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Title:

Implications of Room Ventilation and Containment Design for Minimization of Worker Exposure to Plutonium Aerosols

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Introduction

In many work environments where toxic or radioactive materials are handled there is always a possibility of accidental airborne releases of toxic or radioactive aerosols or gases. This requires that safety professionals and engineers design effective warning systems and countermeasures to minimize a worker's risk. Computer simulations through computational fluid dynamics (CFD) modeling of air flows and aerosol transport, combined with tracer experiments can provide critical information for determining where to place early warning and monitoring instruments, and how to minimize hazardous materials in the worker's breathing zone.

The amount of a toxin inhaled by a worker depends on the temporal and spatial dispersion patterns in the rooms, time-dependent concentrations in the worker's breathing zone, and the achieved level of protection from alarming air monitors. Aerosol dispersion patterns are driven by complex interactions of room ventilation rate and design, room furnishings, airflow characteristics, human presence and activity, and characteristics of the toxin (i.e., particle size, release rate, release location, etc.). Safety professionals usually assume an instantaneous and perfectly uniform (mixed) concentration field when estimating exposures. This assumption can lead to large underestimates of exposure. For example, research has shown that complete mixing is often not attained (Nicas 1996) or it can take up to several hours for complete mixing (Buchanan et al., 1995). In addition, steep, time-dependent concentration gradients can exist in the vicinity of the release, an area which often the worker(s) who caused the release are within and could get large exposures (Dresher et al., 1997; Whicker et al., 1997).

Buchanan et al., (1995), also demonstrated that airflows can be significantly altered with the simple addition of a partition in a room, and that mixing improves as the airflow disruption increases. This disruption depended on the interplay of the obstruction size, shape, and placement relative to convective flows. Nielsen (1998) showed the influence of furniture on air velocities in occupied areas, and that the influence seemed greater at the higher room air exchange rates. Because in the LANL plutonium facility glovebox sections can be added, removed, or modified, and ventilation rates can fluctuate, it is important to investigate how changes in these can influence general airflow characteristics and aerosol transport.

The goals of this study were to investigate changes in airflow characteristics such as velocity and direction, turbulence intensity, and aerosol dispersion rate as affected by changes in ventilation designs (rate and diffuser design), interior room furnishings, and human presence. Ultimately, strategies for enhanced worker protection could be realized through better understanding and accurate prediction of transport of released aerosols as influenced by ventilation induced airflow patterns, containment structures, and interactions with a worker positioned in front of a containment structure.

Materials and Methods

Experimental Room

The simulated plutonium workroom used in this study is a freestanding structure located within a larger building. The room is a modular metal-wall structure with dimensions of 6.1 x 4.8 x 2.4 m (V = 70.3 m^3) and is furnished with two mockup glovebox lines and an overhead passbox (a sealed tunnel used for moving radioactive samples between gloveboxes in a plutonium facility) inside. The gloveboxes made of aluminized foam board were removable so three different configurations can be arranged: 1) two full rows of gloveboxes and passbox (**FB**), 2) half of the gloveboxes removed and passbox (**HB**), and 3) all gloveboxes and passbox removed (**NB**). Schematic cross-sections of the room configurations are presented in Figure 1a, b, and c.

The room is supplied with close-looped HEPA[1]-filtered air using a portable HEPA filtered blower [2]with the incoming air passing through four 0.2 m-diameter inlet nozzles with 0.3 m-diameter horizontal baffle plates that were located in the ceiling (see Figure 1). Four 0.2 m-diameter adjustable flow exhaust registers are located in the room corners, 0.3 m above the floor. The nominal volumetric air exchange rate was set to approximately 6 h^{-1} (**LV-**low ventilation) or 12 h^{-1} (**HV-**high ventilation) by adjusting the baffle plate on the air-blower outlet line. Because the experimental room is located indoors with a thermally insulated floor, there was no significant (less than 0.5 ^oC) temperature gradient detected between opposite walls (including ceiling and floor), as measured with fine wire thermocouples[3]. The room openings (e.g., sampling or cable ports) were sealed to make the structure as air tight as possible.

Air velocity measurements

A commercial sonic anemometer[4] was used to characterize the airflow patterns. Sonic anemometers measure the time-of-flight of pulsed sound waves across a 10-cm measurement path. To measure air velocity on each axis, two ultrasonic signals are pulsed in opposite directions and times-of-flight of the first signal (out) and second signal (back) are measured and air velocity calculated from the time difference. From these measurements the three orthogonal air velocity components are determined with a programmable sampling rate that can be set from 1 to 60 Hz. A detailed description of air velocity measurements in rooms using sonic anemometry is presented in Wasiolek *et al*. (1999).

The sonic anemometer head was mounted on a mobile cart for ease of transport and leveled after every change in sampling location. The mounting arrangement allowed for changes in the sampling height. The sonic anemometer head (Vogt 1997) and the mobile cart were designed to minimize local airflow disturbance.

Sampling frequency of the sonic anemometer was set to 1 Hz and data was collected over a sampling interval of 600s. The raw, binary data files containing air velocity individual components were converted to ASCII text format, corrected for offset,

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[1] High Efficiency Particulate Filter
[2] Model SP-700, Radiation Protection Systems, 10 Vista Dr, Old Lyme, CT 06371-1541
[3] Model FW05, Campbell Scientific, Inc. Logan, UT, USA
[4] Model CSAT3, Campbell Scientific, Inc. , Logan, UT, USA

and rotated to align orientation of the sonic sampling head with common room coordinates.

By vector summation of individual air velocity vector components u_x, u_y and u_z, the absolute air velocity was calculated for every sample, i, with the equation,

$$u_i\,(\text{cm s}^{-1}) = \sqrt{u_{ix}^{\,2} + u_{iy}^{\,2} + u_{iz}^{\,2}}\,. \tag{1}$$

The time average velocity for a 10-min run was calculated as $\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i$.

Turbulence Measurements

A Statistical measure of the dispersion of data of a variable A about the mean $\bar{A}$ is the unbiased variance σ_A^2 defined as,

$$\sigma_A^2 = \frac{1}{N-1}\sum_{i=0}^{i=N-1}(A_i - \bar{A})^2\,. \tag{2}$$

However, any turbulent variable A, can be split into mean and turbulent part as $A = \bar{A} + a'$, and the substitution of a turbulent part $a' = A - \bar{A}$ into the definition of variance gives (Stull 1988),

$$\sigma_A^2 = \frac{1}{N-1}\sum_{i=0}^{i=N-1}(a'_i)^2 = \overline{a'^2}\,. \tag{3}$$

Therefore, since the standard deviation is interpreted as a measure of the magnitude of the spread or dispersion of the original data from its mean, it can be used as a measure of the level of turbulence. The level of turbulence might be expected to depend on the mean wind speed, so it is often normalized to the air velocity. There are several definitions of turbulence intensity used in the literature. Hanzawa *et al*. (1987) defined turbulence intensity as standard deviation, σ of air velocity u, divided by local mean velocity, $\bar{u}$:

$$TI_t = \frac{\sigma}{\bar{u}} \tag{4}$$

The 19 locations marked in Figure 2 were selected for air velocity measurements. As the experimental room in two of the gloveboxes' configurations has a ceiling-mounted passbox, the sampling heights varied depending on location. At locations 7, 8, 9, measurements were made from only the two sampling heights of 60 and 120 cm, whereas for all sampling locations the sampling heights were approximately 60 (2ft), 120 (4ft) and 180 (6ft) cm above the room floor. In the NB room configuration, all three heights were sampled. The sonic anemometer was positioned 50 cm from glovebox faces and the room walls. Measurements were performed under steady-state conditions, which was established by waiting for at least 5-10 min (one nominal air exchange) after closing and sealing the room door.

Aerosols Measurements

The methodology used in the present aerosol study is similar to the one described in Whicker *et al*. (1997). Because most releases that occur in LANL workrooms are acute "puff" releases (McAtee 1990), our study focused on short duration releases (60 s). In addition, the data analysis in the present study emphasized the time dependent nature of aerosol dispersion. The time resolution of concentration measurements in this study was 10 s. This resolution allowed analyses of the time progression of aerosol dispersion.

To simulate an accidental release, polydisperse Dioctyl Sebacate (DOS) oil aerosols were generated using a custom-made orifice nozzle. Operation of the nozzle was adjusted for releases so aerosol exited the nozzle with low velocity (approximately 1cm s^{-1}) and quickly accommodated local airflow conditions. The particle size distribution was approximately lognormal with the count median diameter of 0.52 μm and geometric standard deviation of 2.0. From analysis of historical accident data it was concluded that most releases took place as a result of some worker action, and not a random event. Therefore the aerosol release nozzle was positioned 120 cm above floor (approximately chest high, the height of glovebox gloves) to simulate a glovebox-glove-failure type release which is the most common cause of airborne releases (Whicker 1993).

An array of sixteen laser particle counters[5] (LPCs) was established in the test room to make aerosol measurements resolved in time and space. Figure 3 shows the aerosol release and LPC locations in the test room. The LPCs were suspended at 120 cm above room floor. Location and height of LPCs were selected to be close to the breathing zone of a worker at a glovebox workstation. The airflow rates of the LPCs were controlled by a critical flow orifice with a sampling rate of about 50 cm^3 s^{-1}. All LPCs were coupled to a multiplexer[6] and the raw data were recorded every 10 s using commercial software[7]. Raw concentration data were corrected for LPC-specific airflow rates and for particle coincidence counting. A 60-s release at every location was repeated three times for quality control, and the results are presented as averages of the three releases.

For this study, the lag time was used as the metric for comparison among changes in the ventilation rates and room configurations. The lag-time was defined as time from the start of the release until the time that an aerosol concentration at sample location exceeded three standard deviations above background on two consecutive 10-s measurements.

Data Analysis

The metrics of lag time, air velocity, airflow direction and turbulence intensity were stratified by ventilation and room configuration. They were then compared against one another using non-parametric tests because the measurement distributions were not normally distributed. The Sign Test was used for the paired comparisons of air velocity, turbulence intensities, and lag times. To look for the effects of room configuration and ventilation rates on the variation of lag times across all sampling locations, coefficients of variations in the mean lag times were compared using a dependent t-test.

Changes in airflow direction were measured by the angle (in radians) between the flow vectors for each ventilation and room geometry condition. Direction vectors for each sampling location were paired with the direction vector at the same location but measured under either a different ventilation rate (same room configuration) or a different room configuration (same ventilation rate). This angle in radians was determined by Equation 5.

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[5] Models 3755 and 7550, Particle Measuring Systems, 5475 Airport Blvd, Boulder, CO 80301
[6] Model 3701, TSI Inc., 500 Cardigan Rd., St. Paul, MN 55164-0394
[7] Model 390040 Advanced Cleanroom Software, TSI Inc., 500 Cardigan Rd., St. Paul, MN 55164-0394

$$\cos^{-1}\theta = \frac{x_1x_2 + y_1y_2 + z_1z_2}{\sqrt{{x_1}^2 + {y_1}^2 + {z_1}^2} \times \sqrt{{x_2}^2 + {y_2}^2 + {z_2}^2}} \quad (5)$$

Histograms of the changes in airflow direction as ventilation rate changed (holding the room configuration constant) and as room configuration was altered (holding the ventilation rate constant) were made to measure the effects of each of the variables.

CFD Analysis

Significant progress was made last FY using computer-aided CFD testing of the effects of alternative ventilation designs on room airflow patterns. Along with ESH-1, and NMT-8, and ESA-DE we identified three alternative designs to be tested against the baseline design (similar to that in the PF facility). These three alternatives were designed based on two important criteria. The first was to try and direct airflow in a downward direction at the faces of the mock gloveboxes and the second was that the alternative design be cost effective and easy to install. The three tested alternative designs included a cone-shaped diffuser and a ceiling with deflector plates and an air shower design. Figure 4 shows the designs of the supply diffusers. In addition, the impacts of humans on the airflows were studied (Figure 5).

Results

Air velocity

Figure 6 shows that the average air velocities for different configurations scaled similarly up with increased ventilation rate. The increase in mean flow velocities between low and high ventilation rates were by factors of 2.71, 2.83, and 2.41 for the full set of gloveboxes (AB), for half gloveboxes removed (HB), and for the empty room (NB), respectively. The minimum and maximum measured air velocity for different configurations varied from 1.6 cm s^{-1} for NBLV ((Loc. 5 at 60 cm), 1.2 cm s^{-1} for HBLV (Loc. 6 at 60 cm), and 1.4 cm s^{-1} for ABLV (Loc. 14 at 60 cm), to 22.9 cm s^{-1} for NBHV (Loc. 14 at 180 cm), 21.4 cm s^{-1} for HBHV (Loc. 16 at 120 cm), and 18.5 cm s^{-1} for ABHV (Loc. 16 at 120 cm).

Figure 7 shows the effects of variations in room geometry and ventilation rates on the direction of airflows as calculated using equation 5. These histograms show that changes in direction are mostly less than 90^o (1.57 radians) across the variations. The median change in angle over the variation in air exchange rate was 0.94 radians with a quartile range of 0.6 to 1.4 radians. The median change in direction for variations across changes in room configuration was 0.92 radians with a quartile range of 0.47 to 1.54 radians.

Turbulence

The capability of turbulence measurements with a sonic anemometer is restricted by the volume averaging of the sensor due to the 10-cm spacing between transducers. For this reason the sampling frequency used in our study was only 1 Hz, which is below typical sampling frequencies used in thermal anemometry. However, the advantages of obtaining directional information about the airflow may compensate for these deficiencies.

The average values of TI were very similar for all configurations and ventilation rates. Because CFD simulations often assume isotropic turbulence (i.e. at any point in the flow the mean-square values of the three fluctuating components are equal $\overline{\sigma_x^2} = \overline{\sigma_y^2} = \overline{\sigma_z^2}$), the validity of this assumption for the studied room configuration and ventilation rate was checked. The results are presented in Table 1. The variances of air-velocity-components averaged for all 19 sonic anemometer locations for a particular room geometry and ventilation rate are very similar suggesting that the turbulence was approximately isotropic for each room and ventilation condition.

Aerosols

One of the primary objectives of the study was to obtain data on aerosol dispersion, especially in regard to transport time. The metrics used for this purpose were the lag time and lag time to the maximum concentration defined earlier in section: Aerosol Measurements. The response time is the critical parameter in placement of air monitors in a work place. Figure 4 shows the decrease in mean lag times with increasing ventilation rate, and Figure 8 compares the distributions of lag times categorized by room and ventilation configuration.

The two-fold increase in ventilation rate resulted in the decrease of the lag time by a factor of 2.0, 1.7, and 1.9 for AB, HB, and NB configuration, respectively. It is interesting to notice the difference in lag time to the beginning of aerosol cloud to lag time to maximum aerosol concentration by a factor of about 2.5. This finding could provide data for revision of some common assumptions used in e.g., industrial hygiene like instantaneous mixing of particulate air pollutants or the times needed for evacuation of contaminated facility. There was also a strong dependence of average lag time on the release location. For example, for the ABLV release at Loc III the average lag time was 83 s, versus 223 s for release at Loc I.

The influence of ventilation rate on aerosol dispersion (mixing) rate was studied in more detail by comparing the variation of lag times across all sampling locations for each release. Figure 9 shows the effects of room configuration and ventilation rate on the coefficient of variation of mean lag times as measured across all LPCs in the room for each release location. Statistical comparisons showed that there was a general decrease in the coefficient of variation as glovebox lines were removed. This suggests that complete aerosol mixing throughout the room is more rapid when there were fewer furnishings in the room. We found no significant differences in the COV when only the ventilation rate was varied but the room configuration was the same.

CFD Results

Of all the supply diffusers analyzed, the air shower with an exhaust located under the glovebox provided the most protective airflow patterns that would sweep aerosols downward and away from the breathing zones. Figures 10 and 11 show the predicted airflow velocities in the horizontal direction at the breathing zone height for the current design and the air shower, respectively. The colors represent a velocity scale with positive velocities in the upward direction. The velocity vectors for the air shower were generally downwards at each of the workstations, with the exception of under the trolley. However, the CFD model of each of the designs assumed 7 room air exchanges per hour and this resulted in low air velocities (a few cm/s) with the air shower design. Therefore, it was important to see the effects of human presence at the workstation. Airflow around a human figure was modeled to both as unheated human (to look at flow blockage only) and as a heated human. Preliminary results suggest that humans create significant alterations in local airflow patterns, which could have significant implications when trying to estimate worker exposure. However, the effects of a worker's presence could be localized and may not significantly affect the general airflow patterns in the room.

Discussion

The objective of the study was to investigate how the changes in the room geometry and ventilation rates influence airflow and aerosol dispersion. Changes in these variables occur quite often in many research facilities that contain toxic materials. Therefore, studying their effects is important when evaluating the worker protection a distribution of air monitors in a room provides or for accurate interpretation of air sample results under varying conditions.

We found that ventilation rate (for the same room configuration) significantly affected lag times and airflow velocities, but not turbulence intensity. As ventilation rates increased the lag times decreased which is likely tied directly to the increase in airflow velocities. The rate that aerosols were transported through the rooms also was affected by turbulent eddies. We found that as the airflow velocities increase, the deviations of the velocities also increased proportionally. This resulted in the relatively constant turbulence intensity across all strata of ventilation rate and room configuration. This suggests that the rate of aerosol dispersion, as reflected by the lag time, is effected by both the airflow velocities in a room, but also by turbulent diffusion rate. This confirms the findings of Siurna and Bragg (1986) who showed that the velocity field and turbulence fields are of fundamental importance in contaminant dispersion by room ventilation. We did find that turbulence intensity appeared to be linearly related to airflow velocity, which may also suggest a non-linear relationship between aerosol dispersion rates and ventilation rate because the dispersion rates are affected by both airflow velocity and turbulence. Finally, changes in ventilation rate, while affecting airflow velocities, did not seem to completely alter the direction of the airflows. We found that over 75% of the changes in direction were less than 1.4 radians (80^o) when changes in ventilation alone were considered.

In addition, the results suggested that changes in the room configuration (for the same ventilation rate) had significant effects on the mean lag times, the COV of these mean lag times, but generally had little effect on the direction of the airflow vector, mean airflow velocities, or the turbulence intensity. In general, there was a trend for lag time to decrease with removal of the mock glovebox sections. It is suggested that room structure has a tendency to slow down mixing by creating areas of relatively stagnate air or air pockets. Removal of the furnishings allows the aerosol to mix more rapidly. Changes in room configuration had no significant effect on airflow velocities, except between HBLV and NBLV experimental setup where the HBLV resulted in higher velocities. It is hard to determine if this is due to experimental uncertainty or perhaps to the presence of the structure in the room increasing the air exchange rate and consequently the airflow velocities.

It is also possible that there is an effect not only of adding structure in a room, but also of placement of the structure relative to the airflow direction and velocity. Buchanan (1995) suggested this effect as they found an increase in mixing with an increase in the airflow disturbance. However, the effects of room furnishings and airflow characteristics on worker exposure are complex. Flynn et al. (1996) found that, under certain airflow conditions, the presence of an object could impede contaminant removal from the breathing zone of a worker unless the airflow was from the side of an worker and swept the airborne material out of the space between the worker and the furnishing.

Deliverables

The deliverables included evaluations of a number of possible ventilation and containment configurations that designed to create favorable airflow patterns, on which recommendations will be based. Also, valuable information on CFD model validation was obtained, along with a sensitivity analysis to help determine the important variables influencing the capture efficiency of slot-boxes and local airflow patterns. The larger audience of safety professionals and facility owners were made aware of our findings through technical presentations and peer-reviewed articles.

Peer-reviewed publications

Rodgers, J.C.; Whicker, J.J.; Voss, J.T. “Comparison of continuous air monitor utilization: a case study,” Radiation Protection Management, May/June:56-64, 1998.

Wasiolek, P.T.; Whicker, J.J.; Gong, H.; Rodgers, J.C. “Room airflow studies using sonic anemometry,” Indoor Air, Vol. 9: 125-133, 1999.

Wasiolek, P.T.; Whicker, J.J.; Tavani, R. “Influence of room geometry and ventilation rate on aerosol dispersion,” Submitted to Indoor Air, 1999.

Whicker, J.J.; Baker, G.; Wasiolek, P.T. “Quantitative measurements of airflows in a plutonium laboratory,” Submitted to Health Physics, 1999.

Whicker, J.J.; Rodgers, J.C.; Lopez, R.C. “ Assessment of need for transport tubes when continuously monitoring for radioactive aerosols,” Health Physics, Vol. 77(3): 322-327, 1999.

Other Publications

Whicker, J.J.; Rodgers, J.C.; Wasiolek, P.T. “Implications of room ventilation and containment design to minimize worker exposure to plutonium aerosols,” In: Technology Development, Evaluation, and Application (TDEA) FY 1998 Progress Report, LA-13579-PR, 1999.

Baker, G. “Air Flow Pattern Studies Using Sonic Anemometry”, Master’s Thesis, University of New Mexico, 1999.

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Konecni, S.; Parietti, L.M.; Whicker, J.J.; Martin, R.A. "Computation and measurement of turbulent dispersion of toxic aerosols and gases in enclosures," Los Alamos National Laboratory Report LAUR-99-2330, Presented at the Third Biennial Tri-Laboratory Engineering Conference on Modeling and Simulation, 1999.

Whicker, J.J.; Wasiolek, P.T.; Ammerman, C.; Rodgers, J.C.; Martin, R.; Tavani, R. "Studies on the effects of air distribution on aerosol mixing in rooms," Los Alamos National Laboratory Report LAUR-99-803, Presented to the DOE Air Monitor User's Group Meeting, Santa Fe, NM, 1999.

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Whicker, J.J., Rodgers, J.C. Fairchild, C.I. Scripsick, R.C. and Lopez R.C. (1997) "Evaluation of continuous air monitor placement in a plutonium facility", *Health Physics*, 2(5): 734-743.

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Table 1. Mean square values of the fluctuating velocity components for different room setup and ventilation rate.

	σ_x^2	σ_y^2	σ_z^2
ABLV	2.79	3.16	2.61
ABHV	17.63	16.47	16.86
HBLV	2.92	3.04	3.35
HBHV	18.74	19.07	18.24
NBLV	2.95	3.02	2.94
NBHV	18.57	17.37	16.87

Figure 1.

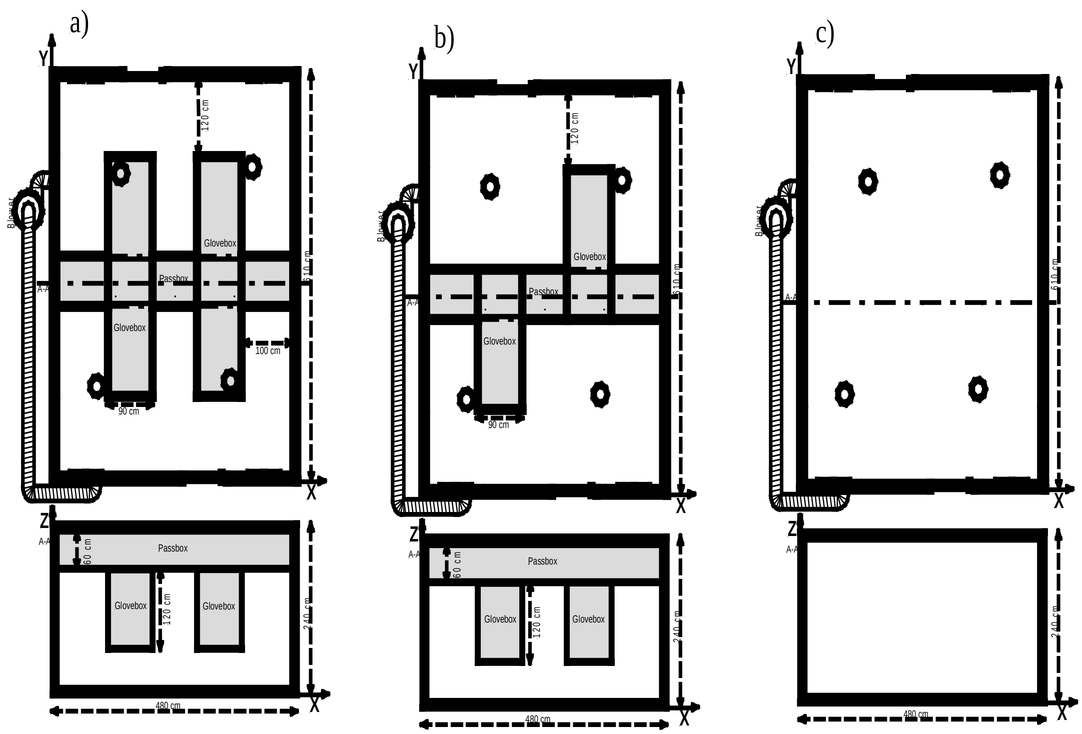


Figure 1. Schematic Diagram of the test-room facility with three different configurations of simulated gloveboxes:

(a) full set of gloveboxes (FB)

(b) half of gloveboxes removed (HB)

(c) no gloveboxes or trolley (NB)

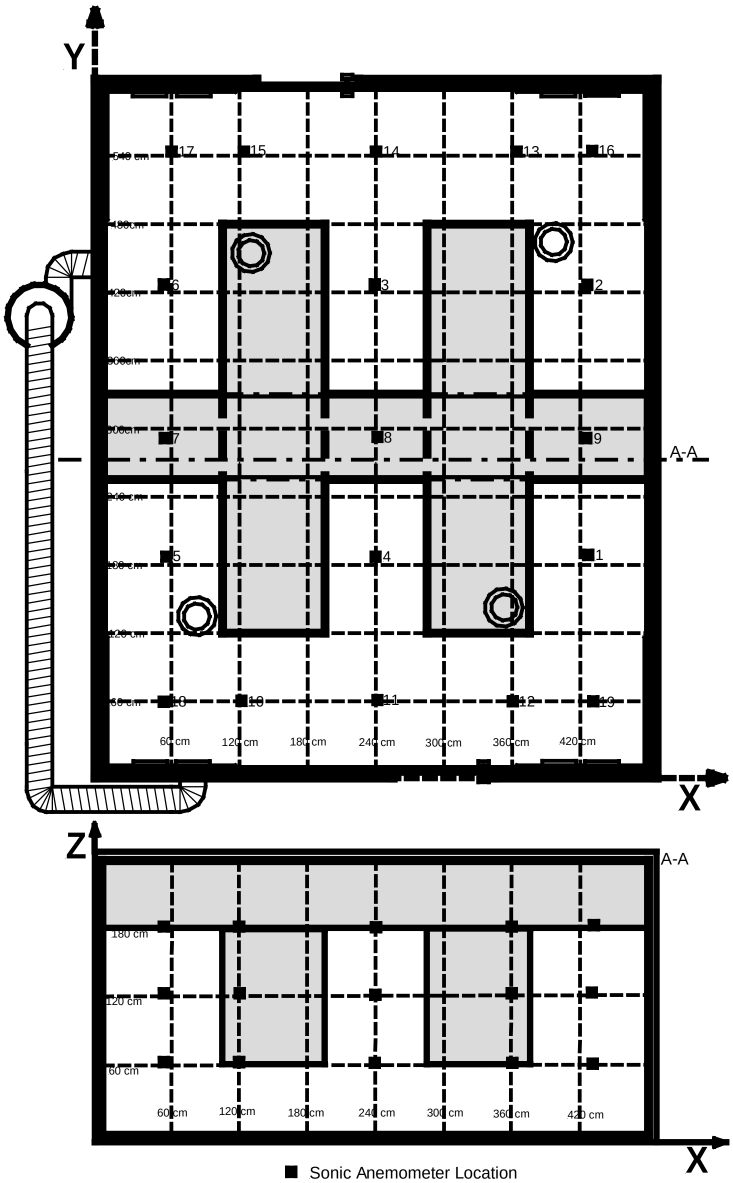


Figure 2. Locations of sonic anemometer measurements in the experimental room.

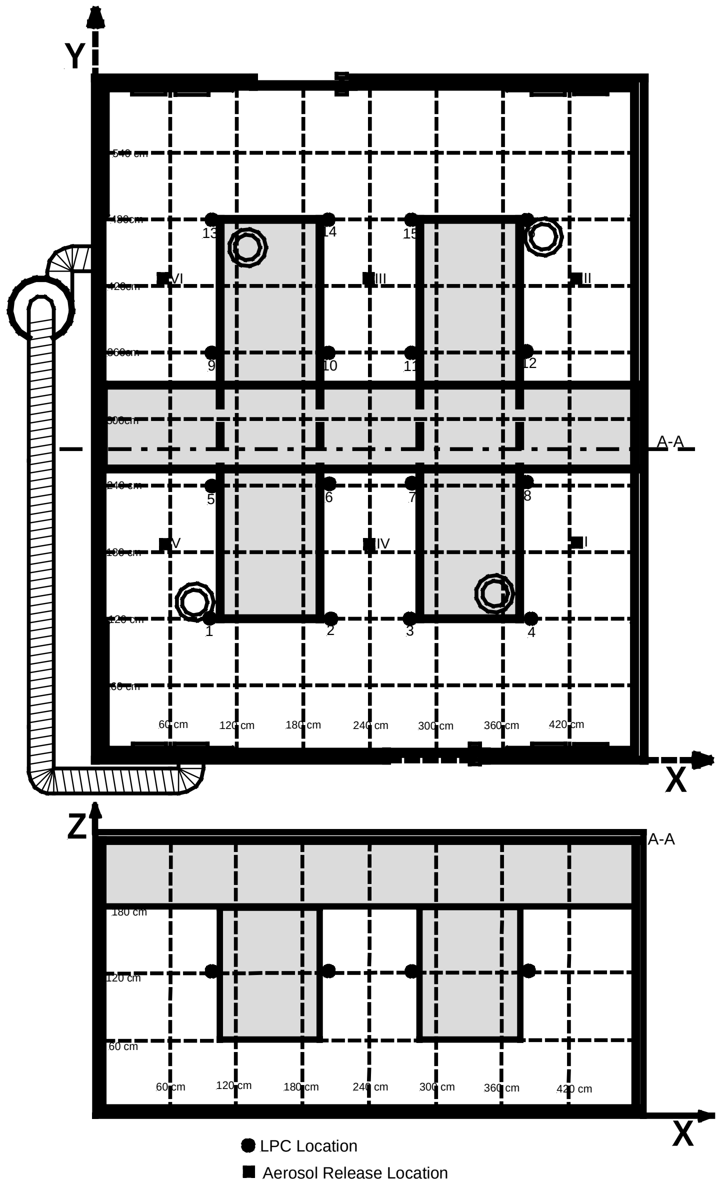
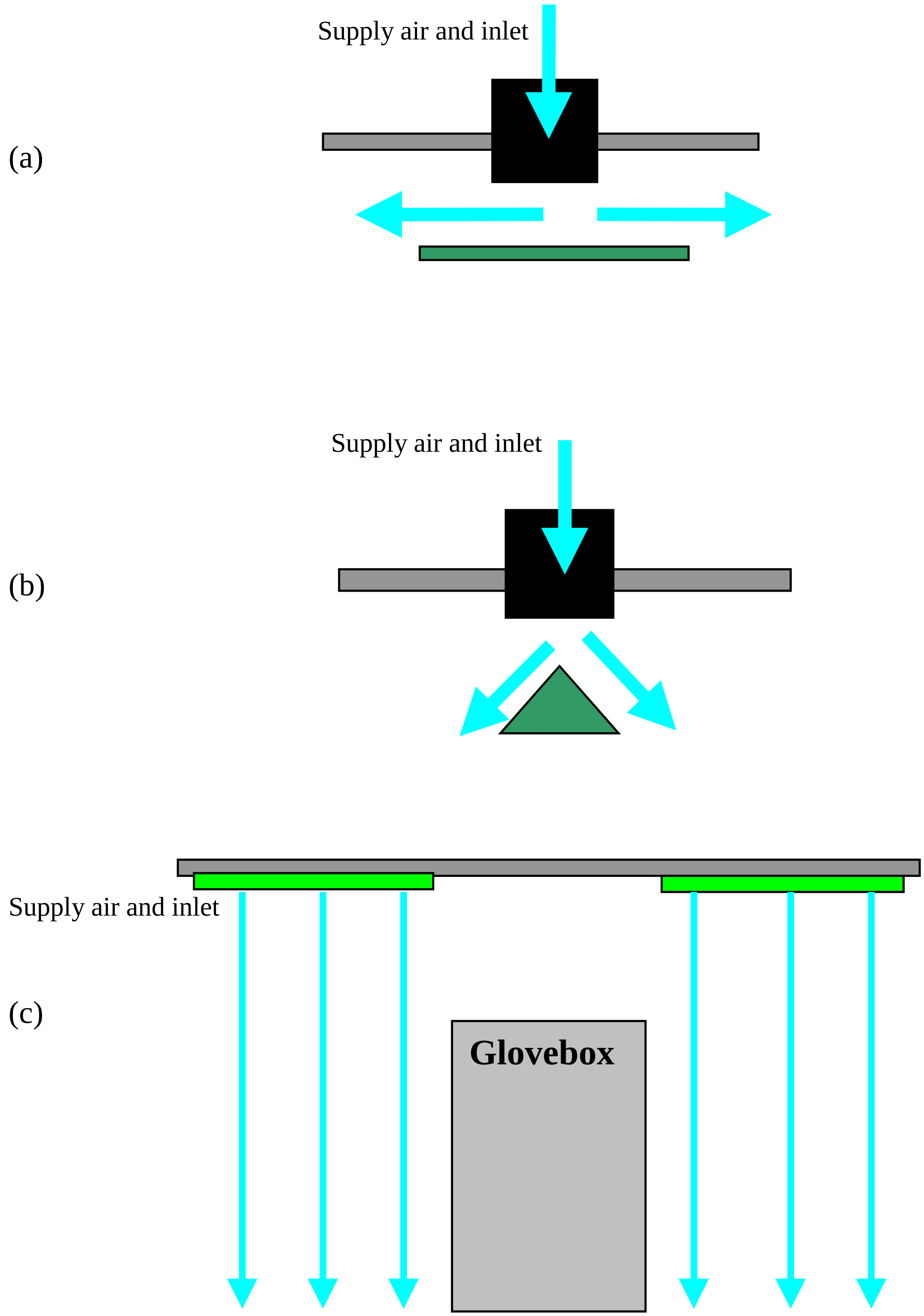


Figure 3. Locations of aerosol releases (Roman numerals) and laser particle counters (LPCs) in the experimental room.

Figure 4. Various supply diffuser designs that were tested for downward airflow in the breathing zone using CFD analysis. Schematic (a) is the current diffuser design, (b) is a cone shaped diffuser, and (c) is the air shower design.



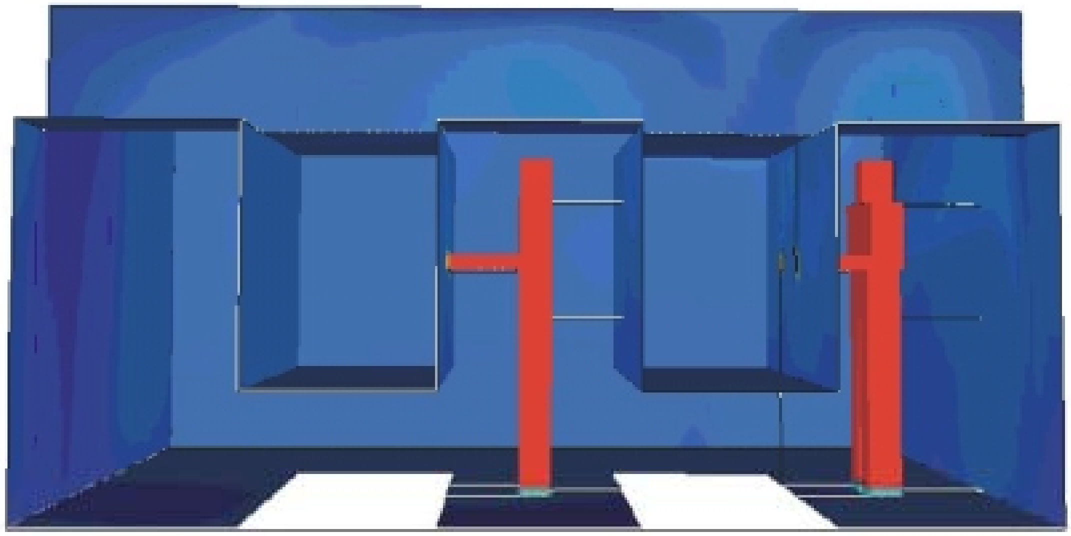


Figure 5. Glovebox Geometry with Simulated Humans

Figure 6. Plot of U_T, the standard deviation of U_T, TI_T, and the lag time as affected by ventilation rate and room configuration.

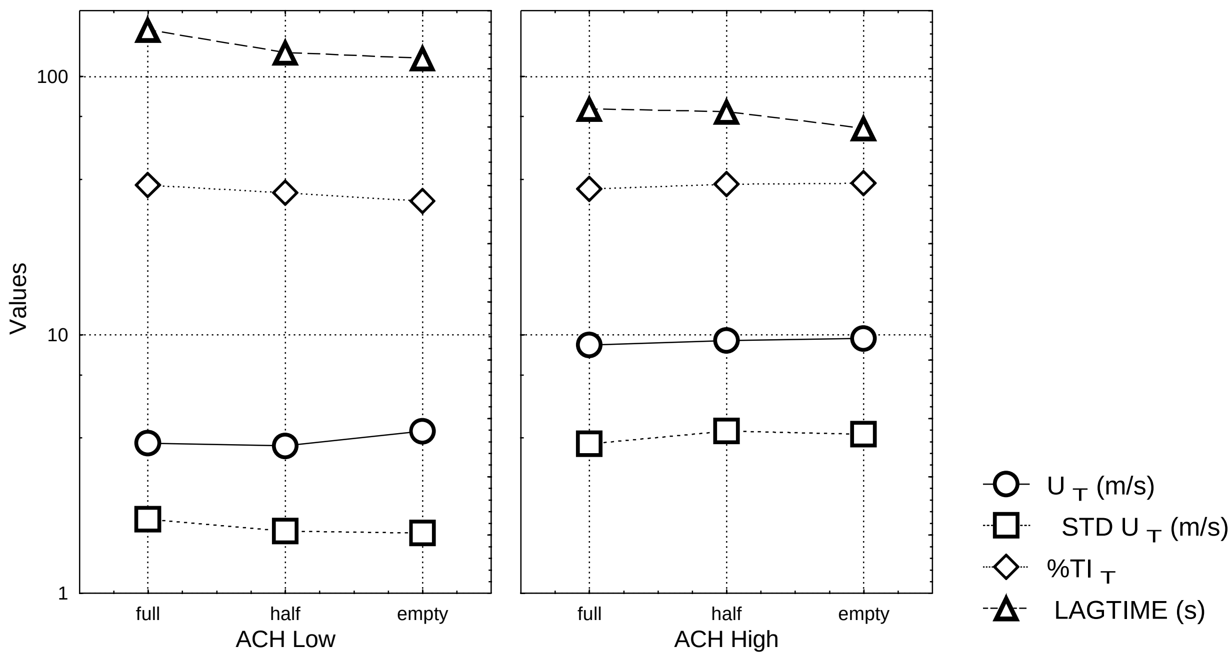


Figure 7. Changes in airflow direction with changes in: (a) glovbox configuration, b) ventilation

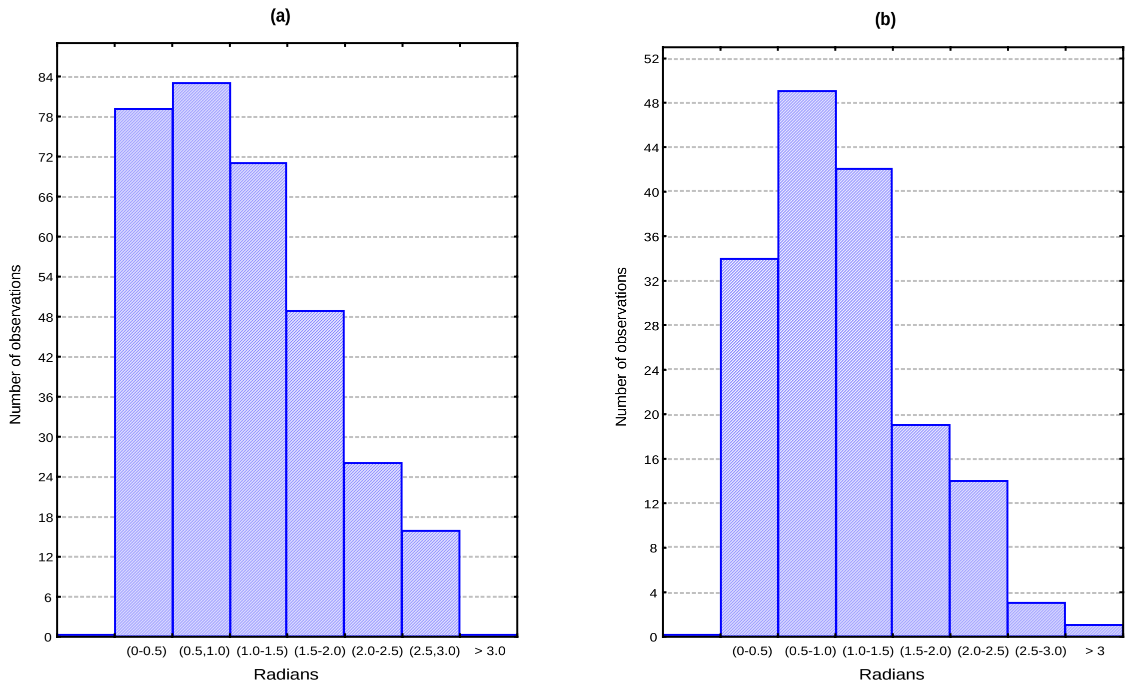


Figure 8. Box & whisker plot of lag times under various room and ventilation conditions.

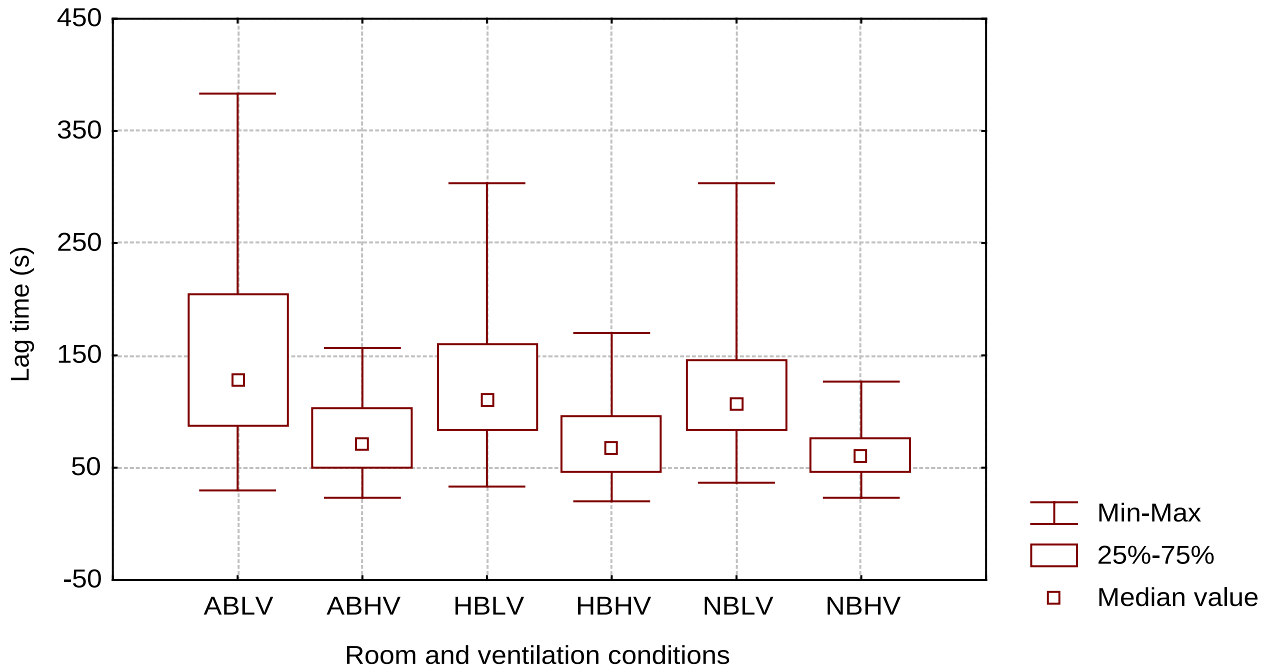
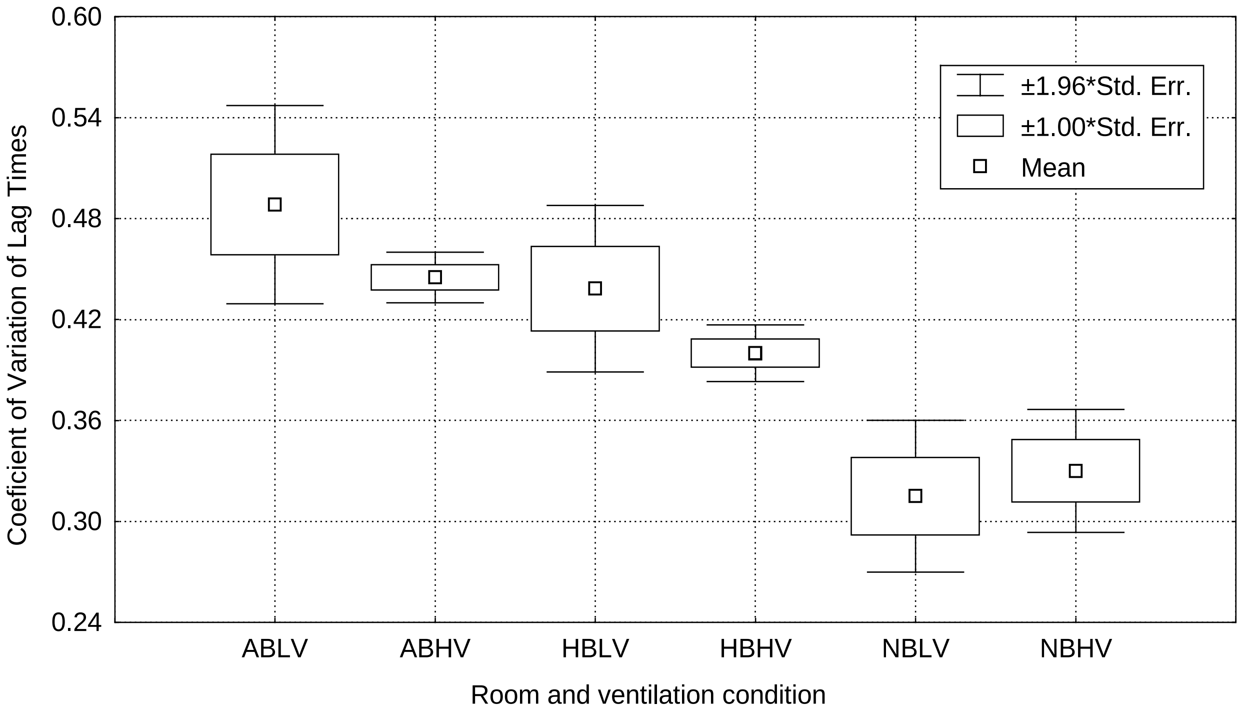


Figure 9. Box & whisker plot of the coefficient of variation among lag times categorized by room and ventilation conditions.



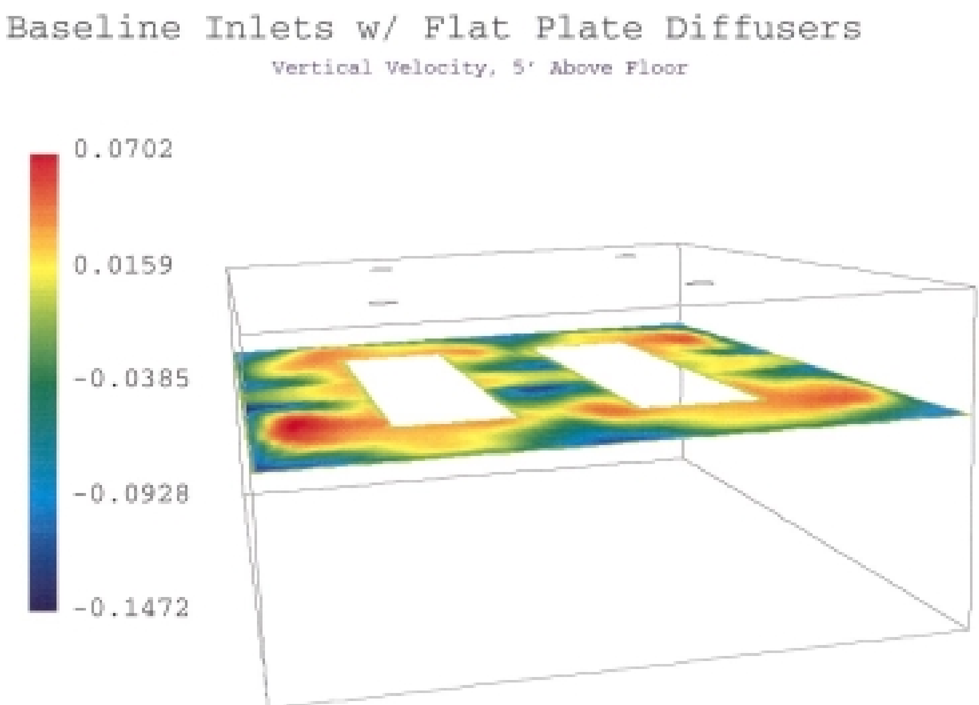


Figure 10. CFD result for flat plate diffuser (baseline PF-4 type)

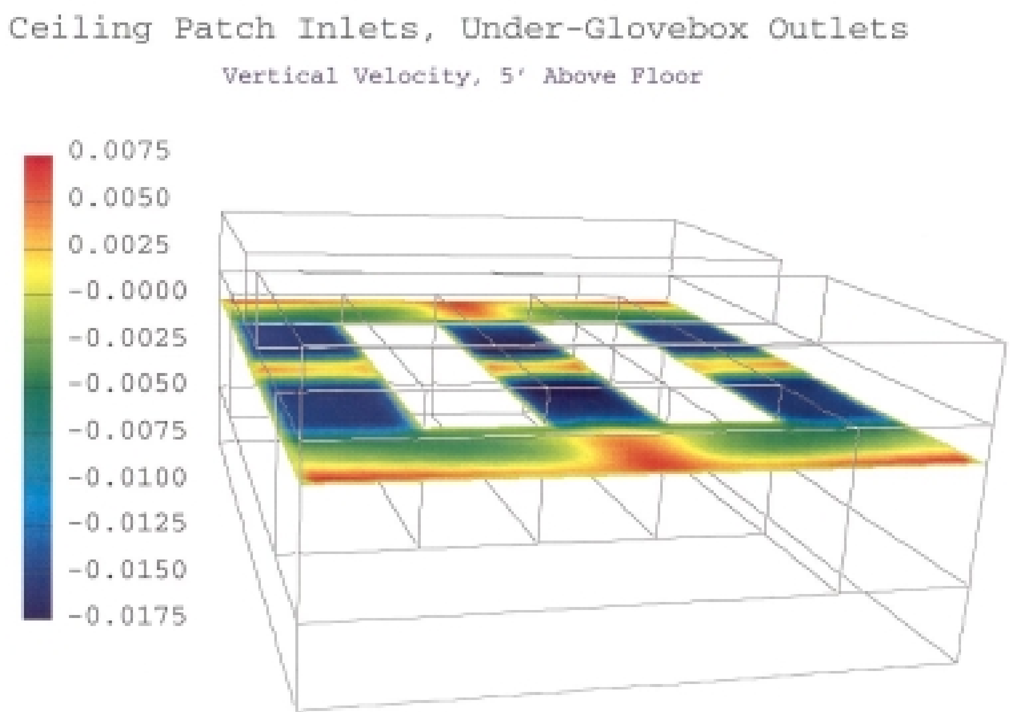


Figure 11. CFD results for air shower diffuser and under glovebox exhausts.