Retrofitting Your Indoor Firing Range to Improve Airflow

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Dedication*: This presentation is dedicated to my first cousin, Deputy Sheriff Gregory Hans, who lost his life March 10, 1997, while performing his duties for the Jefferson County, Kentucky Sheriff's Department, and to all other law enforcement personnel. They face enough hazards while performing their jobs; they should not have to face unnecessary hazards while training to do their jobs.*

Introduction

When selecting an indoor firing range renovation topic for this presentation, I had a broad selection from which to choose. I have witnessed or heard of many mistakes that have contributed to lead exposure in shooters, firing range personnel and occupants of the building in which firing ranges are located. Overall, the most common lead exposure problems are due to poor supply air systems. In this presentation, I will discuss the common reasons why problematic supply air systems cause lead exposure and alternative supply air designs that correct those problems.

Problematic Supply Air Systems

Supply air diffusers and registers used in most heating, ventilating and air conditioning (HVAC) installations are designed to supply a jet of air into an area at a velocity of several hundred feet per minute. A turbulent boundary layer exists between the jet and the surrounding, relatively still air. This turbulence pumps the surrounding air into the supply air jet.

In most HVAC installations, the pumping of room air into the supply air jet is important because it mixes and imparts a velocity to the room air. These actions help eliminate stagnant air zones, which cause hot and cold spots and stale air. In the indoor firing range, the pumping action of the supply air jet can cause overexposure of shooters and range personnel. Some of the air pumped into the jet comes from recirculated jet air, but most of the air comes back-flowing from downrange. During shooting, back-flowing air can be heavily contaminated with lead fume. In fact, in more than one range, I observed air back-flowing from halfway downrange to behind the shooting line.

Based on the supply air system designs I have seen in problematic indoor firing ranges, many designers apparently believe that shooting a jet of clean supply air through the shooter's breathing zone will protect the shooter from lead exposure. Observation of the firearm emissions

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or a fog machine may show that the lead fume from the firearm is blown away from the shooter. A fog machine will show air, which would be contaminated with lead fume during shooting, back-flowing from downrange through the booth at the floor and/or ceiling levels. This contaminated, back-flow air then is pulled into the supply air jet, exposing the shooter through the back door, so to speak. Even when air is aimed totally across the face of a booth, downrange air can back-flow through other booths. In one indoor firing range, downrange air actually back-flowed above the suspended ceiling over the booths to behind the line, where it was pulled through cracks between the ceiling tiles by the supply air jet.

The supply air jet also can create an eddy (i.e., a body wake) as it flows around the shooter's body. If the shooter does not hold the weapon outside of the wake, he or she can be exposed to lead fume trapped inside the wake. Body wakes being what they are, the air in the wake tends to travel toward the head region, assuring that the shooter gets a sure chance at exposure. While lower velocity air also can create a body wake, the distance that the wake extends downrange of the body is proportional to the air velocity. So, the lower the air velocity, the less distance the wake extends beyond the shooter's body, decreasing the chance that the shooter will have his or her firearm inside of the wake.

Probably the worst potential problem with high-velocity supply air is the formation of an eddy behind the shooting line, usually where the line range officers are located. Invariably, these folks are found to have elevated blood lead levels even though they have not used firearms as much as the shooters they are supervising. In these cases, a large stagnant air eddy probably will be found uprange of the shooting booths. The eddy is formed by the supply air jet and may extend through the shooting booth. The eddy picks up contaminated downrange air either directly or from other back-flowing air and continuously recirculates the contaminants in the eddy. Using a fog machine, I have observed that contaminants can circulate inside the eddy for minutes after shooting has stopped. A person standing inside this eddy, such as a range officer, can end up being exposed to lead much longer than the shooters. This finding is significant because sampling has shown that poor supply air design can result in a shooter receiving above the Occupational Safety and Health Administration (OSHA) daily allowable lead exposure in fewer than 15 minutes of shooting (Reh and Klein 1989).

An Answer

In working with one problematic indoor firing range (Reh and Klein 1989), I found that one way to prevent back-flow of contaminated downrange air was to use a laminar airflow system, sometimes termed a plug flow system by engineers. In these systems, low-velocity air is supplied uniformly across the full area of the range at the shooting line and removed from the bullet trap area. Therefore, at any moment in time, a plug of air is traveling from behind the shooter to the bullet trap. In reality, the plugs of air are continuous and constant. (The air is not pulsed. I also am aware of the exhaust point 20 feet downrange from the shooting booths. At this time, the need for such an exhaust take-off still is debatable.)

Properly operating laminar airflow systems have been shown to reduce lead exposures to acceptable and even non-detectable levels in indoor firing ranges (Reh and Klein 1989, Echt and Klein 1992, National Institute for Occupational Safety and Health [NIOSH] unpublished data). Ranges with high-velocity supply air systems usually can be converted to laminar airflow systems with minimal cost using creative engineering, although changes usually are incorporated *into an expensive whole-range renovation. Even when the laminar airflow system is not perfect, I have observed these systems to work effectively in minimizing lead exposure. Another plus for very wide ranges is that a problem in one section of the laminar airflow supply system might not lead to total range shutdown because the problem can be localized.*

Laminar Airflow Supply Orientation Considerations

Several laminar airflow system designs currently are being used in indoor firing ranges, and some of these systems are commercial products. Laminar airflow systems have been adapted to ranges that have widely varying configurations, such as control centers or entrance doors in the wall from which the air is supplied or end-walls that are varying distances from the shooting booths. The majority of these systems supply air through most of the end-wall area behind the shooting booths (denoted as an air-wall from here on). But some reportedly successful systems supply air through only a portion of the end-wall, such as a quarter-round perforated diffuser system that mounts on the upper end-wall. One laminar airflow system also supplies air successfully from the ceiling behind the shooting line, perpendicular to the floor.

With any laminar airflow system, an important design criterion is that the air should be fully distributed across the indoor firing range's cross-section at the entrance to the shooting booths. If it is not, an eddy can form behind the line that causes back-flowing of contaminated downrange air. Unlike with high-velocity airflow systems, eddies that form behind the shooting line with laminar airflow systems usually are not a problem because they are smaller and usually do not extend into the downrange area. For example, the range that supplied air from the ceiling had an eddy behind the line formed by the air making a right-angle turn to go toward the shooting booths (similar to the eddy formed by air flowing through a right angle bend in a duct).

To assure that the laminar airflow totally covers the indoor firing range's cross-section at the entrance to the shooting booths, enough distance is needed between the air-wall or other supply point and the shooting booth. With an air-wall, this distance can be as small as 5 feet because the airflow pattern is developed rapidly after leaving the wall. With other arrangements, more distance usually is needed to develop the airflow pattern. For a ceiling supply air system, Crouch (personal communication with Dr. Keith Crouch, NIOSH; Crouch et al. 1991) found that the distance needed between the supply and the booth entrances was about 15 feet. But in renovations, the distance between the end-wall and the shooting booths is already set and the ventilation system has to be adapted. Therefore, laminar airflow systems not using an air-wall, and even systems not using the full end-wall as an air-wall, might need a special design to obtain a full airflow pattern at the shooting booth entrances. For the previously mentioned range with the ceiling supply, a small high-velocity, ceiling-level jet just behind the shooting booths was installed to forcefully widen the laminar airflow so that it covered the booth faces.

If in doubt about whether a proposed laminar airflow system will work correctly in a particular indoor firing range, a full-size mock-up of the range from the end-wall to just downrange of the shooting booths can be constructed using wood. The width of the mock-up does not have to be more than about 10 feet. (In fact, most of Crouch's experiments on laminar airflow systems for ranges were performed in a tunnel about 10 feet wide.) Installation of an actual shooting booth usually is not necessary unless the booth is believed to affect airflow. Plexiglas windows can be installed in the mock-range walls and ceilings to observe the fog patterns in the area of the shooting booths. Airflow patterns also can be analyzed from inside the mock range as long *as the observer makes sure that he or she does not affect the airflow being visualized. The observer also should be aware that the fog material can be a respiratory irritant.*

Proposed laminar airflow systems then can be tested in the mock-up. Systems should be tested over a range of airflows corresponding to velocities from 50 to 75 feet per minute (?) through a cross-section of the mock-range. Testing can be simply using a fog machine to visualize airflow patterns across the width of the mock range. Testing at various heights also should be done because airflow patterns can vary drastically at different heights. The fog material should show that the airflow covers the entire mock-range cross-section where the shooting booth entrances would be. Any stable eddies that could affect control of lead fume should be looked for and resolved. (Note: stable eddies are those that do not disappear over time even though they may grow and shrink. They indicate a potentially serious problem. Conversely, transient eddies appear and disappear over time and commonly are found in airflows.)

An option to building a mock indoor firing range would be to mock up the proposed laminar airflow system in the actual indoor firing range, particularly if the original HVAC system is being kept. In wide ranges, mocking up the entire supply system would be impractical. Therefore, as with the mock-up range, only a section of the laminar airflow system needs to be mocked up. If only a section of the laminar airflow system is being mocked up, temporary plywood floor-to-ceiling walls from the end-wall through at least the shooting booths need to be installed at the ends of the mock laminar airflow system. Another option is to install the mock laminar airflow system on one side of the range's end-wall and use the adjacent range side-wall in place of one of the temporary walls. The purpose of the walls is to confine the airflow so that the mock-up represents a slice of the range. Airflow characteristics in that part of the range can be extended to the whole range. Airflow testing in sectioned-off part of the range is similar to that for the mock range—fog can be used to visualize the airflow. Likewise, Plexiglas observation windows can be installed in the temporary walls in the shooting booth area to observe the fog patterns, or the patterns can be observed inside the sectioned off area.

In any mock-up, the impact of the exhaust air on the laminar airflow supply system has to be considered. For a mock range, the air can be circulated in the loop from the end of the range back to the supply side without much affect on the supply airflow, although build-up of fog material could be a problem. Using the indoor firing range as a mock-up could be more difficult. The exhaust system should be used to avoid a build-up of fog material in the range. But the exhaust airflow should be proportional to the supply airflow, representing actual conditions. If the exhaust system allows only the total exhaust airflow to be used, the correct proportion of supply air should be supplied outside of the area of the mock laminar airflow system. To minimize the impact of airflow in other parts of the range on the mock-up section, the temporary wall(s) should be extended downrange of the booths about 10 widths of the mock-up section.

Airflow Velocity Considerations

A properly operating laminar airflow system is dependent on certain design considerations. The first is required velocity at the shooting booths. Historically, 75 feet per minute air velocity at the shooting line has been recommended. Most sources are nebulous about the requirement because the velocity through the shooting booths will be higher than up and downstream of the booth because the booths take up some of the cross-sectional area of the indoor firing range. For airflow calculations, only the cross-sectional area of the range should be used.

The origin of the 75 feet per minute velocity appears to be the old NIOSH guidance document for indoor firing ranges (Anania and Seta 1975). Although I have not found the exact origin of this velocity criterion, it appears to come from criteria used in industrial ventilation design. In industrial design, a minimum 100 feet per minute velocity is recommended to capture airborne contaminants. (A velocity of 50 feet per minute usually is considered normal ambient air velocity.) For an indoor firing range, the lead fume already is traveling forcefully in the direction of the airflow, meaning that a lower capture velocity than 100 feet per minute should be needed. Thus, a 75 feet per minute velocity was prescribed.

I have found that air velocities as low as 50 feet per minute can adequately control lead exposures. But, I still recommend 75 feet per minute as a minimum velocity. This velocity allows for design and installation errors that always seem to occur in ventilation systems. It also will provide a safety margin for airflow variations across the shooting line due to supply air distribution. Getting as much airflow downrange to carry the fume to the exhaust system is a further motivating factor for the 75 feet per minute velocity.

In renovations, the existing supply air system might not have the capacity to provide for 75 feet per minute velocity at the shooter's booths. Adding the needed capacity could be a breaking point for whether a renovation project is accepted or not, risking closure of the indoor firing range if the renovation is not performed. In such cases, I would conditionally agree to proceed with the renovation. One of those conditions is that the minimum acceptable velocity at any point across the shooting line is 50 feet per minute. Other conditions depend on the specifics of the range to be renovated. If the laminar airflow system cannot supply a 50 feet per minute minimum velocity at the shooting line, I recommend narrowing the range through the shooting line and applying all of the supply airflow to this narrowed area to get the required velocity. Using the range with a velocity lower than 75 feet per minute velocity at the shooting line should be considered as a temporary measure until a system that can supply 75 feet per minute is funded. Until funding is approved, the range airflow and shooter exposures should be monitored closely to assure that shooters are protected.

Airflow Distribution Considerations

Evenly distributed airflow across the laminar airflow system is important to getting even airflow distribution across all of the shooting booths and preventing eddies that could cause backflow. Adequate airflow resistance (commonly called pressure drop) across the laminar airflow system usually is needed to get even airflow distribution. Common perforated materials, such as commercially available quarter-inch hole-punched metal sheeting and perforated hardboard, have adequate pressure drop to get even airflow distribution. Crouch (Crouch et al. 1991) found that a free area (total whole area divided by total panel area) of about 6 percent is adequate for distribution. The common perforated materials meet this criterion.

As part of renovations, a number of indoor firing ranges have constructed simple air-walls by erecting a wall faced on the downrange side with perforated panels in front of the range end-wall. A supply air plenum is thus formed by the wall of perforated material, the end-wall and adjacent side-walls. The existing supply air then is supplied to this plenum, resulting in the air-wall. These air-walls, however, do not always behave as expected, usually because of effects from the way air is supplied to the air-wall plenum.

Crouch explored alternate air-wall designs. He found that an air-wall with perforated panels on both the upstream and downstream faces of the wall (called a two-faced air-wall in this presentation) had better distribution. Even better air distribution was obtained by misaligning the holes in the upstream and downstream panels. He topped this improvement in air distribution by offsetting the up and downstream studs, allowing air to travel freely within the air-wall. Crouch determined that a minimum wall depth of 5 inches is needed to allow air movement.

Under some conditions, even the materials that provide adequate pressure drop might not be able to provide even airflow distribution. As a rule, the air-wall, or any other laminar airflow system for that matter, should not be solely relied on for even distribution. The way air is supplied to the system is important, too. In his work on air-walls, Crouch found that placing a perforated panel over the outlet of the supply air transition into the air-wall plenum did not improve distribution as well as the inside wall of his two-faced air-wall. In one indoor firing range that had a single-face air-wall and air entering the plenum parallel to the air-wall, damper blades at the transition outlet adequately spread the air to get nearly uniform distribution across the single-wall air-wall. But the air-wall plenum in this case was several feet deep. In another range that also had a single-face air-wall and air entering the plenum parallel to the air-wall, the absence of a supply airflow spreading system caused more air to come from the lower part of the air-wall than the upper part. In this range, the single-face air-wall could not compensate for the supply air being blasted directly at the floor of the air-wall plenum.

To assure proper distribution, when a two-faced air-wall cannot be installed and sometimes even when it can, a flow-spreading system, such as louvers or impingement panels, should be installed at each supply air entrance into the air-wall plenum. A spreading system might be needed for two-wall air-walls where the supply air enters the plenum parallel to the air-wall, but likely will be needed where the supply air enters the air-wall perpendicular to the air-wall. For all configurations of air-walls, air should not be directed down or across the inside face of the air-wall. For laminar airflow systems that do not use air-walls, the impact of supply air on the distribution system should be a consideration, just as for air-wall systems.

Airflow spreading devices aid in pre-distributing the airflow within the air-wall plenum; but not having spreading devices does not mean the laminar airflow system will not work. In the indoor firing range with the single-face air-wall where more air came from the lower part of the air-wall than the upper part, lead exposures were found to be well below regulatory limits. This range's laminar airflow system worked because the distance between the air-wall and the shooting line was enough to allow the airflow to spread out across the shooting line.

Unless the indoor firing range is very narrow, one or two shooting booths wide, air should be supplied to the laminar airflow system at more than one point along the air-wall, but no criteria have been developed for the number and spacing of distribution points. The design of the entrances, the type of flow-spreading devices and the plenum geometry will affect the number of distribution points. A ventilation engineer may be able to determine the number needed. If some doubt exists, a mock-up of the air-wall plenum with changeable supply air entrances can be built and tested. In this testing, fog material can be put into the fan entrance at various airflow rates and observed as it enters the plenum to find the best design.

Air-wall plenum depth undoubtedly has an impact on air-wall performance. However, plenum depth really has not been researched adequately. Generally, the deeper the air-wall *plenum, the greater the chance for air in the plenum to become evenly distributed. Air-wall resistance and the design of the air supply to the plenum also likely interact with plenum depth to impact distribution, but research has not developed a rule of thumb as yet. Generally, the greater the air-wall pressure drop, the less plenum depth is needed. Air-walls with plenum depths of as little as 1 foot have been successful, as well as walls with plenums several feet deep. At the least, the plenum needs to have enough depth and height to allow air to spread across most of the air-wall before it hits the wall. As with the other unknowns in the design, a mock-up of the proposed plenum can be built and tested prior to making a final design.*

In some indoor firing ranges, the plenum depth is not negotiable because these ranges have rooms, such as control rooms, in the proposed air-wall or sometimes totally along the wall. In these cases, the air supplied to the room for HVAC purposes also is the air supplied to the range. To accomplish this design, the common wall between the range and the room is made of perforated wall materials. Where the range needs to be seen from the room, Plexiglas or Lexan with holes in a pattern similar to perforated hardboard is used. In one range, the entire wall was perforated Plexiglas. When a room is part of the air-wall, airflow distribution across the air-wall usually is not a serious concern because the room provides enough volume for air to be distributed across the wall. Nonetheless, an important concern is making sure that the supply airflow does not blow down the inside face of the air-wall, which would disrupt airflow out of the air-wall and possibly set up an eddy inside the range.

HVAC requirements for a room planned to be part of the air-wall might prohibit its being used for the air-wall source. For example, cold air supplied to the room for air conditioning could cause eddies when fed into the indoor firing range (explained in more detail later). Therefore, the room should not be used for the air-wall and should be isolated from the range. In one range where an air-conditioned control room was integral with the air-wall, windows that also were part of the air-wall were constructed from Plexiglas sheets. The range-side Plexiglas was perforated like the rest of the air-wall, while the control room side windows were solid. The control room side windows also were sealed well to prevent air leaks from the air- wall into the control room. The same source of air for the air-walls was ducted into the window plenums. When the room is isolated from the rest of the range, a separate air-handling system should be used for the room because of the differences in tempering requirements for the two areas.

I need to make a couple of additional comments about laminar airflow systems that do not use an air-wall. While air-walls are the most common type of laminar airflow systems, other creative systems, such as quarter-round perforated diffusers, have come on the market. As far as airflow distribution, these systems require the same general concerns as do air-walls. To ensure that these alternate designs are effective in a range, I recommend asking some tough questions of the designers and manufacturers. I also recommend visiting similar indoor firing ranges that have these systems installed and asking for a demonstration using fog material. I recommend asking to review the sample data from the range. Again, if some doubt still exists about the effectiveness of a proposed laminar airflow system design, I recommend doing a mock up.

Door Considerations

Then there are the doors. Doors always seem to be in the wall that is planned for the air-wall. If possible, doors should be placed in the side-walls behind the shooting line. Doors in the air-wall tend to complicate its design. If a door in the air-wall is inevitable, the door can be con-

structed as part of the air-wall system. As a rule, indoor firing ranges should have separate air-wall and range entrance doors (where people enter the range) because this arrangement simplifies the design. The doors also should be directly across the air-wall plenum from each other so that shooters do not have to use the air-wall plenum as a hallway from one door to another. For deep air-wall plenums, both sets of doors can swing in the same direction. For shallow air-walls, the doors might be too close to each other to open in the same direction. In this case, the air-wall door can swing into the range, while the entrance doors can swing out of the range.

The area where people traverse the plenum should be isolated from the rest of the air-wall (that is, a short hallway through the air-wall should be constructed). Separating the traverse area from the rest of the air-wall prevents compromise of the rest of the air-wall should one of the doors be left open or have a serious air leak. Air should be supplied to the air-wall traverse area using a separate supply duct from the rest of the air-wall. Air can be supplied to the traverse area from the air-wall if some type of airflow limiting device is used on the transfer airflow, such as a perforated material for the isolation walls. Methods of obtaining even distribution across the air-wall door should be the same as within the rest of the air-wall, although the supply duct should be placed as far away as possible from the air-wall door to minimize air jets formed by leaks around the door.

The air-wall door might be constructed similar to the rest of the air-wall. If constructing the door similar to the air-wall makes it difficult to use, the space between the perforated panels of the door can be decreased. When this spacing is decreased, misaligning the holes of the perforated panels becomes more critical than for the rest of the air-wall. For example, one indoor firing range simply replaced the panel sections of a common metal door with perforated panels on the two door faces.

For air-walls with shallow plenums, constructing the indoor firing range entrance as part of the air-wall could be cumbersome and worse for ventilation control than the entrance not being part of the air-wall. For some ranges, having an entrance that is not part of the air-wall might be an option. In these cases, the air-wall is constructed around the range entrance door. If the door is far enough from the firing line and not too wide, airflow from the air-wall might be able to fill in the gap in the air-wall left by the door before the airflow reaches the shooting booths. An eddy will be formed near the door. As long as the eddy is upstream of the shooting booths, no back-flow problems should exist.

Even when the distance between the door and the shooting booths is not adequate or when the door is so wide that it creates a very large eddy, supplying laminar airflow into the gap left by the door could result in a successful laminar airflow system. For example, laminar airflow could be supplied through the sides of the alcove formed where the door entrance comes through the air-wall plenum. Even though the air will be entering the range at a right angle to the air from the rest of the air-wall, it will help supply air to the void left by the door, minimizing the eddy size. Other options could be supplying laminar airflow from a hemispherical perforated diffuser or other distribution system in the ceiling above the door.

All indoor firing range entrance and air-wall doors should be air-tight to minimize leaks and air jets. Leaks in air-wall doors cause air to be supplied to the range in an uncontrolled manner. Usually these leaks form small air jets that can cause back-flow every bit as well as the jet from a high-velocity supply air system. For example, one range with a traverse through the air-wall *allowed air to leak from beneath the air-wall door. The jet of air caused back-flow through booths downrange of the leak. Shooters in those booths were found to be overexposed to lead.*

The seriousness of leaks in the range entrance door depends on the design of the door system. When the entrance is not part of the air-wall, air being pulled through the leak by the negative pressure of the range will form a jet that can cause back-flow and lead exposure. Another problem can occur should the range pressure go positive (e.g., if the supply air system is working while the exhaust system is not—it has happened). In this case, contaminated air from the range could be blown out of the range into the building housing the range. If the entrance door is part of the air-wall, a leak through the door into the air-wall plenum could affect airflow distribution from the air-wall, particularly if the air-wall is single-faced.

Doors should have a leak-tight seal around their entire perimeter. Particular care should be given to the bottom edge and hinge end of the door, because these areas tend to be overlooked. Magnetic gaskets similar to those used on refrigerators and metal entrance doors normally provide the tightest seals, although using these gaskets on the bottom edge of the door might not be possible. Double doors should have gasketed overlap strips to cover the gap between the doors. Gaskets should be durable, but they should be inspected routinely and replaced immediately when found damaged.

Range policy should not allow anyone to enter the indoor firing range through any doors during shooting, unless the range has been specifically designed to allow entrance without disrupting airflows. Even better would be a fail-safe electronic lock on the doors to prevent range entrance during shooting. All doors should have safety switches that activate an alarm and prevent the target lights from coming on if the doors are not closed properly. Warning lights or illuminated signs that are automatically activated during shooting should be installed next to all of the range entrance doors to alert shooters that they cannot enter the range at that time. Signs listing range policy about entering the range and proper use of the ventilation system also should be posted next to the doors inside and outside of the range.

In this discussion, I have mentioned only one set of entrance doors. All indoor firing ranges should have two doors for fire safety purposes. If both doors are in the air-wall, all recommendations above apply to both doors. That is, each air-wall door should have a corresponding entrance door, and each set of doors should follow the recommendations. Doors sometimes also are placed in the air-wall to provide access to the air-wall plenum. These doors also should follow the recommendations in this section, including those for safety alarms.

Air Temperature Considerations

The temperature of the indoor firing range's supply air can have a drastic, negative effect on the laminar airflow system. The laminar airflow temperature should be close to the temperature of the air in the range. If the temperature is much colder than range air's temperature, the laminar air will tend to drop as it comes out of the air-wall, flowing under the air in the range. This action will create a very large eddy (called a thermal eddy in this presentation) that likely will extend through the shooting booths, causing back-flow of downrange air. Moreover, this eddy can extend across the entire width of the range. Air that is warmer than the range air will flow over top of the range air, likewise creating an eddy, but in the opposite direction.

Many conditions can lead to the supply air temperature being different than the range air temperature, particularly if the range is air conditioned or heated. Most HVAC systems are not designed to supply air at nearly the same temperature as that of the space to which the air is being supplied. Instead, these systems cycle the heating and cooling systems on and off. This cycling means that the supply air temperature can vary dramatically over time. When one of these systems is installed on an indoor firing range, temperature cycling can cause thermal eddies to appear and disappear over time.

Even if a supply air system that can supply air at nearly the same temperature as the air in the indoor firing range, thermal eddies have a chance of forming. For example, most owners turn off the airflow systems when the range is not being used to save on energy costs. When the systems are off, the range can become hotter or colder than the design temperature of the range. When the systems are turned on, the temperature of the supply air could be less or more than the air in the range, causing a thermal eddy. Eddying will occur until temperatures equilibrate. The large amount of concrete used in ranges creates a large thermal mass that works for or against equilibrium, depending on how much the range is used and how HVAC control systems work. To counter this eddying, the range will need to be held at a constant temperature, or it will need to be brought to temperature equilibrium before shooting begins. Note that holding the range at a constant temperature does not mean constantly running the range's airflow systems. The range's thermal mass can be used in conjunction with an energy control system that cycles the airflow systems on temperature demand or operates the systems constantly at reduced airflow to maintain temperature.

For indoor firing ranges in zones with warm summers, air entering the indoor firing range should be air-conditioned. Otherwise, temperatures in the indoor firing range can become so hot that shooters' alertness and accuracy are adversely affected or the range becomes unusable on hot days. With laminar airflow systems, air conditioning could be needed where it was not needed with a high-velocity airflow system simply because the high-velocity airflow's jet provided some cooling effect. Less heating might be needed with the laminar airflow system than with the high-velocity airflow system because the laminar airflow does not feel as drafty as the high-velocity airflow's jet. Other reasons for air conditioning are the large heat load generated in the range by lighting and the large volume of outdoor air used in the supply airflow.

Air conditioning the range results in design quandaries that do not exist with heating the range. The first of these is the cycling of the supply air temperature (previously mentioned) if the right air-conditioning system is not installed. In fact, most ranges likely do not have the right systems. In most ranges with air conditioning, package air-handling systems with Freon cooling systems are used. These systems cycle the cooling system (compressor) on demand from a sensor, causing fluctuations in the supply air temperature that can lead to eddy problems. An air-conditioning system that maintains supply air temperature near to that of the range likely will require special design and equipment. In some cases, a water-based cooling coil might be a better choice than a Freon-based coil because the former can infinitely vary its cooling by adjusting the flow of chilled water through the coil. Ranges located in buildings that already have a source of chilled water might be better off using chilled water. Small independent ranges or ranges in buildings that use strictly Freon-based cooling might be able to adequately control temperature while satisfying cooling demands by using options such as multi-stage cooling systems, face and bypass damper systems, energy-transfer systems or Freon-reheating systems

A complication with the supply air temperature being near the indoor firing range temperature is that the range could become extremely humid. Under normal conditions in residences and offices, the air conditioning system chills the air below the dew point (the temperature at which water condenses from air), taking moisture out of the air. When the air entering the cooling system is not being cooled much below the temperature at which it enters, little moisture is condensed out of the air. In fact, the air conditioning system might reduce the air temperature to the dew point temperature without removing any moisture. Humid air can feel sticky to the shooters, cause paper to curl or warp wood. To counter the humidity problem, dehumidification systems might be needed when air conditioning is installed for the range. Some options for dehumidification are superchill/reheat systems, desiccant systems, enthalpy-wheel systems, and face and bypass systems.

Energy saving methods, such as low-energy lighting and better insulation, should be considered for renovations and new construction of a range to reduce heat generation. Reducing the range cooling requirements helps reduce the complications of designing the air conditioning system, as well as lowering operating costs.

Heating the range can cause the reverse problem. However, the options for maintaining constant temperature are better. Air handling systems that use gas or oil heating have problems with cycling supply air temperature. Systems with electrical heating can maintain a more constant supply air temperature without cycling, depending on their control system design. But these systems are expensive to operate. Luckily, many of the same systems, such as face and bypass dampers, heat wheels, and other energy transfer systems, also can be used to help control heating temperatures.

In this section, I have used a lot of probability terminology, mights and coulds. I have witnessed eddy formation due to supply air temperature, but have not been able to fully investigate HVAC design to counter the supply air temperature problems. As a mechanical engineer, I know that certain systems and equipment can control temperature. The important point is that HVAC designers need to clearly understand the indoor firing range air tempering requirements and problems that can result from improper design. Designers need to recognize that range requirements are not the same as any other building, and they need to analyze the impact varying conditions can have on the laminar airflow system and its ability to control lead exposure. Designers need to be open-minded and knowledgeable about the broad spectrum of equipment available to the HVAC market, and they need to have that knowledge up-to-date. On the other hand, the range owner needs to know how to evaluate the designers and their work. Most importantly, he or she needs to know which questions to ask.

Those Complicating Considerations

The number and size of obstructions between the air-wall and the shooting booths should be minimized. In the rare case that an obstruction must be in this area, it should be placed as close to the air- wall as possible so that the airflow pattern can be reestablished before it reaches the shooting booths. The face area perpendicular to the airflow also should be minimized. For example, if a flat surface is needed between the air-wall and the shooting booths, a table should be used, if possible, rather than a desk. As another example, building columns should not have bulky decorative facings perpendicular to the airflow. If possible, objects between the air-wall and shooting booths should be streamlined to eliminate turbulent wakes. For example, columns *can have bow-shaped facings that allow the air to glide around the column. Fog testing always should be performed to verify that obstructions do not cause air to back-flow in the booths.*

The indoor firing range's supply and exhaust airflow systems should have low airflow sensing systems. Most times, power to the fan motor relay (an indicator light in line with the motor relay) is used to indicate that a fan is operating correctly. This method of sensing airflow does not account for decreases in airflow due to loose or broken belts, plugged filters, etc. To accurately determine that airflow is within acceptable limits, a flow sensor should be used on each air handler and exhaust fan. When airflow drops below acceptable limits, the sensing system should alarm and disable the target lighting so that shooting cannot occur.

Crouch found that doors in the down-range, lower booth face could contribute to lead exposure. Doors can cause an eddy that can join with the shooter's wake, if the shooter stands too close to the door. Lead fume in the door wake then can travel into the shooter's wake. One solution is to have only a shelf without a door in the booth. Another of Crouch's solutions is to have a shelf in the booth to keep the shooter away from the door and a 4-foot gap between the top of the door and the shelf to allow airflow over the door to separate the door eddy from the shooter's body wake.

Sometimes, when an access door is installed in the plenum, someone will use the plenum for storage. Objects stored in the plenum can affect airflow distribution. Before this practice even begins, a policy should be established forbidding the use of the air-wall plenum for storage. Range officers also should be instructed on this policy.

When mock-ups are used, the temptation is to leave them in place. To cut costs, air-walls or other laminar airflow systems might be constructed from wood materials rather than metal. Because of the fire threat in indoor firing ranges, air-walls should be constructed from perforated metal and metal studs, rather than wood and hardboard.

Verification of System Operation

In this presentation, use of a fog machine with mock-ups to verify whether a certain design will work has been mentioned several times. Even though it is not as sophisticated as air sampling, testing with a fog machine provides more useful information. Where sampling might detail that an exposure problem exists and how bad it is, fog-machine testing specifically identifies the problem. Doing so could save the owner thousands to hundreds of thousands of dollars at the design stage, the most inexpensive point to make changes. A fog machine also should be used to verify that the laminar airflow system is working correctly in the range before a shot is ever fired. To perform this testing, the fog machine should be operated on the shelf and floor area of every shooting booth for at least 10 minutes. The length of time is important because sometimes a back-flow takes several minutes to appear behind the shooting booths. Besides back-flow, steady eddies that could affect lead exposure also should be looked for. In areas where back-flow is found, the fog machine should be moved to various areas between the laminar airflow system and the shooting booths to try to determine its cause. The fog machine also should be used in front of doors to look for air jets and in front of the laminar airflow system to look for airflow being blown at an angle from the system rather than perpendicular (directly toward the shooting booths). Problems identified by the fog-machine testing should be corrected before the range is put to use.

Airflows in all supply air ducts to the air-wall plenum should be measured to ensure that supply airflow is at design specifications and uniformly distributed across the wall. Airflows that are not within acceptable design criteria should be corrected, as well as any airflow uniformity problems. After correcting supply air problems, airflow measurements using a back-pressure compensated airflow instrument, such as a FlowHood, should be made across the air-wall or other flat laminar airflow system. Airflows then should be checked for uniformity. Airflow uniformity at the wall is related to airflow uniformity across the shooting booths, assuming that the air is exiting perpendicular to the airflow system. Airflows that are more than 20 percent different than the overall average airflow should be investigated and brought to within 20 percent.

When airflow problems have been corrected and fog-machine testing completed, personal lead sampling should be performed under the normal conditions for shooters at the indoor firing range. Samples that are found to be out of OSHA compliance should be investigated to determine the cause, beginning with follow-up fog machine testing to determine if a problem was overlooked during previous testing. Fog machine testing also might be performed with a person or mannequin mimicking a shooting position. Problems that are found should be corrected and sampling repeated with another shooter in the booth where shooters were overexposed. Close attention should be paid to personal practices of shooters that could contribute to overexposure. If overexposure occurs again and practices were not found to be a cause, shooting should not be allowed in the problematic booth(s) until corrections can be made.

Conclusions

Laminar airflow systems have been adapted to a wide variety of indoor firing range designs. They can be used for correcting problems in indoor firing ranges that have high-velocity supply air systems. Laminar airflow systems still require careful design and installation to ensure that they work properly. With proper design and care, these systems should provide years of service protecting the indoor firing range users.

Let me close by saying that this presentation has included a number of factors relevant to the proper design of these systems. Although it contains a great amount of detail, the reader should not misconceive that this information alone will provide all of the information needed to get a properly operating range. This presentation only focused on the supply airflow. Other areas of the range, such as the exhaust airflow system and air filtration systems, also can impact lead exposure.

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