Noise Control Insights and Guidelines

Alicia Larsen, **Benjamin Markham**, **Jeffrey Zapfe** and **James Barnes**, Acentech, Cambridge, Massachusetts

Congratulations to Jack Mowry for serving for 50 years as editor and publisher of *Sound & Vibration* magazine. Jack recently received the INCE Award for Excellence in Noise Control Engineering in recognition of his ongoing contributions to the noise control engineering profession by providing, without charge, timely and informative technical articles and access to useful product data to many thousands of readers worldwide. Thank you Jack, keep up the good work.

The noise control insights and guidelines presented here[1] are subdivided into four areas of interest. First we address evaluations and controls of the path-related aspects of airborne and impact sound transmission between neighbors living in multifamily buildings. Then we address ground-borne vibration and sound from rail lines near residential buildings. Third, we provide insights into the source-related aspects of controlling noise and employee noise exposures in manufacturing and power generation plants. And we conclude with guidelines for achieving good acoustics and hearing conditions for students and teachers in classrooms.

Multifamily Living Spaces

Imagine you have just moved into a new condo – excited, eager to love your new space, and laying out your furniture. Now imagine that shortly after moving in, you realize you can hear the TV next door, the dog barking across the hall, and neighbors walking around upstairs. As acoustical consultants, we would love to help, but unfortunately there is little that can be done at this stage without significant cost and intrusion. Sound isolation issues are most effectively addressed before construction, during the design phase.

What can designers do to design multifamily buildings to meet the sound isolation expectations of their client and future residents? Acoustical consultants use several techniques to address these issues. However, before delving into them, one must first understand a little bit about sound isolation.

Sound Isolation 101

Every sound isolation problem has three elements – a source, a path, and a receiver. The "source" is the noise generator. It could be anything from a fourth-grader practicing her saxophone to a piece of mechanical equipment. In many cases, the most effective means of mitigating a noise concern is to choose a quieter source if possible (quieter mechanical equipment, for example), or to increase the distance between the source and sensitive receivers (lengthen the path).

Unfortunately, many times the source is an element that cannot easily be changed. No matter how many rules you put in place, there is no guarantee the student will stop practicing her saxophone at odd hours or the man next door will not fall asleep with his TV on again.

The "path" is the element designers have the most control over, so it is what frequently receives the most focus during the design process. Both the path's length and the building construction intervening between source and receiver (position and composition) can be controlled. The performance of the building construction is more predictable; it does not involve residents.

Finally, the "receiver" in a multifamily building is the resident. Individual sensitivity to noise or vibration varies, so designers have little control over this piece of the sound isolation puzzle either. One exception is the background noise level – designers can control this aspect by introducing steady, broadband (full-spectrum) ambient sound that masks the intruding sound, similar to the white-noise machines some people keep in their bedrooms to help them sleep. The bottom line is that "quiet" does not equate to "private" – in fact, it is often just the opposite: there is greater privacy when there is a steady (but pleasant) level of ambient sound present.

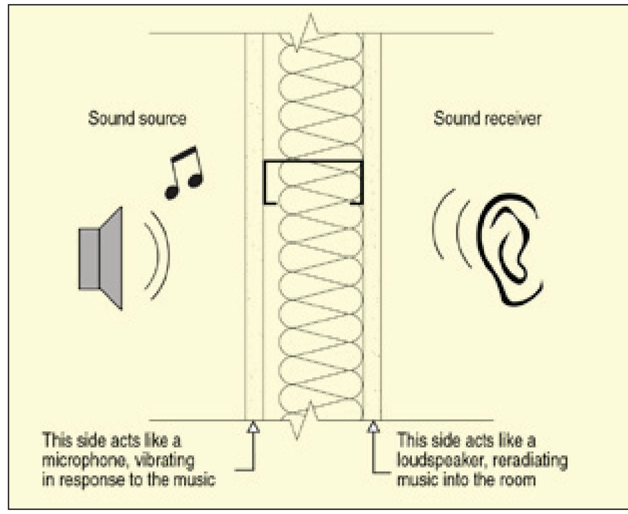

Figure 1. Sound transmission through partition.

Given that the design team has the greatest control over the path, this portion of the article focuses on that aspect of sound isolation: how to design multifamily building constructions that provide substantial sound isolation. There are two types of sound transmission of primary concern in multifamily buildings: airborne sound transmission and impact sound transmission.

Sound and vibration isolation comes down to mass, stiffness, and decoupling. In multifamily buildings, it is necessary to consider wall construction, floor/ceiling assemblies, and environmental noise and vibration sources with these factors in mind. It is sometimes said good fences make good neighbors. In a multifamily building, good building construction can make for good neighbors, too.

Airborne Sound Transmission

Airborne sound is generated in the air before being transmitted through a structure to a receiver. Examples include people talking or a loud stereo system. This can transmit either by a gap in a construction (door undercut) or by causing the intervening construction to vibrate and reradiate the sound energy on the other side.

With a single-stud partition, one side (source side) can be thought of as a microphone and the other side (receiver side) as a loudspeaker (see Figure 1). The sound energy travels through the air and gets picked up by the "microphone," transmits through the structure, and is reradiated by the "loudspeaker" into the air on the other side of the partition.

There are three primary methods to improve sound isolation:

- *Seal all gaps, cracks, and leaks*. This is the easiest and most effective means to reduce transmission of unwanted sound. Sound will always find the weakest path; other attempts to improve sound isolation will be ineffectual if the gaps are not sealed first.
- *Increase the mass of the construction*. This makes it more difficult for the airborne sound to cause the partition to vibrate. In the microphone/loudspeaker analogy, this corresponds to making the microphone and loudspeaker less effective or efficient.
- *Introduce decoupling into the construction*. This allows one side to vibrate without transferring the vibration as easily to the other side, analogous to cutting the connection between the microphone and loudspeaker.

In most cases, all three methods are necessary.

Closing Gaps. ASTM C919, *Standard Practice for Use of Sealants in Acoustical Applications*, contains recommendations on how to apply caulk in acoustical applications. All penetrations should be sealed. Back-to-back electrical boxes should be staggered, preferably in different stud bays, and caulked. Walls should be caulked with one bead of caulk on each side of the partition. (A second bead of caulk on one side of the partition does not result in a substantial improvement in sound isolation.)

Windows and entry doors should have gaskets; poorly sealed entry doors (particularly those with a substantial undercut) can be a significant source of noise intrusion from corridors in some multifamily buildings.

Increasing Mass. A substantial increase in mass is necessary to meaningfully affect sound isolation – on the order of doubling the mass. This could be upgrading from one to two layers of gypsum board on each side of a stud partition or using plaster rather that gypsum board. (Plaster is roughly three times the mass of gypsum board.) If partitions are concrete masonry units (CMUs), increasing the density or thickness or filling the partition with grout both effectively increase the mass.

Introducing Decoupling. The goal is to eliminate rigid connections between one side of the construction and the other. The most effective way to do this is by using a double-stud or double-width construction with an air cavity between the two sides of the wall. When double walls are not possible due to cost or space constraints, other methods such as specialty resilient fasteners can be acceptable alternatives. In general, resilient clip products tend to be more reliable than resilient channels, but either product type can be complicated to implement in actual wall applications, particularly if cabinets, TVs, or other wall-mounted elements must be anchored directly to the studs. These complications are less prevalent in suspended ceiling applications.

Impact Sound Transmission

Impact sound refers to energy directly applied to the structure or partition. The most common example of this is footfall generated in the residence above, but things like chairs scraping along the floor and the thump of people ascending/descending stairs are also prevalent in multifamily buildings.

In addition to the aforementioned sound isolation methods, there are additional considerations for mitigating impact sound.

Increase Structure Stiffness. An important first step in mitigating impact sound (particularly the low-frequency thuds), increasing the structure's stiffness can be a particularly difficult challenge when the construction is already determined. The stiffer the structure, the more effective the sound and vibration isolation will be, particularly at low frequencies. Structures that are not particularly stiff are less able to isolate the low-frequency content of impact sounds.

Decoupling. Decoupling works like the springs and shock absorber in a car. Energy is applied to one side of the construction, but the way in which the sides of the construction are connected prevents the energy from being transmitted to the other side. (The sides of the construction are often connected by a device such as a spring or a resilient pad.) A car can go over a bump, but since the wheels are free to move up and down, the passengers do not feel the impact in their seats.

Carpeting and other soft floor finishes significantly cushion impact sounds, preventing the floor/ceiling assembly from becoming energized in the first place. Most impact sound problems occur with hard floor finishes like wood or tile. In most cases, addressing this issue with decoupling is the most sensible option, since it often has the fewest implications on the project.

The structure's stiffness is typically decided in the earliest stages and changing that could have major implications. On the other hand, the finish floor hardness is often chosen for aesthetic reasons, and changing the finished floor may be undesirable.

Decoupling can be addressed on the floor or ceiling side. In the first option, a floating floor – such as a separately poured concrete slab that rests on resilient isolators or a thin underlayment underneath the finished floor – is installed. The scale of the decoupling depends on the sensitivity of each situation.

Alternatively, one can address decoupling on the ceiling-side by installing a resiliently suspended ceiling. Again, depending on the application, this can range from hanging multiple layers of gypsum board on a network of spring hangers to attaching the gypsum board using resilient channels.

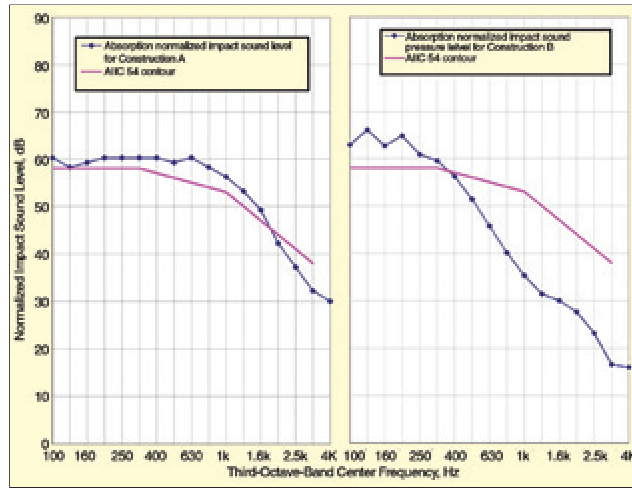

Figure 2. IIC test data for two different constructions.

In either case, it is best to begin with a stiff structure. When faced with an existing structure that lacks stiffness, it is typically necessary to add structural members (more beams) or mass (pour more concrete).

Wood-frame construction is fairly limp, so addressing the stiffness of the construction can make a large impact on the effectiveness of the sound isolation. At least 25 mm (1 inch) of gypsum concrete in wood-frame constructions goes a long way to stiffen the structure and add mass. Steel and concrete buildings tend to be stiffer, but sometimes do require additional steel framing or concrete than might otherwise be required structurally.

Quantifying Sound Isolation. A variety of metrics put forward in the following ASTM standards are used to quantify the sound transmission between spaces and assign a single-number rating to the airborne sound transmission or the impact sound transmission.

- Field: ASTM E336, *Standard Test Method for Measurement of Airborne Sound Attenuation Between Rooms in Buildings.*
- Laboratory: ASTM E90, *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements.*
- Field: ASTM E1007, *Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures.*
- Laboratory: ASTM E492, *Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine.*

Airborne sound transmission is typically quantified using the sound transmission class (STC), a laboratory rating that cannot be measured in the field. Field equivalents include apparent STC (ASTC) and noise insulation class (NIC). The major difference between the two field ratings is that ASTC normalizes the rating to account for the room acoustics in the particular measurement scenario. This means one can test the ASTC of two different constructions, in two different locations, and compare the results to one another as an indication of how the partition is performing. This test is used to measure compliance. NIC, on the other hand, does not normalize for the room conditions as such; it better represents what the occupants actually experience rather than simply how the partition is performing. Higher values indicate better sound isolation.

Impact sound transmission has an analogous set of metrics:

- Impact insulation class (IIC), the lab rating.
- Apparent IIC (AIIC), the normalized field measurement used to determine compliance.
- Impact sound reduction (ISR), the non-normalized field measurement that correlates well to occupant experience. Again, higher values indicate better sound isolation.

Both airborne and impact ratings vary with frequency but are represented by a single number, which means the ratings may not fully describe the circumstances. For instance, the two tests shown in Figures 2a and 2b have the same STC rating but very different properties of airborne sound isolation across frequency. The first shows deficiencies in isolation at low frequencies, while the second shows deficiencies at mid- and high-frequencies. With the partition associated with Figure 2a, one would be able to hear the bass beat of their neighbors' music but not their conversations. In contrast, a resident would have a much easier time understanding their neighbor's phone conversations with the partition in Figure 2b.

A change in STC or IIC of one or two points is not an appreciable difference in sound isolation. However, a change of five points is significant, and a change of 10 points typically corresponds to a largely significant difference – on the order of doubling or halving the perceived loudness of intruding sound.

Code Requirements/Guidelines. Many states have adopted the *International Building Code* (*IBC*) into their state building code requirements. This calls for a minimum STC 50 laboratory rating, or 45 if measured in the field. Similarly, impact sound isolation requirements are IIC 50 or 45 if measured in the field.

It is important to understand that these code requirements do not necessarily equate to occupant satisfaction and certainly do not indicate inaudibility. Higher values are recommended for more sensitive applications. Table 1 shows a summary of various sound isolation guidelines commonly referenced in the industry.

Noise and Sound Control in the Home

We are frequently contacted by individuals who are interested in and sensitive to the acoustical environment where they live. They often request assistance to address many interesting and challenging concerns about noise control or sound control at their home. We define noise control as reducing unwanted intrusive sounds. On the other hand, sound control relates to steps that can be taken at home to enhance and improve desirable sounds such as those associated with music and entertainment systems.

A booklet based on decades of consulting experience has been prepared for homeowners wanting a range of insights about ways to control noise and sound at their home – to improve their acoustical environment and quality of life. The booklet provides basic, simple-to-read information without technical engineering details. Several references are identified for those wanting such technical details.

The booklet is not for sale. Instead, it is available for download without charge as a public information document on the web site of the Institute of Noise Control Engineering (INCE): https://www.inceusa.org/publications/technical-reports/#noise-control

For those interested in researching additional details, the digital library on the INCE-USA website provides access to more than 20,000 technical articles about noise control. Article copies are available without charge to members and for a small charge to nonmembers.

Sound Isolation Pitfalls

- Some "resilient channels" are not really resilient. Two-legged resilient channels do not provide a meaningful acoustical benefit.
- Shear panels in wood-frame construction can be tricky. When a resilient channel/clip is applied between a shear panel and a finish layer of gypsum board, it creates a narrow airspace at the resilient element. This narrow air space of entrapped air is actually quite stiff, preventing the resilient element from flexing. When introducing resiliency, the resilient element should look into as deep an air space as possible.
- Resilient elements are often pinned in place. This occurs commonly at ceiling perimeters – a resiliently suspended ceiling might be anchored to the walls at the perimeter with a rigid wall angle; this pins the ceiling in place, limiting the efficacy of the resilient hangers.
- Some conditions are difficult to seal. For example, the structural beam running parallel to the partition in Figure 3 makes it very difficult to get behind the beam with a caulk gun to adequately seal the partition, exposing the partition to sound isolation problems.

Table 1. Comparison of sound isolation guidelines.

Reference	Airborne	Impact
Code (IBC)	STC 50	IIC 50
HUD, Grade 1 (Luxury)	STC 55	IIC 55-60, Depending on adjacency
IIC Guideline	IIC 55, Acceptable STC 60	STC 55, Acceptable IIC 60, Preferred

Notes:
1. These are lab, not field ratings. IBC and ICC reference field ratings; HUD doesn't.
2. HUD guideline is sometimes referenced in litigation as benchmark for "luxury" buildings. HUD also provides guidelines for Grade 2 and 3 construction, which are less stringent (HUD guideline is from 1963).
3. ICC's guidelines is quite new and places a stronger emphasis on field testing; also applies to non-residential.

Figure 3. Beam parallel to wall partition.

Ground-Borne Vibration and Sound from Rail Lines

Imagine that you hear sounds day and night alerting you to each subway train passing below your new condo. Or perhaps you are responsible for a school, a performance space, or a high-tech research or manufacturing facility where low vibrations are important. Experienced consultants can help address such issues.

Multifamily residential structures are typically found in densely populated urban areas. Many of these urban areas also have extensive public transportation systems, some of which incorporate underground rail lines. Anyone who has visited New York City, Chicago or Boston has likely encountered the characteristic low-frequency rumble from a passing subway train.

Interestingly, vibration is actually the mechanism responsible for the rumble sound. Micro-forces due to imperfections at the wheel-rail interface produce vibration that travels through the soil to nearby buildings. Once inside the building, the vibrations cause the walls, floors, and ceiling to vibrate and radiate sound much like giant loudspeakers. It is this radiated sound people hear when the train passes. With the exception of air vents and other openings, the acoustic sound produced by the train in the tunnel is effectively trapped inside the tunnel.

If the vibration is severe enough, people may feel it, but usually the vibrations cannot be felt even though the resulting sound can still be heard. Since the vibration is propagated through the soil, the resulting sound and vibration inside the building are commonly referred to as ground borne. Surface rail systems also produce ground-borne sound and vibration, although this is often masked by the direct airborne sound from the passing train.

The Federal Transit Administration (FTA) provides guidelines for acceptable levels of ground-borne vibration and sound in residential settings where people normally sleep.[2] While these levels strictly apply to new transit projects near existing communities, they also can be used as a reasonable guideline for a new residential structure near an existing rail line. FTA does not specifically say what the effects will be if its limits are exceeded.

More insight into this aspect is available from the TCRP D-12 study.[3] The D-12 project studied the relationship between ground-borne vibration and sound and community annoyance and provided a method to estimate the likelihood of annoyance based on the vibration or sound level.

Like airborne sound, mitigation of ground-borne sound and vibration can be conceptualized in terms of the source, path, and receiver. In addition to effective maintenance of the track and roll-

Figure 4. Resilient track fastener.

Figure 5. Base isolation pad.

ing stock, source mitigation treatments usually involve a resilient track support. Resilient track supports come in many varied forms, but the basic concept involves the placement of a resilient element (rubber, neoprene or even steel spring) between the rail and the tunnel floor. Figure 4 is one example of a resilient track fastener that is located between the rail and the wood tie. Resilient track supports can be very effective at reducing vibration, however, they also require the direct involvement of the transit agency, which can be challenging.

Path mitigation has limited effectiveness for ground-borne vibration. Trenches are often proposed as a mitigation option, but in addition to being of limited practicality in an urban setting, their effectiveness is modest at best.

Mitigation at the receiver is a viable option, particularly for new construction. Buildings have a natural vibration attenuation of one or two decibels per floor as one moves up away from the source. There is also distance attenuation as you move farther from the rail line. Designers can take advantage of this by locating the most sensitive receivers on upper floors, saving the lowest levels for less-sensitive uses such as parking, mechanical, and retail.

More active steps can also be taken to reduce the amount of vibration entering the building at the foundation. Base isolation systems are used to support the building resiliently. Base isolation is typically done at the column base (see Figure 5), although continuous pads under mat foundations can also be employed. The isolation performance of the isolation is specified based on the source levels (train) and the design goals for the living spaces. Vibration reductions associated with a base isolation system are comparable to what would be expected from a track isolation system at the source.

Mitigation is also possible within the building on a room-by-room basis. Room-within-a-room construction using a floated floor and resiliently supported walls and ceiling can be effective provided constructability challenges like differential floor heights can be dealt with.

Controlling Noise in Manufacturing and Power Plants

Imagine that after moving into your new home you get a job working in a nearby industrial plant. You find the noise levels in the areas of the plant where you work are so high they require the use of hearing protectors all day and make speech communication difficult. Experienced consultants can work with plant designers and owners to address such issues.

The Technology for a Quieter America, (TQA) report[4] published by the National Academies Press in October 2010 followed a five-year study by the National Academy of Engineering to assess environmental noise in the U.S. The report includes findings and recommendations for government, industry, and public actions that may mitigate or eliminate those noise sources that pose a threat to public health and welfare.

In 2011 the Institute of Noise Control Engineering Foundation and the Noise Control Foundation established a TQA follow-up program to identify specific noise topics and to develop relevant recommendations aimed at improving the noise climate in the U.S. The TQA follow-up program consists of a series of events involving experts in selected TQA topic areas to further assess specific noise issues and publish a series of recommended remediation measures.

Below are summaries of three presentations made during TQA follow-up events in 2014[5] and 2015.[6]

Examples of Noise Control Technology Available for Manufacturing Equipment. In the mid-1970s, within the source-path-receiver model for evaluating noise problems, the focus was mainly on path control, adding traditional barriers, such as mufflers and enclosures. Some effort focused on the receiver, trying to move the worker away from the area where the noise was being produced. Controlling noise from the source end involved maintenance, replacing machines, or retrofitting. Costs were most easily obtained for path controls, because supplier costs were obtainable and could be applied to deciding how much a certain noise reduction would be used within a particular industry. Predicting costs for source control, on the other hand, was challenging, because some of the approaches were proprietary.

Today it's a different story because of the noise control pioneers at INCE, who pushed for noise regulations in particular products. For example, the Environmental Agency (EPA) regulated the noise emissions of portable air compressors. In response to demand from Europe and the U.S., today's portable air compressors have incorporated some excellent noise control designs. Newer lines of portable compressors and other equipment have incorporated enclosures or whole processes located apart from the worker so that the worker becomes more of a monitor than an operator. Much of this technology was first developed for the military and is now migrating to industrial and commercial marketplaces.

Some of the technologies available today for noise reduction include:

- Reduced-speed low-noise fans. The Chrysler K car, for example, added quieter radiator fans.
- Quieter high-efficiency motors. The U.S. Navy needed quieter submarines and ships, so high-efficiency motors were developed to reduce noise and save money.
- Quieter gearboxes were also developed for the U.S. Navy for quieter ships and submarines. The techniques used to design and manufacture quieter gearboxes have found their way into other industrial products.
- Direct drive replacing gearboxes and drive shafts. In some cases, gearboxes are being replaced completely with direct-drive systems to eliminate gear noise.
- Variable-frequency drive (VFD) systems with well-matched motors. Rather than having the machine operating a fan, or a pump at its maximum speed, VFD systems can run at reduced speed, reducing both noise and energy consumption.
- Rotary replacing reciprocal. When work is only happening in one direction, it's similar to a ship being fully loaded with

Figure 6. A waterknife designed to be 30 dBA quieter than an older version.

Figure 7. Example of a manufacturer-supplied noise control enclosure on a diesel generator.

cargo during one leg of its trip, but empty on the way back. Rotary equipment does work during the whole cycle. Inherently, rotary machines can operate at higher speeds with higher throughput, producing lower-impact sound and less wear and tear on equipment.
- Local area communication networks enable industry to do away with P/A systems.

A water knife (Figure 6) purchased under a "buy-quiet" program at NASA's Glenn Research Center (GRC) machine shop near Cleveland , OH, was more than 30 dB quieter than an older water knife in the same work area. The manufacturer designed it to be quiet by changing the noise source mechanism, not by applying an after-the-fact noise control treatment or materials.

The manufacturer of the diesel generator in the GRC's central air equipment building met the noise emissions specifications under the "buy-quiet" program by enclosing the nominal (loud) model in an on-skid enclosure (see Figure 7), which provided the required amount of sound attenuation. Manufacturer-supplied enclosures or other controls are specifically designed for a particular piece of equipment. They are far superior to retrofit enclosures or other do-it-yourself designs because they will provide the rated attenuation while also providing proper ventilation and convenient access for maintenance.

It is reasonable to expect continued noise control requirements along with an increased emphasis on robots and other extreme automation to protect the receiver. Finally, 3D printing is a completely different approach to production that reduces noise at the source by eliminating the metalwork. Instead of cutting down or removing material, 3D printing builds up the product. It likely won't replace high-volume production, but for low-volume production, it could be useful and quieter.

Reducing Employee Noise Exposure: Plant Case History. A successful recent program to reduce employee noise exposures at a mid-size U.S. manufacturing facility is described. The goal of the noise abatement program is to define and install reasonable and effective noise controls that are acceptable to management, engineering, production, maintenance, and the workers.

The target of the noise abatement program is to reduce noise levels to 80 dBA or less in frequently occupied plant areas. Consulting steps included:
- Meeting with plant managers, including engineering, operations, and safety
- Documenting current concerns and goals
- Measuring and defining plant areas and jobs with excessive noise
- Identifying principal noise sources and characteristics
- Preparing a noise control plan of action
- Helping to implement selected noise abatements
- Determining if and where adjustments are needed
- Documenting the results

For a noise abatement program to be successful, several additional recommendations beyond the obvious need for excellent noise control engineering are critical:
- Senior management must support the noise control program in keeping with its responsibility to provide a safe and healthful workplace.
- Experienced plant and safety engineers should maintain ongoing ownership of the program.
- Fully engage those responsible for production and maintenance.
- Draw upon experienced noise control engineers for assistance.

The manufacturing plant included many noise sources and a range of methods for reducing noise levels was needed. For example, audible paging and alarm systems frequently produced loud noises throughout large areas of the plant. We recommended installing a local-area network, providing vibrating alarm receivers for employees required to perform quick-response line repairs, providing cell-phone-like receivers for employees being paged, and reserving the audible paging for emergency announcements.

Compressed air is used in many of the lines at this manufacturing plant to move, clean, or cool parts being made. To reduce noise from compressed-air vents, commercially available mufflers were installed on solenoids, and low-noise jets were installed at many vents. In addition, compressed-air pressure and volume was reduced at some locations to reduce both noise and operating costs.

The frequency spectrum of individual noise sources was measured and incorporated into the design of effective noise abatement methods. As an example, vibratory parts feeder bowls at the plant included noise-control enclosures that had been lined with a thin sound absorbing material. However, the noise from the bowls peaked in the 125 Hz octave frequency band. To address noise at this frequency, the thickness of the interior sound-absorbing treatment was increased to about 2 inches with an industrial-grade sound absorptive material providing greater low-frequency sound absorption.

One relatively small area of this manufacturing plant includes air-handling ducts that radiated noise down to locations where employees are stationed full-time removing completed parts from an assembly line. To reduce this noise, the ducts were lagged with sound-absorbing insulation and aluminum sheeting.

To reduce the reverberant build-up of noise from the many items of plant equipment, industrial-grade sound-absorbing panels were installed along the walls in selected plant areas.

Many of the operating lines include wire-mesh safety guards with hinges and line operating interconnects. These wire-mesh guards allowed workers to use long slender rods to move jammed parts off the line without opening the guards that would shut down the line for safety reasons. We made two recommendations to reduce noise on these lines: install hinged transparent shields along the sides of the wire-mesh safety guards to reduce noise radiation, and install solid-metal covers with a lower layer of well-protected, sound-absorbing material above the lines to further reduce noise escaping from specific noisy lines.

Figure 8. Common power generation plant types.

This manufacturing plant included many roof/ceiling-mounted propeller ventilation fans that contributed to the noise level throughout many areas of the plant. Installing commercially available tubular mufflers between the fans and lower workspaces was recommended to reduce noise from these fans.

The noise reduction program in selected noisy areas of this manufacturing plant continues as time and budgets permit. The plant owner is pleased with the program and reported that noise reductions of 2-11 dBA have been achieved to date.

Industrial Power Generation Equipment

Progress in noise reduction in the power generation industry – including improved designs for fans and transformers – has been coming to wide-ranging types of plants. Local residents and workers alike are benefiting from steps being taken for sound attenuation. Regulatory requirements put in place by OSHA and state and local authorities are driving forces in noise control in new plants, along with changing community and worker expectations.

With deregulation of the power generation industry a couple of decades ago, new players including low-cost companies stiffened competition in the industry, increasing pressure to manage costs such as capital and operating costs and, in turn, protect profits. Significant advances have occurred to benefit the noise environment and preserve acoustic integrity, which oftentimes is value-engineered out of projects. Plant control and monitoring systems, though not direct noise technologies themselves, have achieved noise reduction by avoiding issues associated with unnecessary steam releases and inefficient operation of equipment within the plants.

Industry trends over the past decades included, for example, changing fuel mix from coal to oil and then back to cleaner coal designs; and extending the operating life of many existing nuclear power plants, which continue to provide significant electrical capacity.

Various plant types are shown in Figure 8. These include the classic coal-fired power plant that is located by a river or lake for fuel delivery and heat exchange and relies on stacks for air and gas movement. To achieve this movement, very large fans are required, including forced-draft fans, induced-draft fans, and sometimes combustion air fans.

About 20 years ago, the gas-fired combined-cycle plant became popular. This plant uses what has been referred to as an industrial turbine, which resembles a jet engine and which, combined with a heat recovery steam generator, is highly efficient at generating electricity. A power generator supported by many communities today is a combined heat and power plant, and in some cases, also a cooling plant with steam absorbers. The plant is located within the community, near the actual demand, eliminating the need for major transmission lines. Finally, wind turbines represent another power generation alternative that can have associated noise.

Some primary noise sources in various types of plants are shown in Table 2, with overall sound power level estimates normalized to a plant rating of 100 MWe. Coal-fired plants are near the top in terms of noise, up to about 123 dBA. The simple-cycle turbine plant is at 100 dBA, and the combined-cycle plant at 94 dBA (with noise control measures in place). With additional noise reduction steps, the gas turbine combined-cycle plant emits noise at only about 89 dBA, a modest amount for generating that much electricity. As for wind turbines, at about 109 dBA, this highly distributed energy source produces a great deal of sound on a per-megawatt basis.

At combined-cycle turbine power plants, sources of noise can include fuel gas flow as it enters the site; an on-site fuel gas compressor; a enclosed combustion turbine generator (typically indoor); a heat-recovery steam generator that could be either indoor or outdoor; an air-cooled condenser or wet-mechanical-draft cooling tower with very large fans; and electricity that exits and travels to step-up transformers.

Neighbors living relatively nearby benefit from any noise reduction steps put in place, and workers have benefited from some protections, such as locating high-level noise sources in their own isolated rooms and designing effective enclosures for combustion turbines.

Owners interested in improving plant interior sound have options for attenuation. For example, acoustic blocks can be used in place of concrete masonry units (CMUs). In smaller plants such as those used for hospitals, universities, and research facilities, treated ceilings are becoming more common. And sound absorption can also be considered when a steel roof deck is selected.

Variable-frequency drives (VFDs) designed for maximum loads can effectively reduce noise. Rather than choking everything down with flow control devices, one can slow the machine and get dramatic reduction with both less noise and lower energy use. Pumps and fans, in particular, can benefit from this approach.

Packaged cooling towers are typically quieter with wider-chord fans, benefiting from fans running at slower tip speed while still delivering the necessary amount of air. The potential downside: these towers shift the sound spectrum so that more distant neighbors may be exposed to additional lower-frequency sound.

Sound from reduced-speed fans and low-noise fans is illustrated on Figures 9 and 10. Reducing from full speed to half speed – following fan laws, at about 55 times the log speed ratio for a packaged tower – the blade passing frequency and its second harmonic drop significantly, and as expected, the overall level reduces from 94 to 76 dBA. By switching to low-noise fans (for example, by moving from 12 blades to 6 more aerodynamic ones), real reduction can be achieved even while maintaining the same fan capacity.

Table 2. Sound power levels for various power plants.

Plant / Equipment Type	LwA (dBA)*	Notes
Coal-fired	103 - 123 w/coal delivery	Add heat exchanger and transformers
Diesel engine, simple cycle	103	Add transformers
Gas turbine, simple cycle	100	Add transformers
Gas turbine, combined cycle	94	Add heat exchanger and transformers
Gas turbine, combined cycle (with significant treatment)	89	Add heat exchanger and transformers
Nuclear	90	Add heat exchanger and transformers
Hydroelectric	<80	Add transformers
Geothermal	<100	Add heat exchanger and transformers
Ocean thermal	<85	Add transformers
Biomass and waste	103 - 114 w/fuel delivery	Add heat exchanger and transformers
Landfill methane gas capture	103	Add transformers
Solar, thermal	<85	Add heat exchanger and transformers
Solar, PV	<<80	Add transformers
Wind, 100 MWe (whole project)	120	Add transformers
Wind, 75 MWe (estimate effective at receptor)	105	Add transformers

*A-weighted sound power levels normalized to 100 MWe plant with typical noise mitigation treatment

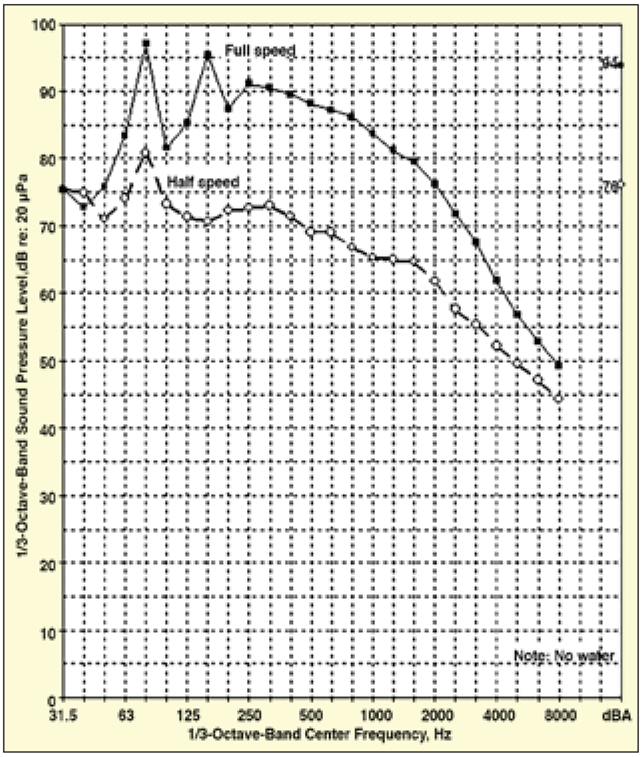

Figure 9. Sound measurements: reduced-speed fans.

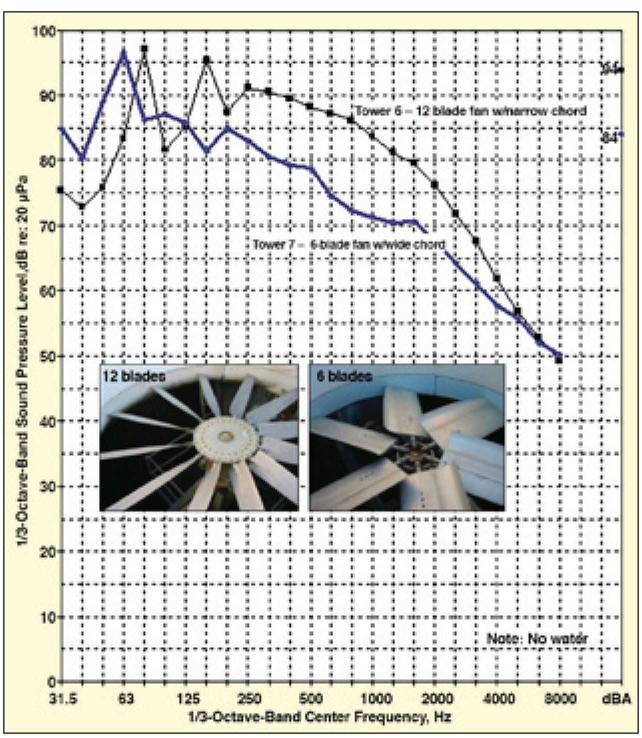

Figure 10. Sound measurements: low-noise fans.

Reduced-noise transformers with their more aerodynamic fan designs and improved internal core and external casing constructions are achieving the sound reductions as reflected in Figure 11. Close in, the average overall sound level was on the order of 63 dBA with all fans operating, compared to the standard NEMA "benchmark" level of 77 dBA. Efficient transformers are achieving much lower sound levels than standard NEMA levels, as people have become willing to pay an up-front premium to achieve the energy saving payback over time. Improved transformers designed and built for low noise – perhaps 5 to 10 dBA or more quieter – are now available.

As for wind turbines, the design has been improved by placing blades upwind of the tower to avoid the "siren" effect inherent

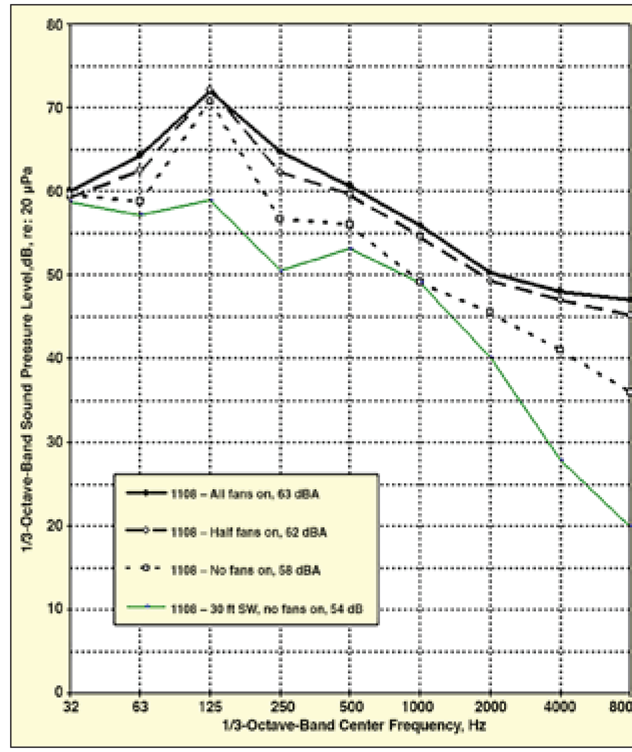

Figure 11. Efficient transformers emitting less noise.

with the obsolete downwind turbine; using quieter gearboxes; improving the design of the nacelles containing the gearboxes; improving the blades (using a serrated blade on the trailing edge, for example); and improving monitoring so that pitch and yaw can be better controlled.

For the future of industrial power generation, smaller plants will become more common; regulatory pressures will be ongoing; and people will be willing to pay more for noise control. Also, a quieter work environment could potentially raise productivity, communication, and the ability of workers to identify steam leaks and other equipment failures.

Classroom Acoustics

Imagine that you are a teacher or a student. Now imagine that your classroom or lecture hall has poor acoustical conditions leading to poor speech communication. Perhaps the classroom is rather reverberant. Or perhaps the classroom has excessive background noises. Or worst yet, perhaps both are leading to less than desirable speech intelligibility. How can teachers be expected to teach effectively, and can students be expected to learn in an environment without good listening conditions where speech intelligibility is compromised?

It is well known that proper acoustic environments help students comprehend, learn, and retain classroom instruction. A good acoustic environment is, of course, particularly important for young students and those students where English is their second language, students with learning disabilities, students with hearing impairment, and students at school with a head cold. While this is intuitively obvious, it is reasonable to first mention some of the causes of poor acoustical conditions found in many classrooms. Fortunately, reasonable steps are available to correct problem conditions in support of good speech intelligibility.

Classroom Background Noise. Undesirable background noises in classrooms can be caused by poorly designed, located, and installed heating, ventilating, and air conditioning mechanical systems (HVAC); sounds from adjacent classrooms and hallways; and outside environmental noise entering the classroom from nearby highway, train, and aircraft traffic. Without adequate controls, such background noise degrades speech communication between teachers and students. To achieve good speech intelligibility, it is necessary for background noise levels to be significantly lower than the sound levels of a teacher's voice for all students throughout the classroom from front to rear.

Outside to Inside. It is good practice to not locate facilities for learning in areas with high levels of environmental noise. The current levels of exterior noise can be checked with environmental noise measurements performed by a knowledgeable experienced professional as an element of site-selection studies. It is reasonable to expect some increase in highway traffic noise levels during the life of the school. Buildings should include external walls, roof, and windows designed and installed to achieve an outdoor-to-indoor transmission class rating selected to adequately reduce airborne environmental noises into classroom spaces.

HVAC Equipment. Without proper attention by a qualified professionals, HVAC equipment is apt to cause unwanted and unnecessary background noises that are disruptive to speech communication. Good acoustical practice in the design of HVAC systems includes:

- Locate HVAC equipment away from classrooms.
- Avoid connecting classrooms with ductwork without suitable muffling.
- Limit velocity of airflow in ducts and into classrooms, and employ low-noise grilles/diffusers.
- Include duct linings or mufflers where determined to be necessary.
- Avoid use of window- and wall-mounted units.
- Specify equipment for low noise operation.
- Vibration isolate equipment from the building structure.

Classroom Reverberation. Reverberation refers to the buildup and persistence of sound as it reflects between hard surfaces in an enclosed space. Room reverberation time refers to the time in seconds for a sound to decay by 60 dB after the sound stops. Good speech communication depends on each of the distinct sounds in individual words that are spoken one after the other. Excessive reverberation causes an overlapping or smearing of word sounds. That is the sounds of words interfering with each other, one word after the other. This reduces speech intelligibility for all students in the classroom. An indoor swimming pool is an example of a highly reverberant space. Essentially all of the surfaces are highly reflective.

Excessive reverberation is controlled with the installation of commercially available sound absorbing wall panels, such as rigid glass fiber covered with fabric, and acoustical tile ceilings. Carpeting will not provide much help in reducing reverberation but it will help reduce the noise of students moving their chairs.

Classroom Acoustical Standard. Fortunately, ANSI/ASA Standard S12.60 *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Parts 1 and 2,* provides the information identified below from the standard's abstract:

> *This document is Part 1 of the ANSI/ASA S12.60 series and is applicable to classrooms and other learning spaces in permanent schools. Part 2 of the ANSI/ASA S12.60 series is applicable to relocatable classrooms and relocatable modular core learning spaces. This standard includes acoustical performance criteria, and design requirements for classrooms and other learning spaces. Annex A provides procedures for optional testing to determine conformance with the source background noise requirements and the noise isolation requirements of this standard. Annex B provides commentary information on various paragraphs of this standard. Annex C provides guidelines for controlling reverberation in classrooms.*

This standard is intended for use by school design professionals, architects, building specialists, educators, and parents. Electronic copies of the National Classroom Acoustics Standard ANSI/ASA S12.60 Parts 1 and 2 and additional materials are available at no cost from the Acoustical Society of America Standards Store.

Flexible Teaching Environments. Flexible environments where learning spaces are semi-open or completely open with multiple learning "class bases" can lead to intrusive noises between adjacent class bases, further increasing background noise and distractions. What to do? Some people advocate that semi-open or completely open classrooms should be avoided in favor of quieter closed classrooms. Others[7] with interests in flexible environments advocate the following:

- *The more students you have in one space, the more noise there will be.* A semi-open plan unit should have no more than three learning class bases. The class base openings should always connect to a shared common area rather than directly to another classroom. Too many adjacent class bases means more noise intrusions that the teachers cannot control.
- *Can you hear me now?* The students sitting farthest from the teacher (and typically closest to the room opening) will have the hardest time hearing the teacher and other students. For critical listening activities when adjacent activities are not coordinated, students should be gathered closely around the teacher, away from the opening of the class base.
- *Coordination between teachers.* Learning activities involving movement, in particular with different technology/work stations, should be coordinated between the class bases in a unit. Otherwise the students seated closest to the opening will be distracted by the intrusive noise next door. How is the teacher in one class base going to make the students do the math problems when they can go next door and have fun with the other students?
- *Design an acoustically dry learning space.* Reverberation time of the entire learning unit should not exceed 0.4 seconds for students to hear well in a busier and noisier learning environment. This is lower than the requirement of 0.6 seconds established by ANSI-S12.60 (Classroom Acoustics Standard) for typical classrooms with normal hearing students. The purpose of such a low reverberation time is to reduce the transmission of student-generated noise. The most effective solution is to provide a highly sound-absorptive ceiling and acoustical wall panels. Carpet does not significantly absorb sound, but it will help reduce footfall and noise from chair movement.
- *Just because they can't see you, doesn't mean they can't hear you.* Consider designing the semi-open class bases with the option to be fully enclosed when the teacher finds it necessary. This can be accomplished by installing operable partitions at the opening of each class base and having full-height stud walls for the demising walls. The type of walls and operable partitions separating the learning spaces should achieve appropriate STC ratings as addressed in ANSI-S12.60, especially for buildings that are designed to meet LEED (Leadership in Energy and Environmental Design) for Schools or CHPS (Collaborative for High Performance Schools).
- *The HVAC system should be quiet.* Why let additional intruding noise sources get in the way of education? With careful space planning and good designs early on, most HVAC noise can be avoided.
- *Don't risk it for special education.* Special-needs education students need quieter and physically separated spaces more than the average students. If you know your school has a high percentage of special-needs students, consider a more traditional fully enclosed classrooms.

References

1. Portions of this article originally appeared in the January 2015 issue of *The Construction Specifier*, the official publication of CSI, http://www.constructionspecifier.com. Portions also appear in reports documenting Technology for a Quieter America workshops hosted at the National Academies' Keck Center, Washington, D.C., www.inceusa.org. Portions also originally appeared in the May 2014 issue of *School Planning & Management* magazine, published by 1105 Media, Inc., https://webspm.com/home.aspx.
2. *Transit Noise and Vibration Impact Assessment*, www.fta.dot.gov/documents/FTA_Noise_and_Vibration_Manual.pdf, FTA VA 90-1003.
3. J. Zalfe, *et al*., "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit," Transit Cooperative Research Project D-12, December 2009.
4. *Technology for a Quieter America*, National Academy of Engineering, Washington, DC, National Academies Press, 2010, http://www.nap.edu/catalog.php?record_id=12928.
5. *Reducing Employee Noise Exposure in Manufacturing: Best Practices, Innovative Techniques, and the Workplace of the Future*, INCE/USA, 2014.
6. *Engineering a Quieter America: Progress on Consumer and Industrial Product Noise Reduction*, INCE/USA, 2015.
7. Rose Mary Su and Julia McFadden, *Do Classrooms Have To Be Designed A Certain Way?* School Planning & Management, May 2014.

The authors can be reached at: bmarkham@acentech.com or jbarnes@acentech.com