INDUSTRIAL, ENVIRONMENTAL AND ARCHITECTURAL NOISE IN AN OFFICE AND MANUFACTURING CAMPUS

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Industrial and manufacturing noises in the environment are subject to property boundary limits to avoid disturbing nearby properties, plus noise intrusion criteria for office, lab and conference spaces to avoid work disturbance. Facility design should consider manufacturing processes, logistics and support equipment noise spectra, levels and intermittent or temporal cycles with regard to nearby office, lab or quiet spaces and propagation across property boundaries.

A provider of technology and equipment for the energy industry that operates 30 production facilities in 17 countries, purchased 70 hectares (173 acres) to consolidate 10 headquarters-city facilities into a single campus combining office, development, equipment manufacturing and renovation facilities. It is in a 1,616 hectare (4,000 acres) master planned enterprise park, which contains rail and multiple roadways serving foreign trade district, industrial district, research and development district and pedestrian-friendly office, dining, services and amenities. The first phase of design and construction will move 1,800 of 3,700 existing employees in the city to a facility with a multi-storey office building, three large industrial buildings, each with 3-story office buildings within and other smaller industrial buildings, exceeding 93 k m² (1,000 k feet²) overall, plus structured parking with central plant, paved service yards and truck staging space.

Acoustical and noise criteria are presented for environmental, industrial building background (related to workplace limits and hearing), office backgrounds and intrusive limits for façades. Sound levels and spectra of existing industrial and office facilities are summarized in comparison to criteria as basis for new building design criteria. General and conceptual design guidelines are summarized for environmental noise control, sound intrusion into buildings and noise control in office and conferencing spaces. Some design and practical conflicts and difficulties are discussed with the compromises and workarounds implemented for design completion.

1. Introduction

An industrial manufacturing and corporate office complex was planned to consolidate multiple remote facilities onto a master planned enterprise park, as described in the abstract above. Design for the facility is subject to multiple overlapping regulatory and design criteria that form the acoustical and noise control Basis of Design (BoD). The office, product development and manufacturing facility will incorporate: i) 6-story office and conference building with other amenities, ii) three large industrial buildings with embedded 3-story office buildings for development, manufacturing and equipment renovation, iii) other smaller warehouse and ancillary buildings, plus iv) exterior paved lay-down yards for equipment and inventory manipulation and storage, v) a large central plant for the entire campus and vi) structured garage for staff and contractors and truck staging area.
Figure 1. Site Vicinity Plan w/Office, Industrial, Central Plant, Parking and Outdoor Pads

The industrial office park has development standards, including permissible noise levels at property boundaries. Acoustical design criteria were established for allowable interior sound levels and related environmental noise intrusion in office and conference spaces. Industrial buildings incorporate spaces with hearing protection requirements that limit industrial noise plus sound intrusion limits into related office spaces. Architectural, civil, mechanical and electrical designs for site development and building construction consider and incorporate acoustical and noise criteria.

This case study excerpts information and has citations derived from unpublished and confidential consultant reports to client, not referenced in footnotes. Other external references are footnoted.

2. Industrial and Environmental Noise and Acoustical Criteria

Site development and building designs were subject to multiple overlapping sets of criteria for noise control and acoustics, including environmental, industrial and architectural.

2.1 Environmental and Industrial Noise

Outdoor on-site noise sources propagating over property boundaries and/or intruding into on-site buildings were limited by development standards and by design criteria established for project:
- Master planned enterprise park development standards are $\leq 65$ dBA day, $\leq 58$ dBA night at property boundaries.
- Facility designs for exterior industrial and building systems noise $65$ dBA at building façades.
- Outside to inside noise intrusion $< 5-10$ dB increase over interior background noise criteria (interior criteria varies with functional space, see Table 1, below).
- Industrial exhaust, ventilation and building systems interior background noise $\leq 65$ dBA.
- Hearing protection regulations limit 8-hour exposure to $85$ dBA (industrial hygiene department responsibility – not included in design scope of services).

2.2 Architectural Acoustics, Sound Isolation/Privacy

Architectural Acoustics incorporates reverberation decay time (RT, seconds) or spatial decay (SD, dB per doubling of distance) and reflections within enclosed spaces for speech intelligibility. Privacy and freedom from intrusive noise considers interior airborne sound transmission vertically and laterally between spaces (for containment or to prevent intrusion) plus potential structure borne vibration resulting in radiated audible sound that may reinforce airborne sound transmissions.
- RT for conference, training and assembly: \( \leq 0.9 \text{ sec} \), speech intelligibility (varies with size).
- RT for video/tele-conferencing space: \( \leq 0.5 \text{ sec} \), audio systems or 2-way communications.
- SD for reverberant build-up: dB per doubling of distance; 5 dB office, 3 dB industrial.
- Reflection Control: avoid flutter echo between parallel surfaces, 90° corner return to origin, rear-wall “backslap” and focussing in conference and/or barrier flanking in industrial.
- Sound Isolation (also known as sound insulation): varies with room function, see Table 1.
- Ceiling Attenuation Class (CAC) 35-40, where interior partitions terminate at ceiling.
- Structure borne caused radiation, limit with demising surface decoupling and/or damping.

Design Criteria: Acoustical speech privacy and control of intrusive airborne noise via demising assemblies considers: (a) typical source noise levels, (b) receiving room ambient noise levels and (c) sound transmission through room envelope. Partitions are rated by Sound Transmission Class (STC) (exterior walls by Outside-Inside Transmission, OITC), as defined by ASTM. Ceiling Attenuation Class (CAC) rates ceiling transmission losses (two passes plus plenum loss).

### Table 1. Interior Sound Transmission Class (STC)* and Exterior Outside-Inside Transmission Class (OITC)

<table>
<thead>
<tr>
<th>Category</th>
<th>STC 65</th>
<th>STC 60</th>
<th>STC 55</th>
<th>STC 45</th>
<th>STC 45</th>
<th>OITC/STC 50</th>
<th>OITC/STC 35</th>
<th>OITC/STC 45</th>
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</thead>
<tbody>
<tr>
<td>Video/Teleconference, Recording (remote transmission)</td>
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<td>Large Conference / Auditorium w/A/V presentation</td>
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<tr>
<td>Medium &amp; Small Conference Rooms</td>
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<td></td>
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<tr>
<td>Dept. Head, Executive Private Offices</td>
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<td></td>
<td></td>
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<tr>
<td>Private and Admin Offices, Small Conference</td>
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<td></td>
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<tr>
<td>Open Office Suites</td>
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<tr>
<td>Break/Lounge, Copy/Work Rooms, Toilets</td>
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<tr>
<td>Partition between Manufacturing and Offices</td>
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<tr>
<td>Glazing between Manufacturing and Offices</td>
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<tr>
<td>Partition between Manufacturing and Labs</td>
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</tbody>
</table>

- STC is a laboratory rating. Field-measured Noise Isolation Class (NIC) ~ 5-10 points lower than STC.
- Outdoor to indoor transmission class (OITC) includes lower frequency sound than STC.

### 2.3 Building Systems Noise Control

Permissible criteria for continuous building systems background noise, according to ASHRAE, are intended to define “neutral, bland-sounding spectrum, indexed to a curve number corresponding to the sound level in the 1000 Hz band.” Occupant perceptions are based on (i) perceived loudness relative to functional use of the space and (ii) sound quality with respect to spectrum balance, tonality and/or temporal (on/off, modulating) characteristics.

### Table 2. Continuous Background Noise, RC (blue) / NC (red)*

<table>
<thead>
<tr>
<th>Category</th>
<th>RC/NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video/Teleconf, Recording (remote transmission)</td>
<td>25</td>
</tr>
<tr>
<td>Large Conf. / Auditorium w/A/V presentation</td>
<td>30</td>
</tr>
<tr>
<td>Large &amp; Medium Conference Rooms</td>
<td>30</td>
</tr>
<tr>
<td>Collaborative Work Space, Sm. Conf. Break-out</td>
<td>35</td>
</tr>
<tr>
<td>Dept. Head, Executive Private Offices</td>
<td>30</td>
</tr>
<tr>
<td>Private and Admin Offices, Small Conference</td>
<td>35</td>
</tr>
<tr>
<td>Open Office Suites (sound masking possible)</td>
<td>40</td>
</tr>
<tr>
<td>Beak/Lounge, Copy/Work Rooms</td>
<td>40</td>
</tr>
<tr>
<td>Corridor, Circulation &amp; Toilets</td>
<td>45</td>
</tr>
<tr>
<td>Manufacturing Space (building systems,</td>
<td></td>
</tr>
<tr>
<td>excluding manufacturing process, conveying,</td>
<td></td>
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<tr>
<td>transport or ancillary support equipment</td>
<td>NC 50</td>
</tr>
<tr>
<td></td>
<td>60 dBA</td>
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</tbody>
</table>

* Continuous noise due to building systems, not including occupant or user equipment noise.
The building systems criteria spectra are intended to achieve an aggregate overall spectrum level from multiple sources that neither interferes with the space use, nor has undesirable perceptible qualities. Level may affect speech intelligibility or mask distractions, while spectrum balance, tonality and level fluctuations may affect occupant comfort, annoyance or fatigue. The combination of low, mid and higher frequency sound sources should produce a smooth, balanced spectrum.

Room Criteria (RC, or RC Mark II, with a qualitative descriptor) are preferred for more sensitive spaces with speech communication and/or microphones for recording or teleconferencing, such as private office and conference. More permissive Noise Criteria (NC) may be applied to work, utility or circulation spaces, open-offices, copy/file, break/lounge, toilets, and lobby/corridors.

3. Sound Sources

Many different sound sources known to exist at owner’s current facilities that will move to the new campus, including truck transport and individuals’ vehicles, outdoor central plant and other equipment, material handling, process and tool equipment, ancillary support equipment, occupant’s activities and speech, plus building systems. Prior to design, existing sources were measured in statistical percentile (Ln) spectra to indicate overall levels and variability or transience.

<table>
<thead>
<tr>
<th>Table 3. Common Sound Sources.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor / Environmental</td>
</tr>
<tr>
<td>Off-Site Roadway</td>
</tr>
<tr>
<td>On-Site Truck/Auto Drives</td>
</tr>
<tr>
<td>Truck Idling, Air-Brakes, Back Alarms</td>
</tr>
<tr>
<td>Building Receiving/Shipping Docks</td>
</tr>
<tr>
<td>Process Vacuum, Air Compressors</td>
</tr>
<tr>
<td>Central Plant Chillers, Cooling Towers</td>
</tr>
<tr>
<td>Process Vacuum, Air Compressors</td>
</tr>
<tr>
<td>Mobile Cranes, Fork Lifts</td>
</tr>
<tr>
<td>Truck Load &amp; Lay-Down Impacts</td>
</tr>
<tr>
<td>Back-up Power Engine-Generators</td>
</tr>
</tbody>
</table>

Figure 2. Statistical (Ln) Spectra – Example: fork-lift alarm beeper. Small range of lower frequencies indicates relatively continuous level. Divergence indicates significant high frequency transient increases.

Ambient Continuous and transient short-duration sound spectra in were measured in existing outdoor, manufacturing and office facilities to determine current noise levels and comparative information for new facility designs. Existing facility conditions include building systems or background noise plus user-installed and manufacturing equipment and occupant activities. Octave band spectrum level versus frequency charts plus overall A- and C-weighted levels, as illustrated in Fig. 2, were used to document known sound sources that would relocate to the new facilities.
4. Key Considerations In Design

4.1 Environmental

Outdoor sound sources are controlled by regulatory limits and practical building design considerations. Source proximity to property edge or to on-site buildings influence design approach.

4.1.1 Property Boundary Noise Limits

Environmental noise sources may be on the property or off-site. Additive effects of on-site and off-site sources should be considered with respect to permissible levels for sound propagation over property boundaries. Off-site noise levels approaching permissible levels effectively reduce limits of on-site noise, e.g., with 65 dBA permissible property boundary level, 61 dBA off-site ambient level effectively limits on-site source(s) aggregate to no more than 64 dBA.

Time factors influence regulatory limits enforcement. A simple sound level limit at property boundary may be interpreted to cover any short-duration or instantaneous transient event, whereas an equivalent level, or minimum portion of defined time limit would result in control of continuous or prevailing sound level, but exempt short duration transients. The property boundary limits at this development are simple A-weighted levels (day and night), including instantaneous peaks.

4.1.2 Outside to Inside Noise Intrusion

Environmental or outdoor sound sources intruding into occupied office and industrial buildings may be permitted to continuous interior background sound criteria by 5-10 dB, respectively. For example, 5 dB increase over 40 dBA interior ambient allows 45 dBA. If window sound transmission is 25 dBA, any environmental noise at the building façade over 70 dBA needs more control. Spectrum balance, tonality and temporal on-off characteristics influence sound source perceptibility versus receiver sensitivity. Slight refinement of the allowable tolerance may be justified, but the intrusion limit above ambient is basis for interior noise control.

4.1.3 Source Proximity and Direction to Receivers

On-site noise sources subject to property boundary limits may have controls designed to achieve simple A-weighted level limits. On-site noise sources that intrude into occupied buildings should have spectrum and level controls designed to neutralize objectionable or perceptible characteristics. For example, an outdoor rotary helical or screw air compressor with tonal spectrum might have a sound barrier or partial enclosure to reduce sound propagation toward property boundary. A pulsation damper or discharge attenuator with insertion loss optimized to the peak tonal frequency would attenuate and smooth spectrum of noise propagating toward nearby buildings.

4.2 Industrial

Industrial noise includes continuous building and process equipment plus on and off cyclical and short-duration or instantaneous transient sound sources. The design scope of this project included building influences on industrial noise, but not analysis and design of production equipment modification or shop layout for hearing protection. Machine and shop noise strategies that might be applied if the scope included hearing protection may be found in Asselineau’s Building Acoustics4.

For architectural control of industrial noise sources, design barriers or enclosures to impede sound propagation. Use absorption and diffusion to improve spatial decay or reduce noise build-up. Design building systems and ventilation noise attenuation for less contribution to industrial sources.

4.2.1 Frequency of Noise

A-weighting factors are small in 500-4k Hz octaves; -3, 0, +1 and -1 dB respectively, whereas the weightings are much greater for lower frequencies. Industrial noise sources with peak frequency dominance near the center of the audible spectrum have first priority for attenuation, but additive effects and continuity of multiple lower frequency sources should also be considered.
4.2.2 Continuous Sources vs. Short-Duration Transient and Cyclical Sources

Continuous sound sources set a threshold noise level. Short duration, transient and cyclical sources can substantially increase worker exposure, even though they might be present for short durations during a given time period or operate intermittently. Impacts, either from material handling or manufacturing/fabrication processes, cause very loud instantaneous levels in shops. Radiated noise from impacted item may increase with radiating surface area. Floor vibration should be considered: “feelable” to humans or effects on sensitive equipment or metrology instruments.

Building design should enclose or attenuate continuous process sources, while shops are segregated in rooms, cubicules or between partition barriers to reduce vicinity of exposure. Absorption should be employed to reduce reflection energy and improve spatial decay of localized noises.

4.3 Architectural Interiors

Discrimination is required between speech sounds that requiring intelligibility or privacy and user-installed business machines or occupant activities needing sound isolation or attenuation.

4.3.1 Building Systems Equipment and Distribution

Continuous background or ambient interior noise is dominated by building systems equipment and distribution, including HVAC air-handlers and terminals, exhaust fans, air ducts, electrical transformers, fluid piping plus elevator traction motors or hydraulic pumps. The design challenge is to manage different low-, mid- and high-frequency dominant spectra to achieve balanced, non-tonal spectra with acceptable levels appropriate for room functions.

4.3.2 Occupants and User-Installed Equipment

Occupant activities generate variable and transient noise, requiring containment to preserve speech privacy in conference and private offices or to control of aggregate level in open offices. Amplified speech in large conference, classroom or auditorium requires containment plus appropriate level and spectrum to achieve speech intelligibility and clarity within the assembly space. Business machines, including copiers and printers, coffee bar appliances, desktop computers, telephones and security shredders, generate locally significant noise, and contribute to overall ambient levels. Whether continuous or transient, sound levels and impacts should be controlled to reduce annoyance, fatigue, communications/speech interference or intrusions into sensitive spaces.

5. Approach to Noise Reduction in Building Designs

Designing noise control conformance to multiple overlapping acoustical criteria requires overall sound level reduction, but it also requires smoothing and balancing sound spectra. For the purpose of estimating potential overall levels in design of industrial and office spaces, individual noise sources’ equivalent levels (Leq), were summed within enclosed areas, with offices assumed to be non-reverberant and industrial spaces to be reverberant, i.e. spatial sound level decay in offices ~5 dB/distance doubling and industrial spaces ~3 dB/distance doubling.

5.1 Barrier and Enclosure Containment

Environmental and industrial noise reductions are, to large degrees, limiting propagation and reducing intrusion into buildings. Where topography permits, use barriers to interrupt sound paths, either near the source(s) or near the property boundaries. Use acoustically absorptive surfaces to reduce reflected sounds. Design building shell to reduce sound transmission from outside to inside.

Barriers may add up to approximately 10 dBA to natural distance losses when the barrier breaks “line-of-sight” propagation path from source(s) to receiver(s). Barriers are effective for mid- to high-frequency audible sound, but lower frequency noise with longer wavelengths diffract over or around barriers, resulting in less effectiveness.
Sound reflections off other surfaces also flank barriers. Acoustically absorptive and/or diffusive finishes on buildings, walls or other large surfaces, may be utilized to reduce flanking. Absorption is effective across all audible frequencies, but thicker depth or Helmholtz resonance will improve lower frequencies with long wavelengths. Varying with many parameters, direct reflections might be reduced 2-4 dBA. Noise build-up within a walled enclosure might be reduced 3-6 dBA.

Building shell walls can be effective at resisting intrusion of noise over a large range of audible frequencies. Common window glazings are weak components of the façade, especially at lower frequencies and provide uneven frequency response due to coincidence dips near 250 Hz and 2k Hz octaves. Common exterior walls may reduce sound transmission 30-65 dBA, while typical monolithic and insulated window glazing may provide 20-35 dBA of noise reduction. Special wall designs, louvers, window products and penetration treatments can produce greater noise reduction.

5.2 Spectrum Neutralization

Spectrum neutralization is utilized to smooth tonal or unbalanced noise spectra for reduction of perceptibility and related annoyance. Noise attenuation design should maximize attenuation at prominent noise source frequencies or frequency spans. Sound absorption coefficients and muffler or attenuator insertion losses should be selected to match attenuation to prominent frequencies, as illustrated in Fig. 3, where a 500 Hz tone is smoothed with 500 Hz attenuator max performance.

![Figure 3. Example of Tonal sound source with matched attenuation and smooth spectrum result.](image)

5.3 Interior Sound Isolation

Room-to-room and floor-to-floor sound isolation generally requires consideration for propagation via airborne and structure borne pathways, which sum together in receiving spaces.

5.3.1 Airborne Sound Transmission Loss.

Demising partitions and floor-ceiling assemblies are initially selected on basis of Sound Transmission Class (STC). STC ratings should be greater than the decibel difference between source sound level and receiver room background sound, with consideration for tonal or temporal sources. Frequency response of the demising assembly should be considered with respect to sound sources’ spectra to assure that transmission loss is adequate at source prominent frequencies. Low frequencies below 100 Hz, not measured for STC ratings, should be considered for music and machinery.

Coordinate ceilings with partitions using Ceiling Attenuation Class (CAC), for sound sources in the ceiling plenum above a room or for sound transmission over top of partition terminating at ceiling (not extending to structural deck above). Acoustically absorptive ceilings are also rated for absorption by Noise Reduction Coefficient (NRC), which has little to do with sound transmission, but reduces reverberant build up. CAC > 35 is recommended (in combination with NRC > 0.70).

Care should be taken to assure no flanking paths via penetrations, gaps, material interfaces, or other demising assembly discontinuities. Assure that interior doors have acoustical seals on frame.
5.3.2 Structure Borne Vibration

Structure borne vibration may propagate to other locations, resulting in radiated audible airborne sound, regardless whether it is induced by acoustic coupling or transmitted by physical connection of source to building. Radiated noise generally serves as reinforcement to airborne sound transmission, but in some cases, may be a primary sound source in a receiver room.

Avoid acoustic coupling by attenuation HVAC noise in the A & B regions of the RC criteria, re: Table 2, or avoid locating loud sources immediately adjacent to partitions. Decouple and/or damp radiating surfaces to reduce structure borne caused sound. Use separated, parallel framing for cavity partitions or resilient mountings for drywall (plaster board), such as resilient furring channels or hybrid metal and elastomeric mountings. Alternately, either place damping compound between layers of drywall or use advanced drywall products with integrated internal damping layers.

5.4 Room Absorption

Reverberant build-up of sound within rooms may be reduced with absorption. Acoustical ceilings, NRC ≥ 0.65, and carpets on floors are appropriate for small and medium size office and conference rooms. If ceiling is part of sound insulation, also specify CAC, as noted in 4.3.1, above. Medium to large lecture, conference and assembly spaces should utilize NRC ≥ 0.80, acoustical absorption, on walls and/or ceilings to limit reverberation decay time, RT < 1.0 second (varies with size of space). Use diffusion to direct reflections toward absorption, in addition to reducing reflection strength by scattering. Shorter decay time and better reflection control are required for microphones, either recording or for two-way transmission, such as video conferencing.

Mechanical, electrical and industrial production spaces benefit from acoustical absorption to reduce reverberant build-up and to limit reflections where shop noise may flank around partition sound barriers. Absorptive reduction of noise build-up within enclosed space reduces sound containment demising assembly transmission loss requirements. Use thicker absorption materials for lower frequencies; 25 mm (1") is adequate for mid (speech) and higher frequencies, but 50 mm (2") or greater is more effective for frequencies in 250 Hz and lower, due to their longer wavelengths.

6. Architectural and Engineering Design Implementation

Multiple overlapping regulatory, ordinance, code and design criteria for noise limits and acoustics presented for a large industrial and office campus design. Early recognition of the disparate requirements and combination into early basis of design parameters allowed logical organization of design solution concepts. The consultant reviewed architectural and engineering design documents with respect to sound generation, propagation and receiver conditions. Sound sources were evaluated for natural or system attenuation and room losses. Excess noise required supplemental attenuation, isolation, absorption, damping and/or vibration control to achieve criteria. Composite, hybrid and compromise solutions were recommended to architects and engineers for integration into building and facility designs for comprehensive environmental and industrial noise controls plus interior architectural acoustics and ambient sound.

REFERENCES