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Defensive Technical Surveillance Countermeasures Doctrine

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Building Services and Occupied Conditions

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Contents

PART VII. BUILDING SERVICES AND OCCUPIED CONDITIONS

Part VII examines building services as active acoustic systems whose condition changes with airflow, control logic, maintenance, occupancy and emergency operation. Walls, doors, glazing and structural junctions establish only part of a secure room's transmission boundary. Ducts, pipes, conduits, loudspeakers, sensors and masking systems create routes that can transmit speech, generate competing sound, alter background levels or mechanically bridge otherwise isolated construction. Chapter 24 begins with ventilation because air-distribution systems combine all of these behaviours: they carry sound in either direction, radiate through thin casings, generate turbulence, transmit vibration, penetrate fire barriers and change state automatically.

Chapter 24. HVAC Ductwork, Silencers, Cross-Talk, Breakout, and Airflow Noise

24.1 HVAC is an acoustic network, not a single attenuation value

A ventilation system is an interconnected network of sources, waveguides, junctions, radiating surfaces and receivers; fans, compressors, dampers, coils, filters, terminal units and turbulent fittings generate airborne and structure-borne energy; speech enters a return grille, supply diffuser, transfer opening or leaky plenum. In-duct energy divides at branches, reflects at discontinuities, is attenuated by lined runs and silencers, and is partly converted into vibration of the duct wall; the same casing can admit room sound, radiate fan noise or carry structure-borne motion into a lightweight ceiling; a room-level conclusion must therefore follow every credible source-path-receiver route rather than assigning one generic “duct loss”.[1]

Propagation is not constrained to the direction of airflow; sound waves travel upstream and downstream relative to the mean flow at speeds approximately equal to the local speed of sound plus or minus the mean velocity; in ordinary building ductwork the flow Mach number is small, so the asymmetry is modest. A return system can therefore carry protected speech from a quiet conference room towards a fan, branch, shaft or adjacent terminal even though air is moving towards the fan; a supply branch can carry speech upstream towards a common trunk and then downstream into another room. Directional arrows on a mechanical drawing do not describe acoustic isolation.

1 MB-0054. ASHRAE, “Noise and Vibration Control”.

The system changes through time. Fan speed, damper angle, VAV box command, filter loading, coil condition, door position and room pressure alter sound generation and transmission; a cross-talk path may be least masked when the fan is off, yet a damper may close only when the fan runs. A silencer may attenuate fan sound at design velocity but create turbulence noise at high flow; a quiet-night setback can remove beneficial background while preserving a direct duct route; commissioning must therefore define credible operating states rather than selecting one convenient point.

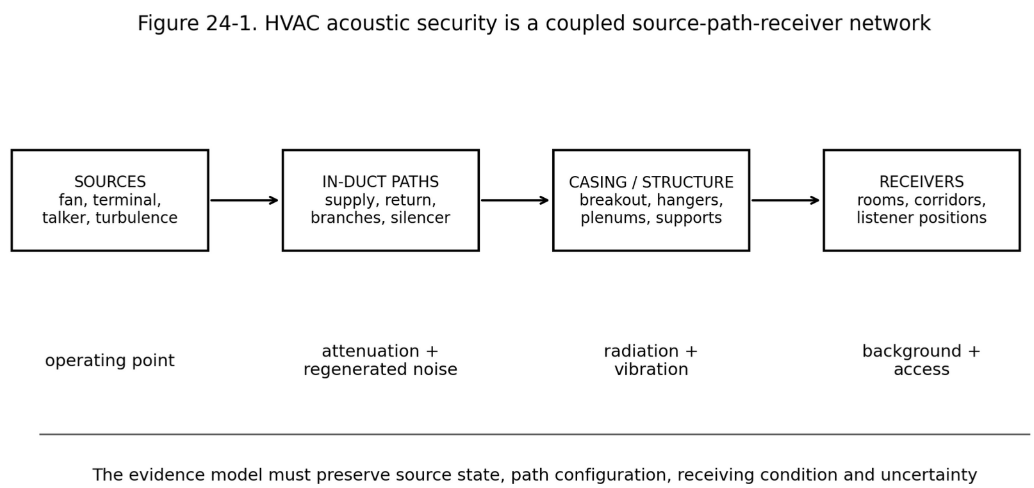

Figure 24-1. HVAC acoustic security is a coupled source-path-receiver network. Author's original diagram.

24.2 Evidence hierarchy and the bounded meaning of standards

Different standards answer different questions. ASTM E477-26 and ISO 7235 address laboratory acoustical and airflow performance of duct liners, silencers and certain terminal elements under prescribed arrangements; ISO 11691:2020 provides a no-flow survey method for insertion loss but expressly excludes regenerated flow noise; ISO 11820:1996 addresses in-situ silencer measurements. ISO 5136:2003 and the ISO 13347 series address sound power radiated by fans or air-moving devices under standardised laboratory conditions; ANSI/AMCA 300-24 and ANSI/AMCA 320-23 provide alternative fan sound-power methods; AHRI 260-2024 maps the sound power of ducted equipment; AHRI 880/881 rates air terminals; ASHRAE Standards 70-2023 and 130-2025 prescribe laboratory tests for outlets, inlets and terminal units.[2]

These documents cannot be collapsed into one generic certification; a fan sound-power test does not measure vibration transmitted through its base; a silencer insertion-loss test does not establish cross-talk attenuation of the complete installed branch; a terminal-unit rating does not prove the room level after ceiling attenuation, duct breakout and plenum transmission. A fire-safety standard does not provide an acoustic rating. A field room-to-room test does not identify which duct element caused a deficit unless the test programme includes diagnostic interventions.

The engineering proof hierarchy begins with product identity and laboratory data, proceeds through design calculations and submittal review, continues through construction surveillance and testing-adjusting-balancing records, and ends with installed acoustic measurements under defined operating states; occupied speech-security assessment adds source vocal effort, listener location, background and access duration. Formal acceptance remains a decision of the competent authority; each evidence class supports a bounded proposition.

2 MB-0292. ASTM International, ASTM E477-26, ISO 7235:2003.

Table 24-1. Standards and the bounded propositions they establish.

Source or method	Principal measurand	Typical use	Material limitation
ASTM E477-26 / ISO 7235	Insertion loss, flow-generated sound and pressure loss	Laboratory silencer and duct-element data	Laboratory configuration and flow field can differ from installation
ISO 11691:2020	No-flow insertion loss	Economical laboratory survey	Does not include regenerated flow noise
ISO 11820:1996	In-situ silencer performance	Installed diagnostic measurement	Requires careful upstream/downstream field definition
ISO 5136:2003	In-duct sound power	Ducted fan or air-moving device source data	Standardised test duct and microphone-flow limits
ISO 13347 / AMCA 300 / AMCA 320	Fan sound power	Product selection and source modelling	Airborne emission only for stated installation category; vibration excluded
AHRI 260-2024	Mapped ducted-equipment sound power	Equipment rating across operating range	Does not reproduce the complete project duct network
AHRI 880/881 and ASHRAE 130	Air-terminal performance	VAV and terminal-unit selection	Room prediction still requires discharge and radiated path corrections
ASHRAE 70-2023	Outlet and inlet aerodynamic and sound generation	Diffuser, grille and register selection	Laboratory terminal data do not establish room privacy
ASTM E1414/E1414M	Common-plenum attenuation	Ceiling-plenum path assessment	Installed field construction can depart substantially from test
ASTM E336 / E2638	Field room attenuation / closed-room privacy	Whole-room commissioning and consequence assessment	Does not by itself isolate the HVAC path

24.3 Sound power, sound pressure and in-duct quantities

Sound power describes the rate at which a source emits acoustic energy; sound pressure describes the local field produced by that energy after propagation, reflection, absorption and interference; a fan can have a stable band sound-power level while measured pressure changes materially with duct termination, microphone position or room absorption. Conversely, a local pressure maximum does not imply a greater source power; equipment schedules should preserve the distinction because room prediction begins with source sound power, while field diagnosis often observes pressure, intensity and vibration.[3]

Band sound powers combine in linear energy, not by arithmetic averaging. If several independent sources contribute to one duct band, total level is

Equation 24.1

$$L_{W,\Sigma}=10\log_{10}\left(\sum_{i=1}^{n}10^{L_{W,i}/10}\right),$$

where $L_{W,i}$ is the band sound-power level of source i in decibels re $10^{-12}W$. The expression assumes incoherent sources for ordinary engineering summation. Strongly coherent tonal sources require phase-aware treatment.

Worked example 24.1. Adding fan and terminal sound power

Engineering question. A duct branch receives 68 dB from the central fan and 62 dB of regenerated sound from a throttling terminal in the 500 Hz octave band. What is the combined sound-power level?

$$L_{W,\Sigma}=10\log_{10}\left(10^{6.8}+10^{6.2}\right)=68.97\,dB.$$

The 62 dB source adds about 1.0 dB because it is 6 dB below the fan contribution; the dimensional check is satisfied because each antilogarithm is a dimensionless ratio to the reference power; a combined standard uncertainty cannot be obtained by adding level uncertainties arithmetically; the underlying source powers and covariance must be considered. The calculation does not include duct attenuation, branch division or room correction.

3 MB-0059. ASHRAE, “Sound and Vibration”.

The inverse operation also demands linear subtraction; if a measured total level contains a known background or auxiliary source, the desired component can be estimated only where total exceeds the unwanted contribution by a sufficient margin.

Worked example 24.2. Subtracting a known background source

A downstream test measures 57.0 dB while the auxiliary fan alone produces 52.0 dB. Estimated test-source level is

$$L_s = 10\log_{10}\left(10^{57/10} - 10^{52/10}\right) = 55.35\, dB.$$

The correction is 1.65 dB. If the difference were only 1 or 2 dB, the subtraction would be unstable and uncertainty large. Reporting extra decimal places would not cure the weak signal-to-background ratio.

24.4 Fan source spectra and installation category

Fan noise contains broadband aerodynamic energy, blade-passing tones, harmonics, motor electromagnetic components and structure-borne contributions. The spectrum depends upon fan type, diameter, blade count, speed, loading, inlet distortion and operating point. A laboratory rating must identify the installation category because an open inlet, ducted inlet, open outlet and ducted outlet impose different acoustic boundary conditions. ISO 13347-1:2025 establishes the general framework for these categories, while later parts prescribe reverberant-room, enveloping-surface and intensity methods.[4]

A fan selected far from its efficient operating region can produce greater turbulence, stall-related low-frequency modulation and tonal content;

4 MB-0927. ISO 13347-1:2025, ANSI/AMCA Standard.

system effects from elbows, abrupt inlet transitions, nonuniform velocity profiles or insufficient straight length can alter both aerodynamic and acoustic performance. A catalogue sound-power table obtained with an orderly inlet does not prove the installed fan will reproduce that table when a sharp elbow sits immediately at the inlet.

Blade-passing frequency is a useful diagnostic feature:

Equation 24.2

$$f_{BPF} = \frac{N_b n}{60},$$

where N_b is blade count and n is rotational speed in revolutions per minute.

Worked example 24.3. Blade-passing frequency

A twelve-blade fan runs at 1,450 r/min:

$$f_{BPF} = \frac{12(1450)}{60} = 290\,Hz.$$

Harmonics appear at integer multiples if aerodynamic asymmetry or periodic loading is significant; a 290 Hz line in both duct pressure and casing vibration supports a fan-related hypothesis, but it does not identify whether the dominant route is airborne, structural or both. The investigation should compare phase, coherence, fan speed and controlled operating changes.

24.5 Fan laws, speed control and operating point

For geometrically similar operation at constant air density, volume flow varies approximately with rotational speed, pressure with the square of speed and aerodynamic power with the cube; sound power does not obey one universal exponent, but a frequently used engineering screening relation takes the form

Equation 24.3

$$\Delta L_W = K \log_{10}\left(\frac{n_2}{n_1}\right),$$

where K is an empirical coefficient commonly near 50 for many broadband fan applications, and n_1, n_2 are speeds. The coefficient must be supported by the particular fan data or a justified method. Tonal and stall components can behave differently.[5]

Worked example 24.4. Screening a variable-speed reduction

If speed decreases from 1,500 to 1,200 r/min and $K=50$,

$$\Delta L_W = 50 \log_{10}(1200/1500) = -4.85\, dB.$$

The screening calculation suggests a reduction of about 4.9 dB in applicable broadband components; it does not guarantee equal change in every band; the operating point moves on the system curve, damper positions can change, and terminal noise may increase or decrease. Commissioning should measure the actual state.

Filter loading shifts the system resistance. A controller may increase fan speed to maintain flow, increasing source sound and pressure; a dirty filter can also alter inlet turbulence; the acoustic baseline should record filter pressure drop and control command, not merely “system on”.

Worked example 24.5. Filter loading and fan speed

A variable-speed fan increases from 1,200 to 1,350 r/min to maintain flow after filters load. With the same $K=50$ screen,

$$\Delta L_W = 50 \log_{10}(1350/1200) = 2.56\, dB.$$

5 MB-0053. ASHRAE, 2023 ASHRAE Handbook, HVAC Applications.

A 2.6 dB source increase can consume a substantial part of a narrow room-noise margin. The result remains an estimate pending mapped equipment data and field confirmation.

24.6 Duct modes, cut-on frequency and plane-wave limits

At sufficiently low frequency, a rigid-walled uniform duct is dominated by its plane wave. Above transverse cut-on, higher-order modes create spatial variation across the cross-section. Microphone location, branch orientation, silencer geometry and bends then become more important. A transfer-matrix model that assumes plane waves can be useful below cut-on but unreliable above it without modal extension.[6]

For a rigid rectangular duct of width a, the first transverse-mode cut-on frequency is screened by

Equation 24.4

$$f_c \approx \frac{c}{2a},$$

where c is sound speed. The analogous second dimension must also be checked.

Worked example 24.6. First transverse cut-on

For $a = 0.60\,m$ and $c = 343\,m/s$,

$$f_c = \frac{343}{1.20} = 286\,Hz.$$

Above roughly 286 Hz, cross-sectional mode structure cannot be ignored; the actual cut-on depends upon duct shape and boundary condition. Flow

6 MB-1007. M. L. Munjal, ISO 5136:2003.

modifies modal propagation slightly. The calculation identifies a modelling transition, not an acoustic-security threshold.

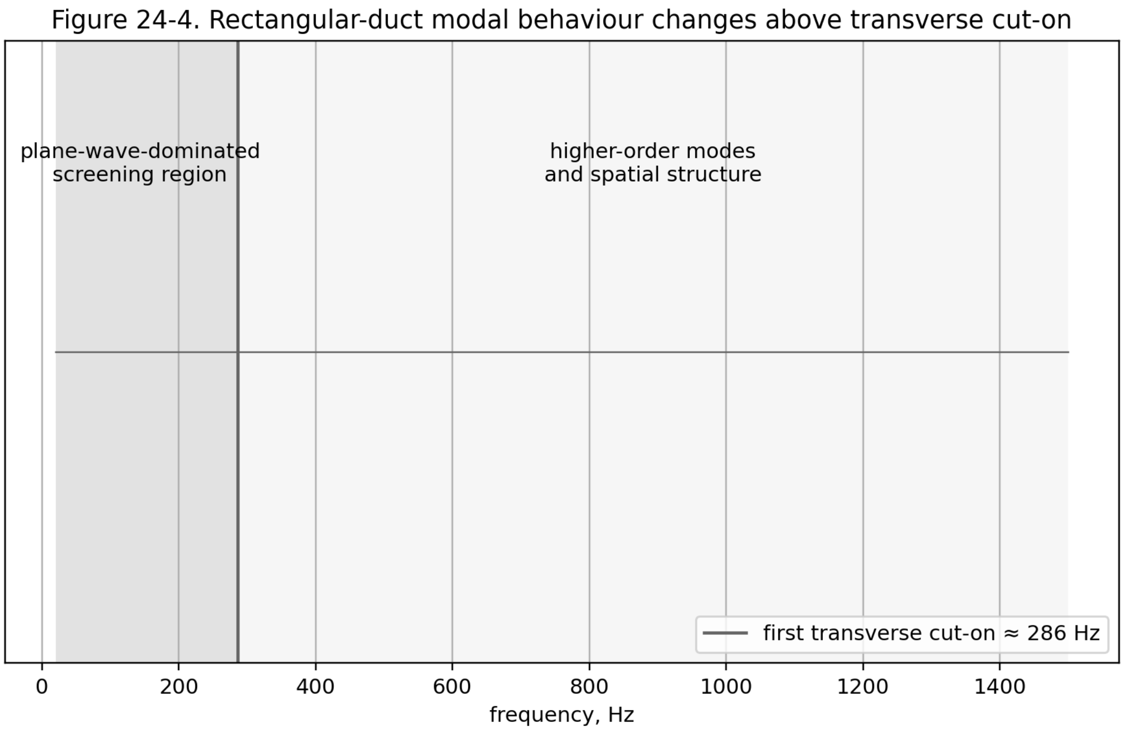

Figure 24-4. Rectangular-duct modal behaviour changes above transverse cut-on. Author's original diagram.

24.7 Straight-duct attenuation and internal lining

Unlined sheet-metal duct provides limited dissipative attenuation. Energy is redistributed among modes, reflected at discontinuities and lost through wall vibration or radiation, but straight runs do not behave as ideal silencers. Internal fibrous lining adds absorption, especially where particle velocity and surface interaction are favourable. Performance depends upon thickness, density, flow resistivity, exposed perimeter, duct size, length, protective facing, flow velocity and frequency.[7]

7 MB-0095. ASTM E477-26.

Lining changes more than attenuation. It can reduce cross-sectional area, alter friction loss, collect contamination, erode under unsuitable velocity or cleaning, and interact with fire and indoor-air-quality requirements; a secure-room design should not depend on an inaccessible liner whose condition cannot be inspected. Where cleanability or contamination control prohibits exposed fibrous material, a purpose-built silencer, lined plenum with protected facing or external treatment may be more appropriate.

A simple exponential screen can be written as

Equation 24.5

$$IL(f) \approx 8.686\,\alpha(f)\,L,$$

where $\alpha(f)$ is an effective amplitude attenuation constant in nepers per metre and L is treated length. This is not a universal duct-lining formula; it expresses the relation between an assumed exponential amplitude decay and decibels.

Worked example 24.7. Lined-run attenuation screen

If an effective attenuation constant at 1 kHz is $0.18\,Np/m$ over $4.0\,m$,

$$IL = 8.686(0.18)(4.0) = 6.25\,dB.$$

Uncertainty in α dominates because it depends on geometry, modes, lining and flow. If α varies by 25 per cent, the screened loss varies by about 1.6 dB. The calculation should be replaced by validated manufacturer or laboratory data for final design.

24.8 Elbows, branches, area changes and end reflection

Elbows and branches can attenuate some modes by reflection and conversion, yet they can also generate turbulence and tones; turning vanes may reduce pressure loss but introduce narrow passages, edge noise or rattling; abrupt area changes create reflection and possible separation. Smooth transitions reduce aerodynamic loss but may transmit sound more efficiently; acoustic and aerodynamic objectives must be solved together.

A branch divides acoustic power according to impedances and modal coupling, not merely airflow percentage; in a low-frequency plane-wave screen with similar impedances, area provides a first approximation; if a trunk divides into two equal branches and other conditions are similar, each receives roughly half the incident power, corresponding to 3 dB reduction. Reflections and different terminations modify the result.

Worked example 24.8. Unequal branch division

Suppose 70 per cent of acoustic power enters Branch A and 30 per cent enters Branch B. Relative levels are

$$\Delta L_A = 10\log_{10}(0.70) = -1.55\, dB,$$

$$\Delta L_B = 10\log_{10}(0.30) = -5.23\, dB.$$

These values are power-division screens. They do not include reflection, branch attenuation, terminal radiation or regenerated noise.

At an open duct termination, radiation impedance causes end reflection, particularly at low frequency; laboratory fan and silencer methods may prescribe end-reflection corrections; applying a correction from one geometry to another without checking duct size, termination and modal range can corrupt the source model.

24.9 Cross-talk routes between protected and adjoining rooms

Cross-talk occurs when speech enters one terminal and emerges from another through a common duct, plenum or transfer route. The route may include two terminals, branch ducts, dampers, a common trunk, a fan casing or an air-handling unit. A path can remain significant when the fan is off because the waveguide persists. When the fan runs, broadband fan noise may mask speech, but it can also excite the same route and complicate measurement.[8]

A cross-talk model should list every element in source-to-receiver order; each band begins with source coupling into the terminal, then includes terminal end reflection, branch loss, fittings, silencers, junction division, common duct, second branch, receiving terminal radiation and receiving-room correction. Casing breakout creates a parallel route, not an additional series loss; multiple routes must be combined in linear energy.

8 MB-0064. ASHRAE, ASTM E1414.

Figure 24-2. Cross-talk is governed by the complete branch, terminal and room route

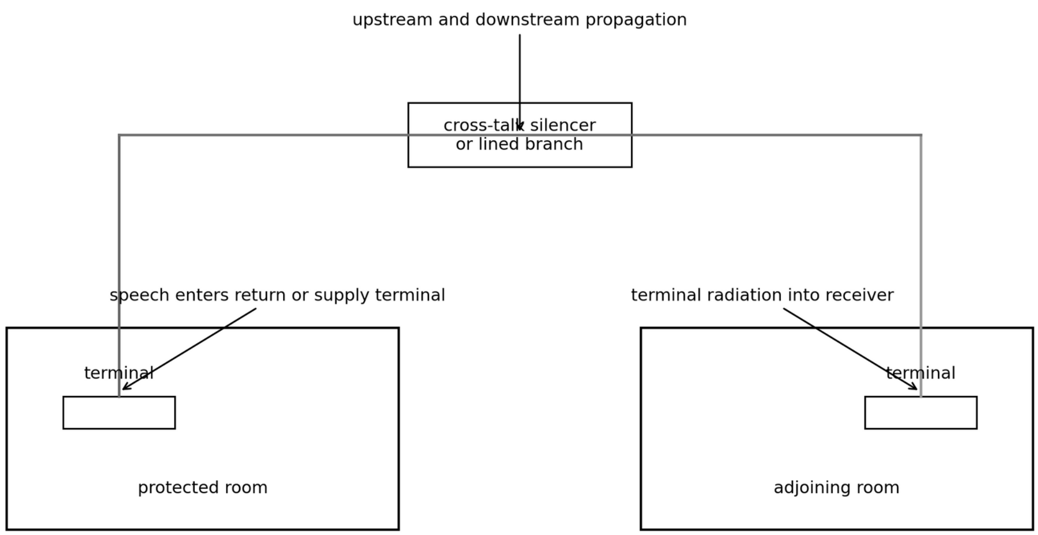

Figure 24-2. Cross-talk is governed by the complete branch, terminal and room route. Author's original diagram.

Worked example 24.9. Series attenuation and terminal radiation

A source couples 78 dB of band sound power into a return terminal; the route has 7 dB branch loss, 18 dB silencer insertion loss, 4 dB junction loss and 6 dB receiving-terminal end/radiation correction. Ignoring regenerated sound,

$$L_{W,r} = 78 - 7 - 18 - 4 - 6 = 43\,dB.$$

If the receiving room conversion from terminal sound power to local sound pressure is $-8\,dB$ at the listener position, the estimated level is 35 dB. Every term is frequency- and configuration-dependent. The result does not establish intelligibility without background, speech spectrum and listener analysis.

24.10 Transfer-air paths and cross-talk silencers

A transfer-air opening intentionally connects two spaces without a full ducted air route; it may be installed above a door, through a wall, above a ceiling or through a shared plenum; a straight transfer grille is an acoustic opening. A lined dog-leg, offset plenum or purpose-built cross-talk silencer can attenuate line-of-sight transmission while preserving airflow; the design must maintain free area, pressure balance, fire and smoke requirements, cleaning access and structural support.

The silencer should be selected for the actual flow direction and spectrum; a device tested under one flow may perform differently when installed with reversed flow, adjacent elbows or poor inlet profile; short splitters placed immediately behind grilles can generate noise at high face velocity. Absorptive baffles require protected edges because turbulent separation and facing damage begin at leading edges.

A transfer path should be shown in plan and section; “provide acoustic transfer grille” is not a complete detail; the drawing should identify duct dimensions, offsets, baffle depth, clear passage, lining, support, perimeter seal, access, damper and fire classification. The specification should require complete laboratory data and state whether insertion loss includes terminals.

24.11 Absorptive silencers

Absorptive silencers dissipate acoustic energy in porous media contained behind perforated or otherwise acoustically transparent facings. Splitters increase treated perimeter and reduce passage width, which improves interaction with the lining but raises velocity and pressure drop. Low-frequency performance is limited by silencer length, cross-section, splitter depth and wave behaviour. High-frequency performance can be reduced by facing impedance, protective film, media compression or flanking through the casing.[9]

The media system must withstand airflow, moisture, cleaning and fire requirements; erosion, delamination or contamination can change both acoustic and hygienic performance; a silencer installed in a secure room path should have an inspection and replacement strategy. An inaccessible product should not be treated as a lifetime component merely because its laboratory rating was satisfactory at installation.

Laboratory insertion loss is measured by comparing a reference duct condition with the silencer condition; the result includes the prescribed test arrangement; field insertion loss can differ because upstream and downstream sound fields, duct modes, leakage, casing radiation and connected fittings differ. A design should preserve band data rather than relying on one weighted value.

24.12 Reactive, dissipative and hybrid silencers

Reactive silencers use changes in acoustic impedance, expansion chambers, resonators or tuned elements to reflect energy; they can provide useful low-frequency attenuation without porous media but are sensitive to geometry and frequency; dissipative silencers rely chiefly on absorption. Hybrid designs combine reflection and absorption. None is universally superior.

A reactive chamber can create pass bands and stop bands; a tuned resonator may control one tone yet provide little broadband speech attenuation; temperature changes sound speed and shifts tuning; flow adds

9 MB-0099. ASTM E477-26, ISO 7235:2003.

convective effects and can generate turbulence at necks or area changes. A secure-room route usually requires broadband control, so narrow reactive features should supplement, not replace, complete spectral analysis.

Where hygiene prohibits fibrous media, microperforated, film-faced, resonant or lined-metal solutions may be considered. Their complete insertion-loss and regenerated-noise data are essential. A product name such as “hospital-grade silencer” does not define acoustical performance.

24.13 Insertion loss, pressure loss and regenerated noise

A silencer has at least three independent performance dimensions: insertion loss, total pressure loss and self-generated sound under flow. Increasing splitter depth or reducing passage width can improve attenuation but increase velocity and pressure loss. Higher velocity increases turbulence and regenerated noise. The selected operating point should therefore be evaluated across all three datasets.[10]

If upstream fan sound after insertion loss falls below silencer-generated sound, further insertion loss yields little receiving benefit. Total downstream power is the energy sum of attenuated incident sound and regenerated sound:

Equation 24.6

$$L_{W,out} = 10\log_{10}\left(10^{(L_{W,in} - IL)/10} + 10^{L_{W,regen}/10}\right).$$

Worked example 24.10. Regenerated-noise crossover

At 1 kHz, incident sound power is 82 dB and silencer insertion loss is 32 dB, leaving 50 dB. Regenerated sound is 55 dB:

10 MB-0096. ASTM E477-26, ISO 7235:2003.

$$L_{W,out} = 10\log_{10}\left(10^{5.0} + 10^{5.5}\right) = 56.19\,dB.$$

The output is controlled by regenerated noise; increasing insertion loss by another 10 dB changes the attenuated incident contribution to 40 dB, but total remains approximately 55.1 dB; reducing face velocity or selecting a lower-regeneration silencer is the effective intervention.

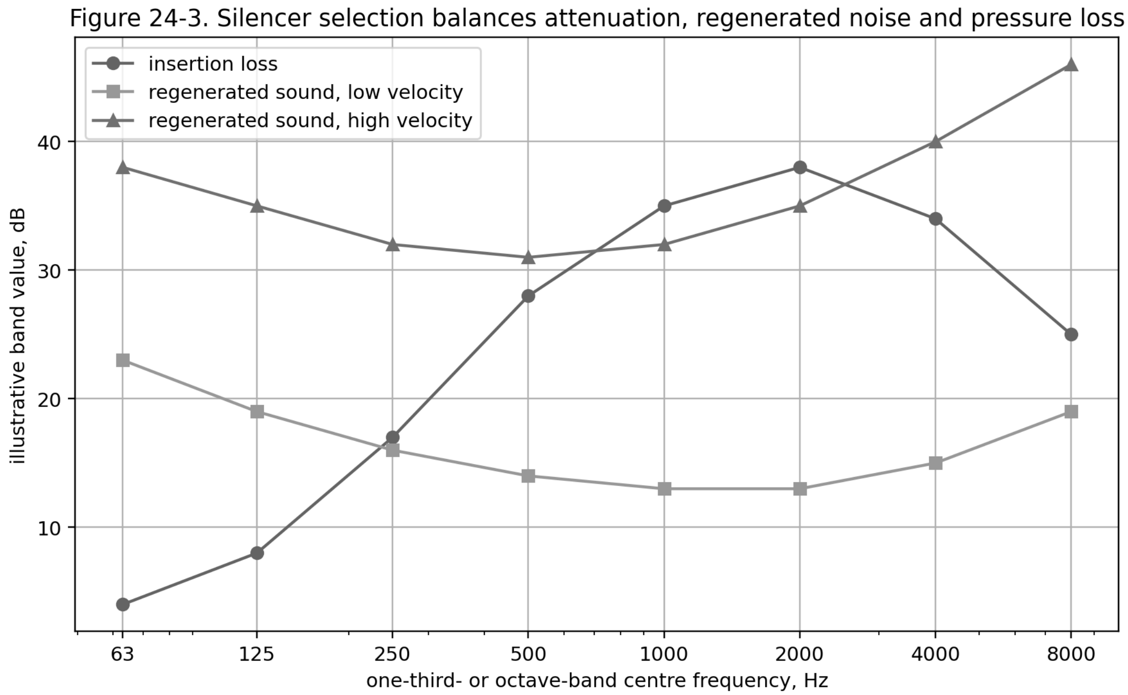

Figure 24-3. Silencer selection balances attenuation, regenerated noise and pressure loss. Author's original diagram.

Pressure loss imposes fan power and operating consequences. Air power associated with a component is

Equation 24.7

$$P_a = Q\,\Delta p,$$

where Q is volume flow in m^3/s and Δp is pressure loss in pascals, giving watts.

Worked example 24.11. Air-power cost of silencer pressure loss

For $Q=2.5\,m^3/s$ and $\Delta p=120\,Pa$,

$$P_a=(2.5)(120)=300\,W.$$

If combined fan and motor efficiency is 0.60, electrical input associated with the loss is about $500\,W$. The calculation is a steady-state screen and does not include control interaction. A high-pressure-loss silencer can force a fan-speed increase that partly offsets acoustic gains.

24.14 Splitters, baffles, face velocity and edge treatment

Splitter silencers divide the total duct area into narrow passages; the gross duct face velocity is not the passage velocity because splitter thickness and framing reduce free area; leading edges, trailing edges, perforated facings and support rods influence both pressure loss and regenerated noise. Manufacturer data should identify passage dimensions and tested velocity.

Worked example 24.12. Splitter passage velocity

A silencer casing is $1.2\,m$ wide by $0.9\,m$ high, gross area $1.08\,m^2$. Four splitters each $0.10\,m$ thick occupy $0.36\,m^2$ of frontal area, leaving $0.72\,m^2$. At $Q=4.0\,m^3/s$,

$$V_{gross}=\frac{4.0}{1.08}=3.70\,m/s,$$

$$V_{passage}=\frac{4.0}{0.72}=5.56\,m/s.$$

Using gross velocity would understate passage velocity by 50 per cent. Pressure loss and regenerated noise should be evaluated at the passage condition. Uncertainty in blockage, frame area and balancing affects the result.

Edge damage can expose media or create whistles; a rounded or aerodynamic leading edge reduces separation; a blunt frame, field-installed screw or distorted splitter can create a local high-velocity jet; construction inspection should compare the installed product with the tested geometry.

24.15 Circular, rectangular and flexible duct construction

Circular duct resists panel vibration efficiently because curvature increases stiffness and seams are limited. Rectangular duct has broad flat panels that can radiate strongly unless gauge, reinforcement and pressure class are adequate. Oval and flat-oval systems lie between these behaviours. SMACNA's construction standards define fabrication and reinforcement practice, but compliance with a construction class does not establish an acoustic transmission loss.[11]

Rectangular panel resonance depends on panel dimensions, sheet thickness, bead or cross-break pattern, external reinforcement, internal pressure and boundary conditions; a large unreinforced access panel can radiate more than the surrounding duct; internal liner adds damping and absorption but does not necessarily control low-frequency panel motion. External lagging can improve breakout when applied as a mass-damping-barrier system, provided seams and supports do not bypass it.

Flexible duct can provide some mechanical decoupling and high-frequency attenuation, yet its corrugations create pressure loss and self-noise; compression changes effective length and internal geometry. Sag creates turbulence. Flexible connectors at fans are intended to interrupt vibration

11 MB-1157. SMACNA, HVAC Duct Construction Standards, Metal and Flexible.

transmission, not to replace proper isolation; a taut connector or connector crossed by stiff control tubing, conduit or safety cable can be short-circuited.

Table 24-2. Duct components, dominant mechanisms and characteristic failure modes.

Component	Dominant acoustic mechanisms	Frequent failure modes	Minimum evidence
Circular metal duct	In-duct propagation, seam leakage, support vibration	Poor joints, rigid hangers, penetrations, thin access doors	Gauge, pressure class, joint type, leakage test, support record
Rectangular metal duct	Panel radiation, modal propagation, joint leakage	Oil-canning, inadequate reinforcement, loose access panels	Dimensions, gauge, reinforcement, panel vibration survey
Flexible duct	Corrugation loss, turbulence, partial decoupling	Excess length, compression, sag, kinks, rigid bridging	Installed length, bend radius, support spacing, airflow
Lined duct	Porous absorption, reduced modal energy	Liner erosion, gaps, contamination, protective-film impedance	Liner type, thickness, facing, continuity, inspection
Plenum	Expansion, absorption, panel radiation, leakage	Thin casing, access-door leaks, shared cavities	Casing construction, lining, doors, connected paths
Silencer	Dissipation/reflection, pressure loss, regenerated noise	Wrong orientation, high velocity, casing bypass, damaged splitters	Complete test, operating point, installation photographs

24.15.1 Sheet-metal panel mobility and reinforcement

Duct gauge is only one determinant of casing radiation; panel bay dimensions between seams and reinforcements determine bending modes; cross-breaking or beading changes stiffness and can redistribute modal response, while external angles and tie rods add concentrated restraints. A reinforcement that improves pressure resistance may create a high-mobility line at another frequency or transmit force into a hanger; the acoustical record should therefore identify panel dimensions, reinforcement spacing and support rather than relying on sheet thickness alone.

For a simply supported rectangular plate, natural frequencies can be screened by

$$f_{mn} = \frac{\pi}{2}\sqrt{\frac{D}{m'}}\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right],$$

where D is bending stiffness, m' is surface mass, a, b are panel dimensions and m, n are modal indices. Real duct panels have folds, seams, internal pressure and nonideal boundaries, so the formula is an order-of-magnitude model.

Worked example 24.13. Effect of reinforcement spacing

Assume identical sheet material and boundary type. Reducing the long panel dimension from $a = 1.20\,m$ to $0.60\,m$ while $b = 0.50\,m$ changes the geometric factor for the $(1, 1)$ mode from

$$\left(\frac{1}{1.20}\right)^2 + \left(\frac{1}{0.50}\right)^2 = 4.694$$

to

$$\left(\frac{1}{0.60}\right)^2 + \left(\frac{1}{0.50}\right)^2 = 6.778.$$

The screened modal frequency rises by $6.778/4.694 = 1.44$, or 44 per cent. The calculation does not show that breakout falls by 44 per cent. Radiation efficiency, damping, internal pressure field and support mobility remain.

24.15.2 Turbulence, Strouhal scaling and local geometry

Aerodynamic sound often arises where flow separates at damper blades, splitter edges, grilles, abrupt transitions and obstructions. A characteristic frequency can be screened by the Strouhal relation

$$St = \frac{f\,L_c}{V},$$

where L_c is a characteristic dimension and V is local velocity. The appropriate Strouhal number depends on geometry and flow regime. The relation is useful for testing whether a whistle or broadband peak scales with velocity.

Worked example 24.14. Velocity scaling of a damper tone

A tonal peak occurs at 620 Hz when local velocity is 7.0 m/s. After flow is reduced to 5.0 m/s, a geometrically similar shedding mechanism would screen at

$$f_2 = f_1 \frac{V_2}{V_1} = 620 \frac{5}{7} = 443\,Hz.$$

If the measured peak remains at 620 Hz, a fixed mechanical or electrical source is more plausible than pure vortex shedding; if it shifts near 443 Hz, the aerodynamic hypothesis strengthens; the inference remains provisional because control changes can alter geometry and fan speed simultaneously.

24.15.3 Duct-wall lagging and composite treatment

External lagging commonly combines damping compound, added mass and an outer barrier; effective treatment requires continuous coverage and controlled seams; if the outer barrier is rigidly attached to the duct at dense intervals, it can move with the casing and provide less improvement than expected. If it is separated by a compliant layer, the system behaves as a constrained or double-layer construction with its own resonance.

The treatment should not trap moisture, cover access identification or interfere with fire-damper inspection; added mass changes support loads and seismic demands; field application around flanges, hangers and branches is often discontinuous, so the actual weakest regions may be precisely where the duct changes geometry.

Worked example 24.15. Added mass and ideal mass-law screen

A duct panel has initial surface mass $m'_1 = 7.5\,kg/m^2$. Lagging increases total effective mass to $m'_2 = 15\,kg/m^2$. The ideal mass-law improvement at fixed frequency is

$$\Delta R = 20\log_{10}\left(\frac{m'_2}{m'_1}\right) = 20\log_{10}(2) = 6.02\,dB.$$

The 6 dB result is an upper-level screen for a limp, homogeneous panel. Real improvement can be smaller or locally greater because damping, resonance, joints, flanges and support bridges govern.

24.16 Casing breakout and break-in

Breakout is sound radiated from a duct or plenum casing into the surrounding space. Break-in is the reverse process, in which room or plant-space sound excites the casing and enters the duct. Reciprocity provides a useful conceptual link, but flow, internal absorption and nonuniform boundary conditions can make the two situations operationally different; a secure-room route can therefore be compromised by fan noise breaking out into a ceiling void, speech breaking into a return plenum, or both.[12]

The casing behaves as a finite plate assembly; internal acoustic pressure excites panel modes; seams, corners and reinforcements alter mobility; external radiation depends on panel size and surrounding space; at low frequency the panel may move approximately as one or a few modes. At

12 MB-0760. Frank Fahy and Paolo Gardonio, Sound and Structural Vibration, 2nd ed.

higher frequency the response becomes spatially complex; stiffening can shift resonances upward but may create efficient force paths into supports. Added mass can improve screening but needs compliant separation or damping to avoid becoming a rigid bridge.

A simple area-weighted breakout calculation can screen a mixed casing:

Equation 24.8

$$\tau_c = \frac{\sum_j S_j 10^{-R_j/10}}{\sum_j S_j}, R_c = -10 \log_{10}(\tau_c),$$

where S_j and R_j are area and effective transmission loss of casing region j.

Worked example 24.16. Access-door control of casing transmission

A plenum has 12 m² of casing at 38 dB effective transmission loss and a 0.5 m² access door at 22 dB:

$$\tau_c = \frac{12(10^{-3.8}) + 0.5(10^{-2.2})}{12.5} = 4.05 \times 10^{-4},$$

$$R_c = 33.9\, dB.$$

The access door occupies 4 per cent of area but reduces the composite result by about 4.1 dB relative to the main casing; real breakout also depends on internal field and panel radiation efficiency; the screen nevertheless identifies the door as a priority.

Figure 24-5. Duct and plenum casings transmit by panel radiation, seams, doors and supports

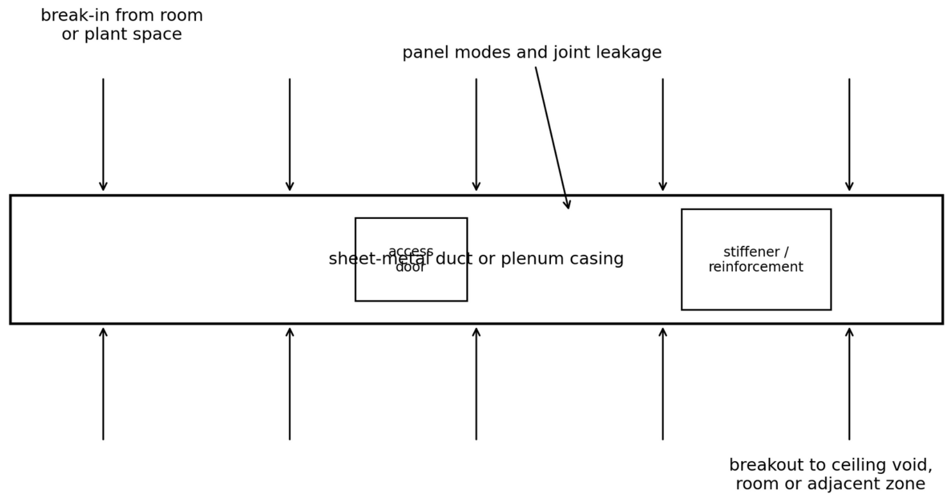

Figure 24-5. Duct and plenum casings transmit by panel radiation, seams, doors and supports. Author's original diagram.

24.17 Plenums and air-handling-unit casings

A plenum can provide useful expansion and absorption, but it also creates a large radiating enclosure with multiple connected paths. Internal surfaces, baffles, coils and filters scatter sound. Thin access doors, removable panels, drain penetrations, control wiring and viewing windows can leak. A factory air-handling unit may have mapped sound power for inlet, discharge and casing-radiated components, yet field assembly joints, base rails, roof curbs and service connections remain project-specific.[13]

Double-wall construction can reduce breakout when inner and outer skins are separated and the cavity is appropriately treated; if both skins are rigidly tied by dense fasteners and framing, improvement may be limited; foam or fibrous insulation provides thermal and acoustic functions but should not be

13 MB-0012. AHRI Standard 260-2024, Sound Rating of Ducted Air Moving and Conditioning Equipment, mapped inlet.

assumed to create a high-performance double leaf. The complete panel test, joint design and installation control matter.

Plenum geometry can also create low-frequency modes; a large return-air plenum above a protected room may couple speech into multiple branches; lining can reduce reverberant build-up but cannot close a direct opening; a well-lined plenum with an unsealed access hatch remains a weak path.

Worked example 24.17. Plenum reverberant build-up screen

A plenum has internal sound power $L_W = 72\,dB$ in a band and equivalent absorption area $A = 8\,m^2$. A diffuse-field screen gives average pressure level

$$L_p \approx L_W + 10\log_{10}\left(\frac{4}{A}\right) = 72 + 10\log_{10}(0.5) = 69.0\,dB.$$

The relation assumes a sufficiently diffuse field and reference conventions consistent with room-acoustic engineering; a narrow plenum with strong modes may not satisfy that assumption; the estimate helps screen casing breakout but does not replace spatial measurement.

24.18 Duct leakage, access doors and service openings

Duct leakage is normally discussed as an energy and air-balance problem; acoustically, every opening is a two-way path; a poorly sealed longitudinal seam, access-door gasket, probe hole or control-cable entry can admit speech into a duct or radiate fan noise into a ceiling void. Leakage class does not translate directly into sound transmission because acoustic impedance depends on opening size, shape, depth, pressure and frequency; nevertheless, leakage testing and visual inspection provide valuable evidence of continuity.

Small openings can dominate high-isolation systems. If a duct wall has high effective transmission loss, a few unsealed holes can control the composite; the open-area calculation used for partitions applies as a conservative upper-bound screen.

Worked example 24.18. Probe-hole leakage

A duct casing area of 6 m² has effective transmission loss 35 dB in a band. Four unsealed probe holes of 8 mm diameter give total area

$$S_o = 4\pi (0.004)^2 = 2.01 \times 10^{-4} m^2.$$

Treating holes as open,

$$\tau_c = \frac{(6 - S_o) 10^{-3.5} + S_o}{6} = 3.49 \times 10^{-4},$$

$$R_c = 34.6 \, dB.$$

The effect is modest here because the casing result is only 35 dB; if the casing were 55 dB, the same holes would dominate and reduce the composite to approximately 44.7 dB; acoustic consequence increases as the surrounding construction improves.

Access doors need continuous gaskets, adequate latch spacing and stable panel stiffness; a single central latch may bow a large door; gaskets can take compression set, collect dust or be damaged during filter changes; commissioning should include contact mapping and closure-force checks where the path is critical.

24.19 Dampers, valves and throttling noise

Dampers change both airflow and acoustic impedance; a fully open damper may add little pressure loss and attenuation; a throttled damper creates jets, separation, broadband noise and sometimes tones; the generated sound depends on velocity, pressure drop, blade geometry, upstream turbulence and downstream duct. A control sequence that uses a nearly closed damper for long periods can create an acoustic condition absent from the product's nominal rating.

A simple air-power screen for throttling is $Q \Delta p$, but only a fraction converts to acoustic power. The conversion efficiency is frequency- and geometry-dependent. An empirical sound-power model should be based on tested data rather than a universal coefficient.

Worked example 24.19. Damper operating-point comparison

A branch carries $Q=1.2\,m^3/s$. At full open, damper pressure drop is 15 Pa; at a throttled state it is 120 Pa. Air power dissipated rises from

$$P_{a,1}=1.2(15)=18\,W$$

to

$$P_{a,2}=1.2(120)=144\,W\,.$$

The eightfold increase does not mean acoustic power rises eightfold, but it identifies a substantially more energetic turbulent state. The throttled condition should be included in terminal sound data and commissioning.

Control dampers can also alter cross-talk. A closed blade may provide attenuation at some bands but leak at blade edges and shafts; a damper position that helps privacy may conflict with ventilation or pressure control; the design should not rely on a control device as the sole acoustic barrier unless its fail-safe state, leakage and lifecycle performance are documented.

24.20 Fire and smoke dampers

Fire and smoke dampers are life-safety devices. Their location, sleeve, retaining method, access, actuator, detector and inspection requirements are governed by applicable codes and listings. An acoustical treatment cannot obstruct operation, restrict access, interfere with heat response or alter the tested installation. NFPA 90A-2024 organises requirements for ducts, connectors, plenums, dampers, controls and acceptance testing, but does not assign secure-speech attenuation.[14]

A damper can create pressure loss and regenerated noise, and its sleeve can bridge a partition; access doors can be weak acoustic points; a damper installed at the wall but connected to rigid ducts on both sides can transmit structure-borne energy around the wall. The solution lies in coordinated listed details, duct routing, remote silencers, lining, flexible connections where permitted and complete system testing.

Acoustic commissioning should test credible damper states without defeating fire safety; smoke-control modes may open or close dampers, start high-speed fans and change room pressure; these emergency states are not ordinary meeting conditions, but they affect configuration control and must not damage seals or silencers.

24.20.1 Acoustic consequences of listed damper installations

The damper assembly is not only the blades; it includes the sleeve, retaining angles or other approved restraint, breakaway connections, actuator, access door and surrounding construction; these features can create an efficient structural bridge through a wall that otherwise has separated leaves.

14 MB-1089. NFPA 90A-2024, Standard for the Installation of Air-Conditioning and Ventilating Systems, chapters on ducts.

Acoustic treatment should be located far enough from the damper to preserve access and listing conditions; a long lined approach or remote silencer may be more defensible than field-added material around the damper frame.

The open damper state and closed state have different acoustical behaviour; in the open state, blade edges and frame create pressure loss and regenerated noise; in the closed state, leakage around blades and shafts controls airborne transmission, while the sleeve and frame remain structural paths. A leakage-rated smoke damper does not thereby possess a speech-security rating; conversely, a damper with useful closed-state attenuation cannot be assumed available during normal occupied operation.

Worked example 24.20. Sleeve bridge screening

A partition provides a direct field level difference of 55 dB in a band; a rigid damper sleeve and connected duct route occupy an effective acoustic area equivalent to 0.015 m² at 20 dB; the remaining wall area is 18 m² at 55 dB:

$$\tau c = \{[(18-0.015)\times 10^{(-5.5)} + 0.015\times 10^{(-2.0)}]\}/18 = 1.15\times 10^{(-5)},$$

so

$$R_c = 49.4\, dB.$$

The small path reduces the screen by about 5.6 dB. Effective area is a model parameter, not literal sleeve area, and must be validated by measurement.

24.20.2 Smoke-control and emergency-state configuration

Smoke-control operation can command fans to maximum speed, reverse flow, open bypasses and reposition dampers; the state may create high pressure differentials and large vibration; although confidential discussions should not ordinarily continue during a fire emergency, the system must return to its normal acoustic baseline without damaged seals, shifted splitters or uncontrolled control changes.

Post-event inspection should therefore include damper function, flexible connections, supports, access doors and room pressure; an emergency test or actual event can expose silencers to velocities above their normal operating range; a recorded before-and-after spectrum helps distinguish damage from unrelated later changes.

24.20.3 Firestopping at duct penetrations

The annular space around a duct or sleeve can transmit sound through gaps, rigid fillers or damaged firestop; fire-resistive systems accommodate specific movement, backing and sealant geometry; substituting a hard patch for a flexible listed system can increase vibration transfer and crack under movement. Substituting soft acoustic foam can compromise fire resistance; the coordinated detail should identify the listed firestop system and the acoustic continuity objective, then preserve both through inspection.

For rectangular ducts, corner geometry and reinforcement complicate the annulus; a visible face seal can conceal a deep void; inspection should occur before escutcheons or lagging conceal the joint; where movement is expected, the field test should include the credible pressure and thermal operating condition.

24.21 Air terminals, diffusers, grilles and registers

Terminals convert duct flow into room air motion; their blades, slots, perforations, dampers and induction jets generate sound. ASHRAE Standard

70-2023 defines laboratory methods for aerodynamic performance and sound generation of air outlets and inlets; a terminal's sound data belong to its tested neck size, flow, pressure, damper position and installation; changing the boot, adding a balancing damper or crowding the inlet with a sharp elbow can alter performance.[15]

A terminal also couples room speech into the duct; a large return grille can be an efficient acoustic aperture; internal lining behind the grille can reduce reflection, but a straight line to a common plenum remains; diffuser selection should therefore consider both room-noise generation and reverse transmission.

Room sound pressure from terminal sound power depends on directivity, distance, room absorption and ceiling/plenum transmission; AHRI 885 provides an application procedure, but its assumptions must be preserved; a quiet conference room with unusual absorption, ceiling construction or listener proximity may differ from a conventional office.

Worked example 24.21. Terminal sound power to local level

A diffuser has 500 Hz sound power $L_W = 43\, dB$. At a listener 2.5 m away, assume directivity factor $Q_d = 2$ and room constant $R = 30\, m^2$. A standard room screen is

$$L_p \approx L_W + 10\log_{10}\left(\frac{Q_d}{4\pi r^2} + \frac{4}{R}\right).$$

Substitution gives

$$L_p \approx 43 + 10\log_{10}\left(\frac{2}{4\pi(2.5)^2} + \frac{4}{30}\right) = 35.0\, dB.$$

15 MB-0046. ANSI/ASHRAE Standard 70-2023, ANSI/ASHRAE Standard.

The result depends strongly on room assumptions and excludes ceiling radiation, multiple terminals and background. It is an application screen, not a compliance measurement.

24.21.1 Terminal directivity, throw and acoustic geometry

A diffuser's aerodynamic objective is to distribute air without objectionable draft or stagnation; its acoustic behaviour follows the same jet geometry; slot width, vane angle, neck transition and ceiling mounting determine local turbulence and directivity; a terminal flush with a hard ceiling radiates into an approximate half-space, while one near a wall or corner experiences additional boundary effects. A laboratory sound-power rating can be converted to a room estimate only after those geometric assumptions are stated.

Terminal throw and drop influence where occupants sit relative to the jet; a high-velocity jet passing close to a microphone or listener can create fluctuating pressure and local noise not represented by a room-average prediction; for secure-room measurement, microphones should not be placed inside strong terminal jets unless that condition is itself under investigation. Wind screens reduce some flow contamination but do not make turbulent pressure fluctuations acoustical.

The return terminal is often quieter as a source but more important as a speech-entry aperture; its neck may connect directly to a shaft or plenum; the designer should therefore schedule return-path attenuation separately from supply-terminal noise. A visually small perforated return can still have large free area.

Worked example 24.22. Free-area velocity at a return grille

A return grille has nominal face dimensions $0.60\,m \times 0.45\,m$, gross area $0.270\,m^2$. Manufacturer free-area ratio is 0.62. At $Q = 0.85\,m^3/s$,

$$A_f = 0.62(0.270) = 0.1674\,m^2,$$

$$V_f = \frac{0.85}{0.1674} = 5.08\,m/s.$$

Using gross face area would predict only 3.15 m/s; the free-area result is 61 per cent higher and better indicates jet, pressure and regenerated-noise conditions; the manufacturer's free-area definition should be verified because blade geometry can make local velocities still higher.

24.22 VAV terminals, fan-powered boxes and induction units

Variable-air-volume terminals generate discharge sound in the duct and radiated sound through the casing. Fan-powered boxes add a local fan and motor. Reheat coils, dampers and induction nozzles add pressure loss and turbulence. AHRI 880/881 and ASHRAE Standard 130-2025 provide rating and laboratory-test frameworks, but room performance still depends on duct attenuation, ceiling transmission, suspension, operating point and installation.[16]

Discharge and radiated paths must be modelled separately; discharge sound travels through downstream duct and diffuser; radiated sound passes through the box casing and ceiling; a box selected solely on one path may fail on the other. At low flow, the damper may throttle and increase regenerated noise. At high flow, duct velocity and diffuser noise rise. A fan-

16 MB-0013. ANSI/ASHRAE Standard.

powered unit can create tonal or low-frequency components that penetrate ceilings more efficiently.

Worked example 24.23. Combining discharge and radiated paths

At 250 Hz, predicted room contributions are 31 dB from the discharge path and 34 dB from casing radiation:

$$L_{\Sigma}=10\log_{10}\left(10^{3.1}+10^{3.4}\right)=35.76\,dB.$$

Treating only the larger path would understate total by 1.8 dB. If both predictions share source-data or room-correction uncertainty, covariance should be considered.

Suspension matters. A box hung from light structure can excite a ceiling. Flexible duct can isolate some motion but can also sag and whistle. Electrical conduit, hydronic connections or rigid controls can bypass isolation.

24.22.1 Control sequence as an acoustic transfer function

A VAV box is not one source state; its discharge and radiated spectra vary with inlet pressure, primary airflow, blade angle, fan command and reheat; pressure-independent control can hold airflow while upstream pressure rises, forcing the damper towards closure and increasing local turbulence. A static-pressure reset strategy can reduce this condition, but its acoustic benefit depends on the entire system.

The controls trend should be preserved with the acoustic measurement; time synchronisation allows the engineer to associate a transient tone with damper command or fan start; a one-minute equivalent level can hide cycling; time-frequency plots reveal bursts produced by control hunting or minimum-flow resets.

Worked example 24.24. Control-hunting duty cycle

A terminal produces 48 dB during a 12-second throttling event and 32 dB during the remaining 48 seconds of each minute. Energy-equivalent one-minute level is

$$L_{eq}=10\log_{10}\left[0.2\left(10^{4.8}\right)+0.8\left(10^{3.2}\right)\right]=41.4\,dB.$$

A slow sound-level display might report approximately 41 dB and conceal the 48 dB bursts. For speech privacy, intermittent background can alternately mask and expose speech. The time structure should therefore be retained.

24.22.2 Ceiling attenuation and radiated terminal sound

Radiated box sound reaches the room through the ceiling system and openings; ceiling attenuation data depend on panel type, plenum depth, light fixtures, diffusers and partition layout; a high-rated ceiling panel cannot compensate for open luminaires or a shared plenum. The radiated path should be combined with discharge sound in linear energy and validated in the installed ceiling.

Where a terminal is placed directly over the protected room, moving it to a corridor or service zone can be more effective than adding enclosure treatment; location controls both casing radiation and maintenance access; enclosures around boxes must preserve service clearances, airflow and fire requirements.

24.23 Fan-coil, packaged and ducted equipment sound data

AHRI 260-2024 establishes mapped sound ratings for factory-assembled ducted air-moving and conditioning equipment across operating ranges. The rating can distinguish inlet, discharge and casing components. Product selection should use band data at the actual operating point, not a single A-weighted value. Low-frequency components often govern transmission through heavy boundaries, while upper bands affect speech clarity and terminal noise.[17]

Packaged equipment installed above or adjacent to a protected room creates multiple routes: ducted sound, casing radiation, vibration through supports, piping, refrigerant lines, condensate drains and electrical connections; a manufacturer certificate cannot represent those field paths; equipment location is often the most effective control. Moving a fan-coil out of the protected envelope can outperform elaborate local treatment.

Sound data should be checked for test standard, installation category, inlet and outlet conditions, octave or one-third-octave range, background limits and operating map; interpolation between mapped points should be conservative and documented; extrapolation beyond the tested range is weak evidence.

24.23.1 Mapped ratings, interpolation and uncertainty

Mapped equipment data may present sound power at several airflow and pressure points; the project point can lie between tested states; interpolation should be performed band by band and should not assume a smooth monotonic relation where fan speed, compressor stage or control mode changes. If a manufacturer publishes only a single rated condition, applying it to a different operating point is weak evidence.

A source-data uncertainty budget should include laboratory reproducibility, unit-to-unit variation, operating-point measurement and interpolation. Field

17 MB-0011. AHRI Standard 260-2024, ISO 13347-1:2025.

system effects are a separate model-form contribution. Combining them into one unexplained margin hides which evidence can be improved.

Worked example 24.25. Linear-power interpolation between mapped points

At one operating point a 250 Hz band is 72 dB; at a higher point it is 78 dB; a project point halfway in airflow should not automatically be assigned the arithmetic midpoint of 75 dB; if one assumes linear interpolation in acoustic power for this screening,

$$W_r = \frac{10^{7.2} + 10^{7.8}}{2},$$

$$L_W = 10\log_{10}\left(W_r\right) = 76.1\, dB.$$

The result is closer to the higher level because decibels are logarithmic. The assumption of power-linear behaviour with airflow is not universal and should be replaced by manufacturer mapping or measurement.

24.23.2 Equipment-room and ceiling-void placement

A ducted unit in a mechanical room can transmit through walls and floors in parallel with duct routes; a fan-coil above a ceiling bypasses the equipment-room boundary entirely; condensate pumps, valves and refrigerant pulsation add sources; the design should locate rotating equipment away from protected rooms and provide service access from outside the controlled envelope where practicable.

Equipment-room noise can enter a return duct through casing break-in, then propagate into the protected room; conversely, protected speech can enter a return and radiate through equipment casing into a plant space; the threat model must include spaces accessible to maintenance personnel, not only occupied offices.

24.24 Background noise, masking and quiet-hour exposure

HVAC sound can mask transmitted speech, but accidental masking is not a reliable security control; fan noise varies with speed, occupancy and maintenance. Tonal or low-frequency noise may be annoying while providing poor masking of speech information; a system that appears private during daytime operation can expose speech after shutdown or night setback; masking must be treated as a deliberate, commissioned and monitored system when it forms part of the design.[18]

The receiving risk depends on residual speech level and background in each band. A change in background can materially change audibility even if the transmission path is constant.

Worked example 24.26. Quiet-hour loss of masking

At a receiving position, residual speech level in a critical band is 28 dB. Daytime HVAC background is 31 dB, giving signal-to-background ratio $-3dB$. At night, background falls to 21 dB, giving $+7dB$. The path did not change, yet the margin changed by 10 dB. The calculation does not establish intelligibility, but it identifies a high-risk operating state for an appropriate speech-privacy test.

Background should be measured as a distribution, not one snapshot. Cycling fans, variable-speed drives, economiser modes and occupancy control create time variation. Commissioning should include quiet credible states and failure modes.

18 MB-0076. ASTM E2638-24.

24.24.1 Spectral quality of HVAC masking

Broadband level alone does not determine masking; a low-frequency rumble can raise A-weighted or overall level while leaving consonant-rich upper bands relatively exposed; tonal components can be perceptually intrusive and provide uneven masking; the receiving analysis should compare residual speech and background by band, supplemented by an appropriate speech metric.

HVAC masking is spatially nonuniform. A listener near a terminal may experience high noise; another near a quiet wall may have lower background and stronger structural leakage; a room-average background can hide the most vulnerable position; quiet accessible locations should be included in the survey.

Worked example 24.27. Equal overall levels with different masking spectra

Background A has 30 dB in each of four speech-relevant bands. Background B has 40 dB in the lowest band and 20 dB in the other three. Linear total levels are

$$L_A = 10\log_{10}\left(4 \times 10^3\right) = 36.0\, dB,$$

$$L_B = 10\log_{10}\left(10^4 + 3 \times 10^2\right) = 40.1\, dB.$$

Background B is higher overall but provides 10 dB less masking in three bands. The example shows why overall level is not a privacy metric.

24.24.2 Background stability and fault detection

A deliberate masking system is normally commissioned for level, spectrum, uniformity and stability; HVAC background is controlled for thermal and ventilation purposes, not privacy; if it contributes to the operational risk model, controls alarms should identify fan failure or schedule changes. A room should not silently move from an acceptable to an exposed state when one air handler stops.

Trend data can support fault detection, but they should not substitute for calibrated acoustic monitoring unless validated; fan command and pressure are proxies; a broken belt can leave the command unchanged while sound and airflow collapse.

24.25 Structural vibration, supports and flexible connectors

Fans and turbulent duct elements apply fluctuating forces to casings and supports; vibration travels through mounts, bases, hangers, walls and slabs, then radiates from building surfaces. A flexible connector interrupts some casing motion but does not isolate the fan base; a connector installed taut, misaligned or crossed by rigid services can transmit substantial force; ISO 13347 and AMCA fan sound standards explicitly limit themselves to airborne sound under specified arrangements; vibration requires separate evidence.[19]

For a single-degree-of-freedom isolator, force transmissibility is

Equation 24.9

$$T_F = \frac{\sqrt{1+(2\zeta r)^2}}{\sqrt{(1-r^2)^2+(2\zeta r)^2}},$$

where $r = f/f_n$ and ζ is damping ratio.

Worked example 24.28. Fan isolator transmissibility

A fan has dominant forcing at 24 Hz. Mount natural frequency is 6 Hz, so $r=4$. With $\zeta=0.08$,

19 MB-0928. ISO 13347-3:2026 and ISO 13347-4:2025, ISO 13347-3:2026, ISO 13347-4:2025.

$$T_F = \frac{\sqrt{1+(0.64)^2}}{\sqrt{(1-16)^2+(0.64)^2}} = 0.079.$$

Ideal force transmission is about 7.9 per cent, or $-22.0\,dB$. The result assumes one mode, linear mounts and no rigid bypass. Ducts, pipes, conduits, restraints and housekeeping pads can dominate field transmission.

Figure 24-6. Airborne attenuation does not control vibration bypasses through mounts, connectors and supports

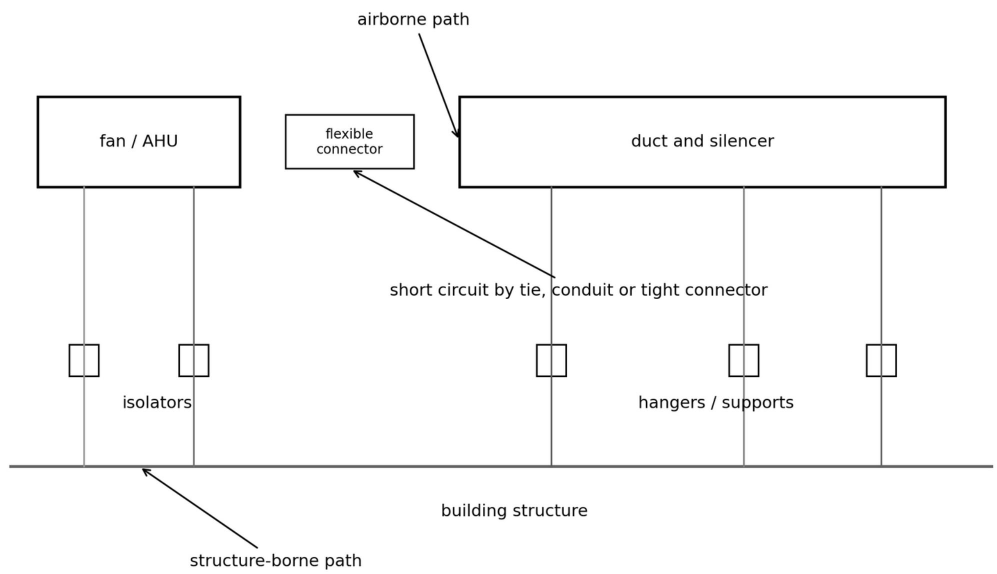

Figure 24-6. Airborne attenuation does not control vibration bypasses through mounts, connectors and supports. Author's original diagram.

24.26 Duct supports, hangers and penetrations

Hangers carry static load and resist seismic or operational forces; they also couple duct vibration into structure; rods, trapezes, anchors and braces form repeated paths; resilient inserts can reduce high-frequency force but must be selected for load, temperature, fire and displacement. A resilient hanger compressed to solid or bypassed by a brace provides little isolation.

Penetrations through protected walls require structural clearance, fire stopping, smoke control and acoustic closure; duct sleeves often become rigid bridges; the wall opening may be much larger than the duct, leaving an annulus filled inconsistently; a fire damper sleeve and angle frame can connect both faces. The acoustic detail must be coordinated with the listed fire assembly and movement requirement.

Worked example 24.29. Support line-force screen

A duct section produces measured RMS casing acceleration $a=0.08\,m/s^2$. Effective moving mass associated with one support is estimated as 45 kg. Inertial-force screen is

$$F=m\,a=(45)(0.08)=3.6\,N.$$

If four supports act coherently, total force is not necessarily four times because phase and structural mobility matter. The calculation provides an order-of-magnitude input for mobility measurement, not a transmitted-force certificate.

24.27 Pressure differential and door/HVAC interaction

HVAC pressure can alter door-seal compression, automatic-bottom contact and sound-lock operation; a room held positive may push the door away from the stop; a negative room may pull it tighter; the effect depends on door area, latch and closer.

Equation 24.10

$$F_p=\Delta p\,A_d,$$

where Δp is pressure difference and A_d is door area.

Worked example 24.30. Pressure force on a door

For $\Delta p=25\,Pa$ and $A_d=2.1\,m^2$,

$$F_p=(25)(2.1)=52.5\,N.$$

That force is about 11.8 lbf; it can materially alter opening force and seal contact; the state matrix should include credible pressure extremes and fan modes; acoustic tests conducted only at the favourable pressure direction can overstate robustness.

Pressure imbalance can also drive airflow through gaps, producing hiss or modulating leakage; air leakage and acoustic leakage are related but not interchangeable; an airflow test can locate a gap but does not supply its frequency-dependent transmission loss.

24.28 Measurement of fan and equipment sound power

Fan and equipment sound-power methods create controlled laboratory source data. ANSI/AMCA 300-24 uses reverberation-room methods; AMCA 320-23 uses intensity; ISO 13347 provides multiple standardised methods; ISO 5136 addresses in-duct sound power. Each method has installation categories, background limits, test arrangements and reporting requirements. The chosen dataset must match the project source path.[20]

One-third-octave data are valuable when tones, blade-passing components or narrow silencer features matter; octave-band ratings can obscure narrow peaks; test reports should identify speed, flow, pressure, density, inlet and outlet arrangement, accessories, control settings and corrections.

Laboratory source power is an input, not a room result; the installed fan can experience system effect, different inlet turbulence, attached silencers, flexible connectors and casing support; field validation should compare spectral features and operating point rather than demand exact equality with the laboratory.

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20 MB-0045. ANSI/AMCA Standard, ISO 13347-1:2025.

24.29 Laboratory silencer testing

ASTM E477-26 and ISO 7235 measure insertion loss, airflow-generated sound and pressure loss under prescribed laboratory conditions. ISO 11691:2020 offers a no-flow survey method but states that it is unsuitable where self-generated flow noise is important. Laboratory insertion loss can be limited by flanking through test ducts or the facility. Censored high values should be reported as bounds rather than exact numbers.[21]

The test specimen must match the proposed silencer; length, cross-section, splitter count, media, facing, casing, end configuration and airflow direction matter; a family curve assembled from related products is weaker evidence than the complete report for the exact model. If the project requires an unusual transition or elbow directly at the silencer, a mock-up may be warranted.

Worked example 24.31. Laboratory dynamic-range bound

Reference path level is 84 dB. With the silencer installed, measured level is 42 dB, but corrected background is 41 dB; energy subtraction gives only a small signal and high uncertainty; the nominal 42 dB difference should not be reported as exact 42 dB insertion loss. A defensible result may be a lower bound, such as “at least 39 dB under the test’s decision rule”, depending on the method and uncertainty budget.

24.30 In-situ silencer and duct-path testing

In-situ measurement evaluates the installed route. ISO 11820 provides a framework for silencers, but the practitioner must define upstream and downstream measurement sections, flow, modes, source stability and

21 MB-0098. ASTM E477-26, ISO 7235:2003.

interfering paths. A downstream room measurement alone cannot distinguish silencer insertion loss from branch loss, terminal radiation and casing breakout.[22]

A substitution test may compare the route with and without a removable element, but many field silencers cannot be removed; transfer-function or sound-power methods can estimate attenuation if the fields are characterised; controlled source injection upstream and downstream can support diagnosis. Any temporary opening or bypass changes the system and must be documented.

Figure 24-7. Cross-talk and breakout diagnosis requires simultaneous source, duct, casing and receiving-room evidence

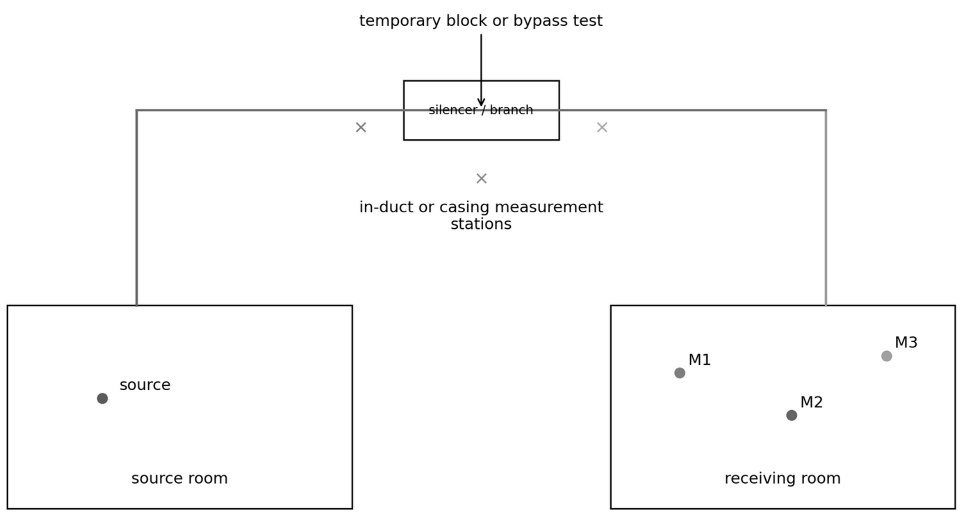

Figure 24-7. Cross-talk and breakout diagnosis requires simultaneous source, duct, casing and receiving-room evidence. Author's original diagram.

Worked example 24.32. Upstream/downstream level difference with area correction

Upstream in-duct average level is 76 dB in a duct area of $0.60\,m^2$. Downstream is 54 dB in $0.30\,m^2$. If the measurement quantity requires a

22 MB-0922. ISO 11820:1996, ISO 5136:2003.

simple area-related sound-power screen,

$$\Delta L_W = (76 + 10\log_{10} 0.60) - (54 + 10\log_{10} 0.30) = 25.0\,dB.$$

The calculation assumes comparable modal and intensity conditions and is not a substitute for the applicable method. Flow noise, reflection and microphone turbulence must be controlled.

24.31 Cross-talk field measurement

A cross-talk test should reproduce the route and state under investigation; the source may be a calibrated loudspeaker in the protected room, a duct-injected source or both; room excitation characterises coupling into the terminal under realistic source geometry. Duct injection isolates part of the path but can create a field unlike speech entering through a grille; the two methods answer different questions.

The receiving survey should include room-average positions, accessible listener positions, terminal-near positions and, where relevant, corridor or ceiling-void locations; source-room and receiving-room background must be recorded for every state; fan operation, damper command, airflow, room pressure and door state are part of the test record. A result obtained with the return damper closed cannot be applied to the occupied state if the damper normally opens.

ASTM E336-25a can support room-to-room field attenuation, while ASTM E2638-24 addresses closed-room speech privacy; neither automatically isolates the ventilation path; diagnostic measurements can temporarily seal a terminal, close a branch, add a known duct plug or alter fan state. The intervention should be reversible, safe and documented.

Worked example 24.33. Temporary terminal block as a diagnostic intervention

At 1 kHz, receiving level is 33 dB with the route normal and 25 dB after an airtight temporary terminal block; background is 20 dB in both states; corrected normal and blocked levels are approximately 32.8 and 23.8 dB, giving a 9.0 dB reduction. The intervention supports the terminal route as significant, but it does not prove the entire 9 dB came from one duct because the block also changes room absorption and local radiation; repeating at several bands and comparing duct stations strengthens the inference.

24.32 Breakout and casing-radiation diagnosis

Breakout diagnosis compares internal duct pressure, external sound pressure, casing vibration and sound intensity; a high internal level with low casing vibration suggests strong casing transmission loss; high vibration with strong external radiation implicates panel mobility; a local external hotspot at an access door or seam indicates leakage or weak panel construction. Coherence with fan tones supports a common source but does not prove direction of transmission.

Sound intensity can map net energy flow across casing panels if the field and probe limitations are respected; near reactive sources, pressure-intensity index and residual intensity capability matter; vibration velocity and structural intensity provide complementary evidence; temporary mass, damping or seam sealing can distinguish panel radiation from opening leakage.

Worked example 24.34. Casing radiation efficiency screen

A rectangular panel area $S = 1.2\,m^2$ has spatially averaged RMS normal velocity $v = 2.0 \times 10^{-4}\,m/s$. With air density $\rho_0 = 1.2\,kg/m^3$, sound speed $c = 343\,m/s$ and assumed radiation efficiency $\sigma = 0.15$, radiated power screen is

$$W = \rho_0 c \sigma S v^2 = (1.2)(343)(0.15)(1.2)\left(2.0 \times 10^{-4}\right)^2 = 2.96 \times 10^{-6}\,W .$$

Sound-power level is

$$L_W = 10 \log_{10}\left(\frac{2.96 \times 10^{-6}}{10^{-12}}\right) = 64.7\,dB .$$

The dimensional check gives watts. Radiation efficiency is highly uncertain and frequency-dependent; the calculation is a screen for measurement planning, not a substitute for intensity measurement.

24.33 Sound intensity, vibration and coherence

Pressure alone cannot reveal direction of energy flow; sound intensity combines pressure and particle velocity to estimate net acoustic power through a surface; it can distinguish a radiating duct panel from a nearby reflected field, provided the measurement surface, frequency range, residual intensity, spatial sampling and field indicators are acceptable. Vibration measurements identify mechanical motion but not necessarily acoustic radiation; coherence and transfer functions connect observations to a controlled source.[23]

A high pressure-vibration coherence at blade-passing frequency suggests linear coupling from fan excitation to casing motion; low coherence can result from multiple sources, time variation, nonlinearity, inadequate averaging or measurement noise; coherence is not causation by itself. A

23 MB-0929. ISO 13347-4:2025.

controlled fan-speed sweep or temporary support change can provide stronger discrimination.

For a two-channel transfer function,

Equation 24.11

$$H_{xy}(f) = \frac{G_{xy}(f)}{G_{xx}(f)},$$

where G_{xy} is cross-spectrum and G_{xx} is input autospectrum. Magnitude and phase should be preserved. Averaging settings, window, overlap and synchronisation belong in the record.

Worked example 24.35. Phase drift between recorders

Two independent recorders differ by 15 parts per million. Over 20 minutes,

$$\Delta t = 15 \times 10^{-6}(1200) = 0.018\,s.$$

At 250 Hz, this equals 4.5 cycles. Cross-phase becomes meaningless without synchronisation or correction. Simultaneous multi-channel acquisition, shared clocks or recorded timing references are therefore necessary for coherent path analysis.

24.34 Uncertainty, censoring and decision rules

HVAC acoustic predictions combine source data, attenuation, branch division, terminal corrections, room absorption, background and model-form assumptions. These inputs are often correlated. The same duct dimensions affect velocity, pressure loss, regenerated noise and attenuation; treating every contribution as independent can understate or overstate uncertainty.

For a measurement model $y=f(x_1,\ldots,x_n)$, combined standard uncertainty is screened by

Equation 24.12

$$u_c^2(y)=\sum_i c_i^2 u^2(x_i)+2\sum_{i<j} c_i c_j u(x_i,x_j),$$

where $c_i=\partial f/\partial x_i$ and covariance terms preserve correlation.[24]

Censored measurements require care. If a downstream level is indistinguishable from background, insertion loss is bounded, not exactly known; if a fan source is below laboratory minimum in a band, the published value may be a limit; substituting that limit as an exact number can create false precision.

Worked example 24.36. Guarded acceptance of a cross-talk result

A specification requires a minimum band level difference of 48 dB. Measured estimate is 49.2 dB with expanded uncertainty $U=2.0\,dB$. A conservative rule requires $D-U\geq 48$:

$$49.2-2.0=47.2\,dB.$$

The result does not pass under that rule. The rule must be specified before testing. A different risk allocation may use another guard band, but it should not be invented after results are known.

24.34.1 Correlated attenuation and source terms

A path budget often subtracts several attenuation terms derived from one geometry; straight-duct loss, silencer end correction and branch loss may share duct area and modal assumptions; treating them as statistically

24 MB-0964. JCGM 100:2008, ISO 12999-1:2020.

independent can understate uncertainty. The covariance sign matters. If a smaller effective area increases both velocity-generated noise and end-reflection correction, those contributions can move in opposite directions in the final room level.

Monte Carlo propagation is useful when equations contain logarithms, maxima, censoring or branch decisions; each trial samples source power, losses, generated sound, room correction and background under a stated joint distribution; the output is a distribution of room levels or pass probability rather than one deterministic margin.

Worked example 24.37. Monte Carlo-style percentile screen

Suppose a calculated receiving level is 27 dB with approximately normal combined standard uncertainty 2.2 dB after model review. The one-sided 95th-percentile screen is

$$L_{95} = 27 + 1.645(2.2) = 30.6\,dB.$$

If a design limit is 30 dB, the mean estimate appears compliant but the percentile screen does not; a normal model may be inappropriate where one route is censored or bounded; the calculation illustrates decision sensitivity, not a universal acceptance rule.

24.34.2 Model discrepancy and validation hierarchy

A detailed calculation can still be wrong because the physical model omits a path; model discrepancy is distinct from parameter uncertainty; increasing the uncertainty on silencer insertion loss does not represent an unmodelled casing bridge; validation should compare predicted and measured spectra, spatial patterns and state dependence. A consistent broad offset suggests source or room correction; a local band difference suggests resonance or data mismatch; a spatial hotspot suggests an omitted path.

The validation hierarchy begins with component data checks, then path transfer measurements, then whole-room results; fitting one arbitrary correction to the final room level may conceal compensating errors; a model that predicts the right total for the wrong path cannot guide remediation reliably.

Worked example 24.38. Compensating model errors

A prediction assigns 26 dB to the return path and 20 dB to casing breakout. Measurement-informed diagnosis finds 22 dB return and 24 dB casing. Predicted total is

$$10\log_{10}\left(10^{2.6}+10^{2.0}\right)=27.0\,dB,$$

while diagnosed total is

$$10\log_{10}\left(10^{2.2}+10^{2.4}\right)=26.1\,dB.$$

Totals differ by less than 1 dB, yet the dominant route changes. Calibrating only the total would preserve the wrong remediation priority.

24.34.3 Decision consequences and conditional acceptance

A marginal result can be addressed by rejection, repair, additional evidence, operational restriction or conditional acceptance by the competent authority; engineering should present the options and their consequences without making an unauthorised security decision; for example, a room may be acceptable only while a masking system and ventilation state are monitored, but that condition creates lifecycle burden and failure exposure.

A conditional decision requires measurable conditions. “Keep HVAC on” is vague. A defensible condition identifies fan state, minimum background spectrum, alarm response, maintenance responsibility and retest interval; if those controls cannot be assured, passive path improvement is preferable.

24.35 Design workflow and path budget

Design begins with protected source states and receiving access; the mechanical engineer supplies airflow, pressure, operating modes and equipment data; the acoustical engineer constructs band path budgets for supply, return, transfer, casing and structural routes; the architect coordinates room boundaries, ceilings, doors and shafts. Fire protection reviews dampers and penetration details. Controls define normal, setback, emergency and failure states.

A path budget should use linear power; each route has a source coupling, a sequence of losses or gains, a receiving radiation condition and uncertainty; the objective is not to maximise every component rating; it is to prevent any route from governing the protected speech spectrum. A 40 dB silencer on a route already limited by a 25 dB transfer grille is wasted. Conversely, improving the wall while leaving a direct return path is irrational.

Worked example 24.39. Comparing three design interventions

At 500 Hz, estimated receiving contributions are 30 dB through the return path, 25 dB through the supply path and 23 dB through casing breakout. Total is

$$L_{\Sigma}=10\log_{10}\left(10^{3.0}+10^{2.5}+10^{2.3}\right)=31.8\,dB.$$

Option A adds 12 dB to supply attenuation, giving total about 30.9 dB; option B adds 10 dB to return attenuation, giving 27.9 dB; option C adds 8 dB to casing performance, giving 31.3 dB. Return treatment yields the greatest single improvement; after it is applied, supply becomes more important. The path ranking must be recalculated after every intervention.

A formal value-of-information analysis can justify measurements; if uncertainty about return attenuation can change the design decision, a mock-up or field test has value; if even the worst credible return result remains well below another path, further precision has little value.

24.35.1 Band-by-band path schedules

A path schedule should identify source sound power, coupling, each series attenuation, each generated source, receiving correction and uncertainty for every relevant frequency band; the schedule should not sum decibel losses from incomparable reference conditions; for example, a laboratory silencer insertion loss can be subtracted from in-duct power only when the duct arrangement and mode assumptions are reasonably compatible. A room-to-room level difference cannot be inserted as though it were a component transmission loss.

Each path is assigned a stable identifier; the identifier appears on drawings, calculations, submittals, inspection photographs and test files; a return branch might be designated HVAC-R-03; its silencer, damper and terminal are child records; this approach prevents design changes from breaking the evidentiary chain.

The schedule should also state whether a value is measured, manufacturer-tested, calculated, assumed or bounded; an assumed 5 dB elbow loss should not visually resemble an accredited laboratory result; during commissioning, measured transfer values can replace assumptions while retaining the history.

Worked example 24.40. Path-schedule arithmetic with a generated source

A supply route begins with 76 dB fan discharge sound power; series losses are 8 dB in duct, 20 dB in a silencer and 5 dB at the terminal; the silencer generates 48 dB downstream. The attenuated fan contribution is

$$L_{W,f} = 76 - 8 - 20 - 5 = 43\,dB.$$

The regenerated contribution also passes the terminal loss:

$$L_{W,g} = 48 - 5 = 43\,dB.$$

Combined terminal sound power is

$$L_W = 10\log_{10}\left(10^{4.3} + 10^{4.3}\right) = 46.0\,dB.$$

Subtracting silencer insertion loss after adding regenerated sound would be physically wrong because the generated source occurs within the silencer. Path order matters.

24.35.2 Sensitivity analysis

Sensitivity identifies which uncertain variable controls the decision; for a series path expressed in decibels, the local sensitivity to each simple loss is often one-for-one, but the total room level is nonlinear when parallel routes combine; improving a path well below the dominant route has little effect.

For path powers W_i, the fractional contribution is

$$s_i = \frac{W_i}{\sum_j W_j}.$$

A small change ΔL_i in one path produces an approximate total-level change $s_i \Delta L_i$ for sufficiently small perturbations in decibels. The relation is a local screen.

Worked example 24.41. Local sensitivity of parallel paths

Three routes contribute 30, 27 and 20 dB. Linear powers are proportional to 1000, 501 and 100, so fractional contributions are 0.625, 0.313 and 0.062. A 2 dB reduction in the dominant path is expected to reduce total by roughly $0.625(2)=1.25\,dB$ locally. A 2 dB reduction in the weakest path yields only about 0.12 dB. Full recalculation should be used for large changes.

24.35.3 Robust design and operating-state envelopes

A robust design does not pass only at one nominal airflow; it remains acceptable across tolerances, seasonal density, filter loading, control reset and credible maintenance states; the operating envelope should be defined before equipment selection; manufacturer data are then checked across that envelope.

The worst acoustic state is not always maximum flow; minimum flow can close a damper, generating a tone. Fan-off can remove masking. Economiser mode can open a direct outdoor path; heating mode can activate a fan-powered box; the path budget should therefore evaluate state-by-state maxima in each band rather than selecting one global “worst case” without analysis.

Worked example 24.42. State-envelope maximum

Predicted receiving levels at 1 kHz are 28 dB normal, 31 dB minimum flow, 29 dB maximum flow and 26 dB fan-off; a design based only on normal operation would miss the controlling minimum-flow state. If uncertainty is

1.5 dB in each state, a conservative screen should compare the applicable decision rule with 31 dB, not with the average 28.5 dB.

24.35.4 Spatial allocation and zoning

Mechanical zoning can reduce cross-talk by avoiding common return paths between protected and uncontrolled rooms; dedicated branches, separated shafts and remote equipment can reduce the need for extreme component attenuation; the design should consider who can access each duct segment, shaft, plant room and ceiling void.

A dedicated system does not automatically create security; it can still connect several protected rooms, provide accessible maintenance paths or radiate into public plant space; zoning is one layer in the path model; it should be documented with access control and maintenance procedures.

24.35.5 Energy and resilience trade-offs

Acoustic measures can increase pressure drop, fan energy and maintenance; oversized duct and silencers reduce velocity and noise but require space; a resilient design considers failure and bypass; two shorter silencers in series may provide maintenance flexibility, but an intermediate casing path can bypass them. A passive offset can remain effective during power failure, while an active damper depends on control and inspection.

The engineering decision should state trade-offs rather than hiding them; a larger low-velocity silencer can reduce both regenerated noise and energy relative to a compact high-loss unit, but capital and spatial costs increase; whole-life comparison should include filter loading, cleaning, replacement access and fan energy.

24.36 Submittals and procurement control

A silencer or terminal submittal should provide complete band data, test method, specimen dimensions, flow, pressure loss, generated sound, orientation and model identification; a fan submittal should provide mapped sound power at the selected operating point, installation category, speed and accessories. Duct construction submittals should identify gauge, reinforcement, joint, seal class, liner, access doors and supports. Generic catalogue excerpts are insufficient.

Substitution review should compare the complete system; a shorter silencer with equal headline insertion loss may have greater regenerated noise or pressure drop; a terminal with lower published NC may use different room assumptions; a fan with better A-weighted sound may have a stronger low-frequency tone. The review should use band data and the path model.

Contract language should state who owns the path calculation, who verifies operating points, who supplies test reports, who performs TAB, who conducts acoustic commissioning and how nonconformance will be corrected; vague requirements such as “provide sound attenuators as required” shift design responsibility without defining acceptance.

Table 24-3. Silencer selection and evidence requirements.

Selection issue	Required evidence	Frequent error	Consequence
Insertion loss	Complete band report for exact size and configuration	Using family maximum or one weighted value	Uncontrolled speech-relevant band
Regenerated noise	Band sound power at passage velocity and flow direction	Evaluating insertion loss alone	Silencer becomes dominant source
Pressure loss	Test data at operating flow and density	Using gross rather than free-area velocity	Fan speed increase and higher source sound
Casing performance	Construction and breakout evidence	Assuming in-duct loss controls casing radiation	Parallel ceiling-void path

Selection issue	Required evidence	Frequent error	Consequence
Installation	Required straight lengths, transitions and orientation	Elbow directly at splitter face	Turbulence, maldistribution and lost performance
Fire and hygiene	Compatible construction, access and maintenance	Field modification of facing or media	Safety, contamination and acoustic degradation

24.36.1 Minimum technical content of an equipment sound submittal

A publication-grade submittal should identify the source standard, laboratory, report number, specimen, operating point and uncertainty or conformance statement; for a fan, the report distinguishes inlet, outlet and casing sound power and states the installation category; for a silencer, it states casing size, passage size, splitter construction, flow direction, velocity, insertion loss, generated sound and total pressure loss. For a terminal unit, it distinguishes discharge and radiated components; for a diffuser or grille, it states neck size, flow, pressure and damper condition.

The reviewer should reject tables that omit low-frequency bands needed by the room model; a single NC, RC, dBA or weighted sound-power value is not sufficient where speech transmission, tones or heavy construction are important; the source data should be supplied in machine-readable form so that transcription can be checked. If the manufacturer provides only plotted curves, the uncertainty introduced by digitisation should be recorded.

Product identity continues into procurement. The purchase order should preserve model suffixes, casing gauge, media facing, splitter count, orientation and accessories; a field substitution described as “equal” can change free area, pressure loss and regenerated noise while leaving the marketing family name similar. Receiving inspection should compare labels and dimensions with the approved submittal before the product disappears above a ceiling.

Worked example 24.43A. Detecting an incomplete silencer submittal

A proposed silencer report lists insertion loss of 8, 19, 31 and 36 dB at 125, 250, 500 and 1,000 Hz, but omits 63, 2,000, 4,000 and 8,000 Hz, regenerated noise, pressure loss and passage velocity. The room path model is controlled at 2,000 Hz and the mechanical design requires 5.5 m/s passage velocity; no defensible room prediction can be completed; the correct disposition is not to interpolate silently, but to request complete data or test the proposed configuration.

24.36.2 Specification language and acceptance hierarchy

A performance specification should define the measurand, frequency range, operating states, source configuration, receiving positions, uncertainty and decision rule; prescriptive clauses then identify geometry, routing, lining, silencers, supports and sealing. The two approaches must agree. A prescriptive silencer cannot be declared acceptable merely because it matches length if the scheduled performance is not met; conversely, a performance result obtained by an unapproved route may violate fire, hygiene or maintenance requirements.

Acceptance should proceed in layers. Product submittal acceptance confirms evidence, not field performance; installation inspection confirms visible configuration, not room consequence; TAB confirms airflow and controls, not acoustic isolation; component and path tests establish installed transfer. Whole-room and speech tests establish the configured room condition. The competent authority then decides formal use. Combining these stages into one “acoustic acceptance” signature obscures responsibility.

A correction plan should identify who pays for retest when a path fails; without a defined rule, parties may debate whether the fan, silencer, duct installer, controls contractor, ceiling contractor or acoustical designer owns the deficit; the path model and inspection record provide a rational basis for allocation.

24.38.1 Commissioning source protocols

Commissioning sources should be selected for the question; broadband noise is efficient for measuring band attenuation; sweeps help identify tones and resonances. Speech-shaped noise supports privacy screening. A calibrated loudspeaker in the room represents coupling through terminals more realistically than an in-duct source, while an in-duct source isolates downstream elements. Both may be needed.

Source level and position should be repeatable; a loudspeaker placed directly beneath a return grille can create an extreme local coupling that may represent a credible occupant position or may be an artificial challenge. The report should state which. Multiple source positions prevent one favourable room mode from dominating the result.

The source should remain within linear operating limits; high levels can rattle dampers, excite nonlinear joints or overload microphones; those responses may be useful diagnostic evidence, but they should not be mixed with ordinary linear transfer without disclosure.

Worked example 24.45A. Source-stability uncertainty

A commissioning loudspeaker varies by 0.7 dB standard deviation across repeated source checks. Microphone calibration contributes 0.3 dB, and spatial repeatability contributes 0.9 dB. Treating these independent for a screening calculation,

$$u_c=\sqrt{0.7^2+0.3^2+0.9^2}=1.18\,dB.$$

With coverage factor $k=2$, expanded uncertainty is approximately 2.36 dB. If source drift is correlated between upstream and downstream measurements, some cancellation may occur; the measurement model should state the covariance rather than assuming independence.

24.38.2 Functional challenge tests

A challenge test deliberately changes one state to confirm control and path behaviour; examples include commanding minimum and maximum VAV flow, closing a return damper, changing fan speed, simulating a loaded filter, switching off masking, opening a ceiling access panel or temporarily sealing a terminal. The test should have a predicted outcome; a change without a prediction is observation, not a discriminating experiment.

Life-safety and equipment limits control the challenge; fire and smoke dampers should be operated under approved procedures; fans should not be driven outside mapped limits; temporary seals must be removed and documented. Controls should be returned to baseline and verified.

24.39.1 Configuration drift after tenant work

Tenant alterations frequently add data cabling, displays, sprinklers, diffusers and access panels; a contractor may move a terminal, shorten a lined duct, remove a baffle or cut a new opening through a return plenum; the acoustic effect can be disproportionate to the apparent scale of the work.

Change control should require review before work penetrates the protected boundary or modifies a service path; the penetration register, duct route drawings and commissioning baseline make that review practical; after work, targeted inspection and testing should focus on the changed path rather than repeating every original test without analysis.

Worked example 24.46A. Post-alteration path update

A new ceiling return adds a parallel path predicted at 32 dB receiving level. The prior HVAC total was 27 dB. New combined level is

$$L_{\Sigma} = 10\log_{10}\left(10^{2.7} + 10^{3.2}\right) = 33.2\,dB.$$

The new path increases the HVAC total by 6.2 dB and becomes dominant; the calculation shows why a seemingly minor terminal addition requires acoustic review; final performance still depends on measured coupling and background.

24.37 Construction surveillance and hold points

Ductwork becomes concealed above ceilings and inside shafts; surveillance should record joints, sealant, liner continuity, silencer orientation, splitter condition, access doors, damper installation, flexible connectors, supports, penetration seals and terminal boots before closure; photographs need location identifiers and scale. A collection of unlabeled ceiling photographs is not an as-built record.

Hold points should precede silencer enclosure, shaft closure, firestop concealment, ceiling installation and final equipment connection; the inspector should verify that flexible connectors are slack, isolators are free, hangers match the design, ducts do not contact walls, and service penetrations are sealed. Damper access must remain available.

Worked example 24.43. Risk-based inspection allocation

A project has 180 ordinary duct joints, 24 silencer connections, 18 wall penetrations and 8 fire/smoke dampers. The plan samples 20 per cent of ordinary joints and inspects all high-consequence items:

$$N = 0.20(180) + 24 + 18 + 8 = 86.$$

The plan inspects 37 per cent of listed items but covers every silencer, penetration and damper; sampling does not prove the uninspected joints are compliant; it documents a risk-based control; clustered defects or one crew's poor work may require expanded inspection.

24.38 TAB, controls and acoustic commissioning

Testing, adjusting and balancing establishes airflow, pressure and component settings. Acoustic commissioning depends on those records because sound generation and attenuation change with flow. The final TAB report should include fan speed, system pressure, branch flows, damper positions, terminal settings and filter condition. Acoustic tests performed before balancing do not represent the accepted system.[25]

Controls create multiple states. Minimum-flow, maximum-flow, economiser, night setback, warm-up, purge, smoke control and failure modes should be listed; not every state requires a full acoustic campaign, but credible occupied and quiet-risk states must be tested; the state matrix identifies which measurements, observations and challenge tests apply.

25 MB-1158. SMACNA, HVAC Systems Testing, Adjusting & Balancing, 4th ed.

Figure 24-8. Commissioning must sample credible HVAC operating states rather than one favourable setting

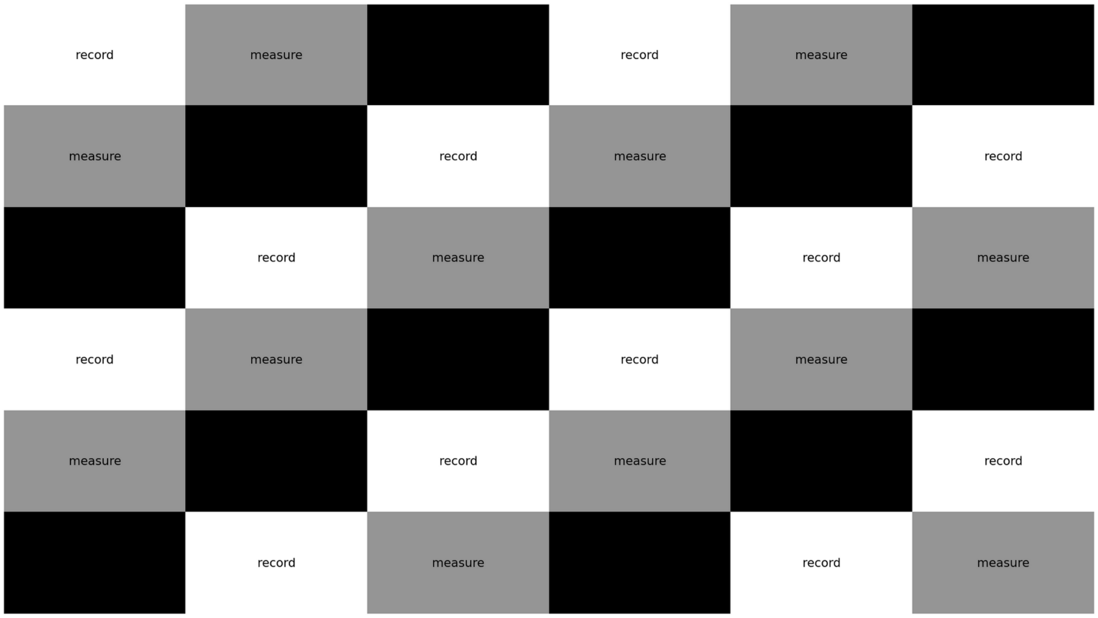

Figure 24-8. Commissioning must sample credible HVAC operating states rather than one favourable setting. Author's original diagram.

Worked example 24.44. Commissioning-state coverage

Six operating states and six evidence categories create 36 possible cells; the plan requires full acoustic measurement in normal occupied, quiet-hour and maximum-flow states, yielding 18 cells; the remaining states receive configuration and pressure records, adding 9 cells. Coverage is 27 of 36 cells, or 75 per cent; this percentage is administrative, not proof of adequacy. The omitted cells must be justified by risk and system logic.

Controls should preserve acoustic configuration. A software update that changes minimum VAV flow or fan-pressure reset can change room noise and cross-talk. Configuration management should treat relevant setpoints as part of the acoustic baseline.

24.39 Maintenance, filter loading and lifecycle drift

Filters load, belts wear, bearings degrade, dampers loosen, flexible connectors stiffen, liners erode and access-door gaskets compress. Dust can obstruct perforated facings. Ceiling work can move flexible duct or remove liner. Fire-damper inspection can disturb seals. The system after five years is not automatically the commissioned system.

A lifecycle programme records fan speed, pressure, selected band levels, vibration, filter differential, damper position and visible condition; trend changes should be interpreted together; an increase in fan speed with stable room level can indicate compensating attenuation; stable fan speed with a new tone suggests mechanical degradation.

Worked example 24.45. Detecting lifecycle drift

Baseline 250 Hz room level is 28.0 dB with repeatability standard uncertainty 0.8 dB; a later measurement is 31.0 dB under matched state. Difference is 3.0 dB. If independent standard uncertainties are both 0.8 dB, difference uncertainty is

$$u_{\Delta}=\sqrt{0.8^2+0.8^2}=1.13\,dB.$$

The change is about 2.65 standard uncertainties, sufficient to trigger investigation but not by itself to identify cause. Fan spectra, damper state, filter pressure and casing vibration should be compared.

24.40 Forensic failure analysis

Forensic investigation begins with the reported condition: what was heard, where, when, under which system state and by whom; the investigator preserves controls history, work orders, TAB reports, drawings, submittals and prior test data; a broad room-to-room test establishes the deficit; targeted measurements discriminate paths.

The sequence should minimise alteration. First record baseline room, duct and vibration data; then apply reversible interventions: temporary terminal seal, damper position, fan speed, removable duct plug, added casing mass, support isolation or access-door seal; each intervention should have a predicted spectral effect. A change inconsistent with the prediction weakens the hypothesis.

Causation must distinguish defect, mechanism and consequence; a torn liner is a condition; reduced duct attenuation is a mechanism; recoverable speech at an authorised receiving position is a consequence. A report should not leap from visible damage to security compromise without connecting these levels.

24.40.1 Evidence preservation and intervention order

The first site visit should preserve the system before controls are reset or contractors open ceilings; trend logs, alarms, setpoints and actuator positions can be lost quickly; microphone, accelerometer and in-duct data should use synchronised time; photographs should identify terminal, damper, silencer and support locations against the drawings.

Interventions proceed from least intrusive to more intrusive; operational changes come first, followed by temporary terminal covers, removable duct plugs, added gasket compression, temporary mass and reversible support changes; destructive opening follows only when earlier evidence justifies the location and the structural, fire and contamination risks have been assessed.

Chain of custody is proportionate to likely use; a routine commissioning correction needs an engineering record; a disputed construction defect or suspected compromise may require sealed samples, instrument logs, file hashes and independent witnesses; the report should state which level was applied.

Worked example 24.46. Selecting the next diagnostic test

Three path hypotheses have prior plausibilities 0.50 for return cross-talk, 0.30 for casing breakout and 0.20 for structural vibration; a temporary return block is expected to produce a large change with probabilities 0.85, 0.10 and 0.05 under the respective hypotheses. The overall probability of a large change is

$$P(E)=0.50(0.85)+0.30(0.10)+0.20(0.05)=0.465.$$

If a large change occurs, Bayes' rule gives return-path posterior

$$P\left(H_R \vee E\right)=\frac{0.50(0.85)}{0.465}=0.914.$$

The illustrative calculation shows why a discriminating reversible test has high value. The numerical priors and likelihoods require expert justification and should not be fabricated for a formal case.

24.40.2 Remediation verification

Repair verification should compare matched states, not merely before-and-after calendar dates; fan speed, flow, filter condition, background, doors and furnishings should be controlled; the repair can shift the dominant route, so the complete spectrum and spatial map must be reviewed. A 12 dB local improvement at one terminal may yield only 2 dB room improvement if casing breakout then controls.

Documentation should record removed materials, new products, serial numbers, installation photographs and changes to controls; the as-built path model is updated; a future maintenance team should be able to identify why a particular silencer, offset or support was installed without access to private oral history.

24.41 Integrated design case: secure conference suite

A new conference suite occupies one floor of a concrete office building. The protected room requires 1.8 m^3/s supply and equal return. The supply branch connects to a common air-handling unit; the return originally entered a shared ceiling plenum. The wall and door assemblies provide strong direct isolation, but the mechanical concept would create a short return cross-talk route to an adjacent support office.

The design replaces the shared return plenum with a dedicated duct extending beyond the controlled zone; a cross-talk silencer is placed where passage velocity remains below the manufacturer's low-regeneration data point; the supply silencer is selected from complete ASTM E477 data. Both routes include lined sections, but the design does not count uncertain field lining as the sole control; VAV boxes are located outside the protected ceiling and mounted on isolated supports. Terminals use low pressure drop and no integral balance damper at the neck.

The path budget includes ordinary speech, maximum unamplified vocal effort and installed loudspeaker programme; at each band, the supply and return routes are calculated separately, then combined with door, wall, glazing, ceiling and structural paths; the receiving corridor is evaluated in daytime and quiet-hour background. The return route governs at 500 Hz during fan-off condition; a motorised isolation damper could improve that state but would create reliance on control logic and life-safety coordination. The design instead lengthens and offsets the passive route.

Construction surveillance verifies silencer orientation, duct joints, penetration seals, flexible connectors and terminal boots; TAB establishes normal and maximum flow; commissioning tests fan-on, fan-off, minimum-flow and maximum-flow states; a temporary terminal block confirms the return route contribution. Whole-room speech testing then evaluates occupied consequence. Formal use remains subject to the competent authority; the engineering record does not claim accreditation.

Worked example 24.47. Integrated return-path budget

Source coupling into the return is 80 dB in a critical band; losses are 6 dB at the terminal, 9 dB in lined duct, 24 dB through the silencer, 5 dB at two elbows and 7 dB at the receiving terminal. Estimated receiving-terminal sound power is

$$L_W = 80 - 6 - 9 - 24 - 5 - 7 = 29\, dB.$$

Casing breakout contributes 24 dB locally and supply cross-talk 22 dB. Combined HVAC contribution is

$$10\log_{10}\left(10^{2.9} + 10^{2.4} + 10^{2.2}\right) = 30.8\, dB.$$

If quiet-hour background is 25 dB, the HVAC residual warrants speech-consequence testing. The calculation identifies the need for evidence; it does not establish intelligibility.

24.42 Failure case: return-air cross-talk

A renovated legal meeting room used a deck-to-deck wall and acoustic door, but both rooms returned air to one ceiling plenum; daytime field testing appeared satisfactory because fan and office noise masked the route; after hours, occupants in the adjoining room recognised names and dates. The original test had not included fan-off or quiet-hour states.

A controlled source in the meeting room produced elevated levels at both return grilles; temporary sealing of the receiving grille reduced upper-band levels by 11 dB; ceiling inspection showed no plenum barrier; the corrective design installed dedicated return ducts with an offset cross-talk silencer and sealed the wall head. Retesting under fan-on and fan-off states reduced the route below the room's other boundaries.

The institutional lesson is that ceiling attenuation and wall STC do not cure a shared air volume. Background during one test state must not be mistaken for path attenuation.

24.43 Failure case: silencer regenerated noise

A high-performance silencer was installed downstream of a variable-air-volume air handler; at design drawings, the gross velocity appeared acceptable; field inspection found that thick splitters reduced free area much more than assumed, and a transition created maldistribution. At maximum flow, regenerated sound controlled 1 and 2 kHz room levels; the fan source itself was well attenuated.

Reducing flow corrected noise but compromised ventilation; the remedy replaced the silencer with a larger casing and lower passage velocity, added straight inlet length and rebalanced branches; the case demonstrates why insertion loss, free-area velocity, pressure drop and regenerated sound must be evaluated together.

Worked example 24.48. Free-area correction in the failure case

Gross area was $0.90\,m^2$, but splitters left $0.52\,m^2$. At $3.6\,m^3/s$, design gross velocity was 4.0 m/s, while actual passage velocity was

$$V=\frac{3.6}{0.52}=6.92\,m/s.$$

The 73 per cent increase explains why regenerated-noise data at 4 m/s were not applicable.

24.44 Failure case: duct bridge and casing breakout

A rooftop fan served a secure briefing room through a long duct and effective silencer; room measurements nevertheless showed a low-frequency tone; duct pressure downstream of the silencer was modest, but ceiling vibration and wall-head acceleration were high. Inspection found the silencer casing rigidly supported from a steel beam continuing into the room wall, and the flexible connector had been installed taut.

Releasing connector tension and inserting properly loaded isolation at the support reduced the tone; added duct lagging alone had produced little improvement because the dominant route was structural; the case shows why airborne and structure-borne models must be tested separately.

24.45 Technical schedules

Table 24-4. Commissioning state matrix.

State	Airflow and controls record	Acoustic measurements	Diagnostic challenge	Acceptance use
Normal occupied	Fan speed, branch flow, terminal command, pressure	Room spectra, duct stations, terminal levels	None unless anomaly appears	Primary operational evidence
Quiet-hour occupied	Night reset, minimum fan state, background distribution	Speech residual and receiving background	Fan-off/on comparison	High-risk audibility condition
Maximum flow	Fan map point, damper positions, passage velocity	Regenerated noise, terminal and casing levels	Silencer and damper hotspot scan	Robustness and comfort
Minimum flow	Throttling position, VAV minimum, fan pressure reset	Damper and terminal tones	Local control override	Low-flow failure mode

State	Airflow and controls record	Acoustic measurements	Diagnostic challenge	Acceptance use
Fire or smoke mode	Damper and fan command, pressure relationship	Configuration and damage observations	No unsafe acoustic intervention	Change-control evidence
Filter-loaded	Differential pressure, fan command, flow	Source and room spectra	Compare clean-filter baseline	Lifecycle drift

Table 24-5. Lifecycle inspection, maintenance and forensic controls.

Item	Baseline record	Degradation indicator	Corrective evidence
Fan and motor	Speed, flow, pressure, band sound power, vibration	New tone, modulation, bearing or balance change	Repair record and matched-state retest
Silencer	Model, orientation, velocity, pressure loss, photographs	Media damage, splitter movement, rising regenerated noise	Inspection, pressure and acoustic retest
Duct casing	Gauge, reinforcement, access doors, vibration map	Oil-canning, loose panels, gasket leakage	Local intensity and post-repair survey
Flexible connector	Slack geometry, clearances, crossing services	Taut fabric, rigid bypass, cracking	Photographs, vibration transfer comparison
Dampers	Type, position, actuator, leakage and access	Blade looseness, throttling noise, failed command	Functional test and spectral comparison
Terminals	Neck size, flow, damper, room location	Dirt, altered blades, moved furniture, whistle	TAB check and room measurement
Filters	Type and clean differential pressure	Rising pressure, fan-speed increase	Clean/loaded comparison and control trend
Penetrations	Sleeve, seal, firestop and movement detail	New cables, failed seal, duct contact	Controlled opening, repair and retest

The schedules are control frameworks, not universal acceptance criteria. Project-specific requirements, risks and authorities must be added.

24.46 Conclusions

HVAC acoustics is governed by a network of airborne, casing-radiated and structure-borne paths; fan sound power, silencer insertion loss, terminal ratings, duct construction and room background are distinct pieces of evidence; they become useful only when assembled in a band-by-band source-path-receiver model tied to actual flow, control and maintenance states.

A silencer can attenuate fan sound and still fail through regenerated noise, pressure loss, casing bypass or poor installation; a quiet terminal can provide a direct cross-talk opening; a compliant duct can radiate through a weak access door. A flexible connector can be defeated by one rigid service; fire and smoke devices cannot be altered for acoustics without preserving their listed function.

The complete proof sequence therefore runs from verified laboratory source data through design path budgets, construction surveillance, TAB, installed measurement, occupied speech assessment and formal authority disposition; the result belongs to the configured system and state; it is not transferred automatically from a catalogue, a fan certificate or a single room-noise reading.

24.47 Chapter 24 glossary

Air terminal. A device at the end of a ducted air-distribution path, including diffusers, grilles, registers and terminal units.

Blade-passing frequency. Rotational frequency multiplied by the number of fan blades, often producing a tonal component.

Break-in. Transmission of external sound through a duct or plenum casing into the internal air path.

Breakout. Radiation of in-duct sound through duct or plenum casing into the surrounding space.

Cross-talk. Transmission between rooms through a common duct, plenum, transfer route or connected terminal system.

Duct insertion loss. Reduction produced by inserting a duct element into a defined reference arrangement.

End reflection. Reflection at a duct termination caused by the radiation impedance mismatch between duct and surrounding space.

Fan installation category. Standardised inlet and outlet arrangement used when determining fan acoustic performance.

Free area. Net open area available for airflow after splitters, blades, frames and obstructions are deducted.

In-duct sound power. Acoustic power propagating within a duct under a defined test method and modal condition.

Passage velocity. Mean velocity through the clear passages of a silencer or terminal, which can exceed gross face velocity.

Regenerated noise. Sound created by airflow through a silencer, damper, fitting or terminal.

Silencer. A duct element intended to reduce sound propagation by dissipative, reactive or hybrid mechanisms.

Sound-power map. Band sound-power data reported across equipment operating points or configurations.

System effect. Difference between laboratory and installed fan or equipment performance caused by inlet, outlet, geometry or flow conditions.

Terminal radiated sound. Sound emitted through the casing of an air terminal into the surrounding plenum or room.

Terminal discharge sound. Sound propagated from an air terminal into the downstream duct or occupied room through the outlet.

Transfer-air path. Intentional opening or duct route that permits air movement between spaces and can also transmit sound.

Velocity pressure. Dynamic pressure associated with mean airflow, commonly used in duct-system calculations.

Whole-path budget. Band-by-band accounting of source, attenuation, generated sound, radiation, receiving correction and uncertainty for every credible path.

Chapter 25. Plumbing, Sprinklers, Electrical Conduits, Data Pathways, and Fire-Stopping Interfaces

A secure boundary is rarely defeated by the broad wall field. It is defeated by the lawful services that must cross it, the supports that tie isolated elements together, the sleeves that are enlarged during installation, and the later cable or pipe that is added after the original evidence has faded. Plumbing, sprinklers, conduits, trays, boxes and fire-stopping systems must therefore be designed as a coordinated three-dimensional network whose acoustic, structural, fire, smoke, electrical, moisture and maintenance duties remain visible.

The chapter preserves four distinct propositions. A listed fire-stop system addresses a defined fire exposure and configuration; an acoustical treatment addresses pressure or vibration transfer; a field test addresses the installed condition under the measured state; formal acceptance remains with the competent project and security authorities. No certificate, sealant label or inspection sticker collapses those propositions into one.

Figure 25-1. A service crossing is a coupled path through the medium, supports, sleeve, treatment and receiving structure. Author's original diagram.

25.1 Services as coupled acoustic and life-safety systems

Every pipe, conduit and cable route couples a protected room to another space, a shaft, a riser, a plant area or the exterior. The route may carry airborne pressure through an open bore, structural vibration through a rigid support, or both at once. The same opening may also be required to resist fire, smoke, water, pests, pressure and unauthorised access. [26][27][28][29]

26 MB-1250. U.S. Department of Defense, UFGS 07 84 00, Firestopping.
27 MB-1029. National Fire Protection Association, NFPA 13, Standard for the Installation of Sprinkler Systems.
28 MB-1231. U.S. Department of Defense, UFC 3-520-01.
29 MB-1235. U.S. Department of Defense, UFC 3-580-01.

The physical path includes the service medium, the wall or slab opening, the sleeve, annular materials, support spacing, bends, terminations and the receiving structure; a water-filled pipe can transmit longitudinal and bending motion well beyond the nearest wall. An empty conduit can behave as a narrow waveguide; a cable bundle can leave connected voids through an otherwise substantial fire-stop; within services as coupled acoustic and life-safety systems, the decisive analysis follows the complete source-path-receiver chain and records each interface capable of carrying pressure, force, information or measurement bias.

The boundary schedule should identify every service crossing by stable identifier and should allocate acoustic closure, fire listing, structural support, electrical or communications function, inspection access and future capacity. Grouping services can reduce the number of openings, but it concentrates consequence and demands a maintainable modular treatment. The design record for services as coupled acoustic and life-safety systems should translate those mechanisms into dimensions, products, tolerances, support conditions, inspection stages and named ownership.

Verification begins with coordinated drawings and continues through sleeve inspection, support inspection, material identity, annular dimensions, photographs, field labels, continuity checks and targeted acoustic measurements; the evidence record should distinguish the opening, the service, the fire system and the separate acoustic treatment. A visually complete escutcheon or finished ceiling proves almost nothing about the concealed annulus, backing depth or support bridge; evidence concerning services as coupled acoustic and life-safety systems should identify the exact observed unit, method, instrument chain, state, limitations and inference supported.

Worked example 25.1. Small opening dominates a high-isolation boundary

A 24 m^2 boundary has idealised field transmission loss of 60 dB. A service slot is 2 mm by 0.8 m, giving area 0.0016 m^2. Treat the slot conservatively as an open path and combine area-weighted transmission coefficients.

Here, tau_c is the composite power-transmission coefficient, R_c is the idealised composite transmission loss in decibels, and the two areas are expressed in square metres.

The calculated composite loss is approximately 41.7 dB. The slot occupies only 0.0067 per cent of the boundary area, yet it reduces the idealised result by more than 18 dB.

The open-slot model is deliberately conservative and frequency independent. Real slot impedance varies with width, depth, lining, terminations and incidence.

25.2 Domestic water and hydronic piping

Water services introduce both airborne and structure-borne risks. Flow noise, valve turbulence, pump vibration, pressure-regulator chatter and water hammer can excite the pipe wall and every rigid bracket. Conversely, protected speech can enter a lightweight pipe chase or wall cavity and re-radiate at a remote support or access panel. [30][31][32]

30 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
31 MB-0819. International Organization for Standardization, ISO 10816, ISO 20816.
32 MB-0428. David A. Bies, Colin H. Hansen and Carl H. Howard, Engineering Noise Control: Theory and Practice.

The relevant variables include pipe material, outside diameter, wall thickness, fluid state, pressure, velocity, support stiffness, span, bends, valve mass and the impedance of connected equipment; copper, steel, plastic and composite pipes do not behave alike; flexible couplings may reduce one force path while anchors, seismic restraints or closely fitted sleeves preserve another. For domestic water and hydronic piping, the mechanism must be traced from excitation through materials, supports, openings, controls and adjoining spaces rather than inferred from the trade name of one component.

Routing should avoid unnecessary boundary crossings and should place valves, clean-outs and maintenance points where access does not require repeated disturbance of the protected envelope; supports should be owned by the mechanical design and coordinated with structural, seismic, fire and acoustic requirements. A resilient support must carry its actual static load without bottoming and must retain required movement clearance; accordingly, domestic water and hydronic piping require a controlled configuration with stable identifiers, coordinated details, access provisions and change triggers that remain usable after handover.

Inspection should record pipe and sleeve dimensions, support type and load range, clearances, flexible connections, anchor locations, water state and operating modes; commissioning should include pumps off and on, low and high flow, valve operation, pressure changes and representative maintenance states. A quiet test with an empty pipe does not represent a pressurised, flowing or thermally moving system; verification of domestic water and hydronic piping should combine documentary reconciliation, direct observation and measurement without allowing one evidence class to substitute silently for another.

Worked example 25.2. Support natural frequency and operating ratio

A pipe and valve segment imposes supported mass m = 180 kg on resilient elements with combined vertical stiffness k = 2.8 x 10^6 N/m. Estimate the undamped natural frequency and the frequency ratio at a 50 Hz pump tone.

The symbol f_n is natural frequency in hertz, k is combined stiffness in newtons per metre, m is supported mass in kilograms, and r is dimensionless frequency ratio.

The natural frequency is about 19.9 Hz and r is about 2.51. The support lies above the resonance region at 50 Hz, but its practical isolation still depends on damping, preload, restraints, pipe flexibility and installation bridges.

The calculation is a single-degree screening model. Distributed pipe modes, horizontal stiffness and hydraulic forcing require separate analysis.

25.3 Drainage, vents, traps and open terminations

Drainage systems create discontinuous but consequential paths. Wastewater impact, falling columns, entrained air, trap motion and stack excitation produce sound. Open vents and poorly sealed clean-outs can also provide a pressure path between rooms, shafts and roofs. The route changes with water level, trap seal, occupancy and maintenance. [33][34][35]

A drain is not acoustically closed merely because it contains a trap; traps control gases under defined water-seal conditions, not broadband sound

33 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
34 MB-0428. David A. Bies, Colin H. Hansen and Carl H. Howard, Engineering Noise Control: Theory and Practice.
35 MB-1033. National Fire Protection Association, NFPA 72, National Fire Alarm and Signaling Code.

transmission; plastic pipe can radiate strongly through lightweight shafts, while cast iron may reduce airborne radiation yet transmit support force. Roof and exterior terminations may become accessible receiver points within an authorised threat model; the engineering model for drainage, vents, traps and open terminations should identify which physical variables change with frequency, operating state, loading, access, maintenance and environmental condition.

The design should separate noisy stacks from sensitive boundaries, use suitable pipe mass and enclosure construction, provide resilient support where compatible, seal penetrations, and preserve access without removable weak panels. Condensate, relief and overflow routes must be considered alongside sanitary systems because their small diameter can invite informal field drilling. Design development should assign every consequential interface in drainage, vents, traps and open terminations to a responsible discipline and should resolve acoustic, structural, fire, accessibility and service obligations together.

Testing should include representative discharge, fixture use, pump cycles and quiet-state listener positions; inspection should confirm trap and clean-out condition, chase continuity, shaft barriers, roof penetrations and the path from room to termination; a room-pair airborne test may not reveal an intermittent drainage event or an exterior vent path unless the state is deliberately exercised. The acceptance record for drainage, vents, traps and open terminations should preserve raw data, calibration, photographs, dimensions, processing and the decision rule needed for later reproduction.

25.4 Fire sprinkler piping, flexible drops and seismic restraints

Sprinkler systems are mandatory life-safety infrastructure and must never be acoustically modified outside the responsible fire-protection design. Their water-filled branches, mains, hangers, braces, flexible drops, valves and alarms can nevertheless transmit vibration or create boundary openings. The acoustic task is coordination, not unilateral alteration. [36][37][38]

A branch crossing a resilient wall can short-circuit the leaves if the sleeve, pipe, escutcheon or brace touches both sides; a flexible drop can reduce movement transfer to a ceiling device, but the main branch and seismic restraint remain force paths. Flow tests, alarm valves and pumps introduce operating states that may be absent during routine room commissioning; a credible treatment of fire sprinkler piping, flexible drops and seismic restraints distinguishes direct transmission, structural coupling, connected air paths, regenerated sound and observational uncertainty before selecting a remedy.

The preferred strategy is to minimise crossings, maintain tested clearances, locate braces and hangers on appropriate structure, and preserve listed or engineered fire-stop geometry; ceiling systems must accommodate sprinkler movement without connecting isolated grids; any enclosure or treatment must preserve discharge pattern, inspection, drainage, temperature rating and access. The project documents should make fire sprinkler piping, flexible drops and seismic restraints buildable and

36 MB-1029. National Fire Protection Association, NFPA 13, Standard for the Installation of Sprinkler Systems.
37 MB-0223. ASTM International, ASTM E2174-24, ASTM E2393-24.
38 MB-1236. U.S. Department of Defense, UFC 3-600-01.

inspectable by defining geometry, sequence, acceptable variation, substitute evidence and the point at which concealment is prohibited.

Records should show hydraulic and seismic design interfaces, sleeve size, listed system, support and brace locations, flexible-drop model, ceiling relationship, photographs before closure and the final inspection disposition. Acoustic tests should not impair system availability or substitute for fire inspection. A favourable vibration result cannot waive NFPA, code, listing or authority requirements. A favourable observation of fire sprinkler piping, flexible drops and seismic restraints remains bounded to the inspected population and measured state, while unseen conditions and untested modes associated with fire sprinkler piping, flexible drops and seismic restraints remain explicit limitations.

Worked example 25.4. Annular area available for a sprinkler crossing

A 33.4 mm outside-diameter branch passes through a 75 mm circular sleeve. Calculate the gross annular area before packing, fire-stop and any acoustic backing are installed.

A_a is annular area, D_s is sleeve inside diameter and D_p is pipe outside diameter. All diameters must use the same units.

Using metres, the annular area is approximately 0.00354 m^2, or 3,540 mm^2. That area is large enough to become an important pressure path if the specified system is incomplete.

Area alone does not determine acoustic transmission or fire performance. Depth, backing, material, movement, temperature and listing geometry govern the installed system.

25.5 Electrical conduits, boxes and panelboards

Metallic and non-metallic conduits can connect boxes, cabinets, panels, floor systems and equipment across the boundary. The bore may transmit pressure, while the conduit wall, straps and rigid couplings transmit vibration. Back-to-back boxes reduce local mass and can create a direct cavity route even when neither conduit passes entirely through the wall. [39][40][41]

Large panelboards and device boxes require backing, access and cable space, making them frequent weak regions; a metal box can stiffen a panel locally and radiate at its edges; putty pads or listed box treatments can restore mass and closure only within their approved configurations. They do not automatically solve an open conduit or a rigid bridge; analysis of electrical conduits, boxes and panelboards begins by mapping the actual configuration, because small differences in geometry, restraint, continuity or software state can reverse the dominant path.

Design should offset boxes, avoid shared studs where possible, cap or seal spare conduits under controlled methods, maintain leaf independence and provide dedicated pathways for expected growth; grounding, bonding, conductor fill, heat, pull tension and electrical code duties remain controlling. Acoustic details should be drawn at full interface scale rather than hidden in generic notes; a robust specification for electrical conduits, boxes and panelboards combines performance language with prescriptive detail wherever the mechanism cannot be verified from a final single-number test.

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39 MB-1231. U.S. Department of Defense, UFC 3-520-01.
40 MB-1032. National Fire Protection Association, NFPA 70, National Electrical Code.
41 MB-0186. ASTM International, ASTM C919-24, ASTM C920-18.

Inspection should record box type, size, location, backing, conduit route, fill, cap or seal, listed treatment and photographs before board closure; later changes require permit screening because a small new conduit can invalidate both the fire and acoustic baseline. Continuity of an electrical bonding path is not evidence of acoustic continuity, and acoustic closure is not evidence of electrical compliance; testing of electrical conduits, boxes and panelboards should report band data and operating conditions before any summary rating, so that background, flanking, drift and method scope can be examined.

25.6 Data, fibre and communications pathways

Communications systems encourage dense bundles, large sleeves, cable trays and frequent change. Fibre reduces conductive signal paths but does not remove the physical opening, the support bridge, the possibility of an electronic transducer, or the need for network and supply-chain controls. Copper, coaxial, fibre and hybrid cables carry different installation constraints yet share the boundary problem. [42][43][44]

Cable bundles create irregular annuli and can prevent uniform backing depth; tray crossings can require large rectangular openings and can rigidly connect structure on both sides; spare capacity is valuable only when it is provided through a maintainable modular system whose fill limits, fire rating, acoustic closure and inspection state remain controlled. The controlling behaviour of data, fibre and communications pathways is system dependent and cannot be reduced to one catalogue value when adjacent construction and services participate in the measured response.

42 MB-1235. U.S. Department of Defense, UFC 3-580-01.
43 MB-1032. National Fire Protection Association, NFPA 70, National Electrical Code.
44 MB-0881. International Organization for Standardization, ISO 19650.

The pathway design should assign zones, routes, sleeves, tray supports, bend radii, separation, grounding or bonding, fire-stop modules, future capacity and access ownership; a protected room should not depend on ad hoc drilling whenever equipment changes; unused pathways should be closed, labelled and included in the change register. Procurement and submittal review should preserve the tested or approved identity of data, fibre and communications pathways, including the features whose alteration would invalidate comparison with the supporting evidence.

Verification should compare installed cable count and size with the approved register, inspect module or seal fit, confirm tray discontinuity where required, and preserve photographs and labels; electronic-security review remains separate from the acoustic inspection even when the same cable creates both concerns. A fibre-only pathway is not an acoustic, cyber or physical-security exemption; where data, fibre and communications pathways are evaluated by intervention, the record should describe collateral changes and restoration duties before attributing the observed difference to one mechanism.

Worked example 25.6. Cable-fill screening for a modular sleeve

A circular sleeve has usable internal area of 8,000 mm^2. Installed cables occupy 3,100 mm^2 and the approved modular system allows no more than 55 per cent service fill for the selected arrangement.

The symbol phi is dimensionless fill ratio, A_c is total cable cross-sectional area, and A_s is usable sleeve area.

The service fill is 38.8 per cent, leaving nominal capacity within the screening limit. The remaining space is not an open void. It must be occupied by the approved modules, fillers and compression arrangement.

Cable cross-sections, module selection and listing rules govern. The arithmetic does not establish installation conformity.

Table 25-1. System, principal mechanism and required evidence.

System	Principal mechanism	Required evidence
Services as coupled acoustic and life-safety systems	The physical path includes the service medium, the wall or slab opening, the sleeve, annular materials, support spacing, bends, terminations and the receiving structure	Verification begins with coordinated drawings and continues through sleeve inspection, support inspection, material identity, annular dimensions, photographs, field labels, continuity checks and targeted acoustic measurements
Domestic water and hydronic piping	The relevant variables include pipe material, outside diameter, wall thickness, fluid state, pressure, velocity, support stiffness, span, bends, valve mass and the impedance of connected equipment	Inspection should record pipe and sleeve dimensions, support type and load range, clearances, flexible connections, anchor locations, water state and operating modes
Drainage, vents, traps and open terminations	A drain is not acoustically closed merely because it contains a trap	Testing should include representative discharge, fixture use, pump cycles and quiet-state listener positions
Fire sprinkler piping, flexible drops and seismic restraints	A branch crossing a resilient wall can short-circuit the leaves if the sleeve, pipe, escutcheon or brace touches both sides	Records should show hydraulic and seismic design interfaces, sleeve size, listed system, support and brace locations, flexible-drop model, ceiling relationship, photographs before closure and the final inspection disposition
Electrical conduits, boxes and panelboards	Large panelboards and device boxes require backing, access and cable space, making them frequent weak regions	Inspection should record box type, size, location, backing, conduit route, fill, cap or seal, listed treatment and photographs before board closure
Data, fibre and communications pathways	Cable bundles create irregular annuli and can prevent uniform backing depth	Verification should compare installed cable count and size with the approved register, inspect module or seal fit, confirm tray discontinuity where required, and preserve photographs and labels

System	Principal mechanism	Required evidence
Penetration sleeves and annular geometry	The acoustic behaviour depends on open area, path length, tortuosity, material impedance, surface mass and leakage continuity	Measurements should capture actual opening, sleeve and service dimensions before installation and after completion
Fire-stopping, smoke sealing and acoustic closure	Elastomeric sealants can provide movement and airtightness, mortars can provide mass, mineral-wool backing can control depth and support, and modular devices can accommodate cable change	Inspection should follow recognised fire-stop practices while separately recording acoustic continuity, support bridges and access
Supports, hangers, braces and structural bypasses	Static strength and dynamic mobility are related but not identical	Commissioning should include vibration measurements or controlled operating contrasts where support force is plausible
Access panels, clean-outs and maintainable weak paths	The complete access assembly includes leaf, frame, anchors, latches, gasket, perimeter seal, substrate, insulation, hardware and the space beyond	Field evidence should include panel identity, dimensions, gasket contact, latch operation, perimeter treatment and local acoustic checks where consequence warrants
Pressure, moisture, condensation and corrosion interfaces	Material compatibility, vapour control, drainage, insulation continuity and movement must therefore be considered with acoustic closure	Commissioning should record pressure state, environmental conditions and moisture-sensitive locations
Penetration registers and lifecycle change control	The register permits the team to distinguish intended spare capacity from an unauthorised opening and to identify which tests predate a modification	Final validation should confirm that every register entry resolves to an installed location and that every observed opening has an entry

Chapter 25 Evidence Matrix

	Design	Submittal	Pre-closure	Test	Lifecycle
Pipe	●	●	●	●	●
Sprinkler	●	●	●	●	●
Conduit	●	●	●		●
Cable tray	●	●	●	●	●
Fire-stop	●	●	●	●	●
Access panel	●	●	●	●	●

The matrix shows where evidence must exist. A filled cell does not imply that the evidence passes its technical review.

Figure 25-2. The matrix shows where evidence must exist. A filled cell does not imply that the evidence passes its technical review. Author’s original diagram.

25.7 Penetration sleeves and annular geometry

Sleeves define the geometry upon which both fire and acoustic treatments depend. Oversized sleeves are often justified by installation convenience, but they increase unsupported area, backing demand, material depth and the opportunity for later unrecorded services. Sleeveless openings can be equally problematic where rough concrete or masonry produces irregular gaps. [45][46][47]

The acoustic behaviour depends on open area, path length, tortuosity, material impedance, surface mass and leakage continuity; fire behaviour depends on the exact tested or engineered system, including substrate,

45 MB-1235. U.S. Department of Defense, UFC 3-580-01.
46 MB-0223. ASTM International, ASTM E2174-24, ASTM E2393-24.
47 MB-0309. ASTM International, ASTM E814.

service, sleeve, annulus, backing, fill material, depth and movement. One treatment may need to be spatially coordinated with another without mixing incompatible products; for the question addressed in section 25.7, penetration sleeves and annular geometry are examined as a time-varying network whose inputs, boundaries and receiver conditions must all remain explicit.

Drawings should schedule opening and sleeve dimensions, service range, approved systems, acoustic closure, movement, corrosion, moisture and inspection access; field enlargement should require controlled approval; the team should reject a generic instruction to seal around services when several distinct assemblies and authorities are involved. For penetration sleeves and annular geometry, the room data sheet and requirement matrix should state source states, adjoining access, operating modes, lifecycle duties and the accepting authority.

Measurements should capture actual opening, sleeve and service dimensions before installation and after completion; the record should identify deviations and should reconcile the penetration register with final drawings and photographs; a listed fire-stop system installed in the wrong annular range is not rescued by an attractive surface finish. The dossier for penetration sleeves and annular geometry should distinguish as-designed, as-submitted, as-installed, as-tested, as-authorised and as-operated states.

25.8 Fire-stopping, smoke sealing and acoustic closure

Fire-stopping and acoustic sealing often occupy the same opening but answer different physical questions. Fire exposure involves heat, flame, pressure and material transformation. Acoustic transmission involves oscillatory pressure, structural motion and radiation across ordinary operating temperatures. Smoke leakage introduces another criterion. The project must preserve each claim. [48][49][50]

Elastomeric sealants can provide movement and airtightness, mortars can provide mass, mineral-wool backing can control depth and support, and modular devices can accommodate cable change. None is universally suitable. A hybrid detail must be supported by the listed or engineered fire system and by an acoustically credible continuous path treatment. The physical inquiry into fire-stopping, smoke sealing and acoustic closure separates what carries energy from what merely appears defective, thereby preserving alternative hypotheses until discriminating evidence is obtained.

The specification should identify system number, substrate, penetrant, sleeve, annular range, backing, depth, sealant, movement, inspection and repair; acoustic requirements should be placed where they can be coordinated without instructing installers to alter the fire system; mock-ups are especially valuable for congested bundles and movement joints. The design team should provide maintainable routes, inspection access and authorised replacement criteria so that later work on fire-stopping, smoke sealing and acoustic closure does not silently alter the boundary.

Inspection should follow recognised fire-stop practices while separately recording acoustic continuity, support bridges and access; where the surface can conceal incomplete depth, photographic or direct pre-closure evidence is essential; failed locations should be bounded by installer, date, detail and material lot. Passing one inspection does not establish the other

48 MB-1250. U.S. Department of Defense, UFGS 07 84 00, Firestopping.
49 MB-0223. ASTM International, ASTM E2174-24, ASTM E2393-24.
50 MB-0309. ASTM International, ASTM E814.

performance proposition; inspection and measurement of fire-stopping, smoke sealing and acoustic closure should be scheduled while the controlling condition is still observable, with missed hold points treated as missing evidence rather than acceptance.

25.9 Supports, hangers, braces and structural bypasses

The service may be perfectly sealed at the wall and still bypass the boundary through supports. Hangers attached to a shared beam, tray brackets spanning isolated leaves, pipe shoes crossing a floor joint and seismic restraints fixed through floating construction can transmit force around the treated opening. [51][52][53]

Static strength and dynamic mobility are related but not identical; a stiff support can be structurally excellent and acoustically consequential; resilient elements require correct loading, direction, natural frequency, damping, restraint and service flexibility; short flexible connectors or loose cable loops may be defeated by rigid parallel paths. Evaluation of supports, hangers, braces and structural bypasses requires a scale-appropriate model, from local joint or support behaviour through room-level and whole-building consequences.

The design should trace load paths from the service to structure and should show which elements may cross an isolation joint; structural and seismic professionals must approve supports and restraints; acoustic specialists should identify bypasses and required flexibility without assuming authority over structural safety. Details governing supports, hangers, braces and

51 MB-0819. International Organization for Standardization, ISO 10816, ISO 20816.
52 MB-0428. David A. Bies, Colin H. Hansen and Carl H. Howard, Engineering Noise Control: Theory and Practice.
53 MB-1236. U.S. Department of Defense, UFC 3-600-01.

structural bypasses should be coordinated in three dimensions, with movement, supports, penetrations, terminations and control states shown rather than left to site improvisation.

Commissioning should include vibration measurements or controlled operating contrasts where support force is plausible; inspection should record fasteners, clearances, restraint slack, spring or elastomer identification, supported weight and the final connected state; a support selected by nominal equipment weight can fail acoustically if the actual load distribution places some elements outside their working range. Reports on supports, hangers, braces and structural bypasses should separate observation, calculation, interpretation, residual alternatives and competent-authority disposition.

25.10 Access panels, clean-outs and maintainable weak paths

Services require inspection, cleaning, valve operation, cable pulling and fire-stop repair. Access panels and removable closures therefore become part of the protected boundary. A heavily rated wall can be controlled by a light, poorly gasketed panel or a ceiling tile that is routinely displaced. [54][55][56]

The complete access assembly includes leaf, frame, anchors, latches, gasket, perimeter seal, substrate, insulation, hardware and the space beyond; repeated opening changes compression and alignment; concealed latches, unlabelled panels and obstructed access encourage unauthorised improvisation during maintenance. The mechanism associated with access panels, clean-outs and maintainable weak paths should be stated in

54 MB-0428. David A. Bies, Colin H. Hansen and Carl H. Howard, Engineering Noise Control: Theory and Practice.
55 MB-1033. National Fire Protection Association, NFPA 72, National Fire Alarm and Signaling Code.
56 MB-0881. International Organization for Standardization, ISO 19650.

measurable terms, including the quantities, directions, frequency bands and operational states that could control the result.

The design should minimise access through critical boundaries, place required panels in controlled locations, specify complete assemblies and preserve tool, clearance and lighting needs. Maintenance instructions should define opening, inspection, closure, seal replacement and post-work verification. The selected treatment of access panels, clean-outs and maintainable weak paths should remain effective under credible extremes, not merely under the convenient condition used for an early demonstration.

Field evidence should include panel identity, dimensions, gasket contact, latch operation, perimeter treatment and local acoustic checks where consequence warrants; the lifecycle schedule should treat frequently opened panels similarly to doors rather than as static wall components. A panel that passed at handover can drift rapidly if its operating duty is ignored; a result for access panels, clean-outs and maintainable weak paths cannot be extended automatically to another room, product, geometry, season or software state without an explicit equivalence analysis.

25.11 Pressure, moisture, condensation and corrosion interfaces

Service penetrations experience temperature gradients, pressure differences, condensation, leakage and cleaning. A sealant that is acoustically effective when dry may lose adhesion on a contaminated pipe. A tightly enclosed cold-water line can condense within a wall. Corrosion can enlarge gaps or weaken supports. Water events can destroy absorbers and records before the defect is visible. [57][58][59]

Material compatibility, vapour control, drainage, insulation continuity and movement must therefore be considered with acoustic closure; pressurised rooms can load flexible seals and door assemblies in a preferred direction; stack effect and wind can reverse pressure across shafts and exterior routes. In pressure, moisture, condensation and corrosion interfaces, interfaces ordinarily deserve more scrutiny than uniform fields because movement, access, fasteners, penetrations and later work concentrate uncertainty there.

Specifications should identify substrates, preparation, primer, temperature, humidity, cure, movement, corrosion protection, inspection and repair; emergency access procedures should preserve life safety and damage control while recording the changed boundary and triggering restoration; where pressure, moisture, condensation and corrosion interfaces depend upon workmanship or configuration, first-of-type construction and explicit hold points should precede repetitive release.

Commissioning should record pressure state, environmental conditions and moisture-sensitive locations; lifecycle inspections should look for staining, cracking, corrosion, insulation damage and changed support contact; absence of audible leakage during one pressure state is not proof of performance under reversed or extreme conditions. Lifecycle evidence for pressure, moisture, condensation and corrosion interfaces should include

57 MB-0819. International Organization for Standardization, ISO 10816, ISO 20816.
58 MB-0186. ASTM International, ASTM C919-24, ASTM C920-18.
59 MB-0309. ASTM International, ASTM E814.

baseline indicators, maintenance criteria, event triggers and the records required to detect later drift.

25.12 Penetration registers and lifecycle change control

A penetration register is the technical memory of the boundary. It should not be compiled from recollection at handover. Each opening requires an identifier linked to location, geometry, service, approved detail, listed system, acoustic treatment, installer, inspection, images, nonconformance, test evidence, maintenance and later change. [60][61][62][63]

The register permits the team to distinguish intended spare capacity from an unauthorised opening and to identify which tests predate a modification; it also supports sampling by risk, inspection after incidents and reconciliation of drawings with the installed state. Coordinates and photographs should be sufficient to recover the opening after finishes conceal it; a secure-room assessment of penetration registers and lifecycle change control should preserve the distinction between acoustic transfer, non-acoustic security questions and the authority that ultimately decides use.

Change control should screen any new cable, pipe, sensor, tray, support, panel or repair before work; emergency work can alter sequence but does not cancel the obligation to document, reconcile, inspect and retest; a like-for-like claim requires evidence of dimensions, material, mounting and interface. The design basis for penetration registers and lifecycle change

60 MB-1235. U.S. Department of Defense, UFC 3-580-01.
61 MB-1032. National Fire Protection Association, NFPA 70, National Electrical Code.
62 MB-0881. International Organization for Standardization, ISO 19650.
63 MB-0309. ASTM International, ASTM E814.

control must identify what is fixed, what may vary, who may approve a change and what evidence is required before return to service.

Final validation should confirm that every register entry resolves to an installed location and that every observed opening has an entry; file checksums help detect later alteration of the record, but they do not prove the physical truth of the entry. A perfect register with an uninspected opening remains incomplete evidence, while a well-built opening with no durable record remains a lifecycle risk; the conclusion drawn from penetration registers and lifecycle change control must be no stronger than the measurand, sampling, uncertainty, configuration knowledge and public-source boundary permit.

Table 25-2. Release gate.

Gate	Controlling question	Minimum record	Failure response
Requirement	What outcome or bounded condition is required?	Source, owner, state and decision authority	Clarify or suspend the affected work
Configuration	What exact physical and operating state is represented?	Drawings, submittals, asset and route identifiers	Reconcile discrepancies before acceptance
Inspection	What conditions were directly observable before concealment?	Hold-point record, measurements and images	Open, reconstruct or carry a stated limitation
Measurement	What quantity was measured, where, when and with what uncertainty?	Raw data, calibration, method, state and processing	Correct the method or repeat the test
Authority	Who may accept, condition, restrict or reject the result?	Signed disposition and limitations	Do not represent technical review as authorisation
Lifecycle	What later change can invalidate the result?	Baseline, maintenance and retest triggers	Reopen review and update the controlled record

25.13 Penetration topology and the service-path graph

A service penetration should be represented as a graph rather than as a circular hole surrounded by sealant. The nodes of that graph are the source, the service medium, the service wall, each support, each change of direction, the sleeve, the annular treatment, the supporting partition or slab, the receiving cavity, the remote termination and every mechanically connected item. The edges are the available transmission mechanisms. They include airborne propagation through a bore or interstice, longitudinal stress in a pipe, flexural motion of the pipe wall, fluid-borne pressure, shear through a support, radiation from a panel, and pressure equalisation through connected boxes or ducts. This representation forces the designer to state how energy can move, where it can divide, and which intervention could discriminate one branch from another. It also reveals why a penetration that appears locally well sealed can remain acoustically weak through a rigidly clamped sleeve, a common support channel, or a connected shaft lining. [64]

The topology changes with operating state. A dry sprinkler branch, a water-filled branch, and a flowing domestic-water pipe possess different characteristic impedances; a cable tray that is initially empty may later carry a dense bundle whose jacketed conductors form connected voids through a putty or mortar treatment. A flexible hose may be compliant until installation leaves it taut; a clean-out may be gasketed when inspected but removed during maintenance; each credible state should therefore be recorded as a configuration variant within the service-path graph, not treated as a minor field note. The graph becomes especially valuable where several services share one opening because the relevant path may move from an air gap to a cable bundle, from the bundle to a metal frame, and from the frame into the partition studs.

64 MB-0056. ASHRAE, 2023 ASHRAE Handbook. HVAC Applications, Chapter 49, Noise and Vibration Control.

A practical graph need not become an elaborate finite-element model; it should identify the physical elements, dominant coupling mechanisms, measurable state variables and likely intervention points; for a pipe crossing, the minimum nodes commonly include the source equipment, upstream support, pipe segment, sleeve, seal system, downstream support and receiving enclosure. For a cable transit, the minimum nodes include source-room air, cable bundle, transit insert, metal frame, boundary assembly, receiving-room air and any connected tray; each edge is annotated with geometry, material, contact condition, estimated stiffness, expected frequency dependence and evidence status. Unknown contact is not represented as zero coupling. It is represented as an unresolved edge requiring inspection or a bounding assumption.

The graph supports design allocation. Airborne closure belongs to the annulus and any connected bore; structure-borne control belongs to supports, restraints, flexible sections and equipment isolation; fire performance belongs to the tested or evaluated firestop system in its exact substrate and penetrant configuration. Electrical, data and hydraulic function belong to their respective systems; the graph therefore prevents one trade from accepting a detail that satisfies its own node while leaving another edge uncontrolled. It also provides a disciplined basis for commissioning, because a temporary mass, clamp, seal, support release or operating-state change can be chosen to perturb one edge while holding the others as constant as practicable.

The path graph should be linked to a stable penetration identifier; that identifier appears on drawings, photographs, inspection records, test files, nonconformance reports and later work orders; coordinates alone are insufficient where ceilings, finishes or room names change. The record should include floor, room pair, boundary identifier, grid or surveyed location, elevation, service identity, sleeve identity and a durable label where permitted; in a restricted project, the public issue may use abstract identifiers while the controlled register preserves exact locations. This separation protects information without sacrificing engineering traceability.

Worked example 25.5. Parallel-path allocation across a shared sleeve

A protected boundary contains a shared sleeve with three idealised parallel paths; path A is residual open area with transmission loss R_A = 18 dB; path B is cable-bundle transfer with R_B = 34 dB; path C is frame and support transfer represented by R_C = 42 dB. For a screening calculation, assume equal normalised incident power is available to each path and combine transmission coefficients.

The variables are as follows. R_A, R_B and R_C are path transmission losses in decibels. τ_{total} is the dimensionless combined power-transmission coefficient; r_{total} is the idealised combined loss in decibels; substitution gives $\tau_{total} = 0.01585 + 0.000398 + 0.000063 = 0.01631$, and R_{total} = 17.88 dB. The nominally strongest two paths improve the total by less than 0.2 dB because the residual opening dominates; if Path A is remediated to 40 dB, the combined result becomes approximately 31.9 dB, and the cable bundle becomes controlling. The calculation demonstrates sequential dominance. It does not predict a field rating because areas, incident fields, radiation efficiency and path normalisation are simplified.

Table 25-3. Minimum service-path graph fields

Field	Engineering purpose	Typical evidence	Release condition
Stable identifier	Links physical opening to all records	Label, plan coordinate, photograph	Unique and recoverable
Source state	Defines excitation and service condition	Flow, pressure, equipment mode	Credible states bounded
Medium and geometry	Establishes wave and force paths	Material, diameter, thickness, fill	As-built dimensions recorded
Supports and contacts	Identifies structural coupling	Hanger type, clearance, restraint	Load and contact verified
Sleeve and substrate	Defines opening boundary	Sleeve material, wall or slab build-up	Exact assembly identified
Firestop system	Preserves life-safety configuration	Listing, system number, engineering judgement	Applicability confirmed
Acoustic treatment	Identifies separate pressure or vibration control	Backing, seal, boot, enclosure	Mechanism and limits stated
Inspection state	Records what was visible and when	Hold-point form, images, measurements	Concealed work accepted or limitation stated
Change triggers	Protects future validity	Spare capacity, access rules, retest criteria	Custodian and approval route assigned

25.14 Pipe-borne wave mechanics and impedance discontinuities

A pipe is simultaneously a pressure vessel, a structural beam, a cylindrical shell and, when filled, an acoustic waveguide. Those behaviours overlap. Internal pressure fluctuations act upon the pipe wall. Wall motion changes the enclosed cross-section and returns energy to the fluid. Supports convert local motion into building-borne force. Bends, valves, reducers and branches reflect and divide both fluid-borne and structural waves. Treating the pipe merely as a mass passing through a wall therefore misses the mechanism that can carry excitation for tens of metres before radiation occurs at a remote chase, bracket or thin panel. [65]

For a first fluid-borne approximation, characteristic impedance is Z_f = rho c / S, where rho is fluid density in kilograms per cubic metre, c is wave speed

65 MB-0055. ASHRAE, 2023 ASHRAE Handbook. HVAC Applications, Chapter 49, Noise and Vibration Control.

in metres per second, and S is internal cross-sectional area in square metres. A smaller bore has higher characteristic impedance; a sudden area change produces reflection; in a rigid-wall, plane-wave screening model, the pressure reflection coefficient at a junction is $\Gamma_p = (Z_2 - Z_1)/(Z_2 + Z_1)$; real building pipework departs from this model because wall compliance reduces wave speed, branches create multiport junctions, viscous losses increase with frequency, and valves introduce complex impedance. Nevertheless, the equation explains why reducers, flexible hoses and equipment connections can alter transmission rather than simply adding distance.

The pipe wall supports longitudinal, torsional and flexural waves; longitudinal wave speed in an ideal slender rod is approximately $c_L = \sqrt{E/\rho_s}$, where E is Young's modulus in pascals and ρ_s is solid density in kilograms per cubic metre. Flexural waves are dispersive. Their phase speed changes with frequency and with bending stiffness EI, where I is the second moment of area. This difference matters in diagnosis. A broad phase-coherent response between two axial points may indicate longitudinal or fluid-borne transfer, while a response that changes rapidly with frequency and support spacing may indicate flexural behaviour; the field investigator should not assign a single generic pipe transmission loss without identifying which family of motion is being measured.

An impedance discontinuity can help or harm; a properly selected flexible connector may reduce force transfer above its effective isolation range; the same connector can create a fluid-borne reflection that shifts pressure pulsation elsewhere, or it can be defeated by a parallel earth conductor, restraint rod, drain line or taut braid. A heavy valve may lower a local structural resonance while increasing the static load carried by nearby isolators; a close-fitting sleeve may short-circuit the intended compliance. The complete installation must therefore be evaluated as a network, including all parallel connections.

Routing decisions should exploit physical separation. A pipe serving a protected room should avoid common support rails with services in uncontrolled spaces; where a crossing is necessary, supports should be placed so that the penetrant does not bear upon the sleeve or annular treatment under dead load, thermal growth, seismic displacement or maintenance force. The support design should state allowable movement and should show how that movement is accommodated without tearing the firestop or closing an isolation gap; a drawing that shows a generic rubber insert without load, deflection and restraint information is not an engineered acoustic detail.

Measurement should distinguish fluid pressure, pipe-wall acceleration and receiving-surface response; a pressure transducer, accelerometer and microphone do not measure the same quantity; coherence and transfer functions can help connect them, but high coherence does not prove a unique causal path when several quantities share one source. Controlled changes, such as varying pump speed, changing a valve position, adding temporary mass, releasing a non-safety restraint under an approved procedure, or comparing filled and drained states, supply stronger discrimination; all such interventions must remain within hydraulic, fire and safety limits.

Worked example 25.6. Reflection at a water-pipe diameter change

Water with density rho = 998 kg/m3 and effective wave speed c = 1,200 m/s passes from a pipe of internal diameter d_1 = 40 mm to a pipe of internal diameter d_2 = 25 mm. For a rigid-wall plane-wave screen, calculate the characteristic impedances and pressure reflection coefficient.

For d_1 = 0.040 m, S_1 = 0.001257 m2 and Z_1 = 9.53 x 10^8 Pa s/m3; for d_2 = 0.025 m, S_2 = 0.000491 m2 and Z_2 = 2.44 x 10^9 Pa s/m3. Gamma_p = 0.438. The reflected pressure amplitude is therefore about 43.8 per cent of the incident amplitude in this idealised model; the transmitted pressure and volume velocity require the full junction relations; the result is not a prediction of room sound level. It is a mechanism screen showing that a substantial bore change can create strong reflection and altered standing-wave conditions.

25.15 Hydraulic transients, water hammer and pressure-regulator excitation

Steady flow is often the least demanding acoustic state. A rapidly closing valve changes fluid momentum and produces a transient pressure wave commonly described as water hammer. The elementary Joukowsky relation is Delta p = rho a Delta v, where Delta p is pressure change in pascals, rho is fluid density, a is effective pressure-wave speed in metres per second, and Delta v is the change in mean fluid velocity in metres per second. The relation assumes a sufficiently rapid event and a one-dimensional wave. Pipe elasticity, entrained air, valve closure law, branches, friction and cavitation modify the result, but the equation reveals why a modest velocity change can produce a large impulsive load. [66]

A transient differs from a continuous pump tone; its short rise time spreads energy across frequency; it can excite pipe spans, brackets, wall studs and panels that are not prominent during steady operation; the audible event may occur far from the initiating valve because reflections concentrate pressure at closed ends or impedance changes. A secure-room test performed only with taps and valves stationary can therefore miss a significant source state. Commissioning should exercise representative fast-acting valves, solenoids, flush valves, pressure-reducing valves and pump transitions while monitoring both local and remote response.

Pressure regulators and control valves can generate sustained noise through turbulence, cavitation, unstable control and mechanical chatter; cavitation begins when local static pressure falls sufficiently for vapour cavities to form and collapse; the collapse produces broadband excitation and can damage trim. A valve selected solely by nominal pipe size may operate at an unsuitable pressure drop or opening fraction; the acoustic design review should therefore examine flow, upstream and downstream pressure, valve authority, expected operating range and manufacturer noise data. The room-security concern is not only whether occupants hear the valve. It is whether the valve excites a connected structure or provides a repeatable carrier for speech-modulated pressure in a coupled network.

Transient control measures include slower valve closure, surge vessels, accumulators, arrestors, controlled pump ramps, correct pipe sizing and

66 MB-1316. Wylie and Streeter, Fluid Transients in Systems.

elimination of trapped air where applicable. Each measure has limits. An arrestor installed at the wrong branch may not intercept the controlling wave; a flexible hose can reduce structural force yet remain hydraulically stiff at relevant transient frequencies; a surge vessel requires maintenance and charge verification; the design should state the protected event, the assumed velocity change, the required response and the evidence by which the measure will be maintained.

The supporting structure should be checked for dynamic load, not merely static weight; a pressure transient creates axial and lateral forces at elbows, tees, valves and closed ends; restraints intended for hydraulic or seismic safety can transmit those forces into a protected boundary. Acoustic isolation cannot override required restraint. Instead, routing, independent support, local mass, compliant sections and separation from sensitive construction should be coordinated so that safety loads are carried without creating an avoidable direct bridge.

For forensic work, event synchronisation is crucial; pressure, flow command, pump status, valve state, pipe acceleration and room sound should share a time base or a recorded trigger; a single audio recording of a bang proves neither location nor mechanism. Repetition at controlled operating states, propagation timing, response polarity and comparison across sensors help distinguish a hydraulic transient from door impact, duct movement or structural settlement; the analysis should preserve the possibility of several coincident paths until interventions separate them.

Worked example 25.7. Joukowsky pressure screen and anchor force

A water line carries mean velocity v = 1.8 m/s; a fast valve closure reduces velocity by Delta v = 1.5 m/s; use rho = 998 kg/m3 and effective wave speed a = 1,100 m/s. The pipe internal diameter is d = 50 mm; estimate the transient pressure rise and the idealised axial force acting over the internal area at a closed end.

Delta p = 998 x 1,100 x 1.5 = 1.647 x 10^6 Pa, or about 1.65 MPa; the internal area is 0.001963 m2, giving F = 3,233 N; the force is approximately 3.23 kN before allowance for dynamic amplification, bends, support distribution and actual valve closure history. The calculation shows why a small service can impose a sharp structural input; it does not establish code design pressure, anchor capacity or fatigue life.

25.16 Drainage impact, entrained air and stack-radiation control

Drainage sound is produced by falling liquid, impact at fittings, intermittent slug flow, entrained air, trap motion, pump discharge and pipe-wall radiation. Unlike a pressurised supply line, a sanitary stack often contains a changing mixture of air and liquid with a moving free surface. Flow regime changes with discharge rate, branch entry, stack diameter, offset geometry and venting. These changes produce non-stationary sound. A five-minute steady broadband test cannot represent every fixture event or simultaneous-use condition. [67]

Plastic drainage pipe has low surface mass and can radiate efficiently when excited; cast iron generally provides greater mass and damping, but its

67 MB-0042. American Society of Plumbing Engineers, Plumbing Engineering Design Handbook.

joints and rigid supports can transmit force into structure; pipe material is therefore one variable, not the entire control strategy. The chase, shaft wall, insulation, brackets, slab penetrations, clean-outs and access doors determine the realised result; a massive pipe passing through a lightly framed shaft with direct stud contact can still create a strong remote radiator.

Offsets deserve particular attention. Liquid falling through a vertical stack changes momentum at an elbow or offset; the fitting receives dynamic force and can excite a slab, wall or support frame; long-radius fittings and controlled routing may reduce impact compared with abrupt changes, but hydraulic and code requirements remain controlling. Supports near offsets must carry loads while avoiding unnecessary attachment to the protected-room leaf or isolated lining; where an offset cannot be relocated, a local independent enclosure and structural separation may be more reliable than adding absorbent material inside an already bridged chase.

Vents are pressure-equalising paths. They can connect the drainage network to roof or exterior terminations and can also connect branches within a building; a water trap is not a broadband acoustic terminator; its effective impedance changes with water depth, geometry, bubbling and evaporation. Dry traps, priming failures and maintenance can change the path radically; a protected-room threat model should therefore consider accessible roof terminations, adjacent service spaces and common vents, while remaining within lawful and authorised security analysis.

Clean-outs and access doors are frequent weak points; a clean-out plug may be massive and threaded, yet its surrounding wall opening may be oversized or poorly sealed; an access panel may have no gasket or may be routinely left ajar. The inspection record should capture the whole assembly; where access occurs through a protected boundary, the panel should have a defined closure force, seal condition and maintenance procedure. Concealed access should not be made so difficult that technicians cut new openings.

Commissioning should use representative fixture discharges, simultaneous events where credible, ejector or sump cycles, and listener positions at both adjoining rooms and remote shaft surfaces; measurements should include maximum time-weighted level, event sound exposure, one-third-octave spectra and, where diagnosis requires, pipe or panel acceleration. The report should state the water state and should not average short events into apparent insignificance; if the security concern is intermittent audibility, peak event evidence can be more important than a long-period equivalent level.

Worked example 25.8. Event sound exposure from repeated drainage discharges

A drainage event produces A-weighted sound exposure level L_AE = 71 dB at a receiver position. Twelve statistically similar events occur during a one-hour occupied period. Estimate the combined event exposure level and the one-hour equivalent continuous level, assuming negligible overlap and ignoring unrelated background.

N is the number of events and T is the observation duration in seconds; l_AE,total = 71 + 10 log10(12) = 81.8 dB; for T = 3,600 s, L_Aeq,1h = 81.8 - 35.6 = 46.2 dB. The hourly average looks moderate, while each 71 dB exposure remains conspicuous; the example shows why event metrics and operational context should accompany long-period averages.

25.17 Pump, valve and hydronic plant coupling

Pumps excite piping through hydraulic pulsation, unbalance, misalignment, bearing defects, motor electromagnetic forces, impeller interaction and turbulence. The forcing spectrum can include rotational frequency, blade-passing frequency, harmonics, broadband cavitation and variable-speed-drive components. A pump nominally located outside the protected room can transmit through a common slab, riser or pipe network. A local enclosure that reduces airborne plant noise may have little effect on structure-borne transfer. [68]

The source should be characterised across its operating map; variable-speed equipment changes both forcing frequency and hydraulic condition; a pump that is quiet near its best-efficiency region can become noisy at low flow, high differential pressure or unstable control. Commissioning at one convenient speed is therefore incomplete; the operating-state matrix should include minimum and maximum credible speed, duty and standby pumps, lead-lag changes, valve positions, bypass operation, filter loading and emergency modes.

Isolation design begins with static load and natural frequency; for a single-degree system, f_n = (1/2pi)sqrt(k/m), where f_n is natural frequency in hertz, k is total stiffness in newtons per metre, and m is supported mass in kilograms. The frequency ratio r = f/f_n compares forcing frequency f with natural frequency; above approximately sqrt(2) in an ideal undamped force-isolation model, transmissibility falls below unity; real installations include damping, multiple modes, piping stiffness, restraints and changing mass. An isolator schedule should therefore identify actual equipment weight

68 MB-0784. Hydraulic Institute, ANSI/HI 9.6.4.

distribution, required static deflection, restraint condition and connected-service flexibility.

Pipe connectors are frequently over-credited. A flexible connector can be effective only when it is correctly selected, aligned, unstressed and not bypassed; a short connector may be stiff laterally; a braided connector may transmit axial force. Shipping bars may remain installed. Nearby rigid conduit, drain, controls tubing or structural restraints can create parallel bridges; inspection should record every connected service, not merely the principal pipe.

Valve noise and pump vibration can also modulate the room background; a stable mechanical tone may mask some bands while making speech fragments more noticeable between cycles; it may interfere with measurement by raising receiving-room background; tests should record equipment states and should apply background correction only within the governing method's valid range. Turning equipment off to obtain a cleaner transmission measurement may create a quiet state that is operationally important, but it does not represent normal occupied background. Both states can matter and should be reported separately.

Diagnosis should compare source orders and transfer paths; order tracking relates spectral components to rotational speed; a component that follows speed is more likely associated with rotating equipment than with a fixed building resonance, though a resonance can amplify it when crossed. Simultaneous accelerometers on the pump base, pipe, supports and receiving surface can show attenuation and amplification along the route; intervention tests can include temporary support mass, authorised changes in speed, valve position or pump selection, provided equipment safety and system function are protected.

Worked example 25.9. Isolation transmissibility screen

A pump assembly has supported mass m = 620 kg and combined isolator stiffness k = 1.40 x 10^6 N/m; the dominant forcing frequency is f = 30 Hz; assume damping ratio zeta = 0.08; calculate natural frequency, frequency ratio and ideal force transmissibility.

The natural frequency is 7.56 Hz, giving r = 3.97; substitution gives T approximately 0.086, corresponding to about 91.4 per cent ideal force isolation; the practical result can be much worse if connected pipes, restraints or conduits bypass the isolators, or if some isolators are overloaded. The equation is a linear single-mode screen and does not establish performance at start-up, at harmonics, or under seismic restraint engagement.

25.18 Sprinkler branch lines, flexible drops and restraint conflicts

Sprinkler systems impose non-negotiable life-safety duties. Their pipe sizes, hydraulic design, support, seismic restraint, obstruction clearance, inspection and testing must satisfy the applicable fire-protection criteria. Acoustic-security design must work around those duties rather than weaken them. The central problem is coordination. A rigid branch crossing a high-isolation partition, a hanger attached to an isolated ceiling, or a seismic brace fixed to both structural and resilient elements can create a direct mechanical path. A fire-protection drawing that is developed after acoustic details are frozen can therefore defeat the intended separation. [69]

A sprinkler pipe can be dry, preaction, wet or intermittently flowing, depending on system type and state; the static mass and internal damping change when water is present; alarm tests, inspector's tests, pump starts and actual discharge create transient excitation. Flexible drops permit sprinkler-head alignment and can reduce some force transfer, but they are not generic vibration isolators; their stiffness, braid, bend radius, length and restraint determine behaviour. If installed taut or bearing against a ceiling opening, the intended flexibility is lost.

Seismic bracing creates a necessary load path; the acoustic design cannot simply request soft supports wherever isolation is desired; instead, the room-within-room system and sprinkler routing should be arranged so that bracing attaches to the correct structural reference without tying the isolated shell to the base building. Clearances should accommodate design movement. Penetration treatments should permit the required displacement without tearing or bearing; the fire-protection engineer, structural engineer and acoustician should review the same three-dimensional detail and should state which element moves relative to which.

Sprinkler-head penetrations through an isolated ceiling are particularly sensitive; the escutcheon is decorative and does not demonstrate acoustic closure; the opening around the drop must accommodate installation tolerance, movement, inspection and replacement; a compliant boot or controlled annular treatment may be appropriate, subject to temperature,

69 MB-1028. National Fire Protection Association, NFPA 13, Standard for the Installation of Sprinkler Systems.

listing, accessibility and fire-protection requirements. The treatment should not support the pipe or restrain the head. Where a suspended acoustic ceiling lies below a rated or isolated hard lid, the team must identify which plane is the true boundary and avoid confusing a finish tile with the protected enclosure.

Inspection should occur before ceiling closure and again after heads, escutcheons and final alignment are complete; records should show branch route, hanger and brace locations, drop type, clearances, penetrations, treatment and any contact with ceiling grids or luminaires. Hydrostatic and alarm testing can alter alignment or reveal movement; final acoustic inspection should therefore follow fire-protection testing, not precede it; any later head relocation or added branch requires a boundary-change review.

A sprinkler-system fire test or installation standard does not provide an acoustic rating; conversely, an acoustic boot does not establish sprinkler compliance; the acceptance matrix should contain separate columns for hydraulic and fire-protection approval, structural and seismic review, boundary-acoustic review, construction evidence and competent-authority security disposition. This prevents a single sign-off from being misread as universal acceptance.

Worked example 25.10. Static-load shift between dry and water-filled branch line

A 12 m steel branch line has pipe mass 3.9 kg/m and contains water mass 2.0 kg/m; fittings and heads add 18 kg; the line is supported by six nominally equal hangers; estimate average hanger load in dry and filled states, ignoring unequal spans and dynamic effects.

With L = 12 m, m_dry = 64.8 kg and m_wet = 88.8 kg; using g = 9.80665 m/s2 and n = 6, the average loads are 106 N dry and 145 N wet; water increases average static load by 37 per cent. Actual hanger loads depend on geometry, branch connections and restraint; the example shows why isolator or resilient-support selection based on empty-pipe weight can be materially wrong.

25.19 Firestop listings, tested systems and engineering judgements

A penetration firestop is a system, not a pail of material. Its performance depends upon the rated wall or floor construction, opening size and shape, penetrant type and size, sleeve condition, annular dimensions, backing material, fill depth, orientation, support and every limitation contained in the tested or certified design. The accessed ASTM E814-24 edition describes fire-test performance for penetration firestop systems under defined exposure and hose-stream conditions, while the active UFGS 07 84 00 provides a federal guide-specification framework for project use. ASTM public catalogue pages returned inconsistent active-version signals for E814 at the 16 August 2026 source freeze, and WK97942 records a revision work item initiated on 30 January 2026. This chapter therefore uses E814-24 as the edition analysed, not as an unqualified claim concerning the controlling edition for every project. Direct catalogue confirmation remains required before project use. [70]

The tested configuration controls applicability. A system evaluated with metallic pipe through concrete cannot be extended automatically to a mixed cable bundle through gypsum board. A system limited to a stated annular

70 MB-0312. ASTM International, ASTM E814-24.

range cannot be installed outside that range merely because more sealant has been applied. A sleeve that is optional in one design may be prohibited or specifically constructed in another. Ratings are also purpose-specific. Fire, temperature, air leakage, water resistance, movement and acoustic performance are different attributes, even when one product is marketed for several of them.

Engineering judgements or technical evaluations may be necessary where the exact field condition lacks a listed design; their legitimacy depends upon the governing code, authority, evaluator competence, supporting test evidence and stated limitations; an engineering judgement is not a casual field sketch. It should identify the actual substrate, penetrant, geometry, materials, expected movement, required rating, supporting systems and deviations; it should be accepted through the project's fire-protection and code route before concealment. Acoustic personnel may contribute boundary requirements, but they should not issue fire judgements outside their competence.

The acoustic treatment may be separate from the firestop; for example, a listed firestop can restore a fire-resistance function while an independent resilient boot, lined enclosure or offset route controls acoustic transfer; the detail must ensure that the additional acoustic treatment does not obstruct inspection, violate spacing, introduce incompatible materials, prevent required movement or conceal firestop labels. Conversely, an acoustically massive mortar fill may be unacceptable for cables requiring movement or future replacement; the design should depict both systems and their interfaces, with named responsibility for compatibility.

On-site identification improves lifecycle control. ASTM E3456-25 addresses identification information for installed firestop systems and judgements. A secure-room penetration register can extend that discipline by linking the firestop identifier to acoustic treatment, photographs, measurement results and later changes. The durable label itself should not disclose restricted room function where that would be inappropriate. A neutral identifier can point to controlled records. [71]

Inspection is not satisfied by viewing the exposed surface; critical variables include backing type and depth, fill depth, annular space, penetrant count, cable fill, sleeve, substrate thickness and condition behind finished escutcheons; special inspection programmes and standards such as ASTM E2174 or E2393 may apply under the governing building code for specified occupancies and risk categories. The acoustic surveillance plan should coordinate with those inspections but preserve its separate questions; a firestop can be installed exactly to its listed design and still leave an acoustic bridge through a rigid sleeve or common support.

The acceptance record should therefore include the exact system number or approved judgement, current edition status, tested assembly, field dimensions, installer qualification where required, inspection findings, deviations and disposition; where a source has been superseded or a work item is pending, the record should show what governed the contract and what was checked at final source freeze. The objective is not to collect certificates; it is to preserve a reproducible connection between the tested evidence and the installed condition.

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71 MB-0281. ASTM International, ASTM E3456-25.

Table 25-4. Firestop and acoustic-control non-equivalence matrix

Evidence item	Fire or smoke proposition supported	Acoustic proposition supported	Proposition not supported without further evidence
ASTM E814 or UL 1479 system	Defined penetration fire-test response for exact system	May describe geometry relevant to acoustic review	Installed field acoustic loss, security approval, durability under all service movement
ASTM E3037 movement test	Relative movement capability under test conditions	May bound movement compatibility of acoustic treatment	Fire rating after arbitrary movement, field sound isolation
Product acoustic data	Product or assembly attenuation under stated method	Limited acoustic comparison	Fire compliance, applicability to field geometry, room authorisation
Field visual inspection	Observed installation features	Can confirm visible gaps, contacts and materials	Concealed depth unless observed, measured transmission performance
Field acoustic test	Installed response under measured state	Room or local transfer evidence	Fire rating, untested operating states, competent-authority approval
Authority disposition	Acceptance or use decision within stated remit	May incorporate technical evidence	Universal product performance outside the decision scope

25.20 Annular geometry, backing depth and workmanship tolerance

Annular geometry is one of the most consequential variables in a penetration. It is also among the easiest to lose during construction. The design may show a centred penetrant with uniform clearance, while the installed pipe rests against the sleeve at one quadrant and leaves a large crescent elsewhere. A system that nominally contains compliant material can then become a rigid bridge. The acoustic consequence is not governed by average annular width. It is governed by the narrowest contact, the connected residual void and the material distribution around the circumference. [72]

72 MB-1247. U.S. Department of Defense, ASTM E814-24.

For a concentric circular penetrant of outside diameter d_p within a circular sleeve of inside diameter d_s, the nominal radial annulus is $a = (d_s - d_p)/2$; this scalar is only a screening value; eccentricity e reduces minimum clearance to $a_{min} = a - e$ and increases maximum clearance to $a_{max} = a + e$. Contact occurs when e is equal to or greater than a; oval holes, bundled cables and deformed sleeves require direct dimensional mapping rather than a circular approximation.

Backing controls fill depth, shape and support; mineral wool, foam, forming material or proprietary devices can establish the required geometry; its density and compression affect both fire and acoustic behaviour; excessive compression can create a stiff force path. Insufficient compression can leave connected voids. Backing inserted from one side may not occupy the full depth assumed on drawings. Where both faces require treatment, the cavity between them can form a resonator whose effect varies with depth and opening area. The designer should therefore state backing material, orientation, nominal and allowable depth, compression range and inspection method.

Workmanship tolerance should be numerical. Terms such as tightly packed, neatly fitted or fully sealed do not tell an inspector what is acceptable; the detail should state allowable annular range, centring requirement, minimum fill depth, maximum recess, permissible surface void, contact prohibition, cure condition and movement allowance. Those values must remain within the listed firestop system and product instructions; if acoustic requirements are tighter than the listed system's permissible geometry, the project should add a compatible secondary measure rather than silently altering the firestop.

Inspection tools can include tapered gauges, callipers, depth pins, borescopes, photographs with scale and, for cable bundles, measured fill or count; measurement should occur before decorative collars or escutcheons conceal the opening; a sample-based inspection plan is weak where every penetration is unique or high consequence. Risk-based sampling is more defensible for repetitive low-consequence openings after a first-of-type installation has passed and installer process capability has been demonstrated.

A statistical tolerance model can help repeated work; if annular width is measured at several angular positions, the mean, minimum and standard deviation should be reported; the minimum is often the immediate contact control, while variation indicates process stability. A high mean with one zero-clearance point is a failure, not a comfortable average; control charts can reveal drift as crews, tools or service sizes change, but they do not replace compliance with the exact listed system.

Worked example 25.11. Eccentric pipe within a sleeve

A pipe has outside diameter d_p = 60 mm; the sleeve inside diameter is d_s = 90 mm; the installed pipe centre is displaced by e = 12 mm from the sleeve centre; calculate nominal, minimum and maximum radial clearance.

The nominal annulus is 15 mm. The minimum clearance is 3 mm and the maximum is 27 mm; a tested system permitting 6 mm to 25 mm annular space would not cover this field geometry, even though the average annulus is 15 mm. The installation requires correction or an accepted alternative design; adding material to the large side does not resolve the out-of-range minimum or the risk of contact under movement.

25.21 Movement, thermal growth and dynamic seal durability

A penetration is not static. Pipes grow with temperature, buildings deflect, gypsum partitions move under pressure, equipment vibrates, seismic restraints engage, and maintenance pushes services sideways; a treatment that seals perfectly at handover can crack, debond or bear upon the sleeve after repeated cycles. Movement should therefore be a design input; it should not appear only as a product brochure adjective.

Linear thermal movement is screened by Delta L = alpha L Delta T, where alpha is the coefficient of thermal expansion per kelvin, L is original length in metres and Delta T is temperature change in kelvins; plastic pipe can move several times more than steel or copper for the same length and temperature change. The restraint arrangement determines whether that movement appears as axial sliding, bowing, anchor force or motion at the penetration; a sleeve detail should show the expected direction and magnitude of relative displacement.

Firestop movement testing addresses a defined attribute under specified conditions. ASTM E3037 provides a method for comparing relative movement capability of through-penetration firestop systems in two planes, while explicitly limiting the inference to the tested configurations and attributes. A 2026 ASTM work item proposes revision of the current method. The publication record should therefore cite the actual edition used and should not describe committee work as a finished requirement. [73]

Acoustic seals need their own durability evidence; a highly damped mastic may accommodate small movement but creep under sustained load; a foam

73 MB-0247. ASTM International, ASTM E3037-20.

may recover after compression but transmit force if overcompressed; a boot may remain compliant until its clamp slips or its fabric stiffens with age. Chemical exposure, water, cleaning agents, temperature and ultraviolet light at exterior terminations can change properties. The design should identify service environment, expected cycles, inspection interval and replacement criteria.

Movement joints and service penetrations can interact; a pipe placed near a slab or partition joint can experience larger relative motion than one in a uniform field; a cable tray crossing a building separation joint requires engineered accommodation. The firestop system, support and acoustic enclosure must all permit the same movement without one component becoming a hidden restraint; coordinated three-dimensional details should show neutral positions and extreme positions.

Commissioning should include a movement challenge where safe and practicable; thermal systems can be observed cold and hot; variable-speed equipment can be tested across operating range. Access panels can be cycled. A penetration with expected maintenance movement can be inspected before and after representative manipulation; the purpose is not to consume service life. It is to verify that the installed geometry accommodates the states already assumed by design.

Worked example 25.12. Differential thermal movement

A 22 m polypropylene pipe with coefficient alpha_p = 1.3 x 10^-4 /K runs parallel to a steel support frame with alpha_s = 1.2 x 10^-5 /K. The temperature rises by Delta T = 35 K. Estimate differential free expansion over the run.

Substitution gives Delta L_differential = (1.18 x 10^-4)(22)(35) = 0.0909 m, or about 91 mm; if anchors force most of this displacement towards one penetration, a small nominal annulus will not survive; the actual distribution depends on anchor positions, friction, bends and pipe restraint. The calculation is a routing and movement screen, not a final stress analysis.

25.22 Conduit waveguides and box-to-box transmission

An empty conduit is a narrow acoustic duct. A cable-filled conduit remains a connected path through interstices, and its metal wall can also transmit structure-borne motion. The acoustic behaviour depends on length, internal diameter, fill, bends, terminations, wall losses and end conditions. Short straight conduits between back-to-back boxes are especially hazardous because they provide little propagation loss and can couple directly into lightweight panels. [74]

For a circular rigid duct, the plane mode can propagate from very low frequency, while higher-order modes appear above cut-on frequencies related to diameter; in ordinary small conduit, much of the speech band may be dominated by the plane mode. Viscous and thermal boundary losses increase as diameter decreases, but a short conduit can still transmit strongly; bends, offsets and absorptive inserts may add attenuation, yet electrical and communications requirements constrain what can be placed inside; the designer should not improvise fibrous stuffing within a conduit that must remain pullable, listed or accessible.

The end conditions matter. A conduit terminating in a sealed box differs from one opening into a plenum; gaskets, box covers and cable fittings can

74 MB-0429. David A. Bies, Colin H. Hansen and Carl Q. Howard, Engineering Noise Control, Theory and Practice.

control local leakage; a pair of boxes on opposite faces of a partition can create both an airborne path and a reduction in wall field performance because board and insulation are removed. Staggering boxes, using putty pads or listed enclosures, adding local backing, and avoiding common conduit can improve performance, subject to electrical and fire requirements.

Conduit routing should include spare capacity without creating uncontrolled open bores; spare conduits require approved caps or plugs at both ends and should remain in the penetration register; a cap that is airtight under hand pressure may not be mechanically secure or fire compliant. Pull strings, bushings and future cable additions can disturb seals; the lifecycle record should define how a spare route is opened, inspected, resealed and retested.

For data pathways, a common sleeve or conduit may connect protected and unprotected equipment spaces; even when the data are encrypted and the cable is fibre optic, the physical path can carry sound or force; information-security status does not remove the acoustic mechanism. Conversely, an acoustically treated conduit does not establish network security; the detail should preserve both disciplines and their separate acceptance routes.

Field diagnosis can use a controlled loudspeaker at one termination and microphones or probes at other terminations; a length change is rarely possible, but temporary end caps, local mass, removable absorptive test inserts outside the permanent conduit, or disconnection from a box can help identify the path. The test should avoid introducing debris or violating electrical safety; a strong narrow resonance that shifts when end condition changes is consistent with a waveguide mechanism, but final attribution should consider box and wall-panel vibration.

Worked example 25.13. Quarter-wave resonance screen for an open-closed conduit

A conduit has effective acoustic length L = 1.25 m; treat one end as approximately open and the other as approximately closed; use sound speed c = 343 m/s; estimate the first three odd quarter-wave resonances.

The first resonance is 68.6 Hz, the second is 205.8 Hz, and the third is 343.0 Hz; end correction, losses, cable fill and non-rigid walls will shift and broaden the peaks; the example explains why a short service path can affect low-frequency and speech-related bands. It does not provide insertion loss or a field rating.

25.23 Cable bundles, tray fill and future-capacity governance

Cable bundles are geometrically complex penetrants. Individual jackets contact one another, leaving tortuous connected voids whose dimensions change with cable count, diameter, lay and compression. A firestop detail tested for a stated cable-fill range may perform differently when the bundle is sparse, densely packed or mixed with future cables. Acoustic closure can also degrade as installers pull cables, remove temporary packing, or add a new route through the edge of an existing treatment. [75]

The design should establish permitted cable types, minimum and maximum fill, separation, support and future-capacity method; a large sleeve left mostly empty for future use may be more difficult to close reliably than several modular transits; a completely packed bundle can prevent adequate

75 MB-1234. U.S. Department of Defense, UFC 3-580-01, ASTM E814-24.

sealant depth or backing placement. The apparent economy of one oversized opening should be weighed against inspection complexity, change frequency and consequence concentration.

Tray penetrations create an additional structural path; a continuous metal tray passing through a boundary can bridge the leaves; terminating the tray on each side and providing an independently supported transit can reduce coupling, subject to cable bend radius, bonding and support requirements. Bonding jumpers required for electrical safety can themselves form a parallel metallic path; their length, routing and flexibility should be considered without compromising fault-current capacity.

Cable pulling imposes force. If the transit carries that force, inserts can shift or tear; pull points and supports should be arranged so that the penetration treatment is not used as a bearing or anchor; the installation sequence should include inspection after pulling, not only before. Temporary sleeves or protective shoes used during pulling must be removed if the final system does not include them.

Future work should proceed under a permit linked to the penetration identifier; the work order records cable added or removed, installer, date, affected firestop system, acoustic treatment, photographs and required tests; a cable abandonment policy should address whether unused cable remains, is removed, or is cut. Pulling abandoned cable through a treatment can create more damage than leaving it, but accumulating dead cable consumes capacity and complicates inspection; the decision should be governed rather than improvised.

A modular transit can provide replaceable blocks or inserts sized to cables, but its frame can become a structural bridge and its installed acoustic performance depends on compression, fill and frame attachment; manufacturer claims should be tied to tested configurations. The project should inspect insert identity, compression hardware, unused-module closure and later modifications; a proprietary system does not eliminate the need for as-built evidence.

Worked example 25.14. Cable-fill ratio and remaining geometric capacity

A rectangular transit has clear internal area A_t = 18,000 mm2. It contains twenty cables of diameter 18 mm and thirty cables of diameter 10 mm. Estimate geometric cable-fill ratio, ignoring packing inefficiency and deformation.

The 18 mm cables occupy 5,089 mm2 and the 10 mm cables occupy 2,356 mm2, for total nominal cable area 7,445 mm2. The geometric fill ratio phi is 0.414, or 41.4 per cent. The remaining gross area is not equivalent to usable future capacity because circular cables do not pack without voids, minimum spacing and insert sizes may govern, and the listed firestop system can impose a different fill range. The calculation is an inventory screen, not an installation acceptance.

25.24 Fibre-optic pathways, innerduct and optical-electrical transition points

Fibre-optic cable does not conduct electrical current through its glass core, but a fibre pathway is not physically inert. The cable jacket, strength members, armour, messenger wire, conductive tracer, innerduct and support system can transmit force. The conduit or transit can carry airborne sound. Media converters, optical network terminals and powered switches create local electronic and acoustic sources. A statement that the route is fibre therefore answers only one electromagnetic-conduction question. [76]

Innerduct and microduct can form small waveguides. Unused cells require controlled closure. Gas-blocking or water-blocking components may not be acoustically characterised, and acoustic plugs may not satisfy fire, pressure or cable-blowing requirements; where blown fibre is used, the route must tolerate installation pressure and later reconfiguration; the penetration detail should be coordinated with the actual installation method so that temporary access does not become a permanent open path.

Armoured fibre needs bonding and grounding according to its construction and applicable electrical criteria; a conductive armour or messenger that passes continuously through an isolated boundary can form a structural bridge; segmentation, bonding jumpers and enclosure transitions require electrical engineering. The acoustic objective is to avoid unnecessary rigid continuity while preserving fault, lightning and electromagnetic safety; no acoustic recommendation should instruct removal of required bonding.

Optical-electrical transition points concentrate risk. A converter enclosure may contain a fan, switching power supply, audible alarm or diagnostic transducer; it may be remotely managed and may record logs; its mounting can excite a lightweight wall; it can also require maintenance access. Locating such equipment outside the protected enclosure can reduce penetrations and internal heat, but may create an accessible information

76 MB-1233. U.S. Department of Defense, UFC 3-580-01.

interface. The project should evaluate physical, cyber, electromagnetic and acoustic consequences together.

The pathway register should distinguish cable construction, armour, spare fibres, innerduct cells, transit module, support and endpoint. Testing may include optical loss and continuity for communications function, visual and dimensional inspection for the physical path, and acoustic or vibration checks where the route is consequential. Success in optical testing proves neither firestop nor acoustic closure.

A fibre route often has long service life and frequent endpoint changes; the change-control process should therefore separate cable replacement from endpoint replacement; an endpoint change can increase fan noise or alter mounting without disturbing the transit. A cable pull can disturb the transit without changing the logical network; both events should trigger the appropriate review, and the record should show which baseline remains valid.

25.25 Electrical rooms, transformers, panelboards and busway excitation

Electrical systems introduce both intentional power pathways and mechanical excitation; transformers produce magnetostriction, electromagnetic force at twice supply frequency, cooling-fan noise and vibration from laminations or loose components; switchgear and panelboards can buzz through magnetic force, contact condition or harmonic current. Busway, cable tray and conduit distribute that vibration through supports; a protected room adjoining an electrical room can therefore receive low-frequency structure-borne energy even when the separating wall has substantial airborne transmission loss.

Current Department of Defense criteria distinguish the general electrical design framework in UFC 3-501-01 from interior-system criteria in UFC 3-520-01. UFC 3-520-01 is active with Change 1 dated 21 January 2026, while UFC 3-501-01 is an active 2024 issue. Those documents govern their stated project applicability and do not themselves establish secure-room acoustic approval. They are nevertheless important because electrical reliability, working clearances, grounding, pathway design and maintainability constrain any acoustic treatment. [77]

A transformer should be located and mounted with source strength, structural route and maintenance in mind; vibration isolators need sufficient static deflection and lateral stability; flexible electrical connections must be designed for current, fault and mechanical duty. A heavy transformer resting on an isolated housekeeping pad can still be bridged by rigid conduit, busway, grounding conductors, seismic restraints or wall contact; every connection should appear on the isolation schematic. The commissioning inspection should verify that temporary shipping restraints have been removed where required and that isolators are neither bottomed nor laterally bound.

Electrical rooms often require ventilation or cooling; fan-coil units, exhaust fans and louvres add airborne and duct-borne paths; a quiet transformer in a noisy electrical room can become a lower concern than a common return-air path; the complete room pair should therefore be modelled, not only the electrical equipment. Penetrations should avoid direct back-to-back routes, and panels should not be recessed into the protected boundary unless the complete assembly has been designed and tested.

77 MB-1229. U.S. Department of Defense, UFC 3-520-01, UFC 3-501-01.

Panelboards and junction boxes remove wall mass and can create connected cavities; surface mounting on independent supports is usually easier to inspect and isolate than deep recessing, though operational and architectural requirements may differ; conduits should enter through controlled sleeves or modular transits rather than through a field-drilled constellation. Spare knockouts and openings should remain closed with approved components; a box cover or panel door should not be treated as an acoustic seal unless the assembly has evidence supporting that proposition.

Harmonic currents can increase transformer and conductor heating and alter audible spectra; variable-frequency drives, switched-mode power supplies and uninterruptible power systems may produce tonal components or fan cycling; measurements should include relevant load states; a no-load test can understate magnetically induced vibration under service, while a full-load test can introduce background that masks other paths. The report should record voltage, current, load, equipment mode and cooling state, with electrical measurements performed by qualified personnel.

Emergency and standby power states matter. A generator transfer can start pumps, fans, cooling equipment and transformers simultaneously. UFC 3-540-01 is active with Change 4 dated 16 January 2026, and UFC 3-520-02 addresses facility energy-system resilience and reliability. Acoustic acceptance should therefore include the emergency sequence where the room is intended to remain operational. The quiet interval during transfer and the later generator-supported state can both be consequential. [78]

78 MB-1232. U.S. Department of Defense, UFC 3-540-01, UFC 3-520-02.

Worked example 25.15. Transformer force-isolation screen

A transformer and inertia base have mass m = 1,150 kg. Four equal spring isolators each have vertical stiffness 3.0 x 10^5 N/m, giving total stiffness k = 1.2 x 10^6 N/m. The principal electromagnetic forcing component is 120 Hz. Estimate the natural frequency and ideal undamped frequency ratio.

The natural frequency is 5.14 Hz and r = 23.3. The high ratio suggests strong ideal isolation at 120 Hz. The conclusion is only provisional. Low-frequency start-up forces, fan frequencies, spring surge, seismic restraints, rigid conduit and grounding paths may dominate. A large calculated ratio cannot excuse inspection of parallel bridges.

25.26 Supports, hangers, seismic restraints and short-circuit bridges

Support systems carry gravity, pressure thrust, thermal load, seismic force and maintenance load. They also decide how readily vibration enters the building. Acoustic design fails when it treats a support as an accessory rather than as part of the transmission path. The relevant properties include location, direction, stiffness, damping, preload, contact area, fastener pattern and the mobility of the supporting structure. A soft element attached to a highly mobile ceiling grid can perform worse than a stiffer element attached to a remote primary frame because the entire source-path-receiver chain differs. [79]

A support short circuit occurs when an intended compliant path is bypassed by a rigid or semi-rigid connection. Common examples include a restraint bolt touching its sleeve, a pipe bearing against a wall opening, a seismic cable pulled taut, a conduit attached across an isolation joint, a

79 MB-0058. ASHRAE, UFC 3-401-01.

housekeeping pad contacting surrounding concrete, or a cable tray supported from both the structural slab and the isolated ceiling frame. These defects can be visually small and dynamically decisive.

Statics should be resolved before isolation. Each support must carry its assigned dead load within allowable deflection. Load distribution is rarely equal. Valves, bends, branches and equipment connections shift reactions; the design should calculate or conservatively bound individual support loads rather than divide total mass by hanger count; resilient elements should be selected by actual load range, and the installed deflection should be measured. An isolator outside its range can be too stiff, unstable or bottomed.

Dynamics then require natural-frequency and mode assessment; a long pipe has distributed modes; a hanger can couple vertical, lateral and torsional movement; seismic restraints remain slack in ordinary operation only if installed with designed clearance, and they become stiff when displacement engages them. Their occasional engagement under start-up or hydraulic transient can create intermittent noise. The commissioning plan should examine both ordinary operation and credible engagement states without compromising safety.

Support location relative to the boundary matters; placing the nearest support too far from a penetration allows the pipe to rest on the sleeve; placing it too close may concentrate force directly into the supporting wall or slab. The detail should show which structure carries the support and should calculate movement at the penetration; where a room-within-room leaf is intended to remain isolated, services should generally be supported from the appropriate structural reference and should cross the leaf through a compliant detail. The exact arrangement depends on fire, seismic and structural requirements.

Inspection should include a force-path walkdown. The reviewer traces every service by hand and sight, noting each support, brace, contact, flexible section and penetration; photographs should show enough context to understand direction and attachment, not merely a close-up of an elastomer; tactile checks can reveal contact, but they should be performed only where safe. Instrumented impact or operational transfer measurements can quantify suspected bridges.

Worked example 25.16. Unequal hanger loading caused by a concentrated valve mass

A simply supported 6 m pipe span has uniformly distributed mass 18 kg/m and a 90 kg valve located 1.5 m from the left support. Estimate static reactions, ignoring pipe continuity beyond the supports.

The distributed pipe mass is 108 kg; total mass is 198 kg and total weight is 1,941.7 N; the right reaction is [(108 x 9.80665 x 3) + (90 x 9.80665 x 1.5)] / 6 = 750.2 N. The left reaction is 1,191.5 N; equal division would predict 970.9 N at each support and would understate the left load by about 19 per cent. Actual continuous piping, branches and restraint can change the reactions further.

25.27 Sleeve modules, transit frames and replaceable insert systems

Sleeves and modular transit frames provide a controlled interface between changing services and a permanent boundary. Their advantage is not merely neatness. A well-designed system can fix opening geometry, provide replaceable inserts, support inspection and reduce repeated destructive drilling. The frame can also concentrate risk. It may be highly conductive mechanically, poorly attached to the wall leaf, or installed with voids around its perimeter. The design must therefore consider frame-to-boundary and service-to-frame paths separately. [80]

A transit frame should be assigned to a specific wall or slab construction; the frame opening, flange, anchors, perimeter firestop, corrosion protection and finish should be shown; if the wall is double-leaf, the detail should state whether one frame bridges both leaves or whether separated frames and a flexible connection are used. A single rigid frame spanning independent leaves can short-circuit the cavity; if fire or structural requirements demand one continuous frame, the acoustic model should include it and provide compensating control.

Replaceable modules require compression. Too little compression can leave gaps. Too much can damage cables, distort the frame or increase stiffness; compression bolts or wedges should be accessible and should have installation criteria; spare modules should be filled with solid blocks or approved closures, not left open. The register should record module size and cable assignment so that later changes do not force field cutting.

Frames for pipes differ from cable transits; pipe movement, thermal growth and hydraulic load can exceed the movement tolerated by tight modular blocks; a boot, gland or flexible link may be necessary; the solution should be compatible with pressure, fire, water and maintenance needs. A system marketed for watertightness may not provide low structure-borne transfer. Conversely, a soft acoustic boot may not resist pressure or fire.

80 MB-1306. UL Solutions, Inspection Based Service Offerings, public firestop special-inspection programme information.

The perimeter around the frame is often overlooked; installers can complete the modules perfectly while leaving a cracked mortar joint between frame and wall; for a high-isolation boundary, the perimeter should be inspected from both sides and, where possible, before finish covers are installed. The frame attachment should not force one leaf against another; shims should be permanent, compatible and shown in the as-built record.

Lifecycle use requires training. Technicians should know which modules may be opened, which tools are permitted, how compression is restored and what inspection follows; the project should retain spare inserts and identify approved replacements; a proprietary system that cannot be serviced after a product line changes creates long-term risk. Equivalence criteria should address geometry, material, compression, fire evidence and acoustic consequence.

Worked example 25.17. Frame bridge added to a double-leaf wall

A double-leaf wall has idealised independent transmission coefficient $\tau_w = 1.0 \times 10^{-6}$ over area $A_w = 20$ m2. A rigid transit frame occupies $A_f = 0.08$ m2 and is assigned screening transmission loss $R_f = 32$ dB. Estimate area-weighted composite transmission loss.

The frame coefficient is 6.31×10^{-4}; the composite coefficient is approximately 3.52×10^{-6}, giving $R_c = 54.5$ dB; the 0.4 per cent frame area reduces the nominal 60 dB wall by about 5.5 dB. The model ignores flanking and frequency variation, but it demonstrates why a small rigid frame can govern a high-performance boundary.

25.28 Membrane penetrations, back-to-back boxes and stagger requirements

Not every service passes completely through a wall. Recessed electrical boxes, data outlets, sensors, panels and access devices penetrate one membrane and remove mass, insulation and cavity depth. Two opposing membrane penetrations can create a short airborne path through the cavity. The effect depends on separation, box construction, perimeter sealing, cavity absorption, stud continuity and the remaining layers. [81]

Back-to-back boxes are a familiar defect because they simplify cabling and alignment; in a high-isolation wall, they should generally be avoided unless an engineered assembly supports the configuration; staggering boxes increases path length and preserves more field material, but distance alone is not a rating. A common stud or conduit can still couple them; the detail should show minimum separation measured in plan and elevation, local backing, putty pads or enclosures where applicable, and the treatment of conduits entering the boxes.

A putty pad can contribute fire or acoustic control only within its evaluated scope and installed coverage; seams, penetrations and grounding connections can leave gaps; the pad can interfere with box access or heat dissipation; it should not be specified as a generic cure without reference to the wall assembly, box size and applicable listing. Acoustic evidence should be separated from fire evidence.

Large recessed panels are more consequential than small boxes; a panelboard, extinguisher cabinet or control enclosure can replace most of one leaf; the rear of the enclosure may be thin sheet metal directly exposed

81 MB-0992. JCGM 100:2008, ISO/IEC 17025:2017.

to the cavity. A local independent enclosure, surface-mounted panel or room-side service chase may be preferable; where recessing is unavoidable, the design should preserve required clearances and construct a complete tested or calculated backing assembly.

Sensors can create small but repeated penetrations; occupancy sensors, thermostats, control keypads and card readers bring low-voltage cables and wall openings; their quantity can become significant, and later technology changes invite new holes; a coordinated device zone or surface raceway can reduce random drilling, subject to security and architectural requirements. Every device should appear on the boundary schedule.

Inspection should verify hidden box spacing before closure; photographs should include a scale and grid location; the record should show box model, size, mounting, conduit, perimeter seal, pad or enclosure, and any deviations; a finished wall test can reveal aggregate weakness but may not identify a specific box without local scanning or controlled intervention. Concealed-work evidence remains essential.

25.29 Fire, smoke, acoustic and information-security non-equivalence

A secure-room penetration often attracts several labels: fire-rated, smoke-sealed, watertight, EMI-shielded, tamper-resistant and acoustically sealed. These labels can coexist, but they are not interchangeable. Each describes a different measurand, test condition, decision process or security function. The project should maintain a proposition matrix that asks exactly what evidence supports each claim. [82]

82 MB-1248. U.S. Department of Defense, ASTM E814-24, ASTM E3037-20.

Fire resistance concerns performance under a defined thermal exposure and assembly configuration; smoke or air leakage concerns pressure-driven flow under stated conditions; acoustic transfer concerns frequency-dependent pressure and vibration; electromagnetic shielding concerns field attenuation under specified test arrangements. Tamper resistance concerns access and manipulation. Water tightness concerns hydrostatic or spray exposure. A product may support several propositions, yet success in one test does not fill an empty cell in another.

The distinction becomes critical when one treatment harms another function; a conductive mesh needed for electromagnetic continuity can create a mechanical bridge; a rigid firestop mortar can transmit vibration; a soft acoustic seal can lack fire evidence. A tightly packed cable bundle can impede sealant depth. The design response is not to select one discipline as supreme in all circumstances. It is to construct a compatible system, document trade-offs and obtain dispositions from the proper authorities.

The hierarchy of evidence should also be explicit; a laboratory test addresses a specimen; a certification or listing addresses conformity within its programme. An inspection addresses observed installation. A field measurement addresses the state and locations tested; an accreditation or use decision addresses institutional authority. The record should avoid statements such as certified secure or government approved unless the exact authority and scope justify them.

Controlled criteria create an additional boundary. Public design documents can state mechanisms, evidence classes and governance without reproducing protected thresholds or construction details; the penetration register can use abstract requirement identifiers that point authorised users to controlled annexes; the public manuscript should not reverse-engineer a non-public criterion from product literature or isolated examples.

A non-equivalence matrix supports procurement. Submittals can be checked against each required proposition; missing evidence remains visibly missing rather than being inferred from a general brochure; deviations are routed to the appropriate reviewer; the matrix also supports maintenance because a replacement product may be equivalent for one attribute and materially different for another.

Table 25-5. Multi-attribute penetration proposition register

Attribute	Typical measurand or decision	Primary evidence class	Required project disposition
Fire resistance	Time-rated response under defined fire test	Tested or certified system, accepted judgement	Fire-protection and code acceptance
Smoke or air leakage	Flow at stated pressure and temperature	Leakage test or certified assembly	Life-safety and mechanical acceptance
Acoustic control	Band-specific pressure or vibration transfer	Laboratory assembly data plus field evidence	Acoustic technical acceptance
Electromagnetic control	Field attenuation or continuity	Applicable test, inspection and configuration record	EMSEC or technical-security disposition
Structural and seismic	Strength, stiffness, movement and restraint	Calculations, details, inspection	Structural acceptance
Electrical or data function	Capacity, safety, performance and maintainability	Electrical or ICT criteria and tests	Discipline acceptance
Physical security	Delay, detection, access or tamper control	Threat-based design and inspection	Security authority disposition
Use authorisation	Permission for defined activity and state	Complete evidence set and authority decision	Competent authority only

25.30 Concealed-work surveillance and hold-point engineering

A penetration becomes hardest to verify when it is easiest to conceal. Backing depth, sleeve contact, support attachment and firestop geometry disappear behind board, ceilings, escutcheons and equipment. A construction-surveillance plan should therefore identify hold points at the states when decisive evidence is visible. Surveillance is not an optional photographic diary. It is a sequence of controlled decisions tied to work release. [83]

The first hold point occurs before drilling or sleeve placement; the reviewer confirms location, boundary, service route, opening size, edge distance, interference and approved detail; this prevents a correct treatment from being installed in the wrong place. The second occurs after the opening and sleeve are prepared but before the service and fill obscure them; dimensions, substrate condition and leaf separation can be verified; the third occurs after service support and centring but before backing and seal. Contact and movement clearance are visible. The fourth occurs after backing and before final fill where backing depth cannot otherwise be seen. The fifth occurs after completion and before covers. Final labels, surface condition and photographs are recorded.

Witness points differ from hold points. At a witness point, invited reviewers may attend under contractual notice rules, but work may proceed as defined; at a hold point, work does not proceed until release; the project should use the terms consistently; high-consequence penetrations, first-of-type installations and work by a new installer normally justify stronger control. Repetitive work may move to risk-based sampling only after process capability is shown.

83 MB-1249. U.S. Department of Defense, UFGS 07 84 00, Firestopping.

A rejected hold point should produce a nonconformance record, not an informal promise to tidy the work later; the record states requirement, observed condition, immediate containment, proposed correction, reviewer, authority and reinspection; if correction would require destructive opening, the project should decide whether to open, test, calculate, accept with limitation or reject. Missing evidence is itself a condition requiring disposition.

Photography needs discipline. Each image should include identifier, orientation and scale. Context images show location. Detail images show dimensions and material. A sequence should show before, during and after treatment; file metadata and checksums can support integrity, while a controlled log links the image to date, photographer and hold point; photographs cannot prove hidden depth after the fact unless the sequence genuinely shows it.

Digital models and drawings should be reconciled with field truth; a penetration added through a request for information should be incorporated into the as-built register; red-line sketches should not remain detached from the master; three-dimensional coordination can reduce clashes, but model accuracy should be tested against surveyed or measured installation. A perfect model of an unverified assumption is not evidence.

Surveillance personnel require competence and access. An acoustician may identify contact and path risk, while a firestop inspector verifies listed-system details and a structural reviewer addresses restraints. Joint inspections are efficient where responsibilities overlap. Each signatory should state scope. A signature should not imply competence outside that scope.

Table 25-6. Recommended penetration hold-point sequence

Hold point	Observable condition	Required record	Release authority
HP-1 Route and opening	Location, boundary, clash, opening method	Approved detail, coordinate, pre-work photograph	Design and security coordination
HP-2 Sleeve and substrate	Diameter, depth, leaf separation, substrate condition	Measurements, sleeve identity, images	Relevant design disciplines
HP-3 Service and supports	Centring, support loads, clearances, flexible links	Support schedule, load or deflection, images	Mechanical, electrical or ICT plus acoustic review
HP-4 Backing	Material, depth, compression, continuity	Depth measurements and circumferential images	Firestop and acoustic reviewers
HP-5 Final treatment	Fill depth, surface, label, perimeter, cure state	System number, installer, images, deviations	Fire and acoustic acceptance routes
HP-6 Post-test condition	Movement, alignment, damage after hydraulic or functional test	Before-and-after comparison, test state	Commissioning authority
HP-7 Handover	Register completeness and retrievability	Final identifier, as-built link, maintenance trigger	Configuration custodian

25.31 Diagnostic testing of penetrations and service-borne paths

A whole-wall field test establishes aggregate installed performance between source and receiving spaces under the measured condition. It rarely identifies which penetration or support controls the result. Local diagnosis requires a hierarchy of tests that moves from non-invasive screening to controlled intervention. The hierarchy should begin with documentary reconciliation, because a missing sleeve, an unrecorded service or a known change may explain the anomaly before instruments are deployed. It then proceeds through visual inspection, listening and scanning, local excitation, operational contrasts, vibration measurements and, only when authorised, opening or temporary modification. [84]

84 MB-0872. International Organization for Standardization, ISO 16283-1:2014, ISO/IEC 17025:2017.

The first diagnostic question is whether the observed response is airborne, structure-borne, fluid-borne or mixed. Microphones measure sound pressure. Accelerometers measure local motion. Laser vibrometers can measure surface velocity without contact when line of sight and surface condition permit; pressure transducers measure fluid or duct pressure; current clamps, tachometers and control logs can identify equipment state; a causal claim should connect source, path and receiver with quantities appropriate to each stage. A microphone peak at 120 Hz near a pipe does not by itself prove pipe-borne transfer. It may reflect a room mode driven by a transformer elsewhere.

Spatial scanning is useful when performed under a stable source; a loudspeaker or tapping source excites the source room, while a probe microphone surveys likely openings, boxes, access panels and service chases; the source spectrum and position should be recorded. A local level maximum is an indicator, not a direct transmission loss; near-field pressure, standing waves and receiver-room modes can move the maximum. Repetition with a second source position and comparison against adjacent intact wall fields improve confidence.

Operational contrasts exploit natural source changes. Pumps can be tested at several speeds, valves opened and closed, pipes filled or drained where operationally permissible, and electronic equipment switched between states; the response should be normalised to an appropriate source quantity; for a rotating machine, transfer from base acceleration to remote surface velocity may be more informative than unnormalised room level. For an airborne loudspeaker test, the source-room spatial average is usually required by the governing field method.

Temporary interventions should be reversible and controlled; a removable mass can lower or split a panel resonance; a temporary external cap can test an open conduit; a soft wrap can damp pipe radiation without changing internal pressure. A clamp or brace should not be altered unless the responsible engineer approves the action. Firestop material should not be disturbed merely to see whether sound changes. Every intervention must be documented so that the room is restored and so that the observed effect is not mistaken for permanent remediation.

Transfer-function analysis can help rank paths. If X(f) is a source reference spectrum and Y(f) is a receiver spectrum, the frequency-response estimate $H(f) = S_{yx}(f)/S_{xx}(f)$ relates cross-spectrum to source autospectrum; magnitude-squared coherence $\gamma^2(f) = |S_{yx}(f)|^2/[S_{xx}(f)S_{yy}(f)]$ indicates linear association under the measured state. Low coherence can arise from noise, multiple independent sources, nonlinearity or changing state; high coherence supports association but not uniqueness; a common source can drive several paths coherently.

Time-domain methods can separate events when propagation delays are resolvable; an impulsive hydraulic event may appear first at the pipe, then at a support, then at a wall panel and microphone. Sampling clocks must be synchronised. Trigger latency and sensor phase should be known; in a small room, airborne and structural arrivals can be separated only by fractions of a second, and reverberation quickly obscures them; time evidence should therefore be combined with spatial and intervention evidence.

Infrared or ultrasonic tools can support inspection but should not be treated as universal leak detectors; thermal imaging can reveal moisture, missing insulation or active flow under favourable conditions; ultrasonic emitters and receivers can locate small gaps when the propagation path and instrument response are suitable. The relevant frequency may lie far above speech, and a gap that transmits ultrasound strongly may not control low-frequency speech; these tools are screening aids whose inference must be stated.

The diagnostic report should rank hypotheses rather than declare certainty prematurely; for each candidate path it records supporting observations, contradictory observations, unresolved variables, intervention results and residual alternatives; the conclusion uses calibrated language such as confirmed under tested states, strongly supported, plausible, not supported, or excluded within stated sensitivity. This forensic structure allows remediation to target the most likely mechanism while preserving an audit trail if the first intervention does not close the defect.

Worked example 25.18. Coherence-supported transfer estimate

At 250 Hz, a source accelerometer autospectrum is $S_{xx} = 4.0 \times 10^{-4}$ (m/s2)^2/Hz. A receiving-panel velocity autospectrum is $S_{yy} = 9.0 \times 10^{-8}$ (m/s)^2/Hz. The complex cross-spectrum magnitude is $|S_{yx}| = 5.4 \times 10^{-6}$ (m/s2)(m/s)/Hz. Calculate magnitude-squared coherence and the magnitude of the H1 transfer estimate.

The coherence is $(5.4 \times 10^{-6})^2 / [(4.0 \times 10^{-4})(9.0 \times 10^{-8})] = 0.81$; the transfer magnitude is 0.0135 (m/s)/(m/s2), dimensionally seconds; the high coherence supports a stable linear association at 250 Hz during the record. It does not prove that the measured support is the only route, and the transfer estimate should not be extended to other operating speeds without verification.

Worked example 25.19. Local treatment insertion loss with uncertainty

A local probe measurement beside a conduit opening gives band level L_{before} = 54.7 dB and L_{after} = 43.9 dB after a reversible external cap is fitted. The standard uncertainties are u_{before} = 0.8 dB and u_{after} = 0.9 dB, treated as independent. Calculate insertion loss and combined standard uncertainty.

IL = 10.8 dB and u_c = 1.20 dB; an approximate expanded uncertainty with coverage factor k = 2 is U = 2.4 dB; the result may be reported as 10.8 dB plus or minus 2.4 dB for the defined position, band and state. It does not represent the whole-room improvement because other paths and spatial averages remain unmeasured.

25.32 Measurement uncertainty and decision rules for local defects

A measured difference is not automatically a real difference, and a real difference is not automatically important. Local penetration diagnosis often involves levels close to background, strong spatial variation, intermittent sources and several instruments. The uncertainty statement should therefore identify the measurand, model, input quantities, correlation and decision rule. A generic instrument tolerance copied from a data sheet is not a complete uncertainty budget. [85]

For a level difference $D = L_1 - L_2$, independent standard uncertainties combine by root sum of squares; if the same instrument, calibration and environment affect both readings, some components are correlated and may cancel partly or reinforce. Spatial sampling can dominate. A probe

85 MB-0993. JCGM 100:2008, NIST Technical Note 1297.

moved 25 mm near a small opening can encounter a different near-field pattern; repeatability should be estimated from repeated placement, not assumed from meter resolution.

Background correction has a limited valid range; when receiving signal-plus-background level is only slightly above background, subtraction becomes unstable; let L_{sb} be signal plus background and L_b be background; corrected signal level is $L_s = 10 \log_{10}(10^{(L_{sb}/10)} - 10^{(L_b/10)})$. As the difference $L_{sb} - L_b$ approaches zero, small level errors produce large correction errors. The governing field method may prohibit or qualify correction below a stated difference. A report should not hide this limitation behind extra decimal places.

Decision rules connect uncertainty to acceptance. Under a simple guard-band rule, acceptance may require the measured value plus expanded uncertainty to remain on the compliant side of a limit; other contracts may use shared risk or a different rule; the rule should be agreed before testing. Choosing it after seeing a borderline result undermines fairness and reproducibility; security authorities may impose additional conservatism, but that is an authority decision rather than a metrological fact.

Local defect tests frequently use comparative evidence rather than a formal rating; the report should state whether the result is diagnostic, acceptance, commissioning or trend evidence; a 6 dB reduction after temporary damping can strongly support a vibrating-panel hypothesis without proving that permanent requirements are met. Conversely, a whole-wall field result can meet a criterion while local diagnosis still identifies a fragile path that warrants repair for lifecycle resilience.

Uncertainty should include state definition. Valve position, water temperature, pipe pressure, cable fill and support contact can vary; if the test state cannot be reproduced, repeatability over time should be measured or the conclusion limited; a single observation in an uncontrolled state should not be assigned a narrow numerical uncertainty. Configuration uncertainty is often qualitative but no less important.

Instrument calibration establishes traceability for stated quantities and ranges; it does not validate source placement, probe technique, data processing or model selection; field checks before and after measurements can detect gross drift; sensor mounting, cable motion and electromagnetic interference should be controlled. A high-sensitivity accelerometer mounted with wax, magnet or stud will have different usable bandwidth and mass loading. Those details belong in the record.

Worked example 25.20. Background correction near the validity limit

At a receiving position, signal plus background level is L_{sb} = 36.0 dB and background is L_b = 34.0 dB. Calculate corrected signal level.

The corrected signal level is approximately 31.7 dB; a 2 dB separation required a 4.3 dB downward correction; if either input has uncertainty near 0.5 dB, the corrected result becomes highly sensitive; the measurement should be reported as background limited unless the governing method expressly permits and qualifies such correction. Increasing source level, reducing background or changing test time may provide stronger evidence.

Worked example 25.21. Guard-banded acceptance of penetration leakage

A project defines a maximum permissible local transfer level of 32.0 dB under a stated test. The measured value is 30.7 dB with expanded uncertainty U = 1.8 dB. Under a conservative rule requiring result plus U not to exceed the limit, determine disposition.

L_decision = 32.5 dB, which exceeds the 32.0 dB limit. The result is not accepted under the stated rule, despite the central value being 1.3 dB below the limit. The project can improve the test, reduce uncertainty, remediate and retest, or seek an authorised alternative disposition. It should not silently discard uncertainty.

Table 25-7. Local diagnostic measurement uncertainty budget template

Input quantity	Unit	Evaluation method	Typical influence	Control measure
Instrument calibration	dB or engineering unit	Certificate and field check	Scale and frequency response	Current traceable calibration
Source stability	dB, rpm, flow or pressure	Repeated record and control log	Changes excitation	Regulated source and reference channel
Position	mm or m	Survey and repeated placement	Near-field and modal variation	Fixtures, coordinates and multiple positions
Background	dB	Source-off measurement	Bias and correction instability	Higher source level or quieter period
Operating state	categorical and measured variables	State matrix	Changes path impedance and force	Record pressure, flow, temperature and controls
Processing	window, bandwidth, averaging	Software validation	Spectral leakage and estimator bias	Frozen method and retained raw data
Repeatability	dB or engineering unit	Independent repeats	Combined field variability	Replicate setup and report dispersion
Model form	qualitative or sensitivity bound	Alternative calculations	Simplification error	State assumptions and compare models

25.33 Moisture, corrosion, microbial growth and material compatibility

Service penetrations inhabit harsh microenvironments. Cold water and refrigerant lines can condense. Drainage leaks can wet backing. Exterior sleeves can admit wind-driven rain. Firestop, acoustic sealant, insulation, pipe jacket, primer and corrosion coating can interact chemically. A detail that performs when new and dry may degrade after months of moisture cycling. The design should therefore address hygrothermal state as part of acoustic durability. [86]

Condensation occurs when a surface falls below the local dew-point temperature; the risk depends on fluid temperature, insulation continuity, vapour retarder, room humidity, airflow and thermal bridges; a metal sleeve can conduct heat through a wall and cool its perimeter. A gap in pipe insulation at the penetration can create a wet annulus; water can reduce fibrous absorption, promote corrosion, debond sealants and stain finishes before a leak becomes audible.

The vapour-control strategy should be continuous. Cutting insulation to fit a firestop can leave exposed cold pipe; wrapping combustible or unapproved insulation through a rated assembly can violate the firestop system; the project may need a specific listed detail, non-combustible insulation transition, vapour-sealed boot or local drainage. Fire-protection, mechanical and acoustic designers should resolve the sequence; no trade should repair its own layer by puncturing another.

Galvanic corrosion can occur where dissimilar metals are electrically connected in the presence of an electrolyte; a copper pipe in contact with a

86 MB-1227. U.S. Department of Defense, UFC 3-401-01.

steel sleeve, wet mineral wool and chloride contamination creates a different risk from a dry isolated interface. Corrosion products can expand, crack sealant or lock a nominally sliding penetrant; protective coatings, isolation materials and drainage should be compatible with fire and electrical requirements.

Microbial growth is primarily a health, moisture and maintenance concern, but it also signals material change. Wet fibrous backing can compact. Organic contamination can affect adhesion. Remediation may require removal of penetration materials and opening of the boundary. The lifecycle plan should define how such work is controlled, what temporary security measures apply, and what inspections and tests are required before return to service.

Sealant compatibility should be confirmed using manufacturer and project evidence; plasticisers, oils, cleaning agents and pipe coatings can inhibit cure or adhesion. Some foams shrink. Some elastomers harden with temperature or ultraviolet exposure; a successful adhesion test on clean laboratory substrate does not establish performance on dusty, painted or oily field surfaces; substrate preparation and primer should be part of the hold point.

Moisture detection can include visual inspection, humidity sensors, surface-temperature measurement, thermal imaging and targeted moisture meters; the method must suit the material; conductance meters can misread metal or salts; infrared images show surface temperature patterns, not moisture directly. Findings should be confirmed before destructive repair. Baseline images can help identify later change.

Worked example 25.22. Condensation screen at a cold pipe sleeve

Room air is 24 degrees C at 60 per cent relative humidity; a simplified psychrometric calculation gives dew point approximately 15.8 degrees C; the exposed sleeve surface is measured at 13.5 degrees C; the surface is therefore about 2.3 K below dew point and condensation is expected if conditions persist and measurement is representative. The engineering response should improve insulation and vapour continuity, verify airflow and inspect adjacent materials. The calculation does not quantify condensation rate or hidden surface conditions.

25.34 Maintainability, clean-outs and controlled access

A secure boundary that cannot be maintained will be defeated by maintenance. Valves need operation, clean-outs need opening, cables need replacement, firestops need inspection and water damage needs repair. The design should provide enough access to perform those tasks without cutting unplanned holes or leaving panels open. Maintainability is therefore a security control as well as an operational convenience. [87]

Access should be placed on the less sensitive side of a boundary where practicable, but personnel, safety and service logic may require otherwise; a service chase can consolidate access while keeping technicians outside the protected room; the chase itself then becomes a controlled adjoining space whose walls, doors, ceiling and penetrations require analysis. Access location should not merely move the weak path to a more accessible receiver.

87 MB-1031. National Fire Protection Association, NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.

Panels should be complete assemblies. Leaf mass, frame, latch, gasket, anchors and perimeter determine performance; a panel with excellent laboratory data can fail if the frame is twisted or the latch does not compress the gasket. Repeated cycles cause wear. The maintenance plan should define inspection frequency, gasket replacement criteria, fastener torque where applicable and closure verification; panels used weekly should be managed like doors, not like static wall fields.

Clean-outs and valves require working clearance. If acoustic enclosures block access, technicians will remove them and may not reinstall them correctly; removable covers should use captive fasteners, keyed orientation and durable seals; their weight should be safe for one or two-person handling as designed. A cover that requires special equipment should have that equipment available; the record should include an illustrated reassembly procedure.

Permits should govern work on penetrations and access panels; the permit identifies the room state, information-protection measures, authorised workers, escort requirements, tools, temporary opening control, debris containment, fire watch if applicable, inspection, restoration and retest; emergency work can use an abbreviated route, but it should still generate a retrospective record and trigger technical review.

Temporary openings require explicit controls. A removed panel can create direct speech leakage in seconds; work scheduling may require the room to be taken out of protected use, adjacent access restricted, masking adjusted, or a temporary barrier installed; the competent authority decides operational restrictions. The engineer supplies the expected physical consequence and verifies restoration.

Spare materials should be controlled. Replacement gaskets, modular blocks, sealants and labels should be stored within shelf-life and environmental limits. Lot and expiry may matter. A substitute selected during an urgent repair should be screened for fire, acoustic, chemical and movement compatibility. Like colour or brand family is not equivalence.

The handover package should include maintenance drawings, register extracts, photographs, system identifiers, access instructions, inspection frequencies, change triggers and contact roles; training should include a physical walkdown; staff turnover is a predictable lifecycle event; a process that relies on one technician's memory is not a controlled process.

Worked example 25.23. Access-panel seal compression tolerance

A rectangular access panel has gasketed perimeter length P = 3.2 m; the gasket design compression is 25 per cent of original thickness t_0 = 8 mm, with permissible range 20 to 30 per cent. Measurements at eight points show compressed thicknesses of 6.1, 6.0, 5.7, 6.2, 6.4, 5.8, 6.0 and 6.3 mm.

The compressions are 23.8, 25.0, 28.8, 22.5, 20.0, 27.5, 25.0 and 21.3 per cent. All points fall within the 20 to 30 per cent range, but the 6.4 mm point is exactly at the lower-compression limit. The panel passes this geometric screen. It still requires checks for continuity, corner gaps, latch operation and perimeter frame seal.

25.35 Digital penetration register, asset identity and chain of custody

The penetration register should function as a configuration-management system rather than as a spreadsheet compiled at handover. Each record represents a physical object and its evidence. The core fields include stable identifier, boundary, location, service, geometry, support, sleeve, firestop system, acoustic treatment, installer, hold points, images, tests, nonconformances, authority dispositions, maintenance and change history. The system should preserve previous states rather than overwriting them. [88]

Identity must survive drawing changes. A penetration number based solely on sheet sequence can change when drawings are reorganised; a globally unique identifier or controlled project identifier can remain stable, while human-readable location fields are updated; labels should be durable and placed where maintainers can find them without advertising restricted function. A QR code can link to an authorised repository, but the code should reveal no sensitive data to an unauthorised scanner.

Location evidence should combine coordinate, room pair, boundary identifier, elevation and photographs; building information models can provide geometry, but a model object should be reconciled to the installed object; survey data or measured offsets may be required. A photograph without context can be misassigned; a context image and a detail image should share the same identifier.

The register should support one-to-many relationships. One opening can contain several services. One firestop system can apply to many openings; one test can cover several paths; one change can affect several records; a relational database or carefully structured data model reduces duplication and preserves referential integrity. Free-text notes remain useful, but critical fields should use controlled values.

88 MB-0884. International Organization for Standardization, ISO 19650-5:2020.

Chain of custody applies when evidence may support a dispute, forensic investigation or authority decision; raw photographs, instrument files and documents should be ingested with date, source, operator and checksum; working copies can be processed, while originals remain read-only. Corrections should create a new version with reason and author; a checksum shows that a file has not changed since hashing. It does not prove that the original observation was accurate or that the person who submitted it was authorised.

Access control should follow information sensitivity and role; installers may need to submit records without viewing the entire room register; maintainers may need location and approved repair details; security authorities may retain controlled criteria and exact room function. The system should log access and export. Backups should be tested. A sophisticated register that cannot be recovered after a system failure does not preserve evidence.

Data validation can catch errors at entry. Diameter fields should use units. Enumerations can limit service type and disposition; required fields can prevent release without photographs or system number; duplicate-coordinate checks can flag two records that may describe the same opening; automated checks support reviewers but cannot determine whether a photograph genuinely shows the stated penetration.

Lifecycle dashboards can show overdue inspections, expired materials, open nonconformances, changes since last test and penetrations with missing evidence. Risk ranking can prioritise high-consequence paths, frequently altered openings and services leading to accessible spaces. The ranking method should be transparent. A numerical score should not conceal an unclosed critical defect.

Table 25-8. Penetration-register minimum data schema

Data group	Required fields	Validation rule	Lifecycle use
Identity	Penetration ID, boundary ID, service ID	Unique, persistent, no reuse	Links all evidence and changes
Location	Building, level, room pair, grid, elevation	Recoverable from drawing and field	Inspection and incident response
Geometry	Opening, sleeve, penetrant, annulus, orientation	Units mandatory, ranges checked	Listing applicability and acoustic model
Configuration	Supports, restraints, fill, operating states	Controlled values plus photographs	Recommissioning and equivalence review
Fire and smoke	System or judgement, rating, inspector	Current document and acceptance recorded	Life-safety maintenance
Acoustic	Treatment, design intent, measurements, limitations	Method and state identified	Security and performance assurance
Evidence	Images, raw data, calibration, reports, checksums	Original retained and linked	Audit and forensic use
Disposition	Reviewer, authority, date, conditions	Named role and scope	Prevents technical review being mistaken for authorisation
Change history	Work order, before and after state, retest	Append-only version history	Detects drift and invalidated evidence
Maintenance	Inspection interval, repair materials, access method	Overdue alerts and closure record	Sustains performance after handover

Worked example 25.24. Risk-priority number for inspection scheduling

A project uses a transparent screening score P = C x A x M, where C is consequence rating from 1 to 5, A is accessibility or exposure rating from 1 to 5, and M is modification likelihood from 1 to 5. A penetration leading to a public service corridor has C = 5, A = 5 and M = 3, giving P = 75. A similar penetration leading to a controlled locked plant room has C = 5, A = 2 and M = 2, giving P = 20. The first receives more frequent inspection. The score is a management tool, not a governmental criterion, and a known defect overrides ranking.

25.36 Integrated design and commissioning case study

Consider a two-room secure conference suite constructed as a double-leaf enclosure within an occupied building; the room requires domestic chilled water for terminal cooling, wet-pipe sprinklers, normal and emergency electrical power, fibre-optic communications and a small condensate drain. The adjoining east side is a public corridor; the north side is a controlled electrical room; the west side is a restricted service chase. The floor and structural slab continue beneath and above the enclosure. The design objective is not represented by one wall rating. It is represented by complete control of each service path under normal, quiet, emergency and maintenance states.

The first design decision is routing. Chilled water, condensate and fibre are consolidated through the west service chase, reducing public-side penetrations; electrical feeders enter from the north electrical room through separated conduits; sprinkler piping follows the chase and crosses the isolated hard lid at controlled drops. No service is allowed through the east corridor wall except required life-safety devices in engineered boxes; the service-path graph identifies the public corridor, electrical room and chase as distinct receiver environments with different access and background conditions.

The chilled-water pair is supported from the base-building slab, not from the isolated ceiling; flexible connectors are placed near the terminal unit, and the pipe crosses the room shell through independent sleeves with compliant acoustic boots; the firestop system is selected for the exact metallic pipe, insulation and gypsum assembly. The acoustic boot is external to the listed fill and remains inspectable; thermal movement is directed towards a controlled guide rather than into the sleeve. Condensation control is continuous through the penetration.

The condensate drain uses heavy-wall pipe within the room and transitions in the chase; the slope is maintained without resting on the sleeve; the trap and clean-out are accessible from the chase; a local enclosure around the chase-side offset reduces radiation, while supports attach to the structural slab. Commissioning includes representative condensate pumping and water discharge. A dry quiet test alone is prohibited as unrepresentative.

The fibre route uses a modular transit with separated frames at the two wall leaves; a short flexible innerduct bridges the cavity without rigid contact. Spare modules are closed. The endpoint equipment is mounted on an independent rack within the room, with no small fan attached to the boundary; the transit register records cable count, module size and unused capacity; future cable work requires a permit and post-work inspection.

Electrical conduits terminate in surface-mounted boxes on independent room-side service panels. No back-to-back boxes are permitted. The conduit sleeves are capped and sealed around conductors using an approved system; grounding and bonding are designed by the electrical engineer; flexible conduit sections and conductor loops prevent rigid short circuits, but their fault and mechanical duties are verified. Transformer vibration in the adjoining electrical room is measured under normal and emergency load.

Sprinkler branch lines remain supported from structure; flexible drops pass through isolated ceiling openings without bearing; seismic braces connect to the approved structural reference and maintain clearance from the isolated shell in ordinary operation; the design is reviewed jointly by fire-protection, structural and acoustic personnel. Hydrostatic and alarm tests occur before final acoustic inspection, so movement caused by pressure testing is captured.

The hold-point plan contains thirty-two identified penetrations and devices; each receives HP-1 through HP-5 records; first-of-type work is completed on one chilled-water sleeve, one fibre transit, one conduit and one sprinkler drop before repetition; the team discovers that the initial chilled-water pipe is 9 mm eccentric within a nominal 12 mm annulus, leaving only 3 mm clearance. The listed system requires at least 6 mm. The sleeve is enlarged and the support adjusted before backing. This early correction prevents repetition across the remaining sleeves.

Commissioning uses four state matrices. State N is normal occupied operation with HVAC, masking and conferencing equipment active; State Q is a quiet night condition with HVAC and masking off; State E is emergency power operation after transfer; State M is maintenance condition with the service-chase access open and authorised work controls in place. Whole-room field tests are supplemented by local scans, pipe acceleration measurements and conduit cap challenges. The report keeps the results separate because each state answers a different operational question.

During State E, a 120 Hz component rises in the protected room; coherence between the electrical-room transformer base and the north wall panel is 0.89; inspection identifies rigid conduit contacting a sleeve and a bonding strap installed taut across the intended flexible section. Electrical engineering redesigns the flexible connection and bonding geometry without reducing fault capacity; retest reduces the 120 Hz wall velocity by 13 dB and room level by 8 dB. The result confirms the principal path under State E, while other paths remain below the diagnostic threshold.

The final penetration register contains as-built geometry, firestop system, acoustic treatment, support state, photographs, test links and authority disposition for every object; two penetrations carry limitations because concealed backing depth could not be witnessed after an emergency schedule change. The project chooses controlled opening and reinspection rather than accepting undocumented work; that decision delays handover but removes a permanent uncertainty from the most accessible boundary.

The case illustrates four broader rules. First, routing can eliminate more risk than heroic treatment; second, every service must be evaluated in its actual operating and maintenance states; third, life-safety, structural, electrical, information and acoustic approvals must remain separate but coordinated; fourth, the penetration register is not administrative residue. It is the durable technical memory that allows the room to survive change.

Worked example 25.25. Combined leakage improvement after two remediations

Before remediation, a boundary has three normalised parallel coefficients: conduit contact tau_1 = 2.0 x 10^-4, chilled-water support tau_2 = 8.0 x 10^-5, and all remaining paths tau_3 = 1.5 x 10^-5. The conduit repair reduces tau_1 by 13 dB, and the support repair reduces tau_2 by 10 dB. Calculate idealised before and after combined loss.

The initial coefficient is 2.95 x 10^-4, giving R_before = 35.3 dB; after repair, tau_after = 1.00 x 10^-5 + 8.0 x 10^-6 + 1.5 x 10^-5 = 3.30 x 10^-5, giving R_after = 44.8 dB. The combined improvement is 9.5 dB, less than the 13 dB conduit change because the support and residual paths become controlling; the model reinforces the need to retest the complete boundary after local repair.

Worked example 25.26. Evidence-completeness index for handover

The case-study register has 32 penetrations. Each requires ten evidence fields, giving 320 required cells. At draft handover, 304 cells are complete, eight are accepted as not applicable with written rationale, four are temporarily unavailable but recoverable, and four are missing without disposition. Assign weights 1.0 for complete, 1.0 for justified not applicable, 0.5 for recoverable pending evidence, and 0 for missing.

$I_e = (304 + 8 + 2) / 320 = 0.98125$, or 98.1 per cent; the high percentage does not release the project because the four missing cells may concern critical penetrations; the index supports management but cannot replace consequence-based review. The correct disposition is to identify the four missing items, apply operational restrictions if necessary, recover evidence or reopen the work, and obtain authorised acceptance.

Table 25-9. Chapter 25 integrated release matrix

Release domain	Required evidence	Minimum technical question	Disposition if incomplete
Service design	Routes, loads, movement, supports, operating states	Is every source-path-receiver chain physically defined?	Return design for coordination
Fire and smoke	Applicable tested system or accepted judgement, inspection	Does the exact installed configuration fall within accepted evidence?	Correct, justify through authority, or reject
Acoustic control	Path model, local treatment, field measurements, uncertainty	Are airborne and structural paths bounded under credible states?	Diagnose, remediate and retest

Release domain	Required evidence	Minimum technical question	Disposition if incomplete
Electrical and ICT	Code and project compliance, bonding, pathway function	Does acoustic treatment preserve safety, capacity and maintainability?	Redesign jointly
Structural and seismic	Support loads, restraint, movement, clearances	Can required loads be carried without avoidable boundary bridges?	Recalculate and reconstruct
Configuration evidence	Hold points, photographs, register, raw data	Can the installed object and its history be recovered later?	Open work or retain explicit limitation
Lifecycle	Maintenance method, spare capacity, change triggers	Will later work preserve the validated state?	Withhold final closure until governance exists
Authority	Signed technical and use dispositions with scope	Who may accept the residual risk and authorise use?	Do not represent technical completion as authorisation

25.37 Medical gas, compressed air, vacuum and pneumatic control lines

Small-bore services are often treated as acoustically negligible because their openings are small. That assumption fails when the line is long, rigidly supported, connected to a pulsating source, or terminated in an accessible space. Medical gas, laboratory gas, compressed air, instrument air, vacuum and pneumatic control lines can carry pressure fluctuations and mechanical vibration. Regulators, ejectors, solenoid valves and vacuum pumps add tonal and impulsive sources. Their small diameter can also encourage informal drilling through a boundary after the principal construction has been accepted. [89]

The design should identify fluid or gas, normal and maximum pressure, flow, cleanliness, material, joining method, valve and alarm states, supports, purging requirements and maintenance; oxygen and other hazardous services impose strict compatibility and fire-safety duties; acoustic treatment

89 MB-1038. National Fire Protection Association, NFPA 99, Health Care Facilities Code.

must never introduce prohibited materials, contaminants or dead legs. Qualified discipline review is required. The security engineer's role is to identify transmission and access paths, not to redefine medical-gas or process-system rules.

Pressure-wave behaviour differs from water because gas density and compressibility are much lower; the characteristic impedance of a gas line remains Z = rho c/S in a plane-wave approximation, but rho and c vary with gas, temperature and pressure. A regulator can generate broadband noise as pressure drops across a restriction; a vacuum line can transmit pump pulsation and also behave as a connected bore; flexible tubing can reduce some structural coupling, yet it may be mechanically vulnerable or incompatible with cleanliness and fire requirements.

Pneumatic control lines deserve lifecycle attention. Legacy building-control systems may remain after digital controls are added; a capped line can be forgotten inside a wall; a technician can later repurpose it; the asset register should record active, spare and abandoned lines. Abandoned lines should be removed or permanently closed under an approved plan, with the penetration restored and evidence updated. Cutting a line flush with the wall and filling the visible end does not address a connected cavity or sleeve.

Vacuum outlets and laboratory panels can become membrane penetrations. Their recessed boxes, flexible hoses and equipment mounts should be assessed similarly to electrical boxes. Alarms and transducers can contain microphones, buzzers or network interfaces. Chapter 26 addresses electronic functionality, but Chapter 25 retains responsibility for the physical opening and support route.

Commissioning should exercise normal draw, regulator action, alarms, purge or test states, and pump cycling as applicable; high-pressure or medical systems require authorised procedures and competent personnel; acoustic sensors should be installed without contamination or interference; a source-reference channel at the pump or regulator can support transfer analysis. The report should record pressure and flow rather than describing the state merely as on.

Worked example 25.27. Gas-line characteristic impedance comparison

Two lines have the same internal area S = 3.0 x 10^-4 m2. Line A contains air at density rho_A = 1.2 kg/m3 with sound speed c_A = 343 m/s. Line B contains water at rho_B = 998 kg/m3 with effective wave speed c_B = 1,200 m/s. Calculate plane-wave characteristic impedances.

Z_A = 1.37 x 10^6 Pa s/m3; z_B = 3.99 x 10^9 Pa s/m3; the water-line value is about 2,910 times larger; this does not mean the air line is harmless. It means pressure and volume-velocity relations differ radically, and source, wall motion, terminations and support paths must be modelled for the actual medium.

25.38 Service shafts, risers and common chases as distributed receivers

A shaft is not merely a void around services. It is a tall coupled enclosure with walls, doors, floor openings, fire and smoke barriers, access points, pressure gradients and many connected rooms. Speech or equipment noise entering one location can propagate, excite shaft linings and emerge at another floor. The receiving point may be far from the protected room and more accessible than the immediately adjoining space. Secure-room threat and measurement plans should therefore identify shafts and risers as distributed receivers. [90]

The shaft path can combine airborne and structure-borne mechanisms; a penetration opens into the shaft. The shaft supports sound vertically. Pipe and tray supports excite shaft walls. Access doors radiate into corridors. Floor seals and fire dampers divide the path imperfectly; stack effect changes pressure with weather and building operation; a local room-pair test may not excite or observe the remote path adequately.

Shaft-wall construction should be continuous and compatible with fire requirements; service supports should attach to appropriate structure rather than lightweight shaft lining unless engineered; access doors should have complete ratings and gaskets where required; a massive shaft wall with a lightly built access door remains controlled by the door. The door's routine opening state should be included in maintenance planning.

Riser penetrations through floors can create vertical flanking that bypasses horizontal room boundaries; firestop systems address rated penetrations but do not by themselves establish acoustic closure; cable and pipe density can vary by floor, creating different conditions within one system. The penetration register should link each riser opening and should show whether a change on another floor can affect the protected room.

Diagnostic testing may require source and receiver positions on several levels; a controlled source can be placed near the protected penetration, while microphones and accelerometers survey shaft doors and walls; building access, safety and information controls should be planned. A strong

90 MB-0057. ASHRAE, ISO 16283-1:2014.

response at a remote door can justify targeted improvement without implying that every point along the shaft is equally vulnerable.

Pressure should be recorded where it can change leakage. Smoke-control modes, stair or shaft pressurisation, exhaust operation and weather can alter direction and magnitude of airflow. A field test under one pressure state should not be generalised silently. In high-rise or overseas facilities, seasonal and emergency states can be materially different.

A service chase adjacent to a protected room can be valuable because it consolidates penetrations and maintenance; its advantage depends on access control, boundary quality and operational discipline; a chase door left open during work can expose many paths simultaneously. The work permit should restrict protected discussions, control adjoining access and require closure verification before use resumes.

Worked example 25.28. Level change produced by shaft-area divergence

A simplified shaft carries constant acoustic power upward. At one section the effective cross-sectional area is S_1 = 2.0 m2; at a larger plenum it becomes S_2 = 8.0 m2. Ignoring losses and modal effects, diffuse intensity scales inversely with area. Estimate level change.

Delta L = 10 log10(0.25) = -6.0 dB. The larger area reduces average intensity by 6 dB in this crude energy model, but reflections, openings and modes can create local increases. The example is a screening relation, not a shaft transmission prediction.

25.39 Exterior, roof and below-grade service penetrations

Exterior penetrations introduce weather, pressure, pests, corrosion, ultraviolet exposure and public accessibility. A pipe or conduit leaving a protected room may terminate at a roof, façade, loading area or below-grade vault. The exterior endpoint can provide a receiver location outside the usual room-pair test. Design should therefore trace the route to its actual termination and assess lawful access within the authorised threat model. [91]

Wind creates fluctuating pressure at façade openings; stack effect and mechanical pressurisation can drive flow through residual gaps; a seal that appears quiet in still conditions can whistle or leak under wind; exterior tests should record weather and pressure. Water tests, where required, should be coordinated so that they do not damage acoustic backing or introduce hidden moisture.

Roof penetrations can connect to mechanical equipment, vents and cable routes; a vent termination may need open airflow and cannot be sealed acoustically; control may require routing, distance, lined offsets, silencers or location within a controlled roof zone. The designer should avoid representing a weather cap as an acoustic terminator; roof access and maintenance patterns should be considered.

Below-grade penetrations face groundwater, soil gas and difficult repair; link seals and mechanical seals can provide pressure or water control, but their rigid compression can transmit force. Waterproofing membranes must remain continuous. A leak repair can involve excavation or internal injection

91 MB-1228. U.S. Department of Defense, UFC 3-401-01, ISO 16283-1:2014.

that changes the acoustic path; baseline photographs and product records are especially important because later access is costly.

Metal sleeves through exterior walls can create thermal bridges and condensation; corrosion can occur at buried or concealed interfaces; cathodic protection, bonding and coating requirements can constrain segmentation; acoustic recommendations must be reviewed by civil, structural, electrical and waterproofing disciplines. A soft material inserted without compatibility evidence can undermine water or fire protection.

Public-facing external labels should be neutral. The detailed register can remain controlled. Service terminations that reveal room function should be screened through security design. Physical protection must not obstruct required ventilation, relief or emergency operation. The competent authority balances these functions.

Commissioning should inspect inside and outside faces, test pressure or water performance where required, and perform acoustic checks at accessible terminations under representative conditions. A passing internal room-pair test does not close an exterior path that lies outside the receiving-room sample.

25.40 Remediation strategy, reversibility and proof of causal closure

Remediation should target a demonstrated mechanism. Applying more sealant to every visible surface can conceal evidence, violate listed systems and leave structural bridges untouched. The corrective process begins with hypothesis ranking, selects the least disruptive intervention capable of testing the leading path, measures the result, and then designs a permanent treatment that preserves fire, structural, electrical and service functions. [92]

Reversibility is valuable during diagnosis. Temporary external caps, removable damping mass, authorised changes in equipment state and non-curing gap covers can test hypotheses without destroying the original condition; their materials and placement must be safe and documented; a reversible intervention that changes the response substantially strengthens causal attribution. A permanent repair should then reproduce the controlling physical effect using approved materials and details.

A repair hierarchy generally favours elimination or rerouting, then structural separation, then closure of openings, then local damping or enclosure, and finally operational restrictions; elimination can remove the path entirely but may be costly; structural separation can be durable but conflicts with required supports. Seal repair is appropriate for residual voids; damping can reduce radiation without controlling fluid-borne transfer. Operational restrictions can manage residual risk but require authority and lifecycle discipline.

Repairs to listed firestop systems should follow the approved system or an accepted evaluation; mixing products or adding incompatible layers is not justified by acoustic benefit; damaged material may need complete removal to sound substrate; surface patching can hide an internal void. The repair record should show removal, preparation, backing, fill, cure and final inspection.

92 MB-0873. International Organization for Standardization, ISO 16283-1:2014, NIST Technical Note 1297.

Proof of causal closure requires more than a better whole-room number; the local indicator associated with the diagnosed path should change in the predicted direction, and the complete boundary should be retested where consequence warrants; if a pipe-contact repair reduces wall vibration at the relevant frequency but room performance does not improve, another path remains. The report should not declare the original diagnosis wrong automatically. Parallel-path dominance may have shifted.

Remediation can introduce new defects. Opening a wall can damage vapour control; moving a support can overload another; adding mass can reduce one resonance and create another; rerouting cable can exceed bend radius. Post-repair inspection should revisit all affected disciplines. A closed acoustic nonconformance does not close the fire or electrical work order unless those reviewers agree.

Worked example 25.29. Sequential repair and diminishing return

Three paths have coefficients tau_1 = 5.0 x 10^-4, tau_2 = 2.0 x 10^-4 and tau_3 = 5.0 x 10^-5. Repair 1 reduces tau_1 by 20 dB. Repair 2 then reduces tau_2 by 15 dB. Calculate losses after each stage.

Initial tau = 7.5 x 10^-4, so R_0 = 31.25 dB; after Repair 1, tau = 5.0 x 10^-6 + 2.0 x 10^-4 + 5.0 x 10^-5 = 2.55 x 10^-4, giving R_1 = 35.93 dB. The 20 dB local improvement yields only 4.68 dB system improvement; after Repair 2, tau = 5.0 x 10^-6 + 6.32 x 10^-6 + 5.0 x 10^-5 = 6.13 x 10^-5, giving R_2 = 42.12 dB. The remaining third path now dominates. This is why remediation plans should anticipate path succession.

25.41 Operational readiness, periodic assurance and retirement

Handover is the beginning of service life. A penetration baseline remains valid only while configuration, access, operating states and materials remain within the accepted bounds. Operational readiness should therefore include custodian assignment, training, spare materials, inspection schedule, change permits, incident response and retest triggers. The room should not enter protected use merely because construction activities have ended. [93]

The readiness review should reconcile every penetration identifier against field location and evidence; open nonconformances are classified by consequence; temporary conditions have expiry dates and authority; maintenance teams receive controlled access to the records needed for their work. Security staff understand which events require room restriction. Fire-protection and facilities staff understand that routine service can alter an acoustic boundary.

Periodic assurance should be risk-based. Frequently accessed panels, high-movement pipes, public-side terminations and densely modified cable transits deserve shorter intervals; stable concealed sleeves with complete evidence may rely on event-triggered review; inspection frequency should be justified and revised when defects are found. Repeated failures at one class of penetration indicate a process problem, not isolated bad luck.

Trend indicators can include gasket compression, support clearance, measured transfer at reference bands, room pressure, background state, cable fill, corrosion and outstanding work orders. Reference measurements should use reproducible source and receiver positions. A trend change

93 MB-1030. National Fire Protection Association, ISO 19650-5:2020.

triggers diagnosis. It should not be forced into a pass-fail conclusion if the reference method was not designed for formal acceptance.

Incidents include water leaks, fire alarm discharge, hydraulic shock, seismic event, construction nearby, unauthorised cable work, panel left open, corrosion, pest intrusion and unexplained acoustic change. The response plan identifies immediate operational restriction, evidence preservation, inspection, repair and authority notification. A leak repair performed at night can be necessary, but the room should not return to protected use until the affected baseline is restored or an authorised limitation is imposed.

Retirement and decommissioning also require control. Removing a protected room can expose restricted construction information, leave active services, disturb fire barriers and create uncontrolled waste. The plan should identify which records are retained, which materials require secure disposal, how penetrations are closed, and who accepts the new building state. A de-accredited or repurposed room is not simply abandoned in its former configuration.

Worked example 25.30. Inspection-interval adjustment from observed defect rate

A class of 80 cable transits is inspected annually; in the first year, eight material defects are found, giving observed proportion 0.10; after process correction and six-month inspection, two defects are found among 80, proportion 0.025. The defect proportion has fallen by 75 per cent; the project may consider extending the interval only after verifying severity, independence, repair quality and continued low rate over additional cycles. One favourable sample does not establish long-term stability.

Table 25-10. Chapter 25 lifecycle trigger register

Trigger	Immediate technical question	Minimum response	Return-to-use condition
New or removed service	Did geometry, fill, support or treatment change?	Permit, inspection, register update, targeted test	Accepted configuration and evidence
Water or condensation event	Were backing, adhesion, insulation or corrosion affected?	Moisture investigation and material assessment	Dry, repaired and inspected state
Hydraulic transient or major vibration event	Did contact, restraint or seal condition change?	Support and penetration inspection, comparison test	No damaging change or accepted repair
Fire or smoke event	Is the firestop system still serviceable?	Fire-protection evaluation and acoustic review	Authority-approved restoration
Software or plant-control change	Did source speed, pressure or cycling change?	State-matrix review and operational measurement	Updated commissioning baseline
Unauthorised opening or work	What was altered and what evidence was lost?	Restrict use, investigate, reconstruct or open	Competent-authority disposition
Periodic trend exceedance	Is the change real and which path controls?	Verify measurement, diagnose, remediate	Trend restored or limitation accepted
Decommissioning	What services, records and controlled features remain?	Controlled closure and record retention	New building state accepted

25.42 Procurement, submittal review and substitution control

Service-penetration performance can be lost before construction begins if procurement documents specify products without configurations; a submittal package should connect every proposed product or system to the exact opening, substrate, penetrant, support, movement and required attribute; a catalogue sheet showing a broad family of firestop or acoustic materials is not an application-specific submittal. The reviewer needs the tested system, system number, revision or publication status, installation detail, limitations, compatible ancillary products and proposed field location.

The specification should separate performance requirements from prescriptive constraints; performance language states the required outcome and test basis; prescriptive language fixes materials, geometry or workmanship; in a high-consequence penetration, both may be necessary. The contractor remains responsible for coordination. The design team should not accept a substitution merely because a single laboratory rating equals or exceeds the original. The proposed system may have different annular limits, movement capability, substrate, support needs, cable fill, cure conditions or maintenance method.

Substitution review should use a structured equivalence matrix; fire evidence is compared with fire evidence; acoustic evidence is compared with acoustic evidence; structural movement, chemical compatibility, electrical function, water resistance and maintainability receive separate rows. A blank row is not assumed equal. The proponent identifies every deviation and supplies evidence. The authority decides whether residual differences are acceptable.

Lead times can create pressure for informal substitutions; a proprietary transit frame may be unavailable. A sealant colour may change. A cable type may be replaced. The project should identify long-lead components early and maintain approved alternates where possible; emergency procurement still requires documented technical review; a field team should not learn that a product differs after half the openings are concealed.

Installer competence is part of procurement. Training, qualification or manufacturer approval may be required by the system or project. Competence evidence should be current and relevant to the installed product. A qualified contractor programme can add quality assurance, but it does not eliminate project inspection. The project's first-of-type hold point remains necessary because competent installers can still receive incorrect drawings or encounter unanticipated geometry. [94]

Samples and mock-ups should use production materials; a demonstration built with ideal openings and selected technicians may not represent crowded field conditions; the review should include eccentric penetrants, mixed cables, difficult access and the actual supporting wall or slab. Rejected samples should be marked and retained long enough to train crews and inspectors where practical.

Submittal changes should propagate to the penetration register and drawings; if the system number changes, affected openings should be identified; if one opening requires an engineering judgement, it should not become the undocumented template for others; the final record should show what was approved and what was installed, not merely the earliest submitted product.

Table 25-11. Penetration-substitution equivalence checklist

Review field	Original basis	Proposed substitute evidence	Required conclusion
Substrate and rating	Exact wall or floor assembly	Tested or evaluated match	Equivalent, more restrictive, or unresolved
Penetrant and fill	Material, size, count, insulation	Listed range and actual field state	Within range or redesign required
Annular geometry	Minimum, maximum, centring	Substitute limitations	Field tolerances compatible
Movement	Thermal, seismic and service displacement	Tested movement and detailing	Required motion accommodated
Acoustic mechanism	Open area, structural bridge, radiation	Assembly or component evidence plus model	Equal or improved path control
Chemical and moisture	Substrates, coatings, water and cleaning	Compatibility and durability data	No adverse interaction identified
Electrical and ICT	Bonding, pull, bend radius and access	Discipline review	Function and safety preserved

94 MB-1307. UL Solutions, Qualified Contractor Program, public firestop-contractor programme information.

Review field	Original basis	Proposed substitute evidence	Required conclusion
Inspection and maintenance	Hold points, labels, repair method	Proposed process	Evidence remains obtainable
Authority	Required reviewers and approvers	Signed dispositions	No substitution released without scope-specific approval

25.43 First-article construction, destructive verification and process capability

A first-article penetration is a production-representative installation completed early enough to change the work. It should include the actual wall or slab, sleeve, service, supports, firestop, acoustic treatment, access and finish sequence. Its purpose is not ceremonial approval. It is to test whether drawings, materials, tools, tolerances, responsibilities and inspection can produce the required configuration under site conditions. [95]

The first article should be selected from a consequential and repeatable class, such as a chilled-water sleeve, cable transit, conduit bank or sprinkler drop. Unusual one-off penetrations still require individual control, but they do not demonstrate process capability for the repetitive work. The team should define acceptance criteria before construction and should record labour sequence, elapsed times, environmental conditions and difficulties.

Destructive verification can be justified where hidden depth or distribution cannot be confirmed reliably; a completed sample may be sectioned, opened or removed after cure to measure backing, fill and adhesion; the cost is small compared with discovering systematic defects after hundreds of openings are concealed. Destructive inspection should occur under an approved plan, with safety and material-disposal controls; the sample

95 MB-1241. U.S. Department of Defense, UFGS 01 45 00, Quality Control.

should then be reconstructed or replaced, and the repair itself can become a training exercise.

Process capability should not be reduced to one successful sample; repeated measurements of annular width, backing depth or installed deflection can show whether the process remains centred and stable; let $\bar{x}$ (x_bar) be sample mean, s be standard deviation, and LSL and USL be lower and upper specification limits. The conventional indices $C_p = (USL - LSL)/(6s)$ and $C_{pk} = \min[(USL - \bar{x})/(3s), (\bar{x} - LSL)/(3s)]$ can support manufacturing-style control when data are approximately stable and the metric is appropriate; they do not replace compliance of each critical opening.

A high C_p with low C_{pk} indicates a capable spread that is poorly centred; for annular space, the crew may produce consistent openings that are systematically eccentric; a high average can still hide local contact if the measured variable is not the true controlling minimum. Statistical methods are useful only when the measurement model matches the physical requirement.

The release from first article to repetitive production should specify which variables are frozen and which may vary; crew, product lot, service size, substrate, sleeve method or access can change; a material or method change can require a new first article. The surveillance plan should define reset triggers rather than assuming the first approval lasts indefinitely.

Worked example 25.31. Capability indices for backing depth

A penetration class requires backing depth between LSL = 45 mm and USL = 60 mm. Twenty production measurements give mean x_bar = 51.0 mm and standard deviation s = 1.8 mm. Calculate C_p and C_pk.

C_p = 15/(10.8) = 1.39. The upper-side index is 9/5.4 = 1.67, and the lower-side index is 6/5.4 = 1.11, so C_pk = 1.11; variation is reasonably contained, but the process is closer to the lower limit; the team should investigate centring and should not use the index to waive direct inspection of high-consequence penetrations.

25.44 Forensic preservation, dispute resolution and expert interpretation

Construction disputes often arise after concealment, when parties possess different photographs, drawings and recollections. A disciplined penetration record reduces speculation. The expert should distinguish contemporaneous observation, later measurement, inferred mechanism and authority decision. A photograph can establish that a sleeve appeared centred from one face on one date. It cannot establish backing depth on the hidden face unless the image shows it. A test report can establish measured response under stated conditions. It cannot prove that every untested operating state is safe. [96]

Evidence preservation begins when an anomaly is recognised; the affected opening should be identified and protected from casual repair; photographs, instrument files, control logs, work orders, product lots and witness accounts should be collected; hashes can demonstrate file integrity after collection. A chain-of-custody log records possession and processing.

96 MB-0912. International Organization for Standardization, ISO/IEC 17025:2017, ASTM E860.

Privilege, confidentiality and security classification should be managed by counsel and the competent authority. Technical staff should not distribute restricted construction details merely because they are relevant to a defect.

Destructive examination should proceed from least to most intrusive; surface covers are documented before removal; each layer is photographed with scale and orientation. Samples are labelled. Dimensions are measured with calibrated tools. If materials require laboratory identification, the sampling plan should preserve representative portions and controls; the opening should remain safe and fire-protected during the investigation, using authorised temporary measures.

Competing hypotheses should be stated before repair where practicable; if the alleged cause is an open annulus, a temporary external closure should reduce local airborne response; if the alleged cause is a rigid support bridge, local vibration and transfer should change when the path is modified under an engineered procedure. A repair performed without pre-repair measurements can solve the problem while destroying proof of cause; operational urgency may justify immediate action, but the lost inference should be disclosed.

Expert opinions should match evidence strength. Exact phrases such as caused by, consistent with, more likely than not, cannot be excluded, or not supported carry different implications; the report should explain the physical model, alternatives, uncertainty and limits; it should not import a legal standard into an engineering calculation without instruction, and it should not imply governmental acceptance from a consultant's conclusion.

Dispute resolution benefits from a common chronology; design issue, approved submittal, installation, hold point, change, test, discovery, intervention and retest are aligned; apparent contradictions often arise because records describe different states; a cable transit can have been compliant at initial handover and later altered. A photograph can predate a cable pull. State reconciliation is therefore central to causation.

The final remedial agreement should update configuration records. A settlement that pays for repair but leaves drawings and registers unchanged creates a future defect. The repaired opening should pass the same technical and authority gates as original work, with added disclosure of any residual limitation.

25.45 Source-currentness, edition control and publication boundary

Technical source status is itself a controlled variable. A project can cite the correct title but the wrong edition, rely on an archived criterion, or mistake a committee work item for a published standard. Chapter 25 therefore uses a dated source freeze and records issuer, title, designation, edition or change, status, locator, jurisdiction and scope limitation. WBDG identifies UFC 3-520-01 as active with Change 1 dated 21 January 2026, UFC 3-580-01 as active with publication date 21 November 2024, UFC 3-401-01 as active with Change 2 dated 14 May 2026, and UFGS 07 84 00 as active within the May 2026 UFGS master. Those facts establish publication status, not project applicability or secure-room acceptance. [97]

The principal ASTM E814 landing page displayed E814-24 as active, while several older-version entries in the same indexed catalogue listed E814-26

97 MB-1230. U.S. Department of Defense, UFC 3-520-01, UFC 3-580-01.

as active; WK97942 separately records a revision work item initiated on 30 January 2026. The register therefore records E814-24 as the accessed edition analysed and requires direct catalogue confirmation before project use. ASTM E3456-25 and ASTM E3037-20 were displayed as active published standards, while WK95859 and WK97854 remained development work items. A work item is not a published replacement. The register preserves these distinctions at the 16 August 2026 source freeze. [98]

Standards and criteria should be cited at proposition level; a fire-test statement points to the fire-test source; an electrical-pathway statement points to the electrical criterion; a movement limitation points to the movement method. One omnibus footnote at the end of a long section can obscure which authority supports which claim. Substantial explanatory notes are appropriate where edition history, applicability or non-equivalence needs clarification, but footnotes should not repeat the body merely to increase count.

Public sources have limits. They do not disclose every project-specific or controlled threshold, and their absence does not authorise invention; a public textbook can explain mechanisms, evidence architecture and governance; it should not infer protected details from product combinations, isolated government examples or unauthorised recollection. Where a controlled criterion governs a project, the public record can identify the existence of a controlled requirement and route authorised users to the proper annex without reproducing it.

98 MB-0311. ASTM International, ASTM E814-24, ASTM E3456-25.

Source freeze is followed by final validation; before publication, links, edition status and pinpoint references should be rechecked; if a source changes after freeze, the release note should state whether the change affects technical conclusions; a new edition does not automatically invalidate prior work, but its effect should be reviewed. Historical sources remain useful when labelled accurately.

This discipline makes the chapter auditable. The reader can separate verified publication status, engineering inference, project recommendation and authority decision. That separation is as important as the equations. It prevents the quiet movement of a statement from guidance to requirement, from specimen evidence to field proof, or from technical sufficiency to official authorisation.

The source register also records conflicts and supersession; where two official pages present different apparent statuses, the release uses the document's current primary landing page and records the conflicting search artefact rather than silently selecting the convenient result. Where a standard is paywalled, the citation is confined to public scope and status information unless the authorised project file contains the full licensed text; no quotation is stretched beyond the accessible source; calculations are independently derived and identify their assumptions, so the engineering reasoning remains reviewable even when the referenced publication must be obtained through a licensed library.

A disciplined source register also records the proposition for which each publication is used; one standard may support fire exposure, another electrical clearance, another measurement uncertainty, and another laboratory competence; the register should not simply list documents beside a chapter number. It should link each claim to the clause, table, figure, annex or public status page that supports it, then record the inference made by the author; this proposition-level linkage permits a later reviewer to update one conclusion without reopening every unrelated part of the chapter. It also exposes unsupported leaps, such as treating an installer qualification as proof that a particular hidden annulus was correctly built.

Edition change requires impact analysis rather than mechanical replacement; a revised standard can alter terminology, specimen geometry, reporting, tolerances, acceptance rules or only editorial wording; the reviewer should compare the old and new provisions relevant to the actual proposition, identify whether the installed configuration remains represented, and record the conclusion. Where a new edition was published after construction, the project may need to preserve the historical criterion for contractual interpretation while separately assessing whether current knowledge identifies a safety, performance or governance concern; the date of the design decision, the date of installation and the date of the present review should therefore remain distinct.

Errata, corrigenda, interpretations and authority memoranda require similar control; a corrected equation can affect calculations immediately, while an interpretive bulletin may clarify only one configuration; search-engine snippets, distributor catalogues and copied extracts are navigation aids, not substitutes for the issuer's controlled publication. When the official source is licensed or access-restricted, the public register should record designation, edition and scope without reproducing protected text; the authorised project file can then carry the licensed pinpoint under its proper access controls. This method preserves scholarly auditability without converting a public textbook into an unauthorised standards repository.

The register should also preserve negative research; if no public source was found for a claimed universal acoustic value, the result should be recorded as unresolved rather than silently replaced by custom, recollection or a manufacturer's unsupported table. A documented absence narrows the claim and directs further review; it does not prove that no controlled, local or later source exists; the competent authority may possess additional criteria, and the publication should provide a clean insertion point for those authorised overlays without inferring their contents.

Finally, source control must extend to calculations and figures created for this work; each original equation application should identify its parent relation, variables, units, geometry, state and valid range; each table should identify whether its fields are requirements, recommended controls, examples or administrative screens. Each figure should distinguish measured geometry from conceptual topology; these labels prevent original synthesis from acquiring a false governmental pedigree merely because it appears beside official citations. They also permit later peer reviewers to challenge the engineering reasoning directly, which is the proper test of an original treatment.

The resulting chapter is intended to function like a carefully indexed evidence bundle laid out beneath clear laboratory light; materials, forces, openings, states and decisions remain separately visible; a future reviewer can hear the difference between a pump tone and a conduit resonance, see where the sleeve touches the pipe, and trace the paper and digital record back to the exact object. That transparency is the foundation of defensible acoustic-security engineering.

No release is complete until physical configuration, documentary provenance and decision authority converge upon the same identified penetration under the same declared state.

Evidence must remain reproducible after every change.

Chapter 25 now treats service penetrations as dynamic engineered systems rather than incidental holes. The controlling mechanism can pass through fluid, pipe wall, cable bundle, frame, support, connected cavity or open bore, and it can change when water, load, temperature, software-controlled plant or maintenance state changes. A durable design therefore begins with routing and topology, continues through exact geometry and parallel-path control, and ends with evidence that remains traceable after concealment.

The chapter also establishes a strict non-equivalence rule; firestop tests, product certifications, visual inspections, acoustic measurements and governmental use decisions answer different questions; they must be coordinated, but none should be silently substituted for another; each proposition has its own evidence, each observation has a known state, and each decision has a named authority.

For publication and project use, the next step is to apply the same depth to the electronic systems that terminate these pathways. Chapter 26 must therefore examine microphones, loudspeakers, conferencing endpoints, sensors, automation, software state and physical mounting with the same source-path-receiver and lifecycle rigour.

Chapter 25 Glossary

Annular space. The region between a penetrant or service and the boundary of its opening or sleeve.

Acoustic closure. Treatment intended to limit pressure or vibration transfer without implying fire, smoke or security approval.

Fire-stop system. Tested, listed or engineered arrangement of penetrant, opening, backing, fill and substrate used to restore a fire-resistance function.

Flexible connector. Element intended to reduce force transfer while accommodating movement, subject to its load and installation conditions.

Penetration register. Lifecycle record linking each boundary opening to geometry, service, treatment, evidence and later change.

Service bridge. Unintended rigid or semi-rigid load path created by a pipe, conduit, tray, support, brace or related element.

Sleeve. Liner or formed opening through which a service passes and whose geometry constrains treatment.

Source state. Defined operating condition of speech, equipment, flow, pressure or system controls used for design or test.

Trap seal. Water barrier in a plumbing trap. It controls gases under defined conditions but is not a general acoustic seal.

Witness point. Inspection point for which attendance is invited under stated notice conditions but work may proceed as contractually defined.

Expanded glossary additions

Characteristic impedance. Ratio relating pressure to volume velocity for a stated propagation model, medium, geometry, and reference condition.

Configuration proposition. A statement about one identified physical state that must be supported by its own evidence and decision rule.

Eccentricity. Offset between penetrant and sleeve centres, reducing minimum local annular clearance.

Engineering judgment. Documented technical evaluation used within the scope permitted by the governing firestop or project process. It is not a universal test report.

First article. Production-representative installation completed early enough to test and correct the construction process.

Hold point. Contractually defined stage at which work may not proceed until the stated inspection or disposition occurs.

Joukowsky relation. One-dimensional screening relation between rapid velocity change and transient pressure change in a fluid line.

Material change. Alteration to geometry, service, support, equipment, access, operation, or evidence that can invalidate an earlier conclusion or authority decision.

Minimum local clearance. Smallest actual separation between a penetrant and its opening or sleeve, rather than the nominal or average annular width.

Non-equivalence rule. Requirement that fire, acoustic, structural, electrical, evidentiary, and governmental conclusions remain separate unless an authorised source establishes a valid relationship.

Parallel path. Additional route whose transmitted energy combines with other routes and can control the total after the principal path is improved.

Penetration class. Controlled grouping of openings sharing the attributes necessary for common design, inspection, testing, and lifecycle treatment.

Process capability. Statistical description of process spread and centring relative to stated limits, valid only under an appropriate stable measurement model.

Recommissioning trigger. Change or condition requiring targeted or full repeat verification of the affected state.

Reversibility. Property of a diagnostic intervention that permits removal without destroying the original condition or creating an uncontrolled permanent alteration.

Shaft receiver. Accessible or consequential point along a common shaft or riser where transmitted sound or vibration may emerge.

Source freeze. Dated record of the editions, statuses, locators, and access conditions used for a release.

State matrix. Controlled list of normal, emergency, maintenance, test, failed, and transitional conditions relevant to design and verification.

Substitution equivalence. Attribute-by-attribute demonstration that a proposed change remains within every controlling technical and authority boundary.

Through-path. Continuous airborne, fluid-borne, or structure-borne route across or around a nominal boundary.

Chapter 26. Audiovisual Systems, Telephones, Conferencing Equipment, Sensors, and Building Automation

A room can possess formidable walls and still reproduce protected speech through a conference loudspeaker, capture it through an overlooked microphone, route it through an approved platform in an unauthorised mode, or lose its intended acoustic state after a remote software update. The secure-room boundary therefore includes equipment identity, mounting, signal paths, gain structure, software, firmware, credentials, network interfaces, mute behaviour, maintenance and change governance.

Acoustic engineering cannot certify cyber security, and technical surveillance countermeasures cannot replace field sound-isolation testing; the disciplines must nevertheless meet at physical interfaces; a camera bar needs anchors and cables; a ceiling array needs penetrations and supports. A controller may alter masking and HVAC. A display may contain microphones or loudspeakers not shown on the architectural schedule.

Figure 26-1. Electronic systems change source level, pickup, routing, structural excitation and the operating state of the room. Author's original diagram.

26.1 Electronic equipment as part of the source-state model

Human speech is only one source in a modern secure room. Conference loudspeakers, presentation systems, assistive devices, alarms, telephone handsets, test modes and vendor diagnostics can generate speech or speech-like signals at levels and bandwidths exceeding ordinary conversation. Their use states must be explicit in the acoustic basis of design. [99][100][101][102]

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99 MB-1260. U.S. Department of State, 12 FAM 510.
100 MB-0797. International Electrotechnical Commission, IEC 60268-16:2020.
101 MB-1239. U.S. Department of Defense, UFC 4-010-06.
102 MB-0805. International Electrotechnical Commission, IEC 61672-1:2013.

Source level depends on loudspeaker sensitivity, amplifier gain, equalisation, compression, limiting, beam steering, room correction, automatic gain control and software presets. A nominal volume setting is not a physical level. The same equipment can produce materially different spectra after firmware revision or automatic calibration. Within electronic equipment as part of the source-state model, the decisive analysis follows the complete source-path-receiver chain and records each interface capable of carrying pressure, force, information or measurement bias.

The source-state matrix should identify every authorised electronic source, its maximum permitted operating mode, position, orientation, gain path, duration, duty cycle, control owner and emergency state. Prohibited states should be technically blocked or administratively governed rather than omitted from the design model. The design record for electronic equipment as part of the source-state model should translate those mechanisms into dimensions, products, tolerances, support conditions, inspection stages and named ownership.

Commissioning should measure actual installed output and should preserve settings, software version, test signal, room state and access credentials; later updates or equipment replacement require impact screening because the original acoustic test may no longer represent the source. A passing wall test under a portable loudspeaker does not bound the room if the installed system can operate louder, closer to a boundary or with wider low-frequency content; evidence concerning electronic equipment as part of the source-state model should identify the exact observed unit, method, instrument chain, state, limitations and inference supported.

Worked example 26.1. Electronic source-level increase

A conference system is commissioned at 78 dB in a reference band at the principal seat. A later preset increases electrical gain by 6 dB while the loudspeaker remains in its linear range.

L_1 and L_2 are sound-pressure levels at the same position and state except for gain, and Delta G is the gain change in decibels.

The source becomes 6 dB more demanding for the boundary. In an ideal linear path, receiving level also rises by approximately 6 dB.

Limiter action, loudspeaker compression, room response and frequency-dependent equalisation can alter the simple level balance.

26.2 Microphones, arrays and intentional capture paths

Installed microphones are deliberate transducers and must be treated as controlled assets. Table microphones, ceiling arrays, camera bars, handsets, hearing-assistance systems and embedded device microphones can capture local speech. Beamforming and automatic steering can change effective pickup without moving the hardware. [103][104][105][106]

Microphone behaviour depends on polar pattern, array geometry, preamplifier gain, automatic level control, echo cancellation, noise reduction, mute logic and network routing. A visible indicator may represent only one software state. Some devices maintain diagnostic, wake-word or remote-management functions while the user interface appears inactive. For microphones, arrays and intentional capture paths, the mechanism must be traced from excitation through materials, supports, openings,

103 MB-1260. U.S. Department of State, 12 FAM 510.
104 MB-1239. U.S. Department of Defense, UFC 4-010-06.
105 MB-1047. NIST SP 800-53.
106 MB-1049. NIST SP 800-82.

controls and adjoining spaces rather than inferred from the trade name of one component.

The equipment schedule should identify every microphone-capable asset, approved purpose, physical location, power, network, firmware, mute design, control path, recording function and maintenance route. Where the authorised programme prohibits or restricts devices, inventory and inspection must be coordinated with the responsible security authority. Accordingly, microphones, arrays and intentional capture paths require a controlled configuration with stable identifiers, coordinated details, access provisions and change triggers that remain usable after handover.

Verification requires asset and serial reconciliation, functional mute tests, signal-path review, configuration capture, network review within authorised scope and physical examination of cabling and mounts. Acoustic measurement should determine intended pickup performance where relevant but should not be represented as a device-security examination. Absence of output on one user interface is not proof that no microphone signal exists elsewhere in the system. Verification of microphones, arrays and intentional capture paths should combine documentary reconciliation, direct observation and measurement without allowing one evidence class to substitute silently for another.

26.3 Loudspeakers, directivity and structural excitation

A loudspeaker changes both airborne and structure-borne excitation. Wall-mounted displays, soundbars, ceiling speakers and table units can place high source energy close to weak boundaries. Low-frequency drivers may excite panels, brackets and framing even when average room level appears moderate. [107][108][109][110]

Directivity varies with frequency and array processing; a beam steered towards occupants at high frequencies can coexist with nearly omnidirectional low-frequency radiation; mounting brackets can inject force into an isolated lining, while cable conduits and backing members create parallel bridges. A structurally safe mount may therefore undermine acoustic decoupling; the engineering model for loudspeakers, directivity and structural excitation should identify which physical variables change with frequency, operating state, loading, access, maintenance and environmental condition.

Design should place high-level sources away from vulnerable boundaries, define maximum gain and equalisation, isolate supports where structurally permissible, and provide independent backing that does not connect isolated leaves. Emergency and accessibility functions must remain operable. The audio design should be reviewed with room acoustics so occupants are not driven to excessive levels. Design development should assign every consequential interface in loudspeakers, directivity and structural excitation to a responsible discipline and should resolve acoustic, structural, fire, accessibility and service obligations together.

Commissioning should map level and spectrum at representative seats and boundaries, exercise presets, inspect mounts and measure vibration where low-frequency coupling is suspected. The record should identify exact

107 MB-0797. International Electrotechnical Commission, IEC 60268-16:2020.
108 MB-0805. International Electrotechnical Commission, IEC 61672-1:2013.
109 MB-0893. International Organization for Standardization, ISO 3382-2:2008.
110 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.

equipment and processing. A single A-weighted value can conceal low-frequency structural demand and high-frequency directional hot spots. The acceptance record for loudspeakers, directivity and structural excitation should preserve raw data, calibration, photographs, dimensions, processing and the decision rule needed for later reproduction.

Worked example 26.3. Bracket force from harmonic acceleration

A 32 kg display and soundbar assembly produces measured harmonic acceleration of 0.18 m/s^2 at its mounting plate during a low-frequency test tone.

F is idealised harmonic force in newtons, m is participating mass in kilograms, and a is acceleration in metres per second squared.

The screening force is 5.76 N before dynamic amplification, distributed modes and bracket geometry are considered. A rigid bridge can transmit a substantial fraction into the primary structure.

The calculation assumes the full mass participates in phase. Real modal force and interface impedance require measured transfer or structural analysis.

26.4 Telephones, secure voice terminals and speakerphones

Telephones concentrate microphones, loudspeakers, network interfaces and user behaviour in one device. A handset can contain local sidetone, speakerphone, Bluetooth, recording, voicemail, remote management and software-defined features. A secure voice terminal may be authorised for a particular use without making the surrounding room acoustically secure. [111][112][113][114]

Speakerphone mode increases source level and distributes speech into the room; handset leakage, cradle state, hookswitch behaviour and auxiliary headsets introduce additional conditions; cables and power supplies create penetrations and equipment supports; a device placed against a partition can excite the boundary more strongly than the same device at the centre of a table. A credible treatment of telephones, secure voice terminals and speakerphones distinguishes direct transmission, structural coupling, connected air paths, regenerated sound and observational uncertainty before selecting a remedy.

The room programme should distinguish ordinary telephony, approved secure voice, prohibited personal devices and emergency communications. Device placement, speakerphone permissions, maximum volume, network connection, maintenance, update and disposal procedures should be documented. The project documents should make telephones, secure voice terminals and speakerphones buildable and inspectable by defining geometry, sequence, acceptable variation, substitute evidence and the point at which concealment is prohibited.

Functional tests should confirm approved modes, mute and hookswitch behaviour, physical inventory, software state, accessories and audio output. The acoustic test should include representative telephone operation where it can govern protected use. Communications accreditation and room

111 MB-1260. U.S. Department of State, 12 FAM 510.
112 MB-1047. NIST SP 800-53.
113 MB-1049. NIST SP 800-82.
114 MB-1107. Office of the Director of National Intelligence, Intelligence Community Standard 705-1 and 705-2, public editions.

acoustic performance remain separate authority decisions. A favourable observation of telephones, secure voice terminals and speakerphones remains bounded to the inspected population and measured state, while unseen conditions and untested modes associated with telephones, secure voice terminals and speakerphones remain explicit limitations.

26.5 Video conferencing, remote participants and automatic processing

Video conferencing can make the electronic source more demanding than local speech. Remote participants may arrive with inconsistent microphone gain, compression, programme audio and background. The installed platform may use automatic gain, echo cancellation, noise suppression, beam steering and loudness normalisation that change dynamically during a meeting. [115][116][117][118]

The acoustic system responds to remote content, room occupancy, reverberation and endpoint algorithms; a quiet room can cause automatic gain to rise; a participant speaking softly may trigger local playback changes; content sharing can introduce music or alert tones with wider spectrum. Software updates can alter processing without a construction permit. Analysis of video conferencing, remote participants and automatic processing begins by mapping the actual configuration, because small differences in geometry, restraint, continuity or software state can reverse the dominant path.

115 MB-0797. International Electrotechnical Commission, IEC 60268-16:2020.
116 MB-1239. U.S. Department of Defense, UFC 4-010-06.
117 MB-0805. International Electrotechnical Commission, IEC 61672-1:2013.
118 MB-0893. International Organization for Standardization, ISO 3382-2:2008.

The basis of design should define approved platforms, endpoint types, speaker layout, maximum reproduction level, test content, software management, network route, remote support and prohibited modes. Room absorption and microphone-loudspeaker geometry should be designed to support communication at controlled source level. A robust specification for video conferencing, remote participants and automatic processing combines performance language with prescriptive detail wherever the mechanism cannot be verified from a final single-number test.

Commissioning should exercise representative speech, simultaneous talk, programme audio, mute, reconnection, update, failure and remote-management states. Logs, firmware and configuration exports should be retained with the acoustic baseline. A test using one locally generated speech file does not demonstrate every adaptive conferencing state. Testing of video conferencing, remote participants and automatic processing should report band data and operating conditions before any summary rating, so that background, flanking, drift and method scope can be examined.

26.6 Displays, camera bars and hidden functional capability

Modern displays are computing devices. They may contain loudspeakers, microphones, cameras, wireless radios, storage, operating systems, remote management and application platforms. A procurement description that says display can therefore conceal functions material to acoustic, cyber and technical-security review. [119][120][121][122]

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119 MB-1260. U.S. Department of State, 12 FAM 510.
120 MB-1047. NIST SP 800-53.
121 MB-1107. Office of the Director of National Intelligence, Intelligence Community Standard 705-1 and 705-2, public editions.
122 MB-0914. International Organization for Standardization, ISO/IEC 27001:2022.

Mounts, ventilation, cable routes and power supplies affect the physical boundary; larger or heavier replacement displays can require new anchors and backing; internal fans or power electronics generate noise; camera bars commonly combine microphone arrays and loudspeakers in one enclosure with vendor cloud or remote-support services. The controlling behaviour of displays, camera bars and hidden functional capability is system dependent and cannot be reduced to one catalogue value when adjacent construction and services participate in the measured response.

Submittals should provide exact model, hardware options, disabled and enabled functions, mounting loads, ventilation, power, network, firmware, management, accessories and end-of-life support. The approved configuration should be compared with delivered hardware because product families can contain materially different variants. Procurement and submittal review should preserve the tested or approved identity of displays, camera bars and hidden functional capability, including the features whose alteration would invalidate comparison with the supporting evidence.

Field verification should reconcile model and serial numbers, inspect mounts and penetrations, capture settings, test approved functions and confirm that disabled features remain governed by the responsible technical authority. Replacement requires a full interface review rather than a like-for-like label. Removing an application icon or placing tape over a camera does not establish control of the underlying hardware or signal path. Where displays, camera bars and hidden functional capability are evaluated by intervention, the record should describe collateral changes and restoration duties before attributing the observed difference to one mechanism.

Table 26-1. System, principal mechanism and required evidence.

System	Principal mechanism	Required evidence
Electronic equipment as part of the source-state model	Source level depends on loudspeaker sensitivity, amplifier gain, equalisation, compression, limiting, beam steering, room correction, automatic gain control and software presets	Commissioning should measure actual installed output and should preserve settings, software version, test signal, room state and access credentials
Microphones, arrays and intentional capture paths	Microphone behaviour depends on polar pattern, array geometry, preamplifier gain, automatic level control, echo cancellation, noise reduction, mute logic and network routing	Verification requires asset and serial reconciliation, functional mute tests, signal-path review, configuration capture, network review within authorised scope and physical examination of cabling and mounts
Loudspeakers, directivity and structural excitation	Directivity varies with frequency and array processing	Commissioning should map level and spectrum at representative seats and boundaries, exercise presets, inspect mounts and measure vibration where low-frequency coupling is suspected
Telephones, secure voice terminals and speakerphones	Speakerphone mode increases source level and distributes speech into the room	Functional tests should confirm approved modes, mute and hookswitch behaviour, physical inventory, software state, accessories and audio output
Video conferencing, remote participants and automatic processing	The acoustic system responds to remote content, room occupancy, reverberation and endpoint algorithms	Commissioning should exercise representative speech, simultaneous talk, programme audio, mute, reconnection, update, failure and remote-management states
Displays, camera bars and hidden functional capability	Mounts, ventilation, cable routes and power supplies affect the physical boundary	Field verification should reconcile model and serial numbers, inspect mounts and penetrations, capture settings, test approved functions and confirm that disabled features remain governed by the responsible technical authority
Sensors, occupancy detection and environmental monitoring	A ceiling sensor can require a boundary penetration or can bridge an isolated ceiling through its mounting and cable support	Inspection should verify model, sensor principle, mounting, cable route, network, wireless state, firmware and authorised data destination

System	Principal mechanism	Required evidence
Building automation and control of acoustic state	Control logic includes sensors, controllers, actuators, networks, software, credentials, alarms, overrides and fail states	Integrated testing should exercise normal, quiet, occupied, unoccupied, emergency, power-loss, network-loss, manual and maintenance modes
Wireless interfaces, personal devices and approved exceptions	A radio-disabled setting may be software controlled, temporary or reset by an update	Verification may include physical inventory, configuration review, authorised technical examination and network monitoring within lawful scope
Power supplies, grounding, bonding and electromagnetic interfaces	Acoustic hum may arise from magnetic force, mechanical resonance, ground-loop-related signal paths or power quality	Testing should distinguish airborne sound, structure-borne vibration and electrical artefact
Asset, software and configuration baselines	A useful asset record identifies model, serial, location, mount, cables, power, network, radios, microphones, loudspeakers, sensors, software, firmware, configuration file, credential owner, support contract, approved functions and retirement date	Validation should compare the installed inventory with the approved register and should hash or sign configuration exports where appropriate
Integrated commissioning, incidents and lifecycle governance	The test plan should define witness roles, authorised content, devices, networks, software, source states, room states, raw data, logs, uncertainty, failure response and restoration	The final report should distinguish what was tested acoustically, what was reviewed electronically, what remained controlled, what limitations persist and who authorised the resulting use

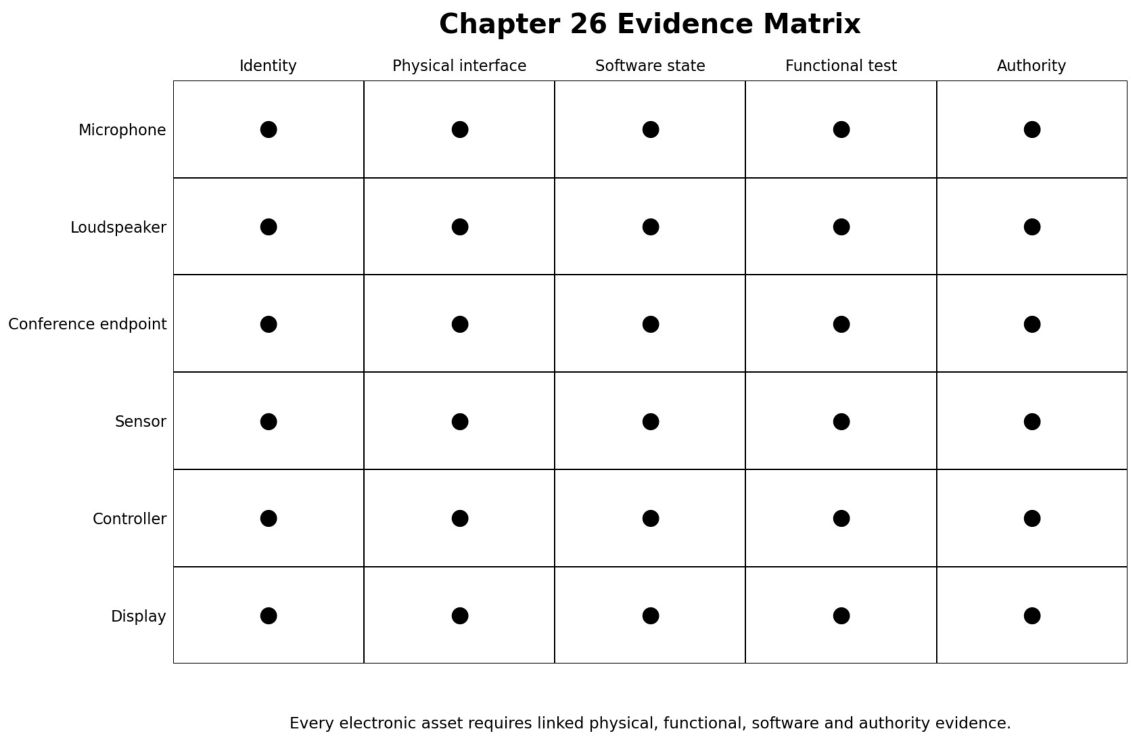

Figure 26-2. Every electronic asset requires linked physical, functional, software and authority evidence. Author's original diagram.

26.7 Sensors, occupancy detection and environmental monitoring

Occupancy, motion, temperature, humidity, carbon-dioxide, air-quality and lighting sensors are installed for legitimate building functions, yet they add transducers, processors, cables, radios and network paths. Some sensor technologies respond to pressure, vibration, ultrasound or radio-frequency phenomena. Their capabilities and data flows must be understood without speculative attribution. [123][124][125][126]

A ceiling sensor can require a boundary penetration or can bridge an isolated ceiling through its mounting and cable support. Ultrasonic or

123 MB-1047. NIST SP 800-53.
124 MB-1049. NIST SP 800-82.
125 MB-0914. International Organization for Standardization, ISO/IEC 27001:2022.
126 MB-1235. U.S. Department of Defense, UFC 3-580-01.

acoustic occupancy devices intentionally emit and receive sound outside ordinary speech bands. Multi-sensor devices may contain microphones or processors not evident from a simplified symbol. For the question addressed in section 26.7, sensors, occupancy detection and environmental monitoring are examined as a time-varying network whose inputs, boundaries and receiver conditions must all remain explicit.

The design should select the minimum functional sensor set, document technology and data use, locate devices to avoid sensitive boundaries, provide approved pathways, and assign cyber and security review. Building function, accessibility, energy and safety requirements remain controlling. For sensors, occupancy detection and environmental monitoring, the room data sheet and requirement matrix should state source states, adjoining access, operating modes, lifecycle duties and the accepting authority.

Inspection should verify model, sensor principle, mounting, cable route, network, wireless state, firmware and authorised data destination. Acoustic or ultrasonic measurements may confirm emitted energy, but they should not be enlarged into claims about software behaviour or malicious use. An unfamiliar signal is an observation requiring classification, not evidence of a covert device. The dossier for sensors, occupancy detection and environmental monitoring should distinguish as-designed, as-submitted, as-installed, as-tested, as-authorised and as-operated states.

26.8 Building automation and control of acoustic state

Building automation can change the room without any person entering it. Fan speed, damper position, pressure, temperature, masking level, lighting, occupancy mode, access state and audiovisual power can be scheduled or remotely commanded. The acoustic baseline is therefore partly a control-system baseline. [127][128][129][130]

Control logic includes sensors, controllers, actuators, networks, software, credentials, alarms, overrides and fail states; a night setback may remove beneficial background; a pressure-control fault can alter door seal contact; a masking controller can mute a zone. A firmware update can change gain or scheduling. The physical inquiry into building automation and control of acoustic state separates what carries energy from what merely appears defective, thereby preserving alternative hypotheses until discriminating evidence is obtained.

The design should identify every control point that affects source, path or receiver state, define authorised ranges, alarm conditions, manual overrides, logging and recovery. Cybersecurity of facility-related control systems should be coordinated with physical and acoustic commissioning while preserving discipline boundaries. The design team should provide maintainable routes, inspection access and authorised replacement criteria so that later work on building automation and control of acoustic state does not silently alter the boundary.

Integrated testing should exercise normal, quiet, occupied, unoccupied, emergency, power-loss, network-loss, manual and maintenance modes; trend logs and configuration exports should be retained; the acoustic report should identify the exact control state measured; a precise sound-isolation result in an unrepresentative control mode is not valid evidence for the

127 MB-1239. U.S. Department of Defense, UFC 4-010-06.
128 MB-1049. NIST SP 800-82.
129 MB-0914. International Organization for Standardization, ISO/IEC 27001:2022.
130 MB-1235. U.S. Department of Defense, UFC 3-580-01.

authorised operating condition. Inspection and measurement of building automation and control of acoustic state should be scheduled while the controlling condition is still observable, with missed hold points treated as missing evidence rather than acceptance.

Worked example 26.8. Quiet-state background change

Receiving background in a service cupboard is 36 dB in the occupied HVAC state and 27 dB during night setback. Transmitted speech level remains 31 dB under the same controlled source.

SNR is the simple level difference between transmitted speech and receiving background in the same band or declared weighting.

The night state changes the local balance by 9 dB and may materially increase detectability even though the boundary is unchanged.

Speech intelligibility depends on spectrum, modulation, listener and method. This level balance is a screening calculation only.

26.9 Wireless interfaces, personal devices and approved exceptions

Wireless capability can reside in conferencing endpoints, displays, sensors, keyboards, headsets, phones and maintenance tools. Bluetooth, Wi-Fi, cellular, near-field and proprietary radios create electronic pathways outside architectural acoustics. Their physical presence can also change source level, mounting, power and cable routing. [131][132][133][134]

131 MB-1260. U.S. Department of State, 12 FAM 510.
132 MB-1047. NIST SP 800-53.
133 MB-1049. NIST SP 800-82.
134 MB-1107. Office of the Director of National Intelligence, Intelligence Community Standard 705-1 and 705-2, public editions.

A radio-disabled setting may be software controlled, temporary or reset by an update; personal devices introduce uncontrolled microphones, speakers, cameras and storage; emergency and accessibility needs may require carefully authorised exceptions; blanket assumptions are unsafe in either direction. Evaluation of wireless interfaces, personal devices and approved exceptions requires a scale-appropriate model, from local joint or support behaviour through room-level and whole-building consequences.

The device policy should be established by the responsible security authority and implemented through inventory, access control, technical configuration, training and incident response. Acoustic design should provide approved communications alternatives so users are not driven towards informal workarounds. Details governing wireless interfaces, personal devices and approved exceptions should be coordinated in three dimensions, with movement, supports, penetrations, terminations and control states shown rather than left to site improvisation.

Verification may include physical inventory, configuration review, authorised technical examination and network monitoring within lawful scope; the acoustic engineer should document physical and source-state implications without claiming expertise or authority beyond the engagement; a quiet radio device can remain an information risk, while a noisy authorised device can remain an acoustic risk. The two questions require separate evidence; reports on wireless interfaces, personal devices and approved exceptions should separate observation, calculation, interpretation, residual alternatives and competent-authority disposition.

26.10 Power supplies, grounding, bonding and electromagnetic interfaces

Electronic equipment depends on power conversion, grounding and bonding. Power supplies, transformers, switch-mode converters, fans and dimmers can generate audible tones, vibration and electromagnetic noise. Grounding and bonding conductors can also create rigid physical routes through an isolated construction. [135][136][137][138]

Acoustic hum may arise from magnetic force, mechanical resonance, ground-loop-related signal paths or power quality; the remedy depends on the verified mechanism; breaking a safety bond is never an acceptable acoustic treatment; adding isolation hardware without electrical review can create shock, fault-current or interference hazards. The mechanism associated with power supplies, grounding, bonding and electromagnetic interfaces should be stated in measurable terms, including the quantities, directions, frequency bands and operational states that could control the result.

Electrical design should locate noisy supplies appropriately, provide independent support where required, coordinate conduit and cable routes, and preserve all code and equipment bonding. Audio signal grounding, shielding and balanced interfaces should be designed by competent specialists rather than improvised during commissioning. The selected treatment of power supplies, grounding, bonding and electromagnetic interfaces should remain effective under credible extremes, not merely under the convenient condition used for an early demonstration.

135 MB-0805. International Electrotechnical Commission, IEC 61672-1:2013.
136 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
137 MB-1235. U.S. Department of Defense, UFC 3-580-01.
138 MB-0802. International Electrotechnical Commission, IEC 60942:2017.

Testing should distinguish airborne sound, structure-borne vibration and electrical artefact; the record should include power state, load, grounding configuration, measurement chain and any controlled intervention; corrective action must be approved by the responsible electrical professional; a spectrum containing 50 or 60 Hz and harmonics does not, by itself, identify the causal path. A result for power supplies, grounding, bonding and electromagnetic interfaces cannot be extended automatically to another room, product, geometry, season or software state without an explicit equivalence analysis.

26.11 Asset, software and configuration baselines

Electronic systems age through replacement and update rather than visible wear alone. Firmware, applications, licences, certificates, cloud endpoints, presets, equalisation, access rights and network addresses can change while the enclosure remains untouched. The room baseline must therefore combine physical and digital configuration. [139][140][141][142]

A useful asset record identifies model, serial, location, mount, cables, power, network, radios, microphones, loudspeakers, sensors, software, firmware, configuration file, credential owner, support contract, approved functions and retirement date. Dependencies should be mapped so that a controller change does not silently alter masking, HVAC or audio. In asset, software and configuration baselines, interfaces ordinarily deserve more scrutiny than uniform fields because movement, access, fasteners, penetrations and later work concentrate uncertainty there.

139 MB-1239. U.S. Department of Defense, UFC 4-010-06.
140 MB-1049. NIST SP 800-82.
141 MB-0914. International Organization for Standardization, ISO/IEC 27001:2022.
142 MB-1235. U.S. Department of Defense, UFC 3-580-01.

Change classification should consider source level, pickup, routing, storage, remote access, processing, mounting, ventilation, penetrations and support loads. Pre-authorised minor changes can be defined, but a label such as software only is insufficient where processing changes the acoustic source or control state. Where asset, software and configuration baselines depend upon workmanship or configuration, first-of-type construction and explicit hold points should precede repetitive release.

Validation should compare the installed inventory with the approved register and should hash or sign configuration exports where appropriate. A checksum detects byte-level change. It does not prove that the settings are correct or that the captured device state was complete. The accepted room is a configuration, not a collection of product names. Lifecycle evidence for asset, software and configuration baselines should include baseline indicators, maintenance criteria, event triggers and the records required to detect later drift.

26.12 Integrated commissioning, incidents and lifecycle governance

Electronic commissioning must be integrated with architectural acoustics, mechanical systems, fire and life safety, accessibility, cyber security and technical-security review. Sequential testing can miss interactions. For example, audio commissioning can increase gain after acoustic testing, or network commissioning can enable a previously inactive function. [143][144][145][146]

143 MB-1260. U.S. Department of State, 12 FAM 510.
144 MB-1239. U.S. Department of Defense, UFC 4-010-06.
145 MB-1047. NIST SP 800-53.
146 MB-1049. NIST SP 800-82.

The test plan should define witness roles, authorised content, devices, networks, software, source states, room states, raw data, logs, uncertainty, failure response and restoration. Incident procedures should preserve logs and configuration while protecting information and essential operations. Speculative attribution should be avoided until evidence supports it. A secure-room assessment of integrated commissioning, incidents and lifecycle governance should preserve the distinction between acoustic transfer, non-acoustic security questions and the authority that ultimately decides use.

Periodic assurance should combine functional checks, asset reconciliation, update review, alarm testing, level and spectrum baselines, mount inspection and event-driven retesting. Training should explain mute behaviour, authorised modes, personal-device restrictions and reporting of unexpected changes. The design basis for integrated commissioning, incidents and lifecycle governance must identify what is fixed, what may vary, who may approve a change and what evidence is required before return to service.

The final report should distinguish what was tested acoustically, what was reviewed electronically, what remained controlled, what limitations persist and who authorised the resulting use. No team should inherit another discipline by implication. A technically strong endpoint does not repair a weak boundary, and a strong boundary does not govern an uncontrolled endpoint. The conclusion drawn from integrated commissioning, incidents and lifecycle governance must be no stronger than the measurand, sampling, uncertainty, configuration knowledge and public-source boundary permit.

26.13 System boundary and source-path-receiver graph

The electronic boundary of a secure room is not the faceplate of a display or the enclosure of a conference codec; it begins at every transducer that converts sound, vibration, light, radio energy or control state into an electrical representation. It continues through analogue stages, digital signal processing, network transport, cloud services, credentials and control logic, and it returns to the room through loudspeakers, actuators, displays, alarms and building systems; a defensible diagram therefore shows capture, processing, routing, reproduction, power, control and evidence paths together. It also identifies the physical penetrations and mounts through which those systems can alter airborne or structure-borne transmission.

Graph analysis helps prevent the common error of testing one obvious route while leaving parallel routes unexamined; nodes represent devices, services, rooms and authorities; directed edges represent audio, video, clock, control, power, vibration, maintenance or evidence flow. A graph cut set can identify the small number of components whose failure or change would connect protected speech to an unauthorised receiver. The graph should distinguish an approved functional route from an unapproved but technically possible route, such as a diagnostic recording service, a wireless pairing state or an emergency override that activates a loudspeaker at maximum level.

The controlled graph becomes an engineering record only when each node has an identifier, location, owner, software state and inspection status, and each edge has a medium, direction, bandwidth, activation condition and test method. The graph is not a claim that every concealed or classified path has been found. It is a bounded model of the accessible configured system, suitable for design review, commissioning and later comparison. Changes to hardware, routing, cloud tenancy, network segmentation, mounting or authorised use should trigger graph reconciliation before the room returns to protected operation.[147]

Worked example 26.13. Parallel capture-path completeness

A conference room inventory identifies four microphone-capable devices. Functional testing proves that three approved devices are muted. A fourth display microphone remains enabled on a maintenance subnet.

C is the verified-path completeness ratio, N_verified is the number of microphone-capable devices whose state was proved, and N_capable is the total known microphone-capable inventory.

The completeness ratio is 0.75, or 75 per cent. The calculation does not quantify confidentiality, but it demonstrates that the test proposition was incomplete. Acceptance should stop until the fourth path is disabled, authorised, or bounded by an explicit control and retest.

Figure 26-3. The system boundary joins capture, processing, transport, reproduction, control and assurance evidence. Author original diagram.

Table 26-2. Electronic boundary node and edge register.

Element	Minimum attributes	Principal test	Change trigger
Transducer node	Model, serial, location, orientation, gain	Functional and calibrated signal test	Replacement, movement, firmware
Processing node	Version, preset, algorithm, inputs and outputs	Configuration export and controlled stimulus	Update, reset, licence
Network edge	Source, destination, protocol, direction, clock	Observed route on authorised segment	Address, VLAN, gateway, cloud
Physical edge	Cable, conduit, mount, penetration, support	Inspection, vibration or transfer test	Opening, reroute, support work
Authority edge	Owner, approver, permitted state, exception	Document and access reconciliation	Policy, role or use change

147 MB-0469. United States Department of Defense, UFGS 27 41 00, Audio-Visual Systems.

26.14 Gain structure, headroom, clipping and limiting

Gain structure determines how a microphone signal or programme source moves from transducer level to digital full scale, through processing, amplification and acoustic output; excessive early gain raises self-noise and increases the chance that a nominal mute or fader position will leave useful residual content. Insufficient early gain encourages later amplification of noise and may drive automatic gain control into unstable behaviour; headroom must be defined at each stage, not inferred from a single output meter; a secure-room commissioning record should preserve input sensitivity, preamplifier gain, nominal operating level, peak level, limiter threshold, equalisation and loudspeaker gain for every approved preset.

Clipping is not merely an audio-quality defect; a clipped signal has a broader harmonic spectrum, can excite weak high-frequency leakage paths, and may cause occupants to raise their voices or move closer to microphones; limiting can protect equipment, yet a slow or frequency-selective limiter can leave brief peaks or low-frequency energy above the design source state. Automatic mixers and conference platforms may also apply level normalisation differently for local and remote participants; the test sequence should include quiet speech, ordinary speech, high vocal effort, programme content, alarms and the highest authorised system level.

Acceptance should compare measured stage levels with a documented gain budget and should test both steady and transient conditions. The result is valid only for the exact signal path, processing version and preset. Meter calibration, detector time constant and reference convention must be recorded because peak, RMS, LUFS and dBFS quantities answer different questions. Any later change to gain, equalisation, limiter threshold, loudspeaker count or room correction should be screened as a possible change to the boundary demand.[148]

Worked example 26.14. Digital headroom and acoustic consequence

A normal conference signal peaks at -18 dBFS. A new automatic level function adds 9 dB before a limiter set at -6 dBFS. The loudspeaker remains linear.

H is remaining digital headroom, L_limit is limiter threshold, L_peak is the original peak level, and G is the added gain, all in decibels relative to full scale.

Only 3 dB of headroom remains. The source can become approximately 9 dB more demanding before limiter action, subject to the complete electroacoustic transfer. The result does not predict room leakage without the installed transfer function.

26.15 Microphone sensitivity, self-noise and dynamic range

Microphone sensitivity converts acoustic pressure into electrical output, but the figure is meaningful only with its reference frequency, load, gain condition and uncertainty; a high-sensitivity microphone can reduce preamplifier noise, while a low-sensitivity device may require more gain and expose analogue or quantisation noise. Self-noise defines the lower useful boundary of capture; maximum sound-pressure level and distortion define the upper boundary; the useful dynamic range is therefore a chain property

148 MB-0470. International Electrotechnical Commission, IEC 60268-21:2018.

that includes microphone, preamplifier, converter and processing, rather than a single catalogue number.

Secure-room analysis must distinguish intended intelligibility from unintended residual capture; a device may be unsuitable for high-quality conferencing yet still recover names, digits or repeated phrases; noise reduction can make weak speech more intelligible even when the unprocessed waveform appears buried. Conversely, a high self-noise figure can mask quiet speech in one state but not after a software update or in a narrower band; test signals should include calibrated speech-like spectra and high-consequence token sets, and the test should preserve both raw and processed outputs where lawful and authorised.

Verification should record microphone identity, orientation, distance, sensitivity setting, analogue gain, digital trim, sample format, self-noise state, automatic processing and room background. A mute test must determine the residual signal at each accessible output, not merely confirm that a user-interface icon changes. Where the platform prevents raw access, the limitation should be stated and alternate evidence, such as network isolation, hardware disconnection or controlled substitution, should be used rather than inventing a noise-floor conclusion.[149]

Worked example 26.15. Microphone output and chain signal-to-noise ratio

A microphone sensitivity is 20 mV/Pa. Speech at the microphone is 0.20 Pa RMS. The equivalent input-noise voltage of the active chain is 0.20 mV RMS.

149 MB-0471. International Electrotechnical Commission, IEC 60268-4:2018.

V_s is signal voltage, M is microphone sensitivity in volts per pascal, p is acoustic pressure, V_n is equivalent noise voltage, and SNR is the voltage signal-to-noise ratio.

The microphone produces 4.0 mV RMS and the simplified chain SNR is 26 dB. Bandwidth, weighting, distortion, processing and calibration uncertainty are omitted, so the calculation is a screening result, not an intelligibility or security determination.

26.16 Polar response, proximity effect and near-field pickup

A polar pattern is frequency dependent and changes with mounting, nearby surfaces and array processing; a cardioid plot at one frequency cannot describe pickup of a ceiling microphone across speech bands; off-axis coloration may reduce some frequencies while preserving consonants. Flush mounting can alter diffraction. A table microphone close to a talker can exploit direct-to-reverberant advantage, while an embedded display microphone may receive a strong reflection from the tabletop or wall; source and microphone positions must therefore be treated as geometry, not merely as device names.

Directional pressure-gradient microphones can exhibit proximity effect, increasing low-frequency response when a source is close. That change can affect automatic gain and noise reduction, even when low-frequency content is not itself decisive for intelligibility. Near-field mechanical and acoustic coupling may also allow a device mounted on furniture or a wall to capture vibration that would not appear in a free-field polar plot. Examination should consider airborne pressure, contact vibration, enclosure resonance and digital processing together.

Commissioning should measure representative angular and distance states, including occupied positions, standing speakers, accessibility use and credible maintenance placement. The test record should preserve the reference axis and define whether angles are acoustic, mechanical or software-steered. A polar map does not prove that unmeasured directions are harmless. It supports a bounded spatial model and identifies positions where a device, reflecting surface or weak boundary warrants direct investigation.[150]

Worked example 26.16. Distance-related level difference

A microphone is moved from 1.20 m to 0.30 m from a talker in a region approximated as free field.

Delta L is the ideal pressure-level increase, r_1 is the original distance and r_2 is the new distance.

The direct sound rises by about 12 dB. Room reflections, directivity, proximity effect and automatic processing can change the actual result. The example shows why an unattended portable microphone placed near a seat can change the capture state substantially.

26.17 Array sampling, beamforming, steering and sidelobes

A microphone array samples a sound field in space; element spacing, aperture, geometry, calibration and sample timing determine the directions and frequencies that can be resolved; above the spatial-alias limit, more than one direction can produce similar phase differences, and grating lobes can create unintended pickup. Beamforming can improve directivity in a target band, but it cannot violate aperture and wavelength limits; low

150 MB-0472. International Electrotechnical Commission, IEC 60268-4:2018.

frequencies remain broad unless the aperture is large, while high frequencies are sensitive to element mismatch and installation geometry.

Modern arrays combine delay-and-sum processing, adaptive filters, voice activity detection and camera or seat information; the resulting beam can change without visible movement; sidelobes may point toward doors, glazing, ceiling voids or reflective corridors; automatic steering can follow an unauthorised sound source or choose a maintenance loudspeaker during testing. The approved configuration should therefore identify steering modes, exclusion zones, element health monitoring, calibration data and the states in which raw or per-element audio is available.

Verification should use several calibrated source positions and frequencies, including off-axis positions and adjoining-space directions. A single successful talker position proves little about sidelobes. The record should preserve firmware, array calibration, room geometry and steering logs. Where proprietary processing prevents internal inspection, measured polar behaviour and controlled state tests should define the accepted boundary, and the limitation should remain attached to the asset baseline.[151]

Worked example 26.17. Spatial-alias screening frequency

Adjacent array elements are spaced 0.085 m apart. Sound speed is taken as 343 m/s.

f_a is the half-wavelength spatial-alias screening frequency, c is sound speed and d is element spacing.

The screening frequency is about 2.02 kHz. Array geometry and steering angle affect the actual onset and lobe structure. The calculation warns that

151 MB-0473. International Electrotechnical Commission, IEC 60268-4:2018.

high-consequence consonant bands can lie in a region where spatial ambiguity requires measurement rather than assumption.

26.18 Mute architecture, privacy indicators and testable states

Mute is a claim about a signal path, not a colour on a screen; a terminal may mute the transmitted conference stream while leaving local recording, voice activation, diagnostics, sidetone, wake-word detection or an alternate application path active. Hardware mute can operate at the transducer power rail, analogue stage, converter, digital mixer, application or cloud service; each location provides different assurance and failure behaviour; the design should define which path is interrupted, whether the state survives restart and update, and what local and remote indicators actually represent.

A test matrix should exercise user mute, administrator mute, privacy shutter, standby, sleep, reboot, network loss, failover, emergency override, diagnostic mode and update mode. Tests should observe every accessible local, network and storage output. Indicator correspondence must be verified after firmware changes and under partial failures, such as a frozen user interface or failed control network. The strongest practical control often combines a physical interruption, a locally powered indication and a configuration rule that prevents automatic re-enablement.

Acceptance language should avoid absolute claims such as microphone off unless the method proves the defined physical condition. A more precise statement identifies the exact device, path, test point, residual level, network state and limitation. Operational training should explain that muting a conference platform does not silence other devices in the room, and that a privacy state may be invalidated by a restart, service visit or software update.[152]

Worked example 26.18. Residual attenuation in a mute path

The active microphone path measures -18 dBFS for a calibrated speech signal. In the declared mute state, the same output measures -78 dBFS after noise subtraction.

A_mute is measured mute attenuation, L_active is active-path level and L_muted is residual muted-path level.

The measured attenuation is 60 dB at that output and state. It does not prove absence of alternate outputs, storage, diagnostics or out-of-band coupling. The report should bind the result to the tested route and configuration.

Table 26-3. Mute and privacy-state verification matrix.

State	Path to observe	Required evidence	Failure implication
User mute	Transmit, record, diagnostic and local monitor	Residual measurement plus route review	Icon cannot support privacy claim
Hardware privacy	Transducer power or physical aperture	Physical inspection and functional test	Alternate transducer remains possible
Standby or sleep	Network, wake, storage and sensor functions	Packet, log and local-output observations	Dormant appearance may be misleading
Restart	Default gain, radios, routes and indicators	Cold-start test with baseline comparison	State may not persist
Emergency override	Loudspeaker, microphone and control priority	Witnessed state and restoration test	Normal controls can be bypassed

152 MB-0474. International Telecommunication Union, ITU-T P.340, Transmission characteristics and speech quality parameters of hands-free terminals.

26.19 Loudspeaker acoustic output, efficiency and compression

Installed loudspeaker output depends upon electrical input, transducer efficiency, enclosure, processing, thermal state and acoustic loading. Sensitivity measured under a standard condition is useful for screening, but an installed soundbar below a display or a ceiling loudspeaker near a boundary has different radiation and loading. Small drivers may compress thermally during sustained high output, while arrays may maintain mid-band level but limit low-frequency content. The secure-room source model should use measured installed spectra at the highest authorised state rather than a marketing maximum.

Dynamic compression can make a short acceptance test appear more demanding or less demanding than a long meeting; voice content has crest factor and pauses, while alarms and programme material may sustain energy; limiter release can pump background or expose quiet words. An amplifier or powered loudspeaker may also enter a protection mode after heating, then recover later; tests should include duration, duty cycle and thermal equilibrium appropriate to credible use, with surface temperatures and protection events recorded when they affect output.

The acceptance record should map level at representative seats, near vulnerable boundaries and at structural mounts. Octave or one-third-octave spectra are needed because A-weighted totals can conceal strong low-frequency excitation or narrow high-frequency peaks. The measured output defines a bounded source condition. It does not establish that every future replacement, preset or room-correction routine will remain within that condition.[153]

153 MB-0475. International Electrotechnical Commission, IEC 60268-21:2018.

Worked example 26.19. Sensitivity, power and distance estimate

A loudspeaker produces 88 dB SPL at 1 m for 1 W. It receives 16 W and a listener is 4 m away in a free-field screening model.

L_p is estimated sound-pressure level, L_sens is sensitivity, P is electrical power and r is distance.

The power increase and distance loss cancel in this idealised example, giving 88 dB. Room gain, directivity, compression, multiple loudspeakers and boundary loading are omitted. Installed measurement controls acceptance.

26.20 Spectral directivity and boundary loading

Directivity is a function of wavelength relative to radiating dimensions; a compact loudspeaker can be nearly omnidirectional at low frequency and increasingly directional through the speech bands; an array can steer and narrow some bands while leaving others broad. Consequently, a system aimed away from a door can still excite the door and adjacent wall at low frequency; boundary placement can add radiation into the room, change modal excitation and alter vibration at mounts.

The design should evaluate loudspeaker position, baffle orientation, distance to boundaries, array steering, crossover, equalisation and room-correction filters. A high-frequency beam may create a hot spot at glazing or a ceiling reflection. A corner placement may increase low-frequency level and reduce amplifier demand, yet increase structural or flanking excitation. These effects should be considered with the room-isolation model, not after AV commissioning has fixed the source positions.

Verification should compare spectra at seats, near weak boundaries and in relevant adjoining zones while exercising each approved preset. Directivity plots supplied by a manufacturer can support design, but the installed system includes the enclosure, mount, room and processing. Where beam steering is software controlled, steering files and checksums belong in the baseline, and a changed file should trigger at least targeted output and boundary measurements.[154]

Worked example 26.20. Directivity-index consequence

At 2 kHz a loudspeaker has directivity index 6 dB toward the occupied zone. A boundary lies approximately 90 degrees off axis and measured off-axis attenuation is 9 dB relative to the main axis.

L_boundary is the boundary incident level, L_axis is measured on-axis level and A_off is measured off-axis attenuation.

The boundary level is 73 dB in that band. The 6 dB directivity index alone could not establish the result because it is an integrated quantity, not the attenuation at one angle. Frequency-resolved installed data are required.

26.21 Displays, soundbars, mounts, mobility and structural bridges

A display assembly can contain loudspeakers, microphones, cameras, fans, power converters and radio interfaces within one moving or wall-mounted object; the mount transfers static weight, operating force and vibration to the building; backing steel, plywood, channels and fasteners can short-circuit an isolated lining if they connect it to the primary structure or opposite leaf. Articulating arms alter lever moment and cable movement;

154 MB-0476. International Electrotechnical Commission, IEC 60268-21:2018.

floor carts introduce different routes through wheels, power cords and temporary data cables.

Coordination should begin with mass, centre of gravity, mount motion, fastener pattern, service clearance and the acoustic construction behind the device. Structural safety remains mandatory. Acoustic isolation cannot be achieved by weakening anchors or omitting required backing. Instead, the wall and support system should be designed together, using independent frames, controlled penetrations, resilient interfaces where technically justified and accessible inspection points. The cable route should not become the stiffest bridge after the mount is isolated.

Commissioning should inspect concealed backing records, fasteners, perimeter contact, cable slack, flexible connections and any contact created at extreme arm positions. Vibration measurements should use operating content that excites the assembly and should compare the lining, mount and primary structure. A passing result for the parked position does not cover a moved cart, extended arm, replacement display or added soundbar. Those states belong in the change register.[155]

Worked example 26.21. Articulating-arm moment

A 52 kg display has its centre of mass 0.42 m from the wall when extended. Gravitational acceleration is 9.81 m/s^2.

M is static wall moment, m is mass, g is gravitational acceleration and e is horizontal eccentricity.

155 MB-0477. International Electrotechnical Commission, IEC 60268-23:2023.

The static moment is about 214 N m before dynamic and safety factors. The calculation is structural screening. It shows why a seemingly minor AV change can require new backing and thereby alter the acoustic junction.

26.22 Fans, coils, transformers and switching-noise mechanisms

Electronic equipment generates sound and vibration even when it is not reproducing programme audio; fans produce blade-passing tones, broadband turbulence and bearing components; transformers and inductors can produce magnetic-striction hum and load-dependent harmonics; ceramic capacitors and circuit boards can radiate switching or control tones. Variable-speed fans create changing spectra that may interact with room modes, panels and background-masking assumptions.

Diagnosis should separate airborne radiation from structure-borne injection. A near-field microphone, accelerometer, current probe and operating-state log can establish whether a tone follows fan speed, electrical load, display brightness or processor activity. Temporary soft support can be a diagnostic intervention, but a permanent treatment must preserve cooling, fire safety, structural support, grounding and manufacturer requirements. Silencing a fan or obstructing a vent is not an acceptable acoustic remedy.

The baseline should record idle, normal, high-load, update and fault states. A quiet room after commissioning can become noisier when filters clog, bearings age, firmware changes fan control or equipment is installed in a cabinet. Conversely, equipment noise that provided incidental masking can disappear after replacement. Periodic assurance should therefore treat device noise as a measured state, not a dependable security control unless it is intentionally designed, monitored and governed.[156]

Worked example 26.22. Fan blade-passing frequency

A cooling fan has seven blades and operates at 2,400 revolutions per minute.

f_BPF is blade-passing frequency, B is blade count and N is rotational speed in revolutions per minute.

The fundamental blade-passing component is 280 Hz, with possible harmonics. Slip, turbulence, structural resonance and speed control can shift or broaden the observed spectrum. The value guides diagnosis but does not identify transmission path alone.

26.23 Hands-free duplex, acoustic echo control, AGC and suppression

Hands-free communication places an active loudspeaker and microphone in the same acoustic space; acoustic echo control estimates the loudspeaker-to-microphone path and subtracts or suppresses its contribution; automatic gain control, noise reduction, comfort noise and double-talk detection alter the signal further. These algorithms are time varying. Their state depends on room response, talker level, remote signal, device motion and software version; a test using one monologue cannot characterise a system used for rapid two-way conversation.

Echo return loss enhancement is useful, but a high value at one moment does not prove that local speech is blocked or that residual echo is unintelligible; during double talk, the filter may freeze or suppression may

156 MB-0478. International Electrotechnical Commission, IEC 60268-22:2020.

relax. Nonlinear loudspeaker distortion and moving participants can reduce cancellation; the system can also store or route pre-cancellation signals for diagnostics; secure-room review should identify the signal point represented by every measurement and whether raw, processed and transmitted streams differ.

Verification should include single talk, far-end talk, near-end talk, double talk, silence, abrupt movement and changing gain. Logs should identify algorithm state if available. The acoustic test should be paired with a route and configuration review so that a favourable transmitted waveform is not mistaken for proof that no other copy exists. Changes to echo-control model, codec, sample rate or room equalisation should be treated as potentially material.[157]

Worked example 26.23. Residual echo after ERLE

The uncancelled echo level at a signal point is -24 dBFS. The measured echo return loss enhancement is 32 dB during stable far-end speech.

L_res is residual echo level, L_echo is uncancelled echo level and ERLE is echo return loss enhancement.

The residual is estimated at -56 dBFS in that state. Double talk, nonlinear distortion and alternate signal taps can produce different results. The calculation is not a confidentiality finding.

26.24 Codec bandwidth, latency, jitter and packet loss

A codec determines bandwidth, sample rate, frame size, packetisation, loss concealment and algorithmic delay; narrower bandwidth can reduce some

157 MB-0479. International Telecommunication Union, ITU-T P.340, Transmission characteristics and speech quality parameters of hands-free terminals.

spectral content but may preserve sufficient speech information for names, digits and context; wideband and full-band codecs can improve naturalness and consonant recovery. Compression artefacts are state dependent and cannot be represented by one broadband level; the source-state model should identify the actual codec negotiated for each service, including fallback modes.

Latency is the sum of capture buffering, algorithmic processing, packetisation, network transit, jitter buffering, decoding and reproduction. Excessive or variable delay changes conversational behaviour, encourages overlap and can cause users to raise their voices. Packet loss concealment may repeat, interpolate or mute frames, changing both intelligibility and residual echo. Network quality therefore influences the acoustic source and user response even when the room construction is unchanged.

Commissioning should measure end-to-end delay, loss, jitter and negotiated media parameters under normal and degraded conditions. Packet capture may be appropriate only on authorised test networks and must respect privacy and security controls. The report should separate network metrics from acoustic measurements and should preserve time synchronisation between them. A pass under an uncongested laboratory network does not bound failover, remote access, cloud-region change or an emergency path.[158]

Worked example 26.24. End-to-end conversational latency

Capture buffering is 12 ms, codec processing 24 ms, network transit 38 ms, jitter buffer 45 ms and reproduction processing 16 ms.

158 MB-0480. International Telecommunication Union, ITU-T P.341, Transmission characteristics for wideband digital hands-free telephony terminals.

T_total is one-way latency and the remaining terms are the measured or configured component delays.

The one-way latency is 135 ms. Queue variation, clock drift, packet loss and remote endpoint processing are omitted. The value should be measured in operation and related to the project conversational criterion.

Table 26-4. Conferencing performance and security-relevant states.

Condition	Acoustic effect	Digital effect	Record
Double talk	Concurrent local and remote excitation	AEC freeze or suppression change	Waveforms, ERLE and algorithm state
Packet loss	Dropout or repeated frames	Concealment and jitter-buffer response	Loss, burst length and codec
Codec fallback	Changed bandwidth and artefacts	New payload and bitrate	Negotiated parameters
Network failover	Possible mute, click or level transient	Alternate route and clock	Timing, subscriptions and logs
Cloud-policy change	Possible recording or processing change	Tenant and service state	Policy export and verification date

26.25 Remote-endpoint variability and cloud-service state

A local secure room can connect to remote endpoints with different microphones, loudspeakers, cameras, software, policies and physical environments. The local team may control only one side of the conversation. Cloud services can change codec selection, recording defaults, transcription, artificial-noise processing, content retention and administrative interfaces without altering local hardware. The approved use case must therefore identify remote-party assumptions and the service features that are permitted, prohibited or outside local control.

A remote participant can generate high-level audio that drives local loudspeakers, or can receive local audio through a service path whose retention and access rules differ from the room policy. A meeting invitation, tenant setting or host role can change recording and transcription. The system should use controlled accounts, approved meeting templates, restricted integrations and clear user indications, but those measures remain subject to competent cyber and policy authority. Acoustic isolation cannot compensate for an authorised digital transmission to the wrong party.

Assurance should preserve service version, tenant, region where relevant, administrative settings, meeting policy, account role and the observed media parameters. Changes should be reviewed even when labelled cloud-side or transparent. Where the service state cannot be independently frozen, the acceptance should state that limitation and define periodic verification, event monitoring and an alternate protected procedure for meetings whose consequence exceeds the service assurance.[159]

26.26 Audio over IP, clocking, multicast and redundancy

Networked audio separates transducers from routing and control; a microphone channel can be subscribed by several receivers, and a loudspeaker can select among sources without physical repatching; media, discovery, control and clock functions may use different protocols and trust relationships. A channel name is not a security boundary; the design should identify source and destination identifiers, multicast groups, quality-of-service markings, clock domains, redundant paths and the administrative system that can create or change subscriptions.

Sample clocks must remain sufficiently aligned for streams to reproduce without slips or buffer failure. A grandmaster change, holdover interval or incorrect domain can create clicks, dropouts, latency changes or loss of

159 MB-0481. NIST SP 800-128.

audio. Redundancy can improve availability but also create an alternate route that bypasses an inspection point or network control. The room graph should therefore show both primary and secondary paths and should test failover rather than assuming it is acoustically or operationally transparent.

Verification should reconcile device identities, media addresses, multicast boundaries, clock state, subscriptions, redundancy mode and access controls. Packet analysis can confirm timing and routing on an authorised test segment, but it does not prove the absence of out-of-band management or local storage. A signed configuration export, network diagram and observed-state record should be preserved with the acoustic results so later changes can be distinguished from measurement drift.[160]

Worked example 26.26. Sample-clock drift

Two unsynchronised devices differ by 25 parts per million at a 48 kHz sample rate.

Delta f_s is sample-rate difference, f_s is nominal sample rate and epsilon is fractional clock error.

The streams diverge by about 1.2 samples each second. Buffers or sample-rate conversion must absorb the difference. The example explains why clock loss can change audio state, but actual failure time depends on buffer depth and implementation.

160 MB-0482. Audio Engineering Society, AES67-2023, AES standard for audio applications of networks - High-performance streaming audio-over-IP interoperability.

Figure 26-4. Networked audiovisual systems couple media, clock, control, power and evidence planes. Author original diagram.

26.27 Power over Ethernet, thermal loading and cable bundles

Power over Ethernet places power and data on the same balanced cabling used for endpoint communication; it can simplify installation, but it changes cable current, bundle heating, switch power budgets and restart behaviour; a ceiling microphone array or camera bar may remain powered from a remote switch even when local receptacles are isolated. Conversely, a switch reboot can remove audio, masking control or sensors from several rooms at once; the power topology must therefore appear in the room state model.

Voltage drop and conductor heating depend on loop resistance and current; bundled cables can operate warmer than isolated cables, affecting resistance, rating and long-term condition; the electrical and ICT design must follow applicable code, cable listing and manufacturer limits. Acoustic personnel should not alter pair use, grounding or conductor configuration to reduce noise; instead, they should coordinate route separation, support, penetration sealing and equipment noise with the responsible electrical and communications disciplines.

Commissioning should record switch port, power class, measured load, cable route, bundle condition, endpoint restart state and any auxiliary power. Tests should include loss and restoration of PoE, redundant supply and low-power mode because each may alter mute, gain, clock or network state. A later addition to a cable bundle or switch can change thermal and power margins without visible alteration inside the room, making the asset and pathway registers essential lifecycle records.[161]

Worked example 26.27. PoE loop loss

An endpoint draws 0.60 A over a channel with 0.32 ohm effective loop resistance.

Delta V is voltage drop, I is current, R is effective loop resistance and P_loss is conductor heat loss.

The simplified channel drop is 0.192 V and loss is 0.115 W. Pair allocation, temperature, connector resistance and actual PoE mode must be included for design. The calculation does not authorise a cable installation.

26.28 USB, HDMI, DisplayPort and device-role ambiguity

Modern interface cables can carry audio, video, control, device identity, power and network tunnelling within one connector family. A display connection may expose an embedded microphone, camera or USB hub. A docking cable can create a network path and charge a personal device. Adapter chains obscure role and ownership; the room register should therefore identify function at each end, permitted alternate modes, power direction, embedded devices and the conditions under which a user-supplied cable may be connected.

Connector presence does not prove that every capability is enabled, and absence of a menu option does not prove that a capability is impossible. Endpoint discovery and role negotiation can change after restart or update. A cable routed through an isolated wall can also become a mechanical bridge if it is taut, heavily bundled or clamped to both leaves. Service loops,

161 MB-0483. Institute of Electrical and Electronics Engineers, IEEE Std 802.3-2022, IEEE Standard for Ethernet.

flexible seals and accessible termination points should be designed with fire, structural and communications requirements.

Verification should inspect the complete chain from source to sink, including extenders, converters, wall plates, patch panels and control processors. Functional tests should attempt only authorised roles and should document device enumeration, power and signal state. Unused ports should be governed by physical, administrative or technical control appropriate to the programme. A port blocked by policy but left unrecorded is likely to reappear during troubleshooting.[162]

26.29 Analogue audio, balanced interfaces, shielding and ground loops

Balanced analogue audio relies on differential reception and controlled impedance to reject common-mode interference. The rejection actually achieved depends on source balance, cable symmetry, receiver impedance, shield termination and frequency. A nominally balanced connector can be wired unbalanced or adapted through equipment that defeats the intended topology. Ground-potential differences can drive shield or signal currents, producing hum and sometimes mechanical vibration in connected equipment.

A ground loop is a network, not a diagnosis based solely on a 50 or 60 Hz spectral line. Magnetic coupling, power-supply ripple, lighting controls and acoustic room modes can produce similar observations. Investigation should combine electrical measurements, controlled routing changes, signal-path isolation within safe practice and vibration or acoustic

162 MB-0484. United States Department of Defense, UFC 3-580-01.

measurements. Safety protective conductors and required bonding must never be lifted as a troubleshooting shortcut.

Design should define cable type, shield strategy, connector wiring, isolation devices where justified, rack bonding, route separation and test points. Commissioning should measure noise under representative power and signal states and should record the exact temporary interventions used to identify the path. Corrective work belongs to qualified electrical and AV personnel. A quiet result after an undocumented adapter substitution is not an acceptable baseline.[163]

Worked example 26.29. Common-mode rejection screening

A 1.0 V common-mode disturbance reaches a balanced input whose effective common-mode rejection ratio is 70 dB at the frequency of interest.

V_res is residual differential-equivalent voltage, V_cm is common-mode voltage and CMRR is common-mode rejection ratio in decibels.

The ideal residual is about 0.316 mV. Cable and source imbalance can reduce system rejection substantially, and the calculation does not identify whether that residual becomes audible or affects confidentiality.

26.30 Wireless radios, Bluetooth, Wi-Fi, NFC and UWB

Wireless capability can be embedded in conference terminals, displays, cameras, keyboards, remotes, hearing systems and sensors. Different radios support different range, discovery, pairing, ranging and data functions. A device can advertise while apparently idle, and a maintenance application can enable a radio that was disabled during commissioning. The room inventory should record hardware capability separately from approved

163 MB-0485. International Electrotechnical Commission, IEC 60268-22:2020.

operational state, including antennas, firmware, pairing records and administrative controls.

Acoustic construction does not contain radio energy in a predictable manner; a room with high airborne isolation can remain transparent at relevant radio frequencies; conversely, a radio-disabled device can still present acoustic capture or structural-vibration issues; the assessment must preserve these boundaries and coordinate with competent cyber, EMSEC and TSCM authorities. Public-source acoustic guidance must not be used to infer controlled radio-security thresholds.

Verification should inspect device settings, management configuration, observed radio state within authorised scope and the persistence of disabled states after restart and update. Personal-device exceptions should define owner, purpose, duration, functions, escort, storage and post-use review. A temporary wireless presentation device can change both the information route and the physical cable or loudspeaker state, so it belongs in the same change-control system as permanent equipment.[164]

Table 26-5. Interface capability and control register.

Interface or radio	Possible functions	Physical/acoustic concern	Control evidence
USB-C	Data, audio, video, network and power	Adapter, cable bridge, portable endpoint	Role restriction and enumeration
HDMI/DisplayPort	Media, control, return audio and device data	Extenders and concealed hubs	Endpoint map and functional test
Bluetooth	Audio, peripherals, control and ranging	Persistent pairing and hidden radio state	Pairing inventory and restart test
Wi-Fi	Media, management, cloud and diagnostics	Alternate network route	Observed state and configuration
NFC/UWB	Pairing, identity, access or ranging	Short-range function not visible in ordinary use	Capability declaration and policy

164 MB-0486. NIST SP 800-213.

26.31 Assistive-listening systems and accessibility controls

Assistive-listening systems may be required to provide equivalent access to audible communication. They can use hearing loops, infrared, radio-frequency or other distribution methods, each with different coverage, receiver, spill and maintenance characteristics. Accessibility obligations must be designed into the room rather than treated as a late exception. At the same time, the system can create an intentional path by which room audio leaves the loudspeaker field, so the authorised security use must address receiver custody, coverage and operating procedure.

A hearing loop creates a magnetic field whose useful and unintended coverage depends on loop geometry, drive current, building metal and adjacent loops; infrared depends on line of sight and reflections; radio-frequency systems may extend beyond the room. None can be judged solely by audible room testing; selection requires accessibility, acoustic, electromagnetic and security review, with competent authority deciding what use is permitted and what alternate accommodation is acceptable.

Commissioning should verify intelligibility, coverage, interference, receiver count, signage, battery condition and the security controls approved for the use. Receivers should have stable identifiers and cleaning, charging, storage and issue records. The result should state the tested area and configuration. A compliant accessibility system can still be unsuitable for a particular protected discussion unless the risk and operating procedure have been explicitly resolved.[165]

165 MB-0487. United States Department of Justice, 2010 ADA Standards for Accessible Design, Sections 219 and 706, Assistive Listening Systems.

Worked example 26.31. Receiver planning from seating count

A room has 120 fixed seats. The applicable accessibility design rule requires receivers based on the relevant table and project interpretation. For a screening scenario, the selected requirement is four per cent of seats, with at least two hearing-aid-compatible receivers.

N_r is the screening receiver count and N_s is fixed seating capacity.

The screening count is five receivers, subject to the actual governing table, exceptions and authority determination. The example is not a legal interpretation and does not resolve the security controls for receiver issue and coverage.

26.32 Alarm, public-address and emergency override integration

Fire alarm, mass notification and public-address systems can be required to override ordinary audio controls and reproduce intelligible emergency messages. Those functions must remain reliable. A secure-room design cannot disable required notification, reduce audibility below the governing criterion or obstruct inspection. The integration problem is to preserve life safety while bounding normal and emergency source states, routing and maintenance access.

Emergency interfaces can activate local loudspeakers, seize amplifiers, change volume, open muting relays or place building systems in a special state. They may rely on supervised circuits and priority logic outside the AV controller. The source-state matrix should include test messages, alarm tones, live paging, fault states and restoration. Where high emergency levels drive the room boundary beyond ordinary conference conditions, that fact should be recognised in the acoustic design rather than hidden by testing only normal presets.

Commissioning should be witnessed by responsible fire, life-safety, AV, acoustic and security personnel. The record should show priority, audibility or intelligibility method, affected zones, measured levels, supervision, fault reporting and return to normal. Security-sensitive test content should not be used on a life-safety network without authorisation. Later fire-alarm programming or loudspeaker replacement should trigger coordinated review because the change can alter both legal compliance and acoustic demand.[166]

Worked example 26.32. Emergency-source margin

The highest authorised conference output at a boundary is 76 dB in a critical band. An emergency message produces 87 dB at the same point.

Delta L is the additional boundary demand, L_emergency is emergency-state level and L_conference is conference-state level.

The emergency state is 11 dB more demanding. It may be lawful and necessary, yet it must be included in the source-state and adjoining-space analysis. The calculation does not permit reduction of emergency level.

26.33 Camera optics, imaging, shutters and indicator limits

Cameras create an optical information path and often share enclosures, networks and processors with microphones and loudspeakers; field of view depends on focal length, sensor size, digital crop, pan, tilt, zoom and mounting; a camera aimed at participants may also capture whiteboards, documents, reflections or display content. Acoustic construction offers no

166 MB-0488. National Fire Protection Association, NFPA 72, 2025 edition, National Fire Alarm and Signaling Code.

remedy for an authorised or unauthorised optical route; the device must be governed as a separate but integrated endpoint.

A privacy shutter can provide strong visible control when it physically blocks the aperture, but only for the lens it covers. A camera bar can contain several imagers or depth sensors. Indicator lights may be software controlled or may represent streaming rather than local capture. Pan-tilt limits can change after calibration. The approved baseline should identify every optical sensor, shutter mechanism, field-of-view limit, preset, recording function and remote-control path.

Verification should use target charts or known geometry to map field of view and should test shutters, indicators, presets, restart and remote commands. Reflective surfaces and display content should be observed from likely camera positions. The result should be stated as a configuration-specific optical finding, not an acoustic one. If optical inspection lies outside the team remit, that limitation should remain explicit rather than being obscured by a general secure-room label.[167]

Worked example 26.33. Horizontal field width

A camera has horizontal field of view 84 degrees. A wall of interest is 3.0 m from the camera on the optical axis.

W is horizontal field width, D is axial distance and theta is horizontal field-of-view angle.

167 MB-0489. National Institute of Standards and Technology, NISTIR 8259A, IoT Device Cybersecurity Capability Core Baseline.

The ideal field width is about 5.40 m. Lens distortion, digital crop, camera rotation and oblique surfaces alter the actual boundary. Direct visual verification is required.

26.34 Occupancy sensors: PIR, ultrasonic, microwave/radar and acoustic

Occupancy sensors use different physical mechanisms and therefore create different interactions with a secure room; passive infrared sensors observe changes in thermal radiation; ultrasonic devices transmit and receive acoustic energy above ordinary hearing; microwave or radar devices radiate radio-frequency energy and infer motion. Some devices use microphones or sound classification. Hybrid units combine methods and can change algorithmic weighting with firmware or environmental conditions.

The device can affect security and acoustics through more than sensing; an ultrasonic transmitter may create intermodulation or become audible through nonlinear equipment; a radar sensor can operate through some lightweight materials; a microphone-based sensor is an intentional capture path even if the application claims only occupancy. Sensor output can control lighting, HVAC, masking, displays and recording, changing the room state when occupancy inference is wrong.

Design should select the mechanism with explicit awareness of privacy, cybersecurity, electromagnetic, acoustic and operational constraints. Commissioning should map detection and non-detection zones, false triggers, timeouts, network outputs and controlled-system responses. Testing must remain within applicable safety and regulatory limits. A sensor that meets an occupancy function does not thereby satisfy secure-room policy, and a sensor disabled for security can undermine energy, accessibility or life-safety functions unless the design is coordinated.[168]

Worked example 26.34. Ultrasonic wavelength

An ultrasonic occupancy sensor operates at 40 kHz. Sound speed is 343 m/s.

lambda is wavelength, c is sound speed and f is frequency.

The wavelength is about 8.6 mm. Small geometry and surface changes can affect scattering. The calculation does not determine coverage, audibility, safety or information risk without device-specific measurement.

26.35 Environmental sensors and diagnostic microphones

Environmental devices may measure temperature, humidity, carbon dioxide, particulate matter, pressure, light, vibration, noise or equipment condition. A noise-monitoring sensor contains an acoustic transducer even when it reports only a level. A diagnostic microphone can retain spectral or event data. The distinction between a scalar environmental measurement and stored audio must be established from architecture, configuration and observed outputs, not assumed from the product description.

Sensors can change the room indirectly. Their outputs may adjust ventilation, masking, lighting, display wake state or alerting; a sensor fault can drive a fail-safe state that is acoustically worse than normal; remote diagnostics can expose data, logs or control paths; calibration gas, reference sources, maintenance laptops and temporary gateways can also enter the protected space during service, creating short-lived but material configuration changes.

168 MB-0490. NIST SP 800-213.

The asset register should state measurand, range, sample rate, data resolution, local storage, retention, network destination, update method and controlled functions. Verification should inspect both normal data and exceptional logs. Where raw audio is technically inaccessible, the record should identify the vendor evidence and test limitations. Periodic assurance should include calibration, time synchronisation, data plausibility and the downstream response to sensor failure.[169]

Worked example 26.35. Storage-volume screening

A diagnostic channel stores one 32-bit value for each of 16 frequency bands every second for 30 days.

B is uncompressed storage, n_b is band count, 4 is bytes per 32-bit value and t is duration in seconds.

The data require about 166 MB before metadata and overhead. This is not raw audio, but long-term spectra can still reveal occupancy or activity patterns. Data minimisation and authorised retention remain necessary.

Table 26-6. Sensor technology and secure-room implications.

Sensor	Primary measurand	Possible secondary path	Verification emphasis
PIR	Thermal-radiation change	Occupancy-driven room-state change	Coverage, timeout and downstream logic
Ultrasonic	Motion from acoustic return	Transmitted ultrasonic energy	Frequency, coverage and nonlinear effects
Microwave/radar	Motion or presence	RF transmission beyond lightweight barriers	Authorised radio and coverage review
Noise monitor	Level or spectrum	Microphone capture and retained data	Data type, rate, storage and destinations
Environmental gateway	Multiple scalar sensors	Remote management and control	Identity, logs, credentials and fail state

169 MB-0491. National Institute of Standards and Technology, NISTIR 8259A, IoT Device Cybersecurity Capability Core Baseline.

26.36 Building automation: points, schedules, overrides and fail-safe states

Building automation represents physical equipment as points, objects, schedules, alarms and commands. A secure-room acoustic state can depend on fan speed, damper position, masking level, door status, occupancy mode and equipment power. The value displayed at a workstation can be commanded, calculated, overridden or stale. The basis of design should identify which points are evidentiary, which are control inputs and which physical measurements independently confirm the state.

Schedules and overrides are frequent sources of state drift; a room tested during occupied mode can enter an energy-saving state at night, reducing airflow background or disabling masking; an operator override can persist after maintenance; a fail-safe response can open a damper or start a fan. Network loss can leave local controllers in last-value, default or autonomous mode. Every credited acoustic dependency requires a defined failure state and a way to detect that state.

Commissioning should exercise normal schedules, unoccupied mode, override, alarm, network loss, controller restart and restoration. Point names, units, priorities and update intervals should be reconciled with the physical equipment. Protocol conformance does not prove that the project logic is correct. The accepted baseline should include point lists, sequence of operation, graphics, trend configuration, alarm routing and the authority that may alter them.[170]

170 MB-0492. ANSI/ASHRAE Standard.

Worked example 26.36. Masking-state exposure interval

A masking controller is scheduled off from 22:00 to 06:00, while protected meetings can occur until 23:30.

T_exposed is the interval in which the meeting continues without the credited masking state.

The schedule creates a 1.5-hour mismatch. The calculation does not quantify resulting intelligibility, but it identifies an operational state that must be tested or prohibited.

26.37 Network segmentation, zones, conduits and remote management

Network segmentation limits communication among systems with different functions, consequences and trust. In a secure-room environment, audiovisual media, building automation, enterprise services, vendor management and life-safety systems should not be assumed to share one security posture. Zones group assets with similar requirements. Conduits define controlled communication between zones. The physical cable pathway may still be shared, so cyber segmentation and acoustic penetration control must be coordinated but not confused.

Remote management can alter gain, routing, firmware, credentials and logs without a local service visit; jump hosts, virtual private networks, cloud portals and vendor tools each create an administrative route; a disabled inbound port does not eliminate outbound cloud control. The design should identify management origin, authentication, authorisation, logging, session approval, time limits and emergency access; where remote access is prohibited, the technical and administrative mechanism should be demonstrable.

Verification should compare the approved data-flow diagram with observed communication on authorised test networks, controller configuration and firewall or access-control rules. The acoustic team need not become the cyber authorising authority, but it must know when a network change can alter source, capture or room state. A later segmentation change, new gateway or vendor tunnel should trigger configuration review and targeted functional or acoustic retesting.[171]

26.38 Device identity, certificates, credentials and logging

A stable asset label is necessary but insufficient for a networked endpoint; device identity may include serial number, hardware address, certificate, account, hostname, platform identifier and tenant registration; several of these can change during repair or reset. Shared default credentials and unmanaged certificates undermine attribution; the baseline should bind physical identity to logical identity and should record who owns the credential lifecycle.

Logs support reconstruction only when time, source, retention and completeness are understood; a local endpoint log can omit cloud-side routing; a controller can record the command but not the physical result; time drift can misorder events across audio, network and building systems. Logging should therefore be designed around defined questions, such as who changed a preset, when a microphone became active, whether a failover occurred and which firmware was running.

171 MB-0493. International Electrotechnical Commission, IEC 62443-3-3:2013.

Commissioning should verify unique credentials, certificate validation, time synchronisation, audit generation, protected export and retention. Sensitive logs must be handled under applicable policy because they can contain meeting metadata, device names or activity patterns. A hash can demonstrate that an exported file has not changed after collection, but it cannot prove that the source logged every relevant event or that its clock was correct.[172]

Worked example 26.38. Clock-offset effect on event ordering

An AV controller clock is 42 seconds fast and a building controller clock is 18 seconds slow. Their logs show events 20 seconds apart without correction.

Delta t_relative is relative clock offset and the remaining terms are each device offset from the reference clock.

The clocks differ by 60 seconds, larger than the apparent 20-second event separation. Event order cannot be inferred until timestamps are corrected and uncertainty is considered.

26.39 Supply chain, procurement, SBOM and support lifecycle

Procurement fixes more than a model number. It selects manufacturer, integrator, software dependencies, update channel, support term, cloud services, spare strategy and evidence rights. A functionally attractive device can become unsuitable if the vendor cannot disclose microphones, radios, storage, interfaces or update behaviour. The specification should require a complete capability declaration, supported versions, vulnerability and incident contacts, configuration-export method, component provenance appropriate to risk and end-of-support notice.

172 MB-0494. NIST SP 800-128.

A software bill of materials can improve dependency visibility, but it is not a product-security certificate. It may omit firmware components, cloud services or proprietary modules and can become stale after an update. The procurement record should connect each delivered version to the evidence used in review. Substitutions require the same scrutiny as the basis product because microphone count, mount geometry, fan noise, codec, power, network and support can all change while the trade description remains similar.

Acceptance should verify delivered identity, authorised distributor, packaging integrity where required, software and firmware, licences, certificates, support account and evidence package. Lifecycle planning should define vulnerability response, spare devices, secure disposal, data erasure, certificate revocation and replacement testing. A product that cannot be maintained within the required assurance period should not become an undocumented permanent exception.[173]

26.40 Configuration baselines, hashes, signed exports and golden state

A configuration baseline is a controlled description of the accepted system, not a screenshot of a few menus. It should include hardware, connections, software, firmware, licences, accounts, certificates, presets, gain, equalisation, routing, mute logic, network settings, building-control points and physical mounting. Machine-readable exports should be retained where available, together with the tool and version needed to interpret them. Human-readable schedules remain necessary because proprietary exports can become unreadable after product retirement.

173 MB-0495. NIST SP 800-161.

Cryptographic hashes can establish byte-level identity of an exported file, firmware image or evidence package. Digital signatures can also bind an authorised signer and signing time when the trust chain is valid. Neither proves that the captured state was complete or correct. A golden state should therefore be created after independent verification, and the capture procedure should specify device state, export scope, privileged access, time reference and any volatile values removed from comparison.

Periodic comparison should distinguish expected dynamic fields from unauthorised change. A hash mismatch is a trigger, not a diagnosis. A match may still miss settings stored outside the export. The baseline should pair machine comparison with inventory, functional tests and selective measurements. Restoration from a golden file should be tested on a representative device and should not be assumed to restore certificates, cloud tenancy, hardware calibration or room-specific acoustic behaviour.[174]

Worked example 26.40. Hash comparison decision

A configuration export has stored SHA-256 digest A. A new export produces digest B, and A is not equal to B. A field-by-field parser identifies only a changed timestamp and a 3 dB gain change.

D_hash is a binary change indicator, H_new is the new digest and H_base is the baseline digest.

The hash correctly signals byte-level change but cannot separate benign timestamp variation from the material 3 dB gain increase. Semantic comparison and functional retest are required before return to service.

174 MB-0496. NIST SP 800-128.

Table 26-7. Configuration baseline minimum record.

Domain	Baseline content	Comparison method	Known limitation
Physical	Model, serial, mount, cable and location	Inventory and inspection	Concealed elements need as-built evidence
Signal	Gain, routing, EQ, mute and presets	Export plus stimulus test	Export may omit volatile state
Network	Addresses, subscriptions, clock and ACLs	Diagram, config and authorised observation	Out-of-band paths may remain
Software	Version, package, licence and dependency	Hash, signature and release record	Hash does not prove correctness
Authority	Owner, permitted use, exception and approver	Document reconciliation	Technical pass is not authorisation

26.41 Firmware updates, rollback and software-change qualification

Firmware and application updates can change audio processing, radio behaviour, certificates, remote access, logs, fan control and user indications. Release notes seldom describe every effect relevant to secure-room use. Update qualification should therefore begin with a change-impact hypothesis and a test selection tied to the functions and paths that might change. A security patch is important, but urgency does not eliminate the need to preserve evidence and verify operation.

Rollback must be planned before deployment. Some devices prevent downgrade, migrate configuration irreversibly or change cloud compatibility; a rollback image can contain a known vulnerability or invalid certificate; the system may also update linked components automatically; the maintenance plan should define staging, backups, configuration export, integrity verification, authorised window, witness, fail criteria, rollback decision and restoration of the protected state.

Post-update verification should include identity, version, configuration comparison, mute and indicator states, gain and routing, clock, remote access, logs, building-control interaction and selected acoustic measurements. The extent should be proportional to plausible impact and consequence. A successful boot and test call are not sufficient. The release record should state what was reverified, what was not, and the authority accepting residual uncertainty.[175]

26.42 Maintenance access, vendor support and temporary devices

Maintenance introduces people, tools, laptops, cables, replacement parts, test signals and temporary network routes into the room. A vendor may require cloud access or a diagnostic account that is not part of normal operation. A portable loudspeaker or microphone can exceed the approved source or capture state. The maintenance procedure should therefore define access authority, escort, equipment inventory, network method, content restrictions, evidence capture and restoration checks before work begins.

Temporary devices should receive temporary identifiers and should appear in the configuration graph; adapters, USB storage, wireless service tools and replacement endpoints can retain data or credentials; test tones can propagate beyond the room; maintenance may require opening panels, moving mounts or disturbing seals. The work package should coordinate cyber, acoustic, physical-security, fire and operational controls rather than assuming one escort addresses every technical consequence.

175 MB-0497. NIST SP 800-218.

Closure should reconcile removed and installed assets, physical condition, cable and penetration state, configuration, credentials, logs, time, radio state and selected performance measurements. Vendor statements should be preserved, but acceptance should rest on observed and controlled evidence. If the system cannot be fully restored or tested before protected use, the room should operate under a documented restriction or remain out of service.[176]

26.43 Commissioning test matrix and worst-case source states

Commissioning should convert requirements into a matrix of assets, functions, states, locations, measurands, methods, witnesses and decision rules. It should not become a demonstration that the system turns on. The matrix must include the combinations most likely to challenge the boundary: maximum authorised loudspeaker level, close microphone placement, steering toward weak surfaces, emergency override, quiet HVAC, masking loss, network failover, double talk, diagnostic mode and restoration after power or software interruption.

Complete factorial testing can be impossible because the state space grows rapidly. The team should use engineering screening to identify dominant and interacting variables, then select boundary states, pairwise combinations and targeted stress cases. Omitted combinations should be recorded with rationale. Measurements should use traceable instruments and preserve raw data, but functional observations, logs and configuration exports are equally important because many failures are logical rather than level based.

176 MB-0498. United States Department of Defense, UFC 4-010-06.

The matrix should identify prerequisites and restoration. A test that changes gain, routing or building controls can contaminate later results if the prior state is not restored and verified. Witness responsibilities should be explicit. The acoustic engineer can determine measured transfer, the AV specialist can establish signal state, the cyber team can review authorised network controls, and the competent authority can decide use. No signature should silently absorb another discipline.[177]

Worked example 26.43. State-space screening

A system has 4 source presets, 3 microphone modes, 2 network paths, 3 HVAC states and 2 masking states.

N_full is the number of complete factorial state combinations.

A full matrix contains 144 combinations before source position and content are added. Engineering screening should retain the credible extremes and interactions, while the omitted states and rationale remain visible. The count does not justify arbitrary reduction.

Table 26-8. Commissioning matrix for principal electronic states.

Test family	Boundary state	Primary measurand	Decision record
Capture	Every microphone mode and mute state	Residual level, route and storage	Approved or restricted path
Reproduction	Maximum preset, alarm and failover	Band levels and mount vibration	Maximum accepted source state
Control	Schedule, override, network loss and restart	Observed physical state and logs	Safe-state and restoration
Network	Primary, redundant and degraded routes	Clock, packet and subscription state	Approved communications graph
Lifecycle	Update, maintenance and replacement	Baseline delta and targeted retest	Return-to-service authority

177 MB-0499. Audiovisual and Integrated Experience Association, AVIXA 10:2013, Audiovisual Systems Performance Verification.

26.44 Periodic assurance, drift metrics and event-driven retest

A room can drift without a dramatic failure. Gain can increase, filters can change, masking can become uneven, microphones can be replaced, mounts can loosen and cloud policies can evolve. Periodic assurance should compare a compact set of sensitive indicators with the accepted baseline. Indicators can include installed level spectra, mute residual, device inventory, configuration hash, clock state, network subscriptions, sensor trends, fan tones and vibration transfer at selected mounts.

A drift threshold should reflect measurement uncertainty, normal variability and consequence. An observed change smaller than expanded uncertainty may not be distinguishable, while a statistically significant change can still be operationally unimportant. The decision rule should therefore combine magnitude, direction, affected path and security consequence. Trend analysis is often more informative than a single annual pass because gradual movement can be seen before a hard threshold is crossed.

Event-driven retest should supplement the calendar. Triggers include firmware, hardware, mount, cable, pathway, room finish, HVAC, masking, network, cloud, policy, incident and unexplained performance change. The retest scope should follow the change-impact graph. A narrow change may justify a targeted test, but several linked changes can require full recommissioning. The closure record should show baseline, trigger, selected tests, results, limitations and return-to-service authority.[178]

178 MB-0500. NIST SP 800-128.

Worked example 26.44. Drift significance against uncertainty

A reference band measured 46.0 dB at acceptance and 49.5 dB during periodic assurance. Expanded uncertainties are 1.2 dB and 1.0 dB, treated as independent.

Delta L is observed drift and U_delta is combined expanded uncertainty under the stated independence assumption.

The 3.5 dB change exceeds the 1.56 dB combined uncertainty and warrants diagnosis. Independence and coverage factors must be reviewed. Statistical significance does not itself identify cause or decide acceptance.

Figure 26-5. Lifecycle assurance returns every material change to a controlled comparison and recommissioning decision. Author original diagram.

Table 26-9. Event-driven retest selection.

Trigger	Minimum review	Likely measurement	Escalation condition
Firmware or software	Release, config and route comparison	Mute, gain and selected output	Processing or capability changed
Hardware or mount	Identity, geometry and pathway inspection	Level and vibration transfer	New support or transducer
Network or cloud	Data-flow and service-state review	Functional and timing tests	New destination or route
Room or HVAC work	Boundary and control-state inspection	Isolation, background and masking	Credited path or state affected
Incident or unexplained drift	Evidence preservation and causal plan	Full targeted diagnostic suite	Cause remains unresolved

26.45 Forensic preservation and bounded conclusions

When an electronic or acoustic incident is suspected, immediate corrective action can destroy the state needed to understand it. Power cycling, resetting, updating, moving equipment or restoring a configuration may alter volatile memory, logs, clock state, routing and physical contact. The response plan should prioritise safety and ongoing protection, then preserve the scene and system proportionately. It should identify who may isolate networks, collect logs, image storage, photograph connections, measure levels and authorise destructive inspection.

Evidence should be linked by time, identity and custody; useful items can include configuration exports, hashes, firmware images, controller logs, network captures, building trends, meeting metadata, photographs, cable labels, acoustic recordings made under authority, calibration records and witness observations. Each item has limitations. A log may be incomplete. A packet capture sees only its observation point; an acoustic spectrum can support a mechanism without identifying an actor; the report should separate fact, calculation, inference and alternate explanation.

The final conclusion should be no stronger than the measurand and preserved configuration. It may state that a defined path was active, that a change preceded a measured increase, or that a controlled intervention reduced a component. It should not state that all leakage was eliminated, that no unobserved route existed, or that a public-source test established classified accreditation. Remediation should be followed by configuration reconciliation and recommissioning, while the evidence package remains immutable and separately retained.[179]

Chapter 26 demonstrates that the electronic room is a configured source, receiver, controller and evidence system. Its microphones, loudspeakers, sensors, networks, power, software and mounts can change the acoustic proposition without a visible change to the wall assembly.

The defensible control is therefore a linked physical and digital baseline, tested in the most demanding authorised states, governed through

179 MB-0501. NIST SP 800-128.

maintenance and change, and reported with strict separation among acoustic performance, cyber security, electromagnetic security, technical surveillance countermeasures and competent-authority approval.

Chapter 27 turns from the electronic equipment chain to the occupied sound field. It examines reverberation, absorption, masking, background, vocal effort, listener access and operational speech discipline as conditions that can strengthen or defeat the intended protection.

Table 26-10. Chapter 26 release gate.

Gate	Controlling question	Minimum record	Failure response
Inventory	Are all transducers, radios, interfaces and controllers identified?	Physical and logical asset register	Stop and reconcile before protected use
Configuration	Is the exact accepted physical and digital state preserved?	Exports, hashes, settings, diagrams and authority	Restore or requalify
Function	Do mute, routing, failover and emergency states behave as specified?	Witnessed matrix, raw data and logs	Correct, retest and bound residual risk
Acoustics	Are source levels, spectra and structural paths within the design state?	Calibrated measurements and uncertainty	Remediate or restrict operating state
Lifecycle	Are change, maintenance and retest triggers enforceable?	Owner, schedule, event logic and records	Withhold final acceptance

Chapter 26 Glossary

Asset baseline. Controlled record of physical hardware, software, firmware, settings, interfaces and ownership.

Automatic gain control. Processing that changes gain in response to signal or operating conditions.

Beamforming. Array processing that changes directional pickup or radiation through phase and amplitude control.

Building automation system. Sensors, controllers, networks, software and actuators that govern building states.

Electronic source state. Defined equipment mode, gain, content, processing and physical arrangement used for design or test.

Endpoint. Device that captures, processes, reproduces, stores or routes communications content.

Firmware. Software embedded in device hardware and capable of changing function or processing.

Mute state. Declared condition intended to inhibit an audio path. It must be defined and functionally verified.

Operational technology. Hardware and software that monitor or control physical processes and building functions.

Signal path. Physical and logical route from transducer or source through processing, networks and outputs.

Acoustic echo control. Adaptive processing intended to reduce loudspeaker signal returned through a microphone path.

Audio over IP. Transport of digital audio streams over Internet Protocol networks, with separate media, clock and control considerations.

Clock domain. Set of devices governed by a common timing reference for sample or control synchronisation.

Codec. Encoder and decoder that define media bandwidth, frame structure, compression, packetisation and delay.

Configuration baseline. Controlled description of accepted hardware, software, settings, routes, identities and authority.

Digital headroom. Level margin between the current signal peak and the clipping or limiting boundary.

Directivity index. Logarithmic measure relating directional radiation or reception to an omnidirectional reference.

Double talk. Hands-free communication condition in which near-end and far-end speech occur simultaneously.

Echo return loss enhancement. Measured reduction of echo produced by echo-control processing at a defined signal point.

Failover state. Configured condition in which a secondary path, clock, controller or power source replaces the primary.

Golden state. Independently verified configuration retained as the controlled restoration and comparison reference.

Grating lobe. Unintended directional lobe caused by spatial sampling ambiguity in an array.

Hardware privacy control. Physical interruption or obstruction intended to disable a transducer or path independently of ordinary software control.

Jitter buffer. Buffer used to absorb packet-arrival variation at the cost of added and potentially variable latency.

Logical identity. Network or service identity associated with an asset, such as a certificate, account, address or platform identifier.

Mute attenuation. Measured difference between active and declared mute levels at a specified signal point and state.

PoE. Power over Ethernet, which supplies electrical power and data over balanced network cabling.

Proximity effect. Low-frequency response change in a pressure-gradient microphone when the source is close.

Remote management. Administrative control of a device or system from outside its local user interface or room.

Sample-clock drift. Difference between actual sample rates that causes streams or buffers to diverge with time.

Security-focused configuration management. Configuration practice directed toward establishing, controlling, monitoring and protecting the security-relevant system state.

Sensor fusion. Combination of outputs from several sensing mechanisms to infer occupancy, activity or another condition.

Sidelobe. Directional response outside the intended main lobe of an array or transducer.

Spatial aliasing. Ambiguity caused when array spacing is too large relative to wavelength for unique directional sampling.

Source-state matrix. Controlled list of credible sources, modes, levels, spectra, positions, durations and governing authorities.

Supply-chain risk. Risk arising from product, component, software, service, supplier and support dependencies.

Transducer. Device that converts energy between acoustic, mechanical, electrical, optical or other physical domains.

Zone and conduit. Control-system security model in which assets of similar requirements form zones and authorised communications form conduits.

Chapter 27. Reverberation Control, Sound Masking, Background Noise, and Operational Speech Discipline

A secure room is not protected by transmission loss alone; speech is generated inside a reverberant volume, modified by absorptive and reflective surfaces, transmitted through a network of paths, and judged against the sound present at potential listener positions. Interior absorption can reduce build-up and improve communication; masking can reduce detectability in receiving areas; neither adds mass or seals an opening, and both can alter human vocal effort.

The chapter therefore treats room acoustics and operational discipline as governed states. Reverberation time, background spectrum, masking level, spatial uniformity, equipment mode, door use, occupancy and speech effort must be measured or bounded. A quiet night, failed emitter or heated discussion can be more demanding than the convenient commissioning condition.

Figure 27-1. Occupied speech protection depends on source effort, room response, boundary transfer, receiving background and listener access. Author's original diagram.

27.1 Room response as part of the source

Speech leaves the mouth as a directional, time-varying source and then interacts with the room. Early reflections can support communication, while late reverberant energy increases average source-room level and sustains energy after syllables end. The boundary is therefore excited by both direct and reverberant fields. [180][181][182][183]

180 MB-0892. International Organization for Standardization, ISO 3382-2:2008.
181 MB-1017. Marshall Long, Architectural Acoustics, 2nd edition.
182 MB-0232. ASTM International, ASTM E2638-24.
183 MB-0869. International Organization for Standardization, ISO 16283-1:2014.

The response depends on volume, geometry, absorption, scattering, occupancy, furniture and frequency; at low modal density, local pressure varies sharply with source and receiver position; at higher frequencies, a diffuse-field approximation may be useful but should not be assumed merely because the room is furnished. Within room response as part of the source, the decisive analysis follows the complete source-path-receiver chain and records each interface capable of carrying pressure, force, information or measurement bias.

The design should select room finishes and geometry to support intelligible communication at moderate vocal effort while avoiding a highly live field that increases boundary excitation; the objective is not an anechoic chamber; excessive absorption can feel unnatural, reduce useful background and encourage electronic gain. The design record for room response as part of the source should translate those mechanisms into dimensions, products, tolerances, support conditions, inspection stages and named ownership.

Commissioning should measure decay and spatial response with the room in its representative furnishing state; the test report should identify source and microphone positions, occupancy approximation, doors, equipment and background limits; a single broadband reverberation number cannot describe every frequency, position or occupied condition. Evidence concerning room response as part of the source should identify the exact observed unit, method, instrument chain, state, limitations and inference supported.

Worked example 27.1. Sabine screening of reverberation time

A room has volume V = 210 m^3 and equivalent absorption area A = 70 m^2 at 1 kHz. Use the Sabine relation as a preliminary screen.

T_60 is the time in seconds for a 60 dB decay under the model, V is room volume in cubic metres, and A is equivalent absorption area in square metres.

The screening value is approximately 0.48 s at 1 kHz. The result may support clear speech without an excessively live field.

Sabine assumes a sufficiently diffuse field and appropriate absorption distribution. Strongly non-diffuse rooms, coupled volumes and low-frequency modes require more careful treatment.

27.2 Absorption, scattering and finish distribution

Absorptive material controls reflected energy but does not directly improve the mass or seal of the boundary. Its placement affects early reflection, flutter, local speech level and the spatial distribution of sound. A visually attractive ceiling with high absorption can coexist with reflective walls that create strong lateral or vertical paths. [184][185][186][187]

Porous absorbers are most effective where particle velocity is appreciable and where sufficient depth and air space exist; thin treatments lose effectiveness at low frequency; panel and membrane absorbers can target lower bands but introduce tuning, construction and fire considerations. Furniture and occupants provide variable absorption rather than a fixed laboratory condition; for absorption, scattering and finish distribution, the

184 MB-0892. International Organization for Standardization, ISO 3382-2:2008.
185 MB-1017. Marshall Long, Architectural Acoustics, 2nd edition.
186 MB-0216. ASTM International, ASTM E1573-22.
187 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.

mechanism must be traced from excitation through materials, supports, openings, controls and adjoining spaces rather than inferred from the trade name of one component.

Design should distribute absorption and scattering according to room geometry, talker locations, electronic sources, cleaning, durability, fire performance and security; treatments should not conceal access panels, defeat sprinkler coverage, bridge isolated construction or create uninspectable cavities; accordingly, absorption, scattering and finish distribution require a controlled configuration with stable identifiers, coordinated details, access provisions and change triggers that remain usable after handover.

Verification should combine product evidence with installed-area measurement, photographs and room decay data; replacements should preserve thickness, mounting, air space, facing and fire classification rather than only colour or appearance; a nominal noise-reduction coefficient does not predict band-resolved room response or installed secure-room performance. Verification of absorption, scattering and finish distribution should combine documentary reconciliation, direct observation and measurement without allowing one evidence class to substitute silently for another.

27.3 Low-frequency modes and boundary excitation

Low-frequency room modes produce spatial maxima and minima that can change source and receiving levels by many decibels. Speech fundamentals, male and female vocal energy, loudspeaker bass extension and mechanical tones can coincide with these modes. A quiet point near the table does not prove low excitation at a wall or service opening. [188][189][190][191]

Modal frequencies depend on geometry and boundary conditions; finite wall stiffness, openings, coupled spaces and furnishings shift the ideal values; electronic room correction can alter steady-state response at selected seats while increasing output elsewhere or changing transient behaviour. The engineering model for low-frequency modes and boundary excitation should identify which physical variables change with frequency, operating state, loading, access, maintenance and environmental condition.

The source plan should include multiple positions and orientations, particularly near weak boundaries and installed loudspeakers. Low-frequency absorption or source relocation may reduce excitation, but the design must not assume that interior treatment repairs structural flanking or a leak. Design development should assign every consequential interface in low-frequency modes and boundary excitation to a responsible discipline and should resolve acoustic, structural, fire, accessibility and service obligations together.

Measurement should use sufficient spatial sampling, stable source signals and frequency resolution to distinguish room modes from transmission features; vibration channels can help identify structural participation; a local low-frequency maximum is evidence of the room field at that point, not automatic proof that the nearest surface is the dominant transmission path. The acceptance record for low-frequency modes and boundary excitation

188 MB-1017. Marshall Long, Architectural Acoustics, 2nd edition.
189 MB-0869. International Organization for Standardization, ISO 16283-1:2014.
190 MB-0763. Frank Fahy and Paolo Gardonio, Sound and Structural Vibration, 2nd edition.
191 MB-1188. Tor Erik Vigran, Building Acoustics, 2008. Status at the 14 August 2026 source freeze: Published. Public locator: Publisher record. Secondary authority. Current standards and project evidence remain controlling.

should preserve raw data, calibration, photographs, dimensions, processing and the decision rule needed for later reproduction.

Worked example 27.3. Axial room-mode screen

A rectangular room is 7.2 m long. Estimate the first axial mode along that dimension using sound speed c = 343 m/s.

f_100 is the first axial modal frequency in hertz, c is sound speed in metres per second, and L is room length in metres.

The first length mode is approximately 23.8 Hz. Higher harmonics occur near integer multiples under the ideal rigid rectangular model.

Real boundaries are not perfectly rigid, and coupled spaces, damping and source position alter modal response. The calculation is a screening aid.

27.4 Background sound as a variable receiver condition

Background sound can reduce detectability of transmitted speech, yet it varies with HVAC mode, occupancy, traffic, weather, plant, cleaning and time. A corridor at midday may be forgiving while the same location at night becomes the controlling listener position. Design based on an average daytime value can therefore be dangerously optimistic. [192][193][194][195]

The relevant quantity is band-resolved level at the listener position during credible quiet, normal and abnormal states; a-weighted summaries can obscure low-frequency rumble or high-frequency speech cues; intermittent events may mask speech temporarily without providing a reliable control. A credible treatment of background sound as a variable receiver condition

192 MB-0232. ASTM International, ASTM E2638-24.
193 MB-0869. International Organization for Standardization, ISO 16283-1:2014.
194 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
195 MB-0254. ASTM International, ASTM E336-25a.

distinguishes direct transmission, structural coupling, connected air paths, regenerated sound and observational uncertainty before selecting a remedy.

The requirement should define which background sources may be relied upon, their authorised range, monitoring, failure state and maintenance; ordinary environmental noise should not be credited unless its persistence and governance are credible; a protected function may require operational restrictions during unusually quiet states. The project documents should make background sound as a variable receiver condition buildable and inspectable by defining geometry, sequence, acceptable variation, substitute evidence and the point at which concealment is prohibited.

Commissioning should measure multiple times and operating modes, document weather and occupancy, and preserve local positions such as service cupboards, ceiling voids and façades; trend monitoring should detect changed plant or tenancy conditions; a high background measurement obtained during construction activity is not an acceptable privacy baseline. A favourable observation of background sound as a variable receiver condition remains bounded to the inspected population and measured state, while unseen conditions and untested modes associated with background sound as a variable receiver condition remain explicit limitations.

27.5 Sound masking as a governed control

Electronic masking can raise receiving background in a controlled spectrum and reduce speech detectability. It is a receiver-side layer, not a repair to the boundary. Its benefit depends on level, spectrum, spatial uniformity, zoning, stability, access control, supervision and the quietest credible failure state. [196][197][198][199]

Emitters, loudspeakers or transducers interact with ceilings, plenums, furnishings and room absorption. Zoning can create discontinuities. A controller or amplifier can fail partially; furniture, partitions and ceiling changes can produce quiet pockets; excessive level can disturb occupants or cause them to raise their voices; analysis of sound masking as a governed control begins by mapping the actual configuration, because small differences in geometry, restraint, continuity or software state can reverse the dominant path.

The design should define protected zones, set-point ranges, spectral shape, emitter layout, controls, credentials, alarms, fail behaviour, maintenance and independent verification. Masking in the source room should be considered cautiously because the Lombard response can increase vocal effort. A robust specification for sound masking as a governed control combines performance language with prescriptive detail wherever the mechanism cannot be verified from a final single-number test.

Commissioning should map one-third-octave or otherwise specified spectra at representative and risk-based positions, verify uniformity and exercise mute, power-loss, network-loss and partial-emitter failures; baseline data should be retained for trend comparison; a system that passes at a few central points can still contain an accessible quiet pocket near a door, grille or service opening. Testing of sound masking as a governed control should

196 MB-0232. ASTM International, ASTM E2638-24.
197 MB-0216. ASTM International, ASTM E1573-22.
198 MB-0254. ASTM International, ASTM E336-25a.
199 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.

report band data and operating conditions before any summary rating, so that background, flanking, drift and method scope can be examined.

Worked example 27.5. Masking benefit reduced by vocal response

Receiving masking is raised by 6 dB, but source-room monitoring shows occupants increase speech level by 2.5 dB under the new condition.

Delta M_net is the simple net receiving margin change, 6.0 dB is masking increase, and 2.5 dB is measured source increase.

The net level-balance benefit is approximately 3.5 dB rather than 6 dB.

The arithmetic does not determine intelligibility. Spectral shape, listener position, modulation and language remain material.

27.6 Masking spectra, uniformity and zoning

Masking effectiveness cannot be reduced to one overall level. Speech cues occupy several bands, while comfort and detectability depend on spectral balance. A system with excessive high-frequency energy can sound hissy and intrusive. A system dominated by low-frequency energy may add annoyance without controlling important cues. [200][201][202][203]

Spatial uniformity is affected by emitter spacing, ceiling absorption, plenum depth, partitions, furniture and source type; adjacent zones can interfere or leave seams; a ceiling loudspeaker may also radiate into a plenum or adjoining room, creating unintended effects beyond the intended receiver area. The controlling behaviour of masking spectra, uniformity and zoning is

200 MB-0216. ASTM International, ASTM E1573-22.
201 MB-0254. ASTM International, ASTM E336-25a.
202 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.
203 MB-0227. ASTM International, ASTM E2235-04.

system dependent and cannot be reduced to one catalogue value when adjacent construction and services participate in the measured response.

The design should specify band data, tolerance, measurement grid, zone boundaries, transition treatment, credential control and retest triggers; it should distinguish masking from ordinary HVAC background and from emergency communication systems; procurement and submittal review should preserve the tested or approved identity of masking spectra, uniformity and zoning, including the features whose alteration would invalidate comparison with the supporting evidence.

Field mapping should retain exact coordinates, heights, room state, analyser settings and calibration; statistics should not hide local minima; risk-based positions deserve separate treatment even when room averages pass; uniformity expressed as a range or standard deviation is useful only when the sampling grid includes the positions that matter to authorised access. Where masking spectra, uniformity and zoning are evaluated by intervention, the record should describe collateral changes and restoration duties before attributing the observed difference to one mechanism.

Table 27-1. System, principal mechanism and required evidence.

System	Principal mechanism	Required evidence
Room response as part of the source	The response depends on volume, geometry, absorption, scattering, occupancy, furniture and frequency	Commissioning should measure decay and spatial response with the room in its representative furnishing state
Absorption, scattering and finish distribution	Porous absorbers are most effective where particle velocity is appreciable and where sufficient depth and air space exist	Verification should combine product evidence with installed-area measurement, photographs and room decay data
Low-frequency modes and boundary excitation	Modal frequencies depend on geometry and boundary conditions	Measurement should use sufficient spatial sampling, stable source signals and frequency resolution to distinguish room modes from transmission features

System	Principal mechanism	Required evidence
Background sound as a variable receiver condition	The relevant quantity is band-resolved level at the listener position during credible quiet, normal and abnormal states	Commissioning should measure multiple times and operating modes, document weather and occupancy, and preserve local positions such as service cupboards, ceiling voids and façades
Sound masking as a governed control	Emitters, loudspeakers or transducers interact with ceilings, plenums, furnishings and room absorption	Commissioning should map one-third-octave or otherwise specified spectra at representative and risk-based positions, verify uniformity and exercise mute, power-loss, network-loss and partial-emitter failures
Masking spectra, uniformity and zoning	Spatial uniformity is affected by emitter spacing, ceiling absorption, plenum depth, partitions, furniture and source type	Field mapping should retain exact coordinates, heights, room state, analyser settings and calibration
Lombard response and human vocal behaviour	Vocal effort is not a fixed scalar	Testing may use calibrated artificial sources for repeatability, but representative human trials or validated source models can be needed to bound actual behaviour
Speech intelligibility, audibility and high-consequence fragments	Metrics such as speech transmission index, signal-to-noise ratio or closed-room privacy indices describe bounded test conditions	Reports should preserve band data, source level, test tokens or signals, listener positions, background, repetitions and decision rule
Doors, meetings and operational discipline	The acoustic boundary changes with every door cycle and with the pressure and seal state at closure	Exercises and incident logs should test the procedure
Quiet states, failures and abnormal operation	Abnormal states can be coupled	Commissioning should exercise credible failures safely and record detection, notification, response and restoration
Commissioning, trend monitoring and recommissioning	The baseline should include decay by band, background by state, masking spectra and spatial map, source-room level, electronic presets, door and HVAC conditions, critical listener positions, instrument chain, calibration, raw data and uncertainty	Recommissioning should follow material changes, incidents, unexplained complaints and significant drift
Integrated acceptance and limits of reliance	A risk-based design may rely on several layers, but the dependency must be explicit	The final conclusion should use bounded language

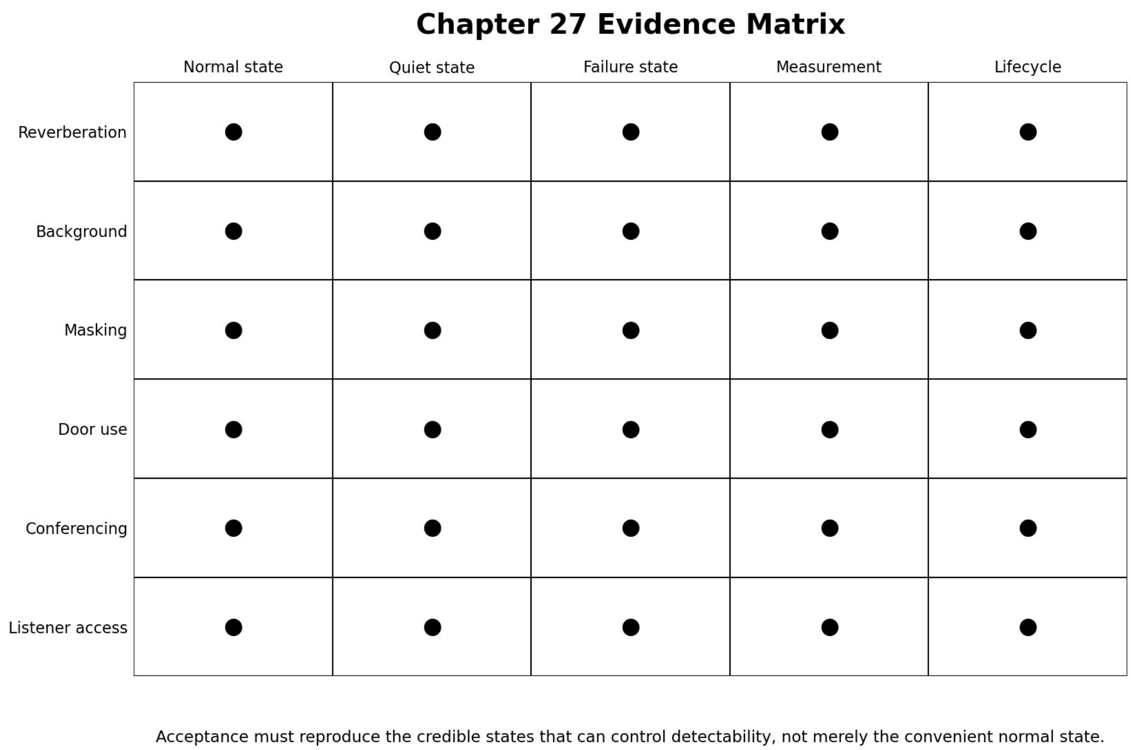

Figure 27-2. Acceptance must reproduce the credible states that can control detectability, not merely the convenient normal state. Author's original diagram.

27.7 Lombard response and human vocal behaviour

People change their voices when they cannot hear comfortably. Background, masking, reverberation, remote participants, hearing ability, stress and group dynamics can increase level, alter spectrum and change direction. This human response can partially cancel a receiving-side masking benefit and can make an intense meeting more demanding than ordinary commissioning speech. [204][205][206][207]

Vocal effort is not a fixed scalar; short emphatic words, names, numbers and commands can exceed long-term averages; standing talkers may move close to a weak wall. Multiple talkers create overlapping energy. Familiar

204 MB-0232. ASTM International, ASTM E2638-24.
205 MB-0869. International Organization for Standardization, ISO 16283-1:2014.
206 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.
207 MB-0960. James M. Atkinson, Acoustic Security Engineering for Secure Rooms, Revision 1.2C2.

listeners can use context and repetition to recover information from poor signals; for the question addressed in section 27.7, Lombard response and human vocal behaviour are examined as a time-varying network whose inputs, boundaries and receiver conditions must all remain explicit.

The authorised use should define ordinary, raised and maximum credible speech states, amplified remote audio, meeting duration, seating and operational controls; interior acoustics and conferencing design should support moderate effort; user training should address door closure, speakerphone use, equipment volume and reporting of masking faults. For lombard response and human vocal behaviour, the room data sheet and requirement matrix should state source states, adjoining access, operating modes, lifecycle duties and the accepting authority.

Testing may use calibrated artificial sources for repeatability, but representative human trials or validated source models can be needed to bound actual behaviour; source monitoring should accompany masking studies where vocal response matters; a normal-speech test cannot support a maximum-effort claim unless the relationship is explicitly modelled and accepted. The dossier for lombard response and human vocal behaviour should distinguish as-designed, as-submitted, as-installed, as-tested, as-authorised and as-operated states.

27.8 Speech intelligibility, audibility and high-consequence fragments

Audibility, intelligibility and comprehension are different outcomes. A listener may detect cadence or speaker activity without understanding words. A short familiar name or number may be recognised even when continuous technical speech is poorly intelligible. Repetition, recording and context can increase recovery opportunity. [208][209][210][211]

Metrics such as speech transmission index, signal-to-noise ratio or closed-room privacy indices describe bounded test conditions; they have assumptions concerning source, listener, background, language, processing and room response; no single metric represents every unaided or aided listener scenario. The physical inquiry into speech intelligibility, audibility and high-consequence fragments separates what carries energy from what merely appears defective, thereby preserving alternative hypotheses until discriminating evidence is obtained.

The project should define the information consequence and the authorised assessment scope without exposing protected content; test material should be ethically and legally controlled; conclusions should state whether the method addressed audibility, intelligibility, privacy index or another proposition. The design team should provide maintainable routes, inspection access and authorised replacement criteria so that later work on speech intelligibility, audibility and high-consequence fragments does not silently alter the boundary.

Reports should preserve band data, source level, test tokens or signals, listener positions, background, repetitions and decision rule; assisted processing should be included only where authorised and technically supported; a statement that speech was not understood during one trial is not a universal claim that no information can be recovered. Inspection and

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208 MB-0232. ASTM International, ASTM E2638-24.
209 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.
210 MB-0227. ASTM International, ASTM E2235-04.
211 MB-0960. James M. Atkinson, Acoustic Security Engineering for Secure Rooms, Revision 1.2C2.

measurement of speech intelligibility, audibility and high-consequence fragments should be scheduled while the controlling condition is still observable, with missed hold points treated as missing evidence rather than acceptance.

Worked example 27.8. Repetition sensitivity screen

A distinctive token is recognised with probability $p = 0.12$ in one controlled trial. Screen the probability of at least one recognition over eight independent repetitions.

P_{>=1} is probability of at least one recognition, p is per-trial recognition probability and n is the number of repetitions.

The independent-trial screen gives approximately 64 per cent.

Speech trials are rarely independent. Learning, context, changing room state and listener adaptation can increase or decrease the real result. The calculation illustrates consequence of repetition, not compromise probability.

27.9 Doors, meetings and operational discipline

Operational behaviour can nullify excellent construction. Doors are propped open, sound locks are bypassed, discussions begin before systems stabilise, personal devices enter, maintenance occurs in adjoining spaces and users raise equipment volume. These are predictable human-system interactions rather than exceptional misconduct. [212][213][214][215]

212 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
213 MB-0254. ASTM International, ASTM E336-25a.
214 MB-0960. James M. Atkinson, Acoustic Security Engineering for Secure Rooms, Revision 1.2C2.
215 MB-0879. International Organization for Standardization, ISO 19650.

The acoustic boundary changes with every door cycle and with the pressure and seal state at closure; meeting arrival and departure create periods of maximum opening frequency; cleaning, catering and technical support increase access; a secure procedure that is too burdensome will be bypassed. Evaluation of doors, meetings and operational discipline requires a scale-appropriate model, from local joint or support behaviour through room-level and whole-building consequences.

Operational rules should be concise, realistic and supported by room layout, scheduling, signage, access control and alternative spaces. Users should know how to confirm masking and equipment state, where to report defects, when discussion must stop and which adjoining areas require control. Details governing doors, meetings and operational discipline should be coordinated in three dimensions, with movement, supports, penetrations, terminations and control states shown rather than left to site improvisation.

Exercises and incident logs should test the procedure; door alarms, status indicators and meeting checklists can provide evidence, but they should not create a false sense that a green light proves every physical and electronic condition; a procedure that depends on perfect human memory under time pressure is not a robust engineering control. Reports on doors, meetings and operational discipline should separate observation, calculation, interpretation, residual alternatives and competent-authority disposition.

27.10 Quiet states, failures and abnormal operation

The most revealing condition may be a failure or maintenance state. A fan stops, masking mutes, a ceiling tile is removed, a door closer is disabled, an adjacent tenancy empties, or a control network reboots. The protected room may remain in use while the receiving environment becomes markedly quieter. [216][217][218][219]

Abnormal states can be coupled. Power loss may disable masking and change HVAC; fire alarm operation may open doors or dampers and activate loudspeakers; maintenance may expose plenums and service cupboards; a single failure matrix should therefore identify combinations rather than isolated component faults. The mechanism associated with quiet states, failures and abnormal operation should be stated in measurable terms, including the quantities, directions, frequency bands and operational states that could control the result.

Design should provide alarms, fail positions, operational restrictions and alternative meeting locations; the authority should decide which failures require immediate suspension of sensitive use and which can be tolerated under documented compensating controls; the selected treatment of quiet states, failures and abnormal operation should remain effective under credible extremes, not merely under the convenient condition used for an early demonstration.

Commissioning should exercise credible failures safely and record detection, notification, response and restoration; periodic tests should confirm that alarms reach the responsible custodian and that logs are retained; a normal-state pass does not prove resilience to the failures that control real exposure. A result for quiet states, failures and abnormal operation cannot

216 MB-0040. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook.
217 MB-0254. ASTM International, ASTM E336-25a.
218 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.
219 MB-0879. International Organization for Standardization, ISO 19650.

be extended automatically to another room, product, geometry, season or software state without an explicit equivalence analysis.

27.11 Commissioning, trend monitoring and recommissioning

Room acoustics and masking require baselines that can be reproduced. Finishes age, furniture moves, emitters fail, controllers change, doors wear and surrounding noise changes. A one-day acceptance test is therefore the beginning of lifecycle assurance rather than its end. [220][221][222][223]

The baseline should include decay by band, background by state, masking spectra and spatial map, source-room level, electronic presets, door and HVAC conditions, critical listener positions, instrument chain, calibration, raw data and uncertainty. Trend indicators should be selected for known failure modes rather than gathered indiscriminately. In commissioning, trend monitoring and recommissioning, interfaces ordinarily deserve more scrutiny than uniform fields because movement, access, fasteners, penetrations and later work concentrate uncertainty there.

Periodic depth should reflect consequence and stability; masking telemetry may be continuous, while full room tests are event triggered or risk based; control limits should account for repeatability and expected physical variation; a monotonic change can be important even when no single observation exceeds a threshold. Where commissioning, trend monitoring and recommissioning depend upon workmanship or configuration, first-of-type construction and explicit hold points should precede repetitive release.

220 MB-0892. International Organization for Standardization, ISO 3382-2:2008.
221 MB-0869. International Organization for Standardization, ISO 16283-1:2014.
222 MB-0216. ASTM International, ASTM E1573-22.
223 MB-0254. ASTM International, ASTM E336-25a.

Recommissioning should follow material changes, incidents, unexplained complaints and significant drift; the report should compare like quantities and states and should update the authorised baseline after closure; comparing unlike metrics or changed room states can manufacture a trend that does not exist. Lifecycle evidence for commissioning, trend monitoring and recommissioning should include baseline indicators, maintenance criteria, event triggers and the records required to detect later drift.

27.12 Integrated acceptance and limits of reliance

The occupied acoustic state combines source, room response, boundary transfer, background, masking, listener access, equipment and behaviour. Acceptance must therefore identify the exact state and the evidence supplied by each method. Interior treatment, masking and procedures can be valuable layers without becoming substitutes for physical isolation. [224][225][226][227]

A risk-based design may rely on several layers, but the dependency must be explicit; if privacy depends materially on masking, the system needs monitoring, credentials, alarms, maintenance and failure procedures; if it depends on door discipline, access and training must be credible. If it depends on naturally high background, the quiet state must be assessed; a secure-room assessment of integrated acceptance and limits of reliance should preserve the distinction between acoustic transfer, non-acoustic security questions and the authority that ultimately decides use.

The acceptance dossier should connect requirements, designs, product evidence, construction records, acoustic measurements, operational

224 MB-0232. ASTM International, ASTM E2638-24.
225 MB-0869. International Organization for Standardization, ISO 16283-1:2014.
226 MB-0799. International Electrotechnical Commission, IEC 60268-16:2020.
227 MB-0879. International Organization for Standardization, ISO 19650.

procedures, authority decisions and change triggers; residual limitations should be visible to custodians and future reviewers; the design basis for integrated acceptance and limits of reliance must identify what is fixed, what may vary, who may approve a change and what evidence is required before return to service.

The final conclusion should use bounded language; it can state measured decay, background, masking and speech metric under identified states; it should not declare that the room is secure in every circumstance; authority does not change the physics, and physics does not assign authority. The conclusion drawn from integrated acceptance and limits of reliance must be no stronger than the measurand, sampling, uncertainty, configuration knowledge and public-source boundary permit.

27.13 Occupied-state model and performance hierarchy

An occupied secure room is a state-dependent system rather than a passive shell; the protected source has a level, spectrum, directivity, position, duration and conversational pattern; the room has a furnishing, occupancy, door position, electronic configuration and decay response. Every receiving zone has a background spectrum, masking state, access condition and plausible listener geometry; a competent acceptance model therefore treats the complete combination as a named state. It does not average normal use, quiet hours, cleaning, maintenance, emergency operation and equipment failure into a single convenient condition.

The hierarchy begins with laboratory evidence for individual products and assemblies, proceeds to field isolation of the installed boundary, then adds occupied-room source and receiver states, and ends with the authorised decision; each level answers a different question. A ceiling absorber can change room decay without changing wall transmission loss; masking can change receiving audibility without repairing a door gap; a closed-room privacy result can bound an unaided listener under the tested background without proving resistance to electronic collection. The report must state which level was measured and which inferences remain outside it.

The state register should identify the governing source, the lowest credible receiving background, the least favourable authorised door condition, all credited active controls, the listener-access envelope and the required duration. It should also identify prohibited combinations, such as protected speech while masking is unavailable or a door is held open. Acceptance is defensible only when the tested state covers the authorised state, or when an enforceable operating restriction closes the difference. This architecture becomes the reference for commissioning, incident analysis and later change control.[228]

Worked example 27.13. State-combination completeness

A room has three credible source states, four receiving-background states, two door states and two masking states. Testing covers 18 distinct combinations.

N_total is the number of defined combinations. N_s, N_b, N_d and N_m are counts of source, background, door and masking states. C_state is the screened test-coverage ratio.

Only 37.5 per cent of the defined combinations were exercised. The arithmetic does not mean all 48 combinations require equal testing. It

228 MB-0502. ASTM International, ASTM E2638-24.

identifies the need for a documented risk-based selection that proves every authorised worst case and every credited failure control.

Figure 27-3. The occupied acoustic claim joins source, room, boundary, receiving state, listener access and controlled evidence. Author original diagram.

Table 27-2. Occupied-state hierarchy and evidence boundary.

Level	Primary question	Representative evidence	Excluded inference
Product or assembly	What did the tested specimen do?	Laboratory report and specimen configuration	Installed room performance
Installed field	What attenuation exists between configured spaces?	Field isolation, path survey, uncertainty	Speech privacy under every background
Occupied state	What can a defined listener recover under defined use?	Source, room, background, masking, listener and time	Technical surveillance immunity
Institutional decision	Is the room authorised for the stated purpose?	Applicable authority, criteria, restrictions and approval	Universal or permanent security

27.14 Reverberation-time budgets and equivalent absorption

Reverberation control should be designed as a frequency-resolved budget; the designer begins with room volume and the target decay range, then allocates equivalent absorption among ceiling, walls, floor, furniture, occupants and discrete objects; the allocation is not merely decorative. It determines where reflected energy returns to talkers, microphones, weak boundaries and receiving paths; a room with the correct mid-band average can still have excessive low-frequency decay, a strong flutter path, or a local reflective zone that raises excitation at a door or grille.

Equivalent absorption area is a useful accounting quantity because it allows differently sized surfaces and objects to be combined; its apparent precision must not conceal model assumptions; sabine behaviour requires a sufficiently mixed field and relatively modest mean absorption. Very absorptive or geometrically complex rooms may need Eyring or measured decay analysis; coupled volumes, ceiling plenums, open storage, curtains, movable partitions and occupied seating can change the effective state. The budget should therefore include design, empty, normally occupied and credible stripped or rearranged conditions.

Procurement should preserve specimen thickness, facing, mounting, backing, air space, edge treatment and tested area; commissioning should compare measured band decay against the budget, while recording source positions, microphone positions, furnishings, occupancy simulation, doors and environmental conditions. A mismatch should prompt diagnosis rather than arbitrary adjustment of one coefficient; the cause may lie in missing treatment, an altered mounting, reflective furniture, coupled cavities, inadequate diffusion, measurement range or background contamination.

Decay analysis also requires control of the excitation and shut-off process. Interrupted noise, integrated impulse methods and swept or maximum-length-sequence techniques do not produce identical artefacts when the source, loudspeaker, room or recorder is nonlinear. The source must excite the relevant bands with adequate signal-to-noise ratio, yet it must remain below compression and avoid rattles that create a second decay. The acquisition chain should retain the unwindowed response, sampling rate, time weighting, filters and regression interval. Analysts should compare repeated decays for slope stability and inspect whether the apparent tail is actually ventilation noise, electrical hum or a late coupled-volume response. When several source and microphone combinations are averaged, the individual results should remain available because an average can conceal one highly reverberant corner or one anomalous source-wall interaction.

The engineering conclusion should identify whether the quantity represents a room mean, a local condition or a method-specific correction used by another acoustic test.[229]

Worked example 27.14. Required equivalent absorption

A conference room has volume $V = 240\ m^3$. The design target is T_60 = 0.50 s at 1 kHz. Estimate the Sabine equivalent absorption area and compare it with 62 m^2 already scheduled.

A_req is required equivalent absorption area in square metres. V is room volume in cubic metres. T_60 is the 60 dB decay time in seconds. A_short is the screened shortfall.

The budget is short by about 15.3 m^2 at the stated band. The result is a preliminary diffuse-field screen. It does not specify a product or location, and it must be reconciled with measured band decay, mounting data, low-frequency behaviour and occupied conditions.

27.15 Eyring decay, non-diffuse fields and model limits

A room can depart materially from Sabine assumptions when mean absorption is high, treatment is concentrated on one surface, geometry creates directional returns, or the volume couples to alcoves and plenums; the Eyring relation accounts for repeated boundary encounters through a logarithmic term, but it still depends on a diffuse-field idealisation. Neither equation can substitute for measured decay where the acceptance claim depends on actual source and receiver geometry; the model choice and its valid range should be stated, not hidden behind software output.

229 MB-0503. International Organization for Standardization, ISO 3382-2:2008.

Decay curves should be examined for linearity over the selected evaluation range; double slopes can indicate coupled volumes, unequal modal decay, background limitations or time-varying controls; a short early slope and longer late tail can have different consequences for speech, electronic echo control and boundary excitation. The test record should preserve the impulse response or time history, regression range, correlation measure, noise floor, extrapolation method and any truncation; a single T value without that context is weak evidence.

Design review should compare predicted and measured decay across octave or fractional-octave bands and several spatial positions. Persistent residual patterns can reveal omitted volume, incorrect surface area, wrong mounting, furnishings, open doors or unusual scattering. The report should resist forcing agreement by changing absorption coefficients beyond their tested provenance. A model that matches only after undocumented tuning is not a transparent engineering basis for security-related decisions.[230]

Worked example 27.15. Sabine and Eyring comparison

A room has volume $V = 180\ m^3$, total surface area $S = 260\ m^2$ and mean absorption coefficient alpha_bar = 0.35. Compare Sabine and Eyring screening values, neglecting air absorption.

T_S and T_E are screened decay times in seconds. V is volume in cubic metres. S is surface area in square metres. alpha_bar is the area-weighted mean absorption coefficient.

The models differ by about 0.060 s, or 19 per cent of the Sabine value. This difference is a warning that model selection matters. Neither value proves

230 MB-0504. ASTM International, ASTM E2235-04.

actual decay in a non-diffuse room, and measured data remain controlling for acceptance.

27.16 Frequency-dependent absorption, mounting and substitution control

Absorber performance is a function of frequency, specimen size, mounting, air space, backing, edge exposure and laboratory method; a single-number rating is convenient for scheduling but insufficient for secure-room design; speech privacy often depends upon bands carrying consonant information, while low-frequency build-up can drive structural or duct paths. The specification should therefore retain band coefficients and the exact mounting that produced them; a nominally identical panel placed directly against a wall may behave differently from one tested over a deep air cavity.

Substitution review must distinguish visual equivalence from acoustical equivalence; changes in thickness, density, facing permeability, perforation, scrim, backing, edge sealing and suspension can alter both absorption and fire behaviour; large-format baffles, clouds, curtains and furniture also introduce directional and spatial effects not represented by a flat area-weighted coefficient. The submittal should show tested construction, specimen area, mounting designation, frequency data, fire classification, cleaning limitations and the intended installed detail.

Field verification should reconcile delivered product identifiers with the approved schedule, photograph concealed mounting before closure and measure room decay after installation; if a substitution is accepted provisionally, the acceptance plan should state the bands and positions that will decide equivalence. Failure should trigger correction or a documented redesign; it should not be obscured by changing the target after measurement or by increasing masking to compensate for a room-response defect without analysing vocal and comfort consequences.

Sampling density should follow the spatial correlation of the field and the consequence of missing an outlier; a regular grid supports reproducibility, but a purely regular grid can align with modal nodes or overlook narrow routes near a threshold, transfer grille or perimeter joint; a defensible survey therefore combines predetermined points with a documented search for maxima and minima. The plan should state the minimum separation among source positions, microphones, boundaries and diffusers, together with the treatment of inaccessible points. Where a moving microphone is used, path geometry, speed and integration time determine the implicit weighting. A slow pass can overweight turning points, while a fast pass can under-sample temporal fluctuation. Confidence intervals derived from repeated points describe repeatability, not necessarily the unsampled remainder of the room; for high-consequence positions, direct confirmation is preferable to extrapolation from a room average; spatial data should be stored with coordinates or a controlled plan so that later furniture, partition or emitter changes can be compared against the same physical locations.[231]

Worked example 27.16. Area-weighted absorption after substitution

A 120 m² ceiling originally has alpha = 0.80 at 1 kHz. A substitution covers 30 m² with material having alpha = 0.45, while the remaining 90 m² stays unchanged.

231 MB-0505. International Organization for Standardization, ISO 354:2003.

A_original and A_sub are screened equivalent absorption areas in square metres at 1 kHz. Alpha values are laboratory coefficients for their stated mountings.

The substitution reduces the screened equivalent absorption by 10.5 m². The calculation does not prove the resulting decay because distribution and field conditions matter, but it establishes a material change requiring review and likely measurement.

Table 27-3. Absorber and finish substitution control.

Attribute	Required record	Failure mechanism	Verification
Band absorption	Tested coefficients and rating	Decay and spectral balance change	Submittal and room decay
Mounting and air space	Exact laboratory mounting and field detail	Low-frequency and broadband shift	Concealed-work photographs
Facing and edges	Permeability, scrim and edge condition	Changed absorption or contamination	Product identity and inspection
Fire and durability	Classification, cleaning and replacement limits	Unsafe or unstable treatment	Code review and maintenance record
Distribution	Plan, elevation and reflected-path rationale	Local reflections and nonuniform field	Spatial response and visual survey

27.17 Scattering, diffusion, early reflections and communication geometry

Scattering redistributes reflected energy, while absorption removes a fraction of incident energy; these mechanisms should not be conflated; a diffuser can reduce a strong specular reflection without lowering total reverberant energy; a porous panel can reduce energy while leaving an untreated opposing wall capable of flutter. The secure-room design should map talker, listener, microphone, loudspeaker, door, glazing and service locations, then identify early reflection paths that affect speech effort, electronic processing and boundary excitation.

Early reflections can support speech when their delay and direction reinforce useful communication; they can also colour microphone signals, destabilise acoustic echo control or create local maxima near a weak element; curved, faceted or highly polished surfaces require particular attention because they can focus energy. The design should not assume that decorative irregularity equals controlled diffusion; diffuser depth, sequence, bandwidth, distance and mounting determine behaviour, and proprietary performance claims require applicable test evidence.

Commissioning can use impulse responses, spatial mapping and directional inspection to identify problematic reflections. A reflected arrival should be interpreted with geometry and source directivity, not merely by its amplitude. Temporary treatment, source relocation or rotation can test causal hypotheses. The final report should distinguish improved communication from improved confidentiality. A reflection treatment may reduce vocal effort and boundary drive, but it does not directly close a transmission path or create formal authorisation.[232]

Worked example 27.17. Reflection-path delay

A direct talker-to-microphone path is 3.2 m. A ceiling reflection travels 5.6 m. Use sound speed c = 343 m/s to estimate the excess delay.

Delta r is excess path length in metres. Delta t is excess arrival time in seconds. c is sound speed in metres per second.

The reflected arrival is about 7 ms later than the direct sound. The calculation does not determine whether the reflection is beneficial or

232 MB-0506. International Organization for Standardization, ISO 3382-2:2008.

harmful. Its level, spectrum, angle, room use and processing must also be assessed.

27.18 Electronic source states and room gain

Electronic sources can dominate the occupied field even when the room is intended primarily for unamplified speech; conference loudspeakers, displays, assistive systems, alarms, media playback and remote participants produce different spectra, directivities and duty cycles; automatic gain, equalisation, limiting and room correction can change output without a visible hardware change. The source-state register should therefore include content class, gain preset, processing, loudspeaker set, routing, maximum authorised level and emergency override.

Room gain is not a universal constant; it varies with source position, directivity, receiver position, frequency, absorption and the ratio of direct to reverberant energy; a source placed near a wall or corner can receive boundary reinforcement. A ceiling loudspeaker can efficiently excite the plenum or suspended structure through its back-can and support; the design should examine both acoustic output into the room and mechanical or airborne energy delivered to weak paths.

Acceptance should include the highest-consequence authorised electronic states, not merely a nominal meeting preset; test signals should be selected and levelled without damaging equipment or occupants; where programme content is used, its crest factor and spectrum should be documented. A maximum-level result should not be inferred from a low-level linear test if limiting, compression, loudspeaker nonlinearity or structural rattle can change the path at higher output.

Reflection diagnosis should separate amplitude, delay, direction and persistence; a strong early reflection can improve level at one seat while reducing clarity at another through comb filtering; parallel hard surfaces can create flutter that is obvious to a listener but poorly represented by an averaged decay number. Curved glazing or stone can focus energy upon a door, ceiling penetration or exterior pane; coupled alcoves and ceiling coffers can release late energy after the principal room has decayed. Time-frequency analysis, directional measurements and controlled temporary absorption can distinguish these mechanisms. Any intervention should be reversible during diagnosis and should not obstruct fire protection, conservation requirements or security inspection. Diffusion should not be specified merely as visual texture. Its dimensions must be substantial relative to wavelength, and its mounting must avoid forming an unintended cavity or structural bridge; the report should preserve impulse-response plots and the intervention sequence because the causal inference depends upon the measured change, not solely upon the final appearance of the room.[233]

Worked example 27.18. Summation of independent electronic sources

Two loudspeakers produce 72 dB and 69 dB at a weak boundary in the same band. Treat the contributions as uncorrelated for a screening sum.

L_total is the combined level in decibels. L_1 and L_2 are individual band levels measured under comparable conditions.

233 MB-0507. International Electrotechnical Commission, IEC 60268-16:2020.

The screened combined level is about 73.8 dB. Coherent sources, different phases, room modes, processing and time variation can alter the result. The calculation does not replace direct measurement in the configured state.

27.19 Source directivity, orientation, position and critical distance

Talkers and loudspeakers are directional. Their orientation relative to doors, glazing, grilles and junctions can change local excitation by more than a change in room-average level suggests; a talker facing a weak door produces a different path than the same talker facing an absorptive wall. Conference loudspeakers mounted beneath a display or in a ceiling create different direct and reflected fields; the basis of design should identify credible source locations and orientations, including informal discussions near entrances and standing presentations.

Critical distance is a useful screening concept for the transition between direct and reverberant dominance; it depends on source directivity, room volume and decay; it is not a sharp physical boundary, and it varies by frequency; inside the direct field, movement and orientation strongly affect level. Beyond it, the room response becomes more influential. Measurement plans should use both representative occupant positions and positions selected to challenge weak boundaries, rather than a single central source location.

Source fixtures should be repeatable. A loudspeaker needs a recorded height, axis, equalisation, level and orientation. A live talker requires monitoring and a defined script or task. Rotation tests can reveal a directional path. Relocation can separate a boundary effect from a room mode. The report should preserve every source coordinate and state required to reproduce the result, while stating that an untested occupant can still create a more demanding orientation.[234]

Worked example 27.19. Critical-distance screening

A room has volume V = 250 m³ and decay time T_60 = 0.60 s. A source has directivity factor Q = 2. Estimate critical distance with the common screening relation.

r_c is the screened critical distance in metres. Q is dimensionless directivity factor. V is cubic metres. T_60 is seconds.

The screened critical distance is about 1.65 m. The relation assumes an idealised diffuse field and should not be used as a precise boundary in modal, coupled or highly non-diffuse rooms.

27.20 Vocal-effort source-state distributions

A design source level should represent a distribution, not a mythical average talker; participants vary by voice, language, age, role, emotion, hearing, distance and conversational purpose; a confidential negotiation may include quiet exchanges, emphatic disagreement, repeated numbers and presentation speech directed across a long table. The source-state register should therefore include normal, raised and high-consequence states, together with the duration and probability assumptions used for design and test.

Percentile-based levels can be useful when their measurement population and geometry are clear; they should not be copied from unrelated conditions without adjustment; a one-metre free-field speech level differs from a room-average level and from the pressure near a door. The register

234 MB-0508. ASTM International, ASTM E1179-13.

should identify reference distance, weighting, time statistic, band spectrum, orientation and whether the value represents continuous speech, peaks or a calibrated artificial source; the governing state is selected by consequence and authorised use, not by statistical convenience alone.

Operational controls can reduce source demand. Seating, local reinforcement, microphones, display layout and communication etiquette can prevent participants from shouting across the room. Those controls must be tested for failure and misuse. If confidentiality depends on all occupants maintaining a quiet voice, the restriction should be explicit, trained and monitored. Engineering should not disguise a fragile behavioural assumption as a wall rating.[235]

Worked example 27.20. Percentile source selection

Measured one-metre speech levels for a representative task have mean 62 dB and standard deviation 4 dB. Screen a 95th-percentile level using a normal model with z = 1.645.

L_95 is the screened 95th-percentile level. mu is the sample mean in decibels. sigma is sample standard deviation in decibels. z is the selected normal quantile.

The screened level is about 68.6 dB. Decibel distributions, sample independence and population representativeness require review. The result does not cover extreme events, different tasks or spectral changes.

235 MB-0509. International Organization for Standardization, ISO 9921:2003.

Table 27-4. Vocal-effort source-state register.

State	Reference descriptor	Use condition	Control or test consequence
Normal seated speech	Level, spectrum, one-metre reference and orientation	Routine discussion	Baseline source state
Raised discussion	Percentile or bounded level with spectrum	Long table, disagreement or impaired communication	Design challenge state
Presentation or playback	Electronic source, preset and directivity	Standing presentation or media	Separate electronic-source test
High-consequence tokens	Names, digits, dates and short commands	Material confidential content	Supplemental listener or metric analysis
Emergency or abnormal	Alarm, override, shouting or open door	Life safety or disruption	Operational restriction, not ordinary acceptance

27.21 Lombard feedback, vocal level and spectral change

When background rises, talkers often increase vocal level and alter articulation, rate and spectrum; this Lombard response can consume part of the apparent masking benefit; the feedback is not one fixed decibel-for-decibel coefficient; it depends on noise spectrum, level, task, language, talker, hearing and communication geometry. A design that raises masking by 6 dB and assumes the received speech margin improves by the same 6 dB is therefore incomplete.

The response can also change the source spectrum; increased high-frequency energy may improve consonant transmission through a weak path even when overall level changes modestly; talkers may lean forward, turn towards a distant participant or move closer to a door. Electronic microphones and automatic gain can interact with these adaptations; commissioning should observe actual communication behaviour under proposed masking, while avoiding the false authority of a small convenience sample.

Operational evaluation should examine comfort, fatigue, complaints and workarounds; occupants may lower masking, disable emitters, open doors or use portable loudspeakers when communication becomes difficult; those reactions are part of system risk; a robust design provides adequate internal communication at moderate effort, keeps receiving backgrounds within governed ranges and detects unauthorised changes. The report should disclose any empirical vocal-response assumption and its uncertainty.

Configuration control must include objects that are rarely treated as acoustic equipment. A full bookcase, upholstered chair, movable writing board, heavy curtain, conference table and group of occupants can alter absorption, scattering, source height and sight lines; the same room can therefore have materially different response during an executive meeting, a sparse maintenance period and a public presentation. A representative occupied-state test may use people, calibrated absorptive substitutes or a validated model, but the chosen representation and its uncertainty must be recorded; movable acoustic panels require position marks, inspection and an authorised storage state; cleaning, conservation and infection-control practices can replace porous finishes with sealed facings or remove curtains without an acoustic review. Furniture procurement should preserve dimensions and material characteristics rather than accepting an appearance-only substitution. When the authorised layout is flexible, acceptance should cover the bounding configurations or define restrictions; a photograph is useful, but a dimensioned room-state schedule gives the later investigator a reproducible baseline.[236]

236 MB-0510. Nature Portfolio / original research authors, Scientific Reports 16, article 49995.

Worked example 27.21. Masking benefit with bounded Lombard response

Masking rises by 6 dB in a receiving zone. A screening assumption bounds the talker response coefficient k between 0.25 and 0.50 dB of vocal increase per decibel of added room noise.

Delta L_voice is vocal-level change, Delta L_mask is masking change, k is an empirical coefficient, and Delta M_net is the screened net margin change.

The apparent 6 dB masking increase yields a screened net benefit of 3.0 to 4.5 dB under the assumed range. This is not a universal prediction. Actual talker behaviour and spectral effects require observation or conservative bounding.

27.22 Background-noise taxonomy and time statistics

Receiving background should be decomposed by source and time behaviour; continuous HVAC, cycling fans, lifts, traffic, weather, adjacent occupancy, cleaning, alarms and intermittent plant create different masking reliability; a broadband average can conceal long quiet intervals; the measurement plan should record equivalent level, percentile levels, maxima, minima and time histories in the bands relevant to transmitted speech. It should also identify whether each source is controlled, incidental or prohibited from being credited.

Time weighting and detector settings affect observed variation; a short sample can overstate a busy condition or miss a rare quiet state; measurements should span representative operating periods and include declared quiet hours, weekends, seasonal plant modes and low-occupancy conditions. Where long-term monitoring is used, clock synchronisation, microphone stability, data completeness and event annotation become part of the evidence chain; a percentile is meaningful only when the observation window and population of states are defined.

The design should separate background used for comfort from background credited for privacy. Environmental sources outside organisational control usually deserve little or no credit. Mechanically generated background may be creditable only if minimum operation, maintenance, alarms and failure response are governed. Masking systems are treated separately because their purpose, spectrum and control are deliberate. The final acceptance table should state which background components are mandatory, incidental or excluded.[237]

Worked example 27.22. Time-weighted equivalent level

A receiving zone is at 38 dB for 45 minutes and 30 dB for 15 minutes. Compute the one-hour energy-equivalent level.

L_eq is energy-equivalent level in decibels. L_1 and L_2 are state levels. t_1 and t_2 are durations in common time units.

The one-hour equivalent is about 37.0 dB, yet the room was at 30 dB for a quarter of the hour. A privacy assessment based only on L_eq could miss the controlling quiet interval.

27.23 Quiet-hour, seasonal and occupancy envelopes

The lowest credible receiving background frequently controls speech detectability; night setbacks, reduced ventilation, unoccupied corridors, snow, closed traffic routes, plant shutdowns and scheduled maintenance can remove background that appeared dependable during commissioning;

237 MB-0511. International Electrotechnical Commission, IEC 61672-1:2013.

the room data sheet should define a quiet-state envelope by season, time, occupancy and plant mode. It should identify which conditions are authorised for protected discussion and which require additional controls or suspension.

Occupancy changes both source and receiver conditions; people add absorption inside the protected room, but they also create background in adjoining spaces; a test with a crowded corridor may overstate protection, while a test in an empty protected room may overstate decay relative to normal use. The acceptance plan should therefore select conservative combinations rather than attempting to reproduce every possible occupancy; empty receiving zones and normally furnished protected-room states often deserve specific examination.

Long-term evidence can be developed through scheduled spot measurements, permanent monitoring or building-control logs, provided the sensor chain and data governance are adequate. Weather and plant records can help explain excursions. The resulting envelope should be reviewed after major occupancy, scheduling or mechanical changes. A quiet-state restriction that depends on staff memory is weak. It should be encoded in operating procedures, room booking, alarms or automatic interlocks where justified.[238]

Worked example 27.23. Quiet-state privacy margin

Residual speech in a critical band is 29 dB. Normal background is 34 dB, but the quiet-hour background is 25 dB. Calculate speech-to-background margins.

238 MB-0512. ASTM International, ASTM E2638-24.

M is band speech-to-background margin. L_s is residual speech level. L_b is background level for the stated condition.

The quiet state worsens the margin by 9 dB and changes it from negative to positive. This does not directly calculate intelligibility, but it establishes that daytime evidence cannot be transferred to quiet hours without further analysis.

Table 27-5. Receiving-background state register.

State	Sources present	Credit status	Required evidence
Normal occupied	HVAC, adjacent occupants, traffic and equipment	Conditional	Band levels, time statistics and operating record
Quiet hour	Reduced plant and low occupancy	Controlling minimum candidate	Night or weekend measurement
Seasonal extreme	Weather and seasonal plant state	Project-specific	Seasonal data or conservative bound
Maintenance or cleaning	Changed plant, open panels and temporary equipment	Usually no credit	Work permit and suspension rule
Masking failure	Environmental background only	Failure state	Alarm, response and restricted use

27.24 Masking-system architecture and security dependency

A masking system is an active dependency composed of signal generation, spectral shaping, distribution, amplification, emitters, power, control, monitoring and physical installation; it may use direct-field emitters in the occupied zone, plenum loudspeakers, distributed transducers or another architecture. Each arrangement creates different spatial, structural, maintenance and fault behaviour; the basis of design should identify which receiving zones are protected, which paths are not addressed, and which functions are required for the room to remain authorised.

The control architecture should prevent silent drift and unauthorised adjustment; setpoints, equalisation, zone assignments, schedules and maximum levels need access control and configuration records; loss of one amplifier channel, a disconnected emitter, a changed ceiling tile or a software update can create a local quiet point while the central controller reports normal operation. Monitoring should therefore test end-to-end acoustic performance or use a justified combination of electrical supervision and periodic field verification.

Power failure, fire alarm, emergency communication, maintenance and network outage states require explicit treatment; life-safety systems take precedence where required, and masking must not interfere with warning audibility or accessible communication; if protected discussion cannot continue safely during a failure, the system should produce a clear operational indication and trigger suspension. Redundancy can improve availability, but common power, control, network or configuration dependencies must be identified rather than hidden by duplicate hardware.

Speech-security evaluation should recognise that information is not uniformly distributed across a sentence; digits, surnames, call signs, dates, short commands and repeated corrections can remain recoverable even when ordinary connected prose is poorly understood. Talkers also adapt. They repeat misunderstood material, spell names, raise their level and turn towards remote participants or displays. Test corpora should therefore include representative high-consequence tokens and should document language, talker population, vocal effort and listener familiarity; synthetic signals can support objective measurement, but they do not reproduce every temporal or contextual feature of live speech; recordings used for listening tests require controlled playback level, directivity and equalisation. Listener scoring should be blinded where practicable and should distinguish audibility, partial recognition and correct transcription. A result derived from one language, hearing population or sentence corpus should not be generalised silently to all users; the report should state whether electronic enhancement, repeated listening or contextual reconstruction was excluded, because those assumptions define the threat model rather than merely the measurement method.[239]

Worked example 27.24. Masking-service availability

A masking subsystem has mean time between failures MTBF = 8,000 h and mean time to repair MTTR = 6 h. Estimate intrinsic steady-state availability.

A_v is intrinsic availability. MTBF and MTTR are hours under the assumed renewal model.

The screened availability is 99.925 per cent, corresponding to about 6.56 h of expected unavailability per year. The calculation excludes detection delay, scheduled maintenance, common-cause failures, misconfiguration and local acoustic underperformance.

Table 27-6. Masking architecture comparison.

Architecture	Principal advantage	Principal risk	Acceptance focus
Direct field	Predictable occupied-zone radiation	Local gradients, visible devices and tampering	Point grid, mounting and control
Plenum	Broad distribution through ceiling system	Structure, duct and tile dependence	Ceiling state, plenum paths and emitter support
Distributed transducer	Can integrate with surfaces	Mechanical coupling and proprietary behaviour	Vibration, substrate and configuration
Hybrid zoned	Tailored coverage and redundancy	Complex control and boundary interactions	Zone maps, failure combinations and common causes

239 MB-0513. ASTM International, ASTM E2638-24.

27.25 Masking spectrum, comfort, exposure and governance

A masking spectrum should be shaped to reduce speech detectability while remaining tolerable and compatible with the occupied function; excess low-frequency energy can raise annoyance without efficiently masking consonants; excess high-frequency energy can sound hissy, aggravate fatigue and encourage vocal compensation. The design should use band targets, not only an A-weighted total, and should evaluate spatial variation at seated and standing ear heights in the accessible receiving zone.

Comfort and occupational-health criteria are distinct from speech-security criteria; a level acceptable for brief testing may be unsuitable for daily exposure; conversely, an occupational exposure limit is not a recommended masking level; the project should apply applicable health, workplace, accessibility and owner criteria separately, then select the lowest masking condition that supports the security objective without creating unacceptable burden. Complaints, hearing diversity and communication needs should be included in the trial and post-occupancy review.

Governance should define who may adjust levels, how changes are documented, and what evidence is required after adjustment. A user-accessible control that can reduce masking below the accepted minimum defeats the dependency unless it triggers an alarm or operating restriction. Spectral changes should be verified with calibrated instrumentation. An apparently small broadband adjustment can create a large local change in a critical band or zone.[240]

240 MB-0514. National Institute for Occupational Safety and Health, NIOSH Recommended Exposure Limit for Occupational Noise, Understand Noise Exposure.

Worked example 27.25. Spectral adjustment without broadband inflation

A designer proposes adding 4 dB in one critical octave band while leaving three other equally weighted screening bands unchanged. The initial band levels are all 36 dB.

L_initial and L_adjusted are screened unweighted sums across four equal-band contributions. Delta L_total is total change.

A 4 dB increase in one band raises the four-band sum by only about 1.0 dB. Broadband level can therefore conceal a consequential spectral change. Actual weighting and band bandwidths must be treated correctly.

27.26 Spatial uniformity, zoning and critical listener positions

Masking performance is spatial. A corridor average can conceal quiet points beside a door jamb, under a grille, near a return-air opening, behind furniture or at a zone boundary. Commissioning should map accessible listener positions at a spacing appropriate to geometry and expected gradients. Measurements need band resolution, consistent microphone height, adequate dwell time and a record of emitters, ceiling state, doors, furnishings and nearby reflective surfaces.

Zoning should follow acoustic need rather than administrative convenience; a long corridor may require separate zones where ceiling height, absorption, emitter spacing or path risk changes; adjacent offices may need different spectra or levels; zone boundaries can create abrupt gradients and control ambiguity. The drawing should show every emitter, controller channel, zone, critical point, path feature and excluded area. Each test point should have stable coordinates so later drift can be compared.

Uniformity criteria should be paired with minimum and maximum band limits. A low standard deviation does not help if the whole zone is below the required minimum, and a compliant mean does not excuse one severe quiet point. The evaluation should separate instrument uncertainty, temporal variation and spatial variation. Where the grid is large, risk-based dense sampling around openings and sparse sampling in uniform regions can be justified, provided the selection is recorded before results are known.[241]

Worked example 27.26. Spatial variation screen

Five critical-point levels in one band are 36, 37, 35, 32 and 36 dB. Calculate the mean, range and population standard deviation.

L_bar is the arithmetic mean of logarithmic level readings used only as a spatial uniformity descriptor. R is range. Sigma is population standard deviation in decibels.

The mean is 35.2 dB, the range is 5 dB and the standard deviation is about 1.72 dB. Point 4 may control even if the average appears satisfactory. Energy averaging is required for energetic combination, but arithmetic statistics are commonly useful for spatial consistency.

Figure 27-4. Masking commissioning maps zones, emitters and critical listener positions at doors, grilles and quiet locations. Author original diagram.

Table 27-7. Spatial masking and listener-position matrix.

Location class	Sampling density	Band requirement	Special state
Open uniform corridor	Regular grid	Minimum, maximum and variation	Normal and quiet-hour HVAC
Door perimeter	Dense targeted points	Critical speech bands	Latched, cycling and adjacent door states
Grille or service opening	Targeted near-field points	Path-specific spectrum	Fan and damper combinations
Zone boundary	Both sides of control transition	Gradient and minimum level	Single-zone failure

241 MB-0515. International Electrotechnical Commission, IEC 61260-1:2014.

Location class	Sampling density	Band requirement	Special state
Occupied office	Representative ear positions	Comfort and privacy	Furniture and occupancy changes

27.27 Temporal stability, alarms and failure detection

A masking zone can pass a brief survey yet fail through schedule changes, thermal drift, intermittent network control, amplifier protection, loose connectors or gradual emitter loss; temporal acceptance should therefore define the observation interval and the permissible variation in each critical band. Short-term stability can be assessed during commissioning; longer-term assurance may require trend data, controller logs, electrical supervision and periodic acoustic verification.

Failure detection should be end-to-end where practicable; monitoring only amplifier output does not prove that an emitter is connected, unobstructed or producing the intended field; a reference microphone can detect acoustic change but introduces its own calibration, privacy, cybersecurity and maintenance questions. Synthetic self-test tones can be inaudible or scheduled, but they may not exercise the full programme path; the selected method should state which failure modes it detects and which remain latent.

Alarms must produce an actionable response. A fault indicator buried in a control interface does not protect a room whose users continue confidential discussion; the operating concept should define severity, notification, acknowledgement, suspension, temporary controls, repair authority and retest; alarm thresholds need guard bands that account for measurement and environmental variation. Repeated nuisance alarms invite bypass, so human-factors review is part of reliability rather than an administrative afterthought.

A spatial acceptance rule should be written before data are collected; mean level, median, percentile, range and maximum deviation answer different questions; a percentile can describe broad uniformity while still permitting a consequential local minimum, so critical locations require separate limits. Measurement uncertainty and short-term fluctuation should be considered before classifying one point as an outlier, but repeated confirmation must not be used to average away a genuine defect; interpolation maps are visually persuasive and can imply information where no measurement occurred. The underlying points, interpolation method and boundary assumptions should therefore accompany every contour plot. The survey should include door arcs, corners, glazing perimeters, return-air openings, lift lobbies, service cupboards and other accessible locations where geometry or zone transitions can reduce masking. Vertical variation may matter where a standing listener, seated listener or ceiling access route changes ear height. After correction, the same points should be retested, and the investigator should verify that raising one zone has not created discomfort, excessive level or cross-zone spill elsewhere.

Spatial acceptance should retain the distribution, not merely its mean and range. Percentiles can describe broad uniformity, but a single consequential minimum near a door, return grille or public circulation route may control security even when it occupies little floor area. The point map should therefore include coordinates, height, instrument orientation and local geometry, while the decision rule separately addresses average conformity and worst-accessible-position conformity. Interpolation graphics are useful for visualisation, yet they must not invent resolution between widely spaced measurements or smooth away a narrow trough caused by destructive interference or zone-boundary cancellation.[242]

Worked example 27.27. Combined latent-failure screen

Three independent masking components have annual failure probabilities 0.010, 0.015 and 0.005. Estimate the probability that at least one fails in a year.

P_any is probability of at least one failure. p_i are component failure probabilities. Independence is assumed.

The screened probability is about 2.97 per cent. Common-cause failures, repair time and detection delay can make actual service risk higher. The equation supports failure budgeting, not a complete reliability demonstration.

27.28 Direct-field and plenum emitters, structure-borne effects

Direct-field emitters radiate into occupied space, while plenum systems use the ceiling cavity and tile transmission to distribute sound; the two architectures differ in efficiency, spatial smoothness, maintainability and interaction with the boundary; a plenum emitter can excite deck, ducts, cable trays and ceiling grid. A direct-field emitter can create visible hardware, local gradients and tamper opportunities. Neither architecture is inherently secure. The selection must follow the actual path and room construction.

Mounts and enclosures can transmit vibration. Lightweight ceilings, shared suspension, rigid conduit and poorly isolated back-cans can carry tonal or

242 MB-0516. International Electrotechnical Commission, IEC 61672-1:2013.

broadband energy into adjacent spaces; structure-borne effects may appear as audible noise, increased background or unintended excitation of a weak boundary; vibration measurement, temporary isolation and controlled source tests can distinguish these mechanisms. Increasing masking output without diagnosing a structural route may worsen rather than improve the system.

Inspection should document emitter model, location, orientation, support, fasteners, back-can, wiring, plenum barrier, nearby services and ceiling tile condition. Replacement of one tile or relocation of an emitter can change the field. Commissioning should include ceiling-open and ceiling-closed states only when operationally relevant and safe, with explicit recognition that an open ceiling may create a different airborne path.[243]

Worked example 27.28. Mount-isolation screening

A vibrating emitter mount measures 82 dB re the selected acceleration reference on the source side and 61 dB on the supported ceiling member under the same test.

D_a is the directional acceleration-level difference in decibels. The levels must share a reference, bandwidth, sensor method and operating state.

The screened difference is 21 dB. It does not establish transmitted sound power or room privacy. Sensor mounting, structural mobility and alternate paths must be examined.

27.29 Speech metrics, audibility and method limits

Audibility, intelligibility and information recovery are related but distinct outcomes; a listener may detect speech rhythm without understanding

243 MB-0517. ASTM International, ASTM E336-25a.

words, recognise digits under conditions that obscure ordinary sentences, or reconstruct meaning through context and repetition; metrics such as STI, signal-to-noise ratio, articulation-based quantities and closed-room privacy measures use different models and inputs. A project should select the metric that answers the stated question and disclose the listener, source, language, background and temporal assumptions.

STI evaluates modulation transfer under defined conditions and is powerful for communication-system assessment; its limitations matter in fluctuating noise, nonlinear processing, strong echoes and privacy applications; closed-room privacy methods combine room isolation and receiving background for a specified listener model. Open-plan methods address different geometry and propagation; none should be renamed or converted casually into a governmental security rating. Method scope is part of the result.

A complete report should retain band levels, source calibration, background, processing settings, spatial positions, uncertainty and the raw data needed to recompute the metric; it should also examine high-consequence fragments separately where appropriate; a pass against one metric does not erase a visible local leak or an abnormal state. Engineering judgement may require remediation even when a broad numerical criterion is met, provided the reason and decision authority are recorded.

Zone boundaries are functional interfaces rather than coloured regions on a reflected-ceiling plan. Sound crosses those boundaries through open circulation paths, ceilings, plenums, doors and structural elements; adjacent controllers may use different target spectra or schedules, producing audible discontinuities and quiet strips; the commissioning plan should measure both sides of every consequential boundary and during every programmed transition. Where plenum emitters serve several rooms, ceiling attenuation, tile replacement and plenum barriers influence the delivered spectrum; direct-field systems depend more visibly on emitter orientation and line of sight, but furniture and partitions can still create shadowing; a boundary near a secure-room door deserves particular scrutiny because door opening changes both transmission and masking fields. The control architecture should prevent unauthorised zone reassignment and should record which output channel serves each emitter. Drawings, controller exports and physical tracing must agree. A software label alone is insufficient where wiring or network routing can differ from the displayed topology.[244]

Worked example 27.29. Band speech-to-background ratio

Residual speech level is 28 dB and background is 33 dB in a critical band at one listener position.

SNR is band speech-to-background ratio in decibels. L_s is residual speech level and L_b is background level under comparable detector and bandwidth settings.

The band SNR is -5 dB. This does not directly predict word recognition because temporal modulation, adjacent bands, listener ability, repetition and room response also matter.

Table 27-8. Speech metric applicability and exclusions.

Quantity or method	Useful question	Required inputs	Do not infer
Band SNR	Where is residual speech above or below background?	Comparable band levels and state	Word recognition probability by itself
STI	How well is speech modulation transmitted?	Method-valid source, noise and processing	Closed-room security or every fluctuating state

244 MB-0518. International Electrotechnical Commission, IEC 60268-16:2020.

Quantity or method	Useful question	Required inputs	Do not infer
Closed-room privacy method	What privacy is provided under bounded source and background?	Isolation, background and listener model	Electronic surveillance resistance
Open-plan privacy method	How does speech decay and background interact in open space?	Open-plan geometry and method	Closed-room equivalence
Token recognition	Can high-consequence fragments be recovered?	Corpus, listeners, scoring and calibration	Universal population result

27.30 Closed-room speech-privacy measurement

Closed-room privacy assessment begins with a defined source spectrum and level, room isolation to accessible receiving positions, and the receiving-side background under the relevant condition; it should include the weakest plausible positions rather than a single room-average point. Door perimeters, grilles, ceiling interfaces and quiet corners deserve deliberate examination; the source and background must be measured or normalised according to the selected method, and the final quantity should retain its proper name and scope.

The test should identify whether the listener model is unaided and whether electronic enhancement, contact listening, directional microphones or repeated exposure are outside scope; it should also identify language and source assumptions; a good closed-room result can support ordinary architectural privacy under the tested state. It does not prove protection against every technical-surveillance method, an insider, a recording device placed in the room or a controlled governmental criterion not available in public sources.

Decision criteria should be specified before testing; if a contract uses a privacy probability, class or margin, the calculation and uncertainty rule should be stated; if the result is close to a threshold, guard-banding or remedial investigation may be appropriate. A local defect should not be averaged away without understanding its consequence; retesting after repair should reproduce source, background, furniture, door, masking and listener geometry sufficiently for comparison.

Fault telemetry should be designed as an evidence chain rather than a decorative dashboard. The monitored variables may include controller health, amplifier output, emitter continuity, zone level, spectral shape, network reachability, clock state, schedule state and unauthorised override. Each alarm requires a defined threshold, persistence time, destination, acknowledgement rule and escalation path. A controller that merely reports its own software state cannot prove that acoustic energy reaches the occupied zone. Independent sensing, periodic challenge signals or comparison with commissioned reference microphones may be necessary for end-to-end confidence.[245]

Worked example 27.30. Isolation-background combined screen

A standardised source band is 70 dB inside the room. Field level difference to the critical receiving point is 43 dB. Receiving background is 30 dB.

L_residual is screened residual speech-band level. L_source is source level. D is field level difference. M is residual-to-background margin.

245 MB-0519. ASTM International, ASTM E2638-24.

The screened margin is -3 dB. A method-specific privacy calculation may use additional spectral weighting and probability functions. This simplified result is diagnostic only.

27.31 High-consequence tokens and listener models

Not all leaked content has equal consequence or equal recognisability; names, digits, dates, call signs, alphanumeric strings and short commands can be recovered under conditions where continuous discourse appears unintelligible; their limited vocabularies and contextual constraints reduce uncertainty. Test corpora and operational analysis should therefore include high-consequence token classes when the room use makes them material; scores should be reported by class rather than hidden in one aggregate percentage.

The listener model should specify hearing, language, prior knowledge, training, position and whether repeated trials are allowed; an unaided casual listener differs from a motivated listener who knows the subject, recognises voices and can correlate speech fragments with visible activity. A public standard may intentionally use a bounded ordinary-listener model; security analysis can supplement that model, but it should not alter the standard result or claim a proprietary metric without validation.

Blinding and randomisation reduce bias. The listener should not know the script, and scorers should follow predeclared rules for partial recognition; multiple listeners allow variability to be estimated; playback chains need calibration if recordings are used; the report should distinguish direct listening from recorded or enhanced listening and state what the test does not cover. High-consequence testing is a supplement to physical path diagnosis, not a substitute for it.

Comfort evaluation should use both level and spectral evidence; two masking spectra with the same A-weighted value can differ substantially in high-frequency hiss, low-frequency rumble and tonal prominence; narrowband tones, modulation, beat frequencies and periodic control artefacts can attract attention even when the broadband level appears moderate. Complaints are diagnostic evidence, but absence of complaint does not prove suitability because occupants may adapt, remove emitters or alter controls informally; the design should distinguish occupational exposure limits from comfort and privacy criteria. A level below a hearing-risk threshold can still impair concentration or communication, while a comfortable level may be insufficient at a critical listener position. Commissioning should include representative work tasks, hearing-assistance considerations and quiet periods. Corrective adjustment must preserve the approved security proposition. Reducing a troublesome band without remeasurement can create a speech cue window, while raising the complete spectrum can drive Lombard response and undermine the intended benefit.

Comfort and security objectives must be balanced through a documented operating envelope. Raising masking can reduce a speech-to-background margin, but it can also increase annoyance, fatigue, communication effort and the temptation to defeat or lower the system. The design should assess spectral balance, temporal variation, tonal content, spatial gradients and exposure duration rather than relying on a single A-weighted value. Complaints should be investigated as technical evidence. A cluster of reports in one zone may indicate spectral imbalance, a defective emitter, excessive high-frequency energy or a control schedule that differs from the commissioning state.[246]

Worked example 27.31. Token-recognition confidence interval screen

A listener correctly identifies 9 of 40 randomly presented high-consequence tokens. Estimate the observed proportion and a simple binomial standard error.

p_hat is observed recognition proportion. x is correct responses. n is trials. SE is the large-sample standard error.

Observed recognition is 22.5 per cent with screened standard error about 6.6 percentage points. Exact intervals may be preferable for small samples. The result depends on corpus, listener and test conditions.

27.32 Repetition and cumulative information recovery

A meeting is a sequence of opportunities; participants repeat names, correct numbers, summarise decisions and refer to visible documents; even a low probability of recognising one exposure can become consequential over many repetitions; cumulative recovery should therefore be considered when meetings are long, the same listener has persistent access, or the same terminology recurs. A brief single-phrase test may understate risk.

The simplest repeated-trial equation assumes independent equal-probability exposures, an assumption rarely exact in speech; context creates dependence, while fatigue and changing positions alter performance; the equation is nevertheless useful as a sensitivity screen; more realistic analysis

246 MB-0520. National Research Council Canada, NRC Canada research report and related peer-reviewed programme, New Framework for Rating the Speech Privacy of Enclosed Rooms.

can model token classes, listener learning, correlated exposures and observation time. The report should avoid presenting a convenient independence calculation as empirical certainty.

Operational controls can reduce repetition and access; closing the door before discussing names, avoiding loud repetition of digits, using secure visual channels and limiting adjacent occupancy time can supplement construction; such controls must be practical and trained. They should never be used to excuse a readily repairable leak; the strongest defence combines a sound physical boundary, governed receiving conditions and disciplined use.

HVAC support should be characterised by operating state and frequency band. Supply volume, return path, fan speed, damper position, terminal-box mode, filter condition and building schedule can each change the receiving background. A daytime average assembled from several fan states may conceal the low-background interval that occurs when a variable-air-volume box satisfies temperature or when night setback begins. The commissioning matrix should therefore include minimum stable flow, normal occupied flow, maximum authorised flow, start-up, shutdown and credible maintenance bypass conditions.[247]

Worked example 27.32. Cumulative recognition probability

Assume a listener has probability p = 0.08 of recognising a particular token on any one of ten independent repetitions.

P_at_least_one is probability of at least one recognition. p is single-trial probability. n is number of independent repetitions.

247 MB-0521. National Research Council Canada, NRC Canada research report and related peer-reviewed programme, New Framework for Rating the Speech Privacy of Enclosed Rooms.

The screened cumulative probability is about 56.6 per cent. Real repetitions are not independent and may carry contextual cues, so this calculation is a sensitivity warning rather than a measured room rating.

27.33 Aided listening, recording and enhancement boundaries

Architectural privacy methods commonly use a bounded listener model; directional microphones, parabolic collectors, contact sensors, hearing aids, recording, spectral filtering and repeated playback can change the effective receiver; these tools should not be silently folded into an unaided-listener result. A security analysis may examine them as separate scenarios, using lawful public information and appropriate authority, but the report must preserve the distinction between standard architectural privacy and technical surveillance resistance.

Recording changes time. A transient fragment can be replayed, slowed, filtered and correlated with other evidence; enhancement can improve some cues while generating artefacts and false confidence; the evidentiary chain should preserve original recordings, calibration, bit depth, sample rate, microphone response, processing history and software versions. Demonstrative enhancement should never overwrite the source data; expert conclusions should state which words were directly audible, algorithmically suggested or inferred from context.

The design response should focus on path control rather than an arms race with hypothetical equipment. Repair openings, reduce structural coupling, manage accessible listener positions and enforce operating states. Where a specific public threat model requires aided-listener assessment, define transducer, distance, orientation, bandwidth, noise, recording duration and decision rule. Do not claim that one unsuccessful test proves immunity to all future sensors or processing.[248]

Worked example 27.33. Receiver self-noise and available margin

A residual signal is 18 dB SPL in a band. The receiving background is 22 dB, while a proposed microphone self-noise equivalent is 16 dB. Combine background and self-noise as uncorrelated levels.

L_noise,total is combined acoustic-background and equivalent self-noise level. M is screened signal margin.

The screened margin is about -5.0 dB. Microphone directivity, processing gain, temporal integration and calibration remain unmodelled. The calculation does not establish intelligibility.

27.34 Listener access, geometry and observation time

A potential listener must have a position, posture, orientation, access duration and reason to remain; accessible corridors, offices, service spaces, ceiling voids, façades and exterior areas differ in probability and consequence; the test plan should map positions that are lawfully or operationally accessible, including temporary access during maintenance and cleaning. A point immediately beside a door may be more important than the centre of a receiving room.

Geometry changes with furniture, storage, doors and partitions; a cabinet can create a sheltered quiet point; a desk can place a listener's ear near a weak junction; exterior vegetation, snow or parked vehicles can alter local noise and reflection. The analysis should distinguish permanent geometry

248 MB-0522. ASTM International, ASTM E2638-24.

from transient arrangements and identify which must be controlled. Photographs and coordinates support later reproduction.

Observation time matters because intermittent speech, masking faults and access schedules can align; a listener present for one minute has fewer opportunities than one in an adjacent office for eight hours; risk assessment can combine path performance with access duration, but it should avoid speculative numerical precision. Engineering acceptance remains based on defined measurable conditions, while operational risk informs which conditions deserve priority.

Door operation creates a time-dependent exposure that steady closed-door testing does not describe. Arrival, departure, catering, document movement and emergency egress can produce repeated opening intervals during which corridor masking, vestibule geometry and speech discipline become decisive. The operating analysis should record opening duration, interlock logic, closer speed, latch engagement and the probability of both leaves being open together. A sound lock reduces line-of-sight transmission only when its dimensions, absorption, seals and operating sequence are maintained. Automatic operators, access-control delays and accessibility settings can lengthen exposure. Training should require a pause in protected speech during vulnerable cycles, but procedural reliance must be tested through observation or exercises rather than assumed. Where operational tempo makes compliance unlikely, the design requires a physical or administrative change. Event logs, door-position monitoring and targeted acoustic measurements can quantify the condition without treating the open state as a rated assembly.[249]

249 MB-0523. ASTM International, ASTM E2638-24.

Worked example 27.34. Exposure-opportunity screen

Protected speech occurs for 90 minutes. A service worker has authorised access to the critical receiving zone for 12 minutes during that interval.

F_access is the fraction of protected-speech time during which the listener position is accessible. Times use the same units.

The screened overlap is 13.3 per cent. It does not quantify recognition or intent. It helps identify whether scheduling, escort or temporary suspension could reduce exposure.

27.35 Door transitions and meeting-cycle risk

Doors create both a high-loss closed state and a near-open path during transitions; the meeting cycle includes arrival, late entry, breaks, deliveries, emergency access and departure; confidential speech often begins before the latch engages or continues while participants leave. Testing only the fully latched state is necessary for the physical boundary but incomplete for operational risk; the room procedure should define when protected speech may begin and how interruptions are managed.

Door closers, seals, latches, access control and user behaviour interact; a closer adjusted for accessibility may not deliver sufficient final latch force against a compressed acoustic seal; a card reader can delay entry and increase open time. A door hold-open, wedge or cable can defeat the boundary; alarm logic can detect prolonged opening but must avoid nuisance bypass. The door-state record should include closed, unlatched, propped, cycling and failed-closer conditions.

Operational controls can include vestibules, visual meeting indicators, controlled delivery points, briefing protocols and automatic suspension of masking-dependent authorisation when a door opens. Those controls should respect egress, accessibility and life safety. Incident review should compare access logs, door-monitor events and meeting times where lawfully available. A procedural failure does not erase a construction defect, and a good door rating does not cure undisciplined operation.[250]

Worked example 27.35. Door-open duty cycle

During a 60-minute meeting, the door opens six times for 8 seconds each. Estimate the open-time fraction.

t_open is cumulative open time in seconds. F_open is the fraction of meeting duration with the door open.

The door is open for about 1.33 per cent of the meeting. That small fraction can still dominate information exposure because attenuation collapses during each event and speech may coincide with it.

Table 27-9. Meeting-cycle transition matrix.

Event	Door or control state	Primary risk	Required response
Arrival and setup	Door cycling, systems starting	Speech begins before readiness	Status confirmation before protected use
Late entry	Temporary open path	Direct exposure to corridor	Pause protected speech
Break or delivery	Repeated transition	Cumulative fragments and propping	Controlled delivery and chair ownership
Emergency	Override, unlock and alarms	Life safety dominates	Stop protected speech and follow emergency plan
Departure	Door cycling and informal continuation	Sensitive closing discussion	End meeting before opening

27.36 Operational source control and briefing protocol

Operational speech discipline should reduce avoidable source demand without becoming a substitute for engineering; participants can be seated

250 MB-0524. ASTM International, ASTM E336-25a.

away from weak doors and glazing, local reinforcement can reduce shouting, remote participants can be levelled correctly, and presentations can use visual rather than repeated spoken identifiers. Briefings can begin only after doors and active controls are confirmed; high-consequence strings can be handled through secure visual or digital methods where policy permits.

The protocol should be brief, observable and compatible with the work. Complex instructions fail under pressure. A room-status indicator can show door, masking and system readiness; the meeting chair can own the start and stop decision; staff need to understand why quiet hours, emergency states and maintenance matter; training should use realistic demonstrations without revealing protected content or controlled criteria.

Compliance evidence may include room booking rules, training records, periodic observation and incident reports; surveillance of occupants should be proportionate and lawful; the aim is to improve system reliability, not to create a punitive culture that drives workarounds. When users repeatedly violate a rule because the room is difficult to use, the engineering design should be reviewed; human behaviour is a feedback signal about system adequacy.

Hybrid meetings can raise the internal source beyond the live-talker assumption. Far-end participants, programme material and alert sounds may be reproduced through loudspeakers with broader bandwidth and longer duty cycle than ordinary speech. Automatic gain control can increase output when a remote talker is quiet, while echo-control adaptation and room equalisation can change after furniture or microphone movement. The acceptance state should include representative codecs, endpoints, far-end levels, content types and maximum authorised volume, with the source measured rather than inferred from a user-interface setting.[251]

Worked example 27.36. Source-level reduction at the receiving point

A seating and local-reinforcement change reduces talker source level by 4 dB while the transmission path and receiving background remain unchanged.

Delta L_received is the ideal linear-path change at the receiving point. Delta L_source is the source-level change.

The residual speech level is screened 4 dB lower. Nonlinear vocal behaviour, changed orientation, electronic gain and room response may reduce or amplify the benefit. Field verification is required.

27.37 Emergency, maintenance, cleaning and abnormal states

Emergency states can override masking, activate public-address systems, unlock doors, change ventilation and admit responders. Life safety governs. The secure-room operating concept should identify which confidentiality controls are suspended and how protected discussion stops. Emergency communication must remain audible and accessible. Security controls should never impair required alarms, evacuation or responder access.

Maintenance and cleaning create quieter backgrounds, open ceilings, removed panels, portable equipment, temporary cables and unfamiliar personnel; firmware or control work can reset masking schedules; a room may appear physically intact while its active state is unavailable. Work

251 MB-0525. International Organization for Standardization, ISO 9921:2003.

permits should identify protected boundaries, required escorts, temporary openings, evidence photographs and post-work tests; the room should not automatically return to protected use because a contractor reports completion.

Abnormal states include stuck dampers, failed fans, disabled emitters, open access panels, temporary furniture, power transfer, fire-alarm testing and construction elsewhere in the building. The state register should rank them by likelihood and consequence. Some require immediate suspension. Others can be managed by restrictions and targeted checks. The decision should be documented by the authorised owner, not improvised by occupants.[252]

Worked example 27.37. Abnormal-state expected exposure screen

A masking fault occurs on average twice per year. Mean detection and suspension time is 20 minutes per fault. Protected use averages 1,200 hours per year and is uniformly distributed for screening.

t_fault is annual undetected fault time. F_exposure is screened fraction of protected-use time exposed to the fault under uniform coincidence.

The screened fraction is 0.0556 per cent. Consequence can still be high, and use is rarely uniformly distributed. Detection integrity, common failures and event timing must be analysed.

27.38 Accessibility and assistive-listening interaction

Accessible communication is a legal and functional requirement, not an optional acoustic compromise. Assistive-listening systems, hearing loops,

252 MB-0526. International Organization for Standardization, ISO 7731:2003.

infrared or radio distribution, captions and remote participation can improve access while introducing new transducers, transmitters, cabling, receivers and operating states. The project team should coordinate accessibility, confidentiality, electromagnetic controls, cyber governance and life safety from the beginning rather than attempting to remove an accessibility feature after security review.

The secure design should determine which system is required, where it operates, how receivers are issued, how content is routed and what happens when it is unavailable. A hearing loop deliberately creates a magnetic field that may extend beyond the room. Radio or infrared systems have different coverage and leakage characteristics. Those questions require discipline-specific assessment. Acoustic masking should not make internal communication unusable for participants with hearing differences.

Commissioning should include users or qualified accessibility representatives where appropriate, while protecting sensitive information; tests should verify intelligibility, coverage, interference, control, storage, cleaning and maintenance; security restrictions should be recorded transparently and supported by authority; the publication cannot determine a project's legal compliance from general information, but it can require that accessibility evidence and security evidence be reconciled rather than traded silently.

Probability-based privacy methods require explicit distributions and listener assumptions. Source level varies among talkers and tasks. Receiving background varies by time and position. Isolation varies across frequency and path; the combined result is therefore not represented faithfully by one nominal source and one average background; a method may use a prescribed source distribution and unaided-listener model to estimate the chance of audibility or intelligibility. That estimate remains conditional upon the method, language, source population and access geometry; it does not address a contact microphone, directional array, recorder placed for long-duration accumulation or other aided collection unless those mechanisms are separately modelled and tested; repeated meetings also change consequence. A low probability for one phrase can become significant when names, numbers and context recur over hours. The report should state the exposure duration, repetition assumptions and whether cumulative recovery was considered. The competent authority then decides whether the quantified residual risk is acceptable for the intended discussion.[253]

Worked example 27.38. Receiver inventory sufficiency

A venue has 180 fixed seats. The project requirement calls for assistive-listening receivers equal to 4 per cent of seats, rounded up, with 25 per cent of receivers hearing-aid compatible.

N_r is required receiver count under the stated project assumption. N_h is the compatible subset. Ceil means round upward.

The screen gives eight receivers, two of the compatible type. Actual legal requirements, exceptions and technical specifications must be confirmed for the jurisdiction and facility. The example illustrates inventory control only.

27.39 Human factors, training, complaints and alarm design

Users are sensors of discomfort, communication difficulty and system drift; complaints about hiss, localisation, fatigue, inaudible remote speech or doors that will not latch can reveal material defects; a disciplined

253 MB-0527. United States Department of Justice and United States Access Board, 2010 ADA Standards for Accessible Design, Sections 219 and 706, Assistive Listening Systems.

programme captures those observations without treating them as calibrated measurements. The complaint record should include time, location, state, activity, perceived change and immediate response, then correlate the report with logs and measurements.

Training should explain the few actions that preserve the accepted state: verify readiness, close and latch doors, avoid unauthorised control changes, stop protected speech on alarm, report unusual sound and request recommissioning after changes. Training should not expose controlled thresholds or encourage amateur testing. Demonstrations can show how a quiet corridor or open door changes audibility, giving staff a practical reason to comply.

Alarm design should balance salience and nuisance; visual, audible and system notifications may be appropriate, but they must respect accessibility and avoid revealing sensitive room status to unauthorised observers; alarm logic should distinguish warning, restriction and immediate suspension. Acknowledgement should identify the responsible person, and the system should preserve the event for later review; repeated bypass or delay indicates a design or organisational failure requiring correction.

Accessible-position analysis should be geometric and temporal; the survey should include the closest lawful approach, likely waiting positions, cleaning and maintenance routes, stair landings, lift lobbies, exterior walkways and locations where a person can remain without attracting attention. Short-duration maxima may occur when an adjacent door opens or a local background source stops; measurement heights should represent standing, seated and crouched ear positions where credible; the record should also identify barriers, access controls and observation constraints, because a technically strong signal at an inaccessible point may carry a different operational consequence from a weaker signal in an unrestricted corridor.

Excluded aided conditions should be catalogued rather than hidden in a general disclaimer; contact transducers, parabolic or highly directional microphones, arrays, post-processing, repeated recordings and mechanically coupled sensors use different transfer mechanisms and listener models; some may require authorised TSCM, structural-vibration, optical or electromagnetic assessment. The acoustic chapter can identify interfaces and preserve evidence without prescribing restricted countermeasure thresholds; a clear cross-disciplinary referral is stronger than claiming that one privacy metric protects against every means of recovery.

The listener model must also address language, familiarity and consequence. A person who knows the meeting topic, names or numerical format may recover useful information from fragments that an unfamiliar listener cannot score. Repeated exposure allows contextual accumulation. Where high-consequence tokens are plausible, testing should include digits, names, call signs, dates and short commands under blinded procedures. Results should be reported by token class and exposure condition, not collapsed into a single sentence-intelligibility score that conceals the easiest information to recover.[254]

254 MB-0528. International Organization for Standardization, ISO 9921:2003.

Worked example 27.39. Alarm-response performance

During a drill series, 18 of 20 masking-fault alarms cause protected speech to stop within the required time. Estimate observed success and simple standard error.

p_hat is observed timely-response proportion. n is trials. SE is a large-sample screening standard error.

Observed success is 90 per cent with screened standard error about 6.7 percentage points. The sample is small, and repeated drills may not represent real events. Failures require causal review rather than statistical reassurance.

27.40 Commissioning measurement plan and raw-data preservation

Commissioning should be planned before construction closes. The plan identifies source states, receiving zones, background states, masking zones, door conditions, occupancy approximations, instruments, calibration, spatial sampling, observation time, raw-data format and decision rules. It should separate room decay, field isolation, masking field, background trend and speech-related tests. Combining all observations into one improvised survey makes later diagnosis and reproduction difficult.

The instrument chain should match the measurand and range; sound level meters, microphones, calibrators, analysers and data acquisition require current calibration and field checks; low-level receiving measurements need adequate self-noise and dynamic range; multi-channel work may require phase and time synchronisation. The record should retain certificates, preand post-test checks, environmental conditions, overload indicators, filter settings, averaging, corrections and processing scripts.

Raw data should be preserved in an open or well-documented format, together with immutable originals, hashes, photographs, drawings and a processing log. Derived plots should link to source files. Manual exclusions and edits should be recorded. The report should state detection limits and untested states. A successful commissioning event is the creation of a reproducible baseline, not merely a signed summary table.[255]

Worked example 27.40. Spatial sample count

An accessible receiving zone is 18 m long by 3 m wide. A base grid uses 1.5 m spacing, including both ends, and adds six critical points at doors and grilles.

N_L and N_W are grid counts along length and width. N_grid is regular points. N_total includes targeted critical points.

The plan contains 45 points. Geometry, obstructions and method requirements may justify a different grid. The calculation makes the intended coverage auditable.

Table 27-10. Chapter 27 commissioning measurement plan.

Work package	Minimum measurements	State controls	Retained evidence
Room response	Band decay and spatial response	Furnishings, doors, occupancy approximation	Impulse responses, positions and regression data
Background	Band time history and percentile statistics	Plant, time, occupancy and season	Raw logs and event annotations
Masking	Band grid, zoning, temporal stability and faults	Setpoints, emitters, controls and ceiling	Point map, configuration export and alarms

255 MB-0529. International Electrotechnical Commission, IEC 60942:2017.

Work package	Minimum measurements	State controls	Retained evidence
Speech/privacy	Source calibration, isolation, background and selected metric	Listener model, source and door state	Raw spectra, calculations and uncertainty
Lifecycle baseline	Critical-point repeat set	Accepted configuration	Hashes, photographs, drawings and trigger register

27.41 Uncertainty budgets, guard bands and decision rules

Every acceptance quantity has uncertainty from calibration, repeatability, spatial sampling, temporal variation, source stability, background correction, environmental effects and data processing; components should be expressed as standard uncertainties and combined with covariance where material; a single generic instrument tolerance is not a complete budget. In secure-room work, state uncertainty can be as important as meter uncertainty because doors, masking, HVAC and occupancy may change during measurement.

The decision rule should be agreed before results are known; a simple rule may require the measured value plus or minus a guard band to remain on the passing side of a limit; more elaborate rules can use risk allocation or method-specific provisions. The report should state whether uncertainty is included, the coverage factor, confidence convention and consequence of an indeterminate result; quietly rounding a marginal result into compliance is unacceptable.

Uncertainty does not excuse a poorly defined state; if the source level, background or listener position is not controlled, statistical calculation can produce a precise number for the wrong proposition; the first task is therefore measurand definition and state control. The second is instrument and sampling uncertainty; the final decision should identify residual risk, operating restrictions and retest triggers.

An incident plan should distinguish loss of evidence from loss of protection; a failed monitor can make the system state unknown even when masking output appears normal; conversely, a confirmed acoustic dropout can require immediate suspension although the controller continues to log healthy network status. Stop-use criteria should therefore include alarm conditions, unverified configuration changes, unexplained spatial drift, failed door control, masking loss, HVAC shutdown and access to a newly quiet adjoining space; temporary controls can include relocation, reduced discussion scope, increased standoff, escorted access or scheduled use, but they require written authority and an expiry condition. Temporary sealing or portable masking may support diagnosis, yet it should not be represented as permanent remediation without fire, accessibility and engineering review. The incident record should preserve times, states, logs, measurements, photographs, personnel actions and the exact moment normal use was restored. A post-incident review should test whether detection, notification and human response were adequate, not merely whether the failed component was replaced.

Triage should establish the last known good state and freeze volatile evidence. Relevant material may include masking-controller logs, building-automation histories, access records, meeting schedules, firmware versions, maintenance tickets, photographs, raw acoustic files and witness observations. Collection should use synchronised time references and preserve original exports with cryptographic hashes. Investigators should distinguish an acoustic anomaly from a confirmed information compromise.

Premature conclusions can distort witness accounts, destroy the failure condition or prompt unrecorded corrective work before causation is understood.[256]

Worked example 27.41. Combined uncertainty and guarded acceptance

Independent standard-uncertainty components are 0.7, 0.9, 1.1 and 0.6 dB. A measured margin is 4.5 dB. Use coverage factor k = 2 and subtract expanded uncertainty as a conservative guard.

u_c is combined standard uncertainty. U is expanded uncertainty. k is coverage factor. M_guarded is conservatively guarded margin.

The guarded margin is about 1.1 dB. Correlation, non-normal components and the project decision rule require review. The example does not dictate a universal pass threshold.

27.42 Drift statistics, control charts and trend interpretation

Lifecycle data should be compared with the accepted baseline using consistent points, bands and states; control charts can distinguish common variation from abrupt changes, but their limits must be based on stable data and engineering judgement; a statistically unusual change can indicate an emitter fault, ceiling alteration, controller update, furniture movement or measurement problem. A statistically ordinary value can still be unacceptable if it crosses an engineering minimum.

Trend interpretation should examine correlated bands and points; a uniform decrease across one zone suggests gain or controller change; a local decrease suggests emitter, obstruction or ceiling condition; a low-frequency

256 MB-0530. NIST Technical Note 1297.

increase may indicate mechanical or HVAC change. Reference channels and repeat measurements help separate instrument drift from room drift. The record should retain calibration and environmental data so that later analysts can test alternative explanations.

Automatic alerts should be conservative enough to detect meaningful drift but not so sensitive that staff ignore them. Thresholds can combine engineering limits, baseline variation and uncertainty. A trend should trigger inspection before indiscriminate gain adjustment. Restoring the measured level without finding the cause can conceal a failed emitter, changed path or unauthorised configuration.[257]

Worked example 27.42. Three-sigma screening limits

A stable baseline at one point has mean 36.0 dB and standard deviation 0.8 dB. Calculate three-sigma screening limits and assess a new value of 33.2 dB.

LCL and UCL are lower and upper screening limits. Mu is baseline mean. Sigma is baseline standard deviation.

The new value 33.2 dB lies below the 33.6 dB lower limit and warrants investigation. This is a statistical signal, not proof of cause or automatic project failure.

27.43 Failure diagnosis and controlled interventions

When privacy or masking performance is poor, diagnosis should move from state verification to controlled intervention; confirm source level, background, masking, doors, equipment and calibration; map the spatial and spectral pattern; operate fans, dampers, emitters and doors one at a

257 MB-0531. International Electrotechnical Commission, IEC 61672-1:2013.

time where safe. Apply reversible seals, temporary absorption or local barriers to test hypotheses. Vibration and intensity measurements can separate airborne and structural participation.

An intervention must be interpreted for collateral effects; sealing a door can alter room pressure and HVAC noise; turning off a fan changes both background and duct transmission; adding absorption changes room source build-up but not wall mass. Raising masking changes vocal behaviour. The test plan should predict the expected direction and magnitude, then compare observed change. A result larger than predicted can mean that several paths changed together.

Evidence custody matters when failure may lead to dispute; photograph conditions, preserve removed components, record settings and maintain raw data; destructive openings require authorisation, safety review and a restoration plan; the final causal conclusion should distinguish observation, calculation, inference and excluded alternatives. Remediation should address the verified mechanism and be followed by a before-and-after comparison under matched states.

The uncertainty model should follow the reported quantity; a room-average decay may include calibration, regression, repeatability, source-position and microphone-position components; a spatial masking minimum adds interpolation, temporal drift and location-reproduction components; a privacy probability can include uncertain source and background distributions as well as measured isolation. Components expressed in decibels cannot always be inserted directly into a linear model without transformation. Correlation also matters. The same calibrator, microphone or background record can cause partial cancellation in a level difference, while shared environmental drift can move several points together. Sensitivity coefficients and probability distributions should be documented rather than hidden in a spreadsheet. Expanded uncertainty requires a stated coverage factor and coverage interpretation. Decision rules should identify which party bears the risk near the limit and whether inconclusive results trigger retest, remediation or authority review. Rounding occurs after the decision calculation. Reporting a result to excessive precision gives a false impression of certainty and can move a borderline case through an acceptance threshold.

Spatial and state variability often dominate instrument specifications. A microphone calibration uncertainty of a few tenths of a decibel may be smaller than variation caused by seating, door position, talker orientation or masking schedule. The budget should avoid false precision by including the terms that materially affect the decision. Correlated quantities require special care. When source and receiving levels use the same calibrated channel, part of the sensitivity error may cancel in a difference; when separate channels or dates are used, it may not. The covariance assumption should be stated rather than silently treated as zero.[258]

Worked example 27.43. Controlled-intervention effect

Residual speech at a door-jamb point is 31 dB. A reversible perimeter seal reduces it to 23 dB, while source and background remain stable within 0.5 dB.

Delta L is the intervention-related change at the same point, band and state.

258 MB-0532. ASTM International, ASTM E336-25a.

The 8 dB reduction strongly supports the perimeter as a material path. It does not prove the permanent repair will achieve the same result or that no parallel path remains.

27.44 Change control, trigger logic and recommissioning

The accepted occupied state can change through finishes, furniture, occupancy, doors, HVAC schedules, masking equipment, software, ceiling work, accessibility systems or organisational policy; change control should classify proposed work by the mechanisms it can affect; a colour-only finish replacement may still change absorption. A controller update may alter masking schedules; a new cabinet can create a quiet listener position. The change record should therefore describe physical and operational consequences, not merely procurement category.

Recommissioning should be proportional but evidence-based. Minor work may need inspection and a focused check; changes to credited active controls, openings, major finishes or room use can require a full affected-system test; trigger logic should include incidents and unexplained drift as well as planned work. The owner should maintain a current baseline, test-point map, configuration export, product schedule, photographs and decision history.

Periodic testing remains useful because some degradation occurs without a declared project; seal wear, emitter ageing, controller drift, furniture movement and informal adjustments accumulate; calendar intervals should be supplemented by condition and event triggers; the room should not be described as permanently secure. It is authorised for a bounded use under a maintained configuration, subject to the actual competent authority and the limitations of public-source engineering evidence.

Trend monitoring should use comparable states and stable reference points. A sequence of room averages taken under different HVAC modes, furniture layouts or masking schedules cannot establish drift without normalisation. Control charts or tolerance bands can assist, but statistical alarms should be tied to physical investigation. A small persistent change across several bands may be more consequential than one isolated broadband excursion. The baseline should include spectra, decay, spatial minima, controller configuration and environmental metadata so that later observations can be compared on more than a single-number basis.[259]

Worked example 27.44. Risk-ranked retest score

A change affects three dimensions scored from 0 to 3: path consequence $C = 3$, configuration breadth $B = 2$ and detectability difficulty $D = 2$. Use a multiplicative screening score $R = C\ B\ D$.

R is a project-defined screening score. C, B and D are ordinal inputs, not physical quantities.

A score of 12 has meaning only against a predeclared project matrix. It can route the change to focused or full recommissioning, but it is not a universal risk measure.

259 MB-0533. International Organization for Standardization, ISO 3382-2:2008.

Figure 27-5. Human response, room excitation, audibility, behaviour and lifecycle change form a feedback loop around the controlled baseline. Author original diagram.

27.45 Bounded conclusions and integration with the weakest-path doctrine

Reverberation, masking, background and operational discipline can materially improve or degrade speech protection; they do not repeal the weakest-path doctrine; the final result is governed by the path and state that yield the greatest recoverable information under authorised use. A door leak can dominate a high-rated wall; a quiet-hour background can defeat a daytime privacy result. A masking failure can expose an otherwise accepted state. A loud electronic source can exceed the design talker.

The four governing propositions remain separate. Laboratory assembly performance describes a specimen. Installed field performance describes the configured room pair and paths; occupied speech-security performance adds source, background, listener and time; formal acceptance or accreditation belongs to the authorised institution; evidence may support movement from one proposition to another only when the additional assumptions and tests are explicit. Public-source engineering cannot manufacture controlled governmental criteria.

The chapter therefore closes with a lifecycle rule; define the protected use and credible states; control room response and source demand. Measure the installed boundary. Govern background and masking. Map listener access and transitions. Quantify uncertainty. Preserve raw evidence. Diagnose failures before remediation. Recommission after material change. State the strongest supported conclusion and every limitation; this disciplined sequence is more valuable than any isolated headline number.

Integrated acceptance should also test internal consistency among evidence classes; drawings should match emitter locations and zone assignments; configuration exports should match checksums and field measurements; door schedules should match observed hardware and operating times; background records should correspond to the plant modes named in the state matrix. Where these records conflict, the conclusion remains open even when individual acoustic values appear favourable. The final dossier should identify the controlling state by frequency, location and operational condition, then trace each mitigation to an owner and maintenance interval; residual risk should be divided into measured risk, modelled risk, untested conditions and threats outside acoustic scope; this prevents a narrow technical pass from becoming a broad institutional assurance. Acceptance authority should be named, and any operational restrictions should appear in user instructions, maintenance plans and change-control workflows. The room remains within the accepted envelope only while those conditions are demonstrably maintained.

Integrated acceptance should be scenario based. Each scenario combines an authorised source, room configuration, door state, electronic state, HVAC state, masking state, occupancy, receiving access and listener model; the engineer then identifies the controlling measurands, uncertainty and decision rule; this approach exposes gaps that separate discipline reports can miss. A wall test may pass, a masking map may pass and a door test may pass, yet the quiet-hour hybrid-meeting scenario can still fail because maximum electronic output coincides with a local receiving minimum.

The weakest-state doctrine does not require testing every imaginable combination. It requires a reasoned enumeration of credible high-consequence combinations, supported by threat assumptions and change history. Sensitivity analysis can identify which variables most influence the outcome and where additional evidence has value. The conclusion should remain bounded: the room demonstrated stated performance under listed configurations and listener assumptions at the measurement date. It did not acquire a permanent universal property, nor did acoustic acceptance substitute for competent governmental approval or other security disciplines.[260]

Worked example 27.45. Residual-risk ranking across states

Three authorised states have screened residual-risk scores based on consequence times likelihood: normal meeting 2 x 1, quiet-hour meeting 3 x 3, and masking-fault meeting 4 x 2.

R values are project-defined ordinal screening products. They are not probabilities or physical measurements.

The quiet-hour state ranks highest and should control test or restriction planning. The exercise demonstrates state prioritisation. It does not replace measured acoustic evidence or authorised risk acceptance.

Chapter 27 demonstrates that occupied speech protection is a maintained state rather than an intrinsic property of a wall. Room response, source demand, receiving background, masking, listener access, door transitions and human procedure can strengthen or defeat the intended boundary.

The defensible method is to preserve the distinction among assembly performance, installed field isolation, occupied speech-security performance and formal institutional approval. Every result remains bounded to its

260 MB-0534. ASTM International, ASTM E2638-24.

source, listener, state, method, uncertainty and competent decision authority.

Chapter 28 moves from occupied-condition engineering to public United States Department of State and diplomatic-facility practice. It will retain the public-source boundary and will not reconstruct controlled thresholds or restricted design criteria.

Table 27-11. Chapter 27 release gate.

Gate	Controlling question	Minimum record	Failure response
State definition	Are source, room, background, masking, door and listener states bounded?	Occupied-state register and restrictions	Stop and define the proposition
Room response	Are decay, absorption and source geometry verified?	Band data, product mounting and spatial measurements	Diagnose and correct configuration
Active controls	Are masking level, spectrum, zones and failure behaviour controlled?	Grid, configuration, alarms and power states	Restrict use until restored and retested
Speech outcome	Does the selected metric answer the stated listener question?	Method, raw data, uncertainty and limitations	Use a suitable method or narrow the claim
Lifecycle	Can material drift and change trigger action?	Baseline, owner, schedule, event logic and records	Withhold full acceptance

Chapter 27 Glossary

Background sound. Sound present at a receiving location apart from the protected source under the defined state.

Equivalent absorption area. Area of ideal absorption producing the same screened room loss as the stated surfaces and objects.

Lombard effect. Change in vocal production caused by background or communication difficulty.

Masking. Deliberately introduced sound used to reduce audibility or intelligibility in a defined receiving zone.

Reverberation time. Time required for a specified decay, commonly expressed as an extrapolated 60 dB decay under the selected method.

Speech privacy. Degree to which speech is not audible or intelligible to a defined listener under stated conditions.

Vocal effort. Talker source condition associated with level, spectrum, articulation and communication demand.

Absorption coefficient. Frequency-dependent ratio used to describe absorbed acoustic energy for a stated specimen and mounting.

Active dependency. Powered or controlled system whose correct operation is credited in the accepted protection state.

Background envelope. Defined range of receiving-side acoustic conditions across time, plant, occupancy and season.

Closed-room speech privacy. Bounded assessment of speech privacy using room isolation, receiving background and a defined listener model.

Critical distance. Screening distance at which direct and reverberant sound contributions are approximately equal under an idealised model.

Critical listener position. Accessible receiving location selected because geometry or path features may create the least favourable result.

Decay curve. Measured reduction of acoustic level with time after excitation ceases.

Direct field. Sound dominated by the source-to-receiver path before room reflections dominate.

Eyring relation. Reverberation-time model using a logarithmic boundary-loss term for higher mean absorption.

Guard band. Decision margin applied to account for measurement uncertainty or decision risk.

High-consequence token. Name, digit, date, code, command or other short item whose recovery can be material despite poor sentence intelligibility.

Listener model. Defined assumptions concerning hearing, language, position, aids, prior knowledge, duration and scoring.

Lombard response. Change in vocal level or speech production caused by increased background or communication difficulty.

Masking zone. Controlled area served by a defined masking spectrum, level, emitter set and control channel.

Modal density. Number of room modes within a frequency interval, influencing whether statistical field assumptions are useful.

Occupied acoustic state. Named combination of source, room, boundary, receiving background, masking, access and operational conditions.

Percentile level. Level exceeded for a stated percentage of the observation interval under a defined time history.

Plenum masking. Masking architecture in which emitters radiate into a ceiling or floor cavity and sound reaches the occupied zone through the construction.
Privacy margin. Project-defined difference or metric margin between residual speech and the receiving condition under a stated method.
Recommissioning trigger. Planned event, observed drift, incident or configuration change requiring renewed verification.
Reverberant field. Room sound dominated by accumulated reflections under the applicable frequency and spatial conditions.
Sabine relation. Diffuse-field screening relation connecting room volume, equivalent absorption area and reverberation time.
Schroeder frequency. Screening transition above which modal overlap may support statistical room-field treatment.
Source-state register. Controlled list of source levels, spectra, positions, orientations, durations and operating modes.
Speech transmission index. Objective metric describing speech-modulation transfer under the selected IEC method and its limitations.
Spatial uniformity. Variation of a measured quantity across defined locations in a zone.
State restriction. Enforceable limitation prohibiting protected use under an unverified or failed condition.
Temporal stability. Ability of an acoustic control or condition to remain within its permitted range over the defined time interval.
Unaided listener. Listener model that excludes electronic, optical or mechanical enhancement unless the method states otherwise.