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Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Pressure Experiments

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Evaluating Positive Pressure Ventilation In Large Structures: High-rise Pressure Experiments

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Abstract

One hundred and sixty experiments were conducted in a thirty-story vacant office building in Toledo, Ohio to evaluate the ability of fire department positive pressure ventilation (PPV) fans to pressurize a stairwell in a high-rise structure in accordance with established performance metrics for fixed stairwell pressurization systems. Variables such as fan size, fan angle, setback distance, number of fans, orientation of fans, number of doors open and location of vents open were varied to examine capability and optimization of each. Fan size varied from 0.4 m (16 in) to 1.2 m (46 in). Fan angle ranged from 90^{o} to 80^{o}. The setback distance went from 0.6 m (2 ft) to 3.6 m (12 ft). One fan to as many as nine fans were used which were located at three different exterior locations and three different interior locations. Fans were oriented both in series and in parallel configurations. Doors throughout the building were opened and closed to evaluate the effects. Finally a door to the roof and a roof hatch were used as vent points. The measurements taken during the experiments included differential pressure, air temperature, carbon monoxide, metrological data and sound levels.

PPV fans utilized correctly can increase the effectiveness of fire fighters and survivability of occupants in high-rise buildings. In a high-rise building it is possible to increase the pressure of a stairwell to prevent the infiltration of smoke if fire crews configure the fans properly. Although many factors contribute and need to be considered for effective PPV operations, properly configured PPV can achieve stairwell pressures that are high enough to meet or exceed the performance metrics for fixed smoke control systems.

Disclaimer

Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

1.0 Introduction

According to the National Fire Protection Association (NFPA) Life Safety Code, a high rise building is "a building greater than 23 m (75 ft) in height measured from the lowest level of fire department vehicle access to the floor of highest occupiable story" [1]. In 1910, the New York City Fire Department Chief, Edward Croker informed the New York State Assembly that the fire department could not successfully combat a fire in a building greater than 7 stories tall. Three months later a fire in the Triangle Shirtwaist Company, which occupied the top three floors of a ten story building in New York City, resulted in the deaths of 146 people [2]. As a result of that fire, many improvements were made in the life safety of buildings.

Between 1985 and 2002 there have been approximately 385,000 fires in high-rise buildings greater than seven stories. These fires resulted in 1600 civilian deaths and more than 20,000 civilian injuries *[3]. Smoke is a major problem in high-rise fires as it travels to building locations remote from the fire and causes a serious life hazard. Stairwells may fill with smoke, hindering evacuation and enabling the spread of smoke to other floors of the building.

Fires in high-rise buildings can produce severe challenges for fire departments. Operations that are normally considered routine, such as fire attack, evacuating occupants and ventilation can become very difficult in high-rises. Smoke and hot gases in the stairwells and the corridors of high rise buildings complicate rescue and firefighting operations. Between 1977 and 2005, 20 fire fighters died from traumatic injuries suffered in high-rise fires in the United States *[4].

Fire fighters often rely upon built-in fire protection systems to help control a high-rise fire and protect building occupants. In many cases the buildings do not have the necessary systems or the systems fail to operate properly. This has created situations where even the most experienced and best equipped fire departments could not readily control the fire [5-8]. Many high-rise incidents have resulted in fire fighter fatalities due to disorientation, running out of air, or changes in wind conditions [7, 9-11].

An effective fire protection system for preventing major high-rise fires is an automatic sprinkler system. Not all high-rise buildings have automatic sprinkler systems and even when they function as intended there is still a serious life hazard created by smoke production and spread. In order to limit the smoke hazard, ventilation systems have been utilized. In particular, pressurization smoke control systems have been incorporated into high-rise buildings since the 1970s.

In 1972, the Brooklyn Polytechnic Institute collaborated with the Fire Department of New York City [12] to conduct a series of fire experiments in a 22 story office building to evaluate the effectiveness of pressurization smoke control. Materials representative of fuels that would be in an office building were burned and it was demonstrated that pressurization could maintain tenable exits during a large unsprinklered fire. Subsequent experiments have been done to

*Not including the World Trade Center losses of September 11, 2001.

examine the ability of pressurization to prevent smoke from entering paths of smoke spread such as stairwells, elevator shafts and areas outside of the fire origin. All of these experiments demonstrated that pressurization could control smoke from large unsprinklered fires.

In 1986, the NFPA began to provide guidance for smoke management systems. NFPA 92A [13] was developed to address smoke control utilizing barriers, airflows and pressure differences so as to confine the smoke of a fire to the zone of fire origin and thus maintain a tenable environment in other zones. Guidance for minimum pressures that are able to inhibit the flow of smoke into the stairwell is provided in Table 1. The values in the table for nonsprinklered buildings are minimum design pressures developed for gas temperatures of 927 ^{o}C (1700 ^{o}F) next to the smoke barrier with a 7.5 Pa (0.03 in. water) safety factor added. These criteria for fixed stairwell pressurization systems provides a metric to assess the ability of fire department positive pressure ventilation (PPV) fans to provide a smoke-free escape route for occupants and a smoke-free staging area for fire fighters.

NFPA 92A also states that a smoke control system should be designed to maintain the minimum design pressure differences under likely conditions of stack effect and wind. Pressure differences produced by smoke-control systems tend to fluctuate due to the wind, fan pulsations, door opening, doors closing, and other factors. Short-term deviations from the suggested minimum design pressure difference might not have serious effect on the protection provided by a smoke-control system. There is no clear-cut allowable value of this deviation. It depends on the tightness of doors, tightness of construction, airflow rates, and the volumes of spaces. Intermittent deviations up to 50 % of the suggested minimum design pressure difference are considered tolerable in most cases [13].

Positive pressure ventilation is a technique used by the fire service to remove smoke, heat and other combustion products from a structure. This allows the fire service to perform tasks in a more tenable environment. PPV fans are commonly powered with an electric or gasoline engine and range in diameter from 0.30 m to 0.91 m (12 in to 36 in) (Figure 1). More recently, fans up to 2.1 m (84 in) have been manufactured and mounted on trucks and trailers. Typically, a PPV fan is placed about 1.2 m to 3.0 m (4 ft to 10 ft) outside the doorway of the structure. It is positioned so that the conical jet of air produced by the fan extends beyond the boundaries of the opening (Figure 2). With the doorway within the air jet, pressure inside the structure increases. An exhaust opening in the structure, such as an opening in the roof or an open window, allows the air to escape due to the difference between the inside and outside air pressure. As a result of the introduced air, the smoke, heat and other combustion products are pushed out of the structure and replaced with ambient air.

Another use of PPV is to increase the pressure in a portion of a structure by not providing a vent location. This increase in pressure, if adequate, will prevent smoke flow to an area to be protected. This may be most useful in larger structures such as schools, hospitals and high-rise buildings. In a high-rise building it is possible to increase the pressure of a stairwell to prevent the infiltration of smoke if the fans are properly configured. This study evaluates the variables associated with the fire department's implementation of PPV fans to achieve stairwell pressurization using fixed smoke control performance metrics.

Table 1. NFPA 92A Minimum Design Pressure Differences Across Smoke Barriers

Building Type	Ceiling Height	Design Pressure Difference
	m (ft)	Pa (in. water)
Sprinklered	Any	12.5 (0.05)
Nonsprinklered	2.7 (9)	24.9 (0.1)
Nonsprinklered	3.6 (11.7)*	28.6 (0.11)*
Nonsprinklered	4.6 (15)	34.9 (0.14)
Nonsprinklered	6.4 (21)	44.8 (0.18)

* Values for these experiments

Figure 1. Two common PPV fans

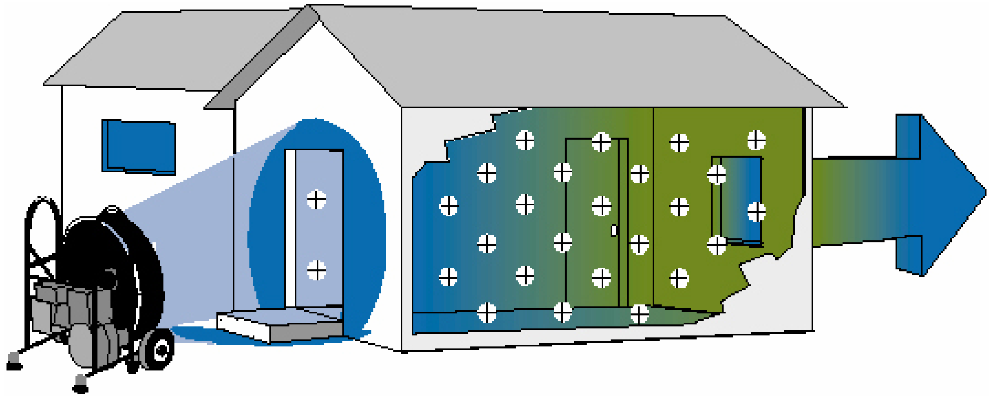

Figure 2. Conical air jet produced by PPV [14]

2.0 Experimental Overview

One hundred and sixty experiments were conducted to evaluate the ability of fire department positive pressure ventilation fans to pressurize a stairwell in a high-rise structure. The stairwell was pressurized in accordance with performance metrics previously established for fixed stairwell pressurization systems. Table 2 displays a broad overview of experimental groups used to analyze the effectiveness of PPV fans. Variables such as fan size, fan angle, setback distance, number of fans, orientation of fans, number of doors open and location of vents open were varied to examine capability and optimization of each. Fan size varied from 0.4 m (16 in) to 1.2 m (46 in). The face of the fan was placed perpendicular to the ground and also tilted backward so that the face was at angles of 85 degrees and 80 degrees to the ground as the fan was tilted backward. The setback distance ranged from 0.6 m (2 ft) to 3.6 m (12 ft). Setback distance was measured from the exterior face of the doorway to the face of the fan. Between one and nine fans were used and fans were located at three different exterior locations and three different interior locations. Fans were oriented in both series and in parallel. Doors throughout the building were opened and closed to evaluate the pressure change. Finally a door to the roof and a roof hatch were used as vent points to evaluate the effects of vent size and location.

Table 2. Experimental overview description

Experiments	Overview Description
1-18	0.4 m (16 in) fan setback/angle analysis at ground floor stairwell door
19-36	0.5 m (21 in) fan setback/angle analysis at ground floor stairwell door
37-54	0.7 m (27 in) fan setback/angle analysis at ground floor stairwell door
56-61	Best setback/angles at ground floor entrance door
62-71	Multiple fans at ground floor entrance door (series and parallel configurations)
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92-100	1.2 m (46 in) trailer mounted fan at ground floor entrances
101-109	Fans in the structure setback configurations

110-122	Roof door ventilation through 29th floor
123-127	Roof hatch ventilation through 29th floor
128-136	Roof hatch ventilation through 28th floor
137-139	Ground floor doorway sealed, Fan efficiency
150-159	Other fan types at ground floor stairwell door
160	Hovercraft at ground floor entrance

2.1 Structure

These experiments were conducted in a thirty-story vacant office building in Toledo, Ohio. The building was constructed in 1969 with an overall height of 121.9 m (400 ft) and an overall floor area of 40,645 m^2 (437,500 ft^2). Each floor was approximately 48.8 m (160 ft) wide by 25.9 m (85 ft) deep with a ceiling height of 3.6 m (11.7 ft). The ground floor was taller and had a ceiling height of 6.3 m (20.7 ft). Figure 3 shows all four sides of the building. Two mechanical floors are located between floors 13 and 14.

Three exterior doors were utilized during the experiments, the single door directly into the stairwell (D2), the double door on the right side of Side A (D1), and the double door on the left side of Side A (D3) (figure 4). Door sizes are in Table 3. The rotary doors inside of D1 and D3 were open for the duration of the experiments. All other doors to the ground floor were closed at all times. The door to the stairwell on side A (S1) remained open during all of the experiments and led to the stairwell that was used for the experiments.

A square stairwell in center of side A opened to the basement and remained open during the experiments. The basement was 1540 m^2 (16,570 ft^2) with a 3.6 m (11.7 ft) ceiling. The second stair that accessed the basement was located near the rotary door on side C and was kept closed.

The building has twelve elevators, ten in the elevator lobby, one freight elevator next to D2i and one adjacent to the basement stair opening. Six of the ten main elevators access floors 1-28. The remaining four only access floors 1 to 13 (figures 5 and 6). The freight elevator extends from the basement to the 29th floor and the elevator adjacent to the basement stair opening only serves the basement to the fifth floor.

The stairwell used for the experiments was located near side A of the building and had a half story of steps that led to a landing that transitioned into the actual stair shaft. The stair shaft measured 2.44 m (8.0 ft) wide and 5.14 m (16.9 ft) long. There was a 0.1 m opening between the stair flights. The stairwell ended at the 29th floor with no access to the exterior of the building. The second stairwell in the building provided access to the roof and roof hatch but opened only to the exterior of the building at the ground floor without room to place a PPV fan (figure 4).

Floors 2 through 13 were similar with the exception of a few partition walls which had no impact on the experiments (figure 5). The two mechanical floors between floor 13 and floor 14 remained closed and were not used during the experiments. Floors 14 through 28 were also similar and differed from the lower floors because of the elevators (figure 6). Floor 29 was not a complete floor and only had a mechanical room and access to the lower roof via the roof door (RD) in the stairwell. A ship ladder to the roof hatch (RH) provided the only access to the upper roof and was also located in the same stairwell as the lower roof door (figure 7).

Figure 3. Front (Side A) and left side (Side B) of the building (left photo) and rear (Side C) and right side (Side D) of the building (right photo)

Table 3. Door and hatch dimensions

Door/Hatch Location	Door Dimensions	
(Reference figures 4, 5, 6)	Width (m)	Height (m)
D1	1.8	2.1
D1i	1.5	2.4
D2	1.1	2.4
D2i	1.1	2.4
D3	1.8	2.1
D3i	1.5	2.4
S1	0.9	2.4
S2-S29, S2-S29a	0.9	2.1
RD	0.9	2.4
Roof Hatch	0.8	0.9

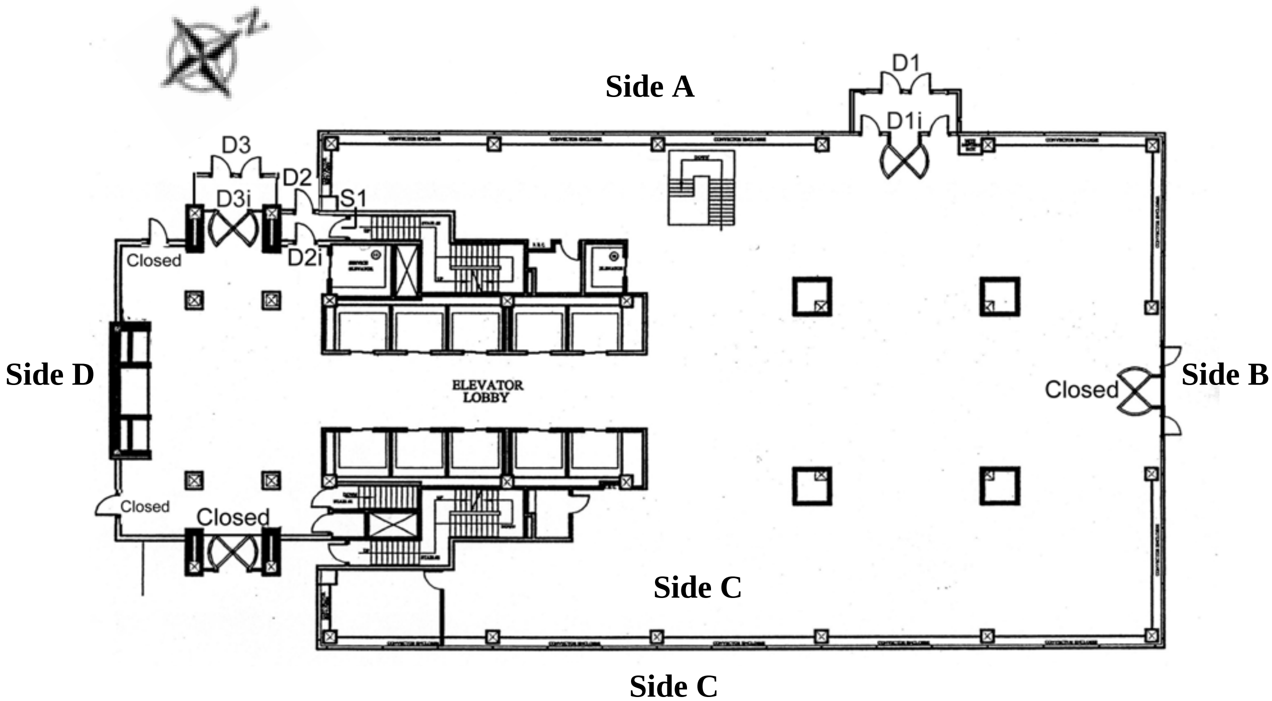

Figure 4. Ground Floor Plan

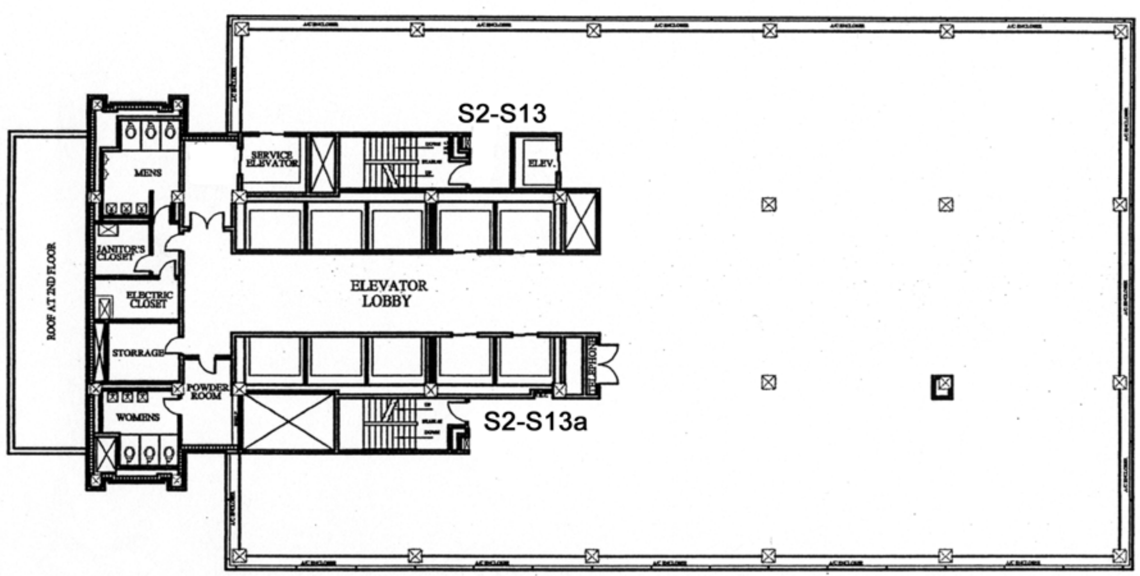

Figure 5. Floors 2-13 floor plan.

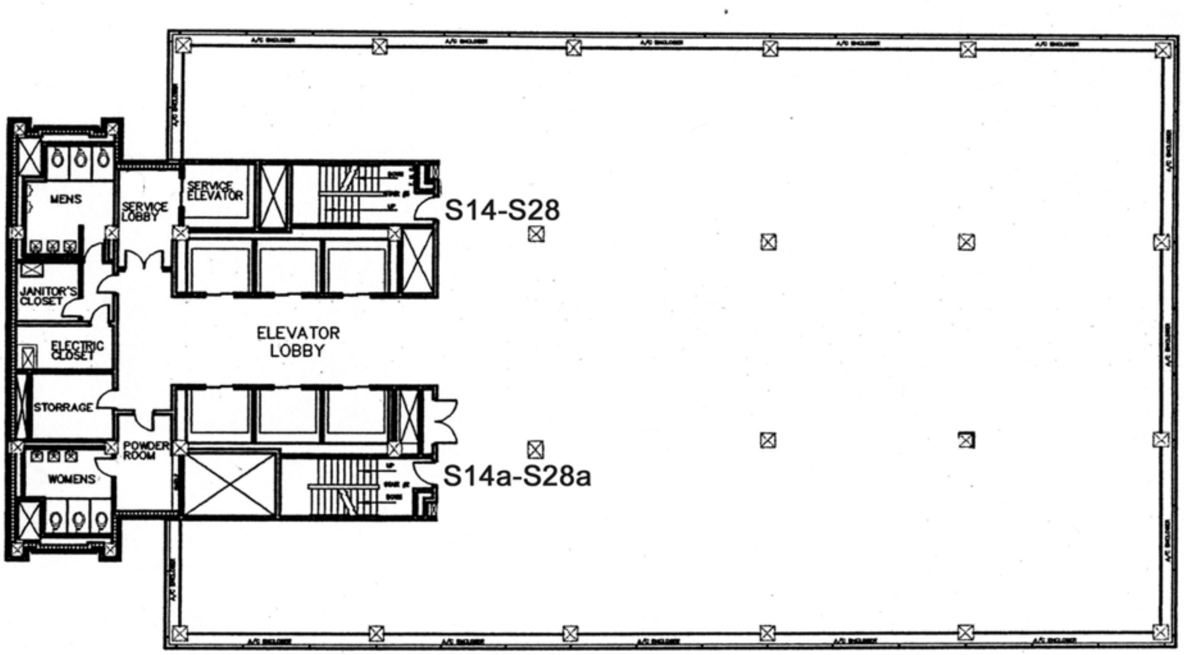

Figure 6. Floor 14-28 floor plan.

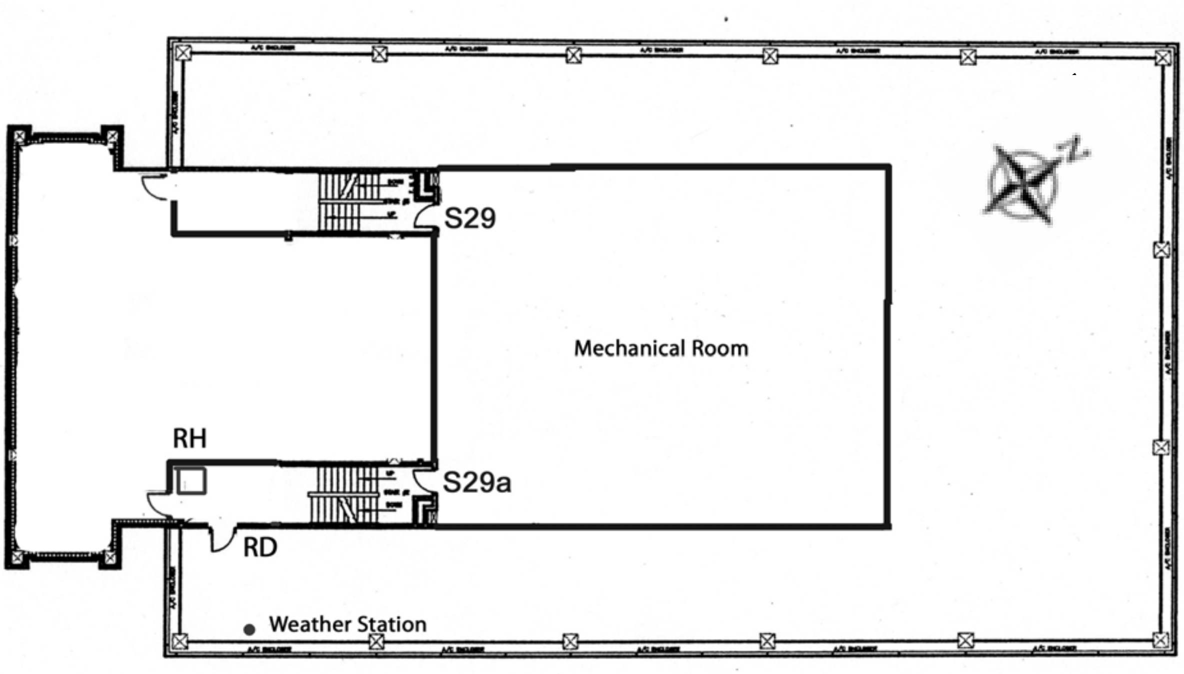

Figure 7. Floor 29 and roof floor plan.

2.2 Instrumentation

The measurements taken during the experiments included differential pressure, air temperature, carbon monoxide, metrological data and sound levels. A differential pressure transducer and thermocouple were located on the door knob of every other floor (figure 8). A plastic tube was run under the door to the opposite door knob to reference the pressure readings to the floor side (figure 9). The thermocouples were bare-bead, type K, with a 0.5 mm (0.02 in) nominal diameter (figure 10).

Carbon monoxide was measured in the stairwell on floors 1, 14 and 28. Measurements were made using a chemical cell monitor with built-in sample pump (figure 11). The monitors were also located on the door handle on their respective floors.

Weather was monitored and recorded during each of the experiments using two portable weather stations. Temperature, relative humidity, average wind speed, average wind direction and barometric pressure were recorded continuously. One weather station was located 9.1 m (30 ft) from the centerline of D2 (figure 12). The second weather station was located on the lower roof outside RD (figure 13).

Sound measurements were taken with an analog sound meter and various locations including next to the fan and inside the structure. The meter had an operating range of 40 dBA to 120 dBA (figure 14).

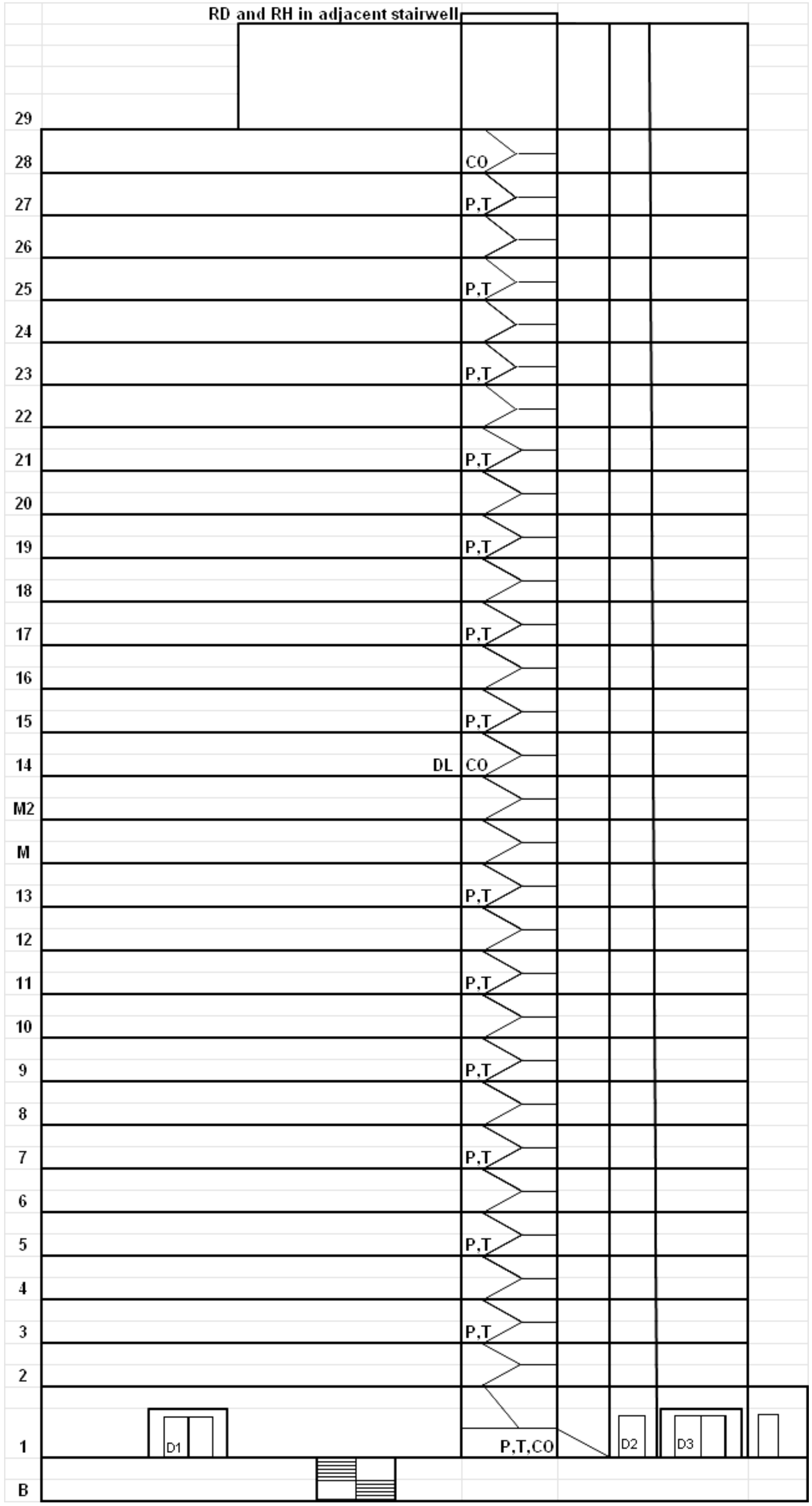

Figure 8. Instrumentation layout diagram (P-pressure, T-temperature, CO-carbon monoxide, DL-data logger)

Figure 9. Differential pressure set-up

Figure 10. Thermocouple location

Figure 11. Carbon monoxide meter

Figure 12. Ground weather station

Figure 13. Roof weather station

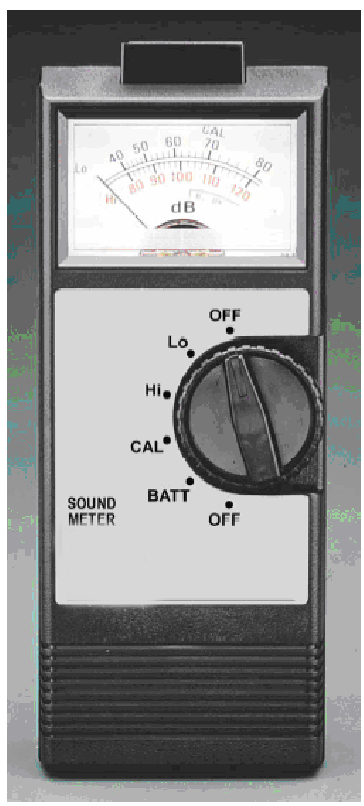

Figure 14. Sound meter

3.0 Experimental Procedure

Prior to each of the experiments the setup was configured according to the variables in tables 4-20. Background measurements were recorded and the fan(s) were started and throttled to full speed. The duration of each experiment was three minutes. At the completion of each experiment the fan was turned off, readings were allowed to return to ambient and the procedure was repeated.

Table 4. 0.4 m (16 in) fan setback/angle analysis at ground floor stairwell door.

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
1	16	90	0.6	D2	D2, S1	None
2	16	85	0.6	D2	D2, S1	None
3	16	80	0.6	D2	D2, S1	None
4	16	90	1.2	D2	D2, S1	None
5	16	85	1.2	D2	D2, S1	None
6	16	80	1.2	D2	D2, S1	None
7	16	90	1.8	D2	D2, S1	None
8	16	85	1.8	D2	D2, S1	None
9	16	80	1.8	D2	D2, S1	None
10	16	90	2.4	D2	D2, S1	None
11	16	85	2.4	D2	D2, S1	None
12	16	80	2.4	D2	D2, S1	None
13	16	90	3.0	D2	D2, S1	None
14	16	85	3.0	D2	D2, S1	None
15	16	80	3.0	D2	D2, S1	None
16	16	90	3.7	D2	D2, S1	None
17	16	85	3.7	D2	D2, S1	None
18	16	80	3.7	D2	D2, S1	None

Table 5. 0.5 m (21 in) fan setback/angle analysis at ground floor stairwell door.

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
19	21	90	0.6	D2	D2, S1	None
20	21	85	0.6	D2	D2, S1	None
21	21	80	0.6	D2	D2, S1	None
22	21	90	1.2	D2	D2, S1	None
23	21	85	1.2	D2	D2, S1	None
24	21	80	1.2	D2	D2, S1	None
25	21	90	1.8	D2	D2, S1	None
26	21	85	1.8	D2	D2, S1	None
27	21	80	1.8	D2	D2, S1	None
28	21	90	2.4	D2	D2, S1	None
29	21	85	2.4	D2	D2, S1	None
30	21	80	2.4	D2	D2, S1	None
31	21	90	3.0	D2	D2, S1	None
32	21	85	3.0	D2	D2, S1	None
33	21	80	3.0	D2	D2, S1	None
34	21	90	3.7	D2	D2, S1	None
35	21	85	3.7	D2	D2, S1	None
36	21	80	3.7	D2	D2, S1	None

Table 6. 0.7 m (27 in) fan setback/angle analysis at ground floor stairwell door.

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
37	27	90	0.6	D2	D2, S1	None
38	27	85	0.6	D2	D2, S1	None
39	27	80	0.6	D2	D2, S1	None
40	27	90	1.2	D2	D2, S1	None
41	27	85	1.2	D2	D2, S1	None
42	27	80	1.2	D2	D2, S1	None
43	27	90	1.8	D2	D2, S1	None
44	27	85	1.8	D2	D2, S1	None
45	27	80	1.8	D2	D2, S1	None
46	27	90	2.4	D2	D2, S1	None
47	27	85	2.4	D2	D2, S1	None
48	27	80	2.4	D2	D2, S1	None
49	27	90	3.0	D2	D2, S1	None
50	27	85	3.0	D2	D2, S1	None
51	27	80	3.0	D2	D2, S1	None
52	27	90	3.7	D2	D2, S1	None
53	27	85	3.7	D2	D2, S1	None
54	27	80	3.7	D2	D2, S1	None

Table 7. Best setback/angles at ground floor entrance door

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(ft)			
56	21	80	1.8	D1	D1, D2i, S1	None
57	21	85	2.4	D1	D1, D2i, S1	None
58	21	80	1.2	D1	D1, D2i, S1	None
59	27	85	1.2	D1	D1, D2i, S1	None
60	27	80	1.8	D1	D1, D2i, S1	None
61	27	80	1.2	D1	D1, D2i, S1	None

Table 8. Multiple fans at ground floor entrance door (series and parallel configurations)

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Fan Orientation	Doors Open	Vents Open
	(in)	(degrees)	(m)				
62	21	80	1.8, 3.0	D1	series	D1, D2i, S1	None
63	21	80, 85	1.8, 1.8	D1	V	D1, D2i, S1	None
64	21	80, 80	1.8, 1.8	D1	V	D1, D2i, S1	None
65	21	75, 90	1.8, 1.8, 1.8	D1	V, w, center	D1, D2i, S1	None
66	21	80, 80, 80	0.6, 1.8, 3.0	D1	series	D1, D2i, S1	None
67	27	85, 85, 85	1.2, 2.4	D1	series	D1, D2i, S1	None
68	27	80, 85	1.8, 1.8	D1	V	D1, D2i, S1	None
69	27	80, 80	1.8, 1.8	D1	V	D1, D2i, S1	None
70	27	80, 90	1.8, 1.8, 1.8	D1	V, w, center	D1, D2i, S1	None
71	27, 21	80, 80, 80	1.8, 3.0	D1	V, w, center	D1, D2i, S1	None

Table 9. Multiple fans at stairwell door

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Fan Orientation	Doors Open	Vents Open
	(in)	(degrees)	(m)				
72	21	80	1.8	D2	NA	D2, S1	None
73	21	80, 85	1.8, 3.0	D2	series	D2, S1	None
74	21	80, 80, 80	0.6, 1.8, 3.0	D2	series	D2, S1	None
75	27	80	1.2	D2	NA	D2, S1	None
76	27	80, 80	1.2, 2.4	D2	series	D2, S1	None
77	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1	None

Table 10. Stairwell door(s) open configuration(s)

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Fan Orientation	Doors Open	Vents Open
	(in)	(degrees)	(m)				
78	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S2(2.5")	None
79	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S2	None
80	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S10(2.5")	None
81	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S10	None
82	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S20(2.5")	None
83	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S20	None
84	27	80, 80, 80	1.2, 2.4, 3.7	D2	series	D2, S1, S10, S20	None

Table 11. Fans at multiple ground floor doors

Experiment	Fan Size	Fan Angle	Fan Location	Fan Orientation	Doors Open	Vents Open
	(in)	(degrees)				
85	27	All 80	D1, D2, D3	Series, V w/center	D1, D2, D3, D2i, S1	None
86	27	All 80	D1, D3	V w/center	D1, D3, D2i, S1	None

Table 12. Fans in the structure

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
87	27	80	1.2	D2	D2, S1	None
88	27	80, 80	1.2, 1.2	D2	D2, S1, S12	None
89	27	80, 80	1.2, 1.2	D2	D2, S1, S22	None
90	27	80, 80, 80	1.2, 1.2, 1.2	D2	D2, S1, S12, S22	None
91	27	80	1.2	D2	D2, S1, S12	None

Table 13. 46 in trailer mounted fan at ground floor entrances

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
		(degrees)	(m)			
92	MVU (1000rpm)	90	10.0	D2	D2, S1	None
93	MVU (1500rpm)	90	10.0	D2	D2, S1	None
94	MVU (2000rpm)	90	10.0	D2	D2, S1	None
95	MVU (2500rpm)	90	10.0	D2	D2, S1	None
96	MVU (3000rpm)	90	10.0	D2	D2, S1	None
97	MVU (3500rpm)	90	10.0	D2	D2, S1	None
98	MVU (4000rpm)	90	10.0	D2	D2, S1	None
99	MVU (4500rpm)	90	10.0	D2	D2, S1	None
100	MVU (4500rpm)	90	10.0	D1	D1, D2i, S1	None

Table 14. Fans in the structure setback configurations

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
101	16	80	in stairwell	NA	S1	None
102	16	80	at S12	S12	S1, S12	None
103	16	80	1.2 m back from S12	S12	S1, S12	None
104	16	80	2.4 m back from S12	S12	S1, S12	None
105	27	80	in stairwell	NA	S1	None
106	27	80	at S12	S12	S1, S12	None
107	27	80	1.2 m back from S12	S12	S1, S12	None
108	27	80	2.4 m back from S12	S12	S1, S12	None
109	16, 27	80, 80	1.2 m, 2.4 m back from S12	S12	S1, S12	None

Table 15. Roof door ventilation through 29th floor

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
110	Natural	NA	NA	NA	S1, S29, S29a	RD
111	Natural	NA	NA	NA	S1, S29, S29a, D2	RD
112	27	80	1.2	D2	S1, S29, S29a, D2	RD
113	27	80	1.8	D2	S1, S29, S29a, D2	RD
114	21	80	1.8	D2	S1, S29, S29a, D2	RD
115	21	80	2.4	D2	S1, S29, S29a, D2	RD
116	16	80	1.2	D2	S1, S29, S29a, D2	RD
117	27	80, 80	1.2, 2.4	D2	S1, S29, S29a, D2	RD
118	21	80, 80	1.2, 2.4	D2	S1, S29, S29a, D2	RD
119	27	80	1.2	S12	S1, S12, S29, S29a, D2	RD
120	27	80	1.2	S12	S1, S12, S29, S29a	RD
121	27	80, 80	1.2, 1.2	D2, S12	S1, S12, S29, S29a, D2	RD
122	27	80, 80, 80	1.2, 1.2, 1.2	D2, S12, S22	S1, S12, S22, S29, S29a, D2	RD

Table 16. Roof hatch ventilation through 29th floor

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
123	27	80, 80, 80	1.2, 1.2, 1.2	D2, S12, S22	S1, S12, S22, S29, S29a, D2	RH
124	27	80, 80	1.2, 1.2	D2, S12	S1, S12, S29, S29a, D2	RH
125	27	80	1.2	D2	S1, S29, S29a, D2	RH
126	NA	NA	NA	NA	S1	RH
127	NA	NA	NA	NA	S1, D2	RH

Table 17. Roof hatch ventilation through 28th floor

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
128	16	85	1.2	D2	S1, D2, S28, S28a	RH
129	21	80	1.8	D2	S1, D2, S28, S28a	RH
130	27	80	1.2	D2	S1, D2, S28, S28a	RH
131	27	80, 80	1.2, 2.4	D2	S1, D2, S28, S28a	RH
132	27	80, 80, 80	1.2, 2.4, 3.7	D2	S1, D2, S28, S28a	RH
133	21	80, 80	1.2, 2.4	D2	S1, D2, S28, S28a	RH
134	27	80	1.2	D2	S1, S12, D2, S28, S28a	RH
135	27	80	1.2	D2	S1, S12, S28, S28a	RH
136	27	80, 80	1.2, 1.2	D2, S12	S1, S12, D2, S28, S28a	RH

Table 18. Ground floor doorway sealed, Fan efficiency

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
	(in)	(degrees)	(m)			
137	Blower Door, 21	90	0	D2	S1	NA
138	Blower Door, 21	90	0	D2	S1	NA
139	Smoke Curtain, 27	90	0	D2	S1	NA

Table 19. Other fan types at ground floor stairwell door

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Fan Orientation	Doors Open	Vents Open
	(in)	(degrees)	(m)				
150	27	80	1.2	D2	NA	D2, S1	NA
151	24	80	1.8	D2	NA	D2, S1	NA
152	31	75	2.4	D2	NA	D2, S1	NA
153	21	70	2.4	D2	NA	D2, S1	NA
154	21	70	1.2	D2	NA	D2, S1	NA
155	21	70, 90	1.5, 2.3	D2	V	D2, S1	NA
156	21	70, 70	2.4, 2.4	D2	V	D2, S1	NA
157	21	70, 70	1.2, 2.4	D2	series	D2, S1	NA
158	21	85	1.8	D2	NA	D2, S1	NA
159	31, 24	90, 70	2.7,3.0	D2	V	D2, S1	NA

Table 20. Hovercraft at ground floor entrance

Experiment	Fan Size	Fan Angle	Fan Setback	Fan Location	Doors Open	Vents Open
		(gegrees)	(m)			
160	Hovercraft	90	3.7	D3	D3, D2i, S1	NA

4.0 Results

4.1 Stairwell Differential Pressure

4.1.1 Optimal fan placement at stairwell door (D2)

Three fan sizes 0.4 m (16 in), 0.5 m (21 in) and 0.7 m (27 in) were used for this series (figure 15). Fan setback was varied from 0.6 m (2 ft) to 3.6 m (12 ft) and fan angle ranged from 90 degrees to 80 degrees to determine the optimal fan placement. The optimal placement is determined by the highest pressures created in the stairwell. Background pressures were recorded with D2 open.

The optimal placement for the 0.4 m (16 in), 5.5 hp fan was 1.2 m (4 ft) and 85 degrees (figure 16). A placement of 0.6 m (2 ft) and 85 degrees is the second most optimal position. These close distances suggest that there is a large amount of air entrained by the air flowing through the shroud of the fan in order to create the seal around the doorway by preventing backflow.

The least optimal placement was 3.0 m (10 ft) and 85 degrees, followed by 3.7 m (12 ft) and 80 degrees. Another least desired position was 1.2 m (4 ft) and 90 degrees. This suggests that the fan tilted to blow straight into the doorway does not create the desired airflow to seal the doorway and increase the pressure.

The 0.4 m (16 in) fan was not able to meet the 28.6 Pa thresholds (Table 1) to prevent smoke flow from unsprinklered buildings into the stairwell on any floor. The 12.5 Pa threshold for sprinklered buildings was achieved up to the third floor using the optimal placement. Many of the non-optimal placements do not meet the sprinklered threshold at any floor.

Increasing the fan size to 0.5 m (21 in) with a 6.5 hp engine resulted in slightly different optimal positions. The optimal placement was 1.8 m (6 ft) and 85 degrees (figure 17). The second most optimal placement was 1.8 m (6 ft) and 80 degrees. The least optimal placement was 3.0 m (10 ft) and 90 degrees. All three angles at 0.6 m (2 ft) and 90 degrees at 1.8 m (6 ft) produced poor results. These placements also reinforce that backflow from the doorway is important to avoid in order to create higher pressures.

The 0.5 m (21 in) fan was also not able to increase the pressure at any floor to 28.6 Pa. However the optimal placement was able to increase the pressure above 12.5 Pa up to the ninth floor. Similar to the 0.4 m (16 in) fan many of the non-optimal placements do not meet the 12.5 Pa sprinklered threshold (Table 1) at any floor.

The 0.7 m (27 in) fan with a 9.0 hp engine had an optimal placement of 1.2 m (4 ft) and 80 degrees (figure 18). The second most optimal placement was 1.8 m (6 ft) and 80 degrees. The least optimal placements were 3.0 m (10 ft) and 85 degrees, 3.0 m (10 ft) and 80 degrees, and 0.6 m (2 ft) and 90 degrees.

Only the optimal placement created pressures above 28.6 Pa for unsprinklered buildings. It achieved this pressure only on the first floor. This placement also created pressures above 12.5 Pa up to the thirteenth floor. All placements with the 0.7 m (27 in) fan were able to reach 12.5 Pa but most were only able to on the lower few floors.

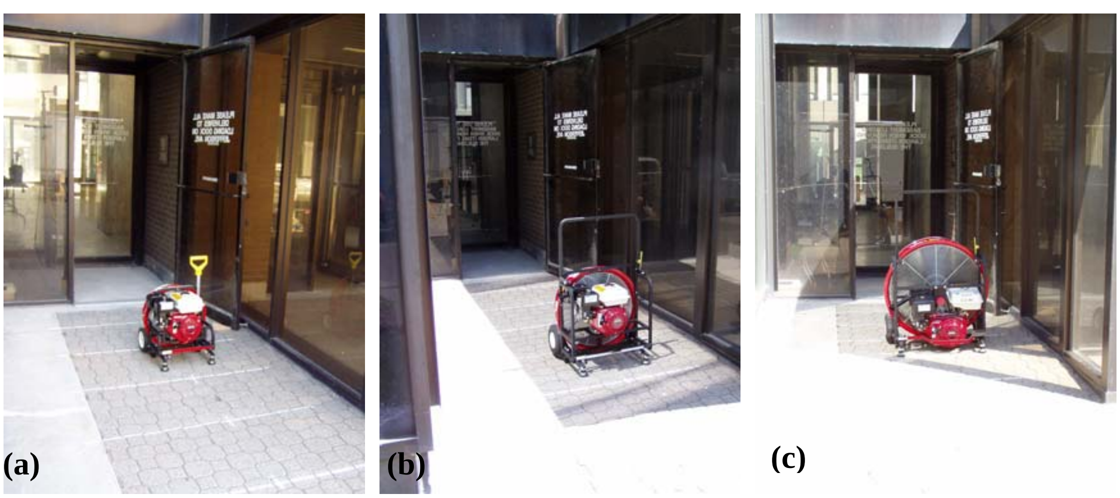

Figure 15. Fans placed at stairwell doorway, (a) 0.4 m (16 in), (b) 0.5 m (21 in), (c) 0.7 m (27 in)

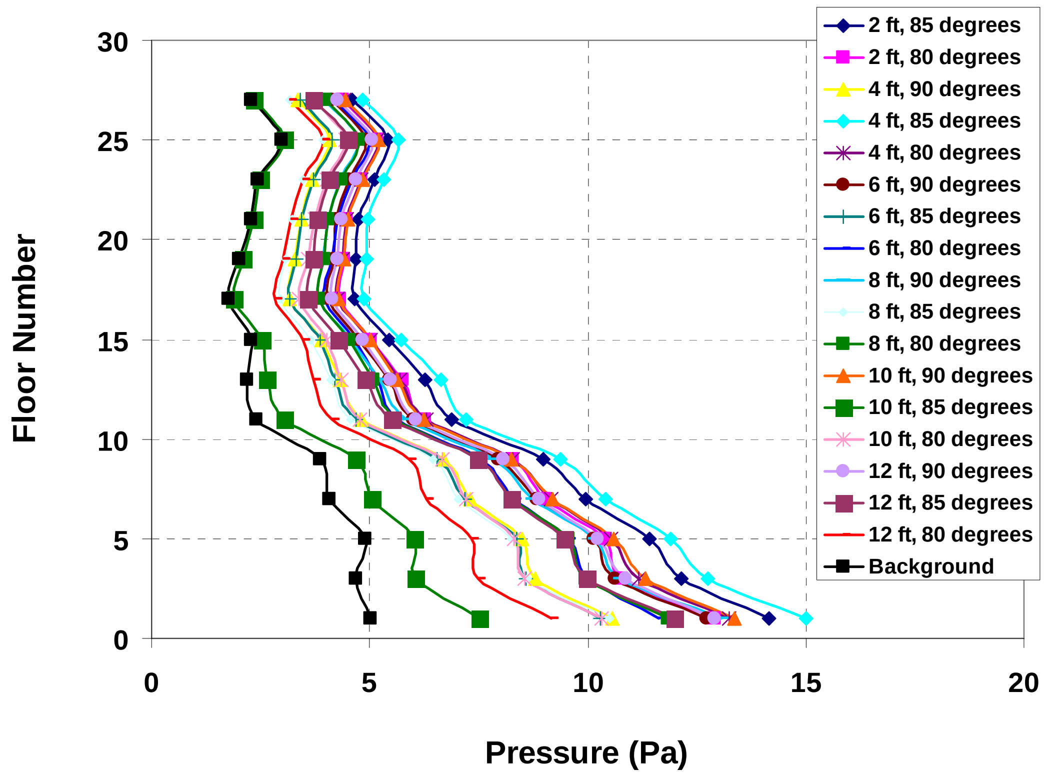

Figure 16. Stairwell pressures created by a 0.4 m (16 in) fan

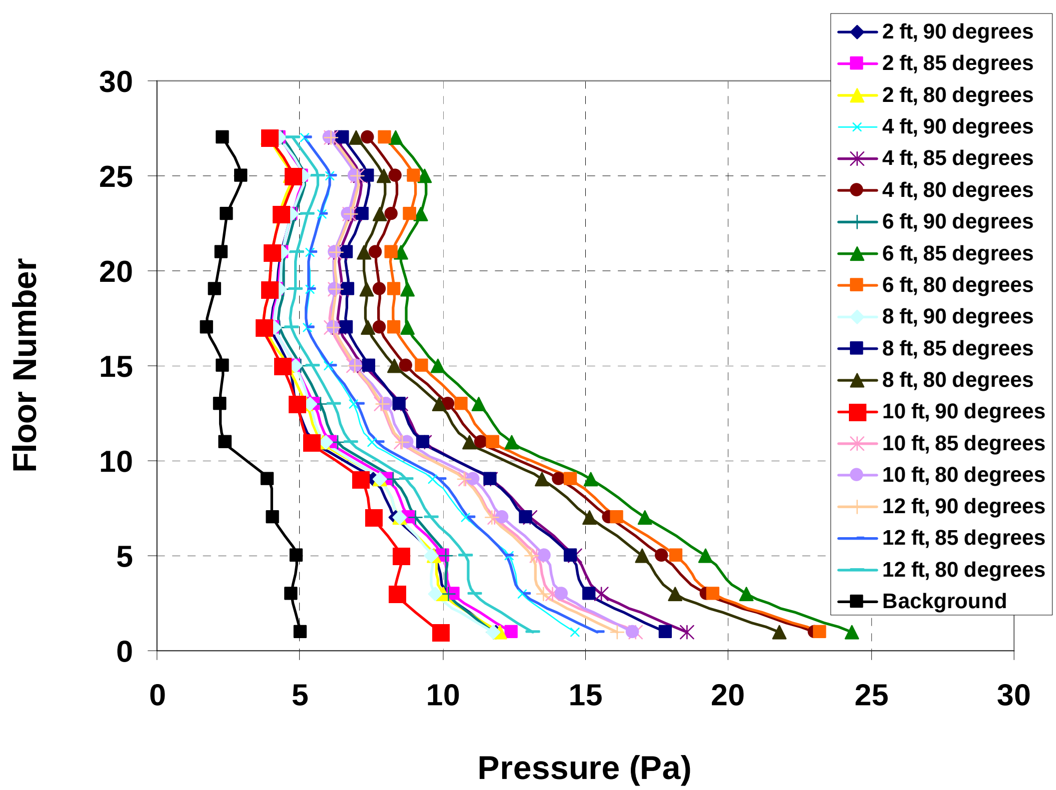

Figure 17. Stairwell pressures created by a 0.5 m (21 in) fan

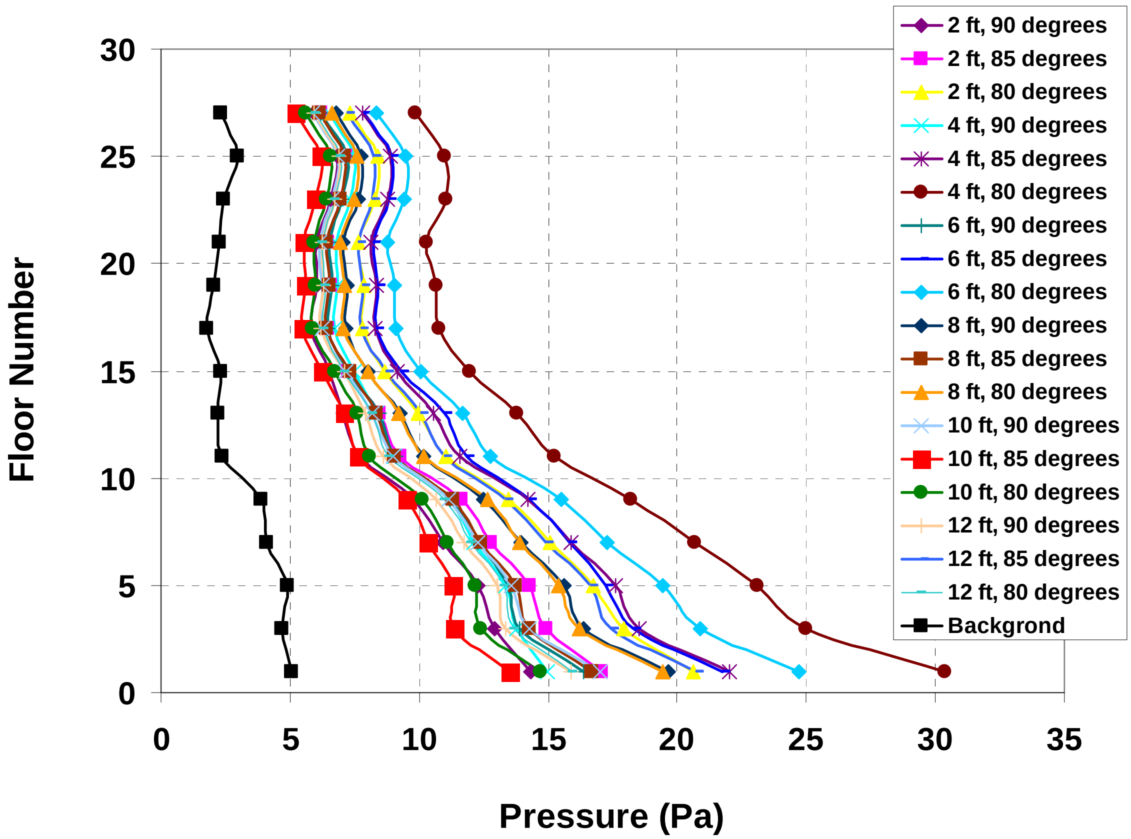

Figure 18. Stairwell pressures created by a 0.7 m (27 in) fan

4.1.2 Optimal fan placements at ground floor entrance (D1)

It is not always possible to place the fan to blow directly into the stairwell doorway. Many high-rise buildings only have stairwells that exit onto the ground floor and not directly to the outside. Experiments 56-61 examine the pressures created in the stairwell by the best placements determined in experiments 1- 54 at a ground floor entrance door remote from the stairwell (figure 19). This configuration requires the fan to pressurize the ground floor and a portion of the basement due to the open stairwell that connects the ground floor to the basement located near side A, adjacent to doorway D1.

The pressures created by a single fan located at its optimal locations are significantly less than those from the fan blowing directly into the stairwell door. At floor 5 the pressures created were approximately one-fourth of those obtained with a fan placed at the stairwell door (figure 20). Pressures were increased less than 2 Pa at all of the floors. This was expected due to the large volume that was added between the fan and the stairwell.

Figure 19. Fan placed at ground level doorway (D1)

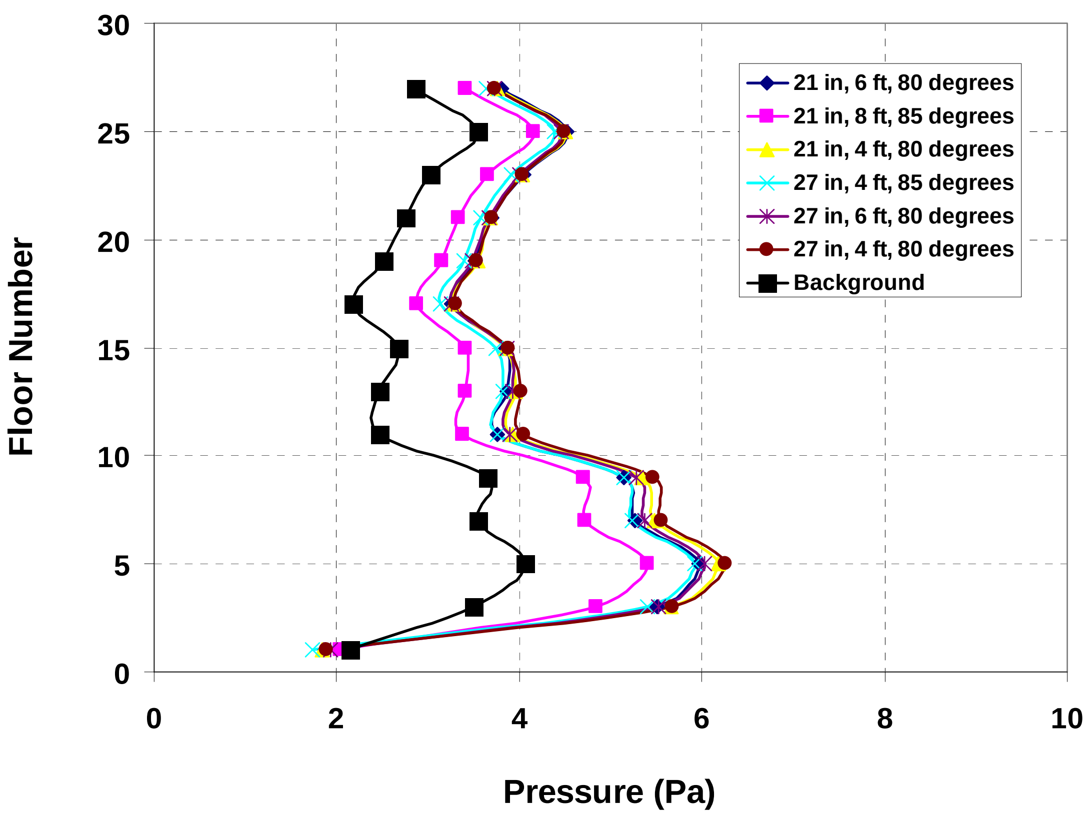

Figure 20. Stairwell pressures from fans blowing into D1

4.1.3 Multiple fans at ground floor entrance (D1)

In order to get better performance fire departments often place more than one fan at a doorway. Two main questions were addressed with experiments 62 through 71. First, does adding a second and third fan double and triple the pressures in the stairwell and what is the best way to arrange the fans to achieve the best results?

Experiments 62 through 66 used 0.5 m (21 in) fans (figure 21). Figure 22 demonstrates using additional fans did not cause the pressures to reach the desired magnitudes. All of the floors remained below 10 Pa which would not prevent smoke infiltration into the stairwell. The orientation of the multiple fans also made a difference in the pressures. Placing the fans in a V-shape was more effective than placing them in series. Placing the fans in a V-shape with one angled at the top of the door and one at the bottom of the door was less effective than angling them both at the center of the door.

Experiments 67 through 70 used 0.7 m (27 in) fans and experiment 71 used a combination of the 0.5 m (21 in) and 0.7 m (27 in) fans. Pressures created by adding additional fans were slightly higher than the single fan but did not come close to creating adequate pressures, with the exception of floors three through seven when six fans were used (figure 23). All of the floors remained below 12.5 Pa, a pressure which would not prevent smoke infiltration into the stairwell. The orientation of the multiple fans also makes a difference in the pressures. Placing the fans in a V-shape is more effective than placing them in series. However with the 0.7 m (27 in) fans, placing the fans in a V-shape with one angled at the top of the door and one at the bottom of the door was more effective than angling them both at the center of the door, which is not consistent with the 0.5 m (21 in) fans.

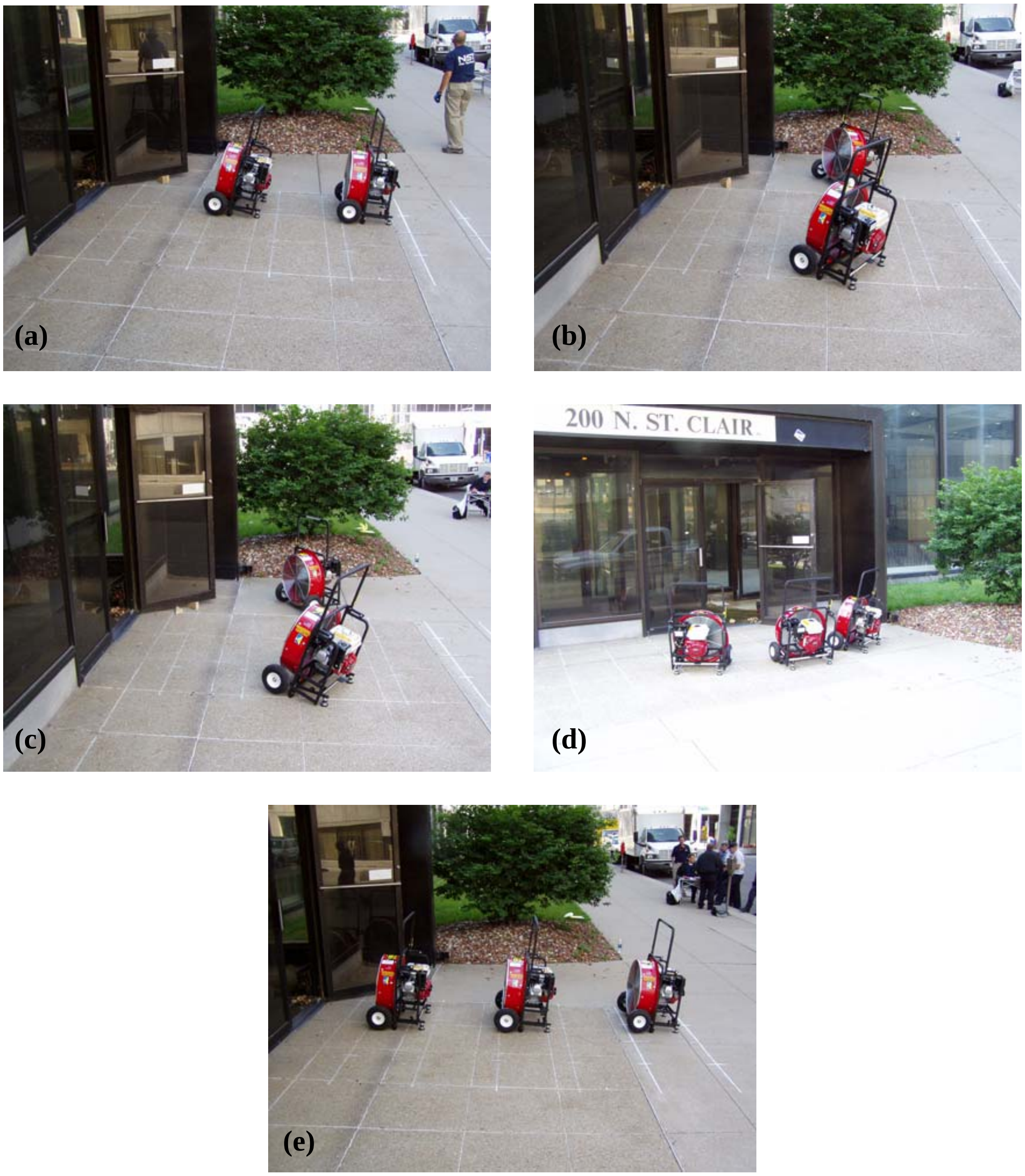

Figure 21. Fans placed at ground floor entrance (D1), a. 2 fans in series, b. 2 fans in V-shape, c. 2 fans in V-shape (top/bottom), d. 3 fans in V-shape w/center, e. 3 fans in series

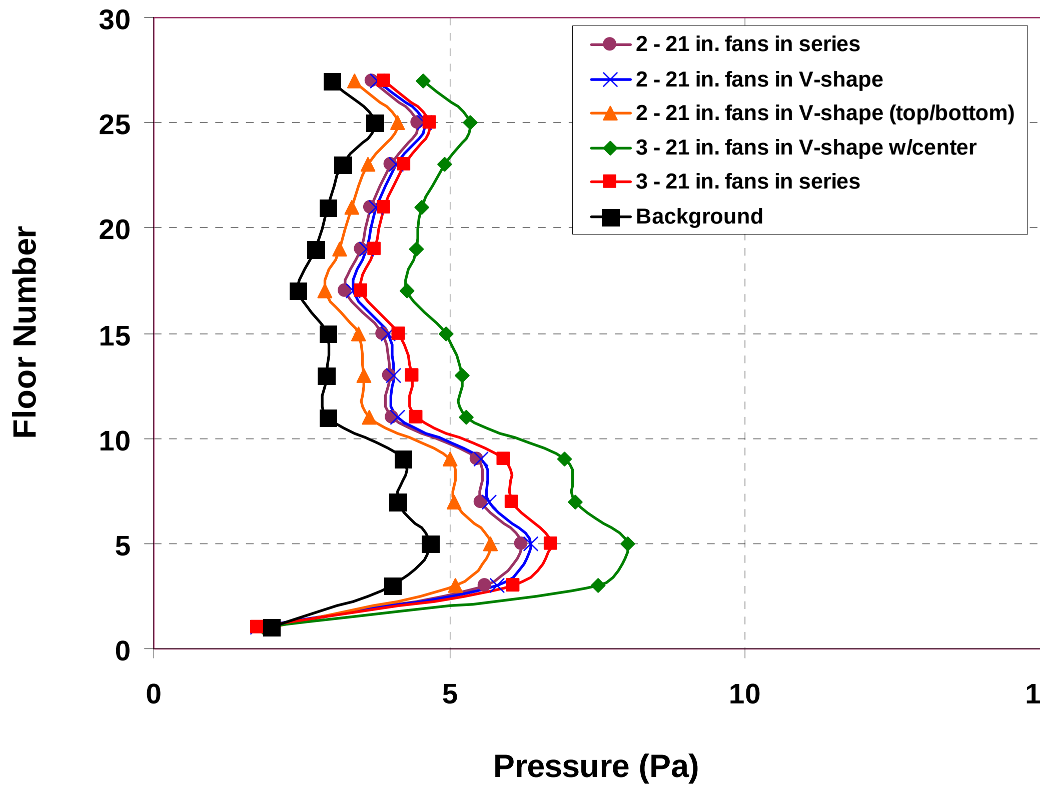

Figure 22. Stairwell pressures from multiple 21 in. fans at D1

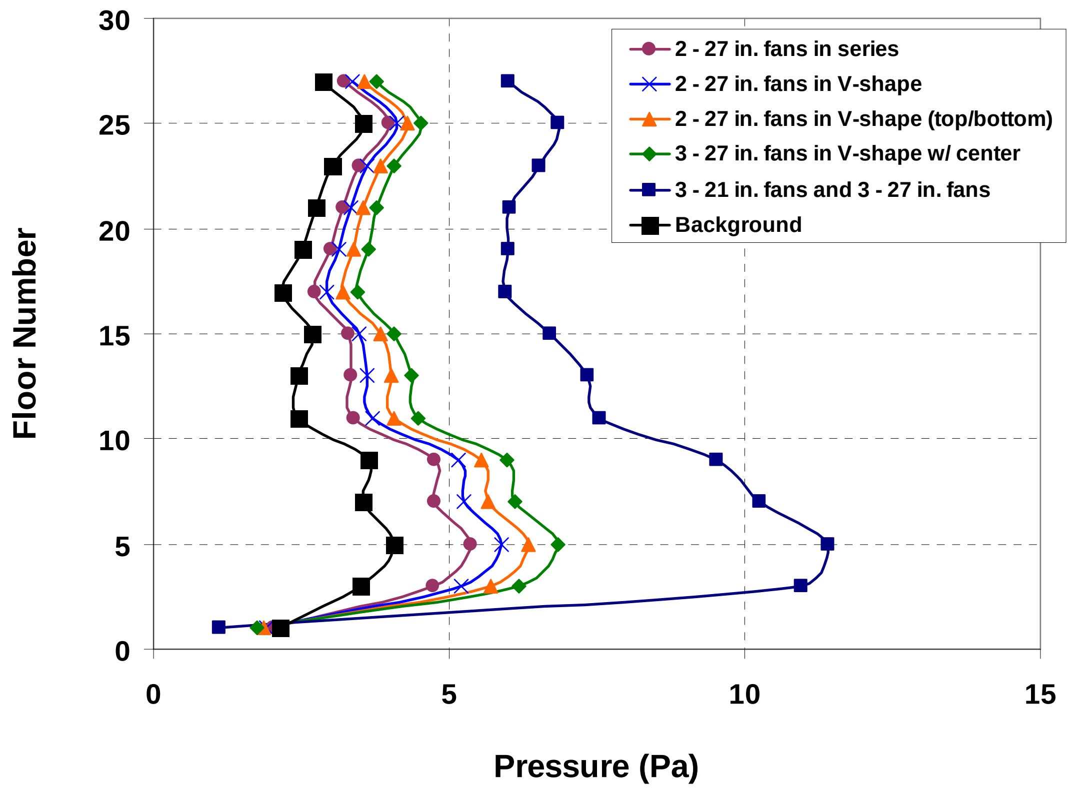

Figure 23. Stairwell pressures from multiple 27 in. fans at D1

4.1.4 Multiple fans at stairwell doorway (D2)

A single fan at the base of the stairwell door (D2) was not able to adequately pressurize the stairwell, so, it was necessary to see if multiple fans would be more effective and how much more effective that adding one and two additional fans in series. The fans were not placed in a V-shape because sufficient space was not available in front of the doorway. The first fan was setback 1.2 m (4 ft) and additional fans were placed in 1.2 m (4 ft) increments. All fans were set at an 80 degree angle (figure 24).

A single 0.5 m (21 in) fan created pressures ranging from 26 Pa at the ground floor to approximately 8 Pa from the 15^{th} floor to the roof (figure 25). Adding a second 0.5 m (21 in) fan in series increased the ground floor pressure to 27 Pa and created a pressure of 10 Pa from the 15^{th} floor to the roof. Three fans increased the ground floor pressure to 31 Pa but did not increase the pressure on the floors above the 13^{th} floor.

A single 0.7 m (27 in) fan created pressures ranging from 24 Pa at the ground floor to approximately 8 Pa from the 15^{th} floor to the roof (figure 26). Adding a second 0.7 m (27 in) fan in series increased the ground floor pressure to 29 Pa and created a pressure of 10 Pa from the 15^{th} floor to the roof. Three fans increased the ground floor pressure to 33 Pa and increased the pressure to 11 Pa on the upper floors.

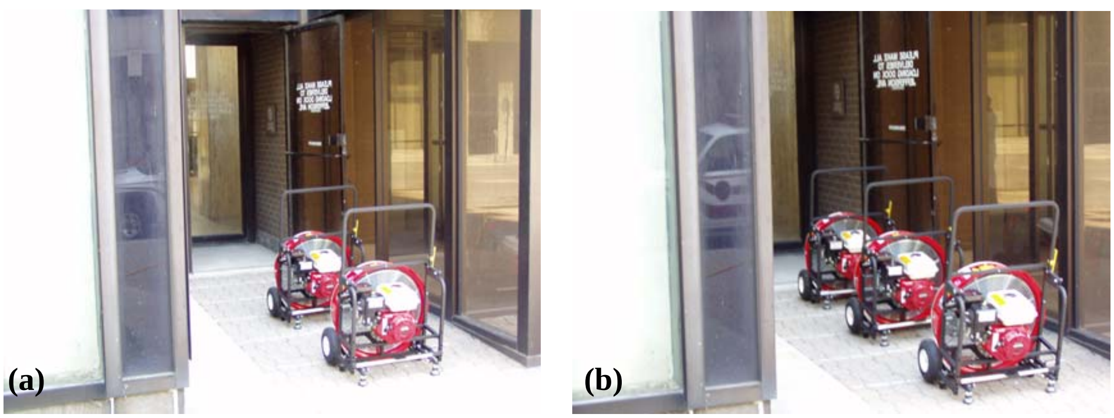

Figure 24. Multiple fans in series at stairwell doorway, a. 1.2 m and 2.4 m, b. 1.2 m, 2.4 m and 3.7 m

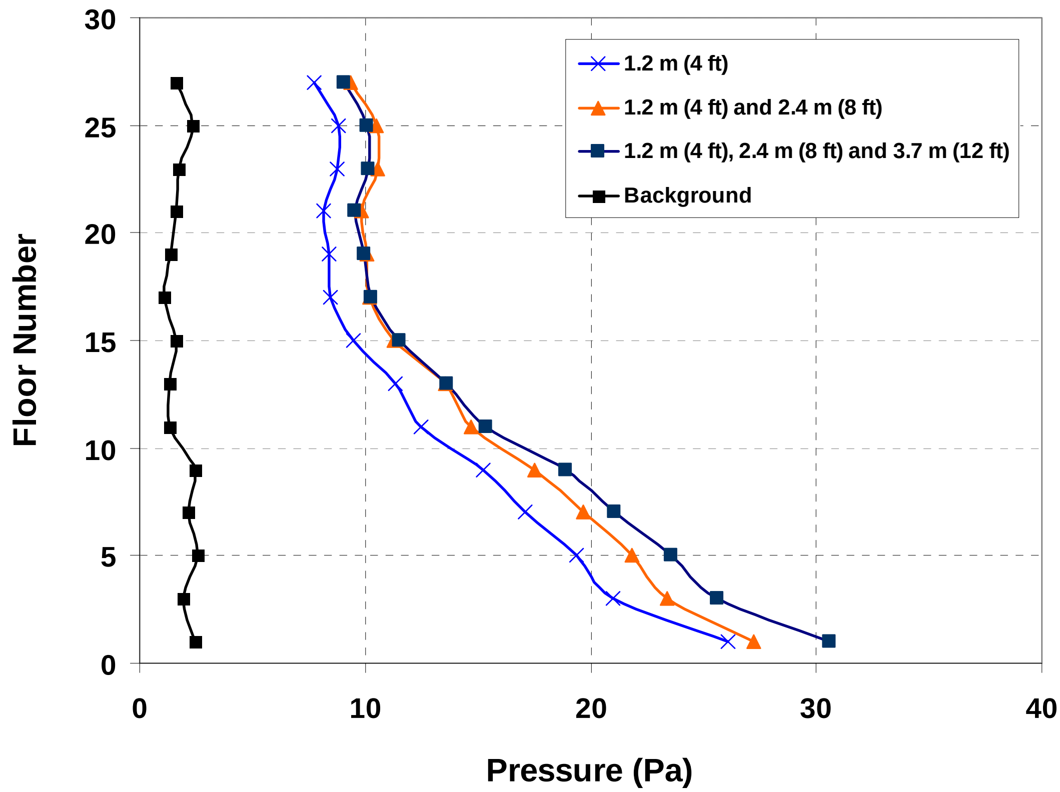

Figure 25. Stairwell pressures from 0.5 m (21 in) fans in series at D2

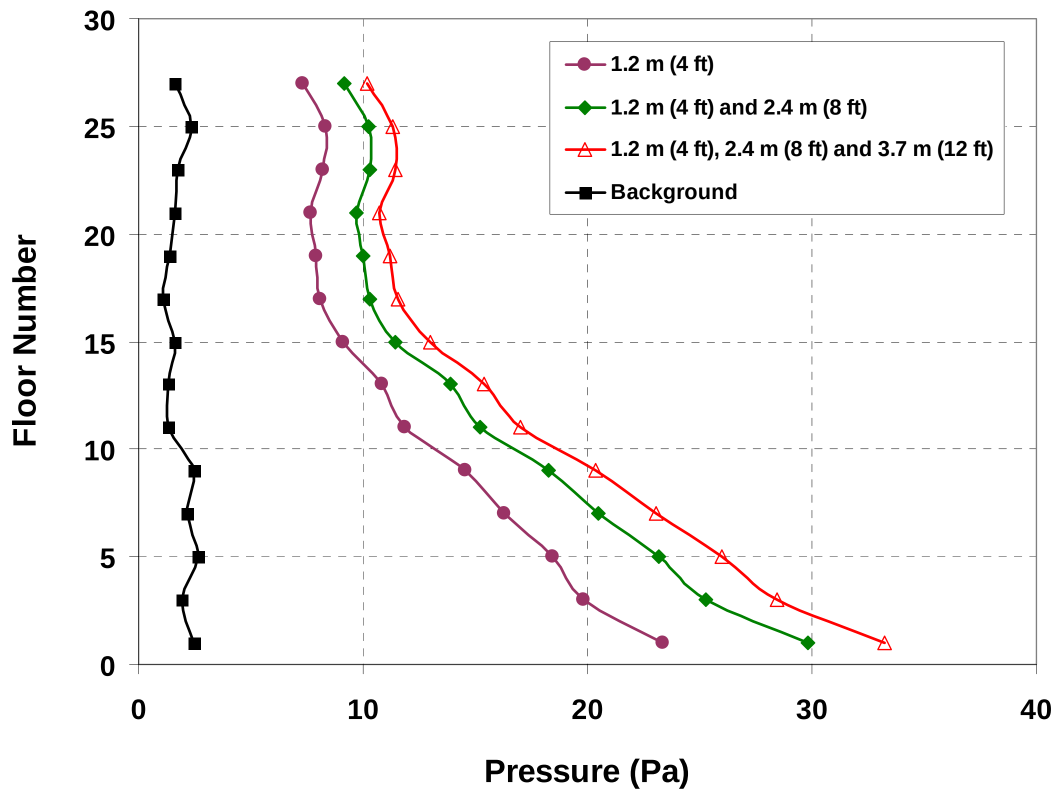

Figure 26. Stairwell pressures from 0.7 m (27 in) fans in series at D2

4.1.5 Open doors in the stairwell

Open doors in the stairwell are an obvious concern due to the need for the fire department to access the floors and for occupants to exit the structure. The added volume of the large floors would certainly affect the pressures the fans were able to create in the stairwell. Doors were either opened 0.08 m (3 in) to simulate the minimum opening achievable by the fire department after stretching a hose line through the doorway or completely open to replicate the worst case scenario. The pressures were created with three 0.7 m (27 in) fans in series, identical to the configuration in the previous series.

Opening the doors 0.08 m (3 in) had little impact on the stairwell pressures (figure 27). Having the 10th floor slightly open allowed for the 28.6 Pa threshold to be met up to the 9th floor and the 12.5 Pa threshold to be met in the entire stairwell. With the 2nd floor and 20th floor slightly opened kept the pressure above 28.6 Pa up to the 5th floor and kept the pressure above 12.5 Pa up to the 15th floor.

Completely opening the doors had a major impact on the stairwell pressures. Having the 20th floor door open had the least impact on the stairwell pressures while the second floor door open had the largest impact. Having the door completely open essentially eliminates the effect of the fan in the stairwell on the floors above the open door and lowers the pressure of the floors below the floor of the open door as well. With the 20th floor door open the pressures still maintained the 28.6 Pa threshold up to the 5th floor and the 12.5 Pa threshold up to the 13th floor. With the 10th floor door open the pressures only maintained the 28.6 Pa threshold on the 1st floor and the 12.5 Pa threshold up to the 7th floor. With the 2nd floor door open only the 12.5 Pa threshold was met on the 1st floor.

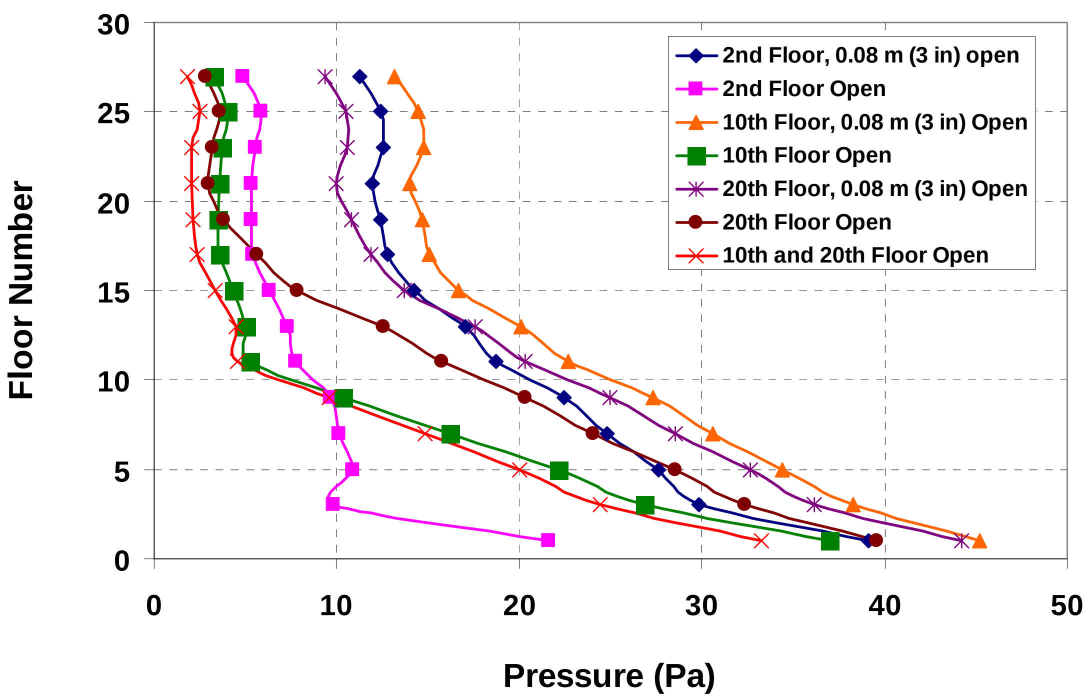

Figure 27. Stairwell pressure with doors open

4.1.6 Multiple fans at multiple ground level doors

An effort was made to pressurize the stairwell from the ground level by utilizing multiple fans in various arrangements. In experiment 85, three 0.7 m (27 in) fans were placed in a V-shape at D1, three 0.5 m (21 in) fans were placed in a V-shape at D3 and three 0.4 m (16 in) fans were placed in series at D2 (figure 28). In experiment 86, three 0.7 m (27 in) fans were placed in a V-shape at D1 and three 0.5 m (21 in) fans were placed in a V-shape at D3, with no fans at D2 assuming that there was no access directly into the stairwell.

Even with nine fans at three different doors the pressure increase was minimal and did not even meet the lower threshold pressure at any floor (figure 29). Apparently the larger fans at D1 and D3 overpressurized or overwhelmed the smaller fans/open doorway at D2 and lower pressures resulted (figure 29). Once the smaller fans were removed and doorway D2 was closed, the larger fans at D1 and D3 provided higher pressures (figure 29). Even with the six fans running the lower sprinklered building threshold of 12.5 was met up to the ninth floor. Using the same six fans at two doors was more effective than using all six at one door as compared to experiment 71 in figure 20.

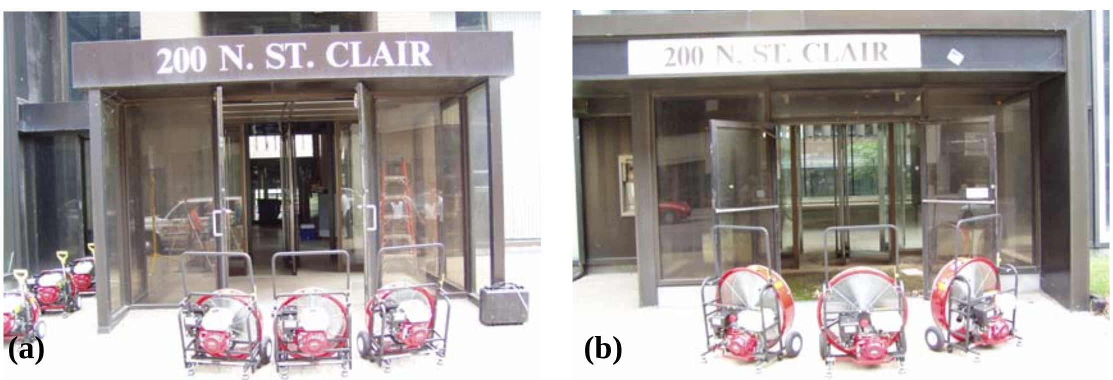

Figure 28. Fans placed at multiple doors, a. Fans at D2 and D3, b. Fans at D1

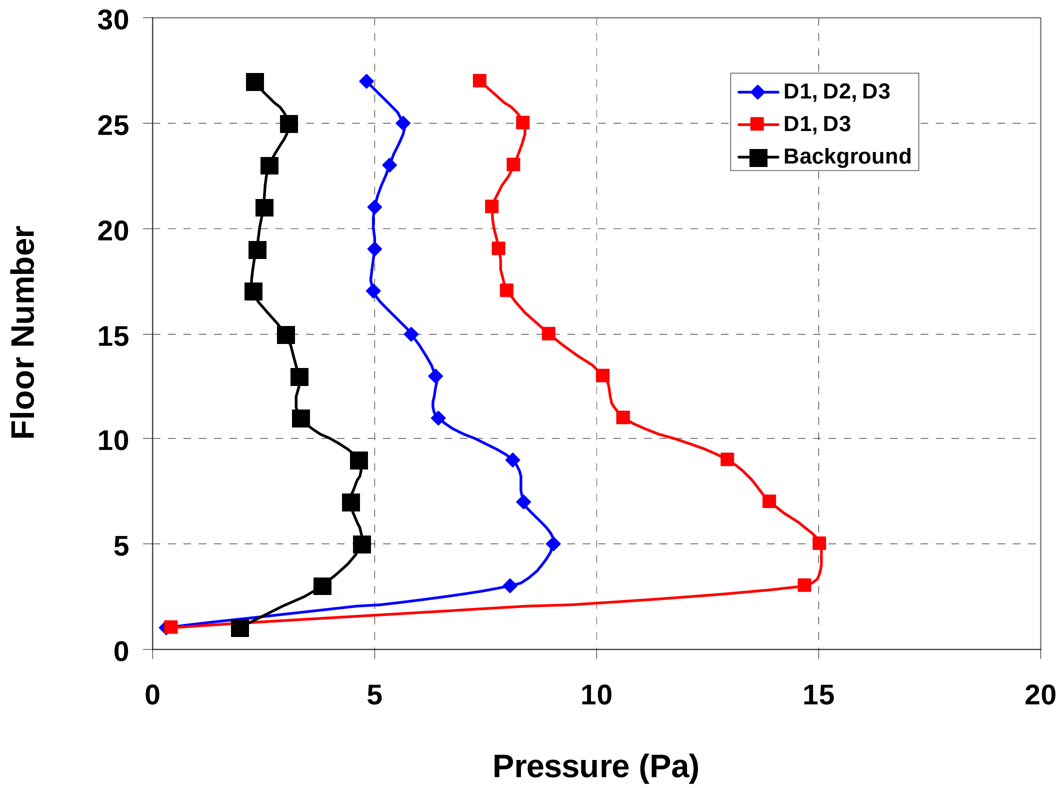

Figure 29. Stairwell pressures with multiple fans at multiple doors

4.1.7 Fans located inside the building

Placing fans at the ground level alone was not effective in meeting the pressure requirements necessary to prevent smoke from flowing into the stairwell. This series tried to replicate a multiple injection stairwell pressurization system that can be found in some buildings. Five different configurations were examined placing 0.7 m (27 in) fans on the ground floor, the 12th floor and the 22nd floor. The fans on the upper floors were setback and angled just as if they were blowing in from the outside, 1.2 m (4 ft) and 80 degrees (figure 30). There was no opening to the outside of the building on the 12th or 22nd floor so little make-up air was available.

The difference between placing a fan at the ground floor and the 12th floor was significant. The fan at the 12th floor created higher pressures from the 5th floor to the top floor (figure 31). The pressures from the 13th floor to the roof were more than double those from the fan on the ground floor. A single fan on the 12th floor created pressures throughout the stairwell that exceeded the 12.5 Pa threshold. Adding a fan at the 1st floor elevated the pressures above the 28.6 Pa threshold up to the 15th floor and adding a fan on the 22nd floor allowed for the 28.6 Pa threshold to be met on all floors with the exception of floors 21 and 27. The lower pressures on 27 appear to be consistent with decrease in pressure as one moves away from the fan.

Figure 30. Fan positioned in the building

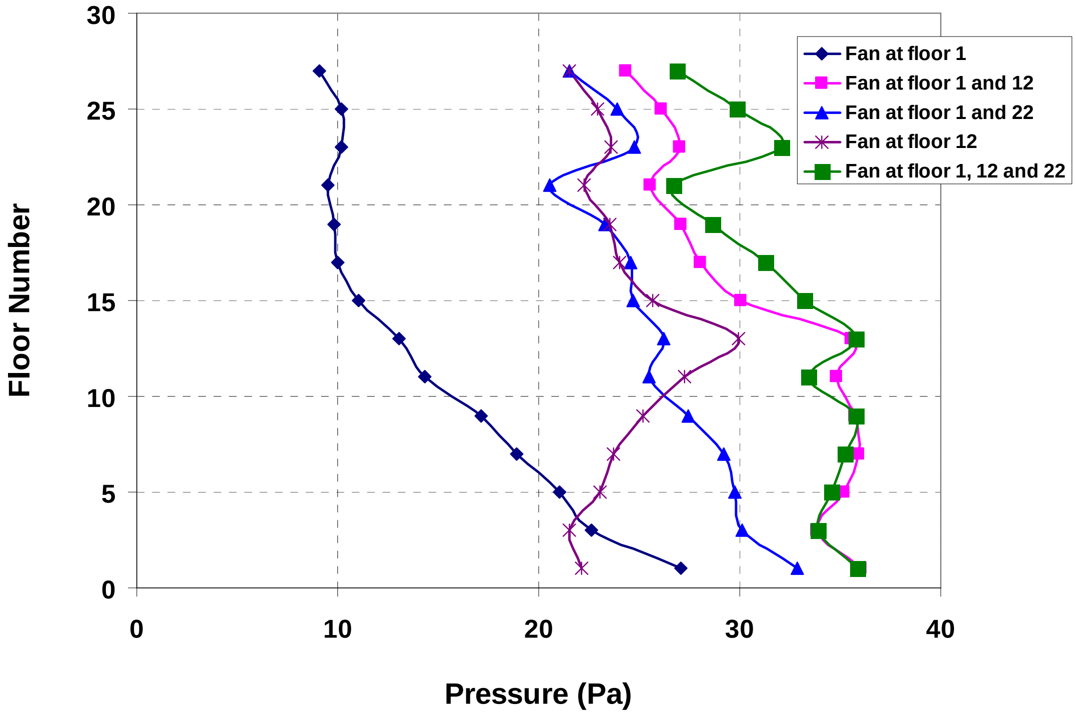

Figure 31. Stairwell pressures with fans inside the building

4.1.8 1.2 m (46 in) trailer mounted fan at ground floor entrance

The smaller, compartment size fans were not effective from the ground so a larger trailer mounted fan was utilized for a series of experiments. The 1.2 m (46 in) fan was positioned 10.0 m (32.8 ft) from the stairwell doorway and was not angled (figure 32). The engine speed was increased by 500 rpm increments, up to 4500 rpm, and steady state pressures were recorded for each level. Experiments were stopped at 4500 rpm, close to the maximum output of the fan, due to concerns for glass breakage.

At 3500 rpm the fan was able to pressurize the entire stairwell to the 12.5 Pa sprinklered building minimum pressure (figure 33). When increased to 4500 rpm the stairwell pressures were above the 28.6 Pa unsprinklered pressure threshold. The highest steady state pressure, 103 Pa, was recorded on the 1st floor, with the fan set to 4500 rpm. Pressures of this magnitude border on the upper threshold which should not be exceeded if occupants are to readily open the doors to exit the building.

Figure 32. Trailer mounted fan at stairwell door.

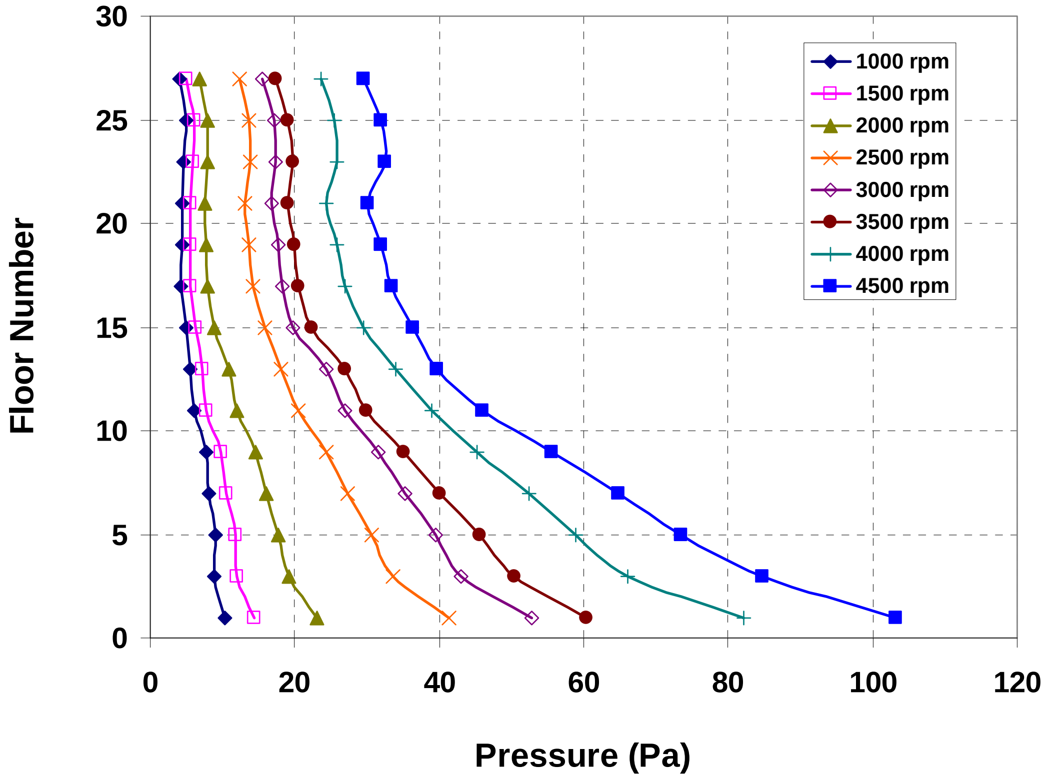

Figure 33. Stairwell pressures made by the 1.2 m (46 in) fan at the stairwell door.

4.1.9 Further analysis of fans located inside the building

Since elevated pressure results were successfully achieved in the previous series of experiments with fans located inside the building, additional configurations were analyzed. This series focused on the setback of the fan in the building at the 12th floor. Fans were placed in the stairwell with the stairwell door shut, at the stairwell door, setback 1.2 m (4 ft), setback 2.4 m (8 ft) and two fans in series at the stairwell doorway (figure 34).

The fans placed in the stairwell slightly increased the stairwell pressures above the 12th floor and decreased the pressures below the fan level (figure 35). This configuration was not effective and could actually draw flows downward in the building. The 0.4 m (16 in) fan was not able to increase the pressure on any floor above 10 Pa which does not meet either desirable pressure threshold. The 1.2 m (4 ft) setback with an angle of 80 degrees was more effective than the 2.4 m (8 ft) setback with an angle of 80 degrees and the fan positioned in the doorway.

The 0.7 m (27 in) fan was able to raise the pressure on all floors above the 12.5 Pa threshold with three different setbacks, in the doorway, 1.2 m (4 ft) back from the door and 2.4 m (8 ft) back from the door. The optimal setback was 1.2 m and 80 degrees. This placement created pressures above 19 Pa on every floor, with a maximum pressure of 28 Pa recorded on floor 13. This setback even outperformed both fans in series.

Figure 34. Fans locations in the stairwell

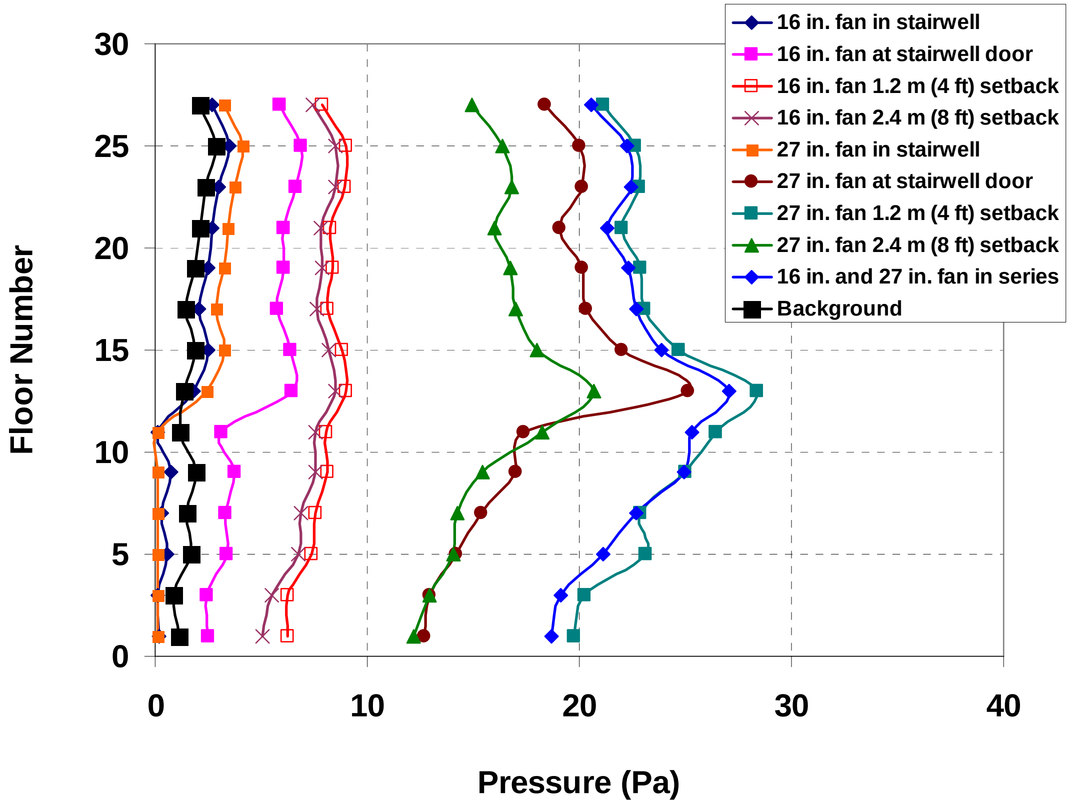

Figure 35. Stairwell pressures created with fans at the 12th floor.

4.1.10 Fans at ground level and in the building with the bulkhead door open

A common tactic in venting a high-rise building is opening the bulkhead door at the top of the stairwell, if there is one. In this building the bulkhead door was in the second stairwell, therefore both doors to the 29th floor were opened so the flow would travel through the 29th floor into the other stairwell and out of the bulkhead door. This tactic often allows for smoke to escape and create more tenable conditions in the stairwell both for civilians attempting to exit and fire fighters. This series of experiments examined the pressure decrease in the stairwell when the 29th floor and the bulkhead door in the other stairwell were opened.

After completing this series of experiments it was noticed that there was an exhaust fan on the 29th floor that forced air to the outside. This is common on mechanical floors but changes the meaning of the pressures recorded for this series only. Pressures in the top of the stairwell were lower than expected because of the negative pressure created by the exhaust fan. The pressures can be treated as a worst case scenario as opposed to ideal which will be examined in a later series which uses the 28th floor as opposed to the 29th floor to eliminate the exhaust fan from the path to the vent locations (bulkhead door and roof hatch).

Background data was recorded to examine the pressures in the building with just the bulkhead door open and then with the stairwell door open. When the stairwell door was opened it induced pressures in the lower portion of the stairwell as high as 11 Pa at the ground floor. The pressure declined to approximately 0 Pa at floor 19 (figure 36).

Three different configurations were analyzed, 0.5 m (21 in) fans at ground level, 0.7 m (27 in) fans at ground level and 0.7 m (27 in) fans on the 12th floor. The pressures on the upper floor drop significantly when the 29th floor and the bulkhead doors were opened. The pressures above the 20th floor dropped from 9 Pa to 0 Pa with the 29th floor and bulkhead doors open. Two 0.5 m (21 in) fans were able to create pressures exceeding the 28.6 Pa threshold up to the 3rd floor and 12.5 Pa threshold up to the 11th floor.

A 0.7 m (27 in) fan located at the ground level created pressures of approximately 9 Pa above the 15th floor with all the stairwell doors closed (figure 37). Those pressures dropped to 0 Pa when the 29th floor and the bulkhead doors were opened. When two fans were used the 12.5 Pa thereshold was exceeded up to the 11th floor, even with the vents opened. When the fan was moved to the 12th floor the doors opened at the top and the bottom of the stairwell were analyzed (figure 38). With the 29th floor and bulkhead doors open, the pressures dropped as much as 21 Pa to 0 Pa at the 27th floor. The ground floor door open in addition to the 29th floor and bulkhead doors had little impact on the stairwell pressures.

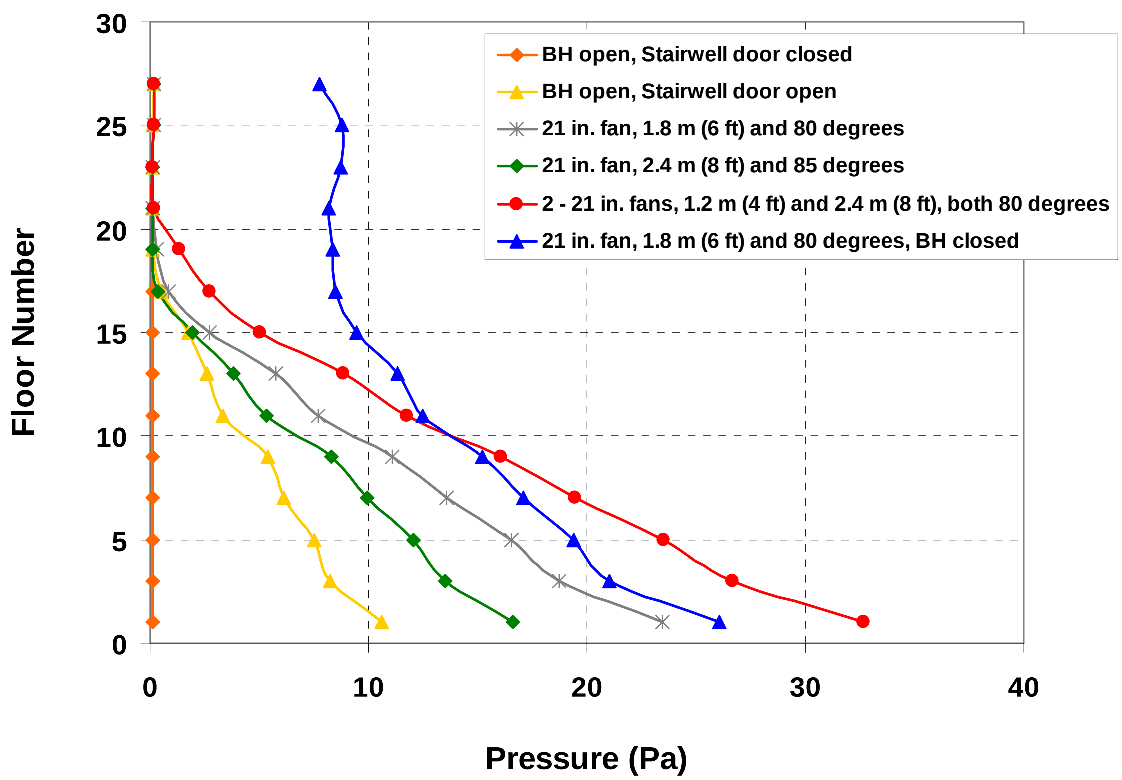

Figure 36. Stairwell pressures created by 0.5 m (21 in) fans with the 29th floor and bulkhead door open.

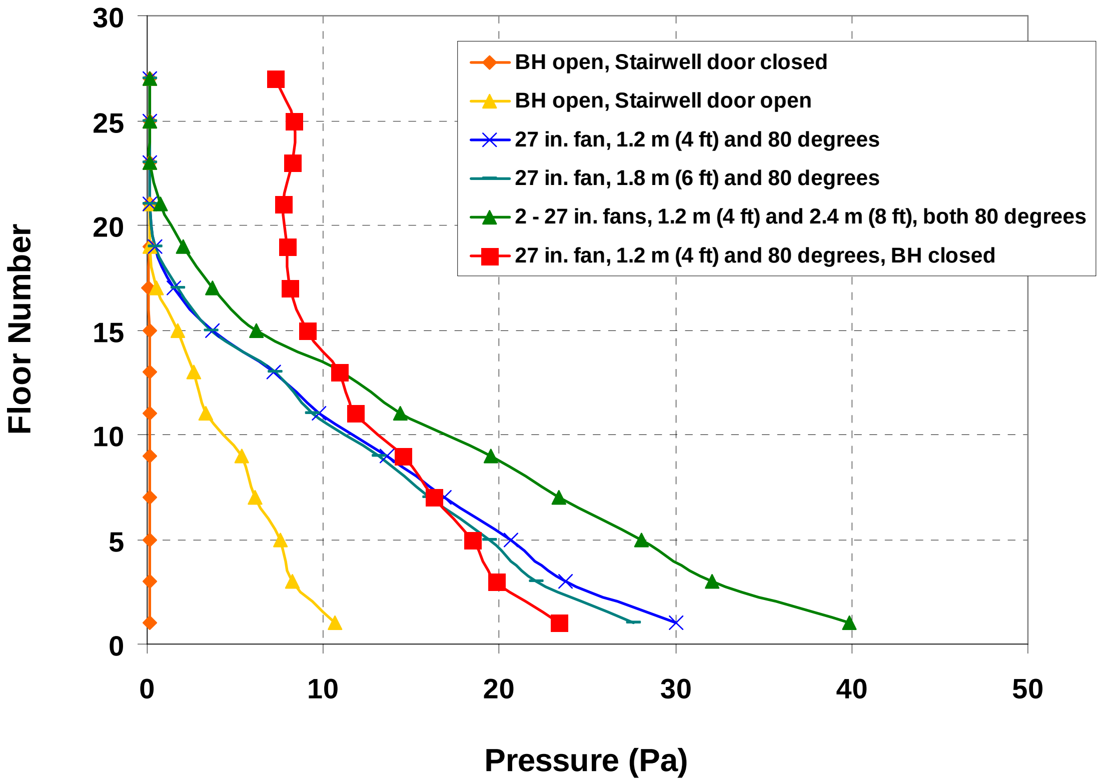

Figure 37. Stairwell pressures created by 0.7 m (27 in) fans at the ground level with the 29th floor and bulkhead door open.

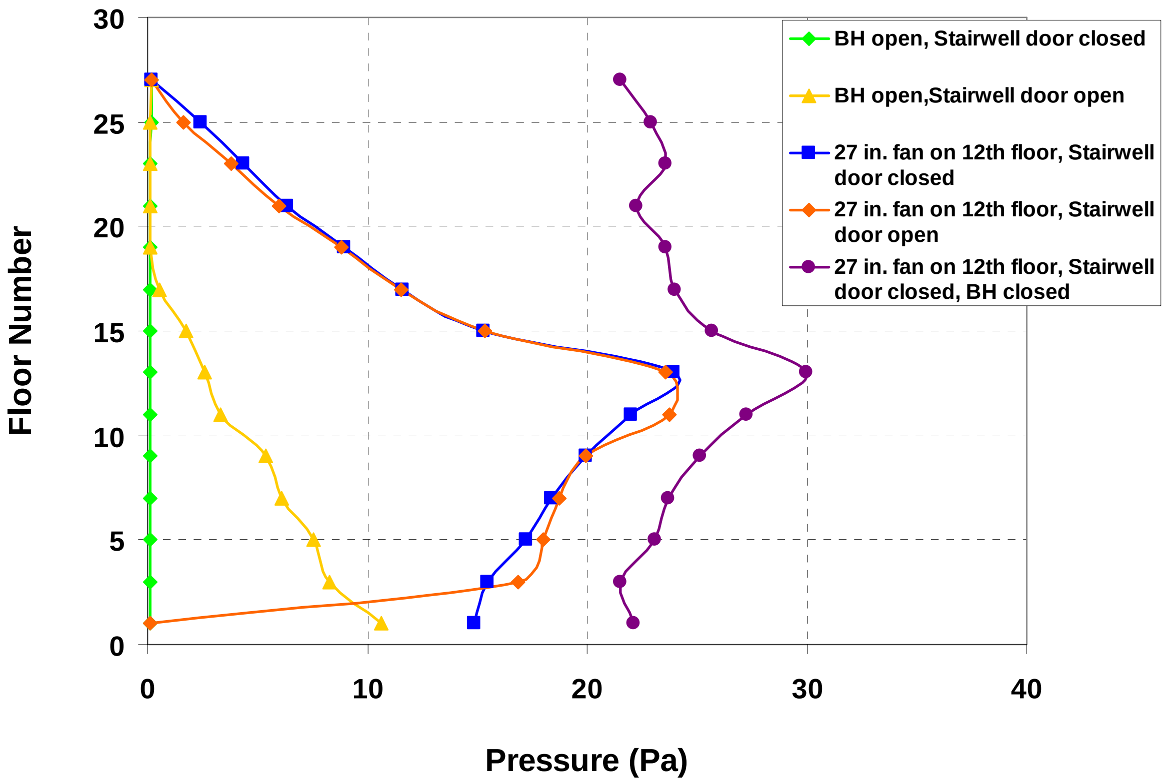

Figure 38. Stairwell pressures created by 0.7 m (27 in) fans on the 12th floor with the 29th floor and bulkhead door open.

4.1.11 Fans at ground level and in the building with the roof hatch open

Adjacent to the bulkhead door on the 29th floor was a ship-style ladder that led to a roof hatch. The roof hatch was the highest point of the building and the most remote ventilation location from the ground level entrances. In this series the exhaust fan on the 29th floor was removed from the flow path by opening both stairwell doors to the 28th floor and flowing through the 28th floor to the roof hatch. Configurations were run with single fans at ground level, multiple fans at ground level, and fans inside the building.

The series of experiments began with pressures recorded with just the roof hatch open. This did not provide any pressure above ambient (figure 39). The stairwell door was opened and pressures below the 15th floor increased. The 1st floor pressure increased to 7 Pa, decreasing down to 1 Pa at the 15th floor. The 0.4 m (16 in) fan was only able to increase pressures approximately 3 Pa and never exceeded 10 Pa. The 0.5 m (21 in) fan increased pressures on the first floor to 25 Pa and met the 12.5 Pa threshold to the 9th floor. Increasing the fan size to 0.7 m (27 in) increased the 1st floor pressure to 32 Pa. The 12.5 Pa threshold was exceeded up to the 11th floor. Without an exhaust fan in the flow path pressures were slightly increased up to the 25th floor whereas in the previous series the pressures were not increased above the 21st floor with single fans located at ground level.

Fans were added in series to try to increase the pressures in the stairwell. When a second 0.5 m (21 in) fan was added in series an increase of approximately 2 Pa was achieved throughout the stairwell (figure 40). This provided little benefit and increased the 12.5 Pa threshold from the 9th floor to the 10th floor. A second 0.7 m (27 in) fan in series increased pressures in the lower floors from approximately 4 to 6 Pa. The 12.5 Pa threshold was raised from the 11th to the 13th floor. Adding a third 0.7 m (27 in) fan in series provided very little benefit and raised stairwell pressures less than 2 Pa at all floors.

A single 0.7 m (27 in) fan was placed on the 12th floor positioned as previously described and the door at the base of the stairwell was placed in the open and closed position. Having the door closed created higher pressures below the 12th floor (figure 41). Closing the door increased the average 1st floor stairwell pressure from 10 Pa to 17 Pa. Above the 12th floor the position of the ground floor stairwell door was irrelevant. When a second 0.7 m (27 in) fan was added at ground level the pressures were increased close to the 28.6 Pa threshold up to the 13th floor. In all three configurations the 12.5 Pa threshold was reached up to the 13th floor.

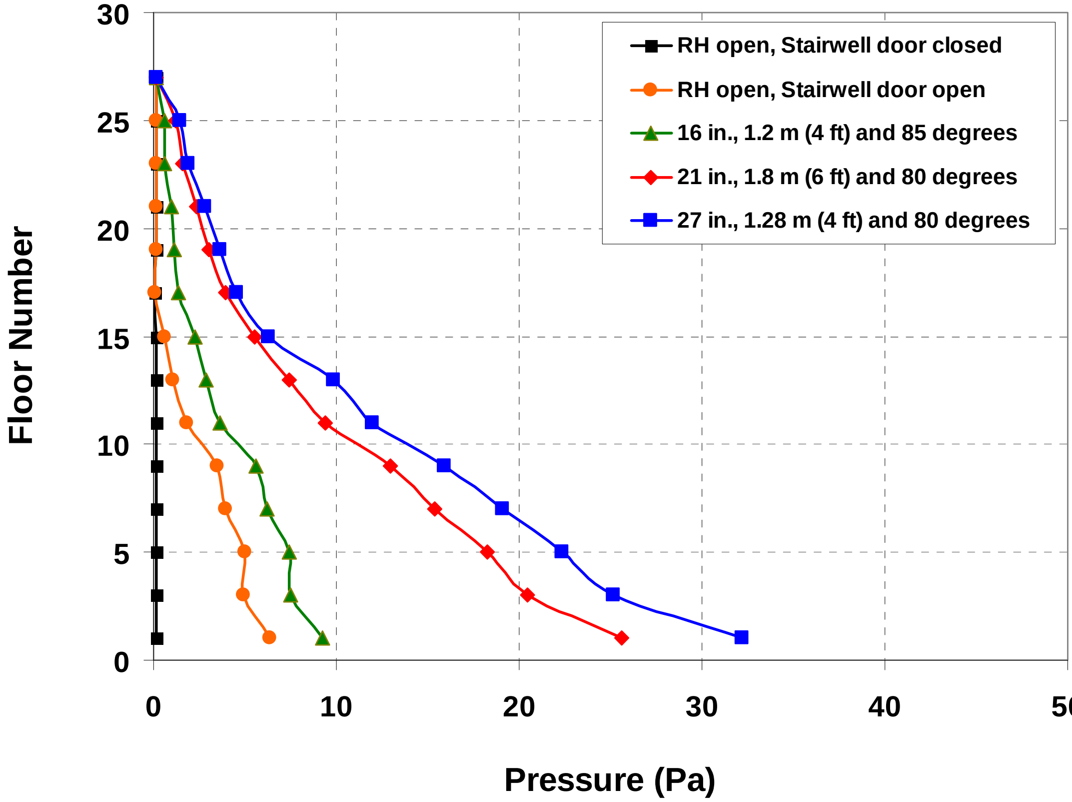

Figure 39. Stairwell pressures created by a single fan with the 28th floor and roof hatch open.

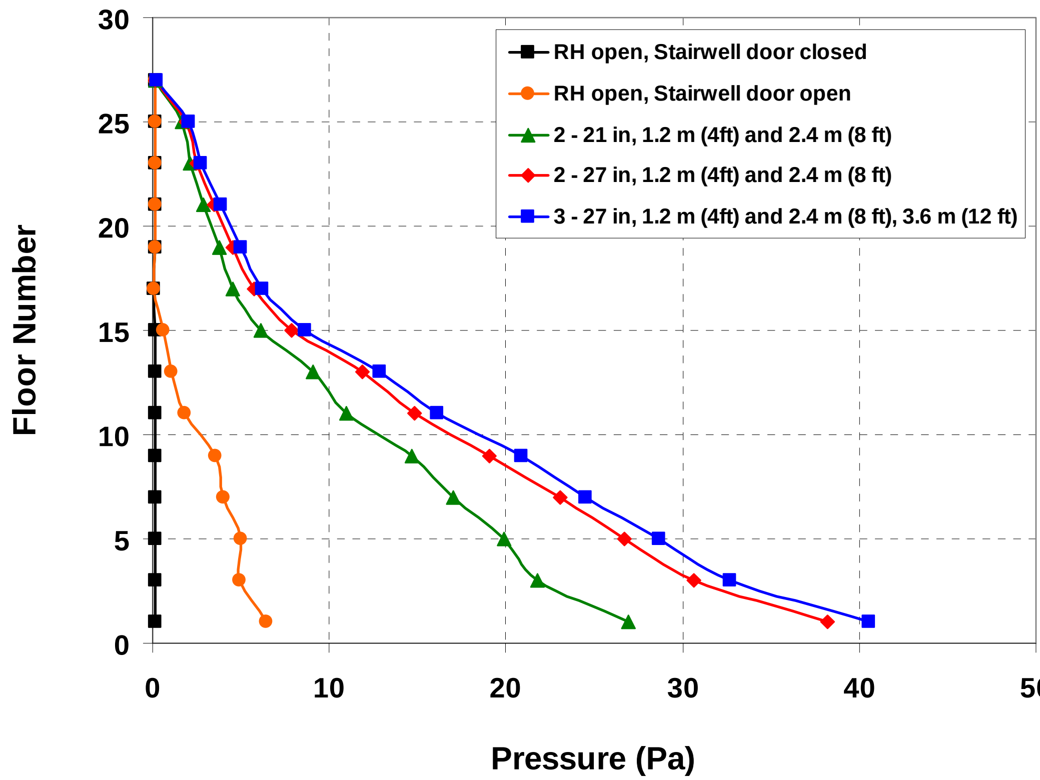

Figure 40. Stairwell pressures created by multiple fans with the 28th floor and roof hatch open.

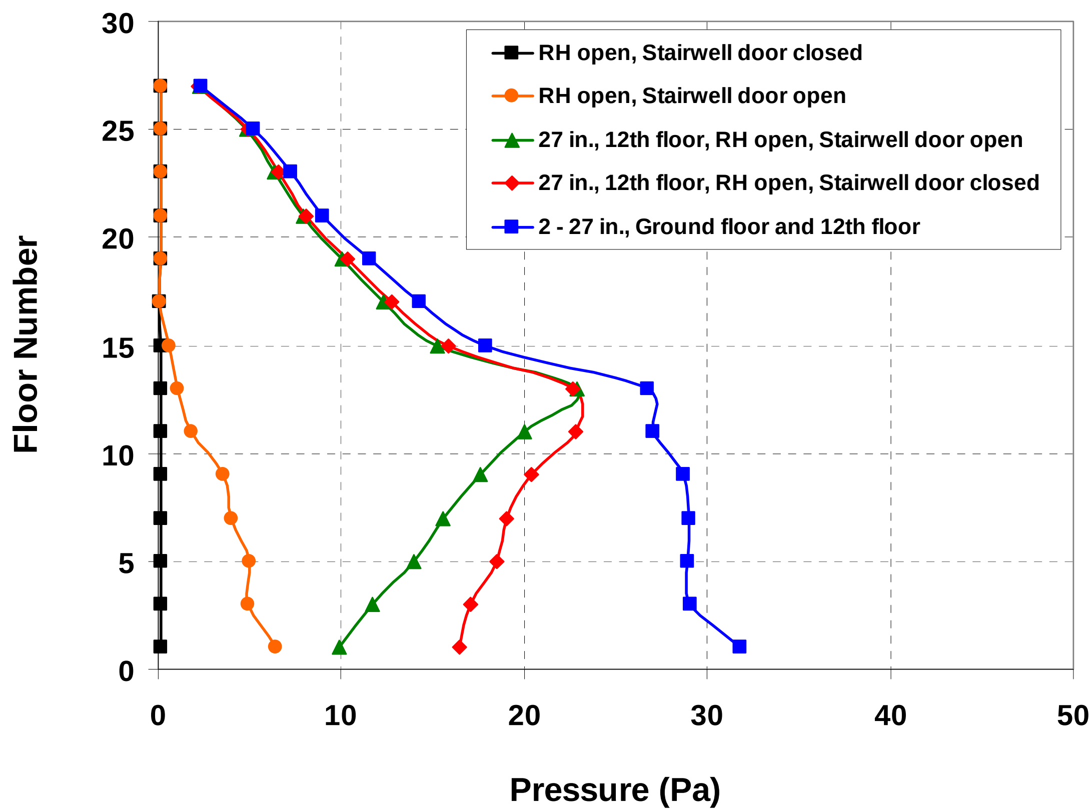

Figure 41. Stairwell pressures created by fans in the building with the 28th floor and roof hatch open.

4.1.12 Ground level doorway sealed / Fan efficiency

Positive pressure ventilation fans setback from a doorway seal the doorway with a cone of air to increase the pressure. The distance the fan is from the doorway, or setback, can impact how effective a PPV "seals" the doorway. A fixed stairwell pressurization system usually has a fan, or multiple fans, that are connected directly to the stairwell with no setback and in turn should be 100 % efficient at using its flow to increase the pressure in the stairwell. In an attempt to recreate a similar situation, the ground floor doorway was sealed with an air infiltration door test frame and a 0.5 m (21 in) fan was placed in the hole to flow into the building with no air escaping because of a setback distance.

As compared to the optimal setback configuration determined in a previous series, sealing the door created higher pressure throughout the stairwell. Pressures increased as much as 8 Pa to 2 Pa at the ground level and at the 27th floor respectively (figure 42). Assuming the fan flowing with the sealed door is completely efficient, the fan setback at its optimal distance and angle is 80 % efficient. While sealing the door is more efficient it eliminates the ability for fire fighters to enter the stairwell from that doorway and for occupants to exit via that doorway.

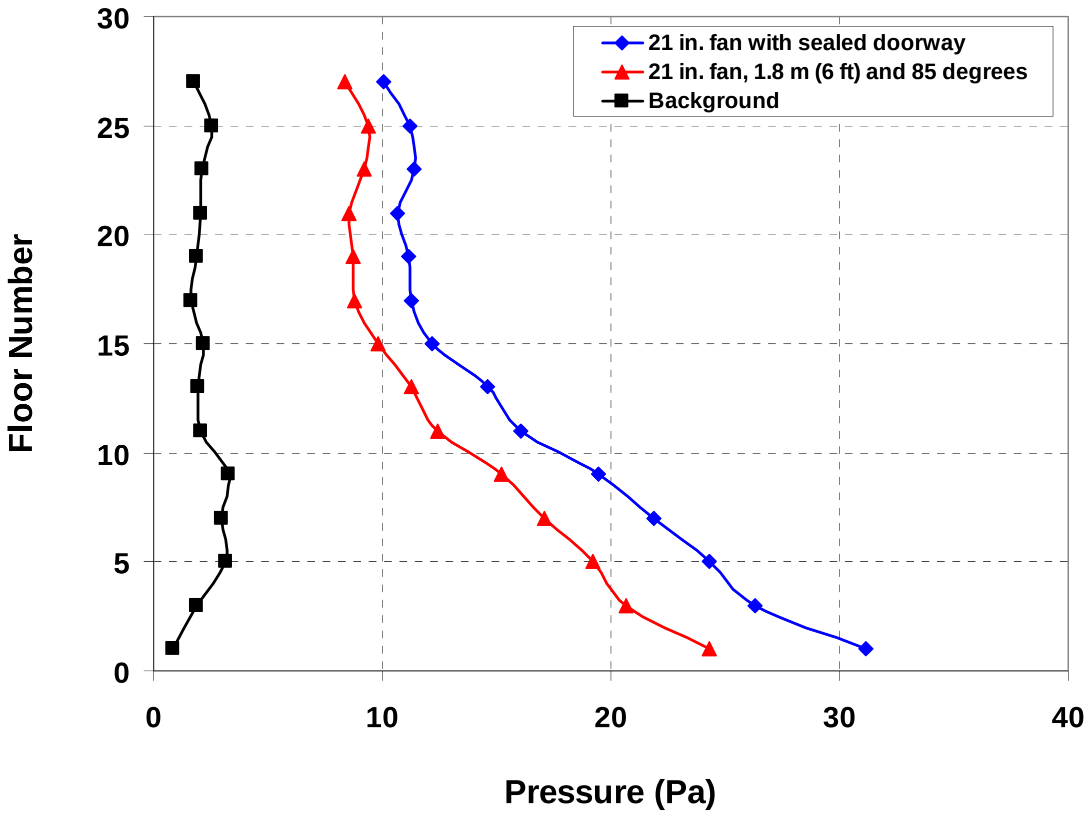

Figure 42. Stairwell pressures created by a 0.5 m (21 in) fan with the doorway sealed and with the fan setback

4.1.13 Other types of fans at the ground level stairwell door

PPV manufacturers and representatives were invited to take part in the experiments. Two additional manufacturers brought fans. The fans ranged in size from 0.5 m (21 in) to 0.8 m (31 in) with engines ranging in size from 5.5 hp to 12.0 hp. The fans were positioned at the ground level stairwell doorway and the stairwell was pressurized with all vents closed. The fans were initially setup at the doorway by the manufacturer's representative. Additional configurations such as side by side and series were done for comparison (figure 43).

As expected, the larger the fan the higher the pressures created in the stairwell (figure 44). The 0.8 m (31 in) fan created pressures as high as 41 Pa at the ground floor. The 0.6 m (24 in) fan peaked at 30 Pa on the ground floor. The 0.5 m (21 in) fan reached 23 Pa and the Toledo truck fan (has been in service for over 10 years on a Toledo Fire Department truck company) only raised the first floor stairwell pressure to 8 Pa. The 0.8 m (31 in) fan was able to exceed the 12.5 Pa threshold in the entire stairwell while the smaller fans were effective for less than half of the stairwell height.

A few different configurations were experimented with the 0.5 m (21 in) fans, 1.2 m setback, 2.4 m setback, side by side (same angle, V), offset (top and bottom, R) and series (S). The 2.4 m setback with a 70 degree angle created higher pressures than the 1.2 m setback with a 70 degree angle. The offset fans with 70 degree and 90 degree angles created higher pressures than the side by side with the same angle which created higher pressures than the fans in series. Adding the 0.6 m (24 in) fan to the 0.8 m (31 in) raised pressures 8 Pa on the ground floor and approximately 1 Pa above the 17th floor. The old fan that was taken off of the Toledo ladder truck did not perform well, not coming close to achieving the 12.5 Pa threshold anywhere in the stairwell.

Different fans are constructed different ways and cannot always be compared directly due to different sized motors, shroud type and size and fan angle adjustments. However, common trends exist. Placing the fans next to each other as opposed to in series is more effective. It is possible to have a single fan achieve 12.5 Pa in the entire stairwell but that fan maybe large and may not fit in a truck compartment. PPV fans have improved greatly in the last 10 years and older fans should be checked for performance and replaced if necessary to allow for increased effectiveness. Different fan manufacturers have different optimal setbacks and angles due to many differences, such as shrouds and fan blades.

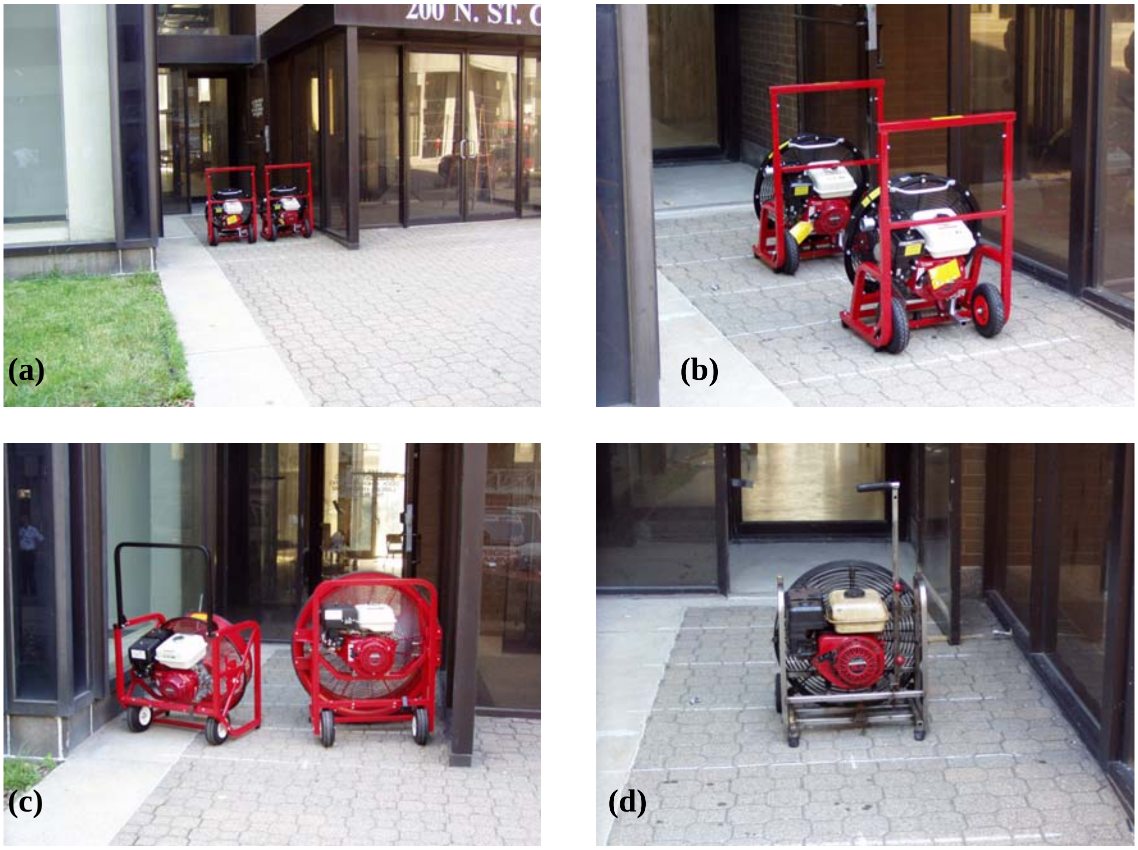

Figure 43. Other types of fans and configurations. (a) 2 – 21 in. fans side by side (b) 2 – 21 in. fans in series (c) 24 in. and 31 in. fans side by side (d) 21 in. Toledo truck fan

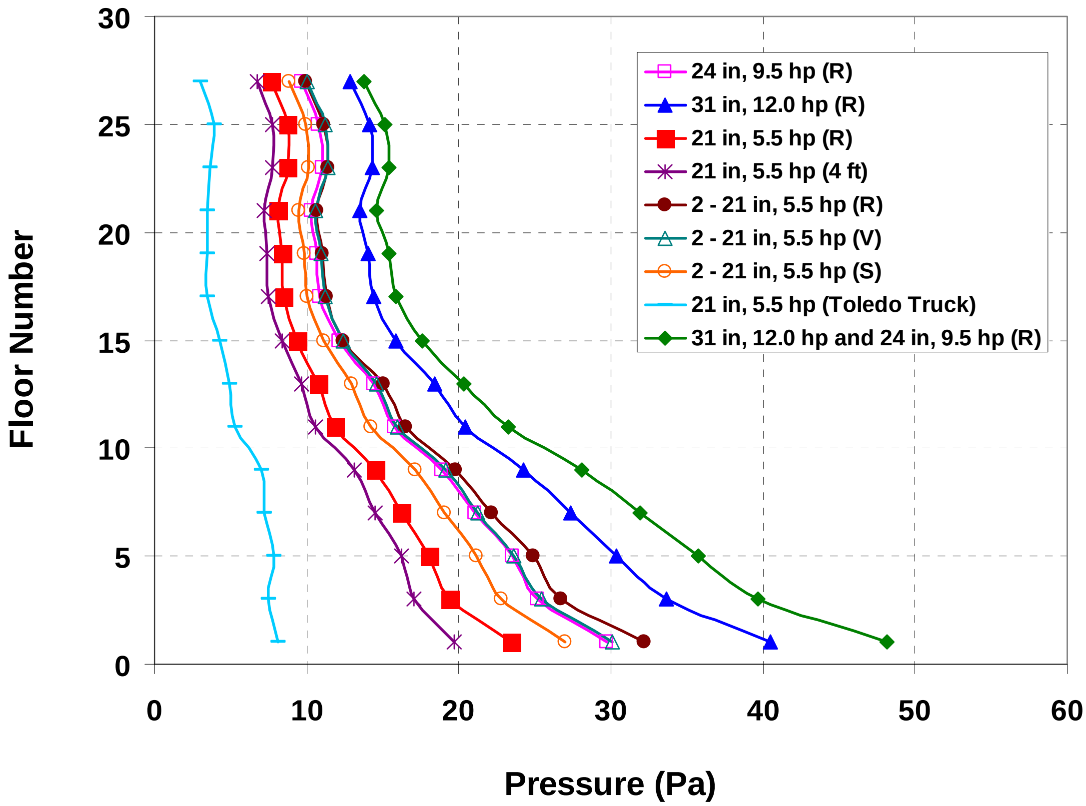

Figure 44. Pressures created by other manufacturer's fans in various configurations

4.1.14 Fans and a hovercraft at ground floor entrances (D1 and D3)

Many fire departments have been resourceful when they had to remove smoke from a large structure and have occasionally used a hovercraft or airboat. Oftentimes, a hovercraft is much more accessible than a large trailer mounted fan. A hovercraft was used in the experiments for comparison against a trailer mounted fan. The hovercraft was setback 3.7 m (12 ft) from the ground entrance door (D3) and was run at full throttle (figure 45).

The hovercraft was approximately as effective as a previous experiment where six fans were utilized (3 - 0.7 m (27 in) fans at D1 and 3 – 0.5 m (21 in) fans at D3) (figure 46). Pressures peaked at 15 Pa on the 5th floor and decreased to an average of 8 Pa in the upper half of the stairwell. The 1.2 m (46 in) trailer mounted fan positioned at D1 created much higher pressures, exceeding the 12.5 Pa threshold in the entire stairwell.

Figure 45. Hovercraft positioned at ground floor entrance (D3)

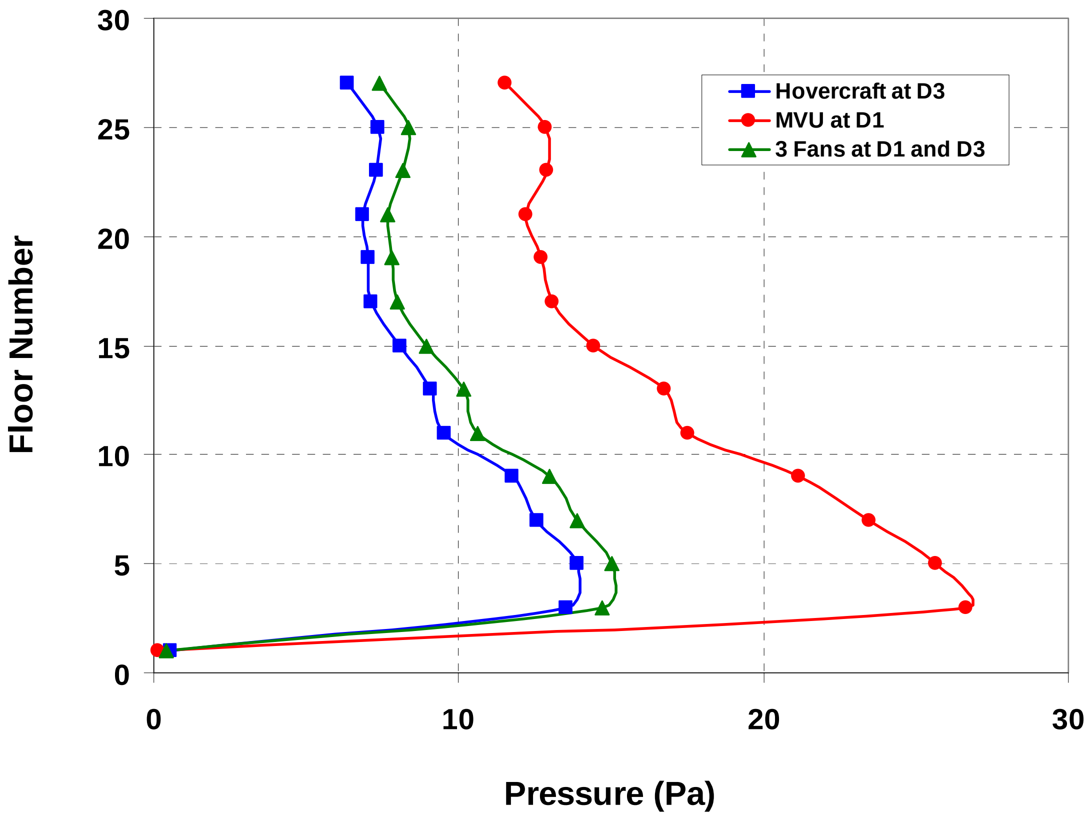

Figure 46. Stairwell pressures created by fans and hovercraft positioned at D1 and D3

4.2 Stairwell Temperature

Temperature was recorded on every other floor with bare-bead, type K thermocouples, with a 0.5 mm (0.02 in) nominal diameter. Thermocouples were located next to each of the differential pressure transducers. There was no temperature control in the building; therefore the stairwell temperatures were very similar to the outside temperatures. The temperature in the lower floors ranged between 19 °C (66 °F) in the morning hours to 23 °C (73 °F) in the afternoon. The temperature in the upper floors of the stairwell remained almost constant at about 25 °C (77 °F) to 26 °C (79 °F) independent of the day the experiments were done or of the time of day (figure 47). This small variation in temperature between the inside temperatures and the outside temperatures suggests the impact of stack effect in the stairwell was minimal

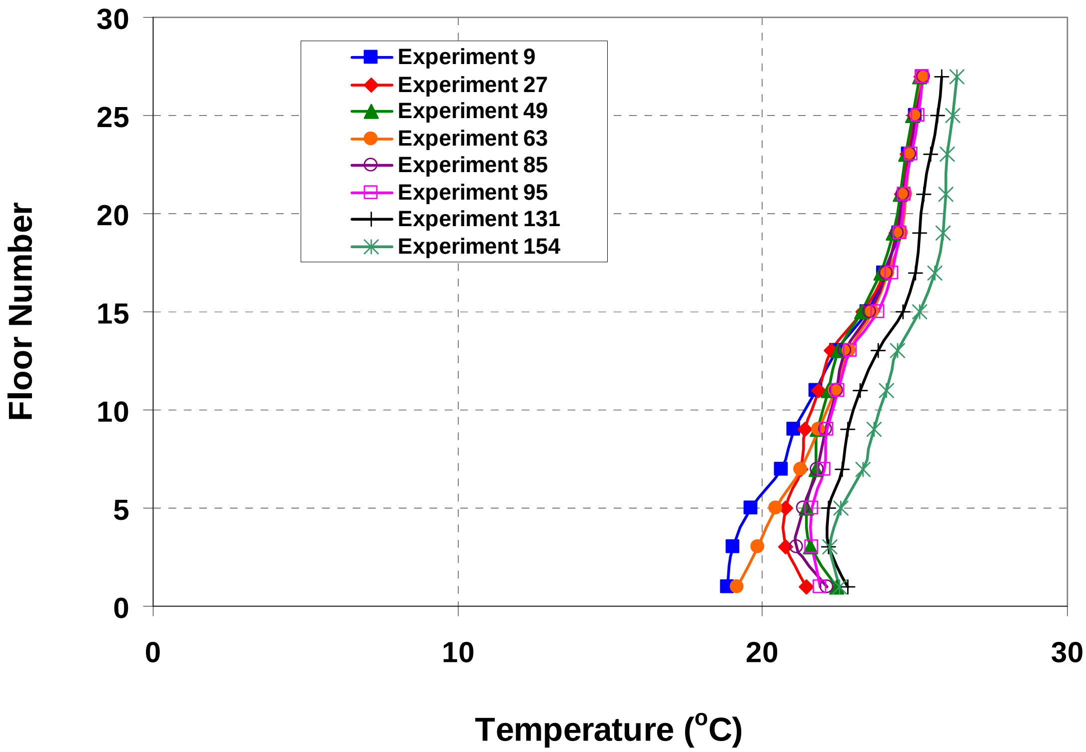

Figure 47. Stairwell temperatures

4.3 Weather

Weather was monitored and recorded during each of the experiments using two portable weather stations. Temperature, relative humidity, average wind speed, average wind direction and barometric pressure were recorded continuously. One weather station was located 9.1 m (30 ft) from the centerline of D2 on ground level. The second weather station was located on the lower roof outside RD. Each day started at time zero and readings were captured every 30 seconds. Technical difficulties with the wireless link between the weather station and the data logger resulted in some data loss, but the trends of the data were captured.

The average air temperature was recorded over the course of the four days of experiments at the ground and the roof. The average temperatures remained fairly constant during all of the experiments. Temperatures ranged between 16 ^{o}C (61 ^{o}F) and 25 ^{o}C (77 ^{o}F) (figure 48). The morning temperatures were cooler than the afternoon temperatures but there was never an increase of more than 5 ^{o}C (9 ^{o}F) during the entire day.

Wind speed has the potential to greatly impact the effectiveness of PPV. Wind blowing against an exhaust vent could decrease the effectiveness of PPV. Wind blowing into an inlet could increase the air flow or increase pressurization of a building. The average wind speed mostly remained below 2 m/s (4.5 mph) (figure 49). The wind had little impact on the experimental results. If there was wind there were no gusts that would give one experiment an advantage or disadvantage from another experiment in the same series. The average wind direction was also examined to determine if the wind was into or out of one of the inlets or vents. The wind mainly impacted the building on side B and C, between zero and 140 degrees from north (figure 50). The north arrow can be referenced to the inlets and outlets in figure 4 and figure 7. Therefore the wind had no direct impact on the inlets on side A and little impact on the roof door on side C. A wind impacting the opposite side of the building from the inlets has the potential to lower the pressure on the leeward side of the building. This phenomenon did not play a role in these experiments due to the low magnitude of the wind speed. The stairwells were also interior to the building which lessened the impact of any wind.

The relative humidity and barometric pressure did not show any variations that may have affected the results. The relative humidity ranged between 20 % and 70 % (figure 51). The relative humidity decreased as it became later in the day. The barometric pressure on the roof was between 98 kPa and 99 kPa and between 99 kPa and 100 kPa at ground level (figure 52).

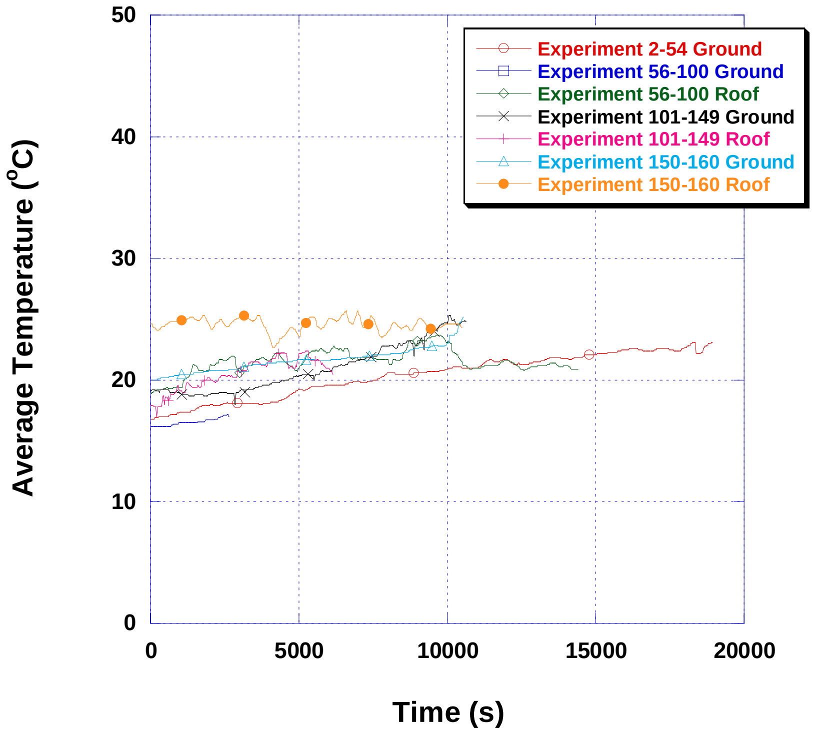

Figure 48. Average temperatures.

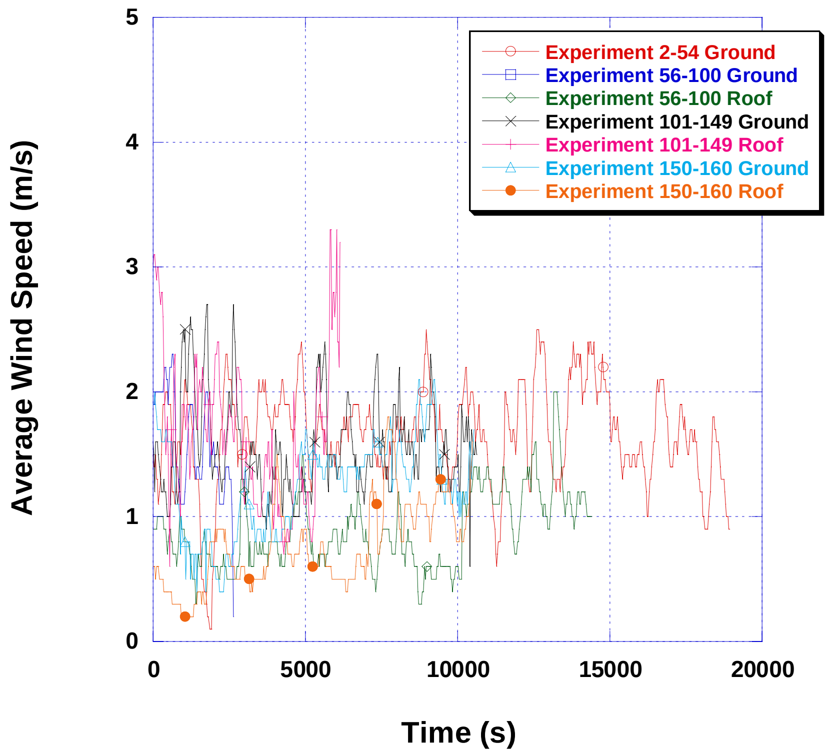

Figure 49. Average wind speed.

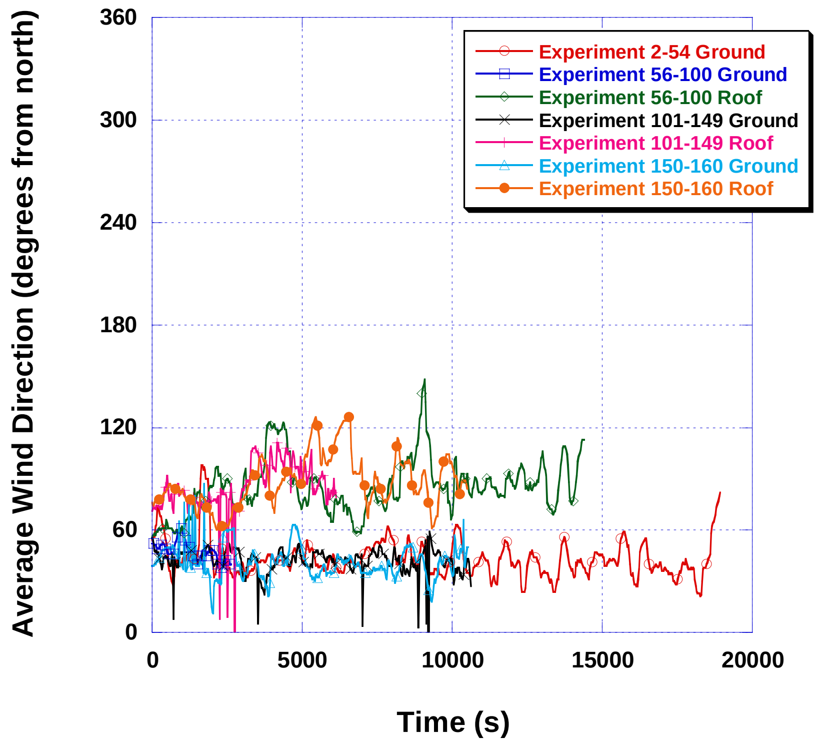

Figure 50. Average wind direction.

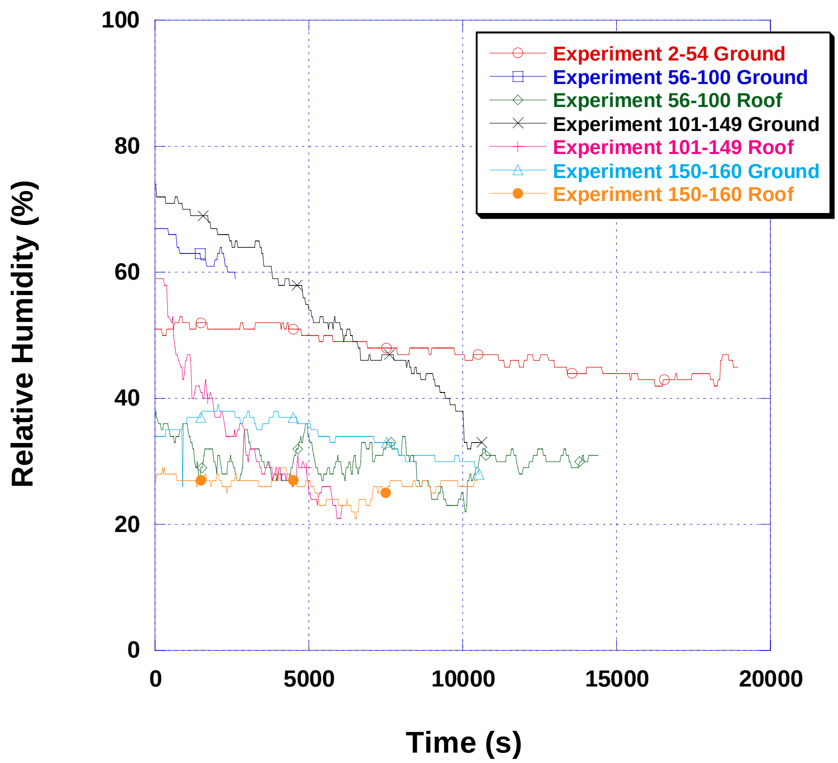

Figure 51. Relative humidity.

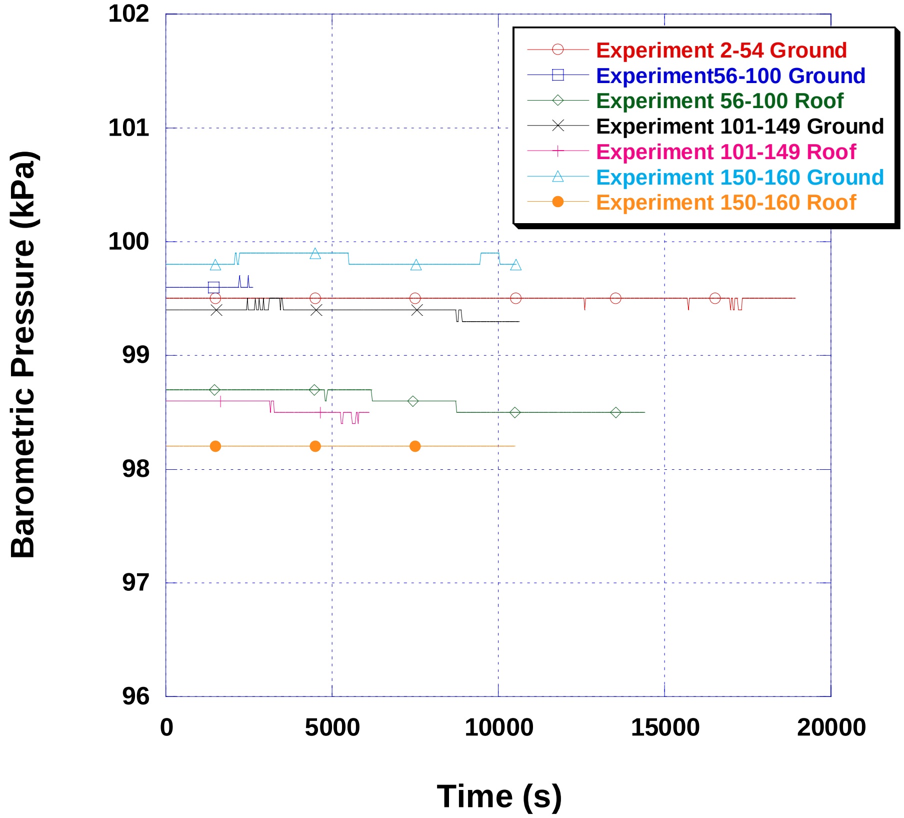

Figure 52. Barometric pressure.

4.4 Carbon Monoxide

One of the main toxic gases in combustion is carbon monoxide (CO). When examining PPV and preventing smoke infiltration there are two types of combustion that are important, the fire creating the smoke and the internal combustion of the fan motor. Both sources of CO must be monitored to maintain a safe environment for victims as well as fire fighters.

A fire has the potential to produce a very large amount of CO. This amount could be on the order of 50,000 ppm in an under-ventilated fire [15]. Tenability limits for incapacitation and death for a 5 minute exposure are 6000 ppm (0.6 %) to 8000 ppm (0.8 %) and 12,000 ppm (1.2 %) to 16,000 ppm (1.6 %) respectively. CO is the major toxic gas in approximately 67 % of fatalities in structure fires [15]. Using PPV fans to keep the CO produced by the fire along with the other harmful combustion products out of the stairwells greatly increases the chances of safe evacuation.

The internal combustion fan motors also produce CO. While the levels are much lower than the fire they have to be analyzed. CO meters were placed at the bottom, middle and top of the stairwell to analyze this level. The National Institute for Occupational Safety and Health (NIOSH) has established a recommended exposure limit for CO of 35 ppm (0.0035 %) as an

8-hour time weighted average (TWA) and 200 ppm (0.02 %) as a ceiling exposure [16]. A reading of 1200 ppm (0.12 %) is considered immediately dangerous to life and health. The National Research Council (NRC) also defines emergency exposure guidance levels of, 1500 ppm (0.15 %) for 10 minutes, 800 ppm (0.08 %) for 30 minutes, 400 ppm (0.04 %) for 60 minutes and 50 ppm (0.005 %) for 24 hours [17].

CO levels for the four days of experiments are graphed in figures 53 through 56. The single fan at the ground floor stairwell created readings as high as 110 ppm (0.011 %) at the 1st floor with a 0.7 m (27 in) fan set back 0.6 m (2 ft) from the doorway. The reading decreased to 30 ppm (0.003 %) when the fan was run at 3.7 m (12 ft). The optimal fan placements for all three sizes of fans created CO readings of 50 ppm (0.005 %) to 80 ppm (0.008 %). The experiments were run one right after another with no venting of any openings between experiments. There was a break between fan sizes to allow for the CO readings to return to ambient.

Any number of fans placed at the ground level did not exceed readings of 100 ppm (0.01 %). Nine fans blowing into the building from three different ground level doorways did not raise the CO reading above 100 ppm (0.01 %). The 1.2 m (46 in) trailer mounted fan did not exceed 50 ppm (0.005 %) at any level in the stairwell.

The fire service becomes very concerned with the idea of taking gasoline powered fans into a structure. This was done multiple times to see the actual CO levels created. A single 0.7 m (27 in) fan set back from the 12th floor door did not exceed 100 ppm (0.01 %). With a 0.7 m (27 in) fan at the ground level in addition to the one on the 12th floor the CO readings peaked at 130 ppm (0.013 %). Adding another 0.7 m (27 in) fan to the 22nd floor increased the peak CO reading on the 14th floor to 140 ppm (0.014 %) but also increased the 28th floor CO level to 110 ppm (0.011 %). The only two experiments that caused the CO levels to exceed the NIOSH ceiling exposure value of 200 ppm (0.02 %) were when a fan was placed in the stairwell and the stairwell doors were closed. In these experiments the 0.4 m (16 in) fan created a peak CO reading of 210 ppm (0.021 %) in the stairwell at the 14th floor and the 0.7 m (27 in) fan had a peak reading of 360 ppm (0.036 %) in the same configuration.

Ultimately the CO produced by the PPV fans was at least one order of magnitude less than that created by a fire. As long as the PPV fans were not placed in the stairwell with the door shut, the NIOSH ceiling exposure was not exceeded and the TWA would not be exceeded for a long period of time. If CO readings are less than 50 ppm (0.005 %), it is not likely that a gasoline powered PPV fan would be effective in ventilating the area. In this case alternatives such as electric PPV fans or natural ventilation should be considered.

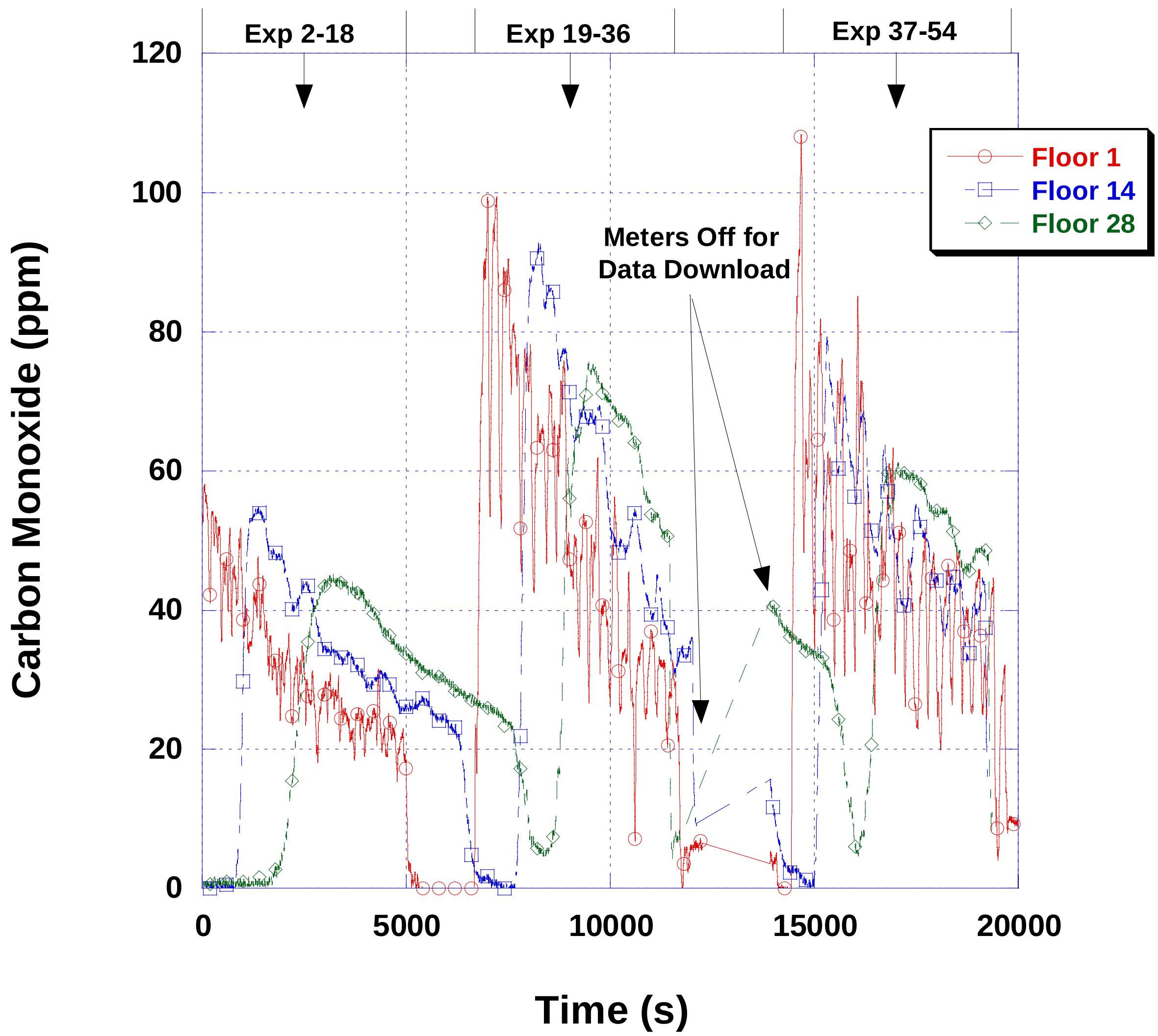

Figure 53. Carbon monoxide levels for experiments 2 through 54.

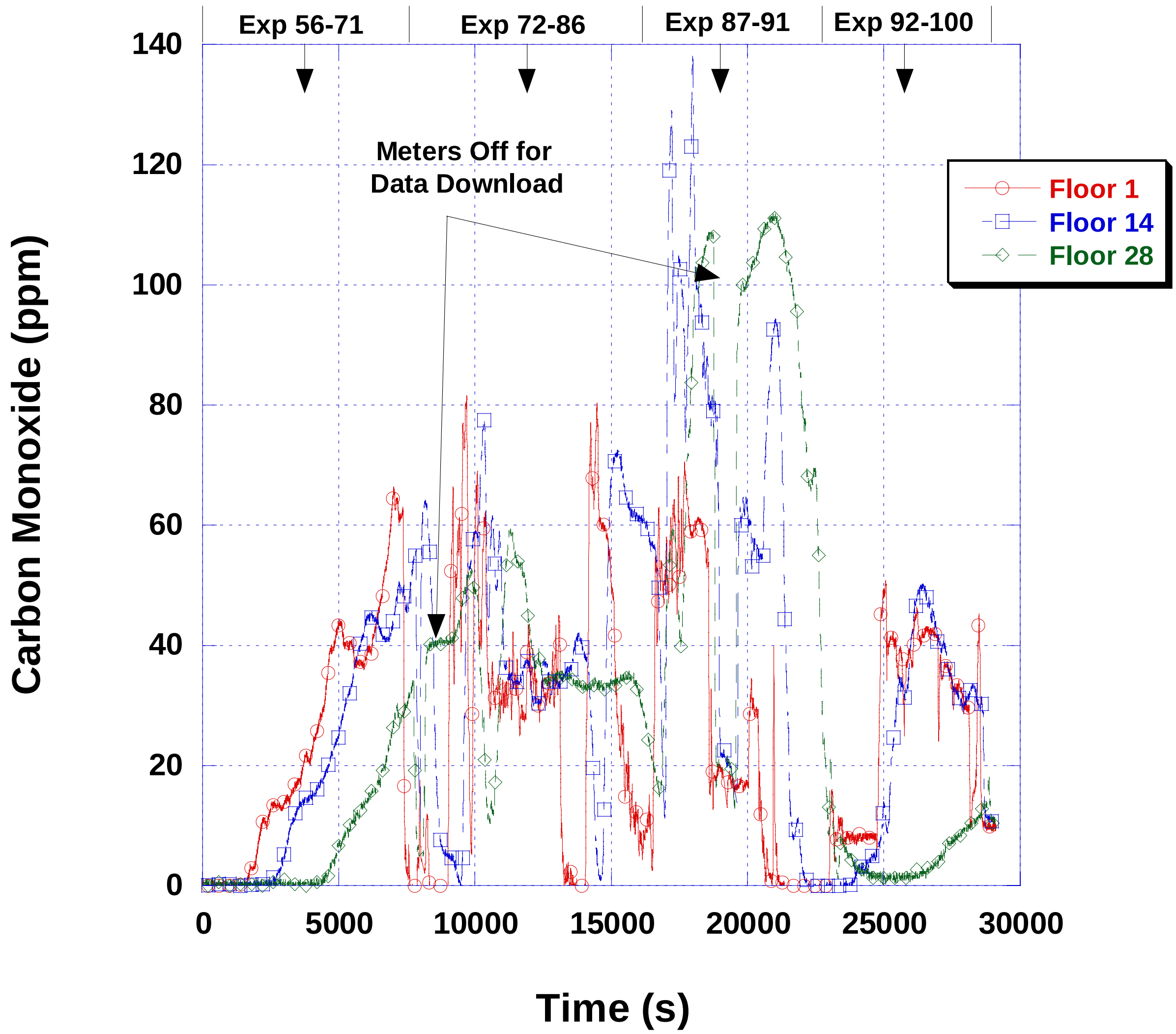

Figure 54. Carbon monoxide levels for experiments 56 through 100.

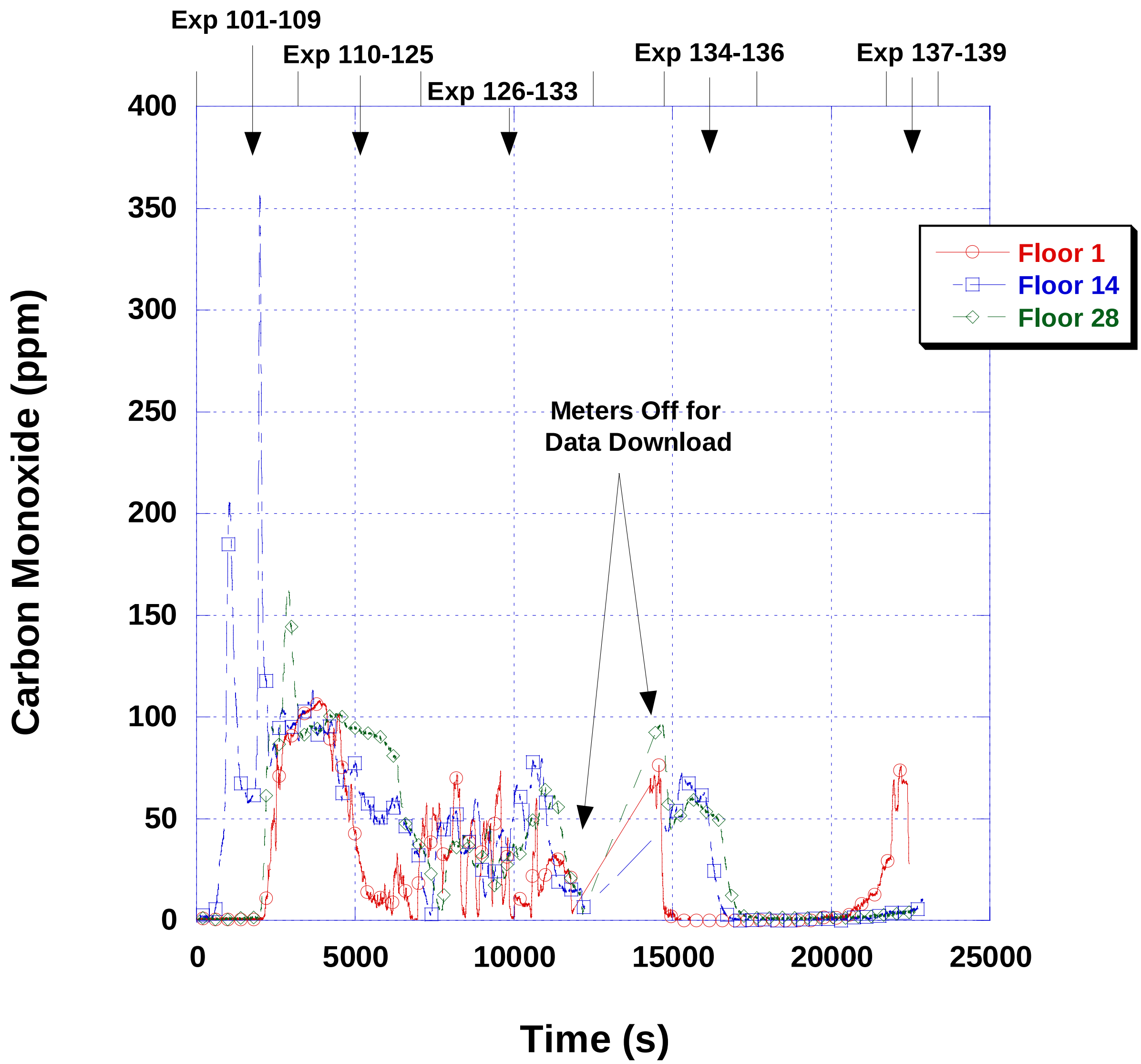

Figure 55. Carbon monoxide levels for experiments 101 through 139.

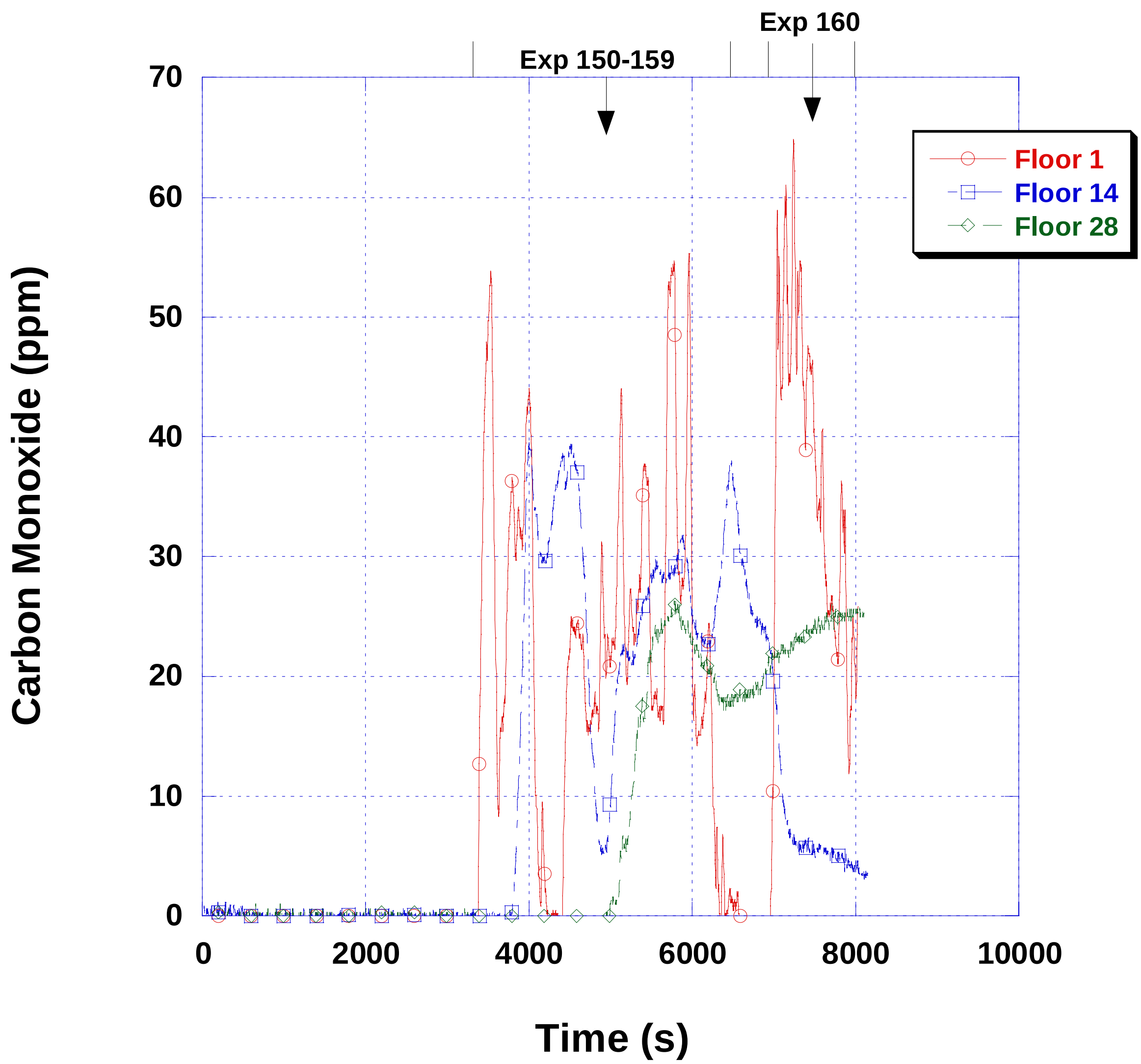

Figure 56. Carbon monoxide levels for experiments 150 through 160.

4.5 Sound Levels

Another concern with the use of PPV fans is the noise they create. Fans placed at the base of a stairwell can increase the ambient noise in the stairwell and may adversely affect the communications of the fire crews. Fans placed at lobby doors have the potential to affect command officers that may set up command posts in high-rise structures.

Noise levels were monitored in certain locations throughout the experimental series to estimate the level of impact to the fire crews and command officers. Ambient noise measurements were 60 to 65 dB. This value rose to 80 dB when traffic went past the building. Measurements next to the compartment size fans were approximately 100 dB to 110 dB depending on the size of the fan. The noise value measured 3.0 m (10 ft) from the fans decreased to 90 to 100 dB. Table 21 has a number of common noise levels for comparison.

A 0.7 m (27 in) fan was placed 3.7 m (12 ft) from the stairwell doorway. Readings next to the fan were 105 dB with the fan at full throttle, directly inside the doorway with the door open were 104 dB. In the lobby with the door shut the readings decreased to 77 dB but increased to 95 dB when the door connecting the stairwell and lobby was opened. On the second floor landing, the reading decreased to 80 dB. Similar readings were obtained with a 0.5 m (21 in) fan placed at the same setback distance.

Table 21. Relative Noise Levels

Source of Sound/Noise	Sound Pressure Level (dB)
Threshold of hearing	0
Quiet bedroom at night	30
Conversational speech	60
Curbside of busy roadway	80
Heavy Truck	90
Jackhammer	100
Chainsaw	110
Threshold of pain	130
Instant perforation of eardrum	160

5.0 Uncertainty

There are different components of uncertainty in the length, differential pressure, gas temperature, metrological, and carbon monoxide data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means [18]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 % confidence interval (2σ). Components of uncertainty are tabulated in Table 22. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as differential pressure, include past experience with the instruments.

Each length measurement was taken carefully. However due to some issues, such as obstructions and unlevel terrain there was a total expanded uncertainty of ± 6 % associated with the length measurements.

Differential pressure reading uncertainty components are derived from pressure transducer instrument specifications. The transducers were factory calibrated and the zero and span of each was checked in the laboratory prior to the experiments.

Gas temperature measurements were taken in a very low range of less than 30 ^{o}C. There were no temperature fluctuations of large magnitude and no radiative effects. Calibration data was obtained from the thermocouple manufacturer and the measurements appeared very repeatable.

Weather, carbon monoxide and sound measurement uncertainty was referenced to each of their published user's manuals. Weather and CO instruments have calibration certificates that are traceable to NIST standards. The carbon monoxide meters were factory calibrated prior to the experiments. The sound meter had a self-calibration setting.

Table 22. Uncertainty

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Length Measurements		± 3 %	± 6 %
Instrumentation Locations	± 1 %		
Fan Location	± 1 %		
Building Dimensions	± 1 %		
Repeatability[1]	± 2 %		
Random[1]	± 2 %		
Differential Pressure		± 5 %	± 10 %
Calibration [19]	± 2 %		
Accuracy [19]	± 1 %		
Repeatability [1]	± 3 %		
Random [1]	± 3 %		
Gas Temperature		± 1 %	± 2 %
Calibration[20]	± 0.75 %		
Repeatability[1]	± 1 %		
Random[1]	± 1 %		
Weather Measurements		± 3 %	± 6 %
Temperature[21]	± 2 %		
Relative Humidity	± 2 %		
Average Wind Speed	± 1 %		
Wind Direction	± 1 %		
Barometric Pressure	± 0.003 %		
Repeatability[1]	± 1 %		
Random[1]	± 1 %		

Carbon Monoxide Measurements Calibration[22] Accuracy[22] Repeatability[1] Random[1]	± 1 % ± 0.002 % ± 2 % ± 2 %	± 2 %	± 4 %
Sound Measurements Calibration[23] Accuracy[23] Repeatability[1] Random[1]	± 1 % ± 3 % ± 2 % ± 2 %	± 4 %	± 8 %
Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.			

6.0 Discussion

For this limited series of experiments, the fan setback distance and angle needed to be optimized in order to maximize the impact of the fan. The fans used in these experiments had optimal configurations of 1.2 m (4 ft) and 85 degrees for the 0.4 m (16 in) fan, 1.8 m (6 ft) and 85 degrees for the 0.5 m (21 in) fan, and 1.2 m (4 ft) and 80 degrees for the 0.7 m (27 in fan). The setback distances suggest that PPV fans rely on the air that is entrained around the shroud from air being pulled through the shroud to achieve the cone of air to seal the doorway. The fans positioned right in front of the doorway, which had limited air entrainment, were not able to raise the pressures in the stairwell as well as the fans set back from the doorway.

This set of full-scale experiments indicates that when possible the PPV fan should be placed at the stairwell doorway and not at another ground floor entrance. Adding the volume of the first floor makes any number of fans at the ground floor entrances ineffective, especially above the 10th floor. This may not hold for buildings with smaller lobbies or with first floors that can be sectioned off to limit the volume, but typically high-rise buildings have large open lobbies.

During these ambient temperature experiments, placing PPV fans in series was less effective than placing the fans in a V-shape. When the fans were in a V-shape it did not seem to make a large difference if the fans were at the same angle or if one was angled at the top and the other at the bottom of the doorway. If building geometry prevents the fans from being placed in a V-shape, adding a second fan in series only increases the pressure by approximately 25 % and a third fan an additional 10 %.

Similar to fixed smoke control systems, opening stairwell doors has a large impact on stairwell pressures. Opening a stairwell door reduces the pressure on floors above the open door to approximately ambient, eliminating the desired impact of the PPV fan. A significant increase in pressure could be achieved by closing the doorway to the width of a hoseline. If the fire crew closes the doorway on their hoseline instead of keeping the door completely open, the amount of smoke that infiltrates into the stairwell will be greatly reduced. This will be of significant benefit to the people exiting through this stairwell and fire crews operating above the fire floor.

Placing fans in the building was the only way to effectively pressurize the stairwell. In a 30-story stairwell a 0.7 m (27 in) fan placed at the ground floor and one 0.7 m (27 in) fan set back from the 12th floor stairwell doorway greatly increased the pressure in the entire stairwell. There was no make-up air provided to the fans set back in the building. This is not necessary as the fan recirculates the same air to the stairwell doorway maintaining the pressure on a continuous basis.

The fans positioned in the building were more effective when configured using the same optimal setback and angle described previously for fans at the ground floor stairwell doorway. Placing the fans in the doorway was ineffective because there was no cone of air to seal the doorway. Also, moving the fans back to 2.4 m (8 ft) was less effective. Fans should not be placed in the stairwell; this resulted in lower pressure differentials and generated significant amounts of CO in the stairwell.

Examining the effects of the fan on the 12th floor and the fan on the 22nd floor it may be most effective to place a 0.7 m (27 in) fan at the stairwell doorway 2 floors below the fire to get the desired pressures and reduce the impact of doors opening on any of the floors. This configuration also allows for ventilation in addition to pressurization. The smoke that has already infiltrated the stairwell could be vented out of the top of the stairwell while the localized pressure will prevent any additional smoke from entering the stairwell. The data suggest that this will work on sprinklered buildings even with the top and bottom of the stairwell open and the pressures are borderline to work on an unsprinklered building based on the threshold pressures required.

When venting the top of the stairwell and pressurizing the stairwell, a smaller vent such as a roof hatch should be considered rather than a bulkhead or roof door in order to maximize the potential pressure differential. A roof hatch is usually large enough to vent sufficient smoke while small enough to increase the pressure in the stairwell.

Fixed stairwell pressurization systems usually have at least one fan that is built into a wall or the top of the stairwell. The pressure loss due to the fire department fan being set back as opposed to sealed in the doorway yielded an 80 % efficiency based on the comparison of pressure differences. This setback allows access and egress from the fan inlet doorway which is essential for most fire department operations. The 20 % loss has little impact on the overall ability of the fans to pressurize the stairwell.

The large trailer-mounted fan was able to pressurize the stairwell to the NFPA 92A unsprinklered threshold in the entire stairwell when utilized on the stairwell doorway. It was also able to pressurize the stairwell to the unsprinklered threshold at the other ground floor entrance when it had to pressurize the entire first floor and basement in addition to the stairwell. Attention needs to be given to the maximum allowable pressure with these large fans in order to ensure that the pressure does not prevent the opening of doors into the stairwell. This value is specified in national codes such as NFPA 101 or in local codes and is a function of stairwell door size, handle location and door closer force. This value is often approximately 80 Pa to100 Pa which the large fans are capable of creating in the lower portions of the stairwell.

The hovercraft created stairwell pressures that were below the standards minimum. The hovercraft's performance could be replicated by multiple compartment sized fans. If multiple compartment sized fans are not available the hovercraft may be a good choice to vent a large volume but not to pressurize a stairwell to a desired pressure differential.

There are multiple fan manufacturers and each of them has differences whether it is blade type, shroud size, engine power rating, etc. Not all PPV fans behave the same and it is important to utilize them optimally to get the desired performance. These results provide guidance to the important variables but may not be relevant to all fan types. As technology improves so will the ability of the fans to move air. The fans used in these experiments represent the best current technology available and the size and power rating of the fans may not be representative of older fans that may currently be on fire apparatus.

Temperature can be an important variable when pressurizing a stairwell. In these experiments the temperature in the stairwell was very similar to the outside temperature which minimized the impact of stack effect. In cases where the outside temperature is lower than the stairwell pressure there tends to be an upward movement of air in the stairwell. Air in the building is often warmer and therefore less dense than outside air causing it to rise in the stairwell. This causes smoke to accumulate on the upper floors and reinforces the need to ventilate along with pressurization.

The CO produced by the PPV fans was at least one order of magnitude less than that created by a fire. As long as the PPV fans were not placed in the stairwell with the door shut, the NIOSH ceiling exposure was not exceeded. However, CO readings less than 50 ppm are unlikely with a gasoline powered PPV fan. Electric PPV fans or natural ventilation should be considered if CO readings less than 50 ppm are desired.

The noise levels created by the fans reached as high as 110 dB next to the fan at full throttle. This is comparable to a chainsaw and can have an impact on communications on the fire ground. Attempting a conversation or radio transmission near the PPV fan was difficult both for the sender and receiver. Attention should be given to the location of the command post and potential for PPV fan usage locations.

7.0 Future Research

The results of these experiments provide guidance for fan placement to be effective against smoke flow due to pressure differences. The performance metric was provided by NFPA 92A but needs to be tested in live fire experiments. The experiments should focus on realistic fire conditions in high-rise structures and integrate the use of the fans into fire department standard operating procedures to determine if conditions can in fact be improved for both the occupants exiting the building and for firefighters performing fire ground operations.

Additionally a standard test needs to be developed and followed to provide the fire service with a set of performance metrics such as flow capacity so that they may make educated decisions on which fans work for their needs. Currently the Air Movement and Control Association

International, Inc. (AMCA) has a standard entitled “Laboratory Method of Testing Positive Pressure Ventilators for Rating.” This standard is meant to establish a uniform method for laboratory testing of PPV fans in order to determine performance in terms of airflow rate, pressure, air density, and speed of rotation for rating or guarantee purposes.

Further testing should be done to determine the relevance of the current AMCA standard to fire fighting operations. If the standard were mandatory for all manufacturers the fire service would have a means to determine the effectiveness of a particular fan for a certain application. Currently the fire service has attributes such as fan size and motor power but that is not directly applicable to particular applications. It would be valuable to be able to label or certify a fan to be capable of generating a specified capacity of air allowing the fire fighter to determine if that flow capacity meets their needs for an incident. Formulas, like those for fire fighting flow rates, could be developed for positive pressure ventilation operations. The formula would incorporate the height of the building or the volume of the building to aid fan selection. Such a standard would require additional data gathered collaboratively with all affected parties.

8.0 Conclusions

Positive pressure ventilation fans utilized correctly can increase the effectiveness of fire fighters and survivability of occupants in high-rise buildings. In a high-rise building it is possible to increase the pressure of a stairwell to prevent the infiltration of smoke if fire crews configure the fans properly. When configured properly PPV fans can meet or exceed previously established performance metrics for fixed smoke control systems. Proper configuration requires the user to consider a range of variables including, fan size, set back, and angle, fan position inside or outside of the building, and number and alignment of multiple fans.

The data collected during this limited set of full-scale experiments in a 30-story office building demonstrated that in order to maximize the capability of PPV fans the following guidelines should be followed:

- Regardless of size, portable PPV fans should be placed 1.2 m (4 ft) to 1.8 m (6ft) set back from the doorway and angled back at least 5 degrees. This maximizes the flow through the fan shroud and air entrainment around the fan shroud as it reaches the doorway.
- Placing fans in a V-shape is more effective than placing them in series.
- When attempting to pressurize a tall stairwell, portable fans at the base of the stairwell or at a ground floor entrance alone will not be effective.
- Placing portable fans inside the building below the fire floor is a way to generate pressure differentials that exceed the NFPA 92A minimum requirements. For example, if the fire is on the 20th floor, placing at least one fan at the base of the stairwell and at least one near the 18th floor blowing air into the stairwell could meet the NFPA 92A minimum requirements.
- Placing a large trailer mounted type fan at the base of the stairwell is another means of generating pressure differentials that exceed the NFPA 92A minimum requirements.
- Fans used inside the building should be set back and angled just as if it were positioned at an outside doorway.

The experiments also document that PPV fans can be loud which may have an impact on fire ground and command post communications. Gasoline powered fans generate carbon monoxide but the magnitude has to be compared to that of the hazard created by the fire in the building. Overall, when properly setup and correctly operated, positive pressure ventilation is a tool which the fire service can use to improve the safety and effectiveness of fire ground operations.

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