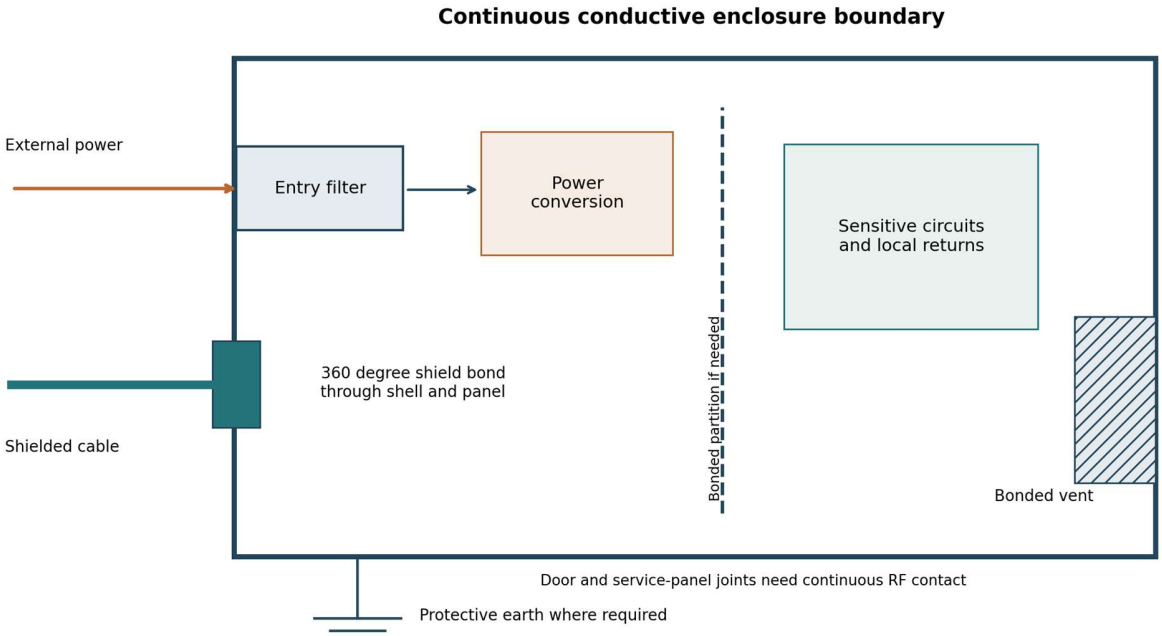


Figure 1. Conceptual protection boundary and entry treatment. The partition is optional; protective earth and circuit return connections require their own design. Schematic only, not a wiring or fabrication drawing.

The first design review should answer four questions: which circuits generate interference, which functions are susceptible, where the interference can travel, and what each boundary crossing does to interrupt that path. Cabinet manufacturers apply zoning, entry filtering and local shielding for the same purpose. [6]

Recommended order of work

- Reduce avoidable noise at switching nodes and current loops, then keep noisy and sensitive circuits apart. This lowers the attenuation demanded from the enclosure.
- Define cable shields, connector shells and filter returns before fixing connector locations. Cable interfaces often determine whether an otherwise continuous enclosure is useful.
- Design the lid, doors and removable plates as RF joints. Check closure force, contact finish, tolerance and service life together.
- Choose ventilation, viewing and mechanical access solutions that preserve the boundary while meeting thermal and usability requirements.
- Reserve access for diagnostic measurements and verify the representative assembly before tooling or enclosure procurement is frozen.

Three different claims need three different kinds of evidence. Material attenuation concerns a sample or wall model. Enclosure shielding concerns a defined box and test configuration. Equipment EMC concerns the operating product and all relevant ports. IEC 61000-5-7 addresses empty enclosure protection to support subsequent assembled equipment performance; it does not replace the latter evaluation. [18]

2 Define the protection requirement

Build an electromagnetic design basis

Document the intended installation before discussing a target such as “40 dB shielding”. Record nearby transmitters, motors and converters; expected cable lengths and routes; the supply architecture; sensitive measurement functions; and the consequences of a reset, false command or measurement error. The same enclosure may be acceptable in one installation and inadequate in another.

Requirement item	Information to record	Why it affects the design
Equipment and installation	Product function, market, mounting location, adjacent equipment and accessible surfaces	Determines the governing product standard and realistic coupling paths
Frequency and field	Frequency bands, electric or magnetic field, radiated or conducted exposure, source distance	Selects appropriate shielding and test models
Performance	Permitted emissions, immunity severity, functional criteria and required enclosure SE by band	Defines measurable acceptance rather than a general claim of protection
Interfaces	Power, data, shields, fibre, displays, vents, service access and unused provisions	Identifies all crossings of the shielding boundary
Service conditions	Temperature, humidity, salt exposure, vibration, cleaning and door cycles	Determines gasket, finish, corrosion and retention requirements
Verification configuration	Cable lengths and loads, operating modes, installed options, measurement method and margin	Makes calculations and measurements reproducible

A useful requirement states the configuration as well as the number: for example, “minimum enclosure electric field SE of the selected value over the specified band, with the released lid, vents and connector plate installed, evaluated by the agreed method and decision rule”. Define probe positions, polarizations and treatment of resonances in the test plan. A single frequency or an unspecified vendor plot is insufficient for a broadband requirement.

Estimate the needed attenuation

For immunity planning, compare the specified external field with a defensible internal field threshold for the susceptible circuit. An illustrative 10 V/m environment and 0.1 V/m internal threshold give 20 $\log_{10}(10/0.1)$ = 40 dB. If the project independently selects 6 dB engineering headroom, the planning target becomes 46 dB. These are example assumptions, not standardised severity levels. The circuit threshold, exposure geometry and coupling mechanism must be established before using this approach.

For emissions planning, the difference between a measured level and the applicable limit can indicate the reduction needed at that test point, with project margin added. It does not prove that the same value of nominal enclosure SE will deliver that reduction: source impedance, enclosure resonance and cable common mode current may change when the housing is fitted. Re-measure the assembled product.

Select the applicable standards route

Choose a dedicated product or product family EMC standard when one applies. For example, IEC 61326-1 addresses measurement, control and laboratory equipment within its scope. Generic

industrial standards are a fallback where a relevant dedicated standard does not exist; installation in a factory alone is not enough to select the route. The product standard supplies the applicable ports, limits, test methods and performance criteria. [21–23]

Record the adopted editions. The newest basic test method does not automatically replace an older dated reference in an applicable product standard or contract. Section 11 and Appendix C identify relevant references and edition transitions as checked on 9 November 2026.

3 Choose the shielding approach

Distinguish electric fields magnetic fields and radiated RF

A conductive boundary redistributes charge and supports surface currents. This is useful for electric field and RF shielding. Slowly varying magnetic fields need a separate assessment: a nonmagnetic conductor relies on induced currents, while a high permeability shield can redirect magnetic flux. Conductivity, permeability, thickness, geometry and source location therefore cannot be reduced to one universal shielding value for a metal. [2, 8]

Exposure or coupling	Main design actions	Limit of a simple aperture rule
Electric field coupling	Conductive enclosure or local shield; controlled reference and return paths	Openings and lead coupling still matter
Low frequency magnetic field	Reduce loop area; increase separation; evaluate a continuous magnetic shield and saturation	λ/20 gives no assurance of magnetic immunity
Radiated RF	Continuous joints; treated apertures; shielded connectors and entry filters	Resonance, polarization and nearby sources can invalidate the estimate
Conducted interference	Correct filtering, common mode control and transient protection at affected ports	A sealed box does not remove disturbance already on a conductor
ESD and fast transients	Controlled chassis current paths and local port protection; functional testing	RF attenuation alone does not establish transient immunity

Define shielding effectiveness explicitly

$$\mathrm{SE_E} = 20 \log_{10} \left| \frac{\mathrm{E_{reference}}}{\mathrm{E_{shielded}}} \right|$$

$$\mathrm{SE_H} = 20 \log_{10} \left| \frac{\mathrm{H_{reference}}}{\mathrm{H_{shielded}}} \right|$$

Use the same defined source normalisation and observation arrangement for each ratio. A 20 dB reduction means a factor of 10 in the relevant field amplitude; 40 dB means 100; 60 dB means 1000. A power ratio uses $10 \log_{10}$. Do not infer magnetic field attenuation from an electric field measurement in a reactive near field. Enclosure field distributions are not necessarily uniform. [4, 5]

For a small source, wavelength divided by 2π is a useful scale when considering reactive near fields, but it is not a universal far field boundary for every radiator. Keep local current loops and sensitive circuitry away from openings where possible, then assess the actual source geometry. Repeating a plane wave calculation at a higher frequency will not resolve a low frequency near field coupling problem.

Account for resonances and parallel leakage

A box is also an electromagnetic cavity. Its contents, openings and losses shape the internal field pattern. Published measurements and enclosure models show that a simple aperture formula can miss resonance related shielding reductions, including negative local SE. Use it to screen geometry, not as a conservative bound for every enclosure. [4]

Leakage through a vent, a seam and a cable interface occurs through parallel paths. Their dB attenuation values must not be added. Diagnose and improve the dominant path, then repeat the measurement: the next largest path may become visible once the first is reduced. This is the basis of the prototype procedure in Section 11.

4 Select metals and finishes

Choose a construction that can maintain electrical continuity

Construction	Useful attributes	Design checks
Aluminium	Low mass, manufacturability and good conductivity for RF work	Alloy conductivity; oxide and anodising at contacts; galvanic compatibility; flange stiffness
Mild or plated carbon steel	Stiffness and potentially useful magnetic properties	Grade dependent permeability; coating continuity; corrosion at cut edges; joint treatment
Stainless steel	Environmental durability for suitable grades	Conductivity and magnetic behaviour vary with grade and processing; do not assume all stainless steel is magnetic
Copper or copper alloy	High conductivity and convenient thin local shielding	Cost, mass, structural support, oxide/tarnish and dissimilar metal contacts
High permeability liner	Targeted low frequency magnetic flux diversion	Saturation, magnetic continuity, final processing, mechanical stress and supplier qualification

The table is a selection framework, not a dB ranking. Specify the actual alloy, thickness, process and mating finish. At RF, once a wall is several skin depths thick, improving a poor joint or cable interface is often a more productive next step than increasing wall thickness. Structural stiffness can still justify a thicker wall because cover bowing changes gasket contact.

Use skin depth as a wall calculation

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

$$A_{bulk} = 8.686 \frac{t}{\delta} \text{ dB}$$

Here δ is skin depth in metres, t is metal thickness, σ is conductivity in S/m, μ is permeability in H/m and ω = 2πf. The usual good conductor approximation and linear material properties are assumed. A_bulk is one way field decay within uniform metal, not total sheet or enclosure shielding. Surface reflections, thin sheet interactions and geometric leakage remain outside this term. [16]

Frequency	Aluminium skin depth	Interpretation for a 1 mm wall
50 Hz	12.03 mm	Only 0.083 skin depths; evaluate magnetic shielding separately
100 kHz	0.269 mm	About 3.7 skin depths; complete geometry still matters

Frequency	Aluminium skin depth	Interpretation for a 1 mm wall
1 MHz	0.0851 mm	About 11.8 skin depths
100 MHz	8.51 µm	Wall is many skin depths; inspect joints and penetrations
1 GHz	2.69 µm	Bulk attenuation is not the likely practical performance limit

Calculated example assumptions: $\sigma = 3.5 \times 10^7$ S/m, $\mu_r = 1$ and $\mu_0 \approx 4\pi \times 10^{-7}$ H/m. Conductivity is an illustrative aluminium value, not a guaranteed property of a specified alloy. At DC, ordinary nonmagnetic metal does not sustain eddy current shielding. For a specialist magnetic liner, define the final forming, annealing and handling process with its supplier; mechanical work can change permeability. [9]

Specify a conductive and durable contact system

Show paint and insulating coating exclusion zones on the drawing. Select a compatible conductive conversion coating or plating where environmental protection is necessary, and qualify the complete metal–finish–gasket combination. Anodised or painted aluminium should not be presumed to provide a reliable RF mating surface. Contact preparation must be reproducible in production and after service.

Separate the cosmetic finish requirement from the electrical contact requirement. Define masked lands, edge protection, allowed cleaning and repair methods, and inspection criteria. A finish substitution can change contact resistance, galvanic behaviour, wear and gasket interaction; subject it to engineering change control. Avoid uncontrolled scraping of paint as a production instruction.

5 Size apertures and recognise model limits

Use the longest uninterrupted dimension

For a long narrow slot, length can be the critical dimension even when width is small. A panel joint with isolated contact points can leave electrically long unbonded sections. A cosmetic overlap or a fastener head does not automatically divide the joint into RF sealed segments. Record opening geometry and electrical continuity, not just the total open area.

$$\lambda = \frac{c}{f}$$

$$SE_{screen} \approx 20 \log_{10}\left(\frac{\lambda}{2L}\right)$$

$$L_{screen} = \frac{\lambda}{2 \times 10^{\frac{SE_{target}}{20}}}$$

These expressions retain the useful preliminary relation in the source note. L is the relevant largest uninterrupted opening dimension; c is approximated as 3.00×10^8 m/s in air. Treat the result as an isolated, thin aperture screening estimate without a wire traversing the opening. It is not a verified installed enclosure value and does not establish a universal minimum. [1, 3, 4]

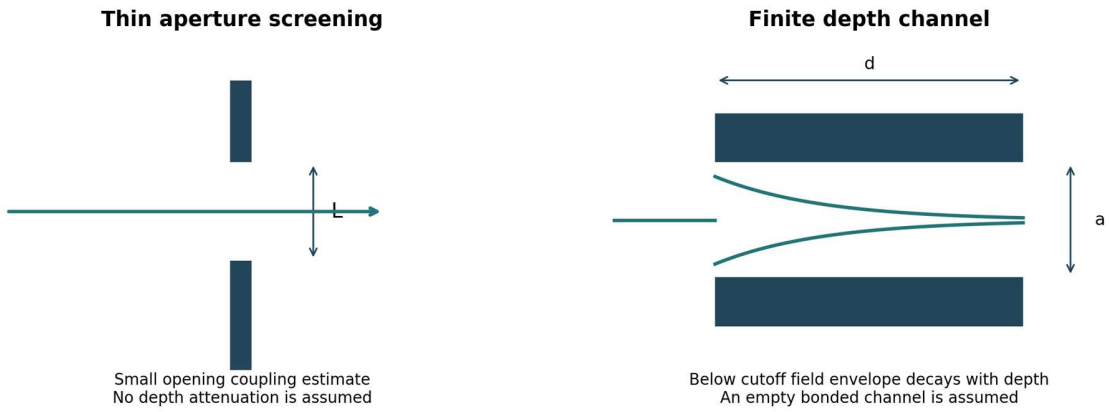


Figure 2. Two distinct calculations. Thin aperture screening concerns coupling through an opening; below cutoff channel attenuation concerns field decay along a finite depth. Dimensions and field envelopes are schematic.

Recalculate the original aperture example

At 2.4 GHz, λ ≈ 125 mm. Substituting into the screening relation gives the values below. The 6.25 mm example is retained, with its status as an estimate made explicit.

Nominal screening estimate	Dimension relationship	L at 2.4 GHz
20 dB	λ / 20	6.25 mm
28 dB approximately	λ / 50	2.50 mm
40 dB	λ / 200	0.625 mm
60 dB	λ / 2000	0.0625 mm or 62.5 µm

Correction to the source table. λ/50 gives 20 $\log_{10}(25)$ = 27.96 dB under this relation. It must not be labelled as more than 40 dB. Likewise, λ/20 gives exactly 20 dB at equality in the model; it does not guarantee more than 20 dB in service. [1]

Use a frequency table for concept screening

Frequency	Wavelength	L for 20 dB	L for 40 dB	L for 60 dB
30 MHz	10 000 mm	500 mm	50 mm	5 mm
100 MHz	3000 mm	150 mm	15 mm	1.5 mm
300 MHz	1000 mm	50 mm	5 mm	0.5 mm
1 GHz	300 mm	15 mm	1.5 mm	0.15 mm
2.4 GHz	125 mm	6.25 mm	0.625 mm	0.0625 mm
6 GHz	50 mm	2.5 mm	0.25 mm	0.025 mm
10 GHz	30 mm	1.5 mm	0.15 mm	0.015 mm

All entries are calculated screening values using the same elementary relation. Large low frequency values are not permission to make a correspondingly large production opening. Small high attenuation values show why designers use bonded mesh, filters, conductive windows or deep vents instead of relying on a bare opening. The table does not model arrays, magnetic near fields or enclosure resonances.

Know when the relation is insufficient

- A source is close to the opening, or its field is strongly magnetic or nonuniform.
- The required band approaches cavity or slot resonances, or multiple apertures interact.
- A cable, shaft, conductive pipe or other conductor crosses the opening.
- There are long seams, uncertain contacts, dielectric loading or significant internal structures.
- A high attenuation requirement leaves little tolerance for manufacturing variation or measurement uncertainty.

A 10 mm opening gives a nominal 20 dB estimate at 1.5 GHz and approximately 14 dB at 3 GHz. There is no abrupt transition at λ/10 where leakage first begins. A half wavelength slot can couple strongly, but the simple formula reaching zero there is not a universal prediction of the enclosure response. [1, 4]

An array cannot be assigned a universal correction solely from its hole count. Equal coherent field contributions and uncorrelated power contributions give different simplified penalties, and mutual coupling changes the situation further. Use a validated array or enclosure model, or measured data for the complete vent assembly. Do not sum shielding dB values from parallel paths or count an array penalty twice.

6 Design seams doors and gaskets

Make the joint an engineered component

Choose whether a joint is permanent or serviceable. A qualified continuous weld can remove a service joint from the boundary; stitch welding leaves intervening discontinuities that require evaluation. Removable covers need a defined conductive contact system. Mechanical attachment and protective bonding do not by themselves demonstrate continuity around the full RF perimeter.

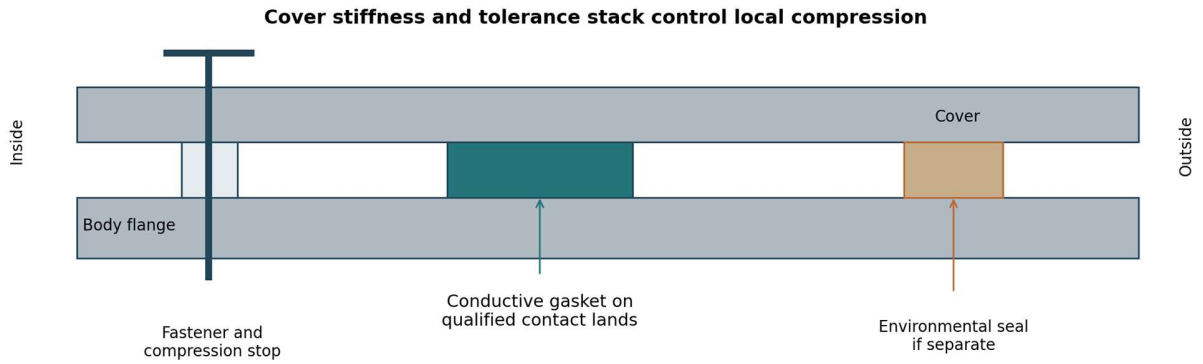


Figure 3. Conceptual gasketed flange with separate environmental sealing where required. Actual land widths, groove dimensions, compression stops and bolt spacing follow the selected gasket data and mechanical analysis.

Select gasket profile and material together with the mating metal and finish. Conductive elastomer, fabric over foam and spring contact products have different closure loads and wear behaviour. Match the technology to compression, wiping or shear motion, access frequency and environment; do not substitute a visually similar seal without review. [10, 11]

Calculate the full compression range

$$\text{Compression}\ (\%)\ =\ 100\ \frac{\mathrm{h_{free}}\ -\ \mathrm{h_{closed}}}{\mathrm{h_{free}}}$$

Evaluate both tolerance extremes. The lowest compression can occur between fasteners or at a warped corner; the highest can occur near bolts or hard stops. Include gasket height tolerance, groove depth, finish thickness, flange flatness, lid bowing, thermal distortion and compression set. Obtain the supplier's usable compression range and force per unit length for the exact material and profile. Check retained contact force after stress relaxation and environmental aging, as well as dimensional compression and recovery after opening. Do not apply one percentage to every conductive gasket.

As an illustrative tolerance exercise, a gasket free height of 2.00 ± 0.05 mm and a closed gap of 1.50 ± 0.05 mm produce compression from 20.5% to 29.3%. This would fit a hypothetical 20–30% approved window before allowing for bowing, aging and other effects. The example is not a recommendation for a particular product; the real permitted range and mechanical reserve must come from its qualification.

Determine bolt pitch from cover stiffness, closure force and the RF contact requirement. Use compression stops where they help control the closed gap. Check corner joints, gasket splices, captive fasteners and latch positions. A hinge or a separate door strap can provide a useful bond while leaving the perimeter seam electrically open at RF.

Qualify the joint after realistic use

Parker identifies gasket geometry, deflection, substrate finish and fastener arrangement as factors in shielding performance, and warns that a DC resistance measurement alone cannot predict RF SE. Use a bond measurement as an assembly control with a defined method, then substantiate shielding with the assembled joint. [10]

Define the service conditions that can degrade contact: repeated opening, wiping, salt deposits, cleaning fluids, vibration, condensation and replacement parts. Inspect continuity around the complete perimeter after representative exposure. Keep a record of gasket part number, lot, finish and closure condition so that an unexplained performance change can be traced to a physical cause.

7 Design ventilation and service openings

Separate cell attenuation from installed vent performance

A deeper, narrow conductive channel can attenuate modes below its cutoff frequency. For a uniform air filled rectangular channel with a ≥ b, depth d and no second conductor, the dominant mode cutoff and its ideal field decay are: [2]

$$f_c = \frac{c}{2a} \qquad \alpha = \frac{\pi}{a}\sqrt{1 - \left(\frac{f}{f_c}\right)^2}$$

$$A_d = 8.686\,\alpha d = 27.29\,\frac{d}{a}\sqrt{1 - \left(\frac{f}{f_c}\right)^2}\ \text{dB}$$

These expressions apply for f < f_c. A_d is positive depth attenuation, defined as 20 $\log_{10}|E(0)/E(d)|$ for the modal field. It does not include all entrance and exit coupling or other leakage paths. A finite below cutoff channel still transmits some energy through evanescent coupling; the cutoff is not a perfect on/off barrier.

For an empty circular channel, use its internal diameter D. The corresponding dominant mode approximations are:

$$f_c \approx 0.5861\,\frac{c}{D} \qquad A_d \approx 31.98\,\frac{d}{D}\sqrt{1 - \left(\frac{f}{f_c}\right)^2}\ \text{dB}$$

Do not replace a hexagonal honeycomb cell with a rectangular or circular channel without qualifying that approximation. Dielectric filling lowers wave velocity and changes cutoff. A wire through the channel can create a transmission path that does not have the cutoff of an empty hollow guide. Such an entry needs the appropriate shielding, bonding or filtering treatment.

Check a practical channel example

For a = 6 mm, d = 12 mm, f = 6 GHz and an air filled rectangular channel, $f_c \approx 25$ GHz and $A_d \approx 53.0$ dB. At the same frequency, a 1 mm depth gives only about 4.4 dB of this modal decay term. This comparison explains the attraction of deep vent cells; it does not assign either value to an installed vent panel. Do not add a thin aperture estimate to 53 dB and call the sum the enclosure SE.

Specify the complete vent and its thermal operating point

Procure and verify the core, frame and perimeter contact as one assembly. Include frequency range, field or measurement basis, polarization, finish, mounting gasket and test fixture in the RF requirement. Separately require airflow and pressure drop at the intended operating condition. Parker publishes both shielding and pressure drop information and shows why the mounting interface and protective grille are part of the design. [14]

- Determine the required heat removal and fan operating point with the actual vent, filters and grille resistance included.
- Check loss of airflow with foreseeable dust or salt loading, and make cleaning access compatible with repeatable shielding restoration.
- Specify frame flatness, contact lands and fasteners so that the mounting perimeter does not bypass the cell structure.
- Control mesh damage, crushed cells, loose frames and coating overspray during handling and service.

Unused cable entries and future options need conductive blanking plates or qualified plugs. Covering a cutout with a plastic cap or an unbonded metal plate does not restore the original boundary. Treat drain holes, shafts and service ports as entries in the penetration schedule, even when they appear mechanically insignificant.

8 Control cable and power entry

Continue the shield through the connector and panel

For RF containment, terminate the cable’s overall shield around its circumference to a conductive gland or connector backshell at the enclosure boundary. Continue that path through the connector shell and mounting flange. The objective is a low impedance path for shield current at the point of entry, without carrying it deep into the enclosure through a drain wire. NASA’s grounding handbook explains the series inductance introduced by pigtails and the value of peripheral shell bonding. [12]

Specify the whole interface stack: cable shield construction, clamp, backshell, connector shell finish, panel contact, gasket and fastening. A shielded cable does not compensate for an insulated connector shell. A connector marked “shielded” still needs a qualified panel installation.

For a simple illustration, an assumed 25 nH connection has inductive reactance $X_L = 2\pi fL$ of 15.7 Ω at 100 MHz. This is not a universal pigtail inductance; it shows why a low DC resistance connection can behave very differently at RF. Above the range where a lumped model is appropriate, the physical connection needs distributed electromagnetic treatment.

Keep protective earth chassis and circuit return functions distinct

Protective earth is a safety function; chassis bonding and an overall cable shield form parts of the electromagnetic boundary; circuit 0 V is the signal or power return reference. Document how these connect in the actual product. TDK distinguishes protective conductor requirements from the broad, short conductive connections used for RF suppression. Never remove required protective earth to cure noise. [13]

For RF, both end bonding of an overall shield is commonly appropriate where the installation supports the intended equipotential structure. Low level analog inner shields, isolated interfaces and installations with substantial ground potential differences need a deliberate system solution. Use isolation, bonding design or a documented hybrid connection where justified; avoid either “always one end” or “always both ends” as a rule for every shield. [12]

Place filtering at the boundary

Locate an EMC filter or feedthrough at the conductor’s crossing of the shield. Give its case or RF reference a short, broad connection to the local chassis. Keep unfiltered wiring outside the clean compartment, or confine it to a separately bonded entry zone. Separate the filtered and unfiltered conductors so that coupling cannot bypass the component. [6, 13]

Interface	Recommended design decision	Evidence to obtain
Mains or DC supply	Select common and differential mode filtering and transient protection; define the chassis return	Ratings, leakage current, temperature, source/load interaction and complete product tests
Shielded data cable	Bond the overall shield through a compatible shell or gland at entry	Connector and cable assembly details; signal integrity and EMC tests
Unshielded low speed signals	Evaluate feedthrough filtering and protection referenced at the boundary	Passband/loading limits and immunity/emissions with real cable lengths
High speed differential signals	Maintain impedance and balance; evaluate suitable common mode measures and shell bonding	Eye or link performance and common mode emissions/immunity
Optical fibre	Prefer nonconductive entry where feasible; treat the physical opening and any metallic armour	Aperture or feedthrough evidence; armour bonding if present
External antenna	Use a defined RF bulkhead interface and control other coupling paths	Radio performance and applicable equipment EMC requirements

Select filter components from the measured noise modes and relevant impedances. A catalogue insertion loss plot is not the loss guaranteed in a different source and load circuit. Check current, voltage, leakage, saturation, dissipation, temperature and interaction with converter control. SCHURTER’s filter selection method explicitly uses iterative measurement and final system remeasurement. [17]

A ferrite fitted around a cable can be a useful diagnostic or part of the released design, but its effectiveness depends on impedance, frequency, bias and installation. Specify the exact part and number of turns or placement if it is retained. Do not treat a clamp ferrite as an automatic substitute for a missing connector shell bond.

9 Arrange internal circuits and transient paths

Reduce the demand placed on the enclosure

Minimise high di/dt current loop area and unnecessary high dv/dt node area at the circuit source. Keep return conductors close to their associated paths. Choose magnetic components and switching layouts with emissions in mind. These measures reduce the energy available to excite enclosure apertures and cable common mode currents. [7]

Place power conversion and high current switching away from sensitive analog circuitry and direct cable exits. Keep noisy harnesses separated from filtered lines. Where partitioning is used, bond the partition to the enclosure and treat its cable crossings; a floating divider or a long gap around it can leave the intended separation ineffective.

Provide defined ESD and surge paths

Accessible metalwork should have a deliberate current path consistent with the safety and EMC architecture. Place port protection near the entry and control its return route so that a discharge does not need to cross the sensitive circuit before reaching the intended chassis reference. Coordinate clearances, insulation and protection component ratings with the product safety design.

Test representative accessible seams, fasteners, controls and connector surfaces using the governing ESD plan. Monitor actual functions rather than only observing whether the unit visibly resets. Silent data corruption, output excursions or lost communications may be the relevant failure. IEC 61000-4-2 defines an ESD test method; the adopted product standard or specification determines its application and performance criteria. [24]

Treat displays indicators and controls as boundary features

A glass or plastic pane leaves an RF opening unless an appropriate conductive mesh, coating or other shield is installed. The shielding element requires an effective perimeter connection through its edge termination and bezel. Parker’s shielded window designs use mesh or conductive coatings with defined edge and gasket options. Balance that RF design with light transmission, readability, touch operation and environmental sealing. [15]

For indicators, consider a light pipe through a small treated aperture while keeping the source circuit behind the shield. For switches, shafts and removable controls, specify the conductive mounting and any remaining clearance path. Every local improvement should remain compatible with service access; an improvised shield that technicians must remove permanently will not preserve the released performance.

Use absorbers for a defined residual problem

An internal RF absorber may reduce a troublesome cavity response, but its selection requires frequency dependent data and confirmation in the enclosure. Check temperature, flammability, adhesion, contamination and placement. Use it after the dominant seam and cable paths are understood, and retain a configuration controlled placement drawing. A resonance calculation alone does not establish the required absorber type or thickness.

10 Calculate an example enclosure

The following is a design exercise for a 300 × 200 × 150 mm internal metal enclosure, using a removable lid, 24 V DC input, one shielded data connector and forced ventilation. Assume a project has selected an RF enclosure target of 40 dB from 100 MHz to 6 GHz, with final product EMC

requirements to be specified separately. This is an illustrative target and construction, not an approved GDS product requirement.

Step 1 Identify the boundary and high risk paths

Select a stiff metal body and a gasketed lid concept. Group the power and data interfaces on a defined entry panel so their bond and filter details are inspectable. Keep the power converter in a zone near its properly filtered supply route, with the sensitive circuitry away from the vent and unfiltered wiring. List the lid perimeter, vent perimeter, connector flanges and unused holes as independent verification items.

Step 2 Screen ordinary openings at the upper band edge

At 6 GHz, λ ≈ 50 mm. The 40 dB aperture relation gives L_screen = 50/200 = 0.25 mm. An untreated 6 mm opening instead gives 20 $\log_{10}[50/(2 \times 6)] \approx 12.4$ dB in that model. This is a useful rejection signal for relying on plain openings, not a prediction of measured enclosure SE. Choose a qualified vent and treated interfaces rather than trying to release a box from this calculation alone.

Step 3 Evaluate a candidate vent concept

A hypothetical 6 mm rectangular channel with 12 mm depth has f_c ≈ 25 GHz and approximately 53 dB ideal depth attenuation at 6 GHz. Obtain a supplier test report for the actual vent core, frame and mounting assembly over the required band. The model result does not demonstrate 13 dB of headroom above a 40 dB enclosure target; the quantities refer to different things. Check the fan operating point and the installed perimeter bond.

Step 4 Flag the cavity resonance region

$$f_{\text{first}} \approx \frac{c}{2}\sqrt{\left(\frac{1}{0.300}\right)^2 + \left(\frac{1}{0.200}\right)^2} \approx 0.901\ \text{GHz}$$

For this ideal empty, closed, air filled rectangular cavity, the lowest mode involves the two longest internal dimensions. The calculated frequency is an alert to investigate, not the resonance of the populated product. PCBs, wiring, openings and losses change the response. Do not use c/(2 × 0.300) ≈ 500 MHz as the first cavity resonance; that single dimension result is not a valid closed box mode. [16]

Step 5 Resolve the lid and interface details

Use the gasket tolerance method in Section 6, a defined mating finish and a closing sequence that produces repeatable contact. Specify the data shield clamp and shell to panel bond. Specify the 24 V filter topology and transient protection from the real supply disturbance, cable and load data. Do not select arbitrary capacitor or choke values from the enclosure dimensions.

Design item	Initial concept	Release evidence
Wall and lid	Metal body with stiff gasketed cover	Released alloy, thickness, flange geometry and finish
Vent	Deep cell panel with conductive frame and perimeter seal	Installed RF data plus airflow/temperature validation
Data entry	Circumferential overall shield connection at bulkhead	Assembly drawing, link performance and EMC tests

Design item	Initial concept	Release evidence
Power entry	Boundary filter and port protection	Ratings, impedance suitability, immunity and emissions evidence
Cavity behaviour	Investigate approximately 0.9 GHz region and higher modes	Simulation or suitably resolved measurement of final configuration
Assembly retention	Controlled closure and service replacement procedure	Repeatability and relevant environmental/service exposure results

Step 6 Close the design with measurements

Measure the representative enclosure and the operating product. If performance is deficient, isolate the dominant path using controlled changes, update the design, and repeat the baseline test. Release only the tested construction and approved variants. This example provides a defensible sequence of decisions; it does not assert that the assumed 40 dB target has been achieved.

11 Verify performance

Agree the test method before freezing the design

Select an enclosure method that matches physical and electrical size and the intended field conditions. IEC 61000-5-7:2001 covers empty enclosure EM protection. IEEE 299-2006 covers enclosures with all dimensions at least 2 m; IEEE 299.1-2013 addresses boxes with all dimensions from 0.1 m to 2 m and further distinguishes electrical size. Both IEEE publications are listed as Inactive-Reserved as of the research date. Their use should be explicitly agreed with the customer and laboratory, rather than described as the current active standard. [18–20]

Define a frequency dependent minimum SE, relevant field component, source/reference arrangement, positions, orientations, measurement uncertainty and acceptance decision rule. Record whether doors, vents, connector panels and cable treatments are installed. Disclose any adaptation from the chosen method. A method intended for an empty box does not automatically characterise every populated configuration.

Use prototype measurements to locate the limiting path

- Record a repeatable baseline with fixed source level, detector settings, probe or antenna position, cable routing, load and operating mode.
- Scan seams, connector flanges, vent frames and cables with suitable diagnostic probes. Use the scan to locate coupling, not to declare compliance.
- Change one feature at a time. Temporary conductive seam tape, a substitute solid panel or a corrected connector bond can identify a path; restore a safe thermal condition and treat the change as a diagnostic only.
- Repeat the baseline after each change and record both improvement and any new dominant peak. Investigate cable common mode current as well as field leakage.
- Convert successful diagnostics into a reproducible mechanical or electrical detail, then repeat testing without temporary fixes.

Würth’s published enclosure experiments demonstrate the effect of connector shell bonding, cable arrangements and interface treatments in a specific setup. Use that work as evidence that the complete connection path matters; do not transfer its measured dB changes or screw spacing to another enclosure as universal values. [25]

Verify the complete operating equipment

Verification	What it establishes	Reference or selection basis
Enclosure SE	Attenuation of the defined housing configuration	IEC 61000-5-7 or a size appropriate method agreed with the laboratory
Radiated and conducted emissions	Operating equipment remains within applicable disturbance limits	Relevant product standard; generic industrial route only when applicable
Radiated RF immunity	Functions remain within defined criteria under the specified RF exposure	IEC 61000-4-3:2020 as invoked by the governing specification
Conducted RF immunity	Affected ports tolerate the prescribed injected disturbance	IEC 61000-4-6:2023 as invoked
ESD	Accessible points and nearby discharges do not cause unacceptable response	IEC 61000-4-2:2025 or the adopted dated edition
EFT and surge	Specified supply and signal ports tolerate the required transients	IEC 61000-4-4:2012; IEC 61000-4-5:2014+AMD1:2017 as invoked
Magnetic and close proximity RF	Relevant local exposure risks are addressed	IEC 61000-4-8:2009; IEC 61000-4-39:2017 where applicable
Supply dips and interruptions	Power architecture and recovery meet criteria independently of the shield	IEC 61000-4-11:2020 for applicable AC; IEC 61000-4-29:2026 for applicable DC
Retention after service exposure	Mechanical and environmental changes have not defeated protection	Project service profile and applicable sector requirements

The table is a planning framework, not a test severity specification. Select applicable ports, levels, frequency ranges, modulation, dwell and functional criteria from the governing standard or contract. The basic method references are listed in Appendix C. No test is mandatory merely because it appears here. [24, 26–33]

Control measurement uncertainty and dynamic range

Keep the reference signal, instrumentation noise floor, ambient interference and saturation limits in the record. If the shielded reading reaches the noise floor, report an appropriately supported lower bound rather than an exact high SE value. Use sufficient frequency resolution to investigate narrow responses, and retain calibration and uncertainty information. A single probe location can miss a local field maximum; the selected method should define the required sampling.

For a populated enclosure, specify the source normalisation and explain what a measured reduction means. NIST research shows that electrically small enclosure field distributions and aperture shapes can change the result, and that putting a source inside a box can affect its impedance. This is a reason to preserve the test configuration, not to equate every before and after emissions difference with a universal enclosure rating. [5]

Add sector requirements only when applicable

For shipboard applications, assess IEC 60945 where navigation, radiocommunication or its EMC scope applies; assess IEC 60533 for equipment on metallic hull ships; and check class type approval requirements such as IACS UR E10. These references have different scopes and are not interchangeable. As of 9 November 2026, IEC 60533 edition 4 is recorded as under publication; confirm the issued and adopted edition before specification freeze. [34, 35, 35a, 36]

For an applicable defence contract, the official DLA record lists MIL-STD-461H dated 17 April 2026 as active. Use the contract's adopted revision and tailored applicability. It is an equipment and subsystem EMI standard, not a general requirement for every commercial metal enclosure. [37]

Keep ingress protection separate from EMC. An IP classification under IEC 60529 addresses a different protection system and does not assign an RF attenuation value. A seal that achieves an environmental rating still requires evidence for its electromagnetic function. [18, 38]

12 Control drawings production and service

Release the information that determines performance

The drawing package should let a technician reproduce the tested boundary without relying on undocumented workmanship. Include the following items as a controlled set. The details below are recommended engineering deliverables; numerical acceptance values must be set by the project.

- An enclosure boundary drawing and penetration schedule with identifiers for every joint, opening and interface.
- Metal grade, thickness, joining process, conductive finish, masked contact lands and corrosion protection details.
- Gasket part and profile, splice method, contact geometry, compression range, tolerance stack and approved replacement procedure.
- Fastener or latch specification, closure sequence and torque or engagement requirements that correspond to the tested assembly.
- Cable shield, backshell, shell to panel and filter mounting details, with unfiltered and filtered routing clearly identified.
- Vent and window assembly specifications, including their perimeter bonds, environmental seals and thermal or optical requirements.
- Inspection methods, functional checks, representative EMC records and a rule for reviewing substitutions and variants.

Control critical assembly characteristics

Inspect contact lands before closure; verify that paint, protective film, adhesive and debris do not interrupt qualified conductive paths. Check gasket continuity and compression, corner seating, connector shell contact, blanking plates and vent mounting. Record departures from the released assembly. A four wire bond check can be useful when its locations, method and limit are defined, but it does not replace RF verification.

Set production sampling according to risk, process capability and consequence of failure. Use representative test coupons or joint assemblies where they provide useful process evidence, and maintain product level correlation. Define which failures stop shipment and which require engineering review; avoid an inspection plan that checks only visually obvious mechanical defects.

Preserve the design through maintenance

Provide service instructions for opening, cleaning, gasket inspection, reassembly and replacement. Identify surfaces that must remain unpainted and parts that require approved substitutes. Require engineering review for changed cutouts, connectors, cable shields, coatings, vents, filter routing or operating modes that alter the emission spectrum.

Requalify affected features after design changes or environmental exposure. Keep the released configuration, test evidence and service instructions together to preserve repeatable protection throughout equipment life.

Appendix A Corrections to the source note

The supplied note remains useful as an introduction to aperture size and wavelength. The following corrections are incorporated into this guide so that its calculations can be used appropriately in enclosure design. Source references are to the visible three page rendering of the supplied version 2 document. [1]

Source statement or location	Correction used in this guide
Page 1 table associates λ/50 with more than 40 dB	The stated screening formula gives approximately 28 dB. A nominal 40 dB estimate corresponds to λ/200.
Page 1 describes λ/20 as blocking the wave and λ/10 as a leakage threshold	There is no abrupt threshold. The elementary relation gives 20 dB at λ/20 and about 14 dB at λ/10; other coupling conditions remain.
Pages 2 and 3 describe the 6.25 mm result as a guaranteed minimum or maximum acceptable opening	Retain 6.25 mm at 2.4 GHz as a nominal 20 dB screening result; determine acceptability from the full design, margin and measurement.
Page 2 explains the thin aperture example using below cutoff depth attenuation	Separate the aperture relation from the modal decay along a finite depth channel. Depth attenuation tends to zero as depth tends to zero.
Page 2 calls the simple formula conservative	No universal conservative bound is claimed. Resonance, source location, field type and other paths can reduce shielding.
Page 1 presents L = λ/2 as the single worst case with effectively 0 dB	A half wave slot is a serious resonance risk. Actual enclosure SE is configuration dependent and can be negative at local resonances.
Pages 2 and 3 contain flattened fraction and subscript notation	The principal design equations are rebuilt as native Word equations, with explicit symbols, units and assumptions.

The corrected interpretation is supported by enclosure research that includes dimensions, internal positions, apertures and losses rather than relying only on L/λ. The source’s qualitative recommendation to make openings electrically small is retained, while the claimed guarantees are removed. [4, 5]

Appendix B Design review worksheet

Complete this worksheet for each enclosure revision. Record drawing references and objective evidence, not only a tick. Use “not applicable” with a reason where an item does not apply. Unresolved items need an owner and closure date before design release.

Project and equipment _____ Enclosure revision _____
Reviewer _____ Date _____
Governing requirements _____
Required SE bands and values _____

Review item	Evidence or drawing reference	Disposition
Environment, frequency bands and performance criteria agreed		
Applicable product standard and adopted editions recorded		
Every seam and penetration appears in the boundary schedule		
Metal, finish and masked conductive lands specified		
Gasket compression and flange tolerance extremes checked		
Lid, doors, corner joints and closure sequence qualified		
Vent RF performance and thermal operating point verified		
Connector shells and overall cable shields bonded as designed		
Filters and transient protection placed and returned correctly		
Dirty and clean wiring separated; circuit return strategy defined		
Protective earth and product safety interfaces reviewed		
Displays, controls, shafts and unused cutouts treated		
Near field magnetic and resonance risks addressed		
Representative product EMC and enclosure tests complete		
Uncertainty, margin and acceptance decision recorded		
Production controls and service replacement instructions released		

Penetration and joint schedule

Record each opening or serviceable joint. Examples of treatment include a conductive gasket, bonded connector shell, entry filter, qualified vent, conductive window or approved blanking plate. Record the maximum relevant opening dimension and the verification evidence.

ID and location	Function and dimensions	Shield treatment and drawing	Verification and status
P01			
P02			
P03			
P04			
P05			
P06			
J01			
J02			

Minimum test configuration record

Record enclosure serial number and revision; metal and finish; gasket and vent parts; closure condition; connector and filter assembly; cable types, lengths and terminations; hardware and firmware versions; operating modes and loads; antenna/probe positions; test method and settings; reference and noise floor; calibration; environmental condition; observed functional response; pass/fail limits; uncertainty and decision rule. Attach photographs and the final configuration drawing.

Change review record

Describe the change _____ Affected boundary item _____
Expected coupling consequence _____
Evidence or retest required _____
Responsible engineer _____ Closure evidence _____

Appendix C Standards and source register

References were checked on 9 November 2026. Publisher scope and status information establishes applicability and edition awareness; obtain the full adopted standards for test execution. Manufacturer examples describe their components and test arrangements. The calculations, design workflow, diagrams and worksheets in this guide are engineering synthesis, with assumptions stated beside numerical results.

Standards status notes: IEEE 299-2006 and 299.1-2013 are Inactive-Reserved. IEC 60533 edition 4 is under publication at the research date. MIL-STD-461H is active. Reconfirm adopted editions at project specification freeze.

[1] **User supplied source.** DrC-Enclosure Shielding for electromagnetic fields v.2.docx. Three page source note with aperture examples and further reading.

[2] **LearnEMC.** Practical EM Shielding. Field mechanisms, enclosure discontinuities and separate below cutoff channel derivation. Open source

[3] **Cadence System Analysis.** The Size of Apertures and the EMI Shield Wavelength. Source for the familiar preliminary aperture relation; its broad performance claims are qualified in this guide. Open source

[4] **Robinson and colleagues.** Analytical Formulation for the Shielding Effectiveness of Enclosures with Apertures. IEEE Transactions on EMC 40(3), 240–248, 1998. Corrected author postprint; DOI 10.1109/15.709422. Open source

[5] **NIST Dunlap and colleagues.** Measurement of Shielding Effectiveness of Electrically Small Enclosures. URSI 2011. Field distribution, aperture shape and source normalisation. Open source

[6] **Rittal.** EMC Practical assembly tips. Cabinet zones, conductive assembly, interfaces and cabling. Open source

[7] **Analog Devices.** Proper Layout and Component Selection Controls EMI. Source loop and switching node design. Open source

[8] **Analog Devices.** AN 347 Shielding and Guarding How to Exclude Interference Type Noise. Electric and magnetic coupling and material considerations. Open source

[9] **Magnetic Shield Corporation.** Perfection Annealing. Processing and handling of specialist magnetic shielding. Open source

[10] **Parker Chomerics.** Conductive Elastomer Engineering Handbook. Gasket, flange, finish and corrosion design; limits of DC resistance as a shielding indicator. Open source

[11] **TE Connectivity.** EMC Shielding Mechanical Fix Electrical Problem. Gasket technologies and mechanical application considerations. Open source

[12] **NASA.** NASA HDBK 4001A Electrical Grounding Architecture for Uncrewed Spacecraft, July 2025. Cable outer and inner shields, connector continuity and pigtail limitations. Spacecraft scope is retained when applying its advice. Open source

[13] **TDK Electronics.** EMC laboratory in Regensburg. EMC basics and mounting instructions for filters, RF bonding and cable routing. Open source

[14] **Parker Chomerics.** Application and Design Guide to EMI Shielding Honeycomb Vents. Installed vent construction, shielding and airflow. Open source

[15] **Parker Chomerics.** WIN SHIELD G EMI Shielded Glass Windows, TB1085 EN, March 2013. Mesh, conductive coating and edge connection options. Open source

[16] **MIT OpenCourseWare David Staelin.** Electromagnetics and Applications, course 6.013, Chapter 9. Section 9.2.4 covers skin depth; Section 9.4.1 covers rectangular cavity resonators. Open source

[17] **SCHURTER.** The ideal EMC filter in just 6 steps. Filter selection, component checks and complete system remeasurement. Open source

[18] **IEC.** IEC 61000-5-7:2001. Degrees of protection provided by enclosures against electromagnetic disturbances, EM code. Empty enclosure scope, 10 kHz to 40 GHz. Open source

[19] **IEEE.** IEEE 299-2006. Shielding enclosure measurement method; all dimensions at least 2 m. Inactive-Reserved status. Open source

[20] **IEEE.** IEEE 299.1-2013. Shielding of enclosures and boxes with all dimensions between 0.1 m and 2 m; electrical size qualifications apply. Inactive-Reserved status. Open source

[21] **IEC.** IEC 61326-1:2020. General EMC requirements for electrical measurement, control and laboratory equipment. Open source

[22] **IEC.** IEC 61000-6-2:2016. Generic industrial immunity where no relevant dedicated product or product family EMC immunity standard exists. Open source

[23] **IEC.** IEC 61000-6-4:2018. Generic industrial emissions within its scope, when no applicable dedicated route governs. Open source

[24] **IEC.** IEC 61000-4-2:2025. Electrostatic discharge immunity test, edition 3. A project may be governed by a dated normative reference to another edition. Open source

[25] **Würth Elektronik Dr Heinz Zenkner.** ANP139a Enclosure Shielding and EMC, dated 26 August 2026. Used for its measured enclosure, connector and cable demonstrations; the guide uses independent equations for calculations. Open source

[26] **IEC.** IEC 61000-4-3:2020. Radiated radio frequency electromagnetic field immunity test. Open source

[27] **IEC.** IEC 61000-4-6:2023. Immunity to conducted disturbances induced by radio frequency fields. Open source

[28] **IEC.** IEC 61000-4-4:2012. Electrical fast transient and burst immunity test. Open source

[29] **IEC.** IEC 61000-4-5:2014+AMD1:2017 consolidated version. Surge immunity test. Open source

[30] **IEC.** IEC 61000-4-8:2009. Power frequency magnetic field immunity test. Open source

[31] **IEC.** IEC 61000-4-39:2017. Radiated fields in close proximity immunity test. Open source

[32] **IEC.** IEC 61000-4-11:2020. Voltage dips, short interruptions and voltage variations for applicable AC equipment up to 16 A per phase. Open source

[33] **IEC.** IEC 61000-4-29:2026. Voltage dips, short interruptions and voltage variations on DC input power ports, edition 2. Open source

[34] **IEC.** IEC 60945:2002 including April 2008 corrigendum. Maritime navigation and radiocommunication equipment and the related EMC scope. Open source

[35] **IEC and Institute for Standardization of Serbia.** IEC 60533:2015, EMC for equipment on metallic hull ships. Edition 4 project status is under publication as of 9 November 2026; confirm publication and adoption before release. Open source

[35a] **Institute for Standardization of Serbia.** IEC 60533 edition 4 project. Stage 60.00 effective 16 October 2026; publication forecast is not evidence that the new edition has already been issued. Open source

[36] **IACS.** UR E10 Test Specification for Type Approval, Revision 10, August 2024. Application depends on relevant class rules and equipment scope. Open source

[37] **US Department of Defense DLA ASSIST.** MIL-STD-461H, 17 April 2026. Requirements for control of EMI characteristics of subsystems and equipment. Active; apply only when invoked by the relevant contract. Open source

[38] **IEC.** IEC 60529, consolidated edition 2.2. Degrees of protection provided by enclosures, IP code. Ingress protection is distinct from EM attenuation. Open source