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Air Volume Migration from Negative Pressure Isolation Rooms During Entry/Exit

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Negative-pressure isolation rooms (NPIRs) are used to isolate patients who have a suspected or known airborne infectious disease from the general hospital environment. When a person passes through an NPIR doorway, there exists an exchange of air between the isolation room and the area beyond its door. In a recent study, National Institute for Occupational Safety and Health researchers used sulfur hexafluoride tracer gas to examine the magnitude of air volume migration (AVM) as a function of several independent variables. A small cart carried a mannequin through a doorway separating a laboratory NPIR and a sulfur hexafluoride measurement chamber. The configuration provided simulated entry/exit of a healthcare worker through the doorway. Upon completion of experiments using a swinging door (including various cycle speeds for the door), a sliding door was installed and the experiments were repeated. In all cases examined, air flow rate differential between the air supplied to, and exhausted from, the NPIR was the only statistically significant factor in determining the level of AVM. Across the range of flow differentials examined (50 to 220 ft³/min), AVM ranged from 35 to 65 ft³. This range of AVM remained statistically unchanged regardless of door type, operating speed of the door, or entry to or exit from the NPIR. (Although entry/exit did significantly increase AVM, travel direction, whether entering or exiting the NPIR, did not.) By knowing the level of AVM during entry/exit through a doorway—a cause of airborne contaminant migration through a facility—a more complete assessment of the risk of transmission of an airborne infectious disease is made possible. This study shows that an anteroom or buffer zone outside the contaminated area's doorway will offer a degree of containment during entry/exit not otherwise obtainable. While this study concerned itself primarily with the engineering control of the transmission of airborne infectious diseases provided by ventilation systems, the results are applicable to any environment where a clean area is separated from a less clean area by a doorway. HAYDEN, II, C.S.; JOHNSTON, O.E.; HUGHES, R.T.; JENSEN, P.A.: AIR VOLUME MIGRATION FROM NEGATIVE PRESSURE ISOLATION ROOMS DURING ENTRY/EXIT. *APPL. OCCUP. ENVIRON. HYG.* 13(7):518-527; 1998. © 1998 AIH.

Negative-pressure isolation rooms (NPIRs) are used to isolate from the general hospital environment patients with a suspected or known airborne infectious disease. Mechanical ventilation systems in NPIRs are balanced to provide negative pressure in the NPIR, compared to surrounding areas, by exhausting more air from the NPIR than is supplied.

A minimum flow differential of 50 ft³/min, or an exhaust flow rate 10 percent greater than supply flow rate (whichever provides the greater flow differential) is recommended.⁽¹⁾ The difference in flow rate or flow differential is provided to the NPIR through leak areas. The aggregate flow restriction through the leak areas determines the level of differential pressure, or negative pressure, between the NPIR and contiguous higher pressure areas. As the leak areas become larger, the aggregate flow restrictions and resulting pressure differential (pressure drop) across them diminish.^(2,3) The minimum recommended negative pressure is 0.001 inches of water column ("H₂O").⁽¹⁾ When the isolation room door is opened, the directional control provided by this level of negative pressure is lost. A person passing through the doorway agitates the air currents, creating turbulence, and an exchange of air between the isolation room and the area outside the NPIR door occurs.^(4,5) The pressure drop across the doorway is effectively zero when the door is opened because of the large leak area provided by the opening. Flow differentials needed to maintain negative pressure across an open doorway would be excessive and costly.^(3,6)

Currently, no documented data are available that demonstrate the level of air volume migration (AVM) from NPIR entry/exit.⁽⁷⁾ In this study by National Institute for Occupational Safety and Health (NIOSH) researchers, sulfur hexafluoride tracer gas was used to examine the magnitude of AVM from an NPIR. Independent variables examined to determine their effect on AVM included design flow differential, measured flow differential, design leakage area, calculated pressure differential, air flow rate through the open doorway, object passing through the door (nothing, cart, or cart/mannequin), occurrence of entry/exit (or "none occurred"), and door cycle times. By knowing the level of AVM during entry/exit through a doorway—a cause of airborne contaminant migration through a facility—a more complete assessment of the risk of transmission of an airborne infectious disease is made possible.

Experimental Setup

NPIR

Design and construction of the experimental laboratory NPIR and ventilation system shown in Figure 1 were detailed in a previous article by Hayden *et al.*⁽³⁾ A 12-ft × 6-ft room was constructed adjacent to the experimental NPIR. This room served as the sulfur hexafluoride capture and measurement chamber in the experiments.

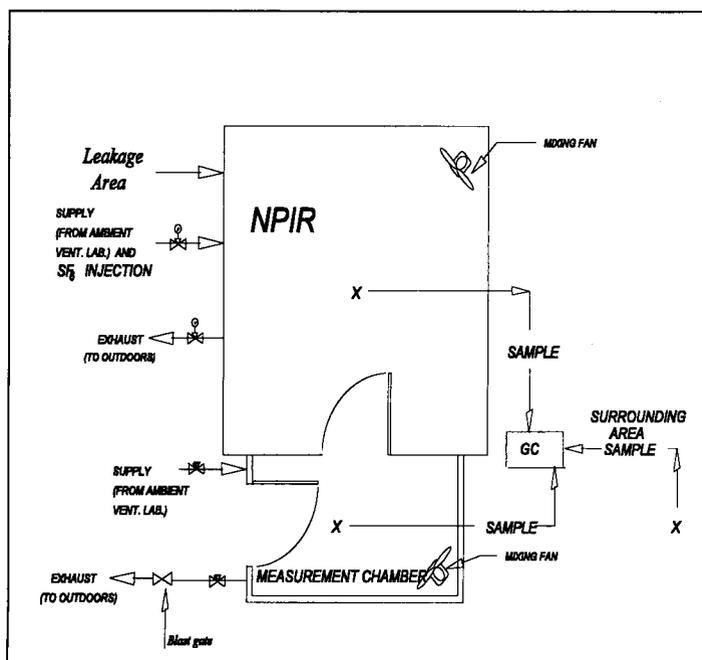


FIGURE 1. Schematic of NPIR experiment setup.

A 42-inch × 80-inch swinging door was installed between the two rooms. The door was outfitted with a Sr-Swing™ (Dor-O-Matic, Harwood Heights, Illinois) door actuator. The door actuator, remotely controlled, cycled the door open and closed during test runs. A Guardsman No. 225 (National Guard Products, Memphis, Tennessee) mortise-mounted automatic door bottom provided a neoprene seal between the door bottom and the floor when the door was closed. Rubber strips provided sealing surfaces at the top and sides of the closed door.

Upon completion of tests using the swinging door, a sliding door was installed. The Originator 110 automatic sliding door (Horton Automatics, Corpus Christi, Texas) provided a 42-inch × 84-inch opening. The sliding door was laboratory tested (Miami Testing Laboratory, Hialeah, Florida) for airtightness as having 2.2 inches² of leakage area.

Exhaust from the measurement chamber was ducted to the laboratory's general exhaust system through two isolating valves, a 10-inch diameter butterfly valve and a 10-inch diameter blast gate. Passive supply air was provided to the measurement chamber through a 10-inch diameter butterfly valve, open to the laboratory environment. This supply butterfly valve provided an 80-inch² flow area into the measurement chamber during door operation.

The leakage area through the butterfly valve into the measurement chamber was less than what might be provided by combined leakage areas in regions contiguous to the NPIR in an actual healthcare setting. The leakage area values in an actual setting could be as high as 3400 inches² (the area through a doorway). The leakage area provided by the butterfly valve nonetheless dominated the other areas of leakage into the NPIR that were less than 80 inches². This ensures that the measurement chamber responds to instantaneous pressure variations caused by the door action in a manner similar to that of a corridor outside of an NPIR. If the measurement chamber

were airtight, these pressure variations or responses would be substantially different than those found in an applied setting. Proper construction of an NPIR for a healthcare facility would ensure that considerably less than 80 inches² of leakage area to the NPIR was allowed.⁽³⁾ In this regard, the actual healthcare setting was properly simulated in the laboratory.

The supply and exhaust butterfly valves were operated pneumatically from a single switch at the computer. The closed butterfly valves isolated the chamber environment for sulfur hexafluoride measurement during the test sequences described later. Open butterfly valves were used to evacuate sulfur hexafluoride between tests and to provide leakage area to the measurement chamber described earlier. The butterfly valves had neoprene seals around the circumference of the valve disc. When the valves were closed, the neoprene seal seated against the valve body, providing a tight seal. Downstream of the exhaust butterfly valve, a closed blast gate allowed investigators to open the butterfly valves (to allow leakage into the measurement chamber during door operation) without exhausting air from the chamber. The blast gate was opened only between test runs as sulfur hexafluoride from a previous run was evacuated from the NPIR and measurement chamber.

Mixing fans were provided in the NPIR and chamber. Fan operation, controlled remotely, minimized sulfur hexafluoride concentration gradients within the rooms. Thermometers were hung in the center of the NPIR and measurement chamber to establish temperature differentials.

Room Entry/Exit

During the entry/exit test runs, a small cart carried a mannequin through the doorway separating the NPIR and the measurement chamber. The configuration provided simulated entry/exit of a healthcare worker through the doorway (Figure

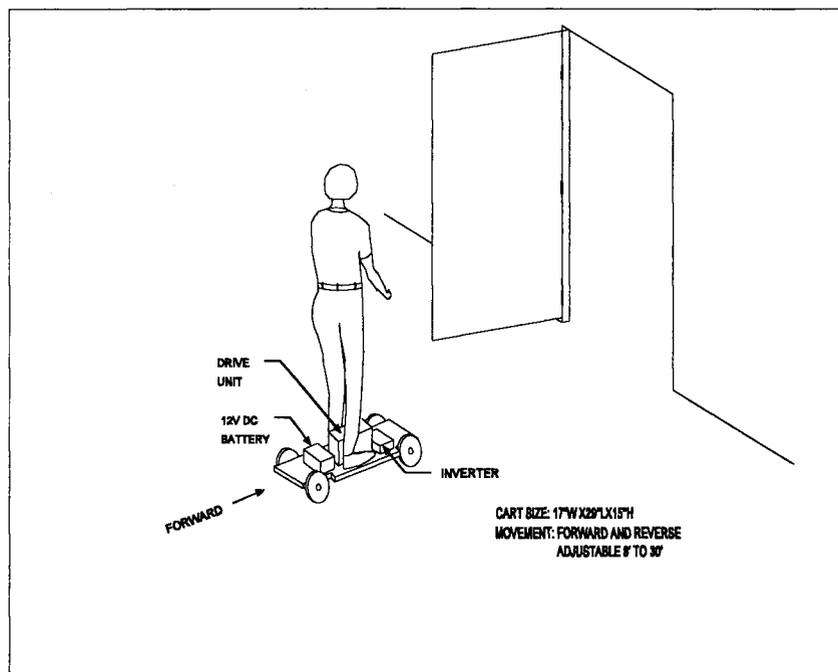


FIGURE 2. Diagram of cart with mannequin.

2). The cart movement was activated by a 3-second delayed trigger. The trigger's count began upon remote operation of the door. The cart was powered by a garage door opener. An on-board battery passed DC voltage through an inverter, thereby providing power to the AC motor of the garage door opener. The stand-alone powered cart had no power cords to impede the motion of the door or the seal around the door when closed. The chain sprockets and cart wheels were sized to provide a forward motion of 2 ft/s.⁽⁵⁾

A Keithley Metrabyte (Taunton, Massachusetts) model DAS20 data acquisition system (DAS) was configured and controlled using Labtech (Wilmington, Massachusetts) Notebook Pro software. Both hardware and software were installed onto a Dell 486-33 computer. The hardware and software provided on/off (open/shut) control of the door actuator mechanism, butterfly isolation valves, cart for mannequin travel, mixing fans in both the measurement chamber and NPIR, and the NPIR supply blower. The DAS also provided real-time monitoring of ventilation flow rates and pressure differentials.

Sulfur Hexafluoride Measurements

A Baseline Industries Inc. model 5550 gas chromatograph (GC) combined with a model 5700 multi-stream sampler measured sulfur hexafluoride concentrations in the NPIR, measurement chamber, and general laboratory environment. The GC instrument was equipped with an electron capture detector and was capable of detecting airborne sulfur hexafluoride concentrations of less than 1 ppb. The GC readout, in counts, was converted to parts per billion from a calibration curve generated prior to commencing the test runs. A 2 percent sulfur hexafluoride concentration gas was supplied to the NPIR supply duct through stainless steel piping and a

rotameter. Supplying the sulfur hexafluoride into the supply duct provided a more uniform, steady-state concentration in the NPIR at a rate faster than if the sulfur hexafluoride had been injected at a location within the NPIR. If the sulfur hexafluoride were injected at a given point within the NPIR, dilution and mixing would be a function of the air flow patterns created by the supply register and the mixing fan. By adding the sulfur hexafluoride in the supply duct, a certain level of dilution and mixing takes place before the supply air ever enters the NPIR, shortening the time to equilibrium. The GC obtained air samples from points located in the geometric center of each room and from the laboratory area outside the measurement chamber door. The GC was continuously exhausted to a chemical fume hood. A limitation of the GC was that only one sample could be obtained and analyzed every 4.5 minutes. Preliminary tests examining the natural decay rates of sulfur hexafluoride in the measurement chamber showed negligible loss of sulfur hexafluoride concentration over a 9-minute period; thus, the time interval between samples was not considered a factor in the test runs.

Experimental Methods

Five experiments were conducted. All experiments examined AVM from the NPIR. The first experiment studied room entry/exit through a swinging door. The second experiment studied NPIR ventilation flow differentials. The third experiment examined a varying-speed swinging door. The fourth and fifth sets were accomplished similarly to the first two sets, except the swing-type door was replaced with a sliding door.

EXPERIMENT 1: ROOM ENTRY/EXIT, SWINGING DOOR. The AVM due to mannequin entry/exit was examined in a group of 24 test runs as shown in Table 1. The runs examined two

TABLE 1. Varying AVM Levels at Measured Flow Differentials Observed When the Swinging-Type Door Was Cycled Opened/Closed During Ingress/Egress

AVM (ft ³)	Measured Flow Differential (ft ³ /min)	Set Leak Area (inches ²)	Calc PD ("H ₂ O)	Pass-Thru	Ingress/Egress
0	57	12.5	0.02	NA	NA*
0	214	45	0.02	NA	NA*
0	214	144	0.003	NA	NA*
4.6	57	80	0.001	NA	NA*
27.7	209	45	0.02	Cart	Ingress
28.5	214	45	0.02	NA	NA
29.7	225	45	0.04	Cart	Egress
32.4	220	144	0.003	NA	NA
33.5	216	45	0.02	Cart/mann	Ingress
36.6	217	45	0.02	Cart/mann	Egress
38.2	216	144	0.003	Cart	Egress
40.9	58	12.5	0.02	NA	NA
41.2	56	12.5	0.02	Cart	Ingress
41.4	52	12.5	0.02	Cart	Egress
43.7	223	144	0.003	Cart	Ingress
45.1	49	80	0.001	Cart	Ingress
46.2	214	144	0.003	Cart/mann	Egress
47.4	57	80	0.001	NA	NA
47.6	51	12.5	0.02	Cart/mann	Ingress
52.3	57	80	0.001	Cart	Egress
53.6	215	144	0.003	Cart/mann	Ingress
54.6	53	80	0.001	Cart/mann	Ingress
58.2	56	12.5	0.02	Cart/mann	Egress
58.7	58	80	0.001	Cart/mann	Egress

*Indicates door remained closed through entire test sequence.

nominal pressure differential levels (high and low, set by varying leakage areas 12.5, 45, 80, and 144 inches²) at two flow differentials (high and low, set at 57 and 214 ft³/min) with the cart or cart/mannequin entering or exiting (a 2 × 2 × 2 experimental design). Control tests consisted of four runs with door cycling only (no entry/exit) and four runs without door cycling (the door remained closed throughout the test run).

To begin a test run, the door between the NPIR and measurement chamber was closed, as was the outer door of the measurement chamber to the ventilation laboratory. Supply flow rate to the NPIR was set at 100 ft³/min. Exhaust flow rate from the NPIR was set at levels corresponding to 157 ft³/min [six air changes per hour (ACH)] or 314 ft³/min (12 ACH). Measured flow differentials and leakage areas to the NPIR for each test run are shown in Table 1. Sulfur hexafluoride was metered into the NPIR at a rate to achieve a steady-state concentration of approximately 500 ppb sulfur hexafluoride. The mixing fans in the NPIR and the measurement chamber were operating to ensure near-perfect mixing within each room.

Each test run was conducted in the following sequence:

At time = 0:

- Air samples were taken from the NPIR until a steady-state sulfur hexafluoride concentration was achieved. A baseline air sample was then taken from the measurement chamber, followed by a baseline air sample from the NPIR. (The measurement chamber air sample verified that the sulfur

hexafluoride had been properly evacuated after the previous run and measured any leakage of sulfur hexafluoride into the measurement chamber during the current run prior to door cycling.)

- The mixing fans were then turned off, the measurement chamber butterfly valves were opened, and the door was cycled opened and closed, during which time the cart and mannequin were activated to either enter or exit the NPIR. The speed of the swinging door was set to open, hold, and close in 5, 2, and 8 seconds, respectively (times are nominal).

When the door returned to the closed position at 0 < time < 1:

- Supply/exhaust to/from the NPIR and sulfur hexafluoride charging to the NPIR room was stopped; measurement chamber butterfly valves were closed. The mixing fan in the measurement chamber was turned on.

At time = 1:

- Steady-state sulfur hexafluoride concentration air samples were obtained from the measurement chamber.

EXPERIMENT 2: FLOW DIFFERENTIALS, SWING DOOR. The AVM at various flow differentials and leakage areas was examined in a group of 32 test runs as shown in Table 2. The runs examined three pressure differential levels (high, medium, and low, set by varying leakage areas of 0, 36, and 80 inches²) at three flow differentials (high, medium, and low, set at 57, 136,

TABLE 2. AVM Levels at Measured Flow Differentials Observed When the Swinging-Type Door Was Cycled Opened/Closed (No Ingress/Egress)

AVM (ft ³)	Measured FD (ft ³ /min)	Set Leak Area (inches ²)	Flow Through Doorway (ft ³ /min)
20.5	216	0	216
25.3	217	36	121
26.7	217	0	217
27.6	215	0	215
29.1	221	80	71
30.0	220	36	120
30.9	135	36	55
30.9	137	36	61
31.2	132	0	132
31.3	137	36	32
33.2	210	36	103
34.2	139	0	139
35.9	145	80	35
36.6	132	36	67
36.6	140	36	64
36.7	137	80	32
37.5	135	0	135
37.8	137	36	61
38.0	143	80	38
38.0	132	36	67
38.0	213	80	71
38.6	54	80	0
38.9	150	36	70
39.0	57	80	0
41.4	60	36	19
41.8	207	80	65
41.9	56	36	11
43.5	58	0	58
43.6	55	80	2
44.1	56	0	56
47.0	50	36	4
47.1	54	0	54

and 214 ft³/min). Supply flow rate to the NPIR was set at 100 ft³/min. Exhaust flow rate from the NPIR was set at levels of 157, 236, and 314 ft³/min, corresponding to 6, 9, and 12 ACH, respectively. Each differential flow/leak area combination was repeated three times. The medium range (differential flow = 136 ft³/min, leakage area = 36 inches²) setting was repeated a total of eight times. The experiment set methods and sequence were as previously described, except the cart and mannequin were not used (i.e., no entry/exit). Additionally, the effect on AVM of varying flow rate through the NPIR doorway was also examined for experiment 2 test runs. Upon completion of each test run in the set, flow rate through the leakage area with the door opened was measured with a flow hood. The flow rate through the NPIR doorway was then calculated as:

$$Q_{\text{door}} = (Q_{\text{exhaust}} - Q_{\text{supply}}) - Q_{\text{LA}} \quad (1)$$

where:

$$Q_{\text{door}} = \text{flow rate through the NPIR door when the door is open}$$

$$\begin{aligned} Q_{\text{exhaust}} &= \text{exhaust flow rate} \\ Q_{\text{supply}} &= \text{supply flow rate} \\ Q_{\text{LA}} &= \text{flow rate through the leak area when the NPIR door is open} \end{aligned}$$

EXPERIMENT 3: VARYING SPEED, SWING DOOR. The third experiment examined the effect of varying the speed of the swinging door on AVM from the NPIR. The speed of the swinging door was set to open, hold, and close in 5, 2, and 8 seconds, respectively (times are nominal). Test runs were completed—the door operating speed was slowed to open in 8 seconds, hold open 2 seconds, and close in 12 seconds (times are nominal)—and then repeated at the slower door speed. As shown in Table 3, each of nine differential flow rate/leakage area configurations was examined for the two door speeds. The experiment set methods and sequence were as described in experiment 1, except the cart and mannequin were not used (i.e., no entry/exit).

EXPERIMENTS 4 AND 5: ROOM ENTRY/EXIT AND VENTILATION PARAMETERS, SLIDING DOOR. As shown in Tables 4 and 5, experiment sets 4 and 5 were conducted in a manner identical to experiment sets 1 and 2 with one exception. The exception was that the swinging door was replaced by a sliding door. The sliding door opened, held open, and closed in 5, 2, and 8 seconds, respectively. The effect on AVM due to varying the speed of the sliding door was not examined.

Data Analysis

The sulfur hexafluoride concentration in the measurement chamber prior to door cycling (time = 0) was measured and subtracted from the concentration in the chamber after opening/closing the door (time = 1). The result was used to calculate the volume of air that transferred from the NPIR to the chamber during door operation only. The calculation used is a simple dilution formula where an unknown volume of known concentration is mixed into another known volume with a resulting known concentration at time = 1. This is shown as:

$$\text{volume}_{\text{unknown}} \times C_{\text{time}=0} = \text{volume}_{\text{known}} \times C_{\text{time}=1} \quad (2)$$

where:

$$\begin{aligned} \text{volume}_{\text{unknown}} &= \text{volume of air migrating from the NPIR to the chamber} \\ C_{\text{time}=0} &= \text{steady-state sulfur hexafluoride concentration in the NPIR at time} = 0 \\ \text{volume}_{\text{known}} &= \text{volume of the measurement chamber} \\ C_{\text{time}=1} &= \text{steady state sulfur hexafluoride concentration in the chamber at time} = 1 \end{aligned}$$

Since the door cycle time was minimal (about 15 seconds), the concentration in the NPIR was assumed to be constant for the duration of this event. Temperature differentials between the NPIR and measurement chamber were less than 2°F, and therefore thermal effects were ignored.⁽⁸⁾ The volume of air leaving the NPIR and migrating into the chamber during door operation can be calculated as follows:

TABLE 3. AVM Levels at Measured Flow Differentials Observed When the Swinging-Type Door Was Cycled Opened/Closed at Variable Speed (No Ingress/Egress)

AVM (ft ³)	Measured Flow Differential (ft ³ /min)	Set Leak Area (inches ²)	Flow Through Doorway (ft ³ /min)	Complete Door Cycle Time (seconds)
20.5	216	0	216	22.1
22.7	213	36	106	14.3
29.0	214	0	214	15.1
29.1	221	80	71	20.2
32.1	140	80	35	13.5
33.2	210	36	103	20.3
34.2	139	0	139	25.0
35.2	213	80	63	13.7
35.6	137	36	61	14.6
36.7	137	80	32	20.3
37.8	137	36	61	20.3
38.3	57	36	11	13.7
38.6	54	80	0	20.1
44.9	148	0	148	15.2
47.0	50	36	4	20.2
47.1	54	0	54	20.4
52.0	55	80	1	13.5
59.7	57	0	57	13.8

TABLE 4. AVM Levels at Measured Flow Differentials Observed When the Sliding-Type Door Was Cycled Opened/Closed During Ingress/Egress

AVM (ft ³)	Measured Flow Differential (ft ³ /min)	Set Leak Area (inches ²)	Calc PD ("H ₂ O)	Pass-Thru	Ingress/Egress
0	214	45	0.02	NA	NA*
0	214	144	0.003	NA	NA*
1.4	57	12.5	0.02	NA	NA*
2.6	57	80	0.001	NA	NA*
9.0	220	45	0.02	Cart	Egress
9.6	213	144	0.003	NA	NA
9.7	218	45	0.02	Cart	Ingress
9.9	214	144	0.003	Cart	Egress
11.7	215	45	0.02	NA	NA
17.7	217	144	0.003	Cart	Ingress
30.8	54	12.5	0.02	NA	NA
31.0	50	80	0.001	NA	NA
33.7	219	45	0.02	Cart/mann	Egress
35.7	56	12.5	0.02	Cart	Ingress
36.1	214	45	0.02	Cart/mann	Ingress
39.8	55	80	0.001	Cart	Egress
41.2	215	144	0.003	Cart/mann	Ingress
41.2	58	12.5	0.02	Cart	Egress
43.8	56	80	0.001	Cart	Ingress
47.0	55	80	0.001	Cart/mann	Egress
49.1	218	144	0.003	Cart/mann	Egress
50.1	53	12.5	0.02	Cart/mann	Egress
66.1	57	12.5	0.02	Cart/mann	Ingress
74.1	58	80	0.001	Cart/mann	Ingress

*Indicates door remained closed through entire test sequence.

TABLE 5. AVM Levels at Measured Flow Differentials Observed When the Sliding-Type Door Was Cycled Opened/Closed (No Ingress/Egress)

AVM (ft ³)	Measured Flow Differential (ft ³ /min)	Set Leak Area (sup2)	Flow Through Doorway (ft ³ /min)
4.8	229	36	135
5.1	217	36	124
5.9	215	80	79
6.5	217	80	82
7.2	219	0	219
8.0	152	0	152
8.1	210	80	85
8.3	216	36	124
9.1	149	36	86
12.5	143	0	143
12.7	143	36	78
13.5	143	36	78
15.5	135	0	135
15.7	138	36	76
15.7	138	36	74
19.0	145	80	41
19.1	146	80	43
19.5	140	36	84
19.5	221	0	221
20.2	141	80	42
20.7	136	36	78
22.7	57	80	0
24.5	144	36	78
26.4	227	0	227
27.0	49	0	49
27.5	58	36	18
31.0	50	0	50
33.7	53	80	0
33.9	51	80	4
35.3	56	36	17
37.6	56	36	17
38.1	52	0	52

$$AVM_{NPIR \rightarrow \text{measurement chamber}} = \frac{(C_1 - C_2) \times \text{volume}_{\text{measurement chamber}}}{C_3} \quad (3)$$

where:

C_1 = sulfur hexafluoride concentration in measurement chamber at time = 1

C_2 = sulfur hexafluoride concentration in measurement chamber at time = 0

C_3 = sulfur hexafluoride concentration in NPIR at time = 0

$$\text{volume}_{\text{measurement chamber}} = 576 \text{ ft}^3$$

A spreadsheet program was used to model AVM by linear regression analyses of the data for each of the five experiment

sets shown in Tables 1 through 5. Independent variables examined in the regression analysis to determine their effect on AVM again included design flow differential, measured flow differential, design leakage area, calculated pressure differential, air flow rate through the open doorway, object passing through the door (nothing, cart, or cart/mannequin), occurrence of entry/exit (or "none occurred"), and door cycle times. Factors that showed no statistically significant effect on AVM were dropped from succeeding regression analyses.

Results

Initial regression analyses showed measured flow differential (and design flow differential) to be the only statistically significant factor in determining the level of AVM in all cases examined. A model from each table of data was developed and used to generate Figure 3A through D and Figure 4, which are discussed below.

With the exception of Figure 4, all graphs describe AVM as a function only of measured flow differential. The model generated from data in Table 3 and shown in Figure 4 illustrates AVM as a function only of swinging door speed.

The data shown in Table 1 indicate the level of AVM occurring as the cart or cart and mannequin enter or exit the NPIR through the swinging door. Also shown are the data for the control test runs where no mannequin or cart passed through the doorway. No statistically significant difference in AVM was noted between entry and exit of the mannequin. (Although entry/exit did significantly increase AVM, direction of travel did not.) Also, the cart alone added no statistically significant amount to the baseline AVM during the entry/exit test runs. A calculated pressure differential is also shown in Table 1. The pressure differential calculations were based on previous work done in the same laboratory NPIR.⁽³⁾ The pressure differential between the NPIR and measurement chamber was lost when the door was opened. Pressure differentials are reported here to indicate nominal high and low pressure differentials for each of the two flow differentials examined.

Table 2 shows data from the 32 test runs accomplished with the swinging door installed and examines how ventilation parameters affect AVM (no entry/exit). Analysis results of Tables 1 and 2 data are shown in Figure 3A. As can be seen in the figure, entry/exit increases AVM very little compared with the AVM caused by the swinging door itself.

Tables 4 and 5 are similar to Tables 1 and 2 except a sliding door was installed in place of the swinging door. Analysis results of Tables 4 and 5 are shown in Figure 3B. Unlike the results shown in Figure 3A, entry/exit was the dominant factor on AVM when a sliding door was in place.

Data from Tables 2 and 5 are compared in Figure 3C. This figure illustrates the action of the sliding door open/close cycle, which caused much less AVM than the swinging door open/close cycle.

Data from Tables 1 and 4 are compared in Figure 3D. The figure shows that when entry/exit occurs, there is no statistically significant difference in AVM between door types.

Figure 4 shows the analysis results of the Table 3 data. Examining AVM as only a function of swinging door speed shows no significant effect.

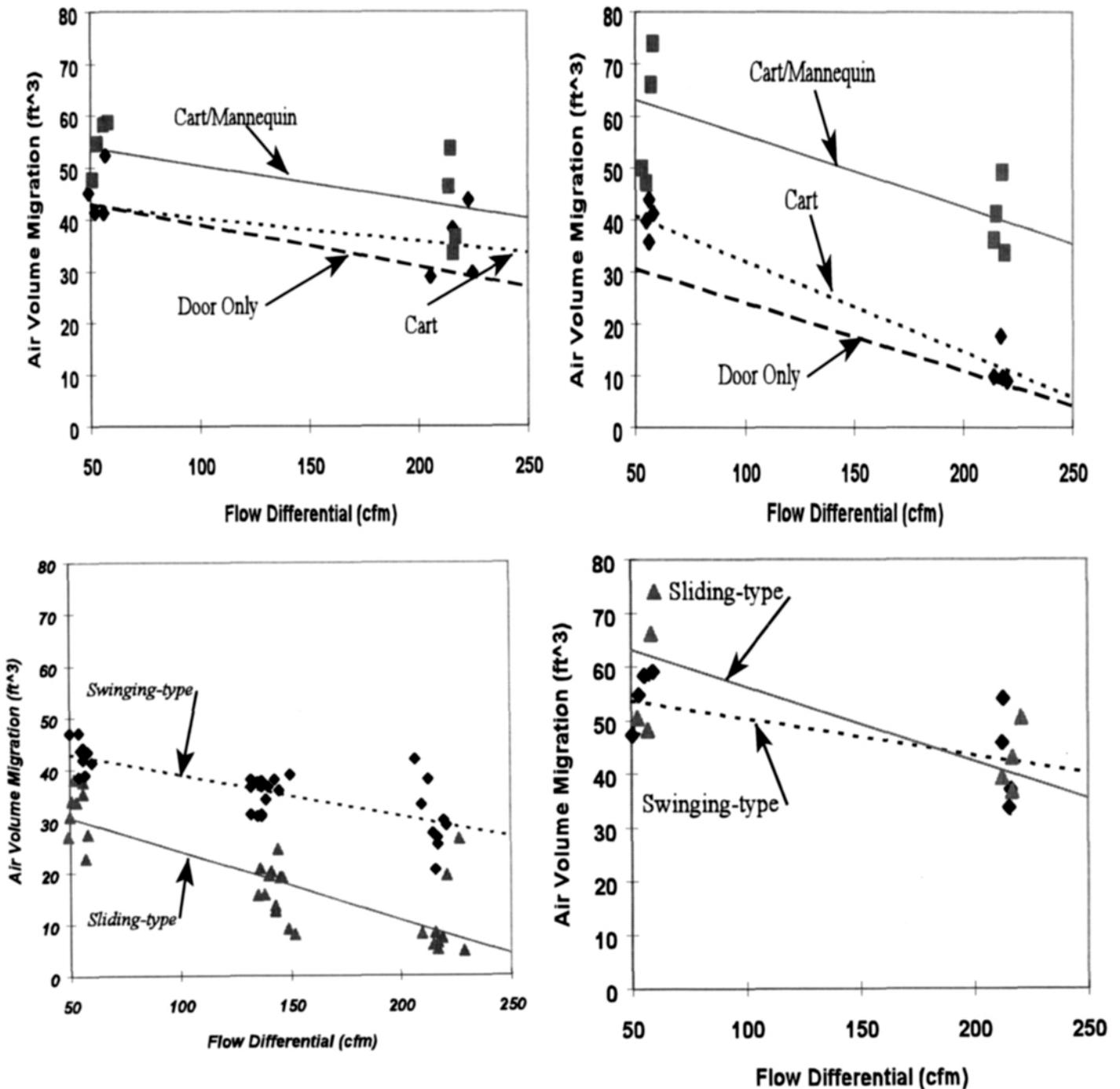


FIGURE 3. AVM (cubic feet) versus flow differential (cubic feet/minute) plots for: (A) swinging-type door: door cycling only (long dashed line), door cycling with cart entry/exit (dotted line), and door cycling with cart/mannequin entry/exit (solid line); (B) sliding-type door: door cycling only (long dashed line), door cycling with cart entry/exit (dotted line), and door cycling with cart/mannequin entry/exit (solid line); (C) door cycling only with no entry/exit for swinging-type door (dotted line) and sliding-type door (solid line); (D) door cycling with cart/mannequin entry/exit for swinging-type door (dotted line) and sliding-type door (solid line).

Discussion

Data from this study show that set leakage areas were dominated by leakage area through the doorway during entry/exit. Hence, the set leakage area and the flow rate through the set leakage area had minimal effect on AVM at the NPIR door-

way. The same should also hold true in an actual healthcare environment, except where an anteroom is adjacent to the NPIR or leakage areas into the NPIR through areas other than the open door are excessive (>80 inches²).

The utility of an anteroom can be inferred from the research

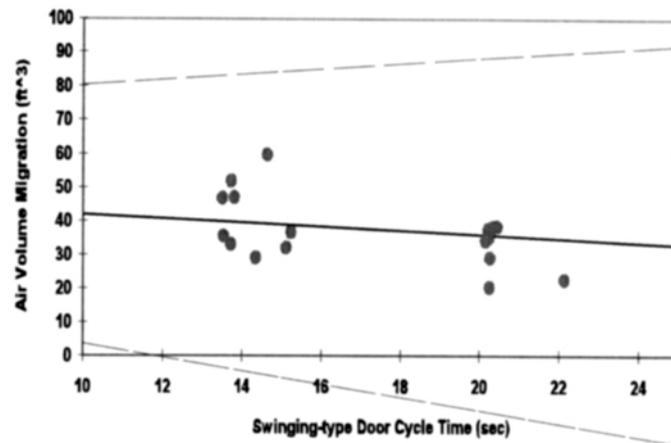


FIGURE 4. AVM (cubic feet) versus swinging-type door cycle time (seconds). Mean (solid line) and 95 percent confidence interval (long dashed line) are shown for door cycling only (no entry/exit).

results. AVM through the anteroom moves into the corridor because of NPIR and subsequent anteroom exit. Entry to the NPIR through the anteroom is not considered since no NPIR air will have migrated to the anteroom when the anteroom-to-corridor door is opened. If we assume that no dilution removal of contaminant occurs in the anteroom where the AVM from the NPIR to the anteroom is perfectly mixed, then a relationship based on anteroom volume would be as follows:

$$AVM_{NPIR-corridor} = \frac{AVM_{NPIR-AR} * AVM_{AR-corridor}}{volume_{AR}} \quad (4)$$

where:

- $AVM_{NPIR-corridor}$ = AVM from the NPIR, through the anteroom, to the corridor
- $AVM_{NPIR-AR}$ = AVM from the NPIR to the anteroom
- $AVM_{AR-corridor}$ = AVM from the anteroom to the corridor
- $volume_{AR}$ = anteroom volume

As an example, if 60 ft³ of contaminated air (let's say at concentration equal to 1 unit of contamination per cubic foot) migrates from an NPIR to an anteroom whose volume equals 300 ft³, followed by the migration of 60 ft³ of well-mixed anteroom air (now at 0.2 units of contamination per cubic foot) to the corridor, then the amount of NPIR air migrating into the corridor would be 12 ft³ (or 12 units of contamination). This is an 80 percent reduction in AVM (and hence units of contamination) from the NPIR to the corridor when compared with the NPIR to corridor AVM without an anteroom. Doubling the size of the anteroom would cause a 90 percent reduction (6 units of contamination), while halving the anteroom size to 150 ft³ would provide a 60 percent reduction (24 units of contamination) in AVM.

NPIR floor plan geometry (just inside the NPIR) was not examined for possible effect on AVM level during entry/exit. However, the swinging door being fully open may baffle out some of the turbulence created by the action of persons passing through the doorway. This baffle effect would not be seen in entry/exit through a sliding door. An intuitive analogy would be to compare walking along a wall versus walking down the

middle of a hallway. More turbulence and eddie generation would be found when walking down the middle of the hallway. Entry/exit through a swinging door is not as significant a contributor to AVM as is entry/exit through a sliding door. Operation of the door only (no entry/exit) showed a much lower AVM when the sliding door was employed. However, operation of doors with entry/exit showed AVM to be relatively equal (across the range of flow differentials examined) for both swinging and sliding doors.

No significant difference in the level of AVM was observed as the mannequin entered or exited the NPIR through the doorway of either the sliding or swinging doors. This could have been the result of two different mechanisms which may have had a quantitatively similar effect on the level of AVM. During entry, sulfur hexafluoride-laden air is displaced from the NPIR into the measurement chamber, while exiting drags sulfur hexafluoride-laden air from the NPIR into the measurement chamber. These mechanisms were not examined in this study.

A variety of factors that might affect AVM, such as objects carried by a worker, weight/height of worker, or different styles and textures of clothing worn by a worker were beyond the scope of this study.

The benefit of raising flow differential to minimize AVM during entry/exit would be of limited value from an economical point of view. While a set flow differential higher than 214 ft³/min was not examined, assuming a linear relationship existed between flow differential and AVM, extrapolation of the sliding door curve from Figure 3D gives a flow differential of about 550 ft³/min to reduce the AVM to about 1 ft³ (close to the limit of detection for the GC, given the volume of the measurement chamber in these experiments). Extrapolation of the swinging door curve from Figure 3D gives a flow differential of around 770 ft³/min to reduce the AVM to about 1 ft³. With no temperature difference between two rooms separated by an open doorway, a flow differential of around 730 ft³/min is recommended to ensure proper direction of air flow through a 42-inch × 80-inch doorway.⁽⁸⁾ The flow differential in NPIRs is provided by an exhaust flow rate greater than supply flow rate. Exhaust from an NPIR is normally directed out-

doors. Because this exhaust air is conditioned and costly, discharging it outdoors is an energy loss and an operational expense.

Conclusions

No significant effect on AVM occurred during entry/exit through either a swinging- or sliding-type door. Direction (entry or exit) through the door also showed no significant effect. AVM was independent of the pressure differential between the NPIR and outer area prior to the door cycling—pressure differential had no significant effect on AVM during entry/exit. Finally, varying the speed of the swing-type door showed no significant effect on AVM between the NPIR and outer area.

The only parameter that demonstrated a significant effect on AVM was flow differential. Field studies have shown that flow differentials of 100 to 200 ft³/min are common; therefore, a certain level of AVM from the NPIR during entry/exit can be expected under most circumstances.⁽⁹⁻¹³⁾ Flow differentials necessary to minimize or eliminate AVM during entry/exit are unreasonably high, both in expected noise levels in the health-care facility environment and in operating cost. However, AVM may be minimized by using a buffer zone or anteroom between the NPIR and corridor areas.

While this NIOSH study was concerned primarily with the engineering control of the transmission of airborne infectious diseases, the results should be applicable to any environment where a clean area is separated from a less clean area by a doorway.

Recommendations

While AVM has been measured, controlled, and reported in this study, the reduction of contaminate migration from a less clean to a clean area was the principal aim. Factors affecting the contaminant concentration near the door of the NPIR, such as supply and exhaust register locations, fans, thermal gradients, and air exchange rates, will ultimately determine the level of contaminant escape (i.e., risk) for a particular level of AVM from the NPIR. Regardless of room mixing and dilution factors, an anteroom or buffer zone outside the contaminated area's doorway will offer a degree of containment during entry/exit not otherwise obtainable.

The AVM from the NPIR to the outer area is a small percentage (about 4% in this study) of the total volume of the NPIR. Further research, however, is needed to examine the concentration gradients within the NPIR, which may maintain a low concentration of contaminant near a doorway. Also, the concentration versus risk of transmission for a particular contaminant must be established. An exposure assessment examining hazards associated with content of the air should be accomplished prior to establishing an upper limit to AVM during NPIR entry/exit. Further research could also include an examination of how NPIR floor plan geometry (adjacent to a door) affects the level of AVM through a door during entry/exit.

Disclaimer

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention, NIOSH.

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