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To cite this article: Keith G. Crouch , Taiyao Peng & Donald J. Murdock (1991) VENTILATION CONTROL OF LEAD IN INDOOR FIRING RANGES: INLET CONFIGURATION AND BOOTH AND FLUCTUATING FLOW CONTRIBUTIONS, American Industrial Hygiene Association Journal, 52:2, 81-91, DOI: [10.1080/15298669191364361](https://doi.org/10.1080/15298669191364361)

To link to this article: <https://doi.org/10.1080/15298669191364361>



Published online: 04 Jun 2010.



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VENTILATION CONTROL OF LEAD IN INDOOR FIRING RANGES: INLET CONFIGURATION AND BOOTH AND FLUCTUATING FLOW CONTRIBUTIONS*

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Workers in and, in some cases, users of indoor firing ranges continue to receive overexposures to airborne lead levels in spite of efforts to produce smooth and ample ventilation. Studies of firing ranges by researchers for the National Institute for Occupational Safety and Health (NIOSH) and others have shown that only on very infrequent occasions will the ventilation airflow adequately control lead exposures. Some firing ranges use only ventilation to control lead exposures, and these have stimulated a search for the ventilation system elements that will ensure successful control. Substitution of nonlead bullets and primer as a control means has shown some success but has not gained widespread acceptance because of its effects on the accuracy, range, and reliability of firearms. Several approaches leading to adequate ventilation control of lead in indoor firing ranges were investigated. Observations of flow patterns in firing ranges led to an investigation of the firing range air inlet as the primary source of backflow and eddy formation causing elevated lead exposures. Work on a full-scale model firing range shows that backflow can be suppressed in several cases by the use of a double pegboard at the inlet. In addition, a dual inlet with flow alternating between inlets effectively eliminates eddy and wake formation. Flow patterns resulting from various inlet configurations were observed during smoke release studies. Systems that produced a flow pattern free of backflow over potentially occupied regions of the model firing range, as shown by the smoke release studies, were further investigated by measurements of velocity and turbulence intensity profiles. Further research will involve incorporating these controls in actual firing ranges as confirmation of their adequacy. Smoke release studies also were used in the model firing range to determine the effects of the shooter's booth on airflow at the firing line. Quantitative measurements of relative exposure for a mannequin simulating a shooter were made using smoke release. A smoke concentration

measurement was made in the breathing zone by an optical particle detector. Several booth modifications involving slots and fins were shown to reduce exposures. The shooter's wake was shown to be a fundamental element of backflow exposure paths in these booth studies.

Figure 1 shows the main features of a typical indoor firing range (IFR) designed according to presently recommended practice.⁽¹⁾ This design includes an air inlet and exhaust, an inlet plenum with a perforated wall, firing booths, and a bullet trap. The main purpose of the ventilation system is to carry gun emissions generated at the firing line away from the occupants and out of the IFR, thus preventing excessive exposures to gun emissions. The airborne lead exposure levels in IFRs, however, frequently exceed the Occupational Safety and Health Administration's (OSHA's) permissible exposure limit (PEL) of 50 $\mu\text{g}/\text{m}^3$, according to published data.⁽²⁻⁴⁾ This airborne lead results in elevated blood lead levels among IFR occupants, especially individuals such as range officers who spend time in IFRs on a regular basis.⁽³⁻⁵⁾ The lead slug and the primer are both sources of lead that contribute to exposures. Some success in controlling lead exposure has been achieved by substituting a nonlead slug and primer for traditional ammunition,^(6,7) but this

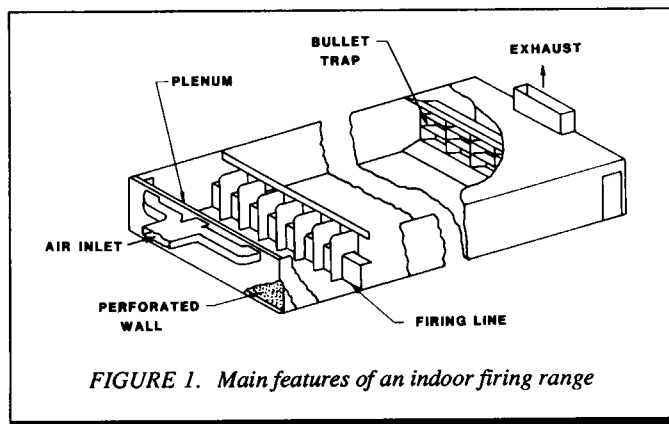


FIGURE 1. Main features of an indoor firing range

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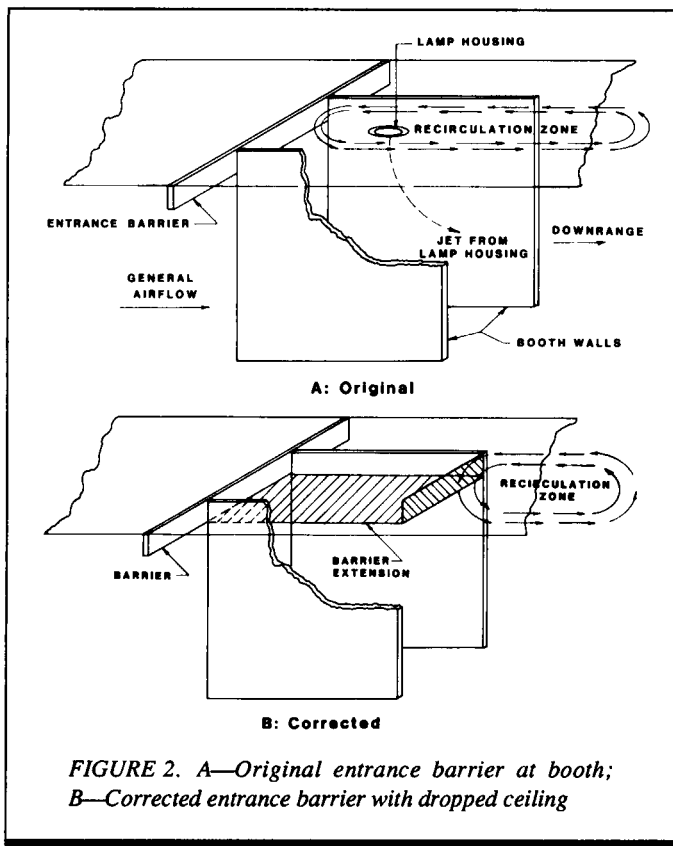


FIGURE 2. A—Original entrance barrier at booth; B—Corrected entrance barrier with dropped ceiling

approach is of concern to the law enforcement community and others because it affects the accuracy, range, and reliability of firearms.^(6,8) Various coatings on bullets also have reduced exposures significantly^(9,10) but have not eliminated them. Isolating the range officer in a fresh air environment protects that individual but can leave other IFR occupants with an unacceptable lead exposure.

Local ventilation can also be helpful,⁽¹⁰⁾ but this requires that the inlet to the local exhaust system be located in close proximity to the firearm. A review of IFR data on lead levels also revealed that on rare occasions, ventilation alone provided sufficient control of the lead emissions to satisfy the OSHA PEL.⁽⁵⁾ During this review, the effective ventilation systems were found to produce a relatively smooth airflow pattern, whereas the ineffective ones produced an airflow pattern with large-scale eddies and recirculation originating at the air inlet

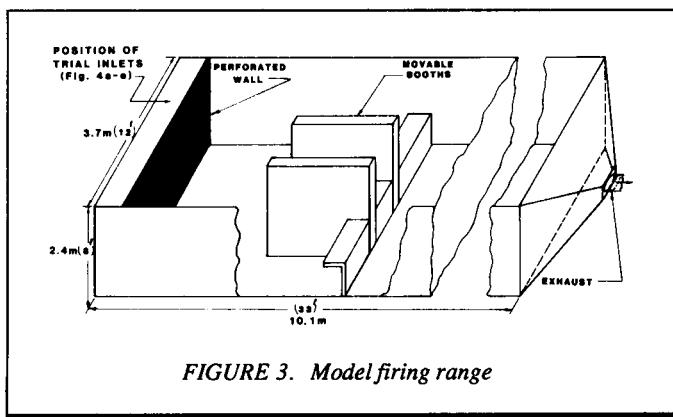


FIGURE 3. Model firing range

to the IFR and encompassing the firing line.⁽⁵⁾ This recirculation results in gun emissions generated at the firing line traveling to points uprange of the firing line and subsequently through occupied regions of the IFR.

With this initial indication of the source of the problem and evidence that a solution based upon a ventilation control system might be feasible, field and laboratory research were initiated to further verify the nature of the problem and to develop one or more reliable ventilation solutions. Substitution is generally preferable to ventilation as a control approach, but substitution has not gained wide acceptance for IFRs, and a need for better ventilation control has been demonstrated.

METHODS

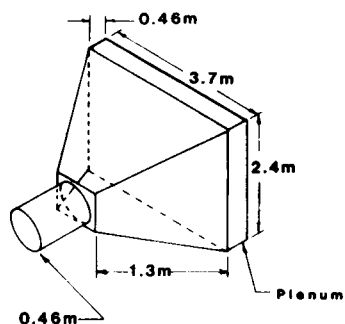
Field Study

The field study involved two IFRs. At the first,⁽¹¹⁾ a single pegboard (6.25-mm [0.25-in.] diameter holes on 2.54-cm [1-in.] centers) had been installed at a distance of 61 cm (2 ft) from the back wall of the IFR. It extended across the full width of the IFR, which was 3.66 m (12 ft) wide with three firing positions. Air entered the plenum formed by the pegboard and the walls of the IFR at the top of one side of the plenum. Smoke release studies of the resulting flow patterns were made throughout the range. Personal and area sampling for lead were conducted during the firing of handguns by three individuals under conditions simulating proficiency qualification trials.

The smoke release study showed that there were some strong eddies contained between the pegboard and the booths. There were also several recirculation cells at points downrange of the booths. Neither of these areas of backflow were likely to contribute to a shooter's exposure to airborne lead. Initially, there was also a weak backflow region at the firing line. This backflow was caused by the wake from an overhead barrier at the entrance to the booths. The barrier extended across the full width of the range (Figure 2A). This type of barrier is common to many IFRs. The barrier wake established a recirculation zone above the firing line in the center booth. The wake gradually filled with the smoke that was released at the firing position.

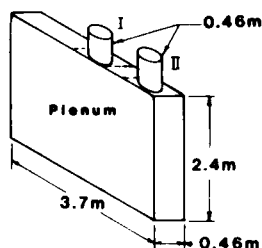
The negative pressure in the IFR caused an air jet⁽¹²⁾ to form below the overhead light fixture for the booth. The air entered through gaps between the fixture and the ceiling. The jet pushed contaminated air from the recirculation zone into the shooter's breathing zone. This exposure path was disrupted by extending a dropped ceiling from the bottom edge of the barrier to the downrange edge of the booth, as shown in Figure 2B. The effect of the dropped ceiling was to move the barrier's recirculation zone to a point downrange of the firing line.

After the above correction was made to the pattern of flow in the IFR, breathing zone samples were taken on three individuals as they fired handguns (.38-caliber revolvers and a 9-mm semiautomatic) representative of law enforcement weapons. The three test and sampling periods conducted on each individual lasted 10–13 min each, during which firing took place at a rate simulating normal qualification procedure. Of the nine resulting personal filter samples that were analyzed for lead, eight had levels below the detectable limit and the ninth was well below the OSHA PEL. Comparable



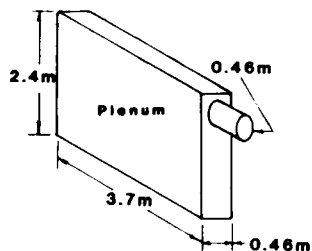
A

1. Single Pegboard: Unacceptable Backflow
2. Double Closed Pegboard: Acceptable > 1.22m With Flow Straightener in Duct Outlet, or With External Vanes Near Side Wall.



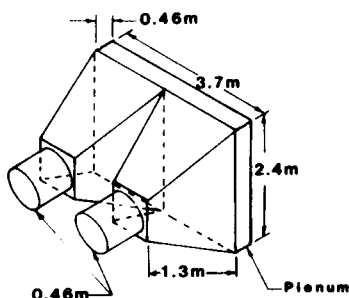
B

- I. At Center.
1. Single Pegboard: Unacceptable Flow
 2. Double Closed Pegboard: Acceptable Flow > 3.0m
- II. At Edge.
1. Single Pegboard: Unacceptable Flow
 2. Double Closed Pegboard: Unacceptable Flow.



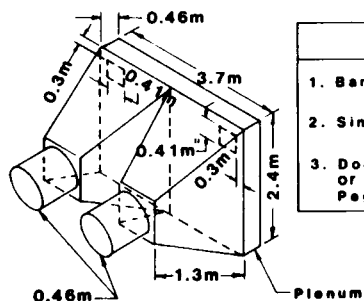
C

1. Single Pegboard: Acceptable Flow > 4.27m
2. Double closed Pegboard: Acceptable Flow > 3.66m
3. Double Open Pegboard: Acceptable Flow > 1.22m



D

Inlet	Steady Flow	Fluctuating Flow (with external vanes)
1. Single Pegboard	> 1.83m	> 1.22m
2. Double Closed Pegboard	> 1.22m	> 1.22m
3. Double Open Pegboard	> 1.22m	> 1.22m



E

Inlet	Steady Flow	Fluctuating Flow
1. Bare	None	None
2. Single Pegboard	None	None
3. Double Open or closed Pegboard	> 1.83m	> 1.52m

FIGURE 4. Summary of inlet configurations and results. A—Single tapered inlet with a variety of internal baffles; B—Single ceiling inlet; C—Single side inlet; D—Double tapered inlet, acceptable flow locations; E—Double rear inlet, acceptable flow locations.

original lead levels prior to installation of the pegboard ranged from 101 to 194 $\mu\text{g}/\text{m}^3$ (11)

The second IFR visited in the field study had a continuous series of perforated panels across the back wall through which air was supplied to 20 booths. The panels occupied the upper 2.13 m (7 ft) of the 2.74-m (9-ft) high back wall. The panels were installed at a 6.8° angle to the vertical so that there was a 30.5-cm (12-in.) space between the panels and the rear wall at the top and 5.1 cm (2 in.) at the bottom. Supply air was ducted to the top of this tapered inlet plenum formed by the wall and the panels. The holes in the panels were 3.8 cm (1.5 in.) in diameter and covered about 8.7% of the panel area. For comparison, the 6.25-mm (0.25-in.) pegboard at the first range had an open area of 4.9%. A smoke release study was done covering the portion of the IFR from the inlet panels to a meter or so (a few feet) downrange of the booths. The booths began at a distance of 4.6 m (15 ft) from the panels. No air samples were taken to establish lead exposure levels.

The smoke release study revealed a strong recirculation zone extending from the inlet panels to at least 6.1 m (20 ft) downrange at all firing positions. The air from the inlet moved down toward the floor, forming a jet about 1.1 m (3.5 ft) high. The air between the 1.1-m (3.5-ft) elevation and the ceiling was traveling uprange. The odor of gun smoke was evident behind the firing line when the IFR was in use, and the range officer reported that he experienced elevated blood lead levels, supporting the conclusion that the ventilation system was not producing a good airflow pattern.

Laboratory Study

Results of the field study and reports from other researchers^(5,11) confirmed the relative importance of the air inlet to the success of the ventilation system

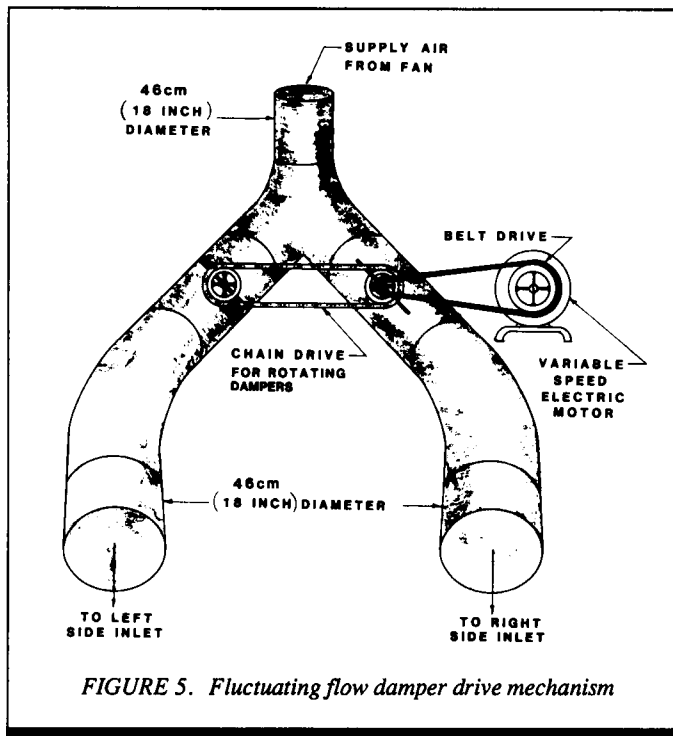


FIGURE 5. Fluctuating flow damper drive mechanism

in controlling lead emissions in IFRs. Other sources of backflow also were found to be significant. The goal of the laboratory study was to discover ways to ensure an acceptable airflow pattern in the IFR.

For this purpose, a full-scale model IFR ($2.4 \times 3.7 \times 10$ m [$8 \times 12 \times 33$ ft]) was constructed (Figure 3). In practice, air is frequently introduced near the back wall of IFRs through one or two openings in the ceiling or the side or back wall, leading to the formation of an inlet jet with its associated backflow. Even the more elaborate inlet installed at the second field site had severe jet formation problems. In order to avoid jet formation, the air must be supplied relatively uniformly over the full cross-section of the range. The generally impractical alternative is to place enough distance between the inlet and the firing line so that the jet dissipates before it gets to the firing line. The installation of a perforated full-wall panel (e.g., pegboard) between the inlets and the rest of the IFR is an approach that has been tried with some success, as seen at the first field site. Therefore, various types of inlets with single and double pegboard with and without internal and external vanes were evaluated in the full-scale model IFR.

Also, a fluctuating flow system has been effective in reducing or eliminating the backflow caused by worker wakes. The system's efficacy in abating the larger scale backflows that develop at IFR inlets was investigated. The inlet was divided into left and right halves and the airflow was supplied alternately to these halves at various frequencies and flow rates. At any point in the IFR, the air velocity tends to alternate in direction, first coming from one inlet and then the other.

Finally, the effect of obstacles contained in some IFRs, such as a bench in the booth and a half-height door at the downrange edge of the booth, with various items placed on the bench, was studied. Several methods of correcting resulting backflow were demonstrated.

Instrumentation

The primary method of evaluation of the various inlets and obstacles to flow was smoke release and observation. A Rosco (Port Chester, N. Y.) 1500 smoke machine was connected to a section of flexible hose about 2.7 m (9 ft) long and 6.4 cm (2.5 in.) in diameter. At the outlet of the hose, a 15.2-cm (6-in.) long section of plastic pipe was inserted. The plastic pipe had a solid cap on the end, with 24 1.3-cm (0.5-in.) diameter holes uniformly distributed on the cylindrical surface of the pipe to permit an even, nondirectional release of smoke into the test area. The temperature of the smoke at this outlet was less than 0.2°C above ambient temperature, resulting in a smoke flow essentially free of buoyancy effects. An initial evaluation of airflow patterns was made by visual observation of the path that the smoke traveled from its release point to the exhaust. Video recordings were made of airflow patterns representative of the IFR configurations under study. For a quantitative comparison of the effectiveness of two or more ventilation approaches, the smoke was released in the wake of a mannequin at a point corresponding to handgun use. A GCA real-time aerosol monitor (GCA/Environmental Instruments, Bedford, Mass.), Model RAM-1, was used to measure the resulting smoke concentration in the breathing zone of the mannequin. A 3-min average was taken as the representative concentration for this quantitative approach. The uniformity of the flow at the various inlets was measured with a Shortridge Instruments (Scottsdale, Ariz.) series 8400 flowhood. Volume flow rates through 24 contiguous 61-cm \times 61-cm (2-ft \times 2-ft) areas were measured with the flowhood over the 2.4-m \times 3.7-m (8-ft \times 12-ft) cross-section of the model IFR. Finally, velocity profiles were taken using Sierra Instruments (Monterey, Calif.) and Kurz Instruments (Monte-

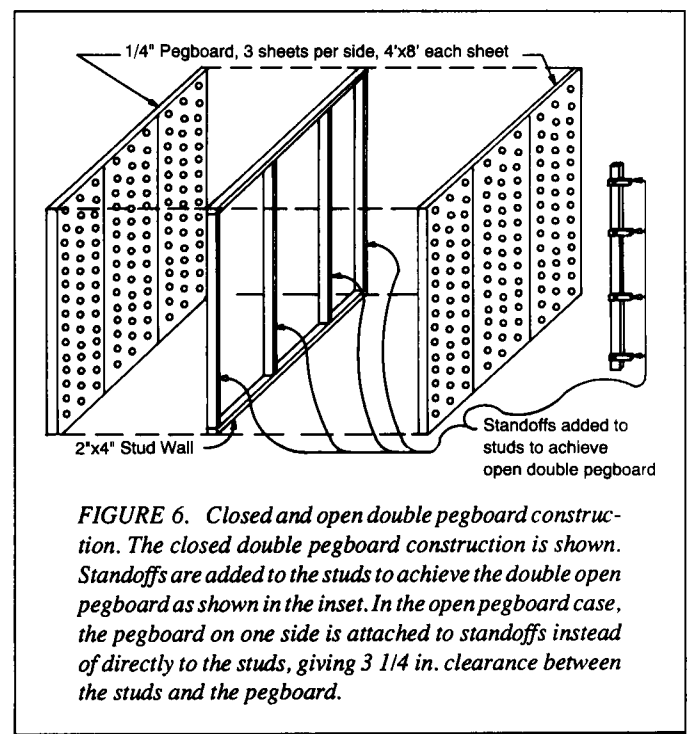


FIGURE 6. Closed and open double pegboard construction. The closed double pegboard construction is shown. Standoffs are added to the studs to achieve the double open pegboard as shown in the inset. In the open pegboard case, the pegboard on one side is attached to standoffs instead of directly to the studs, giving $3 \frac{1}{4}$ in. clearance between the studs and the pegboard.

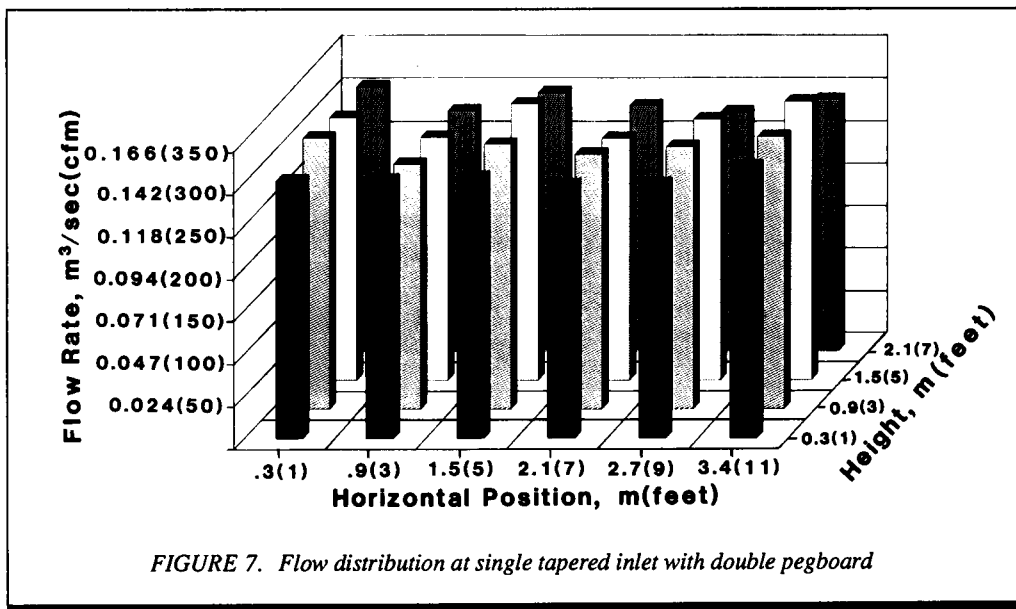


FIGURE 7. Flow distribution at single tapered inlet with double pegboard

[0.25-in.] diameter holes on 2.54-cm [1-in.] centers). For this evaluation, the booths were located between 1.2 m (4 ft) and 3.7 m (12 ft) from the pegboard, and the mannequin was placed alternately at the center (2.4 m [8 ft] from the pegboard) of the three booths. Smoke was released throughout the booths and in the space between the booths and the pegboard to evaluate the effect of the baffles. Tests were conducted at two air speeds in the model IFR, about 40.6 and 25.4 cm/sec (80 and 50 ft/min). Combinations of the following flow correctors were used in the plenum in conjunction with the single pegboard.

rey, Calif.) air velocity meters for the ventilation systems that showed acceptable flow characteristics.

Inlet Configurations and Results

A diagram of the inlet configurations and the corresponding results of the qualitative smoke release study are shown in Figure 4. Observations of airflow patterns resulting from the single inlets were conducted using steady flow only. The double inlets were subjected to steady and fluctuating flows. Figure 5 shows the mechanism used to induce the fluctuating flow. This approach to eddy control and the specific mechanism shown, which was used to produce the fluctuating flow, are the subjects of a pending patent.⁽¹²⁾ The decision as to whether the airflow pattern is acceptable at a given location in the range depends on the path that the smoke travels after it is released from that point. Ideally, the smoke travels directly downrange from the release point to the exhaust at the end of the model IFR. If the smoke begins to travel downrange and subsequently experiences backflow, then the acceptability of the flow pattern depends on whether the path that the smoke travels includes the breathing zone of potential IFR users. Generally, the only backflow that is considered to be acceptable consists of weak flow along the floor, ceiling, or walls. Any other backflow definitely would contribute to the exposure of IFR users, and even weak backflow along the boundaries may have an effect, as observed in the field study.

The smoke release studies summarized in Figure 4 were done in the bare model IFR (no booths or mannequin). The presence of booth walls separating the firing positions did not tend to suppress or enhance the formation of room-scale eddies. These booth walls did redirect the airflow somewhat when they blocked air otherwise flowing with a cross-range velocity component, a relatively minor effect in these studies of room-scale eddy formation.

The single tapered inlet was used in the model IFR to evaluate the effects on the airflow pattern of several combinations of baffles installed in the plenum between the duct outlet for the supply air and a single or a double pegboard (6.4-mm

1. A flow-straightener (a close-packed array of hexagonal tubes 1 cm [0.4 in.] wide and 15.2 cm [6 in.] long) was placed in the duct outlet.
2. A 45.7-cm (18-in.) diameter disc was placed at distances of 10.2–45.7 cm (4–18 in.) from the duct outlet.
3. Two sets of vanes were placed in the jet produced by the outlet duct, at right angles to each other. Each set covered a total area of 91 × 91 cm (3 × 3 ft) and had 9 vanes 2.0 cm (9 in.) wide that were individually adjusted to optimize the flow distribution.
4. Additional vanes were placed to deflect and spread out the jet from the duct outlet.

Although some of these combinations improved the flow pattern, none of them led to a backflow-free pattern at all critical points in the model IFR, using the single pegboard. When a closed double pegboard (Figure 6) was placed at the outlet of the plenum, the only additional requirement necessary to achieve acceptable flow was that the honeycomb flow-straightener be installed in the duct outlet. With this arrangement, some weak backflow occurred at the ceiling and along the upper sides of one booth. Also, the airflow in the 122-cm (4-ft) wide region between the booths and the pegboard was turbulent, which would not be expected to contribute to lead exposures, because the booth would not normally be located there. Flow uniformity data for the single tapered inlet with the honeycomb flow-straightener and a closed double pegboard is shown in Figure 7. The height of the bars in this histogram represents the flow rate through 61 × 61 cm (2 × 2 ft) areas measured at the surface of the outer pegboard with the flowhood. Velocity profiles also were taken in the model IFR using this inlet configuration (Figure 8). The turbulence intensity (relative standard deviation of the velocity) measurements are shown in Figure 9. When the honeycomb was removed from the duct outlet, even with the double pegboard, a backflow developed along the side walls of the range, which caused recirculation of the smoke released at the

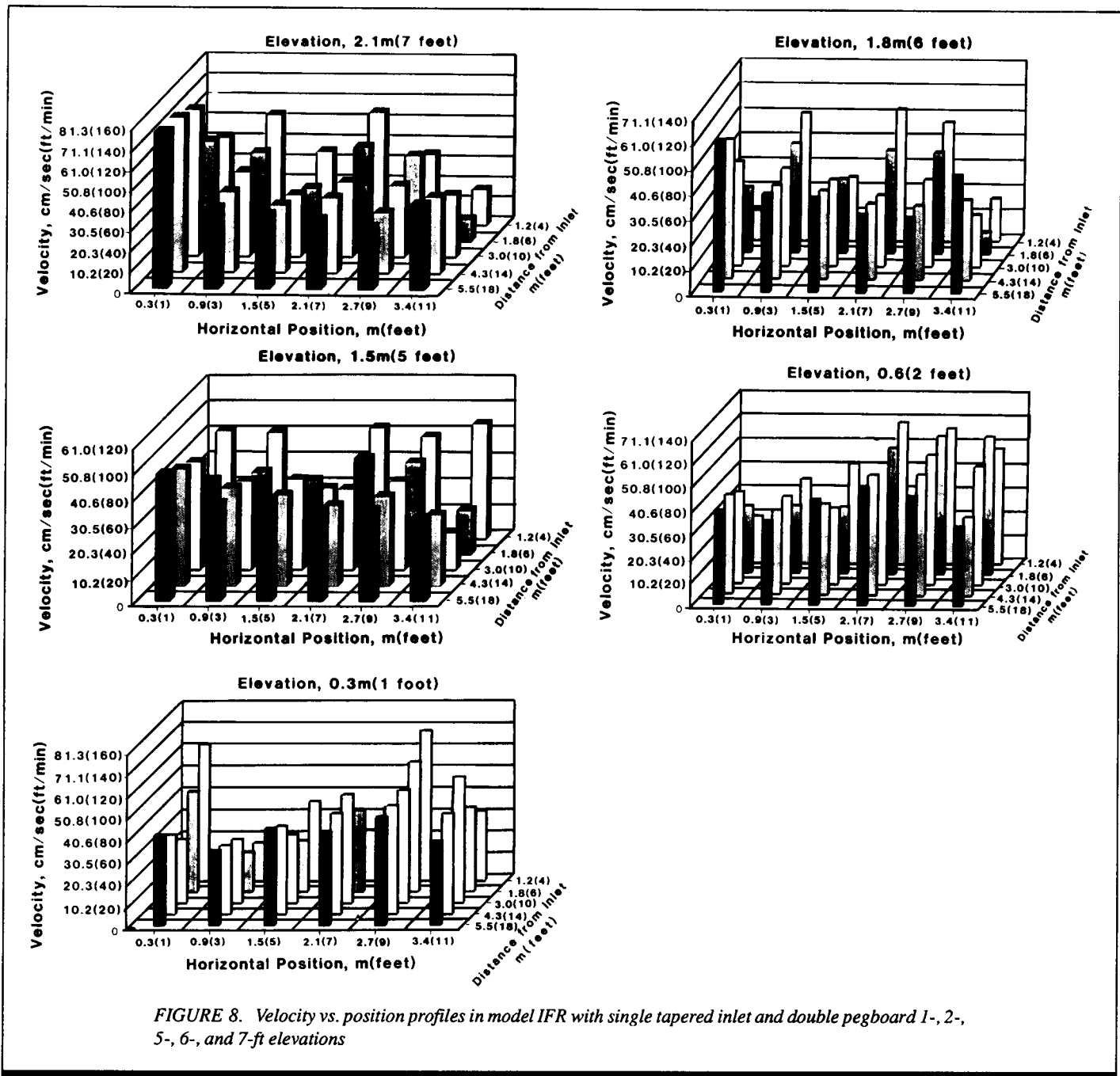


FIGURE 8. Velocity vs. position profiles in model IFR with single tapered inlet and double pegboard 1-, 2-, 5-, 6-, and 7-ft elevations

firing line into the side booths. These side wall eddies were eliminated by placing a 61-cm (2-ft) wide vertical vane at each side of the pegboard (Figure 10), about 30.5 cm (1 ft) from the side wall. Variation of the angle of rotation of the vanes about a vertical axis affected the results, but not very greatly. Vane placement approximately parallel with the side walls gave acceptable results.

The single ceiling inlets (Figure 4B) were evaluated with the duct outlet near the side and at the center of the top of the plenum. A single pegboard and a closed double pegboard were used at the outlet of the plenum. The single pegboard configuration resulted in unacceptable backflow from the pegboard to beyond 3 m (10 ft) downrange. With the closed double pegboard, the flow was acceptable beyond 3 m (10 ft) when the duct was

positioned at the center of the plenum, but not from 0 to 3 m (0 to 10 ft). Even with the closed double pegboard, the flow was unacceptable beyond 3 m (10 ft) when the duct entry point was near the side of the plenum. Data were not taken on these inlets with an open double pegboard. Average air velocity in the IFR was 34 to 38.6 cm/sec (67 to 76 ft/min). These results were obtained in a bare IFR (no booths or mannequin).

The single side inlet (Figure 4C) was evaluated with the duct outlet near the top of the side of the plenum. A single pegboard, a closed double pegboard, and an open double pegboard were used at the outlet of the plenum. With the single pegboard, the flow was acceptable beyond 4.3 m (14 ft); with the closed double pegboard, beyond 3.7 m (12 ft); and with the open double pegboard, beyond 122 cm (4 ft). Average air velocity in the IFR

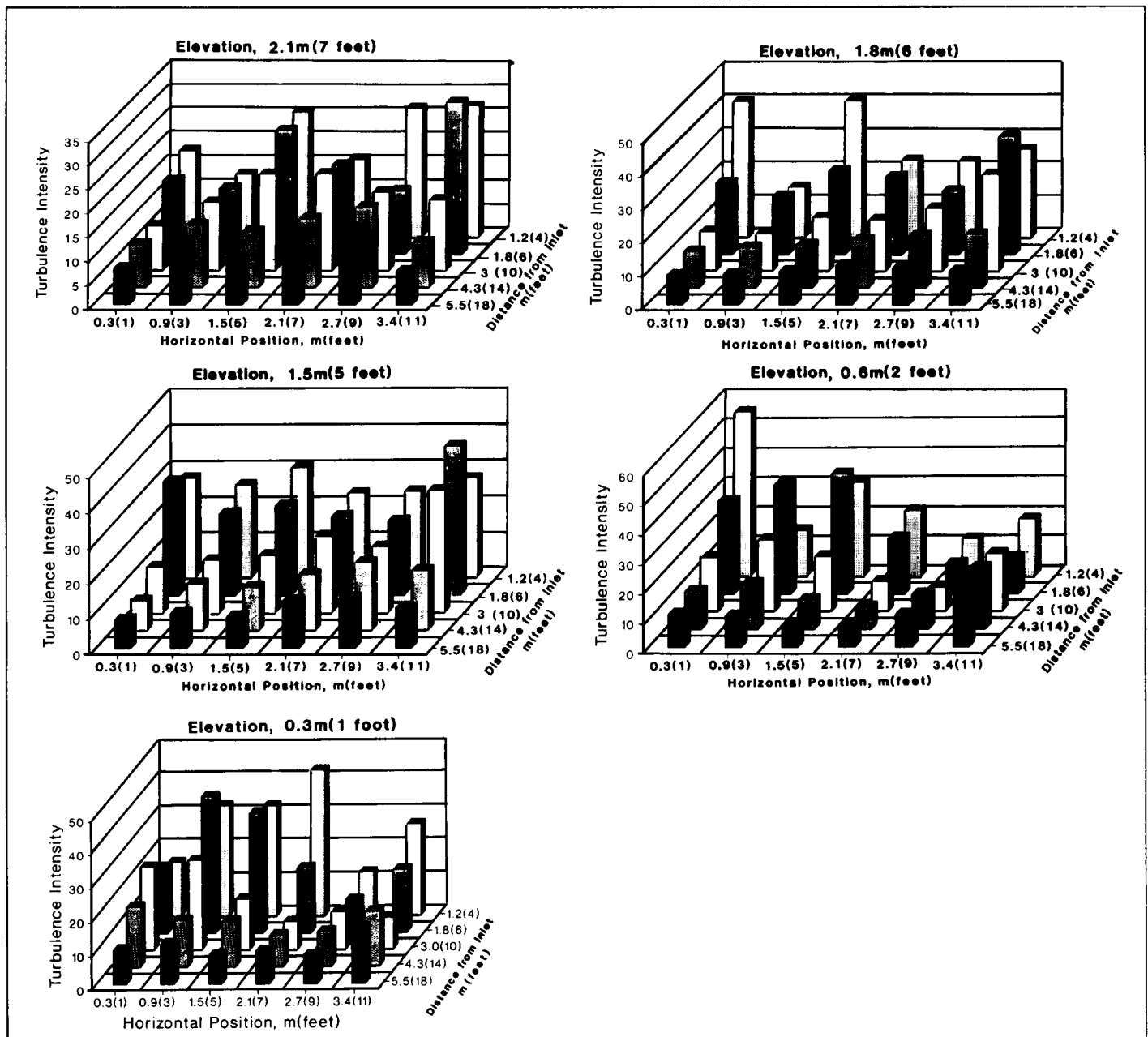


FIGURE 9. Turbulence intensity vs. position profiles in model IFR with single tapered inlet and double pegboard

was 34 to 38.6 cm/sec (67 to 76 ft/min). These results were also obtained in the bare IFR.

The double tapered inlet (Figure 4D) was evaluated using both steady and fluctuating flow with a single, a closed double, and an open double pegboard at the inlet to the model IFR. Also, pegboard was in place across the transition between the tapered and rectangular portions of the plenum at all times, in addition to the various pegboard arrangements at the inlet to the model IFR. When the flow was steady, the pattern was acceptable beyond 1.8 m (6 ft) from the inlet with single pegboard. With either open or closed double pegboard, the flow was acceptable beyond 122 cm (4 ft). For the case of fluctuating flow, all positions beyond 122 cm (4 ft) were acceptable for any of the

three pegboard configurations. The fluctuating flow systems, however, required a modification to achieve this level of effectiveness consisting of the addition of two vanes in the model IFR at the air inlet (Figure 11A). The vanes were 61 cm (2 ft) wide and extended from floor to ceiling. The angle between the vanes and the rear wall of the model IFR was adjusted to minimize room-scale eddies and ranged between 60° and 73°. The lateral location of the vanes was also critical for effective operation. The best contact point between the vanes and the rear wall was between 61 and 91 cm (2 and 3 ft) from either side wall of the model IFR. In addition, a baffle placed inside the plenum along its lower edge (Figure 11B) proved effective in eliminating some cases of backflow along the floor and ceiling.

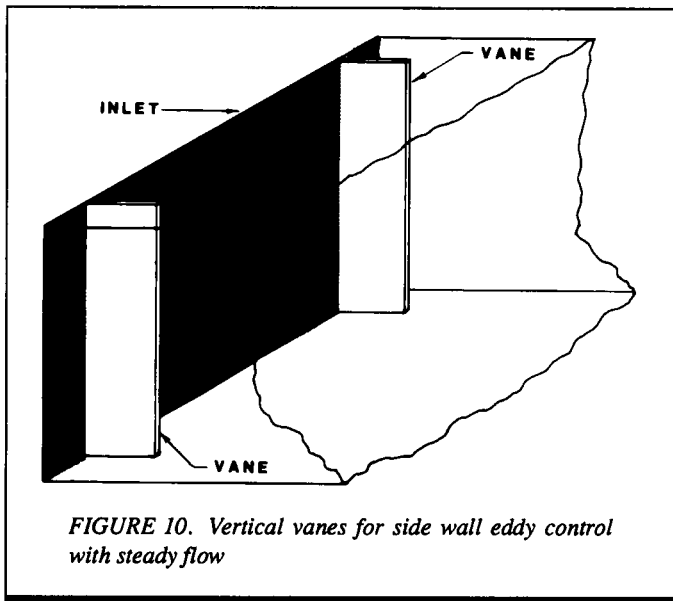


FIGURE 10. Vertical vanes for side wall eddy control with steady flow

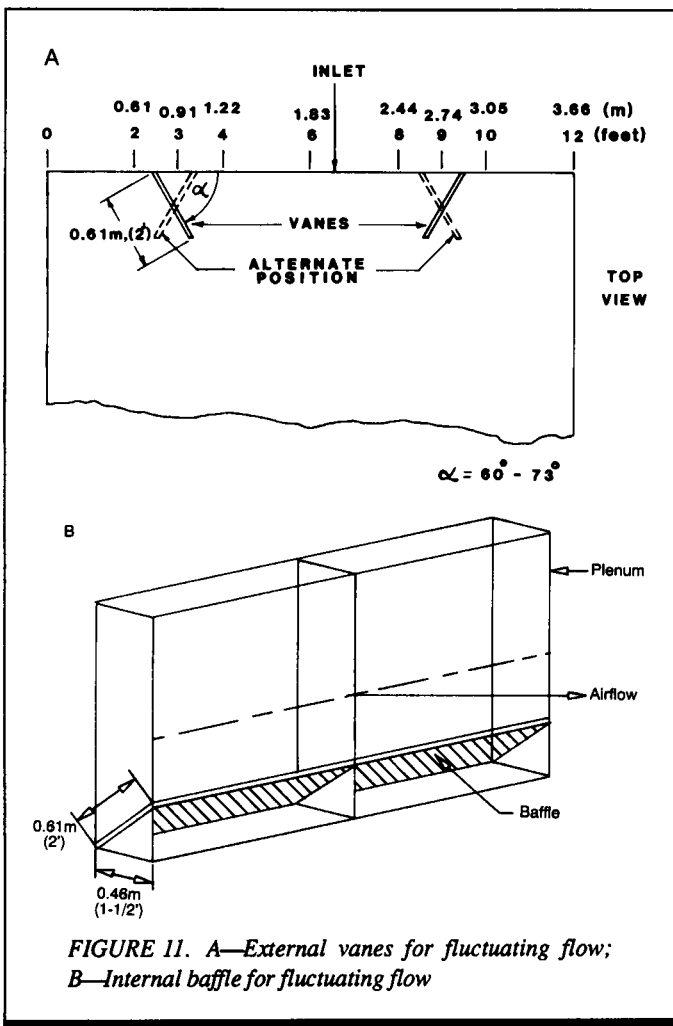


FIGURE 11. A—External vanes for fluctuating flow; B—Internal baffle for fluctuating flow

In preparation for the above study of inlet effects in fluctuating flow systems, the optimum fluctuation rate that should be employed needed to be determined. The double tapered inlet was used in this study with a single pegboard.

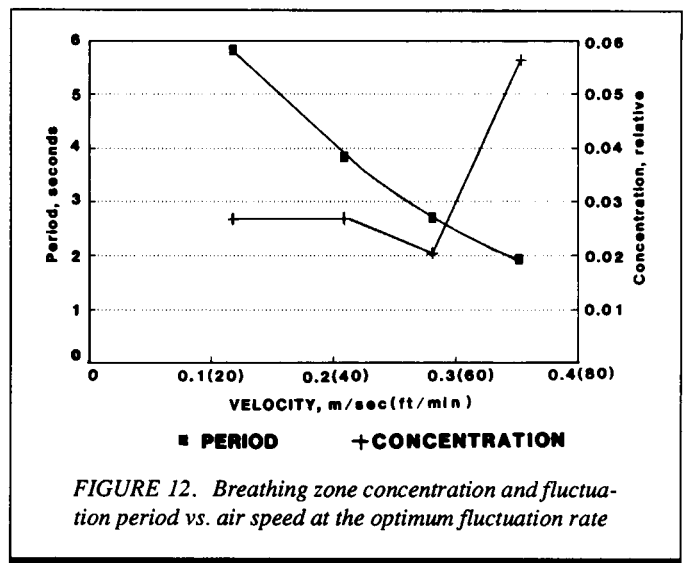


FIGURE 12. Breathing zone concentration and fluctuation period vs. air speed at the optimum fluctuation rate

The outlet duct was bare (no flow-straightener) and the external fins and internal baffle were in place. In this determination, a quantitative measure of ventilation system effectiveness was needed. To this end, a mannequin was placed at a distance of 2.4 m (8 ft) from the inlet in the center booth of the model IFR. The smoke source was placed at a horizontal distance of 53 cm (21 in.) from the mannequin's nose as a simulation of firearm emissions. The RAM-1 was used to sample the breathing zone of the mannequin. Its analogue output (proportional to concentration) was simultaneously recorded on a strip-chart and processed by computer through an analogue-to-digital (A/D) converter. As a result, the average and standard deviations of the concentration were calculated over a 5-min sampling period based on 2000 sampled values of the RAM-1's output. At each of four airflow rates measured at the pegboard in the model IFR, the fluctuation rate was set at three values in a range including and close to the optimum rate, and the time-average smoke concentration was determined. This process yielded a plot of smoke concentration versus fluctuation rate for each of the four airflow rates. A parabolic dependence of concentration on fluctuation rate was assumed, and the minimum in the best-fit parabola determined, giving the optimum fluctuation rate (rate yielding the lowest breathing zone concentration) and the corresponding concentration at the four airflow rates. These optimum data are plotted in Figure 12. A best-fit polynomial from a multiple linear regression is

$$T = 9.300 - 0.1684 v + 9.051 \times 10^{-4} v^2 \quad (1)$$

where T is the optimum period of fluctuation in seconds and v is the average speed of the air flowing in the model IFR in feet per minute. The correlation coefficient $r^2 = 0.9999997$.

Using the same inlet configuration and quantitative evaluation system as described immediately above (mannequin with RAM-1), a comparison of the relative efficiency of the fluctuating flow versus steady flow approach was made at 27 positions in the model IFR from distances of 1.8 to 5.5 m (6 to 18 ft) from the inlet. These data are given in Figure 13. They were collected using an average model IFR air velocity of 28.2 cm/sec (55.5

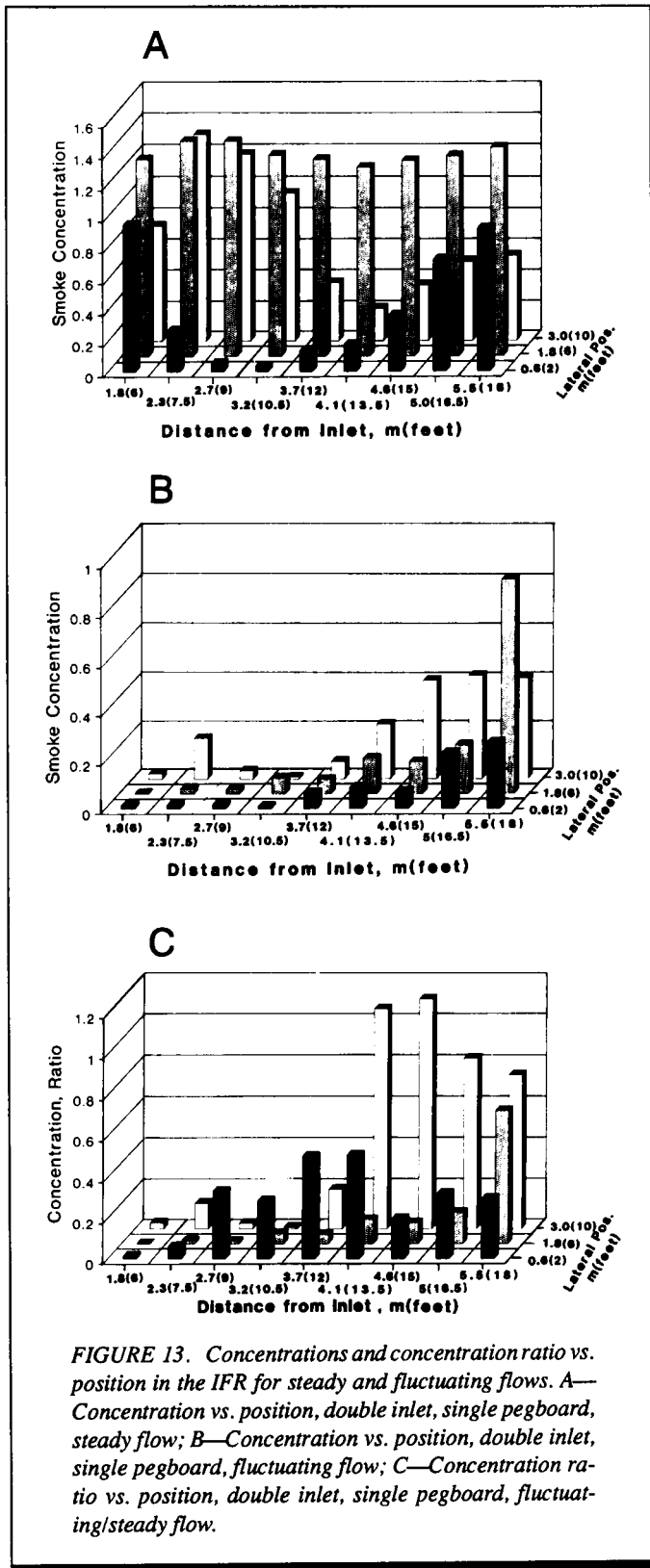


FIGURE 13. Concentrations and concentration ratio vs. position in the IFR for steady and fluctuating flows. A—Concentration vs. position, double inlet, single pegboard, steady flow; B—Concentration vs. position, double inlet, single pegboard, fluctuating flow; C—Concentration ratio vs. position, double inlet, single pegboard, fluctuating/steady flow.

ft/min), near the optimum airflow rate for the fluctuating flow system, according to Figure 12. An example of the concentration versus time data collected at one location in the model IFR is given in Figure 14, allowing a comparison of the results for steady and fluctuating flows.

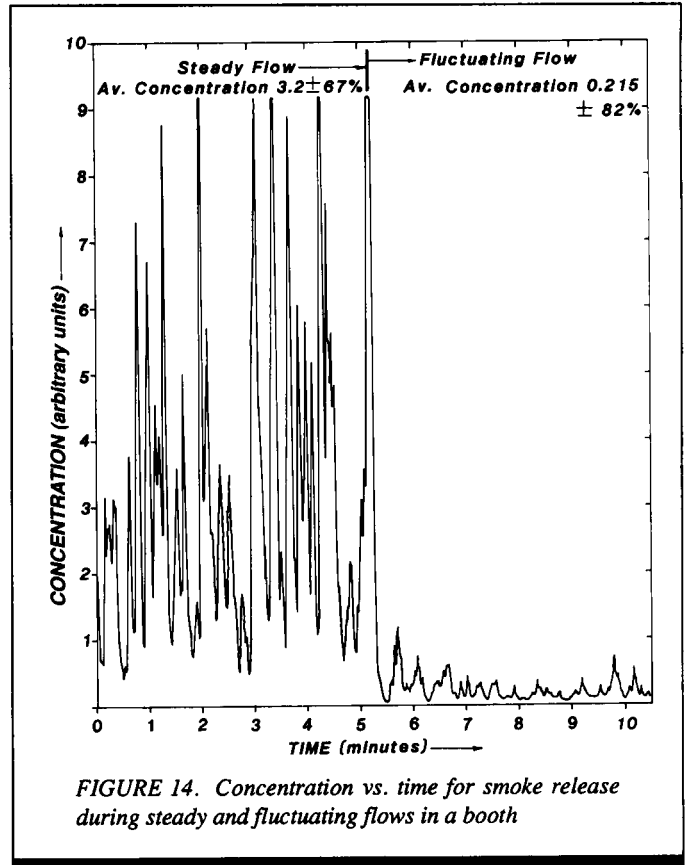


FIGURE 14. Concentration vs. time for smoke release during steady and fluctuating flows in a booth

The final inlet configuration studied consisted of dual square inlets (Figure 4E) operating at a steady airflow rate either with a pegboard grill only or with additional single or open double full cross-section pegboards. The open double pegboard case was also subjected to fluctuating flow. The model IFR contained no booths or mannequin for these evaluations. The square openings were 40.6 cm (16 in.) on a side with 6.35 mm (0.25 in.) pegboard covering the openings. The top edge of the openings was 30.5 cm (1 ft) from the ceiling and a side was 30.5 cm (1 ft) from the side wall of the model IFR. The average velocity of air in the model IFR was 9.5 cm/sec (18 ft/min). The smoke release study for these square openings alone showed that two jets developed, beginning at the openings and extending over the full length of the model IFR, 10 m (33 ft), with strong backflow occurring beneath and between the jets. When a single pegboard was installed, there was still a strong backflow throughout the range below a surface with a 122-cm (4-ft) elevation at the sides of the model IFR and rising to 152 cm (5 ft) at the center. When a closed double pegboard was used, the airflow pattern was acceptable from a distance of 183 cm (6 ft) from the inlet on downrange with a weak backflow occurring between the floor and a height of 61 cm (2 ft) out to the 183-cm (6-ft) distance. The open double pegboard at the inlet yielded acceptable flow also from 183 cm (6 ft) on downrange with a weak backflow near the floor in the 0–183 cm (0–6 ft) range. When a fluctuating airflow was applied to the double pegboard configuration, either open or closed, the acceptable flow region began at 152 cm (5 ft) from the pegboard at the 61 cm (2 ft) elevation,

although there was no backflow from a distance of 61 cm (2 ft) from the pegboard at the breathing zone elevation (1.6 m [5.25 ft]).

Booth Configurations and Results

Discharge of weapons in an IFR takes place in booths, which are separated by walls extending from floor to ceiling (Figure 1). They are open at the uprange end for entrance and egress and may be open or partially closed with a half-height door at the downrange end. In addition, there is usually a waist-high shelf extending across each booth located near its downrange edge. Smoke release studies in the model IFR revealed strong backflow from an eddy attached to the half-height door. The backflow reached back over the top of the shelf and into the breathing zone of a mannequin located in a typical firing position, stomach against the shelf.

When the mannequin was placed 30.5 cm (1 ft) or more away from the shelf, the air coming up from under the shelf prevented emissions at the gun position from entering the breathing zone. A practical way to achieve this separation between shelf and shooter might be to put a bar across the booth 30.5 cm (1 ft) behind the shelf. Objects such as clothing or boxes lying across this gap, however, would provide a path for backflow. Also, a 10-cm (4-in.) wide slot extending across the shelf near its downrange edge resulted in a good flow pattern. Again, objects placed across this slot would provide a path for backflow, probably leading to gun emission exposures. Finally, a curved vane was attached to the uprange edge of the shelf. This vane directed air flowing up from beneath the shelf out over the top surface of the shelf, eliminating backflow over the shelf except when objects blocked the flow.

DISCUSSION AND CONCLUSIONS

A number of possible approaches to eliminating and reducing room-scale eddies generated at the ventilation air inlet to IFRs has been demonstrated. The most effective approach for steady airflow has been the use of a double pegboard at the inlet covering the full cross-section of the model IFR. In most cases, there is an improvement in the airflow pattern if the space between the pegboards is not blocked by the supporting framework but has open channels so that the air can flow laterally between pegboards. Adjacent jets produced by the 0.66-cm (0.25-in.) diameter holes in the pegboard coalesced between 7.6 and 10.2 cm (3 and 4 in.) from the pegboard. The alignment of the holes in the two panels is therefore not considered to be a significant factor in the performance of the inlet. The double pegboard panels were installed so that the holes were not aligned in this study. The effect of the pegboard is to reduce large-scale turbulence levels generated at the inlet so that the portion of the model IFR that is free of backflow begins closer to the inlet. Barriers at the booth will also cause backflow, which can lead to firearm emission exposures, and which can be controlled in several ways. Avoiding the presence of any obstacles to flow between the air inlet and the booths is good practice unless it can be demonstrated, e.g., with a smoke release study, that they will cause no additional exposure to firearm emissions. This prohibition should extend to doors or windows in the inlet that block

airflow. Perforated panels made of transparent materials could be used effectively in some cases where a window through the plenum is necessary.

The introduction of a fluctuating flow at the inlet to the model IFR generally was found to be the most effective approach studied. Fluctuating flow was used along with a perforated panel at the inlet and vanes inside and outside the inlet plenum. The fluctuations not only reduced the occurrence and strength of room-scale backflow but suppressed the backflow and resulting emission exposure caused by the shooter's own wake, at least from a distance of 122 cm (4 ft) to about 5.5 m (18 ft) from the inlet.

The findings reported here are based largely upon observations made in one model IFR. IFRs in use exhibit a variety of inlet and exhaust configurations in addition to variations in overall dimensions⁽¹³⁾ that frequently do not conform to the recommended design. Obviously, there are IFRs to which one or more of these approaches may not apply. An attempt will be made to extend the generality of these results through the use of theoretical models. Also, a field study will be conducted to demonstrate the usefulness of these approaches based upon breathing zone sampling in working IFRs.

Principal Findings

- Obstructions should be kept out of the airflow path between the inlet and firing line. Dense, stationary crowds of people would fit the category of obstruction, as would solid doors or windows located in the inlet wall.
- In booths that have the half-height doors closed, shooters should be prevented from contacting the shelf with their bodies by installing a bar between the shooter and the shelf, for example. Objects placed across the gap between this bar and the shelf would defeat the purpose of the gap.
- For steady airflows, use of a double perforated panel inlet with provision for lateral flow between the panels (open pegboard configuration) was found to be effective in many cases. This inlet panel was not effective for a plenum configuration in which the duct attaches at one end of the top of the plenum.
- In this study, fluctuating airflows significantly reduced exposures caused by eddies. The ventilation system with fluctuating airflow was most effective within 3.7 m (12 ft) of the air inlets, out to 4.6 m (15 ft) with diminished effectiveness, in the model IFR in which the study was conducted.

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