

# Noise control solutions for indoor firing ranges<sup>1)</sup>

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**Peak sound pressure level measurements conducted at indoor firing ranges ranged from 157–168 decibels (dB). Exposure to high-intensity impulsive noise during target shooting at indoor firing ranges has been identified as a significant contributor to noise-induced hearing loss among shooters. In addition, firing ranges that are constructed with adjacent areas or housed within a larger building structure require minimal sound transmission to occur outside the firing range. Several principles of noise control engineering can be applied to improve the absorption of impulse noise inside the firing ranges and limit the transmission of such impulses to adjacent areas and spaces. Although little can be done to control the direct exposure of shooters to the firing of their own firearms, several noise control solutions are presented to reduce the secondary exposure off reflected surfaces and from other shooters. This paper will provide a general overview of noise control solutions aimed to improve sound absorption inside the firing range and reduce the transmission of airborne and structural-borne sounds to adjacent areas and facilities. © 2010 Institute of Noise Control Engineering.**

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## 1 INTRODUCTION

Indoor firing ranges are frequently used by law enforcement and recreational shooters because they offer protection from inclement weather conditions and can be operated around the clock under controlled environmental conditions. The National Institute for Occupational Safety and Health (NIOSH) estimates that 16,000 to 18,000 firing ranges operate in the United States. The Bureau of Justice estimates that there are more than 1 million federal, state, and local law enforcement officers in the United States who regularly train in the accurate and proficient use of firearms<sup>1</sup>. The National Association of Shooting Ranges estimates that 40,000–60,000 workers are directly employed as instructors and range masters<sup>2</sup>. The National Shooting Sports Foundation estimates

that 20 million active target shooters use firing ranges for practice or competition<sup>3</sup>. However, many firing range facilities lack adequate environmental and occupational controls to protect the health of shooters and range personnel from the effects of airborne lead, carbon monoxide (CO), noise, and other potentially harmful exposures. Although lead and CO exposures pose greater long-term health risks, this paper will concentrate on noise control solutions to reduce exposure to impulse noise at indoor firing ranges.

The discharge of weapons produces impulse sound levels that often exceed the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) and the NIOSH recommended exposure limit (REL) of 140 dB peak sound pressure level<sup>4,5</sup>. The International Organization for Standardization (ISO) 1999:1990, and the American National Standards Institute (ANSI) S3.44-1996 also state that no exposure should be permitted if the peak C-frequency-weighted sound level exceeds 140 dB<sup>6,7</sup>. Exposure to impulse noise can cause acute acoustic trauma, which can be followed by symptoms such as tinnitus and temporary hearing impairment<sup>8,9</sup>. Exposure to impulsive sounds that exceed a critical sound pressure level may cause direct mechanical damage to the inner ear and sudden hearing loss<sup>10,11</sup>.

NIOSH has conducted several health hazard evaluations (HHE) of firing ranges for federal and state law enforcement agencies. The evaluations examined the potential risks posed to law enforcement officers who

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### 2.1.3 Roofs and ceilings

Firing range roof construction may vary based on the requirements of adjoining facilities. Typically, roofs are constructed from steel joists or precast concrete panels with a smooth flat surface that will redirect misfired bullets, facilitate maintenance, and prevent lead buildup. Roofs made of steel joists require that a safety ceiling or ceiling baffles be installed to redirect stray bullets and prevent back splatter.

### 2.1.4 Adjoining areas

Many indoor firing ranges provide additional spaces such as a cleaning room for weapons, a classroom, restrooms (including shower facilities), office areas, lounge area, or storage and maintenance rooms. Design considerations must include measures to maximize sound transmission loss between the firing range and the adjacent spaces.

### 2.1.5 Passageways and doors

Passageways are used to physically isolate the firing range from the adjoining areas. Passageways can also serve to reduce sound transmission through the use of acoustically treated walls and self-closing doors.

## 2.2 Physical Components

### 2.2.1 Shooting booths

Some firing ranges are equipped with shooting booths to provide shooters with a defined firing area and to reduce potential hazard from misfires and ejected bullet cartridges from other shooters. Shooting booths are made of partitions or panels which can be acoustically treated to reduce the effect of weapons discharge on shooters. The booths may be equipped with communication or target-operation equipment; target or booth lighting controls; shelves for holding weapons and bullets, or to prevent shooters from going downrange; and equipment for practicing shooting from behind a barrier. The firing line runs along the downrange edge of the shooting booths, and some ranges have detector equipment which sets off an alarm when a shooter passes this line during shooting. Some shooting booth panels are removable to allow for maintenance and service of communication and control systems.

### 2.2.2 Control station

The control station houses the central controls for the firing range equipment, communication, lights, and security. The controls are operated by the range master—the designated official responsible for range operation and management. The control station must



*Fig. 2—A typical control booth overlooking the operations and controls of a 20-lane indoor firing range.*

provide the range master with unobstructed line of sight of the firing lanes and all shooters. Control stations are usually constructed of concrete blocks with bulletproof observation windows. Figure 2 shows a control booth layout for a 20-lane indoor firing range.

### 2.2.3 Backstops and bullet traps

Backstops and bullet traps are used to absorb the energy from the bullet and capture it. Bullet traps come in a variety of designs and are usually constructed of impenetrable metal plates. The thickness of the plates and the materials used depend on the velocity and energy levels of the projectiles to be fired in the range. Most modern traps consist of angled hardened steel plates that deflect the bullets into other metal plates to remove their energy. The plates must be resistant to penetration, abrasion, and metal fatigue. The traps direct the spent bullets to a collection area in front of the trap or, for high-energy projectiles, at the back of the trap. Figure 3 shows an escalator-type bullet trap with rubberized and hardened steel plates; the bullets are collected through the opening between the plates into a collection tray.

### 2.2.4 Target systems

Target systems consist of a target, a target carrier system, and a target control system. Targets for indoor firing ranges are usually a paper sheet or piece of corrugated cardboard with a printed target image on the sheet. The target carrier system allows the firing range to operate more efficiently and safely by transporting the target and frame between the firing line and the target line, in both downrange and uprange directions. The target control system allows the range master to control the operation and movement of the targets through a central control station in the control booth. Some firing ranges provide local control modules that can be operated in the shooting booths.



*Fig. 3—An escalator-type bullet trap with rubberized and hardened steel plate. The bullets are collected through the opening between the plates into a collection tray.*

### 2.2.5 Baffles/deflectors/shields

Baffles are typically constructed of armored plate steel covered with fire-rated plywood and are installed at a 25–30 degree angle measured from the horizontal plane of the ceiling. Baffles are used to protect ceilings, lighting fixtures, ventilation ducts, and any other unprotected element from stray bullets. Deflectors are similar to baffles, but are not usually covered with plywood; they can be installed either vertically or horizontally and are used to redirect stray bullets from unprotected fixtures and elements inside the firing range such as doors, windows, and ventilation registers. Shields are constructed of plate steel and plywood and form a special safety ceiling located directly above the firing line up to 12 feet downrange. Figure 4 shows ceiling baffles used to protect the lighting fixtures and ventilation ducts inside the 20-lane indoor firing range.

### 2.2.6 Windows

Windows present a special challenge to controlling noise inside the firing range and limiting sound trans-



*Fig. 4—Ceiling baffles used to protect the lighting fixtures and ventilation ducts inside the 20-lane indoor firing range.*

mission to adjacent areas because they provide less transmission loss than typical wall structures. However, windows are essential in the control booths and other master control operations. Special attention must be paid to the acoustic rating and bulletproof requirements of windows.

## 2.3 Operational Components

### 2.3.1 Ventilation system

The ventilation system is a critical component of the design of an indoor firing range. Proper ventilation reduces shooters' exposure to airborne lead and other combustion byproducts. Ventilation systems consist of supply and exhaust air systems and associated ductwork. Supply air can be provided through a perforated wall plenum or radial air diffusers mounted at ceiling height. Airflow along the firing line should be no more than 0.38 m/s (75 feet per minute, fpm) with a minimum acceptable flow of 0.25 m/s (50 fpm)<sup>16</sup>. Air is typically exhausted at or behind the bullet trap. Some firing ranges are designed to have multiple exhaust points downrange to maintain downrange flow and desired velocities at the firing line. The exhaust system should be designed to provide minimum duct air velocities of 12.70–15.24 m/s (2,500–3,000 fpm) (Industrial Ventilation Manual, 25th Edition, Table 3–2)<sup>17</sup>. The equipment and designs for the ventilation systems are varied, most firing ranges have one supply and one exhaust fan, however, some have multiple supply or exhaust fans. Very often, the air-flow rate required by the firing range and space constraints for the fans dictate the number and types of fans. Most firing ranges have systems that supply 100% outside air to the firing range and exhaust all of the air to outside the building; but, some firing range ventilation systems are designed to recirculate some of the exhaust air to the supply air system. The exhaust air from most ranges is filtered before being exhausted outside the building or recirculated to the supply system.

### 2.3.2 Lighting

Lighting in the range consists of control booth, uprange area, shooting booth, and downrange lighting systems. Control booth lighting is usually manually controlled and consists of general lighting and low-level lighting used during particular shooting conditions. Lighting uprange of the booths is general ceiling-level lighting and can usually be controlled manually or from the central controls. Lights downrange of the firing line are usually spotlights used to illuminate the targets at various distances downrange of the booths.

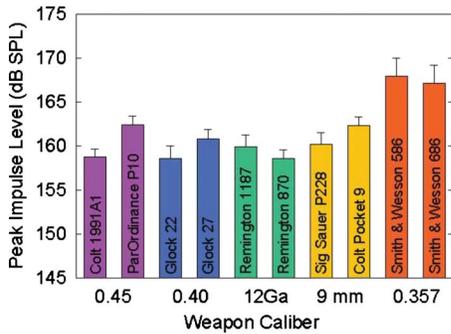


Fig. 5—Measured peak sound pressure levels from a selection of small-caliber firearms. Peak impulse levels range from 157 to 168 dB SPL. The error bars represent one standard deviation for an  $N = 170$  (34 conditions times 5 shots/condition).

### 2.3.3 Safety control systems

Safety control systems are installed to protect the shooters during range malfunction or emergency situations. Such systems may include warning lights, alarm bells, and air-flow and filtration monitors.

## 3 NOISE CONTROL ENGINEERING SOLUTIONS

NIOSH investigators conducted several assessments of indoor firing ranges to identify the salient acoustic

parameters associated with typical live-firing sessions and provide noise abatement recommendations. Peak sound pressure levels measured inside the firing range during a live firearms training exercise ranged from 157 to 168 dB (unweighted) and equivalent sound levels (Leq) of 122 dB (A-weighted). Figure 5 shows the measured peak sound pressure levels obtained at ear level and six feet to the right of the shooter. Figure 6 illustrates the one-third octave band spectra from a selection of small-caliber firearms measured at the same position those in Fig. 5. The ventilation system alone generated sound levels between 75 to 85 dBA. It is important to note that these investigations also highlighted the limitations of current noise measurement equipment (i.e., noise dosimeters and sound level meters) to make accurate measurements in predominantly impulsive noise environments<sup>18</sup>. Special attention must be paid to the use of instrumentation and specialized data acquisition systems that are capable of measuring the type of impulse sounds generated from firing weapons.

An effective hearing conservation program should be implemented for all personnel who use a firing range as a condition of their employment. The program should be designed to meet the minimum requirements set forth in the OSHA noise regulation (29 CFR 1910.95). Included in the requirements of a hearing conservation program are certain key elements such as noise exposure monitoring, audiometric testing, engineering and administrative controls, hearing

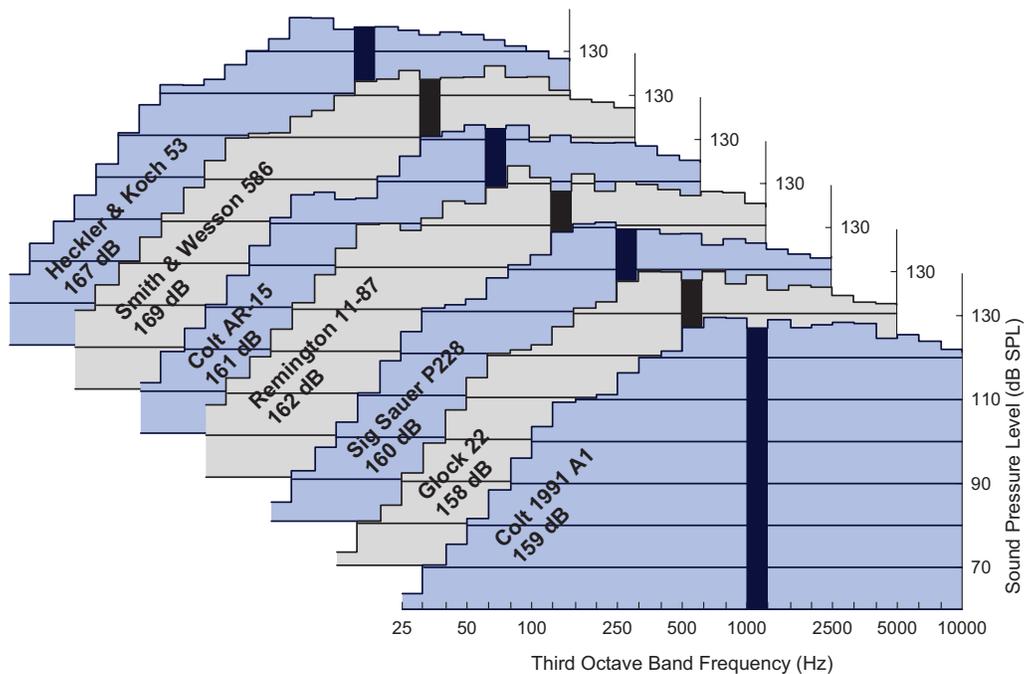


Fig. 6—One-third octave band spectra collected from several types of weapons for 43 millisecond (m)s samples of the initial impulse event. Each spectrum is offset to demonstrate the general character of a small-caliber weapons discharge. Most spectra have a maximum level at about 600 Hz and a change of not more than about  $-10$  dB in the frequency bands above 600 Hz.

*Table 1—Noise reduction coefficient of some common building materials and absorptive materials used at indoor firing ranges.*

Sound absorption coefficient ( $\alpha$ )							
Common Materials	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	NRC
Concrete block (Painted)	0.10	0.05	0.06	0.07	0.09	0.08	0.05
Concrete floor	0.01	0.01	0.01	0.02	0.02	0.02	0.00
Glass	0.18	0.05	0.04	0.03	0.02	0.02	0.05
Plywood	0.28	0.22	0.17	0.09	0.10	0.11	0.05
Absorptive Materials	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	NRC
2" Acoustic ceiling tile	0.13	0.74	1.26	1.18	1.12	1.03	1.10
2" Acoustic ceiling baffles/banners	0.38	0.64	1.28	1.60	1.50	1.12	1.25
1" Acoustic wall panels	0.11	0.30	0.77	1.02	1.00	1.00	0.85
1" Absorptive noise barrier	0.12	0.47	0.85	0.84	0.64	0.62	0.72
1.5" Acoustic steel ceiling deck	0.13	0.55	0.79	1.01	0.53	0.25	0.70

protection devices, education and motivation, and record keeping.

This paper will only examine noise control techniques that can be used to improve sound absorption within the firing range and to reduce sound transmission to adjacent areas by addressing the transmission of airborne and structural-borne sounds. It is important to understand that such noise control techniques and solutions might help reduce overall noise levels inside a firing range and adjacent facilities, but it has limited effect on the noise exposure of the person firing the weapon. Although the use of silencers and other weapon modifications have been shown to reduce the noise emissions generated from small firearms, the overall noise reductions are not significant enough to eliminate the need to wear hearing protection<sup>19,20</sup>.

### 3.1 Sound Absorption

Sound absorption inside the firing range can be improved through the design of acoustically treated walls, floors, and ceilings and the application of absorptive materials to existing structures and elements within the firing range. Table 1 compares the absorption coefficients for some common building materials versus some absorptive materials used inside firing ranges. Note that NRC values higher than 1.0 are provided because the testing of the materials does not take into account diffraction effects at the edges of the material samples.

#### 3.1.1 Interior wall treatments

Indoor firing ranges are typically quite reverberant given that the floor and walls are usually made of concrete and the ceiling may be made of prefabricated slabs or metal sheets. To reduce the reverberant noise

resulting from the blast of ammunition, sound-absorbing products have been installed in firing ranges. These products have been found to be effective in helping a shooter receive less noise from other shooters' weapons by reducing noise reflections from the walls, floors, and ceilings. Reduced reverberant energy will increase speech intelligibility in the range. Reverberation times in poorly treated ranges can easily exceed an  $RT_{60}$  of 3 seconds whereas treated walls and surfaces can reduce the  $RT_{60}$  to between 1.5 and 0.7 seconds. Given the similarity of the spectra from various weapons shown in Fig. 6, the design of absorptive elements in the wall can help to minimize the reflected impulses independently of what weapons are used.

Sakamoto et al.<sup>21</sup> investigated the design of perforated panels and rib/slit structures and placement of absorbers within the wall cavity as well as the separation of the panel and absorber from a backing wall. Nominally, the slits were 10 centimeters (cm) wide and spaced 25 cm on center. The absorptive layer was most effective when placed directly behind the slits with an air cavity between it and the backing wall as shown in Fig. 7. The absorptive cavity principally relies on the Helmholtz resonator. The dimensions of the ribs and slits could be optimized to create the first resonant peak in the 500 to 1000 Hz region. A thicker absorptive layer increased the calculated absorption coefficient near the Helmholtz resonance. Varying the depth of the slit enhanced the resonant peak but reduced absorption in the adjacent frequency regions. If the choice is to use a perforated panel, then absorptive backing should be positioned against the panel and an air space provided. Kristiansen and Vigran<sup>22</sup> demonstrated that increasing the airflow

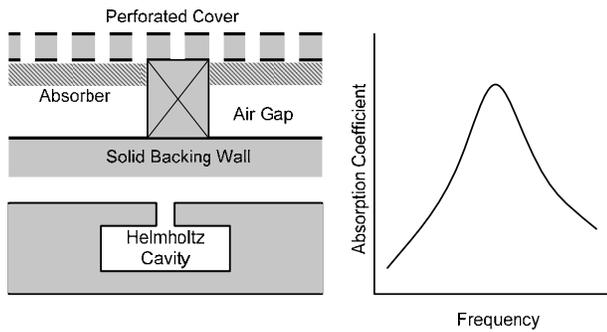


Fig. 7—An example of a resonant cavity, where an absorber is placed directly behind the slot to enhance the performance of the cavity loss.

resistance of the absorptive layer substantially increased the absorption coefficient at the resonant frequency of the Helmholtz slit resonator.

### 3.1.2 Ceiling treatments

Acoustic materials have been applied to the plywood of the safety ceiling shield directly above the firing line and have been shown to be effective in reducing the noise from weapons discharge. Several manufacturers supply acoustically treated safety ceiling panels and baffles that are fire-rated and have excellent sound absorption at 500 and 1000 Hz (sound absorption coefficient between 0.73 and 1.0). Some manufacturers supply perforated-steel acoustic decks that can be used for the construction of roofs and ceilings. The acoustic decks come in different thicknesses and can achieve an NRC from 0.65 to 0.90 while providing the required vertical and horizontal load resistance. The noise absorption coefficients for the 1 1/2" deck is provided in Table 1. Figure 8 shows a cross diagram of the acoustic deck design.

### 3.1.3 Shooting booth treatments

The construction and installation of shooting booths made from hardened fiberglass and the application of absorptive materials have limited the noise from weapons discharge on other shooters. The generated



Fig. 9—State-of-the-art design configuration for shooting booths with clear bullet-resistant, acoustically treated fiberglass panels, and local target and lighting controls.

impulse sound would have to travel around the partition or reflect from the ceiling to reach other shooters. The installation of absorptive ceilings or absorptive panels directly above the shooting booths also serves to limit the reflected noise. Figure 9 shows a state-of-the-art design configuration for shooting booths—clear bullet-resistant, acoustically treated, fiberglass panels with local target and lighting controls.

It is important to note that some acoustical materials and products may be incompatible with the lead found in firing ranges. One characteristic of some sound-absorbing materials is that they are made of soft, porous materials designed to trap noise energy. However, these types of materials can also be effective in trapping and accumulating lead. The types of noise control materials used in firing ranges have to take into account this potential lead contamination. Carpets on the floor of indoor ranges are effective in reducing sound reverberations, but they also become contaminated by lead fairly quickly. Routine vacuuming of the carpets will not eliminate this lead contamination. A rubberized flooring material that has sound deadening properties is more easily cleaned to eliminate the lead hazard. Ceiling panels that show obvious contamination (dark patches) should be replaced when needed. The plate steel used in bullet traps at the end of the

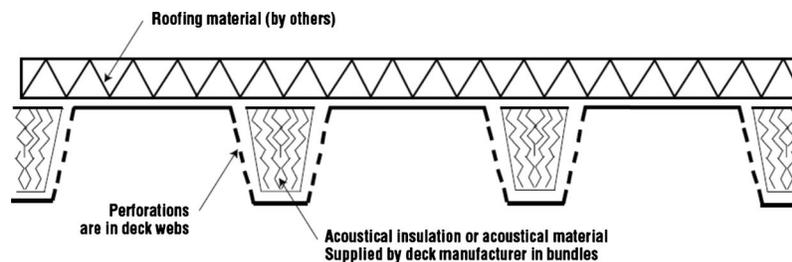


Fig. 8—A cross-sectional diagram of the perforated steel acoustic deck used for constructing roofs and ceilings.

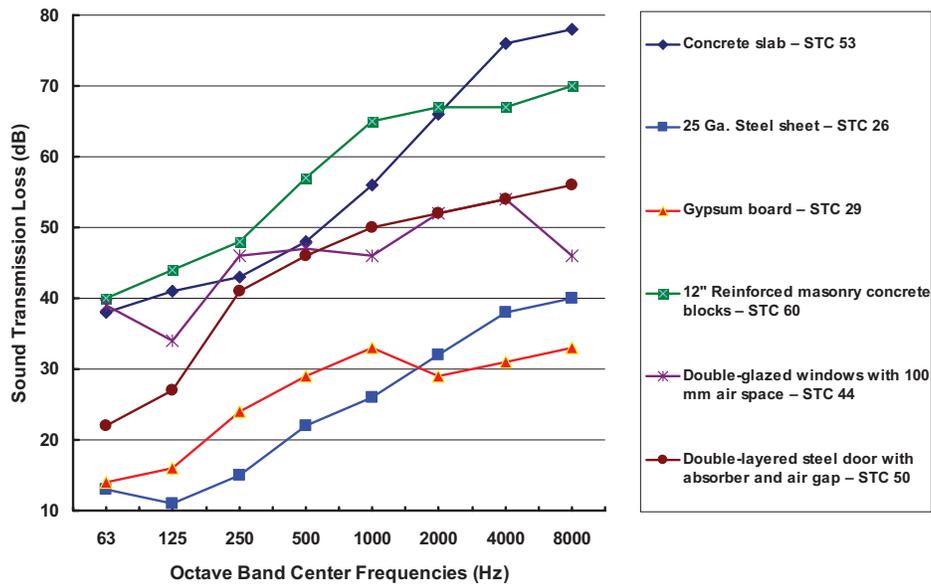


Fig. 10—Sound transmission loss and the STC of some common building materials and acoustically treated elements that can be used to improve sound transmission loss at indoor firing ranges.

range can be replaced with composite metal and plastic products that do not continue to “ring” after being struck by a bullet.

### 3.2 Sound Transmission

Sound transmission between the firing range and other parts of the building structure occurs when the sound waves generated from the discharge of weapons travel through the air and impact the surface of the walls, ceiling, floor, doors, and windows that separate the firing range from the adjoining spaces. In order to provide significant improvement in noise reduction from the firing range into the adjacent spaces, it is necessary to treat both the direct sound transmission paths and all flanking paths. The sound transmission class (STC) method has been developed to assign a single value to the one-third octave band TL data<sup>23</sup>. Figure 10 shows the sound transmission loss and the STC of some common building materials as well as acoustically treated elements that can be used to improve sound transmission loss at indoor firing ranges.

#### 3.2.1 Wall construction

The design and construction of the adjoining walls are critical to making the adjacent rooms usable. In the ranges studied by NIOSH, peak sound pressure levels ranged from 157 to 168 dB depending on the position of the measurement. Sound pressure levels in adjacent areas reached 136 dB in the control booth, 115 dB in the classroom, 110 dB in the cleaning room, and 108 dB in the office. Figure 11 shows octave band sound levels measured in one of the firing ranges and its adjacent areas.

In one of the ranges, the adjoining wall consisted of a concrete block wall that did not extend completely to the roof and was common with both the control room and the classroom. The transmission loss for a simple concrete block wall should have provided nominally 45–50 dB noise reduction between 500 and 1000 Hz.

In order to maximize transmission loss from walls, design considerations should address the construction of wall structures from a combination of mass elements, air gaps and absorptive materials. Several papers examined the transmission of sound through layered wall constructions. Allard et al.<sup>24</sup> demonstrated that a single layer of wall with an air gap and a layer of absorptive batting provided superior performance when compared to the same wall without an air gap. Bolton et al.<sup>25,26</sup> showed that the use of two panels, one layer of absorptive material, and an air gap between the panels provided the greatest transmission loss. Though Bolton et al. examined a specific thickness of aluminum plates and urethane foam, the results should generalize to a broader class of wall construction. The best performance was achieved by having the foam layer bonded to one of the panels and an air space between the panel and the wall. If the common wall was built with wallboard and studs, then it should be double thickness with a gap between the two sets of studs, with added insulation and a mass-loaded septum to provide optimum transmission loss. The range side of the wall should be lined with plates of either steel or aluminum of  $\frac{1}{4}$ " to  $\frac{1}{2}$ " in thickness. For the purpose of calculating the behavior of the plates, these plates can be treated as thin plates for frequencies of interest, 20–20000 Hz. Constructing the wall with a single thickness of studs and

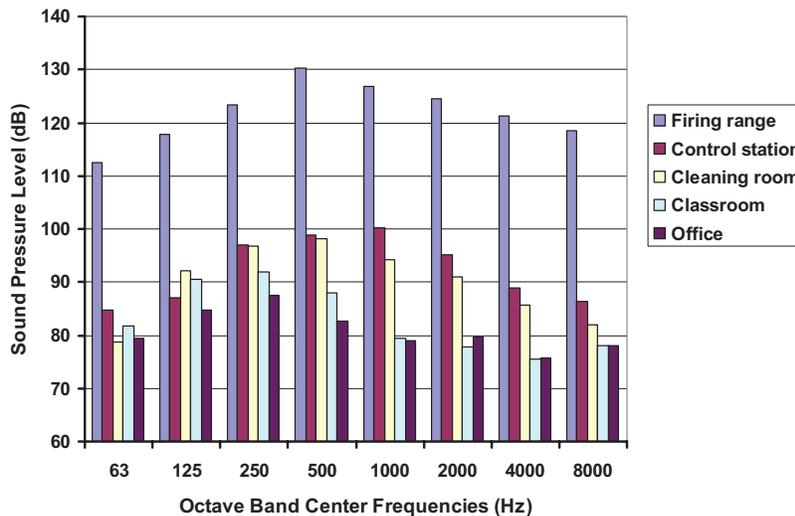


Fig. 11—Octave band sound levels measured in one of the firing ranges and its adjacent areas.

wallboard on both sides of a stud would be markedly less effective in attenuating sound. In this type of design, the airborne impulses from the range side will be directly transmitted through the studs to the wallboard on the other side. Also, the air volume in the wall cavities acts as a spring in a mass-air-mass resonance system. This type of system will have symmetric and asymmetric resonances. Adding the second stud wall decouples the two sides of the wall and increases the transmission loss. Filling one side of the wall with insulation serves two purposes: 1) sealing any leaks due to joints or cuts in the wall surface, and 2) creating a material through which energy will be lost through the friction process. Warnock and Quirt<sup>27</sup> measured an approximate STC of 63 for double-layered 13 millimeter (mm) drywall on both sides of a double stud construction with a 25 mm gap between the stud walls and cavity absorption.

The STC for a block wall with 65 mm steel studs on both sides of the block wall and fiberglass filling in the cavities was 72. The maximum transmission loss of 70–75 dB occurred in the 500–1000 Hz range. Because the use of plates may be necessary to stop errant shots, the plates could be attached with adhesive to the studs on the range side and fiberglass or cellulose filling placed in the cavity. To prevent direct transmission from the range stud-wall to the block wall, the studs should not be directly attached to the block wall. Although TL data for such walls only apply to continuous sounds, it is possible that the peak sound pressure level of an impulse sound of 150 dB can be reduced to less than 80 dB using this design.

### 3.2.2 Passageways and doors

A well-designed passageway serves many important functions, such as the physical isolation of the range's lead contamination traveling to adjoining spaces, and

maintaining negative pressure within the range, which is necessary to move exhaust gases down range and not into unintended spaces. The physical isolation is also critical to reducing sound transmission between the range, while in operation, and the adjacent areas. Any gains from the best-designed wall could easily be diminished if the passageway is poorly designed. For instance, a single solid core wooden door might have an STC of 28, considerably less than an STC of 72 for the wall described above. Warnock and Quirt<sup>27</sup> measured the greatest STC, around 50, for a double door passageway that has either two solid core wood doors or hollow steel doors with a 230 mm space with absorption. A longer passageway almost certainly guarantees that one of the doors will be closed at all times, keeping direct airborne transmission of the impulse sounds to a minimum.

The design of the doors can be improved to provide greater noise reduction. Hongisto et al.<sup>28,29</sup> developed a theoretical treatment for analyzing transmission through a multilayered door as well as measuring the effective leak of the door seals. The door that provided the best performance (STC of 48) was built with a layer of steel, an absorber, an air gap, another absorber and steel. Substituting the better door for the hollow steel doors on either end of the passageway ought to greatly improve the transmission loss performance of the passage. The seals around the door are critical to maintaining high noise isolation of the range. According to Warnock and Quirt<sup>27</sup>, the use of a magnetic seal will provide the best performance. The proper installation of doors is also critical to achieve high sound insulation, the doorframe must be well-fitted to the wall with no cracks or leaks, and the gaskets must be well adjusted.

### 3.2.3 Windows

In several of the ranges studied by NIOSH, the control booths had glass windows that permitted the range master an unobstructed view of the shooters (see Fig. 2). In one of the ranges, the adjoining walls had additional windows to the cleaning room and the passageways. The glass windows were designed to be bulletproof and be able to stop a 0.223 caliber round. Windows usually provide less transmission loss than the surrounding wall. It is always advantageous, from a noise control perspective, to reduce the size of the window as much as possible, or in some cases, eliminate the use of windows altogether if they are not critical to the operation of the range.

Glass, in general, obeys the "Mass Law" principle, where a linear relationship exists between the mass per unit area and the sound transmission loss typically over a range from the panel resonant frequency on the lower end to the one half of the critical frequency on the upper end. Laminated glass functions as a constrained layer damping system. Flexure of the glass plate sets up shearing within the damping layer of the glass. Some laminated glass exhibited transmission loss of 35 to 45 dB in the 500 to 1000 Hz region for an 11 mm thick sample of glass (4 mm glass, 1 mm polymethylmethacrylate layer, 6 mm glass)<sup>30</sup>. The thickness of two glass laminates should be different to avoid having the same critical frequency for each plate. Ford<sup>30</sup> measured the critical frequencies for the 7, 9, and 11 mm laminates to be 4260, 3075, and 2272 Hz, respectively. For a thicker laminate, the critical frequency could very likely fall in the region where the greatest transmission loss is desired. Therefore the design of the window must be carefully analyzed to optimize both safety and transmission loss. The frames and seals around the window are also important to obtaining excellent performance. The use of a lightweight frame can compromise the effort expended in installing laminated glass. In fact, one window layer could be installed in one of the walls and a second window layer in the other wall layer.

Double-glazed windows with at least 3 inches of airspace between the layers have been shown to be effective in reducing measured sound levels inside the control station to be below the NIOSH REL of 85 dBA.

In addition, to minimize vibration transmission from one pane of glass to the next (known as inter-panel resonance effect), the first and second glass layers should differ in thickness by 30–50%, should be mounted in resilient channels, and should be inclined slightly (not parallel) to reduce objectionable reflections. Proper installation and sealing of windows are critical elements to ensure optimum transmission loss performance.

### 3.2.4 Ventilation systems

Ventilation is the most important engineering control for protection against primary lead exposure in indoor firing ranges. Well-designed supply air and exhaust ventilation systems have been shown to control exposures to lead fumes and dust in firing ranges. However, the proper operation of two separate ventilation systems, several supply and exhaust fans, and the requirement to distribute 50–75 fpm of air at the firing line can generate significant noise inside the firing range and the adjoining areas. NIOSH measurements of ventilation system sound levels inside a firing range ranged from 77 to 84 dBA. Although these levels may not be considered hazardous to hearing, they can impede speech intelligibility and communication among shooters and between the range master and the shooters. In addition, impulse sounds can travel through the piping and duct system from the firing range to the adjoining areas.

Ventilation ducts that provide a direct acoustic path into adjacent spaces can be fitted with acoustic absorptive materials, both to remediate vibrations in the walls of the duct and to absorb noise transmitted along the duct. Duct lagging with 1" or 2" quilted fiberglass acting as decouplers/absorbers have been shown to provide effective noise reduction (STC rating of 26–30) as well as thermal insulation. Special attention must be paid to the maintenance and handling of acoustic absorptive materials to prevent lead dust accumulation. It is also critical that the ventilation systems are properly maintained and serviced regularly to ensure optimum performance.

### 3.2.5 Flanking paths and leaks

Impulse sound energy can be transmitted from the firing range to the adjacent spaces by flanking paths such as leaks in and around the walls and direct coupling of the structural wall at intersections with the floor, outside walls, and ceilings<sup>31–34</sup>. Essentially, any air gap that has been designed to minimize structural-borne transmission should not be bridged by any continuous element such as drywall, oriented strand board sheathing, roofing, mechanical connections such as conduit or plumbing, and, if double masonry walls are used, loose mortar, and wall ties. Design considerations should favor building an envelope within the firing range that is separate from the rest of the structure. That is, the floor should be poured on its own foundation and not rigidly coupled to the rest of the building. At the very least, the common wall(s) should have a joint in the floor that will decouple the two spaces. As mentioned above, the roofing elements will likely span across the firing lanes making it possible to design a natural flexible joint between the range and the

adjacent spaces. Bullet traps can be anchored to the floor—not the super-structure of the building—to prevent noise and vibration from being transmitted throughout the building<sup>35</sup>. The perimeter of the wall or ceiling should be sealed or caulked air-tight to provide an effective acoustic isolation.

Noise leaks occur when high-frequency sounds pass through small openings or cracks in the walls, ceiling, or floor of the firing range. To reduce leaks, openings must be sealed or caulked and holes or cracks must be properly repaired. Because leaks permit mainly high frequency sounds to be transmitted through, the application of sound absorption material and making the sounds travel through a longer path can significantly reduce the effects of leakage. Electrical connections that span between the adjacent spaces and the firing range should have flexible conduit with added length to minimize transmission. The electrical service should make a single crossing and then branch out to outlets and lighting as opposed to making several crossings of the common wall. Outlets, light switches, and electrical boxes on common walls should be offset and sealed airtight to prevent a direct path for noise. Water service may be necessary for cleaning the floor, but washroom and drinking facilities should not be in the range because of the possibility of lead exposure. Plumbing connections should incorporate isolation wherever the supply and waste piping comes in contact with the walls. Flexible hose tubing can connect the sink and faucet to the supply. A rubber boot can isolate the waste line from the exposed mass of the sink.

#### 4 SUMMARY

Noise control solutions focused on improving the sound absorption inside the firing range and minimizing the noise transmission from the firing range to the adjacent spaces would significantly reduce shooting noise. General sound absorption treatment of the firing range walls and ceilings would improve the reverberant environment within the range, and solutions for the construction and treatment of shooting booths should reduce personal noise exposures of the shooters. A range of noise control solutions to reduce sound transmissions to the adjacent areas addressed the construction of the common wall, passageways, windows, and concerns for the potential flanking pathways. It is important to note that the noise control solutions highlighted in this paper are not intended to be comprehensive or universal in application. Indoor firing ranges have differing requirements and specific building codes. Some elements may seem excessive or expensive (double door passageways, double-glazed laminated windows), but the expense of designing and

including these elements up front will certainly be less costly than attempting to retrofit an unusable facility.

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