Austin, Texas USA

9th International Conference for Enhanced Building Operations

2009 November 17-19

Acoustical and Noise Control Criteria and Guidelines for Building Design and Operations

Jack B. Evans, PE[a] Chad N. Himmel, PE[b]
Principal Associate

JEAcoustics
Engineered Vibration Acoustics & Noise Solutions
Austin, Texas, USA 78756

ABSTRACT

Noise, vibration and acoustical design, construction, commissioning and operation practices influence building cost, efficiency, performance and effectiveness. Parameters for structural vibration, building systems noise, acoustics and environmental noise crossing property boundaries will be presented with brief case studies illustrating noise and vibration problems with successful solutions. Building mechanical, power, and plumbing systems contribute to building operations noise and vibration, which affects building occupants, sensitive installations, and functional uses. Various noise and vibration design criteria, field measurements, design concepts and specifications can be applied in facilities to achieve noise mitigation and vibration control to enhance building operations and reduce tenant or neighbor problems. Concepts for enhancement will be presented that achieve specific program criteria and improve the built environment for occupants and functional uses, including items to incorporate in specifications and construction documents. Concepts relating to noise and vibration control can also reduce short and long-term operations costs and save energy. Acoustical designs can be implemented in new construction to achieve specific requirements for LEED certification in healthcare and educational facilities. Common problems, objective criteria, sensitive installations, and solutions will be presented to offer a basic understanding of effective noise and vibration control for central plant equipment, power systems, transformers, standby generators, and roof mounted HVAC equipment.

Topics covered include:

- Roof mounted building equipment.
- Fan sizing for low noise and improved efficiency.
- Noise and vibration control for building electrical and power systems.
- Equipment selection for central plants and outdoor HVAC equipment for low environmental noise emissions.
- Engine-generator noise and vibration control for building interior and environmental noise crossing property boundaries
- Power plant turbine-generator vibration isolation and noise control
- Acoustics in LEED certification.
- Structural concepts for imaging and research.

1. INTRODUCTION

Acoustics, noise, vibration and similar words should be found from beginning to end of any dictionary of terminology for enhanced building operations. Energy efficiency of building systems may be related to noise generation. The functional efficiency, behavior and satisfaction of building occupants may be related to perceptions of sound and vibration as well as the effects on communication, annoyance and health. Neighboring property owners and regulations may cause restrictions on a facility if its impacts on surrounding properties are deemed unacceptable. The noise impacts from external sources, including adjacent properties or

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[a] Email address: Evans@JEAcoustics.com

[b] Email address: Himmel@JEAcoustics.com

transportation systems, may limit compatible land uses or appropriate functions. Noise and vibration control are integral to building design and construction as well as effective facility management and operations. Acoustical conditions and issues of concern in development, design, construction and operations are discussed with reference to common criteria, parameters and regulations.

2. MANDATED CODES AND REGULATIONS

A. Community Noise

Community noise refers to outdoor or environmental noise that affects use of property and/or crosses property boundaries. The discussion of noise and its effects as a rationale or justification for regulation are beyond the scope of this paper, but much can be found in the works of A.H. Suter, S. Fidell, T.J. Schultz, K. Persson-Weye and many others with regard to annoyance, interference with speech and other communications, sleep interference, noise-induced hearing loss, performance and behavior, extra-auditory health effects, etc. With regard to building operations, owners and facility managers should be concerned with conformance to regulations and “good neighbor” policies that make uninterrupted operations possible with out distraction or restriction due to complaints from others.

Many governmental entities and jurisdictions have regulations, ordinances, codes and mandates on community noise. Examples include environmental impact assessments and studies for transportation system additions, extensions, expansions, etc., such as railroads, highways, transit ways and airports. Building and development is restricted in the higher noise exposure zones surrounding airports. Industrial, commercial, residential and other categories of land uses often have limits of noise level at property boundaries, often with supplemental restrictions for tonality, temporal (on/off), time of day or other characteristics that increase perceptibility of noise. The noise level restrictions at property boundaries may affect placement and operation of cooling towers, air-cooled chillers, standby engine-generators, residential air conditioning condensers, retail and industrial truck docks, roof-top building HVAC equipment, large electrical transformers and other outside installations.

A model community noise ordinance was included in the 1973 EPA regulation.[1] Although enforcement of that regulation was discontinued in 1981,[2] many cities and other small jurisdictions have adopted ordinances based on the EPA model ordinance. In addition, federally backed financing, such as Veterans Administration (VA) and Federal Housing Authority (FHA), have mandated noise limits mandated by Housing and Urban Development (HUD), which can be traced to the EPA guidelines,[3] State departments of transportation mandate roadway noise limits set forth by Federal Highway Administration (FHWA) and metropolitan transit authorities must conform to restrictions from the Federal Transit Authority (FTA). Each of these regulatory frameworks can be traced to the 1973 EPA regulation.

Table 1. Federal Environmental Noise Criteria

	FAA	**FHWA**	**FTA**
Residential	DNL 65	67 dBA Leq	Ambient Ldn +10-15
Schools, Hospitals	DNL 65	67 dBA Leq	Ambient Leq(H) +15-20
Other Sensitive Receiver	DNL 65-85	57-72 dBA Leq	Ambient Leq(H) +10-15

Note different time-weighted average descriptors

With regard to building operations, limiting the operation, scheduling or use of processes or building equipment or otherwise not permitting tenants or occupants full use of a facility can hardly be considered an enhancement. It is obvious that regulations and ordinances must be conformed to, but it should also be realized that future complaints of noise annoyance, can cause restrictions to facility operation. Development of property or design and construction of facilities needs to consider compatible land uses with adjacent properties and control of potential noise sources and propagation paths. Not only the level of noise, but the spectral characteristics and other sound quality parameters should be compatible with existing day and night background or ambient levels.

A technical study group (TSG 3) was established by the International Institute of Noise Control Engineering (I-INCE) to survey effectiveness of noise policies and regulations which initially received data from twenty-two countries from Asia, Europe and North America regarding administrative/or regulatory structures, enumerations of major environmental noise laws or ordinances, who or what is regulated, noise limits for various (generally environmental) noise sources, and effectiveness based on experience. While the results indicate difficulty with direct comparisons, the TSG3 work documented widespread community noise guidelines, environmental noise regulation, particularly for transportation systems noise and sound insulation mandates for residential facilities exposed to significant noise.[4]

B. Occupational Noise

In the United Sates, OSHA 1910.95 is the federal standard regulating occupational noise exposure.[5] In the European Community, Directive 2003/10/EC mandates regulation of noise exposure and ISO 9612[6] is a standard for noise evaluation. Many other countries have occupational or workplace noise regulations. Generally there is a decreasing allowable duration of exposure for each increasing increment of noise level. OSHA 1910.95 permits 90 dBA for 8 hours or half the duration for each 5 dBA increase in level, i.e., 4 hours at 95 dBA, 2 hours at 100 dBA, etc. A "continuing, effective hearing conservation program" is mandated when employee noise exposures equal or exceed time[7] weighted average sound level (TWA) of 85 dBA.

It should be noted that as an acoustical criterion for occupied spaces within the building, such as office, dining, lobbies, and any other space where normal speech communication takes place, the occupational noise standards are not relevant, and other architectural acoustical criteria should prevail.

While employee noise exposure is often dominated by workplace machinery, process equipment and work noise, the building facility can contribute to overall noise levels. Reflective surfaces contribute to reverberant buildup of noise and directional reflection (re: Q factor), and building systems noise; particularly ventilation and exhaust. Tenants and owner-occupants can achieve more productive workplaces if the building contributions to noise are restrained.

Where feasible, acoustically absorptive building materials should be specified for industrial spaces, such as acoustical structural roof deck, slotted concrete masonry units, etc. Building HVAC and exhaust should be evaluated for noise level at the workstation, and attenuated to non-contributing levels (at least 10 dB below production machinery, tool or work support equipment noise level). Dust-collection, process compressed air, and similar services should be considered for acoustical treatment if they are provided to tenant as building systems or utilities. For example, compressed air inlet and supply mufflers and waste air discharge diffusers should be incorporated as system components in lieu of individual workstation components.

C. Residential Codes (IBC)

Several North American model building codes containing noise parameters are adopted in whole or in part by municipalities or other local jurisdictions, including International Building Code (IBC) Southern Building Code Congress (SBCC), Universal Building Code (UBC). Some incorporate minimum interior separations between residential units in multi-family structures. For example, the IBC, Section 1207 Sound Transmission,[8] limits airborne sound transmission through demising partitions to sound transmission class (STC) 50 (Field STC 45), re: ASTM E 90 (E 336). Masonry sound transmission may be calculated according to TMS 0302 or tested as described above. Structure borne transmission must meet impact insulation class (IIC) 50 re: ASTM E 492 (45 if field-tested), re: ASTM E 1007.

The IBC requirements on airborne and impact sound insulation might be estimated to give satisfactory conditions for approximately 40 % of people,[9] *because codes only set minimum acceptable performance*, whereas residential occupants may have significantly greater expectations, depending on sensitivity, activities, time of day, and/or investment in the facility, i.e. owner-occupied.

Therefore, to go *beyond the minimum* code criteria established by the IBC, refer *to* other more detailed guidelines available that offer goals for airborne sound (STC) and impact sound isolation (IIC) in residential construction, based on the type and quality of a residential project.

Table 2. Federal Environmental Noise Criteria[10]

Class of Building	**STC**	**IIC**
Code Minimum	50	50
Minimum Quality / Apartments	55	55
Medium Quality / Normal Condos	60	65
High Quality / High Quality Condos	65	75

D. HIPAA

The U.S. Health Insurance Portability and Accountability Act of 1995 (HIPAA) went into effect in 2004 and stipulates that speech privacy in healthcare facilities must be protected. However, until recently, no criteria had been approved for enforcement of the speech privacy provision. HIPAA is enforced by the Office for Civil Rights, a division of the U.S. Department of Health and Human Services, working with the U.S. Department of Justice. Federal regulatory agencies like the Office for Civil Rights require practical, standards-based, criteria that do compromise security considerations. To address the need for practical enforcement guidelines, new code-level criteria are now being implemented by WEDI-SNIP (2005), FGI (2010), LEED for Healthcare (2009), and the Green Guide for Healthcare (2007). All of these agencies have agreed to "harmonize" enforcement criteria for speech privacy by adopting the same uniform Reference Standard. This Reference Standard, which covers speech privacy and all other aspects of acoustics in healthcare facilities, was developed between 2003-2009 by ANSI S12 WG44, a 500-member joint subcommittee of the ASA, INCE and the NCAC (TC-AA.NS.SC).

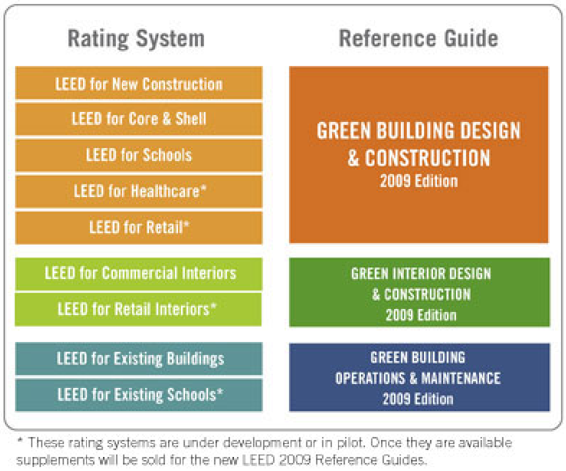
3. VOLUNTARY AND REFERENCED STANDARDS

A. USGBC / LEED

The U.S. Green Building Council (USGBC) initially developed the Leadership in Energy and Environmental Design (LEED) Green Building System in 1998 to be an "open and transparent process where the technical criteria proposed by the LEED committees are publically reviewed for approval by … membership organizations that constitute the USGBC."[11]

There are variations of the rating systems for various project types, from new construction to specific facility types to renovation.

Table 3. LEED Versions for Specific Project Types[12]



Rating System	Reference Guide
LEED for New Construction LEED for Core & Shell LEED for Schools LEED for Healthcare* LEED for Retail*	GREEN BUILDING DESIGN & CONSTRUCTION 2009 Edition
LEED for Commercial Interiors LEED for Retail Interiors*	GREEN INTERIOR DESIGN & CONSTRUCTION 2009 Edition
LEED for Existing Buildings LEED for Existing Schools*	GREEN BUILDING OPERATIONS & MAINTENANCE 2009 Edition

* These rating systems are under development or in pilot. Once they are available supplements will be sold for the new LEED 2009 Reference Guides.

There have been recent concerns that enough sustainable materials and design LEED points are available that energy efficiency and/or efficient operations may have suffered. It appears that reviews of power usage and utility costs will occur in the future to improve future LEED efficiency ratings. Under the new V3.0, newly constructed buildings will be required to provide energy and water bulls for the first five years as a condition of certification.[13]

In each LEED rating system, acoustics and noise control points are granted for Innovation and Design. However, when creating LEED-rated schools and healthcare facilities, acoustical design credits can be earned in additional ways.

As a minimum for school facilities, USGBC LEED for Schools prerequisites require the design of classrooms and other learning spaces to meet the Reverberation Time (RT) requirements of ANSI Standard S12.60-2002 "Acoustical Performance Criteria, Design Requirements and Guidelines for Schools."

Going beyond, it is possible for designers to earn one point with LEED V3.0 for Schools' enhanced EQ Credit 9, by achieving the following for classrooms and other core learning spaces:

> meet the Sound Transmission Class (STC) requirements, excepting windows, of an STC rating of at least 35, and
>
> achieve a maximum background noise level from HVAC systems of 40 dBA.

Credits for healthcare facilities are discussed under *LEED HC (Healthcare)*, below.

B. ASA / ANSI – Classroom Acoustics

Recognizing that poor spoken communications due to inaudible or unintelligible speech for students and teachers may create selective acoustical barriers to learning, the Acoustical Society of America (ASA) formed a working group in 1997 with representatives of eleven national groups on "eliminating acoustical barriers to learning in classrooms." In 1998, recognizing the same learning barriers, the United States Architectural and Transportation Barriers Compliance Board (ATBCB), also known as the Access Board, published a request for information on acoustics in schools in 1998. The Access Board partnered with the ASA, in association with the American National Standards Institute (ANSI), to develop a new standard, which was first distributed in 2001. After review and public comment, the process was completed and American National Standard S12.60-2002 "Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools" was introduced in 2002.[14]

The rationale of the standard is best summarized in its Abstract that says, "These criteria, requirements, and guidelines are keyed to the acoustical qualities needed to achieve a high degree of speech intelligibility in learning spaces." Spoken language communication is essential to most classroom learning, where as much as 60% of the activities involve students listening to and participating in spoken communications with a teacher and other students. It is important in any general discussion of classroom acoustics to mention that (a) neither children's hearing (physiology) nor their vocabulary is well developed, and (b) English as a Second

Language (ESL) speakers' vocabularies are not well developed. As an environment for learning through speech communication, the classroom should be free of acoustical barriers. Signal-to-noise ratio (SNR) needs to be +/- 15 dB for enough words to be heard that listeners do not have to rely on their limited vocabularies "fill in blanks." Limiting reverberation assists in SNR by reducing build-up of noise and assists in speech intelligibility by reducing the "smear" or muddiness of speech clarity. Therefore, classrooms are recommended to have a reverberation decay time (T60) of not more than 0.6 seconds for teens, and shorter times, if possible, for younger students. Mature students over 18 years of age can tolerate somewhat longer reverberation decay times, but classrooms up to 50-60 seats should be kept below 0.75 seconds.

The standard is available for download at no cost from http://asastore.aip.org/.

Similar requirements are mandated as regulations, ordinances or codes in many countries around the world.[15]

C. AIA & AHA / FGI – Medical-Healthcare

Uniform, code-level guidelines for design and construction of healthcare facilities were first developed in 1948 by the Public Health Service in response to the Hill-Burton Act. But during the Reagan Administration in the early 1980s, this public work was “privatized,” i.e., responsibility for editing, revising and publishing it was handed off to a group called The Facilities Guideline Institute (FGI), which continues to revise the publication and re-publish it every four years. Since the mid-1980s, this group (a partnership between the American Hospital Association (AHA) and the American Institute of Architects (AIA) funded by the U.S. Department of Health and Human Services) was created specifically to manage this public document, which is accepted as code by approximately 47 states and 7 federal agencies, and is also in use in 15 other countries, including Canada.[16] The most recent edition of this volume was published in 2006 and was the first edition to mention HIPAA. The next edition will be published in January 2010, and is the first edition to provide comprehensive criteria for acoustics and speech privacy in healthcare facilities of all types.[17]

Figure 1. FGI Health Care Facilities Guidelines

C. GGHC

The Green Guide for Health Care (GGHC) is a “self-certifying best practices tool kit” for sustainable medical facility design and construction, which utilizes the LEED rating system criteria. GGHC is an independent entity that is not affiliated with USGBC (www.gghc.org). However, the USGBC considers GGHC as a suitable “pilot phase” for its ongoing criteria development GGHC originally derived from sustainable design guidance published in 2002 by American Society of Healthcare Engineers (ASHE), which was developed more fully by working groups for different sections under a Steering Committee made up of industry professionals. In February 2007, GGHC published V2.2, in which it adopted the FGI interim guideline on acoustics as the sole Reference Standard for two new Environmental Quality (EQ) credits. Following the initial version and revisions an *Operations* section was added in V 2.1. The current version 2.2 is in effect, which included enhancements, plus an Operations section update in 2008. Under GGHC V2.2 EQ credits 9.1 and 9.2, up to two points could be achieved with design and analysis or with post-construction testing and measurements.

> 1 point – EQ 9.1 Acoustic Environment. Exterior Noise, Acoustical Finishes, & Room Noise Levels. Design the facility’s acoustic environment in accordance with the following sections of the 2006 AIA/AHA Draft Interim Sound and Vibration Design Guidelines for Hospital and Healthcare Facilities: Exterior Noise, Acoustical Finishes, and Room Noise Levels.
>
> 1 point – EQ 9.2 Acoustic Environment. Sound Isolation, Paging & Call Systems, & Building Vibration. In addition to Credit Goals outlined in EQ Credit 9.1: Acoustic Environment, meet two out of the three following sections of the 2006 AIA/AHA Draft Interim Sound and Vibration Design Guidelines for Hospital and Healthcare Facilities: Sound Isolation, Paging & Call Systems, and Building Vibration.

D. LEED HC (Healthcare)

Subsequent to GGHC’s adoption of the FGI acoustical criteria, and consistent with the “harmonizing” process, USGBC adopted the FGI interim guideline on acoustics as its own sole Reference Standard for two EQ credits in LEED HC. However, it is important to remember that each of these two groups, GGHC and USGBC, has its own independent interpretation about how these credits may be earned.

New LEED HC EQ Credit 2 will require both design and analysis documentation and post-construction testing and measurement data. A total of two points will be available through one of two optional paths.

Option 1:

1 point - Speech Privacy Goal. Achieve sound transmission class (STC) acoustical separations between various functional spaces, such as:

Patient Room | Patient Room; STC 45
Patient Room | Public Space; STC 50
Exam Room | Exam Room; STC 50
Patient Room | MRI Room; STC 60

1 point - Acoustical Finishes and Details. Design the facility by selecting & specifying materials, products, mechanical systems & design features to meet criteria for sound & vibration & to meet or exceed room average sound absorption coefficients ($\bar{\alpha}$), such as:

Atrium; $\bar{\alpha}$ = .10 or “Medium live”
Patient Room; $\bar{\alpha}$ = .15 or “Average”
Waiting Area; $\bar{\alpha}$ = .25 or “Medium dry”

Option 2:

2 points - Site Exterior Noise. Design the building envelope composite STC rating to meet the design goals for the Exterior Site Noise Exposure Category that applies, based on proximity to nearest noise sources such as highway, aircraft flight track, and rail line. In addition, determine principal sources of facility produced exterior noise exposure, and implement designs to reduce impacts on facility occupants and residential neighboring receivers.

E. Office / Indoor Workspaces, CBE

Acoustical privacy and freedom from intrusive noise distractions has been shown to be a significant parameter of environmental satisfaction in offices. Consideration for office and conference acoustics in building design can therefore be an important contributor to office operations enhancement.

A large statistical post-occupancy survey by the U.C. Berkeley Center for the Built Environment (CBE) of over 4000 occupants in 15 U.S. buildings with a variety of office configurations showed over 60% reporting acoustical interference with ability to work.[18] In the same study, data was reviewed from over 23,000 respondents in 142 buildings in the US (not an international survey). Acoustical categories received the lowest average occupant satisfaction scoring for indoor environmental quality (IEQ).

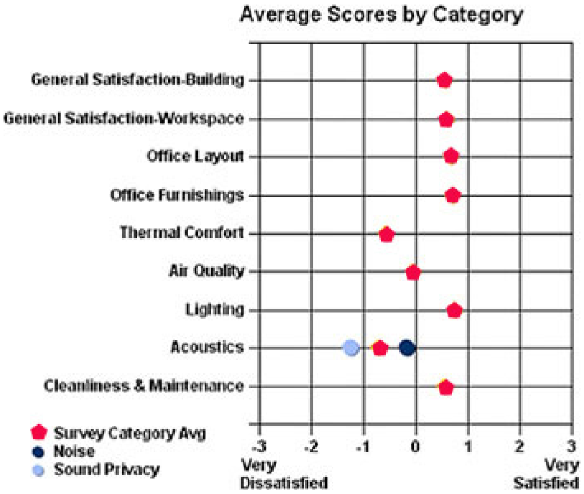


Figure 2. CBE Indoor Environmental Quality (IEQ) Satisfaction Survey Scoring[19]

Office designers, constructors, managers and owners have significant opportunity to enhance office operations by implementing acoustical and noise control criteria and guidelines in building design, office layouts and demising assemblies, building mechanical and electrical systems vibration and noise and data and communication systems.

Acoustically absorptive ceilings and wall surfaces reduce buildup of reverberant noise and undesirable reflections while improving speech communications. Continuous background noise should be suppressed within enclosed conference and office spaces where speech intelligibility is needed. In open office areas where speech privacy needs prevail, continuous background noise should be somewhat greater, and may be enhanced with electronic masking (which is more controllable than mechanical noise).

4. ACOUSTICAL CRITERIA

A. Architectural Acoustics

1) Reverberation Decay Time (RT60)

Reverberation in spaces is of concern in relatively large spaces where speech intelligibility or clarity of audio-video presentation is a primary concern. Disturbing sound reflection patterns should be avoided in spaces where speech intelligibility is of concern. In rooms with live microphones (including but not limited to spaces where educational instruction or presentations are made, or where teleconferencing might occur) reverberant build-up and unwanted reflection patterns should be prevented. Reverberant build-up of noise should also be prevented in loud spaces, such as mechanical equipment rooms, where the noise could disturb or limit speech intelligibility within the adjacent spaces.

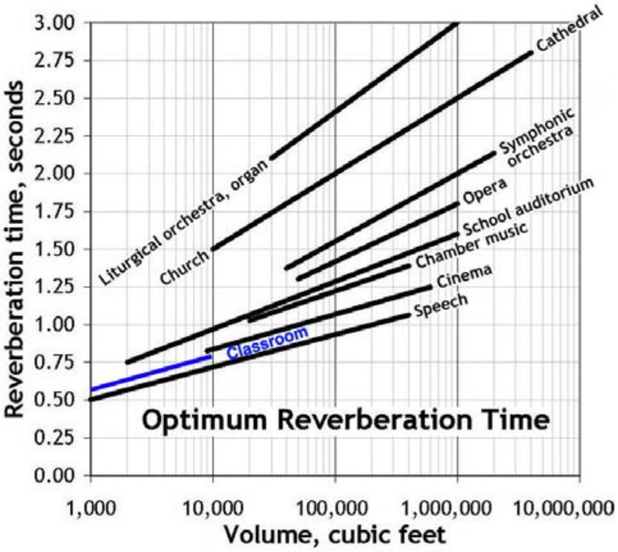


Figure 3. Reverberation Decay Time (T60) Criteria[20,21]

2) Sound Insulation (STC, Rw)

Acoustical separation by interior demising assemblies reduces source sound transmission to a receiver. It is difficult to deal with multiple parameters of sound, such as low, mid and/or high frequency, tonality, and other characteristics, but single-number ratings have been devised and in use for decades for that purpose. In North America, Sound Transmission Class (STC) is calculated according to ASTM E 413 over the frequency span of 125 Hz to 4000 Hz. R represents sound reduction index in Europe, a similar single number rating, including weighted reduction index, Rw, over 100 Hz to 3150 Hz, according to ISO 717, which takes strong lower frequencies of music and machinery into account.[22]

Application of STC or Rw ratings considers the source sound level and the continuous background level of the receiving room, to provide adequate noise reduction to intrusive noise to achieve an acceptable background.

3) Outside to Inside Noise Transmission (OITL)

Exterior walls, doors, roofs and other demising assemblies that reduce outside noise intrusion into interior occupied spaces are rated by a system similar to STC, except that lower and higher frequency noise is accounted for. The outside to inside transmission loss (OITL) spans 80 Hz to 5000 Hz. OITL also uses a different source spectrum from Rw, which can cause significant the same assembly's ratings to vary.

4) Speech Privacy Criteria

Speech privacy is a function of multiple variables, chief among them being background noise and distance between source and receiver. Articulation Index (AI)[23] and Speech Intelligibility Index (SII)[24] are two, based on the relationship between decreasing speech intelligibility and increasing speech privacy. For example AI < 0.05, or less than 5% of syllables being intelligible, is considered confidential, whereas AI $\leq$ 0.15 is considered acceptable or normal privacy for open offices. SII is similar, but expressed in percentiles, i.e. 39% is confidential and 75% is normal privacy.[25] These standards, and other weighted signal-to-noise ratios (SNR) are somewhat difficult for everyday use by non-professionals, but should be determined and evaluated for building designs where speech privacy is mandated or desirable.

A new standard has been developed, ASTM E2638-08,[26] which uses a simplified "discrete point" measurement procedure in existing facilities where source and receiver are separated by partitions (not be appropriate for open office). The Speech Privacy Class (SPC) relates background noise and sound isolation (re: STC). It is a relatively easy test to perform, and perhaps is more easily understood by designers and owners.[27]

B. Generic Floor Vibration

Floor vibration criteria (VC),[28] developed by Ungar and White in the late 1970's[29] following work by T.M. Murray[30] and others, as a graduated family of generic extrapolations from ISO criteria for human perception, have been used for various facility and occupancy types, but particularly in research, medical imaging and high-tech manufacturing facilities. The basic criteria have constant velocity from 4 to 8 Hz and constant velocity from 8 Hz to 80 Hz. Criteria for amplitudes below human perception have been modified for sensitive lab installations to constant velocity from 1 Hz to 80 Hz.[31,32] The VC limits of 1/3 octave RMS velocity vibration amplitudes are utilized in structural design. There are variations, such as acceleration and displacement conversions and specialized NIST-A[33] for metrology, which reduces the permissible amplitudes from VC-E below 20 Hz, but all are intended to provide acceptable vibration environments for occupants or sensitive instruments or installations. VC should be incorporated into initial program requirements for facility design. Site selection, structural system and design and architectural layouts should consider the criteria in regard to disturbing vibration sources, sensitive receivers and potential vibration transmission paths.

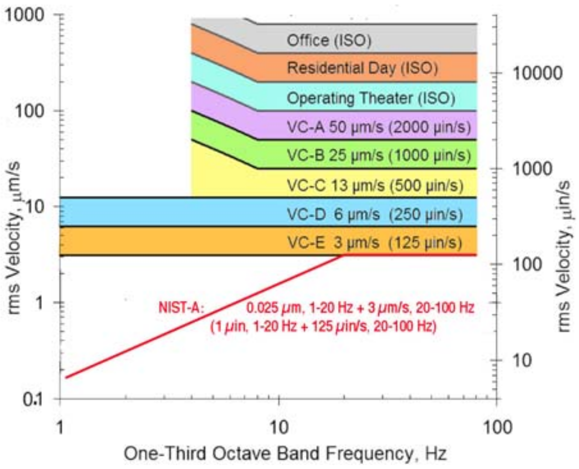
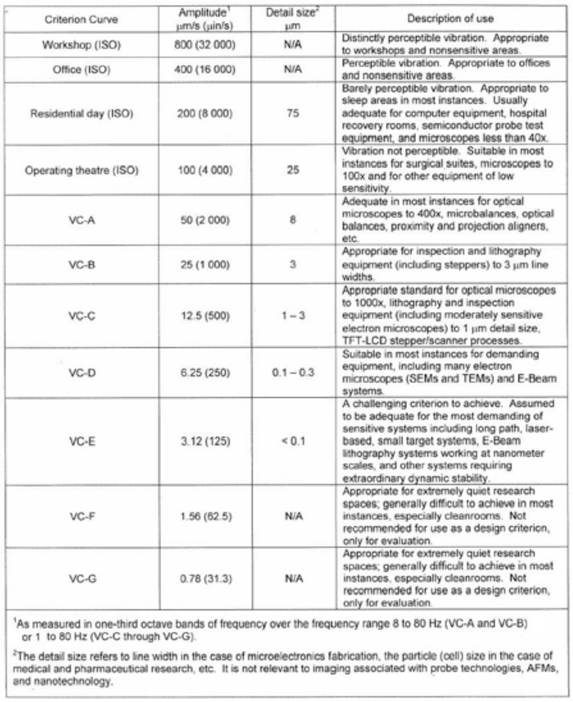


Figure 4. Generic Floor Vibration Criteria (VC)

Table 4. Interpretation of Generic Vibration Criteria



Criterion Curve	Amplitude[1] µm/s (µin/s)	Detail size[2] µm	Description of use
Workshop (ISO)	800 (32 000)	N/A	Distinctly perceptible vibration. Appropriate to workshops and nonsensitive areas.
Office (ISO)	400 (16 000)	N/A	Perceptible vibration. Appropriate to offices and nonsensitive areas.
Residential day (ISO)	200 (8 000)	75	Barely perceptible vibration. Appropriate to sleep areas in most instances. Usually adequate for computer equipment, hospital recovery rooms, semiconductor probe test equipment, and microscopes less than 40x.
Operating theatre (ISO)	100 (4 000)	25	Vibration not perceptible. Suitable in most instances for surgical suites, microscopes to 100x and for other equipment of low sensitivity.
VC-A	50 (2 000)	8	Adequate in most instances for optical microscopes to 400x, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	25 (1 000)	3	Appropriate for inspection and lithography equipment (including steppers) to 3 µm line widths.
VC-C	12.5 (500)	1 – 3	Appropriate standard for optical microscopes to 1000x, lithography and inspection equipment (including moderately sensitive electron microscopes) to 1 µm detail size, TFT-LCD stepper/scanner processes.
VC-D	6.25 (250)	0.1 – 0.3	Suitable in most instances for demanding equipment, including many electron microscopes (SEMs and TEMs) and E-Beam systems.
VC-E	3.12 (125)	< 0.1	A challenging criterion to achieve. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, E-Beam lithography systems working at nanometer scales, and other systems requiring extraordinary dynamic stability.
VC-F	1.56 (62.5)	N/A	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.
VC-G	0.78 (31.3)	N/A	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.

[1] As measured in one-third octave bands of frequency over the frequency range 8 to 80 Hz (VC-A and VC-B) or 1 to 80 Hz (VC-C through VC-G).

[2] The detail size refers to line width in the case of microelectronics fabrication, the particle (cell) size in the case of medical and pharmaceutical research, etc. It is not relevant to imaging associated with probe technologies, AFMs, and nanotechnology.

C. Continuous Background Noise (ASHRAE)

Criteria for permissible continuous background noise have been published in North America for decades, beginning with Noise Criteria (NC) originally developed by L. Beranek, replaced with Room Criteria (RC), as developed by W. Blazier. Other variations exist, such as NCB and RC Mk II.[34] In Europe, similar Noise Rating (NR) curves are common. Each system has a family of curves specifying maximum continuous background noise for audible octaves due to building systems (in unoccupied spaces). The RC curves incorporate "A" and "B" regions of low frequency noise limitations to prevent acoustically induced vibration in lightweight structures, such as partitions and ceilings.

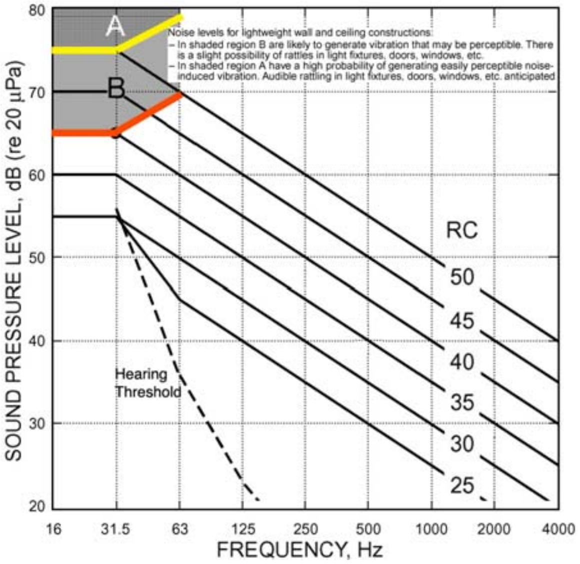


Figure 5. Permissible Continuous Background Noise[35]

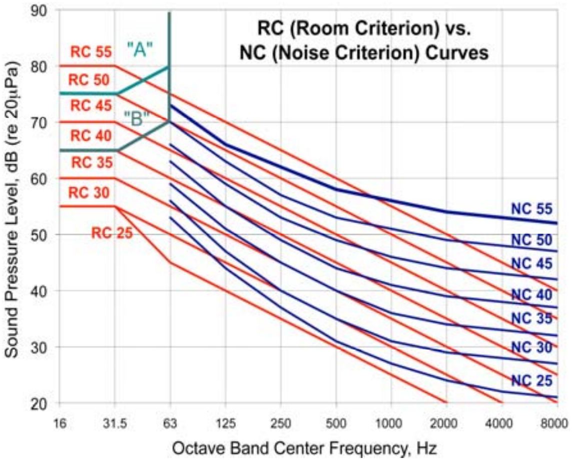


Figure 6. Room Criteria (RC) vs. Noise Criteria (NC) Note: RC criteria extend two octaves lower than NC.

5. CASE STUDIES

A. Power Plants: Turbine-Generator Vibration and Noise Disturbance Prevention to Neighboring Facilities

Very few buildings or campus developments incorporate a power generation plant (exclusive of standby or backup engine-generators), but design and installation of large power generators near sensitive buildings or residential areas can result in vibration disturbances or noise intrusions in sensitive facilities.

When power plants are planned, permissible vibration criteria should be in the program, and adequate vibration control measures should be implemented to prevent ground borne vibration transmission to adjacent properties. Steam and exhaust discharge and/or radiated generator noise should be evaluated relative to permissible environmental noise levels. Conversely, new facilities being planned near power plants should include evaluation of existing ground borne vibration and airborne environmental noise during preliminary planning, in case structural foundation or building shells need to be designed to resist intrusion of excess vibration and noise.

Case Study 1. A university with on-campus power generation planned replacement of an older generator with a 25 MW steam turbine generator. There had been vibration problems for years that affected sensitive installations in labs and structure borne vibration even caused re-radiated audible hum in buildings.

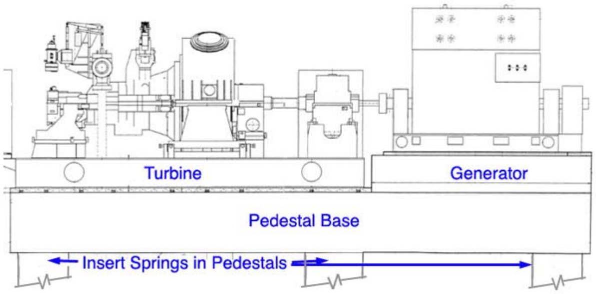


Figure 7. Turbine Generator Elevation

Spring isolators were designed for insertion into large pedestals supporting the massive generator base. Ground borne vibration measurements were made around the utility facility before and after construction that showed negligible increase in the vibration environment from the new generator.[36]

Figure 8. Turbine Pedestal Base with Spring Isolators

Vibration with elevated peaks at turbine and generator rotational rates show suppressed reactions in nearby buildings.

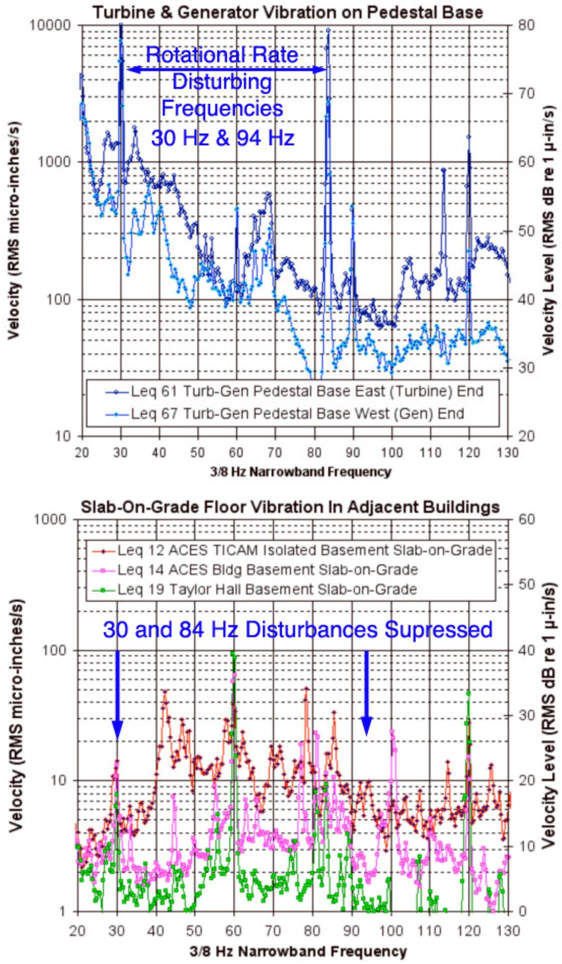


Figure 9. Turbine Vibration vs. Receiver Buildings Note how 30 Hz and 84 Hz source levels are reduced.

Case Study 2. A package turbine generator was installed at an electrical substation of a multi-use development with office, retail, hospital, residential and other occupancies. Noise complaints were received shortly after commissioning from nearby hospital offices about undesirable tonal noise intrusions. Investigations found loud broadband noise in the vicinity of the turbine, with strong tonal peaks in the 31, 250 and 1250 Hz 1/3 octaves, which relate to turbine and generator rotational rates. Intrusive noise in the offices was in the 250 Hz 1/3 octave.[37]

Various noise-mitigating measures were proposed, including insertion (or replacement) of silencers in inlets and discharges and solid sound barrier wall on the sides of the installation facing more sensitive facilities.

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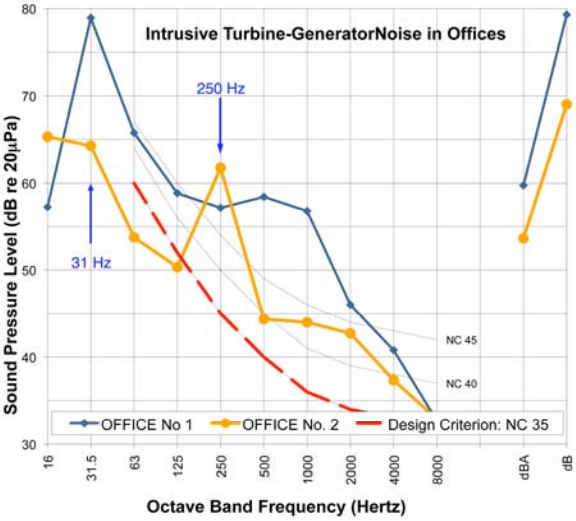

Figure 10. Intrusive Noise Spectra in Offices

Ultimately, the bottom pan of the turbine-generator enclosure was filled with grout. The resulting damping substantially reduced noise radiation from the installation.

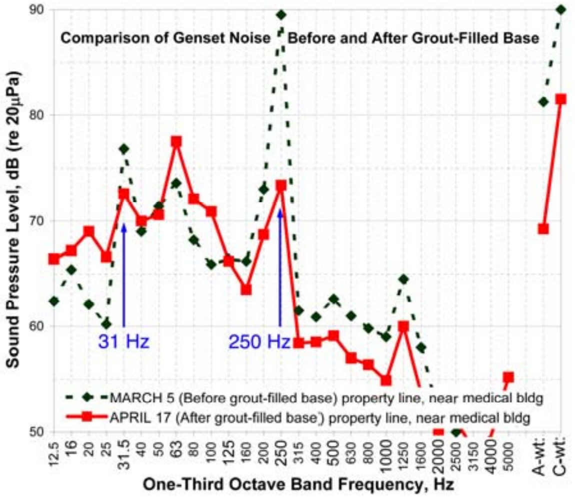

Figure 11. Turbine Generator Noise Reduction

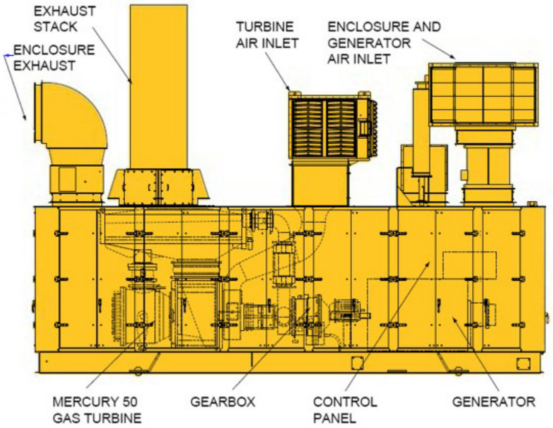

Figure 12. Package Turbine Generator in Enclosure (Courtesy Solar Turbines, A Caterpillar Company)

B. <u>Sites: Environmental Noise from Generators, Cooling Towers, etc</u>.

Outdoor cooling towers, air-cooled chillers, engine-generators, transformers and similar equipment radiates noise that may enter the occupied building on the site or cross property boundaries to potentially disturb sensitive receivers. Community standards for environmental noise, as expressed in building codes and/or ordinances, should be considered in selection, siting, and installation designs. No only should the overall sound level in A-weighted (dBA) or linear (dB) be considered, but the spectrum should be evaluated for tonality. Some codes and ordinance incorporate 3 dB to 7 dB penalties for tonality. Similarly, time of day or night should be considered for operations. Federal and many community standards penalize nighttime noise sources.

Architectural building shell assemblies and materials adjacent to outdoor equipment should be evaluated for sound transmission loss and frequency response. Window glazing is often the weakest wall component. Glass fixture sound transmission spectral characteristics are readily available from manufacturers and glazers. Similarly, equipment noise spectrum data are available. The peak noise emission levels of equipment should be compared to weaker frequencies of glass. Where they are coincidental, other glass fixtures or formulations should be considered, such as using laminated in lieu of plate or tempered glass to achieve smoother overall spectrum. The chart below contracts plate glass weak frequencies against smaller laminated glass weakness.

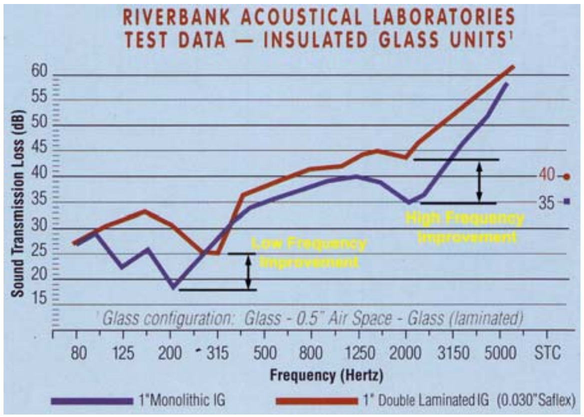

Figure 13. Comparison: Insulated Glass vs. Insulated Laminated Glass Transmission Loss[38]
(Courtesy Saflex/Solutia)

With regard to equipment noise tonality, in our firm's experience, we have been contacted many more times about annoyance from screw or helical rotary compressors than for reciprocating compressors, and we have not had to deal with scroll compressor noise. With regard to cooling towers, we have had more contacts about the low frequency noise of slow-rotation (draw-through) propeller fans than for broadband (blow-through) centrifugal fans. Therefore, in equipment selection, designers and facility managers should favor smooth-spectrum broadband noise over tonal or unbalanced spectrum.

After considering tonality, compare overall equipment noise level with allowable level at property boundary, including distance loss to boundary and any reflection or barrier effects from large surfaces. Attenuation at the source or noise barriers at the boundaries should be provided for any excess noise.

<u>Case Study</u>. A new hospital facility was constructed with three air-cooled refrigeration chillers for the facility HVAC system. The chillers incorporated helical rotary, or screw refrigeration compressors. The chillers were located on level three roof decks behind tall parapet walls, so that they were not visible from the ground level. The hospital building was several stories higher than the chiller installations, enabling wall reflections to degrade the parapet barrier effects. Shortly after commissioning the system, the facility began to receive complaints from residential neighborhoods between 5 and 9 blocks away. Unfortunately for the owner occupant, the situation was publicized in the local newspaper.

After investigation, it was determined that the chillers were not too loud to meet code allowable noise levels at the property boundaries, but that the character of the sound was too tonal, and as a result was annoyingly perceptible. The local paper quoted a music professor from the local university who could not play the piano in his residence because the chiller pure tone was out of tune with his compositions.[39]

Figure 14. Hospital Chiller Installations

Recommendations were made and implemented to (a) enclose the screw compressors in acoustically lined sheet metal enclosures to contain radiated noise, (b) replace rigid refrigerant pipe attachments to the chiller frame with resilient mountings to decouple the pipe vibration from the casing and (c) install acoustically absorptive exterior finishes on the building wall to reduce reflections over the parapet (barrier). Recommendations to insert a pulse diffuser or hot gas muffler in the compressor piping and to install condenser fan discharge attenuators were not implemented.

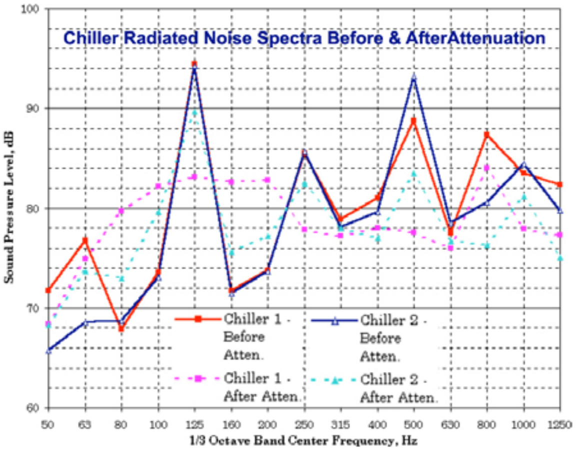

Figure 15. Screw Chiller Compressor Noise Reduction

The noise mitigation measures reduced the tonal noise peaks 5 dB, resulting in cessation of complaints.[40]

C. <u>Building Structures: Vibration Control for Sensitive Facilities</u>

Structural vibration control in sensitive facilities, such as research laboratories with electron microscopes, high-tech manufacturing clean rooms, medical imaging and surgical microscopes, etc. may involve several design disciplines. Site selection should include evaluation of ground borne vibration. Appropriate vibration criteria should be established before design of foundations and floor structures, re: 2.E. criteria, above. Architectural layouts should include relative placement of vibration sources and sensitive receivers and building systems should be selected, laid out, and specified for low noise and vibration (low frequency noise can acoustically induce vibration into light weight structures, so mechanical systems vibration control incorporates sound control, re: RC criteria A & B noise regions).

In general, slab-on-grade floor slabs will have relatively lower amplitude vibration levels because the contact with ground will damp vibration. Suspended or column-supported floors, in contrast, exhibit resonant amplification at natural frequencies of the beam and/or slab, usually between 5-15 Hz, depending on stiffness, with stiffer structures having higher frequency resonance and smaller amplitude vibration. Dominant ground borne vibration is also normally in the 5 Hz to15 Hz frequency range. Based on results of site evaluations, structural design should seek to create floor resonant frequencies that are different from the dominant ground frequency. For example, if 5 Hz disturbances are noted when trucks and busses pass by the site, the suspended floor structures should be designed for 7-9 Hz and 12-14 Hz natural frequencies. This “de-tuning” will tend to resist sympathetic vibration when external events transmit disturbance vibration into the foundation.

Architectural layouts should separate vibration source areas from vibration sensitive zones. Parking garage structures, for example should not be structurally tied, either vertically or laterally, to floors with vibration sensitive installations, unless structural vibration isolation measures are feasible. Similarly interior space planning should consider structural characteristics. On a given floor, deflections will be greater near the center of the structural bay and smaller near beams and columns. In vibration sensitive areas, advantages may be gained by placing partitions near mid-span and locating vibration sensitive installations over beams.

Case Study. A nanotechnology research facility was proposed on a university campus, which would incorporate research labs, lithography clean rooms, microscopy, laboratory technical support, office and conference areas. The design had to consider external vibration from roadway traffic, a nearby power generation plant and other building mechanical equipment. Building equipment, user-installed lab equipment and occupant activities, including footfall and rolling carts, would contribute internal vibration energy. The floor velocity vibration criteria for research spaces were VC-A, 50 µm/sec (2000 µinch/sec) RMS and VC-B for clean rooms, 25 µm/sec (1000 µinch/sec) RMS.[41]

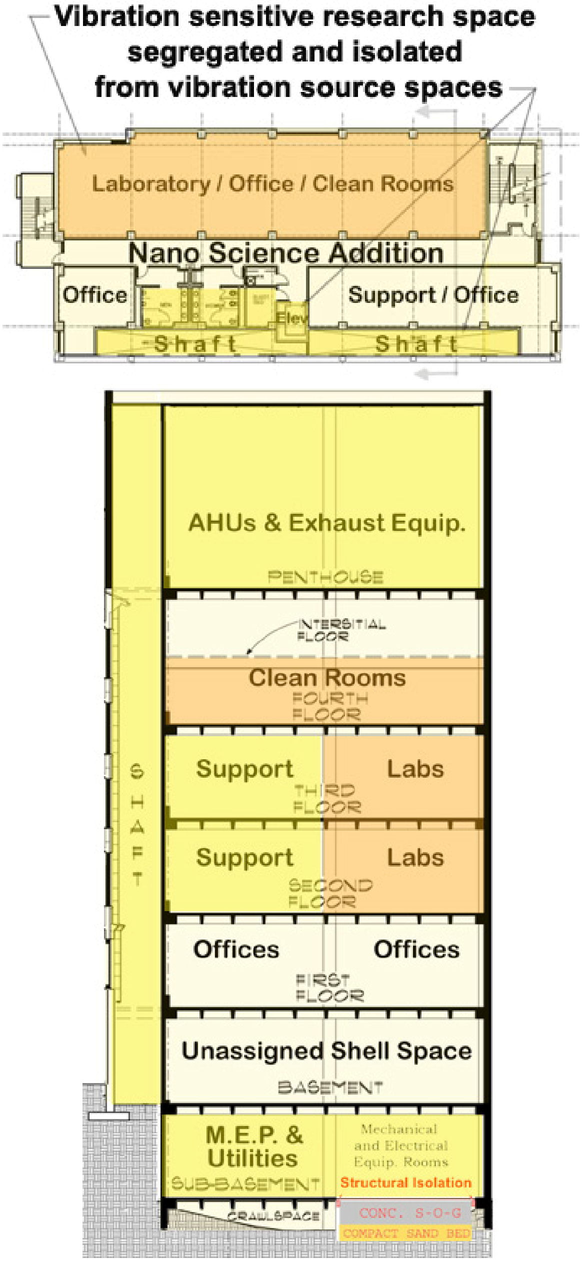

Figure 16. Vibration Control in Research Building, Floor Plan (top) and Building Section (bottom)[42]

Pre-design vibration analyses showed ambient conditions slightly below floor criteria, with narrowband peaks at 30 and 60 Hz (re: power plant) and at 29 and 59 Hz (re: other electric motors). It was determined that structural design should not permit resonance at 5, 10 and 15 Hz to avoid coincidence with electrical line frequency and harmonics, so goals were established for vibration sensitive floors to avoid 7-8 Hz or 14-16 Hz resonant frequencies for their harmonic frequencies (multiples) to be non-coincident with 29-30 Hz motor and power frequencies.

Vibration control schemes were developed to separate vibration sensitive spaces from non-sensitive or source areas and to "de-tune" or design research and clean room floors to be different resonant frequencies from other floors to prevent sympathetic vibration oscillation or transfer. All building equipment and distribution (pipes, ducts, conduits) were to be vibration isolated, including flexible connections where rigid elements crossed from non-sensitive to vibration sensitive zones. The primary mechanical and electrical equipment rooms in the sub-basement were on structurally isolated slab-on-grade foundation (critically damped by ground contact) with pipes and conduits flexibly connected to equipment and mounted on vibration-isolated supports.

Pre-occupancy commissioning phase floor validation measurement showed that implementation of vibration control measures resulted in all research and clean room floors achieving the vibration criteria.

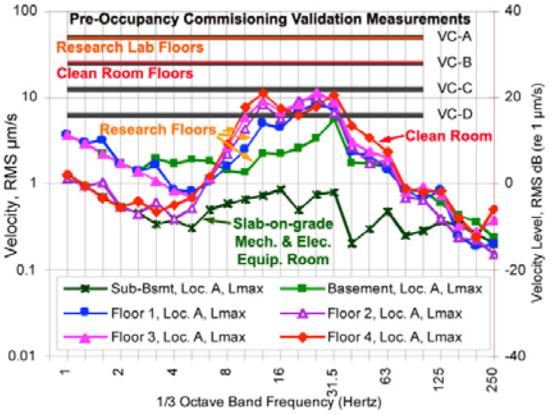

Figure 17. Pre-Occupancy Floor Vibration Validation Measurement Results on Sub-Basement S-O-G and Sensitive Research Floors[43]

Other design strategies can be employed to reduce disturbance transmissions to sensitive areas, such as differentiating structures to create stiffer, higher-frequency floors for sensitive areas and less stiff, lower frequency floors for support areas, equipment rooms office and conference areas, etc. Evaluate vertical pipe, conduit and duct risers that may act like structural elements to vertically transmit impacts, disturbances or vibration from floor to floor and employ vibration isolation supports, even if the pipe, conduit or duct does not carry equipment vibration. Footfall and rolling traffic in corridors easily excites structural resonances. Locations of sensitive installations should consider disturbances from corridors and building systems equipment rooms.

D. Building Systems: Fan Sizing for Energy Savings and Noise Control

Fans are often selected and oversized to meet conservatively estimated demands or future expansion. Energy efficiency and noise generation are functions of fan operation. If the fan operates to the right of the maximum efficiency point of the fan curve high frequency noise is increased. To the left of the maximum efficiency point, low frequency noise increases. Both of these conditions increase need for fan noise attenuation, with costs for space, materials, and pressure drop. Variable speed fans may move up and down the system curve, but as the operating point moves down, it approaches rotating stall or surge, resulting in excessive low frequency rumble and poor air delivery performance.

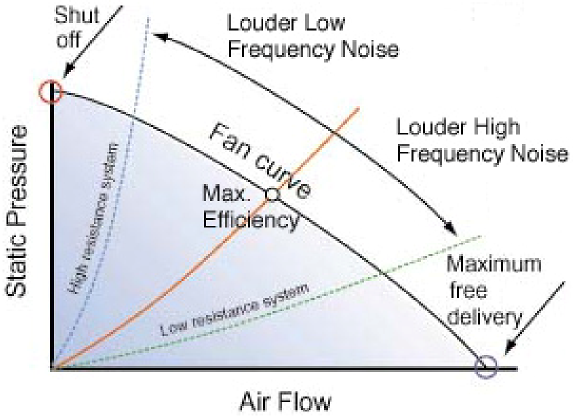

Figure 18. Generic Fan Curve with Noise Effects [44]

Fans should be selected and sized appropriately for the actual anticipated range of demands, in lieu of over sizing for future or unrealized excess demand. [45] The wheel size and operating curve for a given range of demand may determine the efficiency and noise characteristics. Two different fan selections with similar demand range (system curve) are superimposed below to illustrate how selection may affect surge and low frequency rumble. Variable frequency fans typically operate over a range below the maximum efficiency point. If the fan is oversized, the range is far more likely to approach surge at low demand. One should consider selecting maximum demand at 110-115% of peak efficiency so that "normal" demand, where the fan operates the majority of the time, is near the max efficiency point on the fan curve. This would also result in minimum demand higher on the system curve and less likely to cause surge conditions with low frequency rumble.

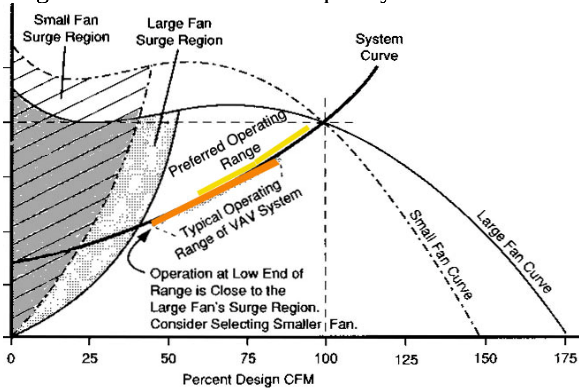

Figure 19**.** Two Fan Curves vs. One Demand Range [46]

While different fan types and operating curves will provide varying parameters, it is likely that over time, the decreased cost of high-efficiency operation of fan wheels sized for actual current demands will save enough operations funds to pay for future wheel exchange when future or additional demands are realized. The right-sized fans will also generate less noise in the building, potentially resulting in lower cost noise control measures.

6. CONCLUSION

Acoustics, building systems noise and vibration, structural vibration and environmental noise considerations in facility planning, design and operation can assure conformance with mandated codes and standards and also enhance operational efficiency and occupant comfort, privacy and performance. Many acoustical criteria and guideline sources are available to assist design, construction and operations professionals in application and implementation of good practice concepts.

7. ACKNOWLEDGEMENTS

Thank you to David M. Sykes, Co-Chairman, Joint ASA/INCE/NCAC Subcommittee on Speech Privacy and Healthcare Acoustics – TC-AA.NS.SC and ANSI S12 WG344, for assistance with acoustical criteria history and implementation in FGI, LEED HC & GGHC.

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