NISTIR 7342

Full-Scale Evaluation of Positive Pressure Ventilation In a Fire Fighter Training Building

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Homeland Security

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Full-Scale Evaluation of Positive Pressure Ventilation in a Fire Fighter Training Building

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Abstract

A series of full-scale experiments was conducted in a three-story fire fighter training burn building to compare natural ventilation with positive pressure ventilation (PPV). A wood pallet and dry hay fire was allowed to burn in the structure with all doors and windows closed until the fire reached an oxygen-limited state. A door and window were then opened. The structure was ventilated naturally or with a positive pressure fan placed at the front door. Fourteen different configurations of fire room and vent locations were examined, each with both natural and positive pressure ventilation. Gas temperatures, air velocities, fire room oxygen concentrations and differential pressures were recorded and compared for the different configurations and ventilation techniques.

The data indicate that, with both natural and positive pressure ventilation techniques, using correct ventilation scenarios resulted in lower temperatures within the structure at the 0.61 m (2 ft) height, where victims may have been located, and at the 1.22 m (4 ft) height, where fire fighters may have been operating. There were only limited ventilation configurations where the temperatures in rooms other than the fire room exceeded the victim or fire fighter threshold temperatures with either ventilation technique. The use of positive pressure ventilation resulted in visibility improving more rapidly and, in many cases, cooled rooms surrounding the fire room. However, the use of positive pressure ventilation also caused the fire to grow more quickly, and in some cases, created higher temperatures at the lower elevations within the structure. Overall, this limited series of experiments suggests that PPV can assist in making the environment in the structure more conducive for firefighting operations.

Disclaimer

1.0 Introduction

Positive pressure ventilation (PPV) 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 within the structure in a more tenable atmosphere. A PPV fan differs from conventional portable ventilation fans used by the fire service in that the discharge from a PPV fan is designed to cover the entire doorway with flow into the structure (Figure 1). The discharge from a conventional ventilation fan is cylindrically shaped, while the discharge from a PPV fan is cone-shaped. Typically a PPV fan is placed about 1.8 m to 3.1 m (6 ft to 10 ft) in front of a ground level door to the structure. With the doorway within the fan discharge, air pressure inside the structure increases; thus, the term PPV. Exhaust openings in the structure, such as an opening in the roof or an open window, cause the smoke, heat and products of combustion to leave the structure due to the difference between the inside and outside air pressure. Outside "fresh" air enters the structure through the building opening in the fan discharge [1].

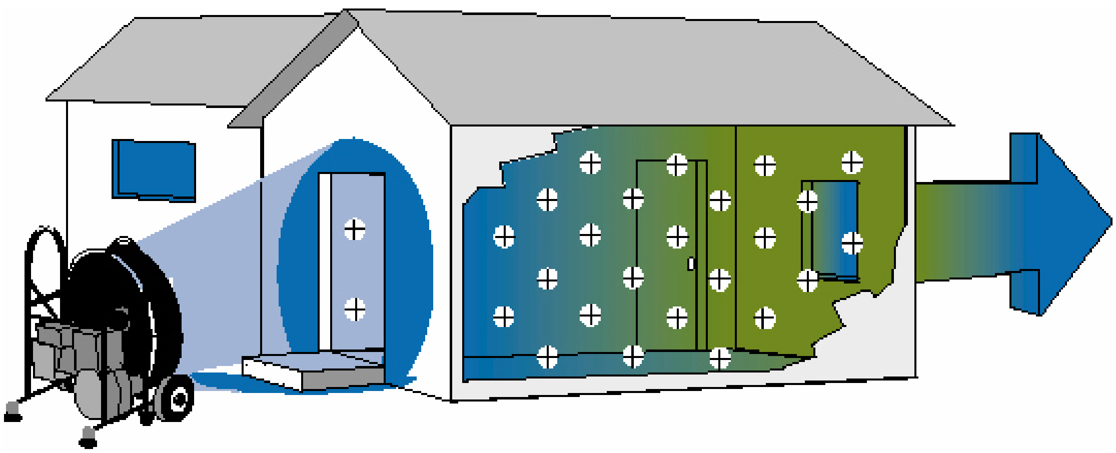


Figure 1. The Cone of Air and How PPV Works

A conventional ventilation fan is usually used in the exhaust mode. The fan is placed in a door, window, or other opening in the structure with the fan exhaust directed to the outside of the structure. This may subject the fan to high temperature gas or flames from the fire. Since the fan is rarely the same size as the opening, outside air may enter the structure next to fan thus reducing the effectiveness of the fan. Conventional fans may be used in the positive pressure mode but are generally not as effective as a PPV fan. As in the exhaust mode, the conventional fan rarely exactly fits the opening allowing air to escape the structure past the fan. Conventional fans are usually placed within the opening, thus in the case of a door, prohibiting the use of the door by fire fighters.

A significant advantage of PPV fans over conventional fans is ease of deployment. A PPV fan is normally placed at ground level in front of a door. When a conventional fan is placed in a window in the exhaust mode, the fan must be secured or balanced to prevent it from falling out the window. This becomes more difficult if placement is required above ground level.

PPV fans may be used by fire departments to ventilate a structure after a fire has been extinguished. This allows fire fighters to complete salvage and overhaul operations in a less hazardous atmosphere. PPV can also be implemented as a tactic for fire attack. The fan is started in coordination with a ventilation opening placed downwind of the fire during the initial phase of fire attack. The objective of this tactic is to increase visibility and force heat away from the attack team as they locate and extinguish the fire. Just as with any tactic, the fire service has used it with both success and failure. These failures have given rise to several questions: When should PPV be used, and just as important, when should it not be used? What is the best location to position the fan and where should the exhaust opening be made? Does PPV provide oxygen to the fire and allow for quicker growth? What if building occupants or fire fighters are between the fire and the exhaust opening? Are there certain types of construction where PPV should not be used? Can PPV cause a re-ignition during salvage and overhaul? These are just a few of the questions that the fire service has developed since the inception of PPV.

This research effort used a series of full-scale experiments to examine how PPV may impact structural fire ventilation. The objective is to develop a better understanding of the impact PPV has on fire behavior and the fire-induced conditions inside a structure.

2.0 Overview of Experimental Series

A series of full-scale experiments were performed at the Delaware County Emergency Services Training Center in Sharon Hill, Pennsylvania in a three-story fire fighter training burn building (Figures 2, 3). The burn building was concrete block construction with concrete floors and steel windows and doors. Temperature resistant panels protected the interior walls of the structure. Gypsum board on wood frames and fiberglass insulation were used to isolate sections of the building (Figure 4). The ceiling heights in the rooms were 3.4 m (11.0 ft) and the slab thickness between the first and the second floors was 0.2 m (8.0 in).

The experimental series focused on the first two floors and the three-story stairwell. The garage area and the third floor were isolated with temporary walls (Figures 5-7). In these figures, rooms are indicated with an R, doors with a D, windows with a W, and open passageways with a P. The doors and passageways were 0.9 m wide by 2.1 m high (3 ft by 7 ft). The windows were 1.2 m wide by 1.4 m high (4 ft by 4.7 ft), with a sill height of 0.8 m (2.7 ft). Fourteen configurations were used to examine the effects of both natural and PPV ventilated fires with different fire and ventilation locations (Table 1). The configurations were also compared based on the correctness of the ventilation location. Each experiment only had one exit vent; all other exterior vent locations were closed.

For all of the configurations, the front door (D1) was opened at the same time as the ventilation location. The fan used for the experiments was a 0.6 m (2 ft), 4.1 kW (5.5 hp) gasoline engine powered, belt driven positive pressure ventilator. For the experiments with the fan running, the PPV fan was located 2.4 m (8 ft) from the front door and brought to full speed at the time of ventilation (Figure 8).

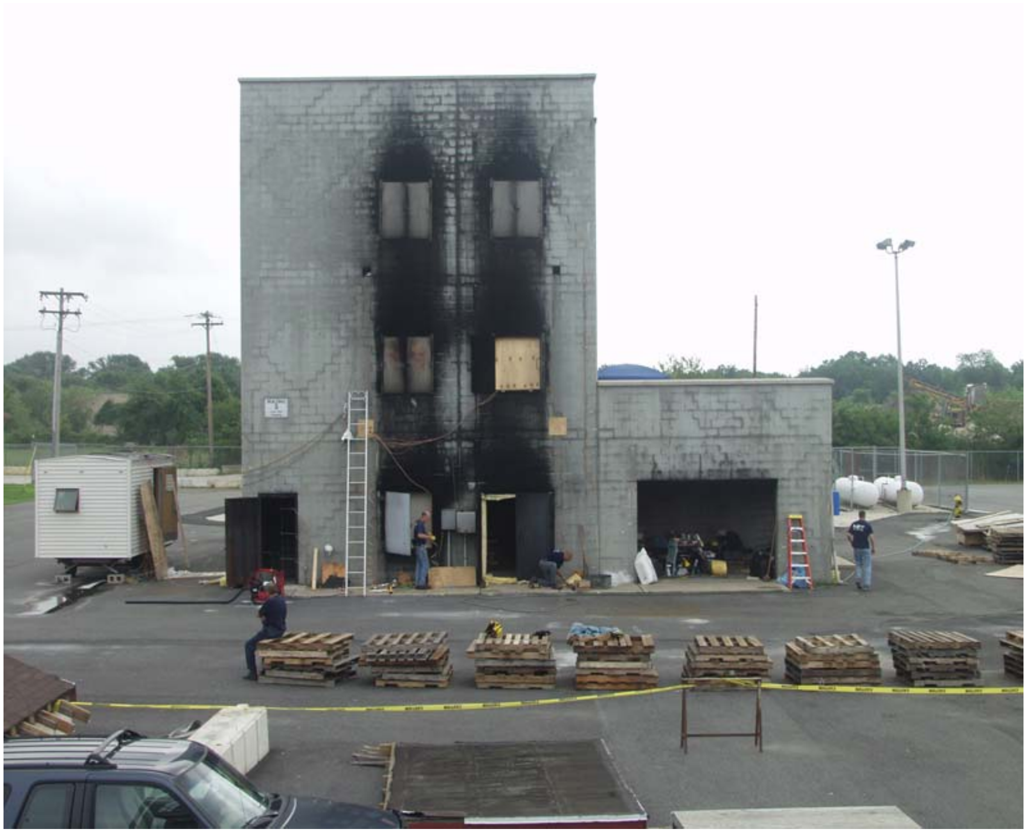
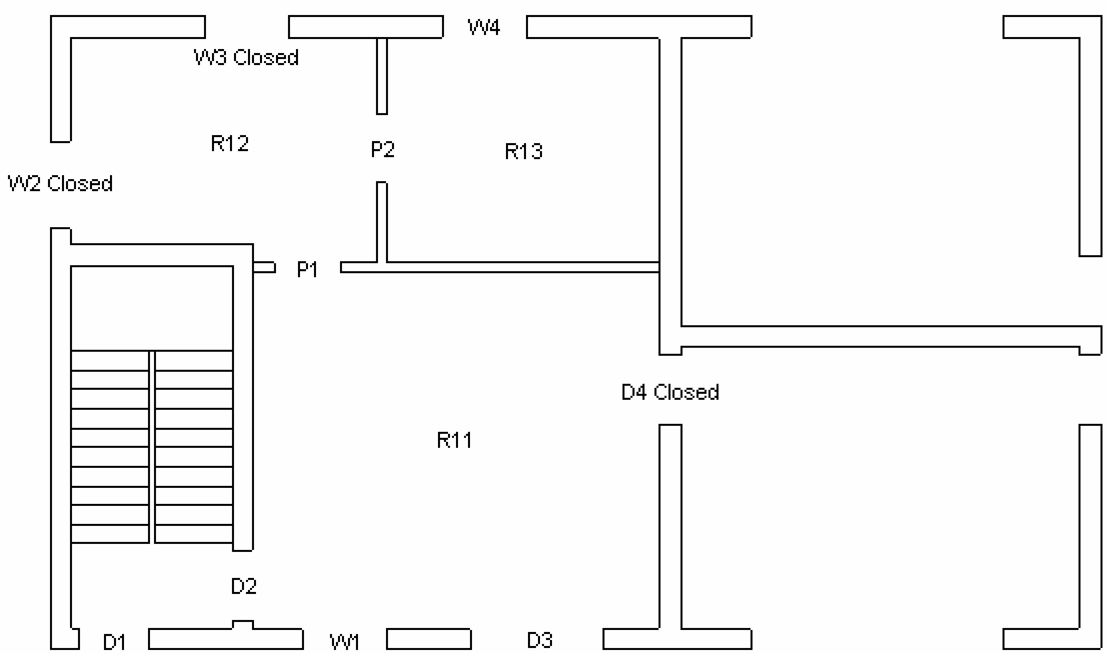


Figure 2. Front of Fire Fighter Training Burn Building

Figure 3. Rear of Fire Fighter Training Burn Building

Figure 4. Door D3 Sealed with Wood Frame and Insulation

Rear



Front

Figure 5. First Floor Experimental Layout

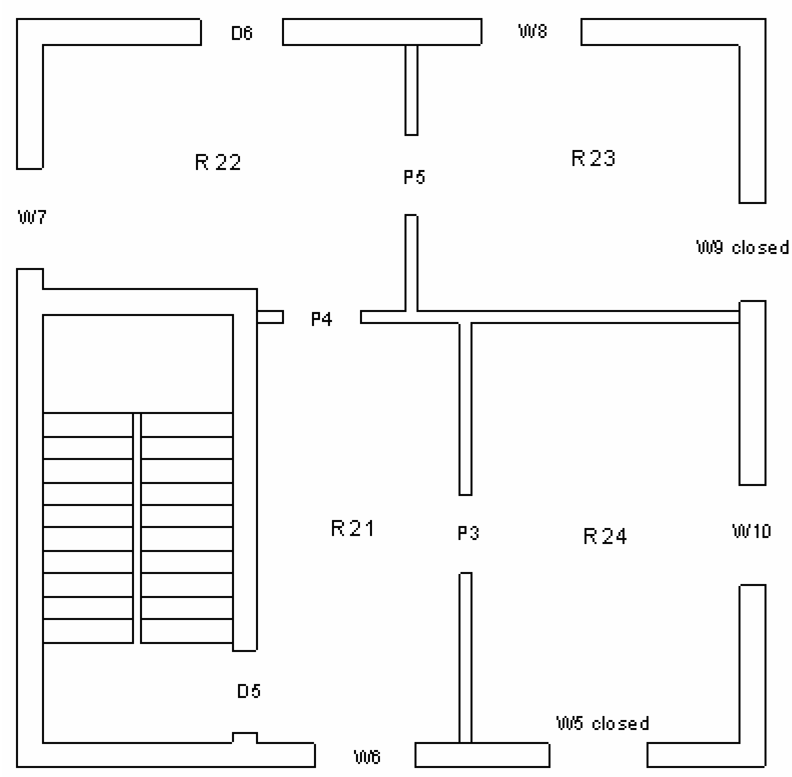


Figure 6. Second Floor Experimental Layout

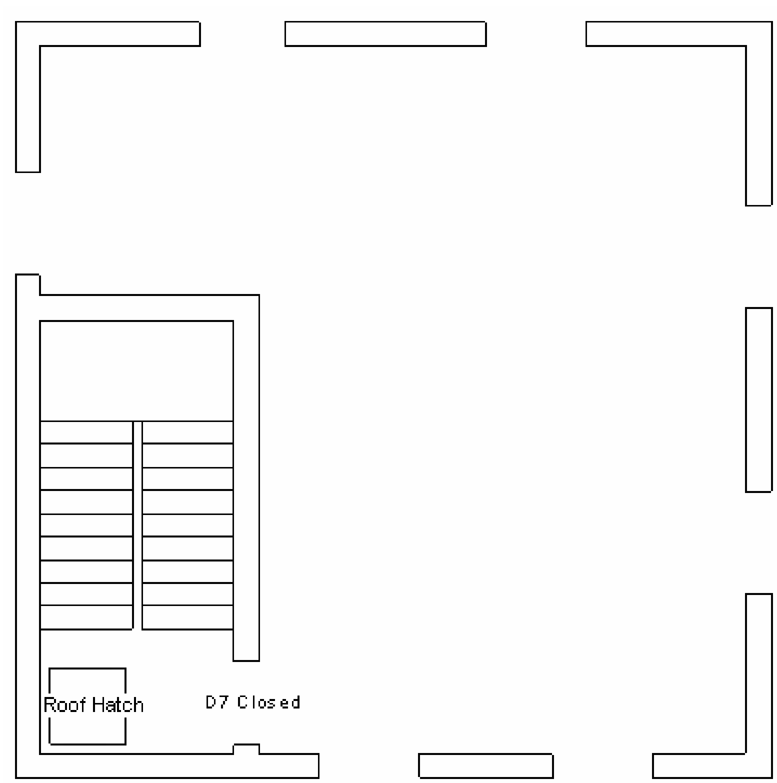


Figure 7. Third Floor Experimental Layout

Figure 8. PPV Fan Positioned in Front of Building

Table 1. Experimental Matrix

Configuration	Tests	Fire Room	Ventilation Location	Tactical Ventilation Accuracy
1	2,3	R23	W8	Correct
2	4,5	R21	W8	Incorrect
3	7,8	R11	W8	Incorrect
4	9,10	R22	W8	Incorrect
5	11,12	R24	W8	Incorrect
6	13,14	R11	W4	Incorrect
7	16,17	R11	W4	Incorrect
8	18,19	R11	W1	Correct
9	20,21	R24	W10	Correct
10	22,23	R11	No Vent	Incorrect
11	24,25	R22	W7	Correct
12	26,27	R23	W7	Incorrect
13	28,29	R21	W6	Correct
14	30,31	R11	V1	Incorrect

The configurations selected were designed to compare naturally ventilated fires with PPV ventilated fires with various fire and vent locations. Some of the configurations were correct ventilation procedures and while others were incorrect. According to the Essentials of Fire Fighting, a widely used manual published by the International Fire Service Training Association (IFSTA), ventilation procedures are defined as correct when the ventilation opening occurs near the seat of the fire and localizes the fire [2]. Incorrect ventilation procedures, where the ventilation opening is remote from the seat of the fire, may contribute to the spread of the fire. The IFSTA manual does not make reference to the use of PPV ventilation during fire attack. The definition of correct use of PPV was based on material developed by the Tempest Technology Corporation in cooperation with the Salt Lake City Fire Department, which also advised to make the exhaust opening near the seat of the fire when practical [3]. The labeling of correct and incorrect was based on the ideal situation with no outside factors. Scenarios were considered incorrect because the flow from the fire had to pass through other rooms before reaching the vent. These scenarios may be considered correct during actual fires depending on factors such as location of victims or fire fighters operating in the structure.

For this series of experiments, correct ventilation configurations were where the vent from the fire room opened directly to the outside. An example of this was configuration 1, where room R23 was vented directly out window W8.

For this study, incorrect ventilation configurations were where the vent from the fire room opened into at least one additional room before combustion gases were vented to the outside. An example of incorrect ventilation was configuration 11, where the combustion gases from room R23 had to pass through room R22 to be exhausted through window W7. The use of correct and/or incorrect ventilation tactics were further analyzed in the configuration results section (Table 1). The results of each experiment in this report are referenced by their sequential test numbers, Test 1, 2, etc.

2.1 Instrumentation

The measurements taken during the experiments included gas temperature, gas velocity, oxygen concentration and meteorological data (Figures 9-11). Temperature measurements were made with 0.51 mm (0.02 in) nominal diameter, bare-bead, type K thermocouples. Each room and the top of the stairwell had a vertical thermocouple array with measurement locations 0.30 m, 0.91 m, 1.52 m, 2.13 and 2.74 m (1 ft, 3 ft, 5 ft, 7 ft and 9 ft) below the ceiling. Each doorway and passageway had a vertical array with measurement locations 0.30 m, 0.91 m and 1.52 m (1 ft, 3 ft and 5 ft) below the top of the door opening (Figure 12). Four additional thermocouples were placed in the ventilation window 0.30 m, 0.61 m, 0.91 m and 1.22 m (1 ft, 2 ft, 3 ft and 4 ft) below the top of the window opening (Figure 13).

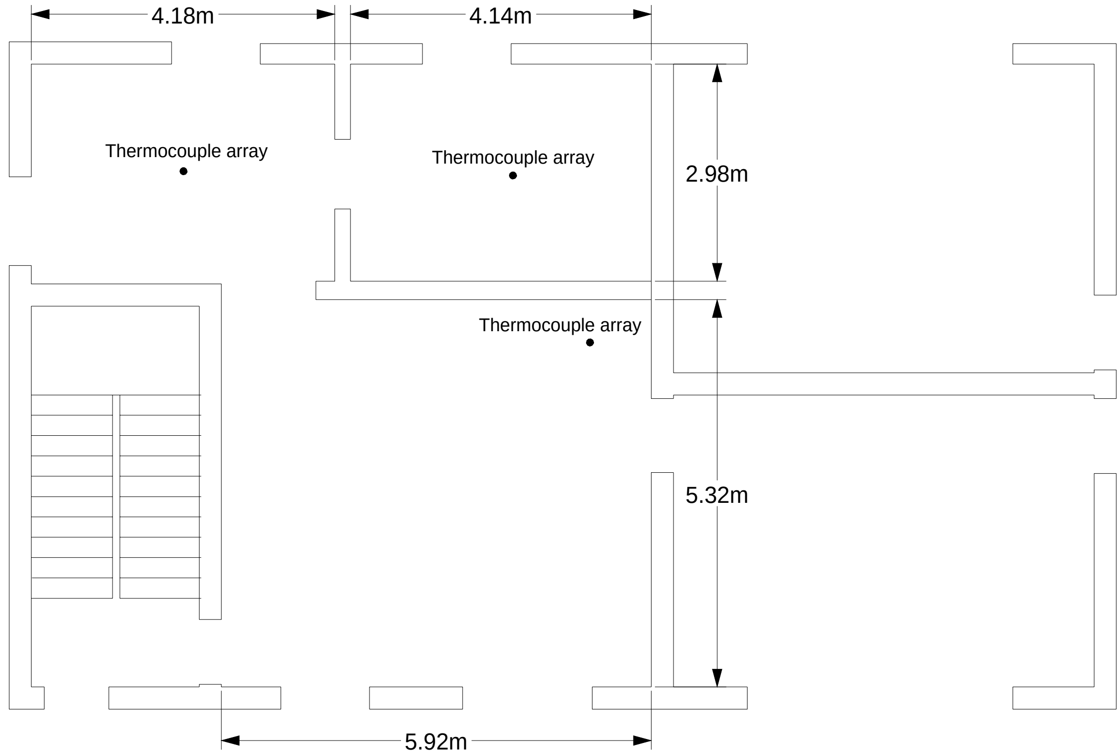


Figure 9. First Floor Dimensions and Instrumentation

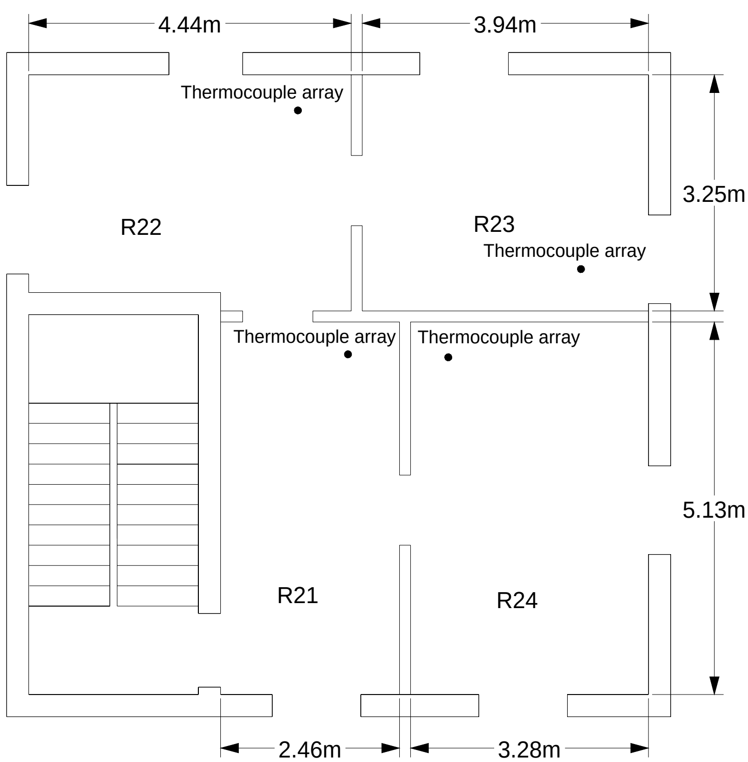


Figure 10. Second Floor Dimensions and Instrumentation

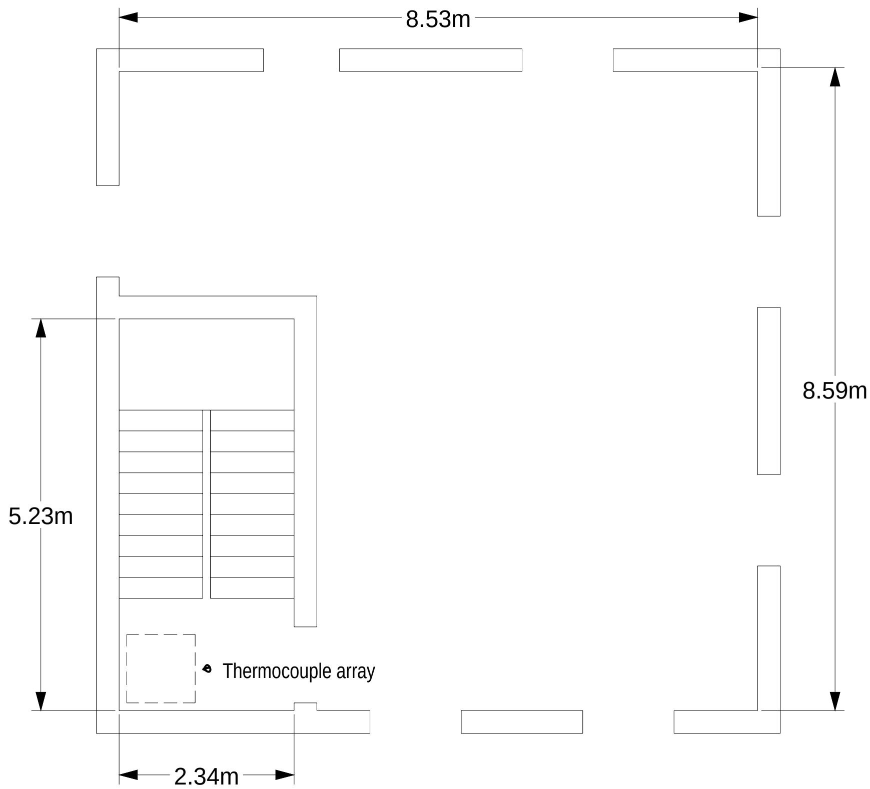


Figure 11. Third Floor Dimensions and Instrumentation

Figure 12. Doorway and Passageway Instrumentation and High Temperature Panels

Figure 13. Window Instrumentation

Gas velocity measurements were recorded in the open doorway to the fire room in the ventilation path and the ventilation window using vertical arrays of bi-directional probes (Figure 14). A thermocouple was located adjacent to each bi-directional probe (Figure 15). The doorways and passageways had measurement locations of 0.30 m, 0.91 m and 1.52 m (1 ft, 3 ft and 5 ft) below the top of the door opening (Figure 12).

The ventilation window had six bi-directional probes in locations shown in Figure 13. The probes were numbered from 1 to 6 with probe 1 at the top-left side of the window, probe 2 at the center-left, probe 3 at the bottom-left, probe 4 at the top-right, probe 5 at the center-right, and probe 6 at the bottom-right. The top probes were 0.3 m (1 ft) below the window lintel and 0.3 m (1 ft) from the window sides. The bottom probes were 0.3 m (1 ft) above the window sill and 0.3 m (1 ft) from the window sides. The center probes were centered in the window top to bottom, 0.7 m (2.3 ft) below the lintel and 0.5 m (1.7 ft) from the window sides.

The building was ventilated in the last test using a 0.91 m by 0.76 m (3.0 ft by 2.5 ft) roof hatch the top of stairwell. The longer dimension of the hatch ran from the front to the back of the building. Two bi-directional probes were placed along the front to back centerline of the hatch positioned 0.36 m (1.2 ft) from the front and rear edges of the hatch.

The probes were connected to differential pressure transducers mounted outside the structure. Door flows were positive when the flow was in the direction of the fan. For the first 19 tests, positive flow was into the window and negative flow out of the window. For all remaining tests, positive flow was out of the window and negative flow into the window. A pressure transducer was also positioned on the third floor landing to examine the difference between the pressure created in the stairwell and the pressure outside the building.

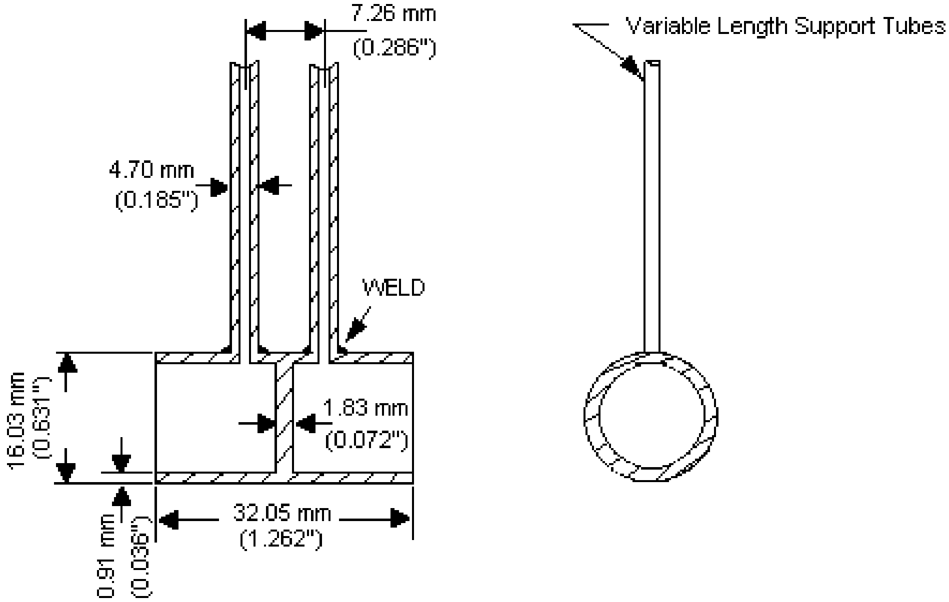


Figure 14. Bidirectional Probe

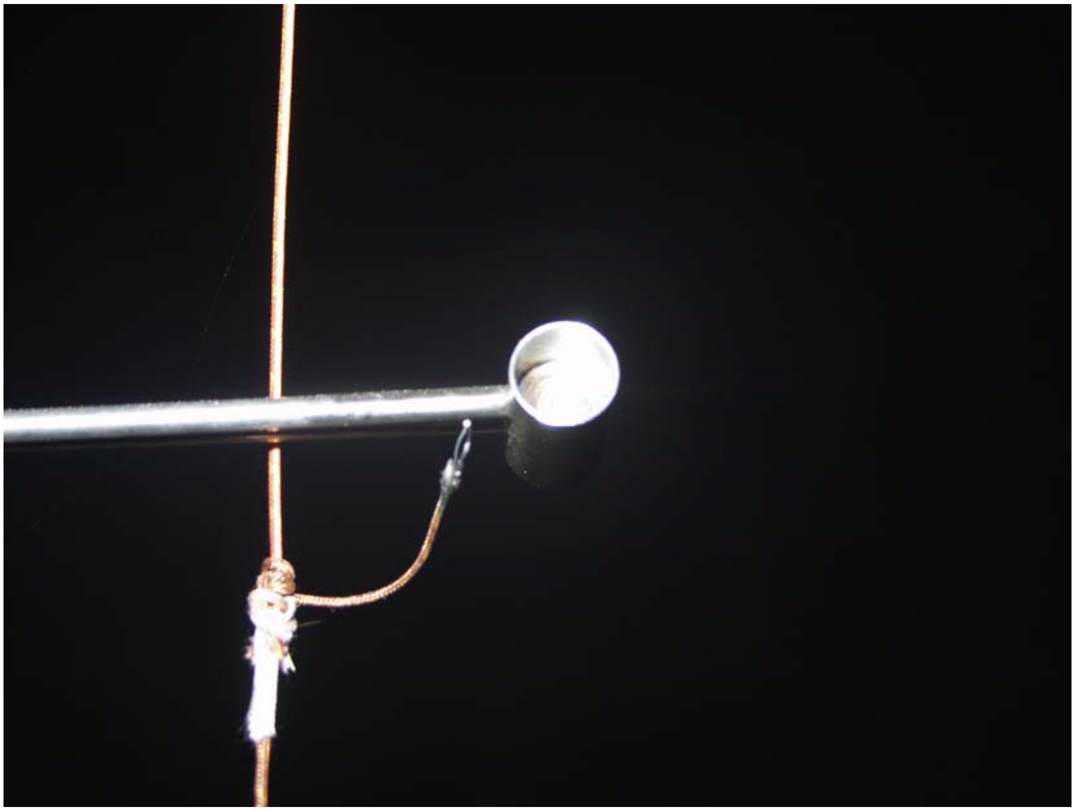


Figure 15. Bidirectional Probe and Thermocouple Combination

Oxygen concentration measurements were taken in the fire room, using a portable paramagnetic oxygen analyzer, at 0.61 m (2 ft) and 2.13 m (7 ft) above the floor. These readings were used to indicate when the fire was oxygen limited and when the fire room received oxygen after ventilation.

Video was recorded during each test. One camera was positioned on the exterior of the building recording the ventilation location. Another camera was positioned inside the building recording the fire room from an adjacent room. Some additional cameras were used depending on the scenario to examine both smoke movement and fire spread.

Weather was monitored and recorded during each of the tests using a portable weather station. Temperature, relative humidity, wind speed and direction were recorded continuously. The measured values remained relatively constant throughout each test and the average values are presented in Table 2.

Table 2. Average Environmental Conditions

Test	Temperature	Relative Humidity	Average Wind Speed	Wind Direction	Barometric Pressure
	(˚C)	(%)	(m/s)	(°)	(kPa)
1	26.4	50.9	2.22	197	101.2
2	26.5	55.0	2.44	194	101.1
3	27.0	51.8	2.93	195	101.0
4	23.0	65.2	1.46	173	101.5
5	22.8	72.8	1.34	191	101.5
6	26.2	50.2	2.73	204	101.4
7	26.3	50.4	2.02	189	101.3
8	22.9	67.3	0.97	129	102.0
9	26.2	50.2	0.99	171	102.1
10	29.0	35.2	1.53	217	102.0
11	29.8	35.9	2.16	214	102.0
12	27.2	49.6	2.54	188	102.1
13	25.2	88.0	0.28	277	102.5
14	25.6	85.5	0.52	206	102.6
15	29.8	64.1	1.68	228	102.4
16	30.7	59.9	1.79	223	102.3
17	27.7	66.0	1.11	43	102.6
18	30.0	46.1	1.89	8	102.5
19	32.4	37.4	1.46	5	102.4
20	33.3	33.9	1.76	0	102.3
21	30.4	39.5	2.31	359	101.6
22	31.4	40.0	2.11	353	101.5
23	32.6	37.1	2.10	301	101.3
24	32.9	38.3	1.82	319	101.2
25	27.7	64.8	1.32	240	101.0
26	30.7	54.1	1.49	266	100.8
27	24.9	86.4	1.09	304	100.9
28	24.3	86.8	1.32	346	100.8

Note: Weather measurement total expanded uncertainty is ±6%. See table 6.

The total air leakage in the structure was measured with an air infiltration test device. With all vents closed, pressured was applied to front door by a calibrated fan and the equivalent leakage area was determined from the pressure difference between the inside and outside of the building. Table 3 shows the equivalent leakage area as a function of pressure. The building was very tight which allowed for maximum impact from ventilation.

Table 3. Leakage Test Results

Pressure Difference	Equivalent leakage Total area
(Pa)	(cm^2)
5.3	240
6.3	250
10.1	271
13.6	280
13.8	284
19.2	300
23	309

Note: Leakage measurement total expanded uncertainty is ±15%. See table 6.

2.2 Fuel Load

Each test had a fire load that consisted of six pallets and 7.5 kg (16.5 lb) of field-cut dry hay. The fire load was selected to achieve flashover or near flashover conditions in the fire room based on the estimation of the minimum heat release rate required to achieve flashover: [4]

$$\dot{Q} = 750 A_o h_o^{1/2}$$

where:

$\dot{Q}$ - energy (heat) release rate of the fire (kW)

A_o - area of opening (m^2)

h_o - height of opening (m)

The predicted heat release rate required to achieve flashover was 2.1 MW (120 000 BTU/min). An estimate of the number of pallets required to achieve this heat release rate was obtained from work done by Babrauskas [5]. The quantity of hay used was selected to be the minimum amount of hay to ignite the pallets and maintain sustained burning.

A series of experiments was conducted in the NIST Building and Fire Research Laboratory Large Fire Research Facility to determine the heat release rate and the mass loss rate produced by the six pallets and 7.5 kg (16.5 lb) of hay (Figure 16). Two experiments (tests 1 and 2) were conducted with no obstructions under the calorimetric hood and two experiments were conducted with a ceiling above the fire (tests 3 and 4). The results of these experiments are shown in Figure 17. The average of these tests is displayed as the resultant. These tests demonstrated that six pallets and 7.5 kg (16.5 lb) of hay would achieve an average peak heat release rate of 2.25 MW (128 000 BTU/min), which was just above the desired amount.

In the fire training structure, the fire loads were configured to be as close to identical as possible. The mass of the six pallet stacks varied between 103 kg (227 lb) and 112 kg (247 lb) for the experiments. Gypsum board sheets were placed beneath the pallets to protect the concrete floor of the building. A layer of hay was placed on the gypsum board, followed by the first pallet and another layer of hay. This was repeated until all six pallets were stacked and with hay in between each pallet (Figure 18). The conditions at the fire training center did not allow the pallets and hay to be conditioned at a constant humidity prior to the experiments. The ignition source consisted of two standard matchbooks with electric igniters placed at the open ends of the pallets at floor level.

Figure 16. Pallet Test at Maximum Heat Release Rate

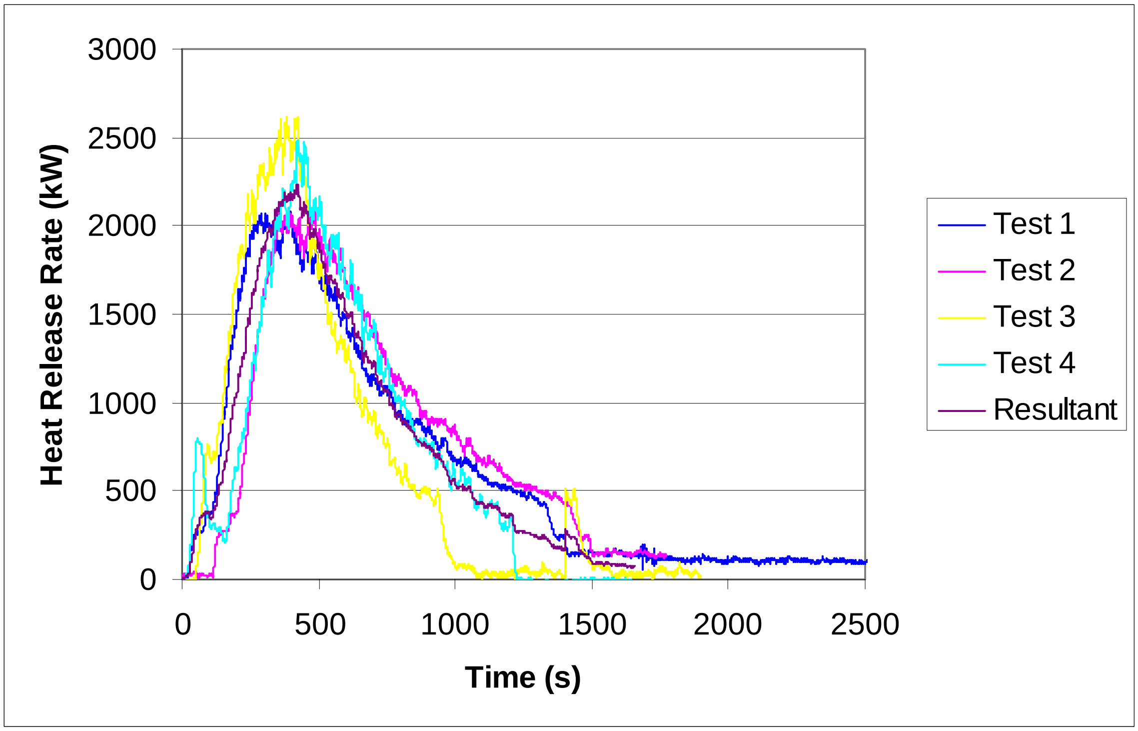


Figure 17. Heat Release Rates Versus Time for Pallet Tests

Figure 18. Pallets and Hay

2.3 Experimental Procedure

Prior to ignition, measurements were recorded with all vents closed, followed by measurements with the appropriate vents open. For the tests with the fan, measurements were then taken with the fan at full speed with the appropriate vents open to establish a baseline for airflow velocities without the effects of the fire. Once the background measurements were taken, the vents were closed and the fire was ignited.

The fire was allowed to grow to its maximum as indicated by the gas temperatures within the structure. When the temperatures and oxygen concentrations declined and the visibility was substantially reduced as seen on the interior video cameras, the fire was considered to be in an oxygen-limited environment. Once these criteria were met, the front door (D1) and the designated ventilation point were opened simultaneously. In the scenarios with the fan, the fan was started immediately following the opening of the vents. Once the vents were opened, the fire was allowed to burn to near completion. At that time, other vents in the structure were opened and the fire was manually extinguished. A timeline of events is given in Table 4, time periods are seconds.

Table 4. Experimental Timeline

TEST	Begin Test All Vents Closed	Open Front Door and Vent	Fan On	Close All Vents Fan Off	Ignition	Open Front Door and Vent	Fan On	End Test
1	0	120	NA	420	600	Fire Failed to Ignite	NA	NA
2	0	120	NA	420	480	1294	NA	2280
3	0	120	300	600	780	1785	1785	2289
4	0	120	NA	300	480	1498	NA	2100
5	0	120	300	600	780	1593	1717	2455
6	0	120	NA	300	480	Fire Failed to Ignite	NA	NA
7	0	120	NA	300	480	1340	NA	2030
8	0	120	300	600	780	1377	1389	2220
9	0	120	NA	300	480	1380	NA	1740
10	0	120	300	600	780	1440	1446	1860
11	0	120	NA	300	480	840	NA	2130
12	0	120	300	600	780	1380	1387	2160
13	0	120	NA	300	480	1020	NA	2340
14	0	120	300	600	780	1397	1397	1965
15	0	120	NA	300	600	Fire Failed to Ignite	NA	NA
16	0	120	NA	300	360	860	NA	1860
17	0	120	300	600	660	1045	1045	2044
18	0	120	NA	300	360	665	NA	2354
19	0	120	300	600	660	1215	1215	2481
20	0	120	NA	300	420	975	NA	1709
21	0	120	300	600	660	1260	1320	1735
22	0	120	NA	300	360	931	NA	1645
23	0	120	300	600	660	1188	1188	2169
24	0	120	NA	300	360	975	NA	1810
25	0	120	300	600	720	1365	1365	2020
26	0	120	NA	300	420	1170	NA	2220
27	0	120	300	600	720	1380	1380	2223
28	0	120	NA	300	420	1080	NA	1664
29	0	120	300	600	720	1565	1565	2167
30	0	120	NA	300	360	1160	NA	2100
31	0	120	300	600	720	1750	1750	2280

3.0 Training Structure Experiment Results

Fourteen configurations were used to examine the effects of both natural and PPV ventilated fires with different fire and ventilation locations. Air velocities, temperatures, fire compartment oxygen levels and differential pressure readings were recorded.

A summary of temperature and oxygen concentration measurements in the fire room is given in Table 5. The first column is the maximum temperature before ventilation started. The second column is the minimum oxygen concentrations at 0.61 m and 2.13 m (2 ft and 7 ft) above the floor before ventilation started. Column three is the time to maximum temperature after ventilation and column four is the maximum temperature after ventilation. The fifth column is time rate of change of temperature from the time of ventilation to the time of maximum temperature after ventilation. Column six is the oxygen concentration at the time of maximum temperature after ventilation.

Table 5. Temperature and Oxygen Concentration Summary

TEST	T_{max} Before Ventilation	$O_{2\ min}$ Before Ventilation (0.61 m, 2.13 m)	Time to T_{max} After Ventilation	T_{max} After Ventilation	$\Delta T/\Delta t$ After Ventilation	O_2 at T_{max} After Ventilation (0.61 m, 2.13 m)
	(˚C)	(Volume Fraction %)	(s)	(˚C)	(˚C/s)	(Volume Fraction %)
1	NA	NA	NA	NA	NA	NA
2	280	15,10	186	580	1.61	20,16
3	260	13,10	110	775	4.68	19,12
4	300	11,10	112	675	3.35	20,10
5	260	11,10	97	690	4.43	20,15
6	NA	NA	NA	NA	NA	NA
7	150	16,15	310	400	0.81	16,16
8	220	14,13	303	510	0.96	14,11
9	290	10,8	110	705	3.77	13,9
10	270	10,9	100	800	5.30	7,6
11	200	16,15	360	620	1.17	21,19
12	230	15,13	135	800	4.22	20,18
13	120	19,18	660	520	0.61	19,14
14	220	15,13	203	600	1.87	17,15
15	NA	NA	NA	NA	NA	NA
16	200	14,12	255	560	1.41	19,12
17	140	17,17	405	590	1.11	19,12
18	100	20,19	890	500	0.45	20,12
19	220	14,13	175	560	1.94	16,12
20	250	12,11	130	680	3.31	16,8
21	250	14,13	120	650	3.33	18,18
22	250	13,11	104	460	2.02	13,12
23	250	15,13	202	560	1.53	16,12
24	280	11,9	270	580	1.11	17,12
25	270	11,10	130	620	2.69	17,13
26	190	18,15	175	760	3.26	10,5
27	260	13,13	220	900	2.91	14,11
28	280	10,8	135	550	2.00	14,10
29	300	11,10	125	605	2.44	14,13
30	210	13,13	150	490	1.87	13,13
31	260	12,12	110	455	1.77	13,13

Note: Gas Temperature measurement total expanded uncertainty is ±15 % and oxygen measurement total expanded uncertainty is 14 %. See table 6.

Air velocity measurements allowed for the mapping of the direction and magnitude of the airflow. Measurements without the fire showed how the PPV fan moved air in the structure representing the condition where the fire department was only removing smoke from the building. Velocity measurements during the fire showed how the flows changed with the increase of heat and combustion products created by the fire representing the condition where the fire department was using PPV prior to applying water to the fire.

Temperature measurements taken throughout the building allowed for the analysis of occupant conditions and potential fire spread. Research by Montgomery [6] in 1975 indicated that in humid air, rapid skin burns would occur at 100 ˚C (212 ˚F), and 150 ˚C (302 ˚F) was the exposure temperature at which escape was not likely. In 1947, Moritz [6] conducted experiments on large animals and found that 100 ˚C (212 ˚F) represented the threshold for local burning and hyperemia (general burning). For this analysis, a temperature value of 100 ˚C (212 ˚F) was considered the temperature at which victims would be incapacitated. The measurements at 0.61 m (2 ft) above the floor were used, assuming that the victim was lying on the floor where the lowest temperatures are typically found.

Fire fighters operating in structures are also susceptible to harm from exposure to elevated temperatures. Fire fighter protective clothing standards such as NFPA 1971 require that protective clothing withstand exposure to 260 ˚C (500 ˚F) for five minutes without substantial damage [7]. Other data indicate that a fire fighter can survive flashover conditions of 816 ˚C (1500 ˚F) for up to 15 seconds depending on the conditions. For this analysis, a temperature value of 300 ˚C (572 ˚F) was considered the upper limit for a fire fighter to remain in the environment for a short period of time. The temperatures were evaluated at 1.22 m (4 ft) above the floor assuming that fire fighters would be crawling in an attempt to operate in the lowest temperature region of the room.

Fire compartment oxygen concentrations were recorded in the fire room to help determine when the fire was oxygen limited and the oxygen concentration value prior to ventilation. It was also a good indication as to how fast air entered the fire room after ventilation occurred. The oxygen concentration in the fire room was related to the rate of combustion that could take place in the room and the total quantity of heat generated by the fire.

Differential pressure readings in the third floor stairwell provided a comparison between the naturally ventilated and positive pressure ventilated scenarios. The pressure in the naturally ventilated cases would be related to the fire and vent locations. In the cases with the PPV fan operating, the pressure rise in the stairwell would be dominated by the fan and less dependent on the location of the fire and the vent.

For each of the configurations a diagram was made of the layout, the expected fan flow to the fire room and the flow to the exhaust opening. These are shown in figures 20 through 33 to assist with visualizing the results. Details of the flow into the building or the flow of combustion gases and smoke out of the building are not included in these diagrams.

Graphs of the data are compiled in the appendix. Maximum temperatures are compared for both natural and PPV ventilated scenarios for all rooms. Temperature, window velocities, doorway velocities, oxygen concentrations and differential pressures are graphed versus time for each test with lines to detail ventilation changes.

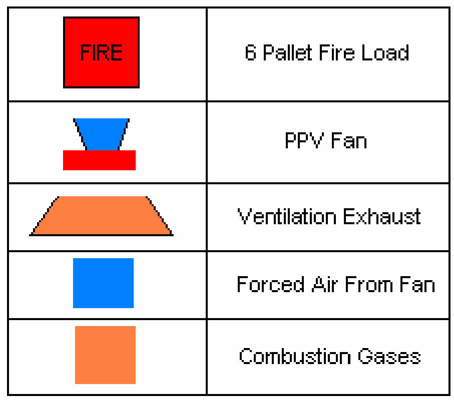


Figure 19. Configuration Symbol Key

3.1 Configuration 1 (Tests 2, 3)

The first configuration examined a fire in the room farthest from the PPV fan (R23), vented through the window on the back of the room opposite the fan (W8) (Figure 20). All other exterior vents are closed. This was classified as a correct ventilation scenario.

The maximum fire room temperature for the naturally ventilated test was 550 ˚C (1020 ˚F) and the maximum temperature for the PPV ventilated test was 780 ˚C (1440 ˚F) (Figure A-1). In the adjacent room (R22), the temperature with PPV was nearly 50 ˚C (90 ˚F) higher than the naturally ventilated test. All of the other rooms in the structure had approximately the same maximum temperatures at the ceiling level for both scenarios. The first floor remained at ambient temperatures during both scenarios.

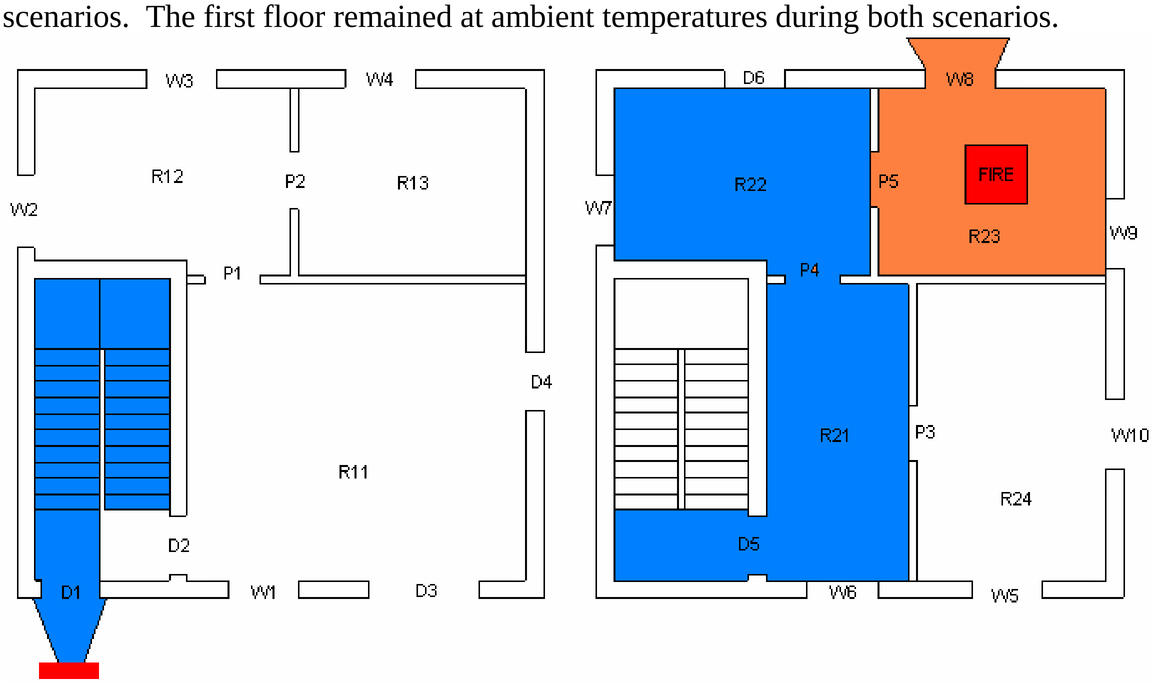


Figure 20. Configuration 1 Layout

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room was 180 ˚C (356 ˚F) for the naturally ventilated test and 370 ˚C (698 ˚F) for the PPV ventilated test. The temperature in the PPV ventilated test was 190 ˚C (342 ˚F) greater than in the naturally ventilated test, which was most likely due to the mixing created by the fan (Figure A-15). This is a significant increase, although victims in the fire room would have been subjected to the 100 ˚C (212 ˚F) incapacitation threshold for either of the ventilation tactics. None of the other rooms in the structure reached the 100 ˚C (212 ˚F) incapacitation threshold during either scenario and the temperatures were essentially the same for both tests.

At the 1.22 m (4 ft) height, where the fire fighters may have been operating, the fire room temperatures were also higher in the PPV ventilated test. The maximum temperature was 500 ˚C (932 ˚F) for the naturally ventilated test and 725 ˚C (1337 ˚F) for the PPV ventilated test. The increase at this level in the PPV ventilated test was also likely due to mixing and in both cases the maximum fire room temperatures were well above the 300 ˚C (572 ˚F) fire fighter threshold (Figure A-29). The temperature in the room adjacent to the fire room (R22) was 30 ˚C (54 ˚F) higher in the PPV ventilated test as compared to the naturally ventilated test but only reached a temperature of 200 ˚C (392 ˚F), which was below the 300 ˚C (572 ˚F) fire fighter threshold (Figure A-29).

The use of the PPV fan caused a more rapid increase in temperature than with natural ventilation (Figures A-43, A-44). After ventilation, the rate of temperature increase was 1.61 ˚C/s (2.90 ˚F/s) for the naturally ventilated test and 4.68 ˚C/s (8.42 ˚F/s) for the PPV ventilated test. The peak temperatures were sustained longer for the naturally ventilated test, which could have been a function of the available fuel.

Air velocities without the fire and without the fan ranged between 0.0 m/s (0.0 ft/s) and 1.5 m/s (4.9 ft/s) (Figure A-71). For the first 21 tests, positive flow was into the window and negative flow out of the window. When the fan was used, the velocities out the window (W8) rose to between 1.0 m/s (3.3 ft/s) and 3.0 m/s (9.8 ft/s), with the higher velocities at the top portion of the window (Figure A-72). When ventilation was started after the fire, the there was a bi-directional flow for the naturally ventilated fire of 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) out of the top two thirds of the window and 0.0 m/s (0.0 ft/s) to 3.0 m/s (9.8 ft/s) into the bottom third of the window (Figure A-95). Then in the PPV ventilated test, there was a unidirectional flow out of the window with a magnitude of 2.0 m/s (6.6 ft/s) to 6.0 m/s (19.7 ft/s) (Figure A-96) (One set of bidirectional probes failed to function during test 3.) The outflow velocities were higher after the fire than in the pretest condition due to the added buoyancy produced by the fire.

The air velocities into the fire room through the doorway (P5) without the PPV fan were bidirectional and ranged from 4.0 m/s (13.1 ft/s) into the room to 2.0 m/s (6.6 ft/s) out of the room, both before and after ventilation. In the PPV ventilated test, the neutral plane was near the top of the door. The flow fluctuated between completely unidirectional into the room at 2.0 m/s (6.6 ft/s) to partial flow out the top of the door at 2.0 m/s (6.6 ft/s) (Figures A-123, A-124).

The oxygen concentration in the fire room dropped as low as 5 % at the lower level in both scenarios but was 10 % at the upper level and 15 % at the lower level at the time of ventilation (Figures A-151, A-152). For the PPV scenario, the oxygen concentration returned to the ambient value of 21 % much faster than in the naturally ventilated fire, especially at the lower level.

The differential pressure in the stairwell remained between 0 Pa (0.0 lb/in^2) and 7 Pa (0.001 lb/in^2) for the naturally ventilated scenario. For the PPV ventilated scenario, the pressure in the stairwell rose to 21 Pa (0.003 lb/in^2) and mainly fluctuated between 14 Pa (0.002 lb/in^2) and 21 Pa (0.003 lb/in^2) while the fan was operating (Figure A-179). This pressure was comparable with a stairwell pressurization system. (By code is required to pressurize the stairwells of non-sprinklered buildings to 25 Pa (0.0036 lb/in^2) [8].)

3.2 Configuration 2 (Tests 4, 5)

Configuration 2 used the same ventilation window (W8) as in configuration 1 but the fire was moved to the room on the second floor that was nearest the stairwell (R21) (Figure 21). This was an incorrect ventilation scenario in that the combustion products had to pass through rooms R22 and R23 prior to venting to the exterior.

Maximum temperatures in all of the rooms for both the naturally and PPV ventilated tests were within 25 ˚C (45 ˚F). Maximum temperatures on the entire second floor were above 200 ˚C (392 ˚F), while the fire room reached nearly 700 ˚C (1292 ˚F) at the ceiling in both the naturally ventilated and PPV ventilated tests (Figure A-2).

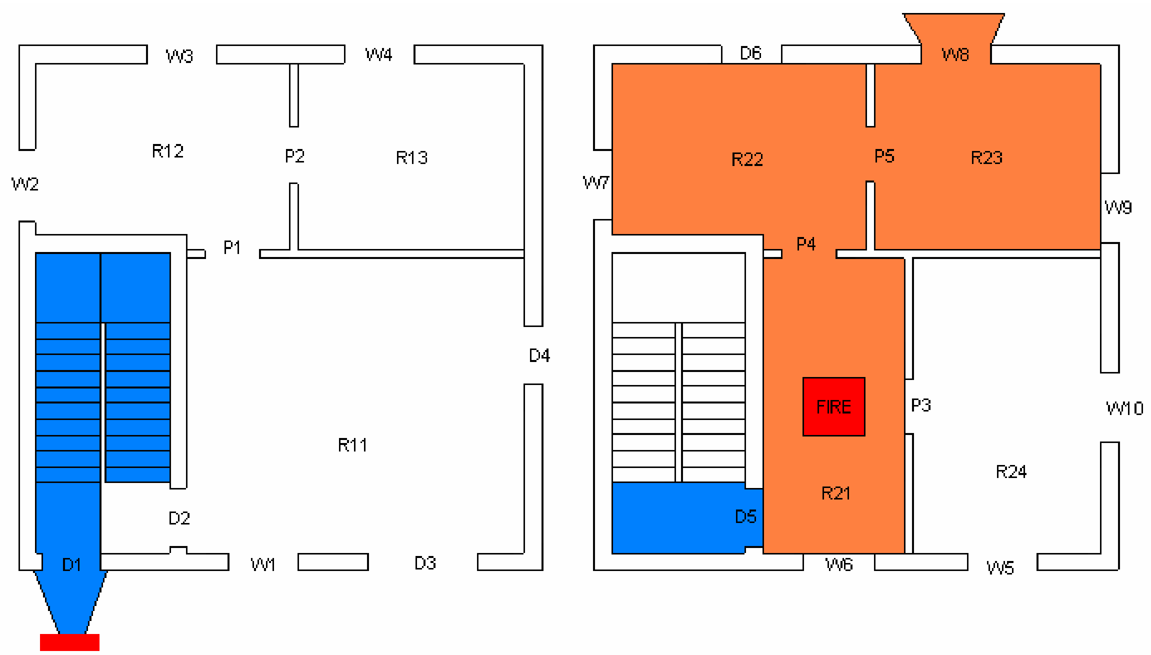


Figure 21. Configuration 2 Layout

At the 0.61 m (2 ft) height, where victims may have been located, the maximum fire room temperature was 170 ˚C (338 ˚F) for the naturally ventilated test and 280 ˚C (536 ˚F) for the PPV ventilated test, an increase of 100 ˚C (180 ˚F). In R22, the maximum temperature was 140 ˚C (284 ˚F) for the naturally ventilated test and 200 ˚C (392 ˚F) for the PPV ventilated test, an increase of 60 ˚C (108 ˚F). In R23, the maximum temperature was 140 ˚C (284 ˚F) for the naturally ventilated test and 170 ˚C (338 ˚F) for the PPV ventilated test, an increase of 30 ˚C (54 ˚F) (Figure A-16). While the use of the PPV fan resulted in increased temperatures at the 0.61 m (2 ft) height in all of the rooms between the fire and the vent, the temperatures in all of the rooms on the second floor were above the 100 ˚C (212 ˚F) incapacitation threshold temperature for both the naturally and PPV ventilated tests.

In R21, at the 1.22 m (4 ft) height, where the fire fighters may have been operating, the maximum fire room temperature was 596 ˚C (1104˚F) for the naturally ventilated test and 606 ˚C (1123 ˚F) for the PPV ventilated test, an increase of 10 ˚C (18 ˚F). In R22, the maximum temperature was 250 ˚C (482 ˚F) for the naturally ventilated test and 295 ˚C (563 ˚F) for the PPV ventilated test, an increase of 50 ˚C (90 ˚F) (Figure A-30). This approached the 300 ˚C (572 ˚F) threshold to cause harm to fire fighters. In rooms R23 and R24, the maximum temperatures were slightly higher temperatures in the PPV ventilated test as compared to the natural ventilated burn.

In both scenarios, there was a rapid increase in temperature after ventilation. In the naturally ventilated fire, the temperature increased at a rate of 3.35 ˚C/s (6.03 ˚F/s) reaching a maximum temperature of almost 700 ˚C (1290 ˚F). In the PPV ventilated test, the temperature increased at a rate of 4.43 ˚C/s (7.97 ˚F/s) (Figures A-45, A-46). In both tests, the temperatures above the 1.83 m (6 ft) height were uniform after ventilation.

Air velocities through the window (W8) without the fire and without the fan ranged between 0.0 m/s (0.0 ft/s) and 1.5 m/s (4.9 ft/s) (Figure A-73). When the fan was used, the velocity out the window rose to between 1.0 m/s (3.3 ft/s) and 3.5 m/s (11.5 ft/s), with the higher velocities at the top portion of the window (Figure A-74). In the naturally ventilated test with the fire, after ventilation, the window flow was bidirectional with velocities of 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) out of the top two thirds of the window and 0.0 m/s (0.0 ft/s) to 3.0 m/s (9.8 ft/s) into the bottom third of the window (Figure A-97). The test with the fan resulted in unidirectional flow out of the window with a magnitude of 1.0 m/s (3.3 ft/s) to 5.0 m/s (16.4 ft/s) (Figure A-98).

The air velocities into the fire room through the door (D5) without the PPV fan were bidirectional and ranged from 2.0 m/s (6.6 ft/s) into the room and 3.0 m/s (9.8 ft/s) out of the room after ventilation. In the fan test, the flow began bidirectional with a range of 2.0 m/s (6.6 ft/s) out of the room and 0.5 m/s (1.6 ft/s) into the room, but once ventilation occurred and the fan was turned on, the flow became unidirectional into the room at a velocity of 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) (Figures A-125, A-126).

In both scenarios, oxygen concentrations dropped to approximately 10 % at both the lower and upper level. Once ventilation occurred, the concentration at the lower level for both scenarios recovered to 21 % quickly. In the naturally ventilated test, this took 120 s while in the PPV ventilated test it took 60 s (Figures A-153, A-154). The difference in time was primarily due to the room's location, connecting to the stairwell. The upper concentration in the PPV ventilated test recovered to 15 % rather quickly but dropped again to 10 % as the fire redeveloped. After the fire reached its maximum burning rate, the oxygen concentration increased, returning to 21 % in 600 s. The oxygen concentration in the naturally ventilated test took much longer to reach to 21 %.

The differential pressures in the stairwell remained between 0 Pa (0.0 lb/in^2) and 14 Pa (0.002 lb/in^2) for the naturally ventilated scenario. For the PPV ventilated scenario, the pressure in the stairwell increased to 14 Pa (0.002 lb/in^2) but fluctuated between 7 Pa (0.001 lb/in^2) and 14 Pa (0.002 lb/in^2) while the fan was operating (Figure A-180). The proximity of fire to the stairwell may have resulted in lower pressures as compared to configuration 1.

3.3 Configuration 3 (Tests 7, 8)

In the third configuration, the fire was located in the large room on the first floor (R11) (Figure 22). The vent window remained the same as for configuration 2 (W8). This was an extreme test where the products of combustion had to travel up a stairwell and through the second floor to the back room before being vented to the outside. This was an incorrect ventilation scenario because there was not a direct ventilation path from the fire to the outside.

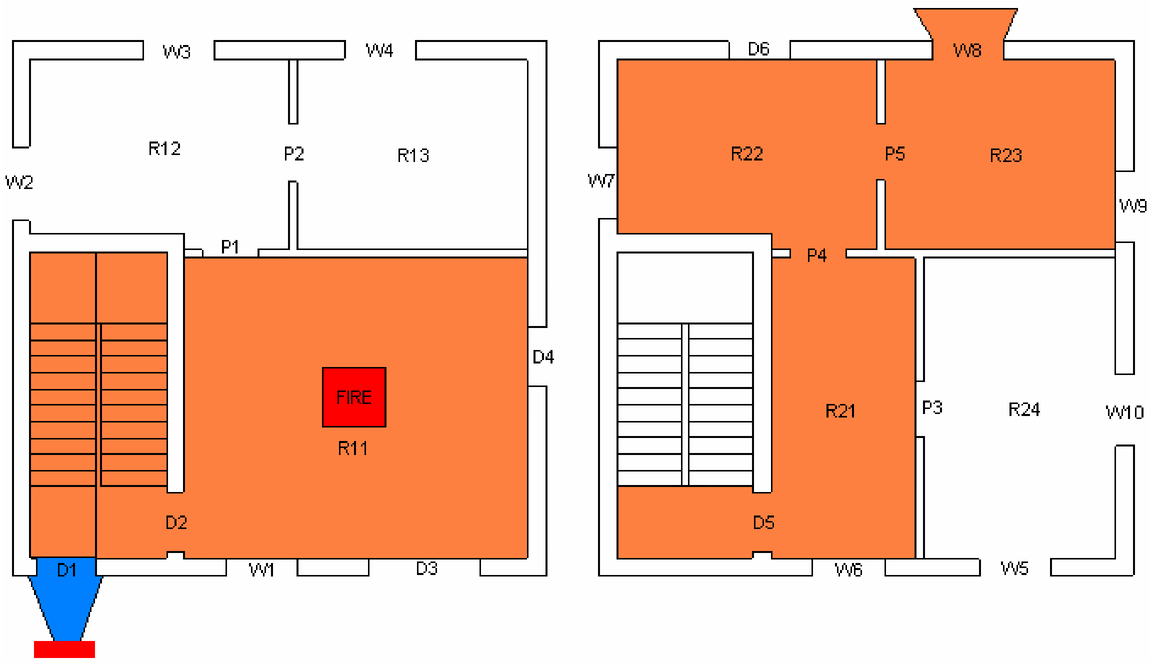


Figure 22. Configuration 3 Layout

In this configuration, maximum temperatures on the first floor were slightly higher for the PPV ventilated test but the maximum temperatures on the second floor were slightly less for the PPV ventilated test. The lower temperatures on the second floor were due to the fan mixing the combustion gases with the ambient air from outside with a direct path up the stairs. Maximum temperatures in the fire room reached 440 ˚C (824 ˚F) for the naturally ventilated test and 510 ˚C (954 ˚F) for the PPV ventilated test. The temperature in the room next to the stairwell on the second floor (R21) reached 110 ˚C (230 ˚F) in the naturally ventilated test and 90 ˚C (194 ˚F) for the PPV ventilated test (Figure A-3).

The results were similar at the 0.61 m (2 ft) height, where victims may have been located. In R11, the maximum temperature in the naturally ventilated test was 100 ˚C (212 ˚F) and in the PPV ventilated test was 200 ˚C (392 ˚F) for an increase of 100 ˚C (180 ˚F). In R21, the maximum temperature in the naturally ventilated test was 100 ˚C (212 ˚F) and in the PPV ventilated test was 70 ˚C (158 ˚F) for a decrease of 30 ˚C (54 ˚F) (Figure A-17). With PPV ventilation, the temperatures were higher on the first floor and lower on the second floor. In the fire room (R11), the maximum temperature reached the 100 ˚C (212 ˚F) threshold with natural ventilation and exceeded it with PPV ventilation. In room

R21, the maximum temperature where a victim may have been located on the second floor was below the threshold temperature with PPV ventilation.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, only the maximum temperatures in the fire room exceeded the 300 ˚C (572 ˚F) threshold in both the naturally and PPV ventilated tests. The maximum temperatures in the other first floor rooms were 200 ˚C (392 ˚F) and the maximum second floor temperature was 100 ˚C (212 ˚F), all below the threshold (Figure A-31).

The maximum fire room temperature in the naturally ventilated test occurred prior to ventilation. In both ventilation tests, the fire grew slower after ventilation than in the previous tests (Figures A-47, A-48). The temperature in the naturally ventilated fire increased at a rate of 0.81 ˚C/s (1.46 ˚F/s), while the temperature in the PPV ventilated test increased at a rate of 0.96 ˚C/s (1.73 ˚F/s). The small difference in rates between the tests could be due to the fact that the fan was moving air past the fire room and not through the fire room as in the previous configurations.

Pretest air velocities through the window (W8) were very similar to those in configurations 1 and 2, since with no fire, the airflow path to the window was similar (Figures A-75, A-76). During the fire for both tests there was a unidirectional flow out of the window. This was expected due to the remoteness of the window and because the flow of oxygen to the fire was through the open door and not from the window on the second floor. The fan increased this flow by 1.0 m/s (3.3 ft/s), from 1.5 m/s (4.9 ft/s) to 2.5 m/s (8.2 ft/s) (Figures A-99, A-100).

In both scenarios, there was a bidirectional flow of similar magnitude through the door to the fire room (D2). This would indicate that most of the air from the fan was blowing past the door and had little influence on the natural flow created by the fire (Figures A-127, A-128).

Oxygen concentrations in the naturally ventilated scenario recovered more rapidly than those in the PPV ventilated test (Figures A-155, A-156). This was also due to the air flowing past the fire room to the vent and not through the fire room. Oxygen concentrations in both tests were approximately 15 % at the time of ventilation and the increased to 17 % more rapidly in the naturally ventilated test than in the PPV ventilated test; however in the PPV ventilated test, ambient oxygen concentrations were attained sooner.

In this configuration, the naturally ventilated fire caused an increase in the stairwell pressure of 10 Pa (0.0015 lb/in^2), while the PPV ventilated test caused an increase of over 21 Pa (0.003 lb/in^2) (Figure A-181). The PPV generated pressure fluctuated between 14 Pa (0.002 lb/in^2) and 28 Pa (0.004 lb/in^2) while the fan was running. This was the highest pressure generated with D1 and W8 used as ventilation locations.

3.4 Configuration 4 (Tests 9, 10)

In the fourth configuration, the fire was on the second floor in room R22 with the same window used for ventilation as the previous configuration (W8) (Figure 23). In this configuration, the fire was directly in the path of the ventilation flow with one room downstream of the fire. This ventilation scenario was considered incorrect because the combustion products had to flow through room R23 prior to ventilation.

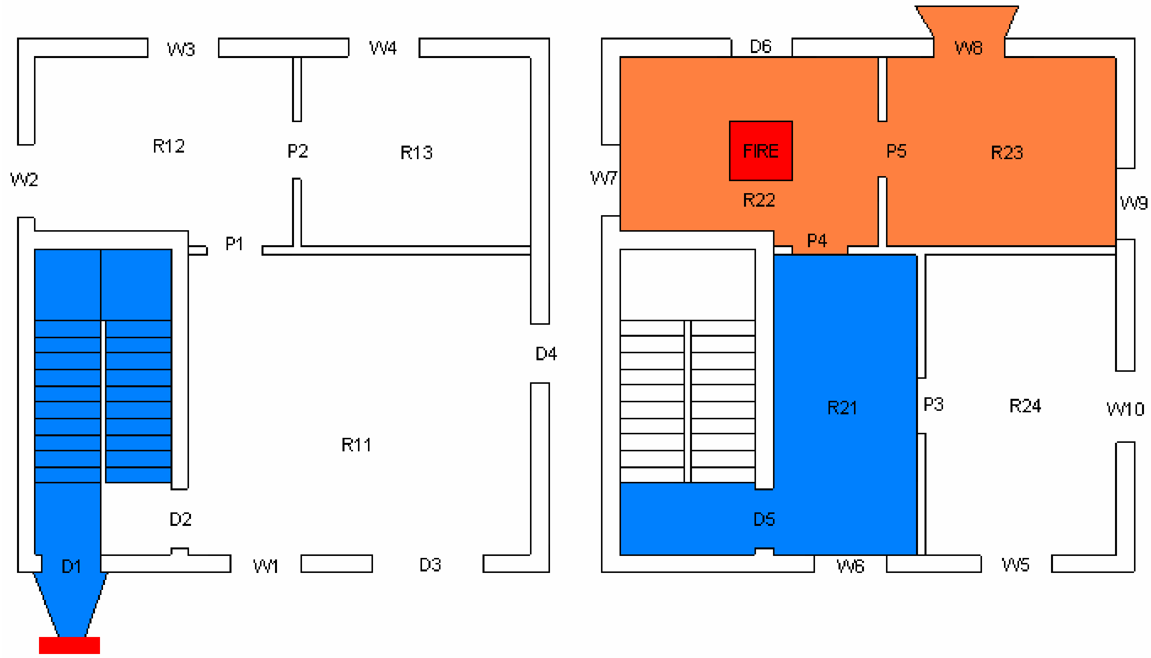


Figure 23. Configuration 4 Layout

Maximum temperatures in the fire room were just over 700 ˚C (1290 ˚F) during the naturally ventilated test and 800 ˚C (1492 ˚F) for the PPV ventilated test. The maximum temperatures in the two rooms adjacent to the fire room, R23 and R21, were 350 ˚C (662 ˚F) and 340 ˚C (644 ˚F) for the naturally ventilated test, and 480 ˚C (896 ˚F) and 410 ˚C (770 ˚F) for the PPV ventilated test respectively (Figure A-4).

At the 0.61 m (2 ft) height, where victims may have been located, maximum temperatures were significantly higher in the fire room (R22), and the room between the fire room and the ventilation window (R23) for the PPV ventilated test. The maximum temperatures for the naturally ventilated test in R22 and R23 were 160 ˚C (320 ˚F) and 120 ˚C (248 ˚F) respectively; while the temperatures in the PPV ventilated test were 360 ˚C (680 ˚F) and 330 ˚C (626 ˚F) (Figure A-18). The maximum temperatures at 0.61 m (2 ft) in the other rooms on the second floor, R21 and R24, were lower than the 100 ˚C (212 ˚F) threshold for victim incapacitation.

High temperatures existed in the fire room at the 1.22 m (4 ft) height, where fire fighters may have been operating, for both tests in this configuration. The maximum fire room temperatures in both the naturally and PPV ventilated fires were just over 500 ˚C (932 ˚F). The maximum temperature in room R23 was 333 ˚C (631 ˚F) for the naturally ventilated test and 421 ˚C (790 ˚F) for the PPV ventilated test. The maximum temperatures in the fire room and room R23 all exceeded the 300 ˚C (572 ˚F) threshold, while the maximum temperatures in room R21 were below the threshold for both tests (Figure A-32).

The rate of temperature increase and the maximum fire room temperatures were greater in the PPV ventilated test than in the naturally ventilated test (Figures A-49, A-50). After ventilation for the naturally ventilated scenario, the rate of temperature increase was 3.80 ˚C/s (6.84 ˚F/s) while in the PPV ventilated test, the rate of temperature increase was 5.30 ˚C/s (9.54 ˚F/s).

Air velocities prior to ignition ranged between 1.0 m/s (3.3 ft/s) into the window and 1.5 m/s (4.9 ft/s) out of the window. When the fan was turned on, the velocity became unidirectional out of the window with velocities ranging between 1.0 m/s (3.3 ft/s) and 3.0 m/s (9.8 ft/s). The larger velocities were observed on the right side of the window as viewed from the exterior (Figures A-77, A-78). The velocities after ventilation with the naturally ventilated fire showed a strong bidirectional flow. The velocity into the room at the bottom of the window fluctuated between 0.0 m/s (0.0 ft/s) to 2.0 m/s (6.6 ft/s), while the flow in the top two thirds of the window was outwards with velocities ranging from 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) (Figure A-101). Once the fan was turned on during the PPV ventilated test, the velocity became unidirectional out of the window at 2.0 m/s (6.6 ft/s) to 5.0 m/s (16.4 ft/s) (Figure A-102). The higher velocities were still out of the top third of the window indicating the buoyancy from the hot fire gasses was increasing the flow in the top of the window.

The door (P4) flows indicated that once the vent opened during the naturally ventilated test, the neutral plane between flow into and out of the room was located near the center of the doorway. In the PPV ventilated test, the neutral plane was near the top of the door. The flow fluctuated between completely unidirectional into the room at 2.0 m/s (6.6 ft/s) to partial flow out the top of the door at 2.0 m/s (6.6 ft/s) (Figures A-129, A-130).

The oxygen concentration in these tests dropped to between 8 % and 10 % at the time of ventilation. Once ventilation occurred, the concentration at the lower level of the naturally ventilated test began to steadily increase to 21 %, while the upper concentration declined to 5 % before returning to ambient. The concentrations at both levels in the PPV ventilated test quickly declined to less than 5 % before returning to ambient. In this test, once the concentrations began to return to ambient, they did so rather quickly and at the same rate (Figures A-157, A-158). The concentrations in the ventilated test differed at the two levels. In the PPV ventilated test the concentrations were nearly the same due to the mixing of the combustion products, which formed a more uniform environment in the fire room.

The differential pressures in the stairwell increased from 14 Pa (0.002 lb/in^2) to 21 Pa (0.003 lb/in^2) for the naturally ventilated scenario. For the PPV ventilated scenario, the pressure in the stairwell increased to 21 Pa (0.003 lb/in^2) and fluctuated between 7 Pa (0.001 lb/in^2) and 21 Pa (0.003 lb/in^2) while the fan was operating (Figure A-182). After ventilation in both scenarios, the pressure remained nearly constant for the duration of the test.

3.5 Configuration 5 (Tests 11, 12)

In the fifth configuration, the fire was located in room R24 and was ventilated through window W8 (Figure 24). In this configuration, like configuration 3, the principal flow was from the first floor door (D1) past the fire room. Configuration 5 was also an incorrect ventilation scenario.

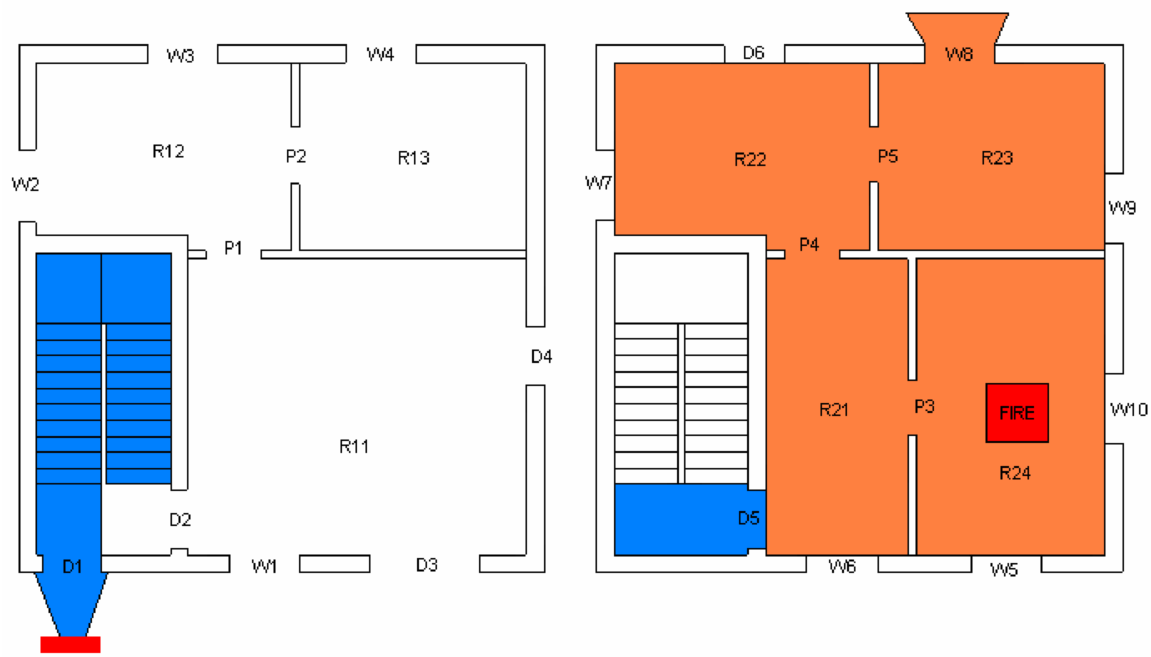


Figure 24. Configuration 5 Layout

The maximum temperature in the fire room for the PPV ventilated test was 800 ˚C (1470 ˚F) and was 150 ˚C (270 ˚F) above that of the naturally ventilated test. All of the other maximum temperatures on the second floor were within 30 ˚C (54 ˚F) of each other with PPV generated temperatures higher in R21 and lower in R22 and R23. First floor temperatures remained near ambient during both tests (Figure A-5).

At the 0.61 m (2 ft) height, where victims may have been located, there was a significant increase in the fire room temperature for the PPV ventilated test. The maximum temperature in the fire room for the naturally ventilated test was 300 ˚C (572 ˚F) and the maximum temperature for the PPV ventilated test was 680 ˚C (1256 ˚F) or an increase of almost 400 ˚C (720 ˚F). Both temperatures were well above the 100 ˚C (212 ˚F) incapacitation threshold. The maximum temperatures in all of the other rooms on the second floor were below the threshold temperature even though the use of a PPV fan caused temperature increases of approximately 20 ˚C (36 ˚F) from the naturally ventilated maximum temperatures of 80 ˚C (176 ˚F) (Figure A-19).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum fire room temperature for the naturally ventilated test was 560 ˚C (1040 ˚F) and the maximum temperature for the PPV ventilated test was 720 ˚C (1330˚F). These temperatures were well above the threshold temperature of 300 ˚C (572 ˚F). All of the other maximum temperatures were below the threshold temperature for both ventilation scenarios (Figure A-33).

The temperatures in the naturally ventilated test increased at a rate of 1.17 ˚C/s (2.11 ˚F/s) while the temperatures in the PPV ventilated test increased at a rate of 4.22 ˚C/s (7.60 ˚F/s) (Figures A-51, A-52). The temperatures in the fire room were more uniform immediately after ventilation during the PPV ventilated test.

Without the fire and without the fan, there was no airflow through the window (Figure A-79). When the fan was used, the velocity out the window (W8) rose to between

1.0 m/s (3.3 ft/s) and 3.5 m/s (11.5 ft/s), with the higher velocities at the top-right portion of the window (Figure A-80). After ventilation, the window velocities in the naturally ventilated test produced a bidirectional flow of 0.5 m/s (1.6 ft/s) to 2.0 m/s (6.6 ft/s) out of the top two thirds of the window and 0.0 m/s (0.0 ft/s) to 1.5 m/s (4.9 ft/s) into the bottom third of the window (Figure A-103). In the PPV ventilated test, there was a unidirectional flow out of the window with a magnitude of 2.0 m/s (6.6 ft/s) to 4.0 m/s (13.1 ft/s) (Figure A-104).

Door (P3) flows remained bidirectional after ventilation in both the naturally ventilated test and the PPV ventilated test. After the initial fluctuation when ventilation was started, the velocities in both tests were of a similar magnitude, indicating the flow from the PPV fan was largely though the room outside the fire room and did not have a significant impact on the flow into the fire room (Figures A-131, A-132).

The oxygen concentration in both tests dropped to between 14 % and 16 % at the time of ventilation. Once ventilation occurred, the concentration at the lower level for the naturally ventilated test fluctuated but never dropped below 10 %, while the concentration at the upper level declined to 6 % before returning to ambient level (Figures A-159, A-160). The concentrations at both levels in the PPV ventilated test quickly reached 20 % after fan started before they declined to as low as 2 % then quickly returned to near ambient levels. Changes in the oxygen concentration in the naturally ventilated test occurred more gradually than in the PPV ventilated test, especially as the fire grew after ventilation.

The differential pressures in the stairwell increased to 7 Pa (0.001 lb/in^2) for the naturally ventilated scenario. For the PPV ventilated test the pressure in the stairwell rose to 21 Pa (0.003 lb/in^2) and averaged 17 Pa (0.0025 lb/in^2) while the fan was operating (Figure A-183). After ventilation in the naturally ventilated test, the pressure rose gradually to the maximum while in the PPV ventilated test, the maximum pressure was reached rapidly.

3.6 Configuration 6 (Tests 13, 14)

In the sixth configuration, both the fire and the vent were on the first floor (Figure 25). The fire was in the large room (R11) and the vent (W4) was in R13 on the side of the building opposite the fan. The door to the second floor (D5) was open in this configuration. This was an incorrect ventilation scenario since the products of combustion had to flow through rooms R12 and R13 prior to exiting the building.

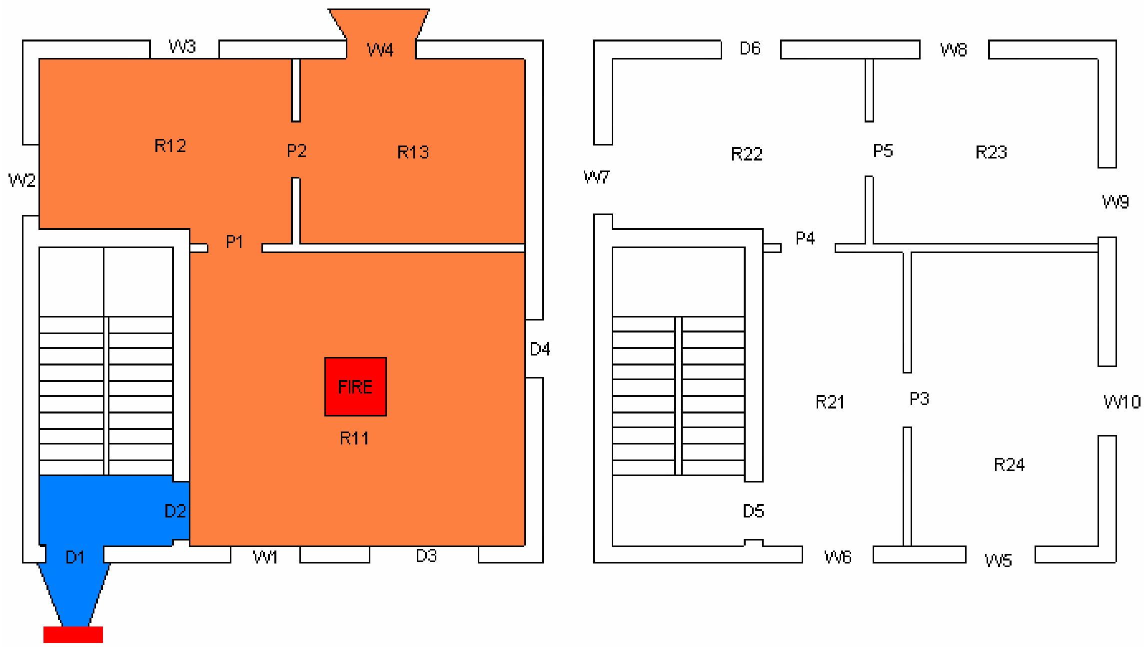


Figure 25. Configuration 6 Layout

The maximum temperature in the fire room for the naturally ventilated test reached 520 ˚C (970 ˚F) while maximum temperature in the PPV ventilated test was 80 ˚C (144 ˚F) higher. In the two other rooms on the first floor, the maximum temperatures in the PPV ventilated test were slightly higher while on the second floor, the maximum temperatures in the naturally ventilated test were slightly higher (Figure A-6).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 111 ˚C (232 ˚F) and 114 ˚C (237 ˚F) in the adjacent room (R12). The temperatures in both rooms were above the incapacitation threshold temperature of 100 ˚C (212 ˚F). In the room with the ventilation window (R13), the maximum temperature was 90 ˚C (194 ˚F), which was below the threshold. In the test with PPV ventilation, the maximum temperature in the fire room was 160 ˚C (320 ˚F), in room R12 was 175 ˚C (347 ˚F), and in room R13 was 170 ˚C (338 ˚F) (Figure A-20). The maximum temperatures in all of the rooms exceeded the threshold temperature and were significantly higher than those with natural ventilation.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, for the naturally ventilated test the maximum temperature was 474 ˚C (885˚F) in the fire room, 208 ˚C (406 ˚F) in the adjacent room (R12), and 135 ˚C (275 ˚F) in room R13. For the PPV ventilated test the maximum temperature was 357 ˚C (675 ˚F) in the fire room, 210 ˚C (410 ˚F) in the adjacent room (R12), and 190 ˚C (374 ˚F) in room R13. Although the use of the fan resulted in a decrease in the maximum fire room temperature of 117 ˚C (211 ˚F) the maximum temperature was above the 300 ˚C (572 ˚F) threshold for both ventilation techniques; however, the temperature was below the threshold in the other first floor rooms (Figure A-34).

The rate of temperature increase was nearly three times greater in the PPV ventilated test than in the naturally ventilated test (Figures A-53, A-54). After ventilation, the rate of temperature increase in the naturally ventilated test was 0.61 ˚C/s (1 .10 ˚F/s) while in the

PPV ventilated test the rate of temperature increase was 1.87 ˚C/s (3.37 ˚F/s). The maximum temperature in the PPV ventilated test was approximately 100 ˚C (180 ˚F) greater than in the naturally ventilated test but the temperature prior to ventilation was approximately 150 ˚C (270 ˚F) higher than in the naturally ventilated test and was sustained for a longer period of time.

Air velocities without the fire and without the fan through the window (W8) ranged between 0.0 m/s (0.0 ft/s) and 2.0 m/s (6.6 ft/s) (Figure A-81). When the fan was used, the velocity out the window rose to between 0.5 m/s (1.6 ft/s) and 3.5 m/s (11.5 ft/s), with the higher velocities at the top portion of the window (Figure A-82). After ventilation, the naturally ventilated fire produced a bidirectional flow with velocities of 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) out of the top two thirds of the window and 0.0 m/s (0.0 ft/s) to 1.5 m/s (4.9 ft/s) into the bottom third of the window (Figure A-105). In the PPV ventilated test, there was unidirectional flow out of the window with a magnitude of 2.0 m/s (6.6 ft/s) to 4.0 m/s (13.1 ft/s) (Figure A-106).

Door (D2) velocities in the naturally ventilated test were unidirectional for a short period of time after ventilation before becoming bidirectional (Figure A-133). In the PPV ventilated test, the flow was largely unidirectional with fluctuations at the top of the door to flow out of the room (Figure A-134).

The oxygen concentrations in the naturally ventilated test did not drop significantly during the test because they were influenced by the fresh air pulled in through D1. The concentration at the lower level was 19 % at the time of ventilation and quickly returned to 21 %. It then fluctuated, dropping to as low as 17 % as the fire intensified. The concentration at the upper level was 18 % when ventilation started and slowly declined to 14 % before returning to ambient (Figure A-161). The oxygen concentrations in the PPV ventilated test were generally lower. The concentrations at the upper and lower levels followed similar profiles from ventilation until the end of the test. At the time of ventilation, the upper level concentration was 13 %, then grew to 18 %, dropped to 10 % and finally returned to 19 %. The concentration of the lower level followed the upper level concentration although 2 % to 4 % higher (Figure A-162).

The differential pressure in the stairwell for the naturally ventilated test slowly increased from 0 Pa (0.0 lb/in^2) to an average maximum pressure of 14 Pa (0.002 lb/in^2). In the PPV ventilated test, the pressure rapidly increased to 28 Pa (0.004 lb/in^2) and slowly declined to 17 Pa (0.0025 lb/in^2) (Figure A-184).

3.7 Configuration 7 (Tests 16, 17)

This configuration used the same ventilation scenario as configuration 6 with the fire in R11, venting through W4 (Figure 27). The difference was the closing of the door to the second floor (D5). This configuration was used to evaluate the issue of restricting flow to areas of the building unaffected by the fire. This was an incorrect ventilation scenario since the products of combustion had to flow through rooms R12 and R13 prior to exiting the building.

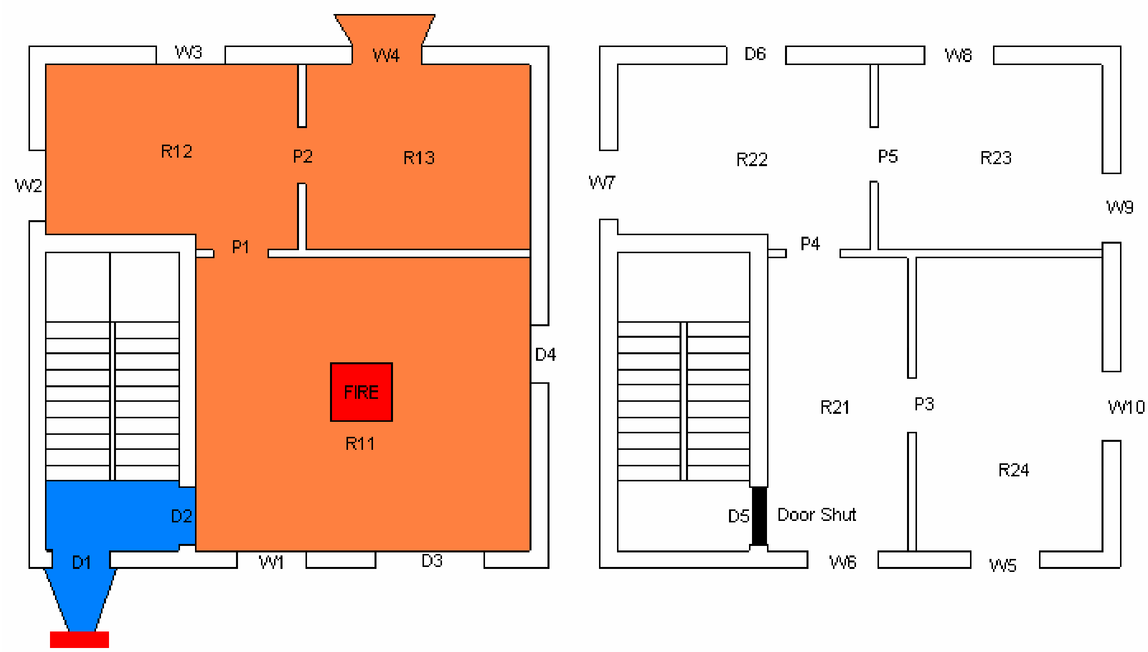


Figure 26. Configuration 7 Layout

The maximum temperatures reached nearly 600 ˚C (1112 ˚F) in the fire room in both tests. In all three rooms on the first floor, the maximum temperatures in both the naturally ventilated and PPV ventilated tests were within 40 ˚C (72 ˚F). The maximum temperature at the top of the third floor stairwell was slightly higher for the naturally ventilated test (Figure A-7).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 151 ˚C (304 ˚F) and 106 ˚C (223 ˚F) in the adjacent room (R12). The temperatures in both rooms were above the incapacitation threshold temperature of 100 ˚C (212 ˚F). In the room with the ventilation window (R13), the maximum temperature was 98 ˚C (208 ˚F), which was just below the threshold. In the test with PPV ventilation, the maximum temperature in the fire room was 151 ˚C (304 ˚F), in room R12 was 173 ˚C (343 ˚F) and in room R13 was 159 ˚C (318 ˚F) (Figure A-21). The maximum temperatures in all of the rooms exceeded the threshold temperature and were significantly higher than those with natural ventilation.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperatures were nearly the same as those in configuration 6. The maximum temperature in the fire room in the naturally ventilated test was approximately 150 ˚C (270 ˚F) higher than in the PPV ventilated test, but in both scenarios the temperatures were above the 300 ˚C (572 ˚F) threshold temperature. The maximum temperature in both of the other rooms on the first floor remained below the threshold (Figure A-35).

The temperatures in the naturally ventilated test increased at a rate of 1.41 ˚C/s (2.54 ˚F/s) while the temperatures in the PPV ventilated test increased at a rate of 1.11 ˚C/s (2.00 ˚F/s). The temperature at the 1.22 m (4 ft) height was lower in the PPV ventilated test as compared with the naturally ventilated test, which was similar to the temperature pattern in configuration 6 (Figures A-55, A-56).

For the naturally ventilated test, there was nearly zero flow through the window (W4) prior to the fire. For the test with the PPV ventilated test, the velocity ranged from 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) out of the window (Figures A-83, A-84). When the fire was vented during the naturally ventilated test, the flow was bidirectional with flow out the top third of the window at 1.5 m/s (4.9 ft/s) and flow into the bottom third of the window at 1.0 m/s (3.3 ft/s). The flow in the center of the window started out of the room and then fluctuated between inflow and outflow (Figure A-107). The flow in the PPV ventilated test was unidirectional out of the room after the window was opened, with an average velocity of 3.0 m/s (9.8 ft/s) (Figure A-108).

The door (D2) velocities of the naturally ventilated test were bidirectional with the flow out the top of the door decreasing as the fire progressed. In the PPV ventilated test, the flow was initially unidirectional then the flow at the top of the door began fluctuating in and out of the room (Figures A-135, A-136).

Oxygen concentrations for the naturally ventilated test at the time of ventilation were 14 % at the lower layer and 12 % at the upper layer. The concentration at the upper location initially increased, then as the fire grew, decreased to a minimum of 10 % before returning to ambient. The concentration at the lower location increased at slower rate until it reached 21 % (Figure A-163). For the PPV ventilated test, the concentration was approximately 17 % at the time of ventilation. The concentration at both locations quickly rose to 21 % and remained there for some time before declining. The concentration at the lower level decreased slightly while the concentration at the upper level decreased to 10 % before slowly rising to 20 % (Figure A-164).

The differential pressures in the stairwell for both tests were very similar. After ventilation, the pressure increased to slightly above 21 Pa (0.003 lb/in^2) then slowly decreased to 14 Pa (0.002 lb/in^2) by the end of the test. The pressures in the PPV ventilated test were only slightly above those of the naturally ventilated test (Figure A-185).

3.8 Configuration 8 (Tests 18, 19)

Configuration 8 used the same fire room (R11) as configurations 6 and 7, but the vent was a window (W1) in the fire room on the front of the building. This configuration was unique in that the fire, fire room door, vent window and PPV fan were all in close proximity. Even though the ventilation flow was not past the fire but to a window located next to the fire, this was a correct ventilation scenario for room R11.

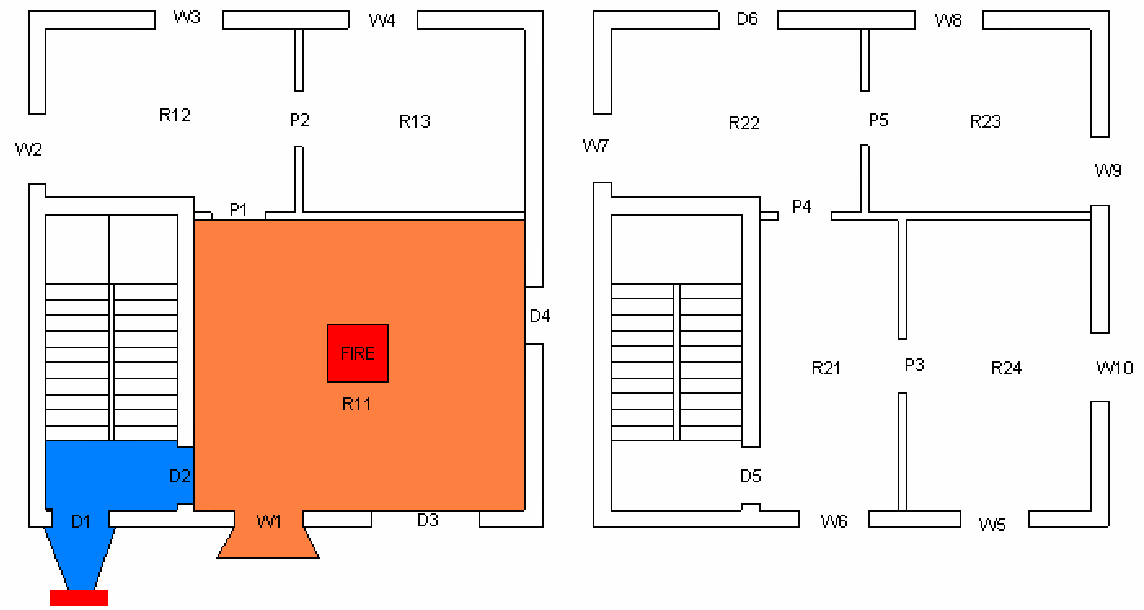


Figure 27. Configuration 8 Layout

The maximum temperatures in the naturally ventilated test were less than those in the PPV ventilated test throughout the entire structure. In the fire room, the maximum temperature in the naturally ventilated test was 510 ˚C (950 ˚F) while the temperature in the PPV ventilated test was 570 ˚C (1058 ˚F). The maximum temperatures in the second floor rooms for the naturally ventilated test were typically 25 ˚C (45 ˚F) lower than those in the PPV ventilated test (Figure A-8).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 138 ˚C (280 ˚F), 104 ˚C (219 ˚F) in room R12, and 101 ˚C (214 ˚F) in room R13. In the test with PPV ventilation, the maximum temperature in the fire room was 161 ˚C (322 ˚F), in room R12 was 140 ˚C (284 ˚F) and in room R13 was 138 ˚C (280 ˚F) (Figure A-22). The temperatures in all the rooms for both tests were above the incapacitation threshold temperature of 100 ˚C (212 ˚F). The temperatures were similar to those in configurations 6 and 7 even though there was no open vent in the adjacent rooms.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the temperatures in all of the rooms on the first floor were below the 300 ˚C (572 ˚F) threshold temperature. The maximum temperature in the fire room in the naturally ventilated test was 138 ˚C (280 ˚F) and 234 ˚C (453 ˚F) in the PPV ventilated test. Unlike configurations 6 and 7, the maximum fire room temperature was higher in the PPV ventilated test (Figure A-36).

The temperatures in the naturally ventilated test increased at a rate of 0.45 ˚C/s (0.81 ˚F/s) while the temperatures in the PPV ventilated test increased at a rate of 1.94 ˚C/s (3.49 ˚F/s). The temperature at the 1.22 m (4 ft) height was lower in the naturally ventilated test as compared to the PPV ventilated test, which was the reverse of the temperature pattern in configurations 6 and 7 (Figures A-57, A-58).

For the naturally ventilated test, there was a small flow into the lower third of the window (W1) prior to the fire. For the test with the fan, a failure occurred and no velocity data was recorded (Figures A-85, A-86). For the naturally ventilated test, a strong bidirectional flow developed with the fire. There was an average velocity of 1.0 m/s (3.3 ft/s) into the room at the bottom of the window, while in the top two thirds of the window the flow was out of the room with velocities ranging from 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) (Figure A-109). During the PPV ventilated test, the instrumentation failure continued so there was no comparative data (Figure A-110).

The door (P3) velocities for the naturally ventilated test indicate that a neutral plane existed near the center of the doorway. For the PPV ventilated test, the flow fluctuated across the entire door. (Figures A-137, A-138)

Oxygen concentrations in the naturally ventilated test did not decrease significantly. The concentration at the lower layer was 20 % at the time of ventilation, and quickly returned to 21 % and then fluctuated to as low as 18 % as the fire intensified. The concentration at the upper layer was 19 % when ventilation started then slowly declined to 13 % before it increased (Figure A-165). The concentration in the PPV ventilated test was lower. At the time of ventilation, the concentration at the upper layer was 13 %, and grew to 16 %, dropped to 10 % and finally recovered to 17 % by the end of the test. The concentration at the lower layer remained 2 % to 4 % higher as the fire grew and then followed the upper level concentration for the duration of the test (Figure A-166).

The differential pressure in the stairwell for the naturally ventilated test slowly increased from 0 Pa (0.0 lb/in^2) to a maximum pressure of 21 Pa (0.003 lb/in^2), then slowly decreased to 7 Pa (0.001 lb/in^2) as the fire burned to completion. The pressure in the PPV ventilated test increased to 34 Pa (0.005 lb/in^2) quickly and fluctuated between 21 Pa (0.003 lb/in^2) and 34 Pa (0.005 lb/in^2) reaching the maximum range of the pressure transducer at times (Figure A-186).

3.9 Configuration 9 (Tests 20, 21)

In the ninth configuration the fire was on the second floor in room R24 (Figure 28). The vent was through window (W10) located in the back of room R24. Since the combustion products did not flow through adjacent rooms, this was considered a correct ventilation scenario. The incorrect ventilation scenario with the fire in room R24 was configuration 5.

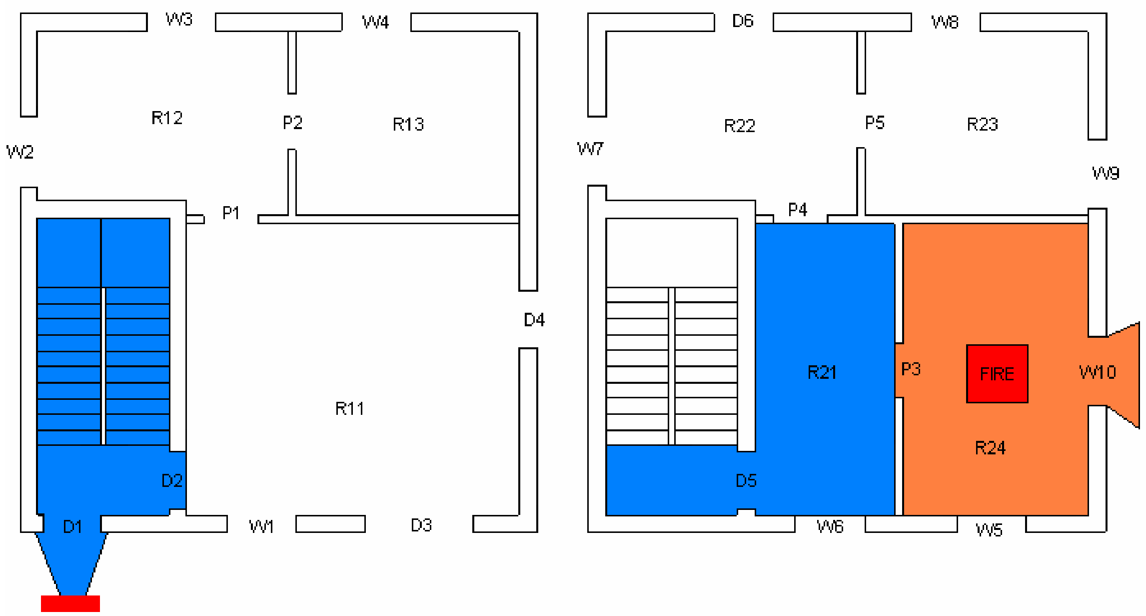


Figure 28. Configuration 9 Layout

This was the first configuration where the fire room maximum temperatures were slightly higher for the naturally ventilated test. The maximum fire room temperature for the naturally ventilated test was 680 ˚C (1260 ˚F) while the maximum temperature in the PPV ventilated test was 660 ˚C (1220 ˚F). The maximum temperatures in the other rooms on the second floor and top of the stairwell were similar for the two tests (Figure A-9).

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room was 280 ˚C (536 ˚F) in the naturally ventilated test and 310 ˚C (590 ˚F) in the PPV ventilated test. These temperatures were above the 100 ˚C (212 ˚F) incapacitation threshold. The temperatures in all of the other rooms on the second floor were just below the threshold temperature for both ventilation methods (Figure A-23).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the naturally ventilated test was 550 ˚C (1022 ˚F) and 560 ˚C (1040 ˚F) in the PPV ventilated test. These temperatures were well above the threshold temperature of 300 ˚C (572 ˚F). All of the maximum temperatures in the other second floor rooms were below the threshold for both ventilation scenarios (Figure A-37).

After ventilation, the rate of temperature increase for the naturally ventilated test was 3.31 ˚C/s (5.96 ˚F/s) while the rate of increase for the PPV ventilated test was nearly the same at 3.33 ˚C/s (5.99 ˚F/s). The temperature profiles were also similar for the two tests (Figure A-59, A-60).

Prior to the naturally ventilated test, there were small flows out the window (W10). For the PPV ventilated test, the velocity fluctuated between in and out flow. With the fan operating, the flow out the window ranged between 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.8 ft/s) (Figures A-87, A-88). These were the first tests in which the flow measurement devices were mounted in the reverse direction. For these tests and all remaining tests, positive flow was out of the window and negative flow into the window. In the naturally ventilated test, after the fire was vented, the flow in the top third of the window was outward at 2.0 m/s (6.6 ft/s) to 4.0 m/s (13.1 ft/s), the flow in the bottom third was into the room at 1.0 m/s (3.3 ft/s) to 2.0 m/s (6.6 ft/s) and the flow in the center of the window fluctuated between inflow and outflow (Figure A-111). During the PPV ventilated test, the flow became unidirectional out of the window at an average velocity of 3.0 m/s (9.8 ft/s) (Figure A-112). The flow decreased with time as the intensity of the fire decreased.

The door (D2) flows in the naturally ventilated test indicate instrument failure and are not deemed reliable (Figure A-139). In the PPV ventilated test, after the vent was opened, a neutral plane was located near the center of the doorway with the velocities in top of the door approximately twice the velocities in the bottom of the door (Figure A-140).

The oxygen concentrations dropped as low as 4 % in both scenarios but were 11 % to 14 % at all locations at the time of ventilation. The lower location concentrations in both tests recovered in a similar manner while the upper level concentrations showed significant differences. The upper location concentration for the naturally ventilated test dropped to 6 % as the fire intensified, but in the PPV ventilated test the upper location concentration only dropped to 12 % as the maximum temperature in the fire room was reached (Figures A-167, A-168).

The differential pressure in the stairwell for the naturally ventilated test fluctuated after ventilation but never went above 7 Pa (0.001 lb/in^2). The pressure in the PPV ventilated test fluctuated over the range of 0 Pa (0.0 lb/in^2) and 21 Pa (0.003 lb/in^2). Towards the end of the test, the pressure dropped to almost zero with no fire burning (Figure A-187).

3.10 Configuration 10 (Tests 22, 23)

Configuration 10 was similar to configuration 8 with the fire in R11 except that there was no window as a vent (Figure 29). The only ventilation opening and source of oxygen was the front door (D1). For the PPV ventilated test, the only opening for flow from the fan to leave the building was the door through which the flow entered the building and leakage from the structure. This was an incorrect ventilation scenario.

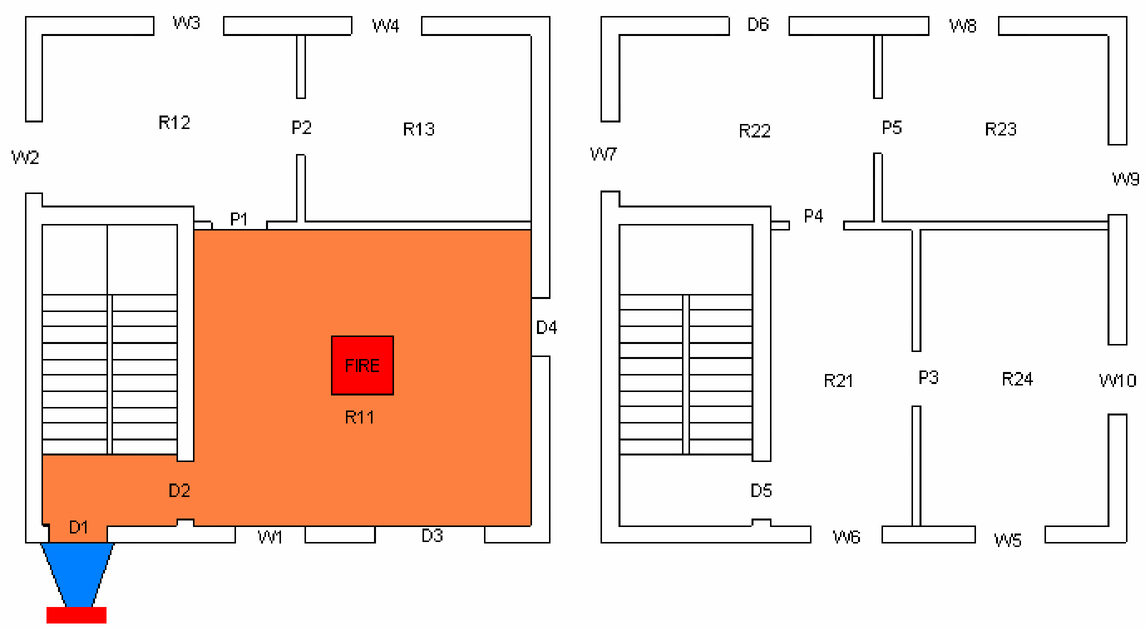


Figure 29. Configuration 10 Layout

The maximum fire room temperature for the naturally ventilated test was 530 ˚C (990 ˚F) and 570 ˚C (1060 ˚F) for PPV ventilated test. The maximum temperature at the top of the stairwell was 100 ˚C (212 ˚F) for both tests (Figure A-10).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 145 ˚C (293 ˚F), 125 ˚C (257 ˚F) in room R12, and 122 ˚C (252 ˚F) in room R13. In the test with PPV ventilation, the maximum temperature in the fire room was 161 ˚C (322 ˚F), in room R12 was 140 ˚C (284 ˚F) and in room R13 was 138 ˚C (280 ˚F) (Figure A-22). The temperatures in all the first floor rooms for both tests were above the incapacitation threshold temperature of 100 ˚C (212 ˚F). The maximum temperatures on the second floor and at the top of the stairwell were below the threshold and nearly equal for both ventilation scenarios (Figure A-24).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the fire room for naturally ventilated test was 380 ˚C (716 ˚F) and 450 ˚C (842 ˚F) in the PPV ventilated test, which exceeded the threshold temperature of 300 ˚C (572 ˚F). All of the other maximum temperatures were below the threshold temperature for both ventilation scenarios (Figure A-38).

After ventilation, the rate of temperature increase for the naturally ventilated test was 2.02 ˚C/s (3.64 ˚F/s) and 1.53 ˚C/s (2.75 ˚F/s) for the PPV ventilated test (Figures A-61, A-62).

The windows remained closed throughout the tests so there were no velocities prior to the test. The pressures generated during the fire resulted in the indication of small flows through the window (W1) (Figures A-113, A-114).

The flows through the door to the fire door (D2) were similar for both the naturally ventilated test and PPV ventilated test. In both cases, there was a bidirectional flow with flow into the room at the bottom of the door and out of the room at the top of the door (Figures A-141, A-142).

The oxygen concentrations for these two tests were similar. At the time of ventilation the concentrations at both levels were between 10 % and 15 %. After ventilation in the PPV ventilated test, the concentrations were slightly higher before they declined. The concentrations in both levels in both tests increased at nearly the same rate at the end of the tests (Figures A-169, A-170).

The differential pressures in the stairwell were high for both tests with this configuration. After ventilation, the pressure in the naturally ventilated test increased rapidly to 14 Pa (0.002 lb/in^2) and reached 21 Pa (0.003 lb/in^2) at the peak of the fire. After the peak, the pressure decreased to 14 Pa (0.002 lb/in^2) by the end of the test. The pressure in the PPV ventilated test rapidly increased to 28 Pa (0.004 lb/in^2) and then continued to rise to 34 Pa (0.005 lb/in^2). The pressure fluctuated between 21 Pa (0.003 lb/in^2) and 34 Pa (0.005 lb/in^2) occasionally reaching the maximum range of the pressure transducer until the fire burned out (Figure A-188).

3.11 Configuration 11 (Tests 24, 25)

In the eleventh configuration is the correct ventilation scenario corresponding to the incorrect ventilation scenario in configuration 4 (Figures 30 and 23). The fire was located in room R22 and the ventilation was out window W7 on the side of room R22.

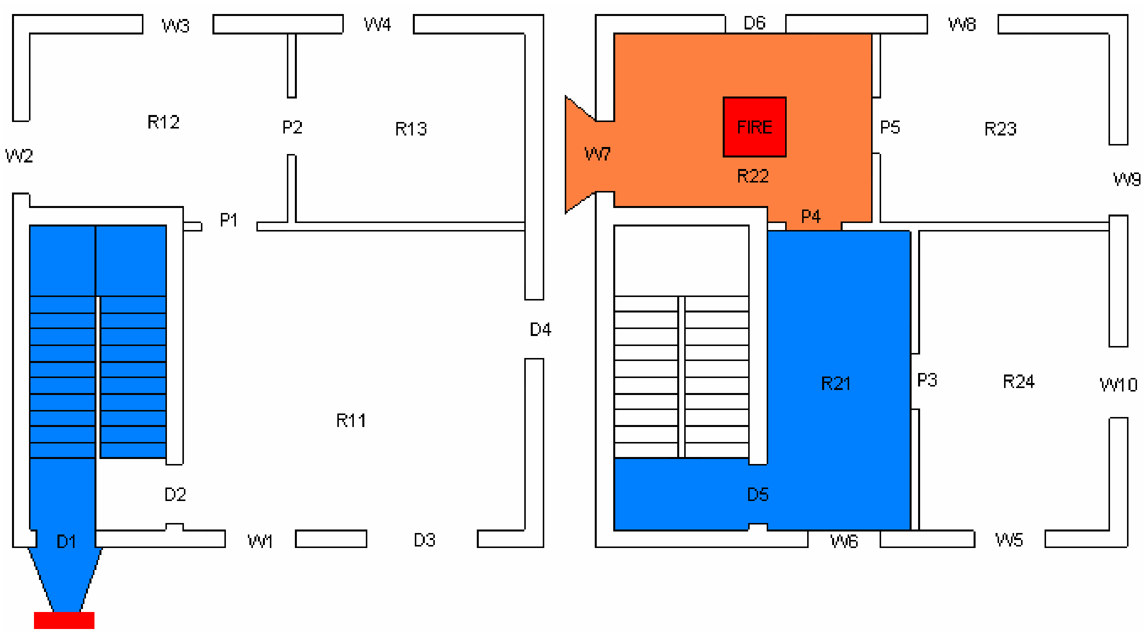


Figure 30 Configuration 11 Layout

The maximum fire room temperature for the naturally ventilated test was 680 ˚C (1256 ˚F), which was slightly higher than the maximum temperature of 640 ˚C (1184 ˚F) for the PPV ventilated test (Figure A-11).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 270 ˚C (518 ˚F) and 200 ˚C (392 ˚F) for the PPV ventilated test. In the naturally ventilated test, the maximum temperatures for all rooms on second floor were all above the 100 ˚C (212 ˚F) incapacitation threshold. In the PPV ventilated test, the temperature in two of the rooms, R21 at 87 ˚C (189 ˚F) and R24 at 90 ˚C (194 ˚F), were below the threshold temperature (Figure A-25).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the fire room for the naturally ventilated test was 532 ˚C (990 ˚F) and 465 ˚C (869 ˚F) in the PPV ventilated test. The temperature was above the 300 ˚C (572 ˚F) threshold for both tests. Maximum temperatures at this height in the other rooms on the second floor were slightly higher for the naturally ventilated test but were below the threshold temperature for both tests (Figure A-39).

The rate of temperature increase in the naturally ventilated test was 1.11 ˚C/s (2.00 ˚F/s), while the rate in the PPV ventilated test was 2.69 ˚C/s (4.84 ˚F/s). (Figures A-63, A-64).

For the naturally ventilated test, air velocities without the fire and without the fan through the window (W7) ranged between 2.0 m/s (6.6 ft/s) out of the room and 3.0 m/s (9.8 ft/s) into the room (Figure A-89). When the fan was used, the velocity out the window became unidirectional at 1.0 m/s (3.3 ft/s) and 4.0 m/s (13.1 ft/s) (Figure A-90). After ventilation of the fire in the naturally ventilated test, the window velocities fluctuated greatly producing both a unidirectional flow out of the room and bidirectional flow (Figure A-115). In the PPV ventilated test, the flow was unidirectional out of the window with a magnitude of 3.0 m/s (9.8 ft/s) to 7.0 m/s (23.0 ft/s) (Figure A-116).

The flow through the door (P4) to the fire room in the naturally ventilated test was predominantly unidirectional into the room with an average velocity of 2.0 m/s (6.6 ft/s). The flow through the top of the door showed the greatest fluctuation, reversing to flow out of the room part of the time. In the PPV ventilated test, the flow through the door was predominately into the room with an average of velocity 3.0 m/s (9.8 ft/s) (Figures A-143, A-144).

The oxygen concentrations in both tests at the upper and lower locations were approximately 10 % at the time of ventilation. It took nearly twice as long for the concentrations in the naturally ventilated test to reach 21 % as it did for the PPV ventilated test, even though the upper location concentration in the PPV ventilated test dropped lower as the fire reached its peak (Figures A-171, A-172).

The differential pressures in the stairwell remained approximately 0 Pa (0.0 lb/in^2) to 7 Pa (0.001 lb/in^2) for the naturally ventilated scenario. For the PPV ventilated scenario, the pressure in the stairwell rose to 21 Pa (0.003 lb/in^2) and mainly fluctuated between 14 Pa (0.002 lb/in^2) and 21 Pa (0.003 lb/in^2) while the fan was operating (Figure A-189). While it took a period of time to reach the maximum pressure in the naturally ventilated test, the pressure grew rapidly in the PPV ventilated test.

3.12 Configuration 12 (Tests 26, 27)

In the twelfth configuration the fire was on the second floor in room R23 with the ventilation window (W7) in room R22 (Figure 31). This was an incorrect ventilation scenario since the fire was not in the flow path from door D1 to window W7. The correct ventilation scenario for a fire in room R23 was configuration 1 where the vent flow was through window W8.

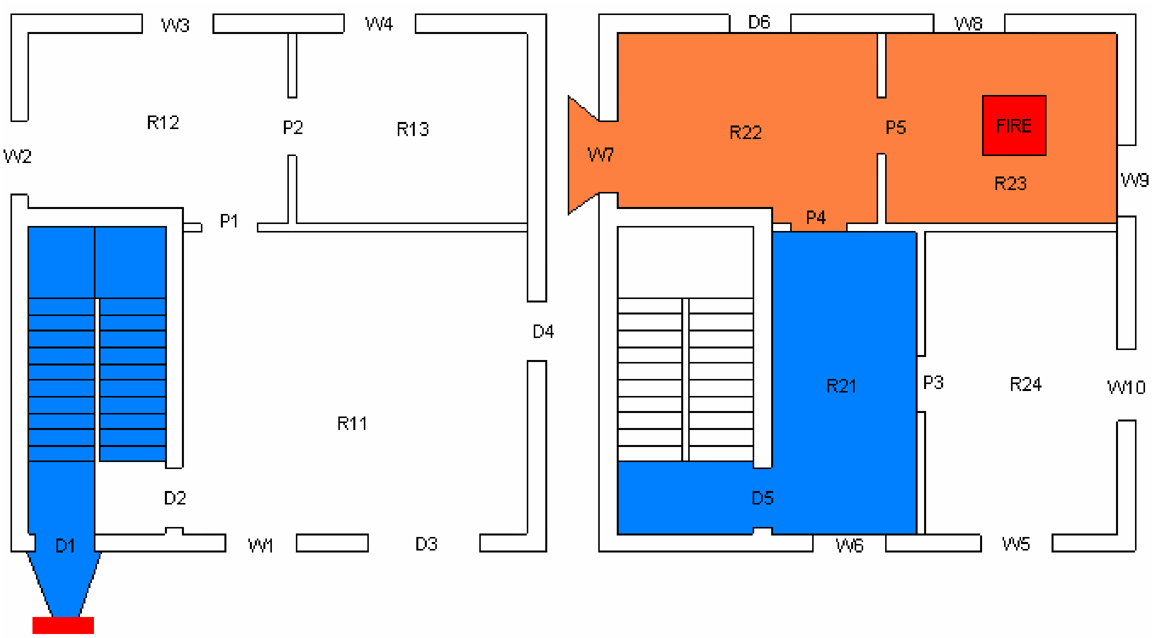


Figure 31. Configuration 12 Layout

The maximum temperature in the fire room was 759 ˚C (1398 ˚F) for the naturally ventilated test and 900 ˚C (1652 ˚F) for the PPV ventilated test. The maximum temperature in room R22 was 469 ˚C (876 ˚F) for the naturally ventilated test and 452 ˚C (846 ˚F) for the PPV ventilated test. The maximum temperature in room R21 was 571 ˚C (1060 ˚F) for the naturally ventilated test and 259 ˚C (498 ˚F) for the PPV ventilated test. The maximum temperature in room R24 was 608 ˚C (1126 ˚F) for the naturally ventilated test and 543 ˚C (1009 ˚F) for the PPV ventilated test (Figure A-12).

The maximum temperatures in the fire room and room R22 indicate that the temperatures were highest in the fire room and lower in the adjacent room. The maximum temperatures in rooms R21 and R24 are higher than the adjacent room except for R21 during the PPV ventilated test. This result is unexpected in that the temperature should be lower in rooms farther away from the fire. A detailed examination of all of the temperatures revealed that prior to ventilation the temperature in the rooms decreased with increasing distance from the fire and the temperatures were highest near the ceiling and lowest near the floor. After ventilation, the fire grew to fill the fire room with flames. At that time, there was a rapid rise in the temperatures in rooms R21 and R24 at all levels. The temperatures remained high for approximately 100 s before rapidly returning to values approximately the equal to those before the rise. There are three potential explanations for this result. First is an unusual flow pattern, which seems unlikely particularly in the naturally ventilated test. The second explanation is combustion taking place in room R24. Unfortunately, the instrumentation was not designed to detect this phenomenon and, although ignition of unburned products of combustion would explain the rapid temperature rise, it is unlikely the temperature would fall as rapidly. Finally, the most likely explanation is an instrumentation failure. The thermocouple wire from rooms R21 and R24 passed through room R23 in route to the data acquisition system. Although these wires were protected from the heat, it is possible the high temperature in the fire room caused a false signal to be created for those thermocouples. Due to the uncertainty in the temperature measurements in rooms R21 and R24, the temperatures in those rooms are not included in the discussion below.

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 623 ˚C 1153 ˚F), and 99 ˚C (210 ˚F) in room R22. In the PPV ventilated test, the maximum temperature in the fire room was 675 ˚C (1247 ˚F), and 113 ˚C (235 ˚F) in room R22. The temperatures in the fire room were well above the 100 ˚C (212 ˚F) incapacitation threshold for both tests and the temperatures in the adjacent room were just below the threshold in the naturally ventilated test and just above in the PPV ventilated test (Figure A-26).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in fire room for the naturally ventilated test was 748 ˚C (1378 ˚F) and 853 ˚C (1567 ˚F) in the PPV ventilated test. The maximum temperature in the adjacent room R22 was 314 ˚C (597 ˚F) in the naturally ventilated test and 330 ˚C (626 ˚F) in the PPV ventilated test. The temperatures were above the 300 ˚C (572 ˚F) threshold for both rooms in both tests. (Figure A-40).

The rate of temperature increase in the fire room of the naturally ventilated test was 3.26 ˚C/s (5.87 ˚F/s). In the PPV ventilated test, the rate of temperature increase was slower at 2.91 ˚C/s (5.24 ˚F/s) but the maximum temperature of 900 ˚C (1652 ˚F) was greater than for the naturally ventilated test (Figures A-65, A-66). During both tests, it appeared that after ventilation there were flames throughout the room and the temperatures were relatively uniform from floor to ceiling.

For the naturally ventilated test, air velocities without the fire and without the fan through the window (W7) were predominately between 0.5 m/s (1.6 ft/s) and 2.0 m/s (6.6 ft/s) out of the window. There was a short period of time when the flow was into the room (Figure A-91). When the fan was operating, the flow became 2.0 m/s (6.6 ft/s) to 4.0 m/s (13.1 ft/s) out of the window (Figure A-92). When the fire was ventilated during the naturally ventilated test, the flow was predominately unidirectional out of the window ranging from 1.0 m/s (3.3 ft/s) to 4.0 m/s (13.1 ft/s) (Figure A-117). There were however, several periods of bidirectional flow. For the PPV ventilated test, the velocity out of the window ranged from 2.0 m/s (6.6 ft/s) to 6.0 m/s (19.7 ft/s), with an average velocity of 3.0 m/s (9.8 ft/s) (Figure A-118). The highest velocities were out the right side of the window in both tests.

The flows through the door (P5) to the fire room were similar for both the naturally ventilated test and PPV ventilated test. In both cases, there was a bidirectional flow with flow into the room at the bottom of the door and out of the room at the top of the door. As the fire size decreased, the flow out the top of the door decreased (Figures A-145, A-146).

There were significant variations in the oxygen concentrations in both tests. Prior to ventilation in both tests, upper location concentration decreased to less than 3 % in the fire room. In both tests, the concentration at both the upper and lower positions was approximately 13 % at the time of ventilation. Once ventilated, concentrations in the naturally ventilated test recovered more rapidly than in the PPV ventilated test. Air could enter the naturally ventilated room from the window while in the PPV ventilated test the air had to travel from the front door (D1). Once air reached the fire room in both tests the fire intensified and the oxygen concentration at the upper level decreased to approximately 2 %. In the naturally ventilated test, the concentration at the lower location decreased to 4 % while in the PPV ventilated test the lower position concentration remained above 12 %. After the fire reached its peak, the concentrations at both locations in the naturally ventilated test increased at nearly the same rate while in the PPV ventilated test the concentration at the upper position lagged the concentration at the lower level (Figures A-173, A-174).

The differential pressure in the stairwell in the naturally ventilated test fluctuated between 0 Pa (0 lb/in^2) and 7 Pa (0.001 lb/in^2) after a spike of 24 Pa (0.0035 lb/in^2) just after the window was opened. The pressure in the PPV ventilated test fluctuated between 7 Pa (0.001 lb/in^2) and 21 Pa (0.003 lb/in^2) for the entire duration of the test (Figure A-190).

3.13 Configuration 13 (Tests 28, 29)

In the thirteenth configuration the fire was located in room R21 on the second floor (Figure 32). Window W6 in room R21 on the front of the building was used for ventilation. This was the correct ventilation scenario even though the fire was not directly in the path of the flow from door D1 to window W6. Configuration 2 was an incorrect ventilation scenario for a fire in room R21.

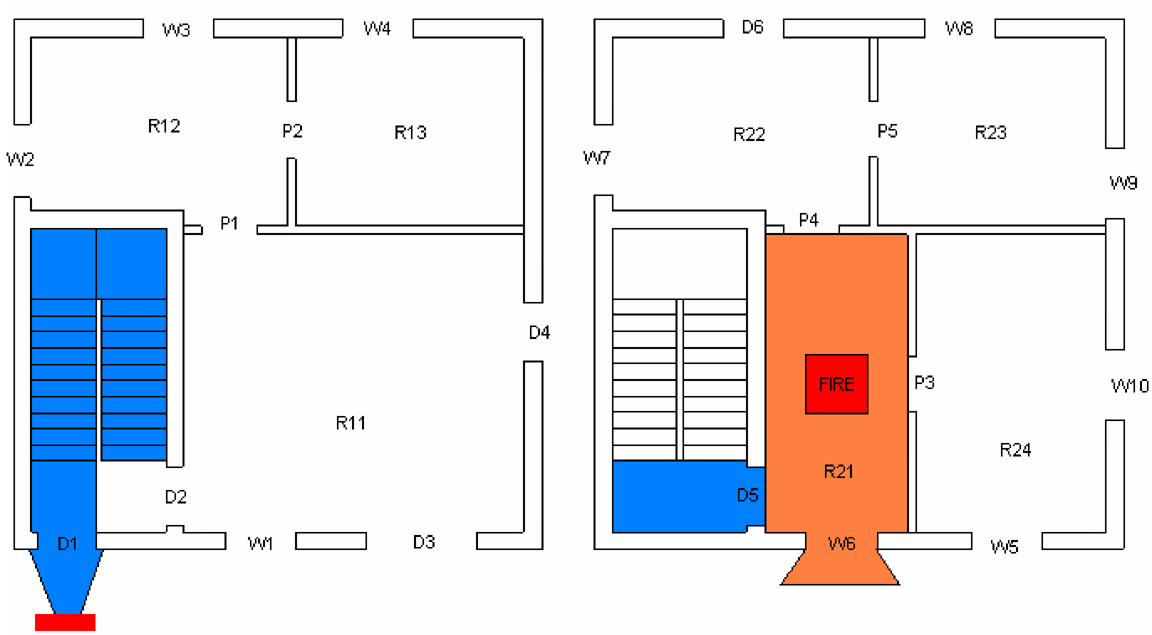


Figure 32. Configuration 13 Layout

The maximum temperatures in the naturally ventilated test were higher than the temperatures in the PPV ventilated test throughout the structure. The maximum fire room temperature in the naturally ventilated test was 640 ˚C (1184 ˚F) as compared to 605 ˚C (1121 ˚F) in the PPV ventilated test. The maximum temperature at the top of the stairwell was 20 ˚C (36 ˚F) higher in the naturally ventilated test than for the PPV ventilated test (Figure A-13).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 146 ˚C (295 ˚F). In the PPV ventilated test, the maximum temperature in the fire room was 180 ˚C (356 ˚F) an increase of 34 ˚C (61 ˚F). All of the temperatures on the second floor, for both scenarios, were above the 100 ˚C (212 ˚F) incapacitation threshold ranging from 108 ˚C (226 ˚F) to 148 ˚C (298 ˚F) (Figure A-27).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in fire room for the naturally ventilated test was 504 ˚C (939 ˚F) and 453 ˚C (847 ˚F) for the PPV ventilated test. In both the naturally and PPV ventilated tests, the maximum was above the 300 ˚C (572 ˚F) threshold. The maximum temperatures the other rooms were below 200 ˚C (392 ˚F). The maximum temperatures in the naturally ventilated test were slightly lower than those in the PPV ventilated test. (Figure A-41).

After ventilation in the naturally ventilated test, the ceiling temperature in the fire room increased at a rate of 2.00 ˚C/s (3.60 ˚F/s). In the PPV ventilated test, the rate of increase was slightly greater at 2.44 ˚C/s (4.39 ˚F/s) even though the maximum temperature in both tests was approximately the same at just over 600 ˚C (1112 ˚F) (Figures A-67, A-68).

The flow through the window (W6) prior to the fire in the naturally ventilated was unidirectional out of the window with a maximum velocity of 1.0 m/s (3.3 ft/s) (Figure A-93). For the PPV ventilated test, without the fire the velocities were predominately out of the window from 2.0 m/s (6.6 ft/s) to 4.0 m/s (13.1 ft/s) (Figure A-94). When the fire was ventilated during the naturally ventilated test, the flow was bidirectional with the flow in the top two thirds of the window out of the fire room with velocities up to 3.0 m/s (9.8 ft/s). The inflow to the room in the bottom third of the window had a maximum velocity of approximately 2.0 m/s (6.6 ft/s) (Figure A-119). For the PPV ventilated test, with the fire the flow was predominately out of the room with a maximum velocity of 7.0 m/s (23.0 ft/s). There was fluctuating flow on one side of the bottom third of the window with an occasional inflow of 2.0 m/s (6.6 ft/s) (Figure A-120).

The flow through the door (D5) to the fire room for the naturally ventilated test was bidirectional with the flow in the upper part of the door out of the room and the flow in the lower part of the door into the room. The flow out of the room ranged from 0.5 m/s (1.6 ft/s) to 1.5 m/s (4.9 ft/s). For the PPV ventilated test, the flow was unidirectional into the room with velocities from 1.0 m/s (3.3 ft/s) to 3.0 m/s (9.9 ft/s). (Figures A-147, A-148).

In both scenarios, the oxygen concentration in the upper and lower sampling locations was approximately 10 % at the time of ventilation. After ventilation, the concentrations in both test at the upper and lower positions increased at approximately the same rate after ventilation (Figures A-175, A-176).

The differential pressure in the stairwell for the naturally ventilated test ranged between 0 Pa (0.0 lb/in^2) and 14 Pa (0.002 lb/in^2), with an average of 7 Pa (0.001 lb/in^2). For the PPV ventilated test, the pressure in the stairwell rose to 21 Pa (0.003 lb/in^2) and fluctuated between 14 Pa (0.002 lb/in^2) and 21 Pa (0.003 lb/in^2) while the fan was operating (Figure A-191).

3.14 Configuration 14 (Tests 30, 31)

The configuration 14 was unique in that it was the only scenario with vertical ventilation (Figure 33). The fire was located in room R11, the large room on the first floor, and ventilation was through the hatch at the top of the stairwell. This was an incorrect ventilation scenario in that the ventilation flow path from door D1 was directly up the stairs to the roof hatch and not through the fire room R11.

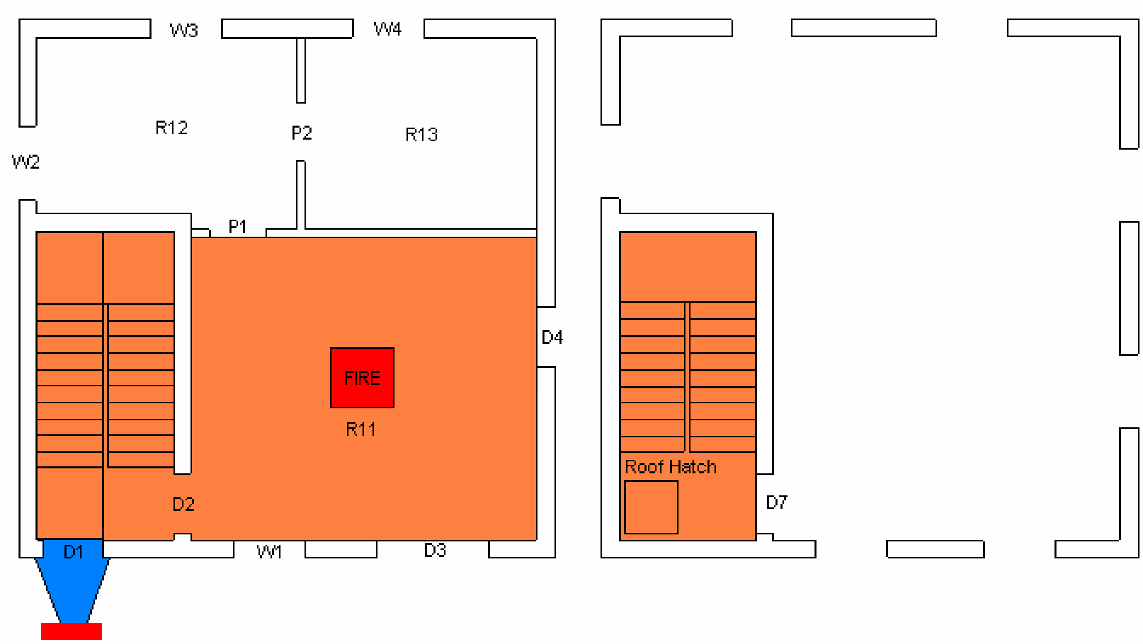


Figure 33. Configuration 14 Layout

The maximum fire room temperature for the naturally ventilated test was 540 ˚C (1000 ˚F) while the maximum temperature for the PPV ventilated test was 460 ˚C (860 ˚F). The maximum temperature at the top of the stairwell was approximately 100 ˚C (212 ˚F) for both tests (Figure A-14).

At the 0.61 m (2 ft) height, where victims may have been located, for the naturally ventilated test the maximum temperature in the fire room was 150 ˚C (300 ˚F). In the PPV ventilated test, the maximum temperature in the fire room was 130 ˚C (266 ˚F) a decrease of 20 ˚C (36 ˚F). All of the maximum temperatures for both tests on the first floor were above the incapacitation threshold temperature of 100 ˚C (212 ˚F) (Figure A-28).

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in fire room for the naturally ventilated test was 439 ˚C (822 ˚F) and 332 ˚C (630 ˚F) for the PPV ventilated test. In both the naturally and PPV ventilated tests, the maximum was above the 300 ˚C (572 ˚F) threshold. The maximum temperatures in the other rooms on both floors were all below 200 ˚C (392 ˚F). The temperatures in the naturally ventilated test were slightly higher than those in the PPV ventilated test in all of the rooms (Figure A-42).

After ventilation in the naturally ventilated test, the ceiling temperature in the fire room increased at a rate of 1.87 ˚C/s (3.37 ˚F/s). In the PPV ventilated test, the rate of increase was slightly slower at 1.77 ˚C/s (3.19 ˚F/s) (Figures A-69, A-70).

These tests utilized the roof hatch for ventilation instead of a window used in the previous tests. During the naturally ventilated test with the fire, a velocity up to 6.0 m/s (19.7 ft/s) was generated through the hatch (Figure A-121). As the fire decreased the flow through the hatch decreased. In the PPV ventilated test, the velocity was as high as 7.5 m/s (24.6 ft/s) (Figure A-122). The flow through the hatch with the fan remained relatively constant as the fire decreased.

The flows through the door (D2) to the fire room were similar for both the naturally ventilated and the PPV ventilated test. The flow was bidirectional with the neutral pressure plane located at about the center of the door. The flow in the upper part of the door was out of the room and the flow in the lower part of the door into the room (Figures A-149, A-150).

The oxygen concentration in both tests at the time of ventilation at both the upper and lower locations was 12 %. In the naturally ventilated test, it took approximately twice as long to reach ambient concentrations as it did in the PPV ventilated test. In the naturally ventilated test, the concentration dropped briefly after ventilation before returning to ambient. In the PPV ventilated test, the concentration rose steadily after ventilation until the fire burned to completion (Figures A-177, A-178).

The differential pressure in the third floor stairwell for the naturally ventilated fire slowly increased and decreased with the fire development over a range of 7 Pa (0.001 lb/in^2) to 10 Pa (0.0015 lb/in^2). For the PPV ventilated test, the pressure fluctuated between 14 Pa (0.002 lb/in^2) and 21 Pa (0.003 lb/in^2) after ventilation (Figure A-192).

4.0 Comparison of Correct and Incorrect Ventilation Scenarios

A number of the fire experiments were designed to compare correct and incorrect ventilation scenarios with a fire located in a given room within the structure. In this section, the results of configurations with correct and incorrect ventilation scenarios are compared. A scenario is defined as correct when the ventilation opening occurs near the seat of the fire and localizes the fire. Scenarios were considered incorrect when the flow from the fire had to pass through other rooms before reaching the vent. During actual fire fighting operations, the selection of a ventilation procedure will depend on additional factors such as access to the structure and the location of victims or fire fighters operating within the structure. In addition, fire fighters may not know the exact location of the fire prior to entering the structure.

4.1 Configurations 1 and 12, Fire Room (R23)

Configuration 1 (tests 2, 3) was the correct ventilation scenario and configuration 12 (tests 26, 27) was an incorrect scenario. The maximum temperatures in the fire room and the adjacent room were higher in the incorrect scenario. The oxygen concentrations in the fire room were significantly lower and the window velocities higher with the incorrect scenario. The differential pressure at the top of the stairwell was similar in both scenarios.

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room was above the 100 ˚C (212 ˚F) incapacitation threshold in both configurations. The maximum temperatures in all of the other rooms were below the threshold temperature for both configurations except for the adjacent room R22 with the incorrect scenario where the temperatures just below the threshold in the naturally ventilated test and just above in the PPV ventilated test.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the fire room and the adjacent room R22 were above the threshold temperature of 300 ˚C (572 ˚F) for both configurations. The maximum temperatures in the other rooms were below the threshold for both configurations.

4.2 Configurations 8 and 3/6, Fire Room (R11)

Configuration 8 (tests 18, 19) was the correct ventilation scenario and configurations 3 (tests 7, 8) and 6 (tests 13, 14) were incorrect scenarios. Maximum room temperatures were similar for all three configurations. However, the maximum temperatures at the 1.22 m (4 ft) height were lower in the correct ventilation scenario than those in the two incorrect configurations. The fire room oxygen concentrations and the window velocities were similar in all three configurations. The stairwell differential pressure was higher in the correct ventilation scenario than in the two incorrect configurations.

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room and rooms R12 and R13 were at or above the 100 ˚C (212 ˚F) incapacitation threshold in both configurations with the exception of the temperature in room R13 for the naturally ventilated test in configuration 6 which was just below the threshold. The maximum temperatures in all of the other rooms were below the threshold temperature for both configurations with the exception of the temperature in room R21 for the naturally ventilated test in configuration 3, which was at the threshold.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in fire room was below the 300 ˚C (572 ˚F) threshold for correct configuration and above the threshold for the incorrect configurations. The maximum temperatures in the other rooms were below the threshold for both configurations.

4.3 Configurations 9 and 5, Fire Room (R24)

Configuration 9 (tests 20, 21) was the correct ventilation scenario and configuration 5 (tests 11, 12) was an incorrect scenario. These two configurations produced similar temperatures with the correct ventilation scenario having slightly lower temperatures in the rooms adjacent to the fire room. The most substantial difference was that the oxygen concentration in the fire room increased rapidly in the PPV ventilated tests. There was little difference in the ventilation velocities in the two configurations. The incorrect ventilation scenario resulted in slightly higher pressures at the top of the stairwell readings.

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room was above the 100 ˚C (212 ˚F) incapacitation threshold in both configurations. The maximum temperatures in the other rooms on the second floor were below the threshold temperature for both configurations.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the fire room for both configurations were above the threshold temperature of 300 ˚C (572 ˚F). The maximum temperatures in the other rooms were below the threshold for both configurations.

4.4 Configurations 11 and 4, Fire Room (R22)

Configuration 11 (tests 24, 25) was the correct ventilation scenario and configuration 4 (tests 9, 10) was an incorrect scenario. The main difference between the two configurations were the lower temperatures in room R23 with the correct scenario, since the combustion products did not have to pass through room R23 in route to the vent. Window velocities after ventilation of the fire were greater in the correct ventilation scenario and the oxygen concentration in the fire room returned to near ambient levels sooner in the correct scenario. Stairwell pressures were nearly the same for both configurations.

At the 0.61 m (2 ft) height, where victims may have been located, the maximum temperature in the fire room and room R23 exceeded the 100 ˚C (212 ˚F) incapacitation threshold temperature in both configurations. The maximum temperature in the other rooms was below the threshold for victim incapacitation in both configurations.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in fire room exceeded the 300 ˚C (572 ˚F) threshold for both configurations. Maximum temperatures in the other rooms were below the threshold temperature for both configurations except for the temperature in room R23 that exceeded the threshold in the incorrect configuration for both the naturally and PPV ventilated tests.

4.5 Configurations 13 and 2, Fire Room (R21)

Configuration 13 (tests 28, 29) was the correct ventilation scenario and configuration 2 (tests 4, 5) was an incorrect scenario. The maximum temperatures in the rooms on second floor were slightly lower in the correct ventilation tests as compared to the incorrect tests. The fire durations in the correct ventilation tests were also less than those in the incorrect ventilation tests. The velocities out of the window were slightly higher in the correct ventilation configuration tests as compared to the incorrect tests. The oxygen concentrations were similar for all of the tests and differential pressures in the third floor stairwell were comparable for both configurations.

At the 0.61 m (2 ft) height, where victims may have been located, the temperatures in all of the rooms on the second floor, for both configurations were above the 100 ˚C (212 ˚F) incapacitation threshold.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, the maximum temperature in the fire room was above the 300 ˚C (572 ˚F) threshold for both configurations. The maximum temperature in the other rooms was below the threshold for both configurations although the temperature in room R22 approached the threshold in the incorrect scenario PPV ventilated test.

5.0 Uncertainty

There are different components of uncertainty in the gas temperatures, mass of fuel packages, gas velocity and heat release rate 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 [9]. 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 6. Some of these components, such as the zero and calibration elements, are derived from instrument specifications. Other components, such as radiative cooling/heating, include past experience with thermocouples in high temperature fuel rich environments.

The uncertainty in the upper layer gas temperature measurements includes radiative cooling in each of the experimental series, but also includes radiative heating for thermocouple located in the lower layer of the full-scale experiments. Pitts et al. [10] quantified the errors of bare bead thermocouples as ranging from 7 % in the hot upper gas layer to as much as 75 % in the lower layer. The potential for large errors in the lower layer are a function of the effective temperature of the surroundings. In cases where the effective temperature of the surroundings is high, the error can be more significant. Small diameter thermocouples were used to limit the impact of radiative heating and cooling. This resulted in an estimate of ±15 % total expanded uncertainty in temperature.

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. The readings from the pressure transducers were used to generate gas velocities.

Load cells were utilized to measure fuel package mass. The load cell was calibrated with a standard mass prior to recording the mass of each fuel item. After obtaining mass data on each of the fuel components, items were selected at random to be reweighed in order to estimate repeatability.

Each length measurement was taken carefully. However, due to some construction issues, such as the size and straightness of the lumber, the curves of the furniture, and the symmetry of the large room, the total expanded uncertainty for room dimensions was estimated to be 6 %.

Weather, leakage and oxygen measurement uncertainty was referenced to each of their published user's manuals.

Table 6. Uncertainty

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Gas Temperature Calibration[11] Radiative Cooling Radiative Heating Repeatability [1] Random [1]	 ± 1 % - 5 % to + 0 % - 0 % to + 5 % ± 5 % ± 3 %	± 8 %	± 15 %
Differential Pressure Calibration[12] Accuracy [12] Repeatability [1] Random [1]	 ± 2 % ± 1 % ± 5 % ± 5 %	± 8 %	± 15 %
Mass of Fuel Package Zero Calibration Repeatability[1] Random[1]	 ± 0.02 % ± 1 % ± 5 % ± 3 %	± 6 %	± 12 %
Length Measurements Instrumentation Locations Furniture Dimensions Fan Location Room Dimensions Repeatability[1] Random[1]	 ± 1 % ± 1 % ± 1 % ± 1 % ± 2 % ± 2 %	± 3 %	± 6 %

Weather Measurements Temperature[13] Relative Humidity Average Wind Speed Wind Direction Barometric Pressure Repeatability[1] Random[1]	 ± 2 % ± 2 % ± 1 % ± 1 % ± 0.003 % ± 1 % ± 1 %	± 3 %	± 6 %
Leakage Measurements Calibration[14] Accuracy Repeatability[1] Random[1]	 ± 3 % ± 1 % ± 5 % ± 5 %	± 8 %	± 15 %
Oxygen Concentration Measurements Calibration[15] Accuracy[15] Repeatability[1] Random[1]	 ± 1 % ± 1 % ± 5 % ± 5 %	± 7 %	± 14 %
Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.			

6.0 Conclusions

In this series of experiments, a number of different fire and vent locations were used to compare correct and incorrect ventilation scenarios with natural and positive pressure fan ventilation.

Based on the air velocity measurements taken prior to ignition for each test, there was generally a small pretest velocity through the ventilation window. On average, this value was approximately 0.0 m/s (0.0 ft/s) to 1.0 m/s (3.3 ft/s), which did not appear to significantly influence the results. With the PPV fan operating without a fire, the average velocity through the vent window was 1.5 m/s (4.9 ft/s) to 2.5 m/s (8.2 ft/s). The fan-induced velocity through the vent window was essentially independent of the location of the window. This result was consistent with relatively small size of the structure and would not be expected in large structures. Using an overall average velocity of 2.0 m/s (6.6 ft/s) yields a volumetric flow rate of 3.46 m^3/s (7.34 x 10^3 ft^3/min) through the ventilation window. The volumetric flow rate provided by the manufacturer for the PPV fan is 8.56 m^3/s (18.1 x 10^3 ft^3/min). Comparing the flow rates indicates that 40 % of the air moving thought the fan reached the window. The rest of the flow either did not enter the structure or was dissipated within the structure.

The average velocity through the window in the tests with natural ventilation ranged from 1.0 m/s (3.3 ft/s) to 2.0 m/s (6.6 ft/s). This demonstrates that the fire-induced flow value was as much as twice the pretest flow. In the naturally ventilated tests, the flow through the window was almost always bidirectional with outside air entering the bottom of the window and hot fire gasses leaving the structure through the top of the window. In many of the naturally ventilated tests, especially when the window was in the fire room, the velocity out the top of the window was nearly double the velocity into the bottom of the window.

When the PPV fan was used at the time of ventilation, the flow velocities increased to an average of approximately 3.0 m/s (9.8 ft/s). This was an increase of more than 1.0 m/s (3.3 ft/s) from the natural ventilation test velocities. With the addition of the buoyancy produced by the fire, 62.5 % of the air moving through the fan reached the window. When the vent was opened without the fan operating, in most cases a bidirectional flow developed through the window. When the fan was started, the flow through the window became unidirectional through the window out of the structure. The result of this flow pattern was that in the naturally ventilated tests the primary source of oxygen for the fire would have been through the ventilation window, while in the PPV ventilated tests the primary source of oxygen was from the flow through the building generated by the fan.

In the case where the hatch at the top of the stairwell was used as the ventilation point, the flow created by the fan averaged 2.0 m/s (6.6 ft/s) greater than that flow created in the naturally ventilated test. This was an increased volumetric flow of 1.7 m^3/s (3.5×10^3 ft^3/min). The volume of air flowing through the roof hatch was approximately the same as the volume of air flowing through the windows during ventilation. Since the fan was introducing air at the bottom of the stairwell that contained the vent hatch and the hatch open area was smaller than the windows, further experiments would be required to compare the effectiveness of horizontal and vertical vents.

In the naturally ventilated tests, the flow thorough the door into the fire room was bidirectional with flow out of the room through the top of the door and into the room through the bottom of the door. In the PPV ventilated tests, the flow through the door depended on the location with respect to the vent window and the fan. When the ventilation window opposite the fan, a unidirectional flow was created through the doorway into the fire room. When the ventilation window was located so the flow from the fan to the window did not pass through the fire room, a bidirectional flow was created. With the PPV fan operating, the flow into the room in the lower third of the door increased, as did the outflow in the top two thirds of the door.

The maximum fire room ceiling temperature ranged from 400 ˚C to 900 ˚C (752 ˚F to 1652 ˚F). The average maximum temperature in the naturally ventilated tests was 600 ˚C (1110 ˚F) while the average maximum temperature in PPV ventilated tests was 650 ˚C (1200 ˚F). Maximum temperatures in the naturally ventilated tests were generally similar to those in the PPV ventilated tests in all of the rooms throughout the structure. There was only one configuration that produced a temperature difference greater than 200 ˚C (360 ˚F), while in most of the configurations the difference was less than 100 ˚C (180 ˚F). In all but four of the configurations, the maximum fire room temperature with the naturally ventilated fires was lower than those with the PPV ventilated fires.

At the 0.61 m (2 ft) height, where victims may have been located, in the PPV ventilated tests, the maximum temperature in the fire room and the rooms located in the ventilation path beyond the fire room were generally higher than the temperatures in the naturally ventilated tests. This was due to the mixing created by the fan. In the naturally ventilated tests, a high temperature layer formed in the upper part of the room with a cooler layer near the floor. In the PPV ventilated tests, the flow from the fan caused mixing of the layers creating higher temperatures in the lower part of the room. While the temperatures in the fire room and the rooms between the fire room and vent were higher with PPV ventilation, the temperatures between the fan and the fire room tended to be lower. This was due to outside air being forced into the structure by the fan.

At the 1.22 m (4 ft) height, where fire fighters may have been operating, fire room temperatures were as high as 700 ˚C (1290 ˚F) and exceeded the 300 ˚C (572 ˚F) in all of the tests. In the correct ventilation configurations, the maximum temperatures in the other rooms within the structure were below the threshold temperature for both ventilation techniques. For two incorrect ventilation configurations 4 (tests 9, 10) and 12 (tests 26, 27) temperatures in the adjacent rooms exceeded the threshold. In configuration 4, the temperature in room R23 exceeded the threshold for both the naturally and PPV ventilated tests. In configuration 12, the temperatures in room R22 were just below the threshold in the naturally ventilated test and just above in the PPV ventilated test.

The growth of the fire after ventilation was influenced by the path the outside air traveled to provide oxygen to the fire. When the ventilation window was in proximity of the fire, usually in the correct ventilation scenarios, the initial fire growth was more rapid in the naturally ventilated tests. In the PPV ventilated tests, the pressure generated by the fan caused a unidirectional flow out of the window. The primary source of oxygen was the air from the fan, which had to travel from the front door, through the building to the fire room. This could result in an initial temperature decrease in the PPV ventilated tests prior to outside air reaching the fire room and provided a source of oxygen for the fire. Once the outside air reached the fire in the PPV ventilated tests the fan was generally able to deliver oxygen to the fire more effective than natural ventilation.

In most of the tests, the PPV ventilated fires grew at a faster rate after ventilation was initiated. The average rate of temperature increase for the naturally ventilated tests was 1.91 ˚C/s (3.44 ˚F/s) as compared to 2.80 ˚C/s (5.04 ˚F/s) for the PPV ventilated tests. The values were primarily dependent on the ventilation technique but could have been influenced by other factors such as variability in the fuel package and oxygen concentration in the fire room at the time of ventilation. The fire growth in the fuel package prior to ventilation was not the same for each test and the oxygen concentration in the fire room was not the same at the time of ventilation even though each test was ventilated in an oxygen-limited state. Although the fuel for the tests was stored in inside an unheated building prior to the tests, there was no means to control the moisture content of the fuel and the mass of each fuel package was not identical.

Prior to ventilation, the differential pressures in the stairwell on the third floor landing were as high as 21 Pa (0.003 lb/in^2) but generally approached 0 Pa (0 lb/in^2) just prior to ventilation as the fires became oxygen limited. After ventilation, the pressures increased as the fires developed. In the naturally ventilated tests, after ventilation the average pressure increase was 7 Pa (0.001 lb/in^2). The average pressure increase in the PPV ventilated tests was 21 Pa (0.003 lb/in^2). With all vents closed, the PPV fan created an average pressure of 28 Pa to 34 Pa (0.004 lb/in^2 to 0.005 lb/in^2).

In this experimental series, a number of correct and incorrect ventilation scenarios were examined with both the natural and PPV ventilation with a single type of fire in a relatively small structure. The data indicates that using correct ventilation scenarios resulted in lower temperatures within the structure at the 0.61 m (2 ft) height, where victims may have been located, and at the 1.22 m (4 ft) height, where fire fighters may have been operating. There were only a few ventilation configurations where the temperatures in rooms other than the fire room exceeded the victim or fire fighter threshold temperatures with either ventilation technique.

The use of PPV caused the fire to grow more quickly and in some cases created higher temperatures at the lower elevations within the structure. The use of PPV ventilation resulted in visibility improving more rapidly and in many cases cooled rooms surrounding the fire room. Overall, this limited series of experiments suggests that PPV can assist in making the environment in the structure more conducive for firefighting operations.

7.0 References

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8.0 Acknowledgments

Appreciation is extended to Bill Twilley and Roy McLane of the Building and Fire Research Laboratory for their support with setting up and running the experiments. I would also like to thank Meredith Lawler of the United States Fire Administration for her support of this project.

Figure 34. Pressure Transducer Implementation

Figure 35. Window after Ventilation

Figure 36. R23 Well Involved after Ventilation

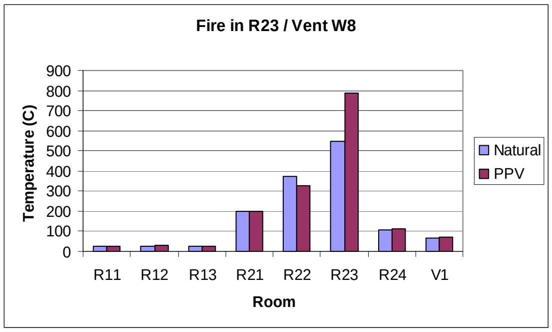


Figure A-1. Test 2, 3 Maximum Temperatures

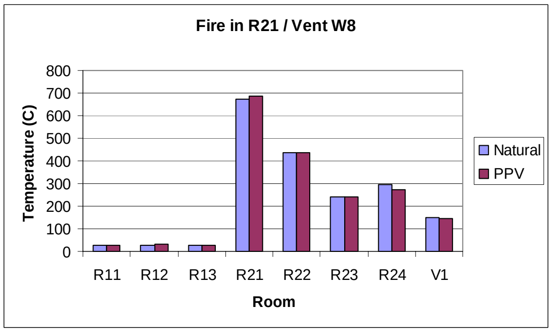


Figure A-2. Test 4, 5 Maximum Temperatures

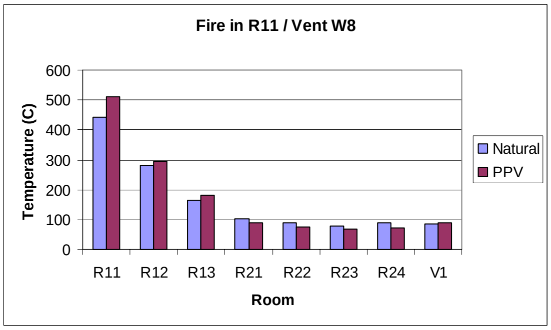


Figure A-3. Test 7, 8 Maximum Temperatures

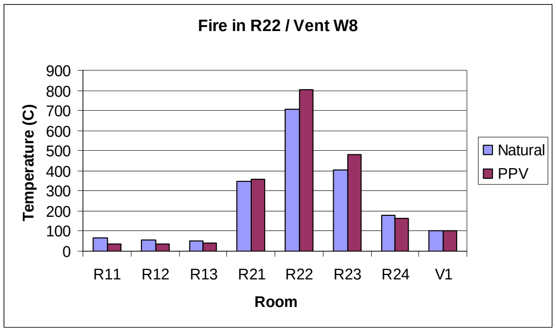


Figure A-4. Test 9, 10 Maximum Temperatures

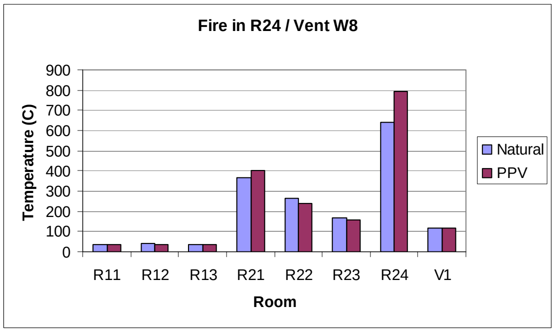


Figure A-5. Test 11, 12 Maximum Temperatures

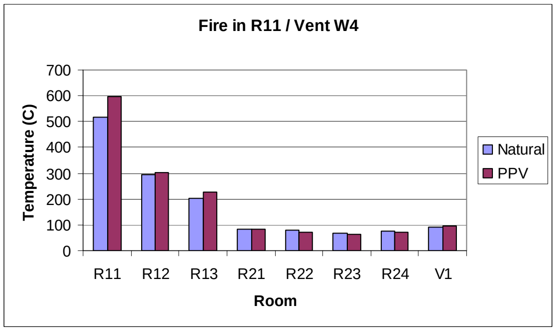


Figure A-6. Test 13, 14 Maximum Temperatures

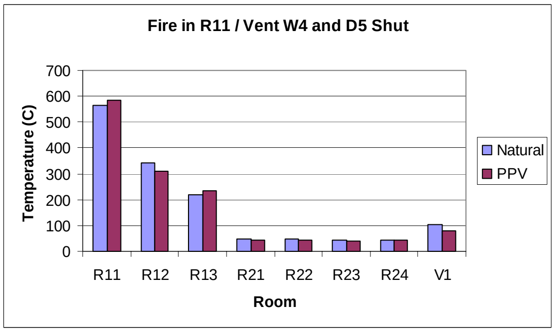


Figure A-7. Test 16, 17 Maximum Temperatures

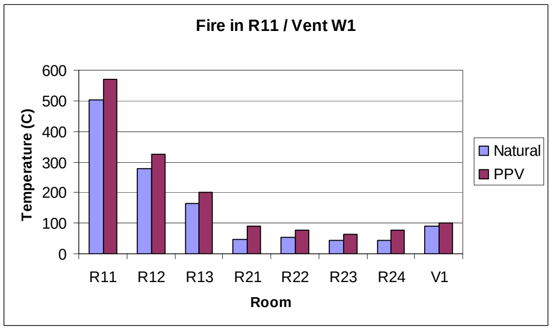


Figure A-8. Test 18, 19 Maximum Temperatures

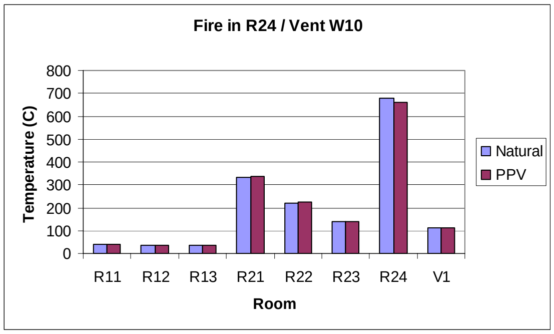


Figure A-9. Test 20, 21 Maximum Temperatures

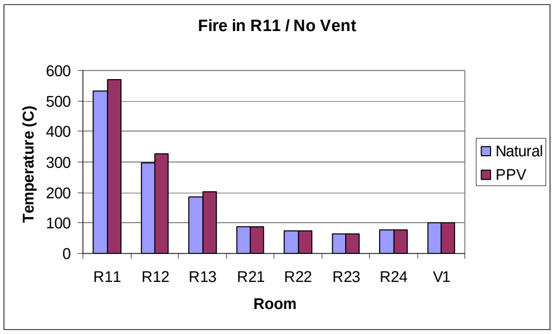


Figure A-10. Test 22, 23 Maximum Temperatures

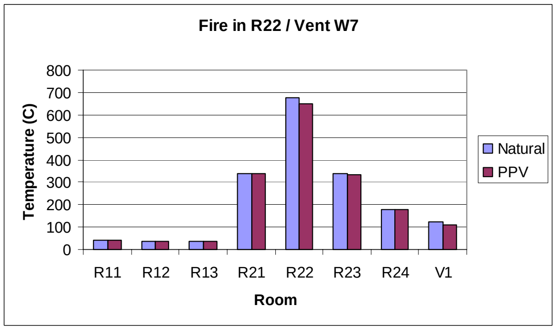


Figure A-11. Test 24, 25 Maximum Temperatures

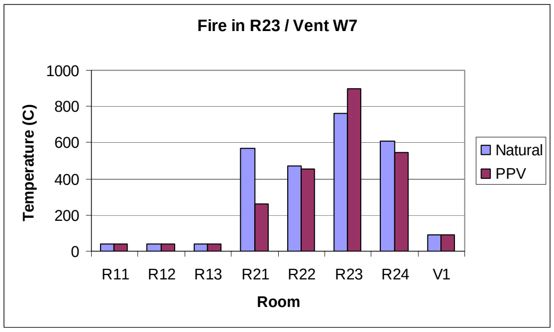


Figure A-12. Test 26, 27 Maximum Temperatures

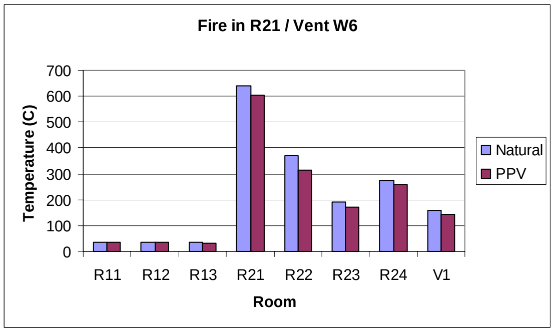


Figure A-13. Test 28, 29 Maximum Temperatures

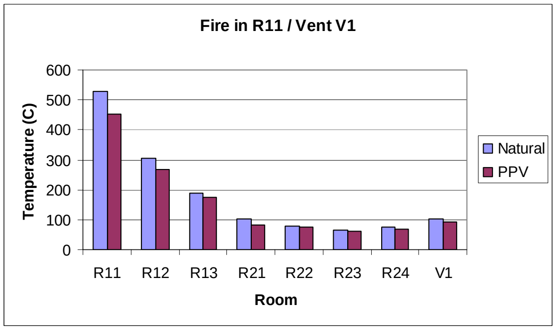


Figure A-14. Test 30, 31 Maximum Temperatures

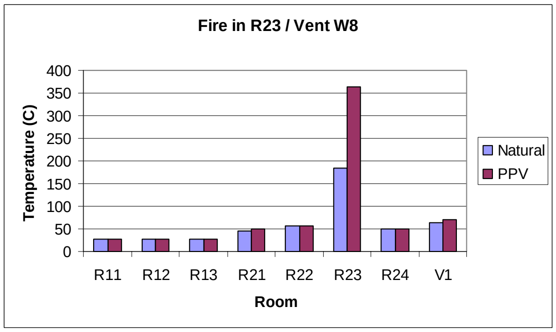


Figure A-15. Test 2, 3 Max Temperatures at 0.61 m

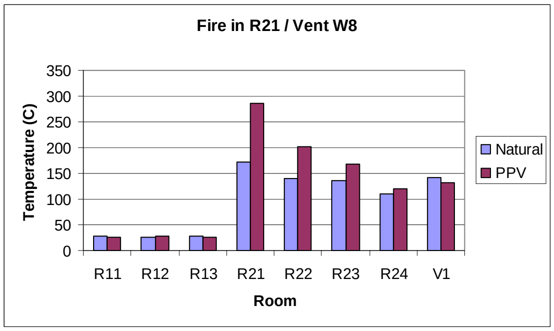


Figure A-16. Test 4, 5 Max Temperatures at 0.61 m

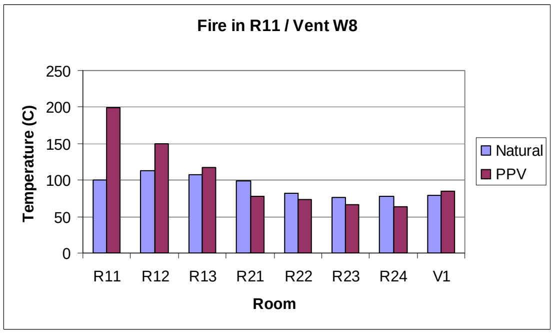


Figure A-17. Test 7, 8 Max Temperatures at 0.61 m

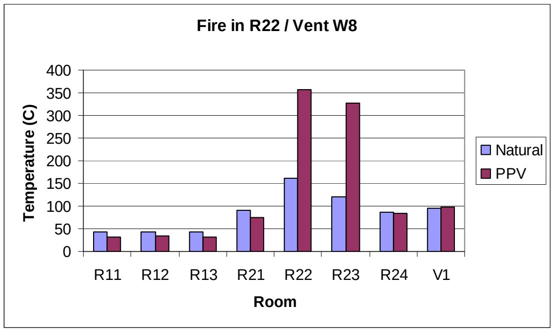


Figure A-18. Test 9, 10 Max Temperatures at 0.61 m

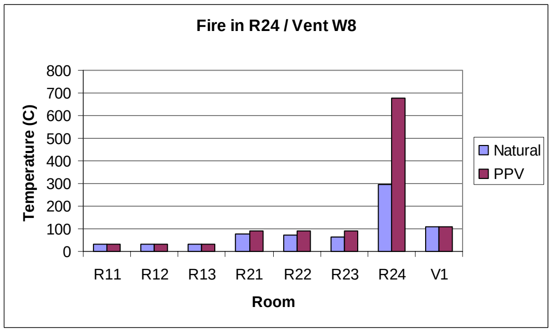


Figure A-19. Test 11, 12 Max Temperatures at 0.61 m

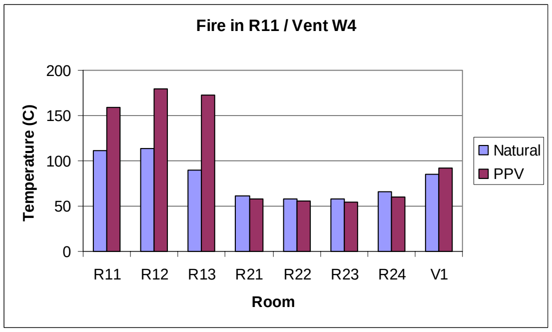


Figure A-20. Test 13, 14 Max Temperatures at 0.61 m

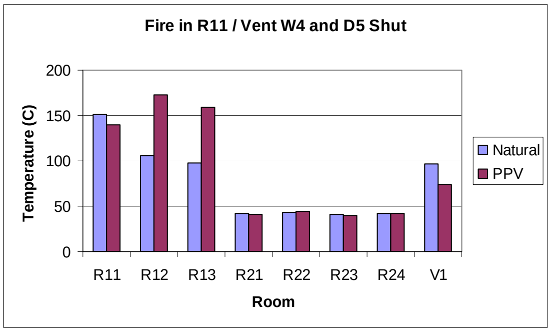


Figure A-21. Test 16, 17 Max Temperatures at 0.61 m

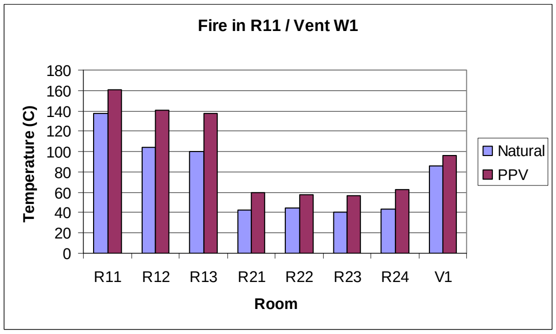


Figure A-22. Test 18, 19 Max Temperatures at 0.61 m

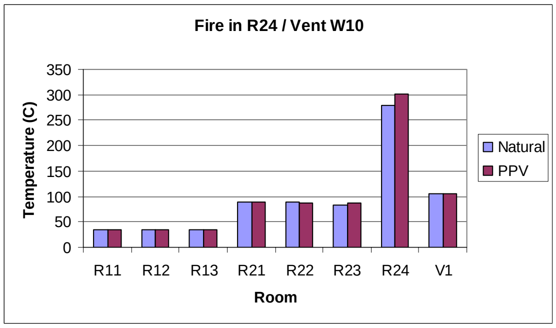


Figure A-23. Test 20, 21 Max Temperatures at 0.61 m

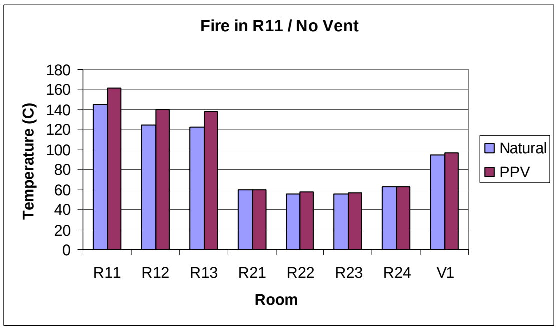


Figure A-24. Test 22, 23 Max Temperatures at 0.61 m

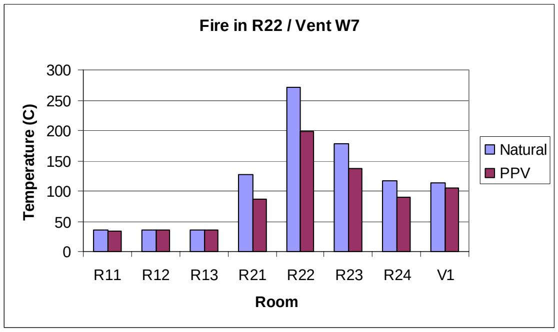


Figure A-25. Test 24, 25 Max Temperatures at 0.61 m

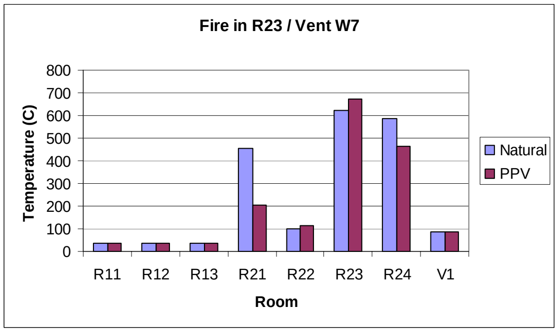


Figure A-26. Test 26, 27 Max Temperatures at 0.61 m

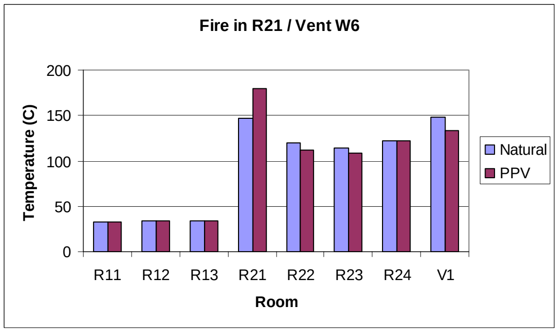


Figure A-27. Test 28, 29 Max Temperatures at 0.61 m

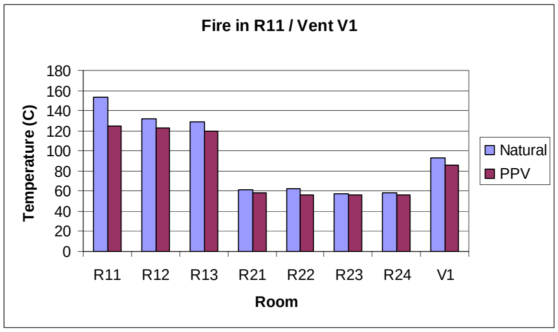


Figure A-28. Test 30, 31 Max Temperatures at 0.61 m

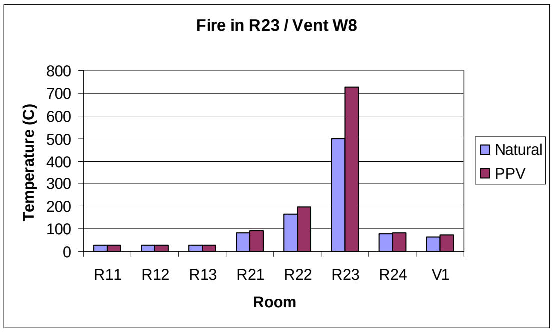
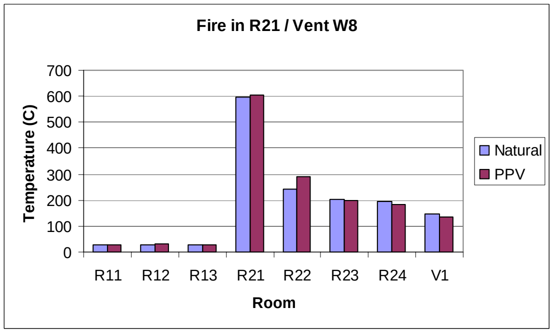


Figure A-29. Test 2, 3 Max Temperatures at 1.22 m



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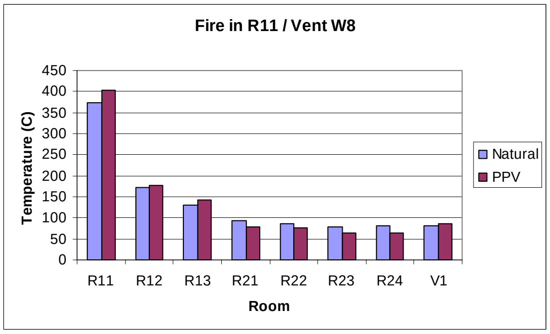

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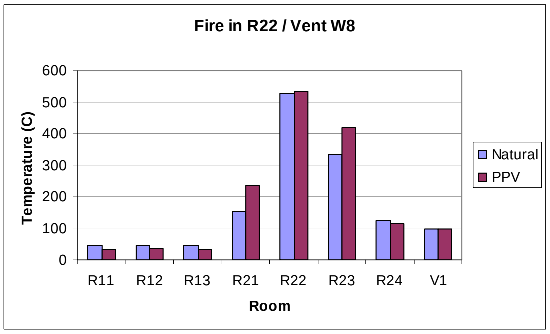

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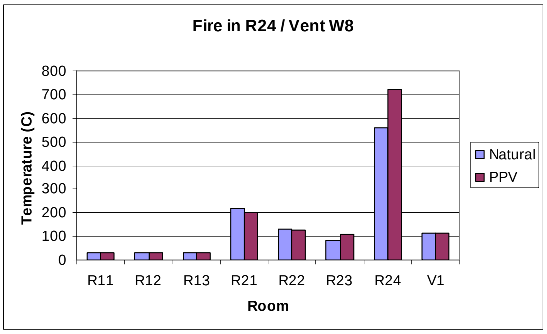

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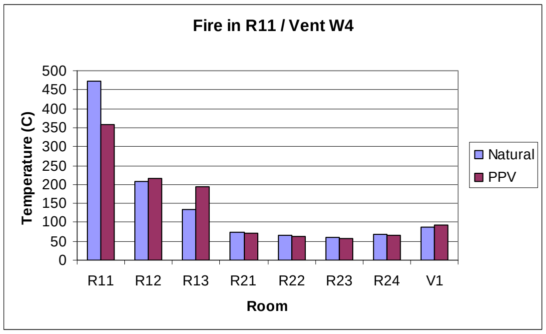

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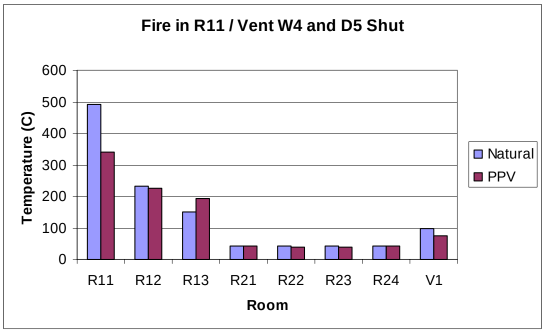

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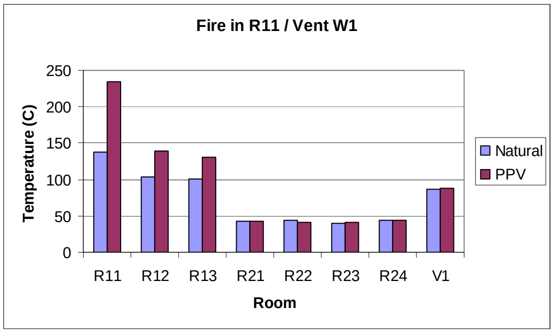

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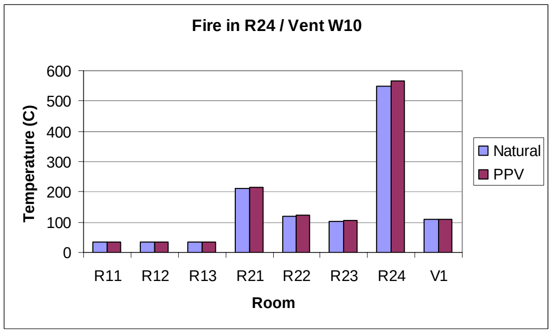


Figure A-37. Test 20, 21 Max Temperatures at 1.22 m

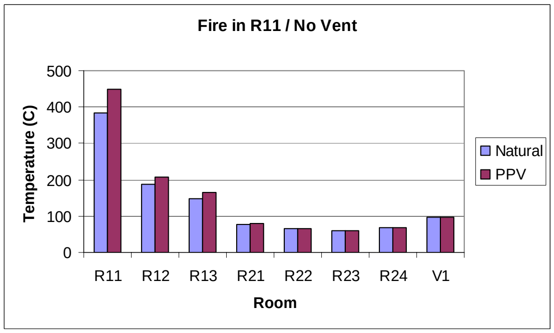


Figure A-38. Test 22, 23 Max Temperatures at 1.22 m

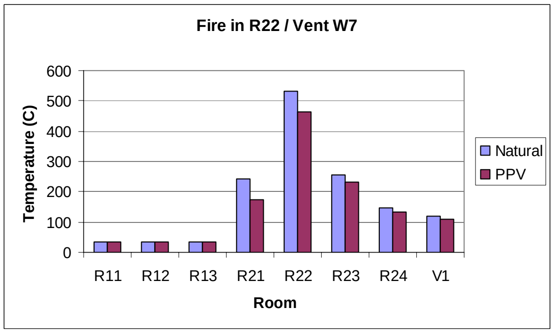


Figure A-39. Test 24, 25 Max Temperatures at 1.22 m

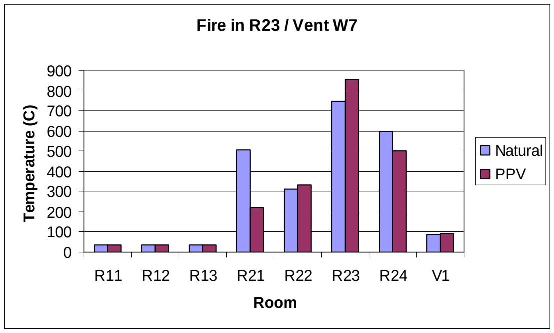
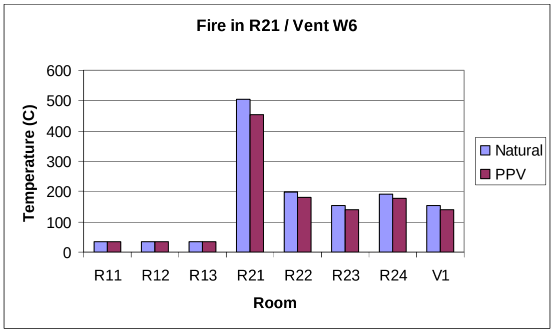


Figure A-40. Test 26, 27 Max Temperatures at 1.22 m



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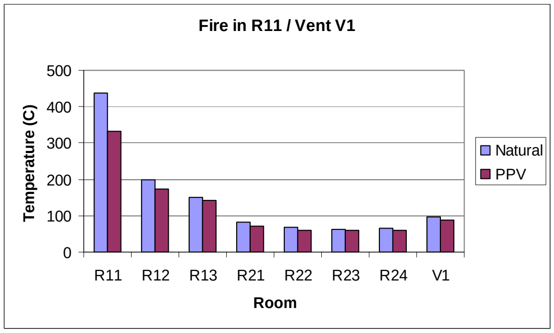


Figure A-42. Test 30, 31 Max Temperatures at 1.22 m

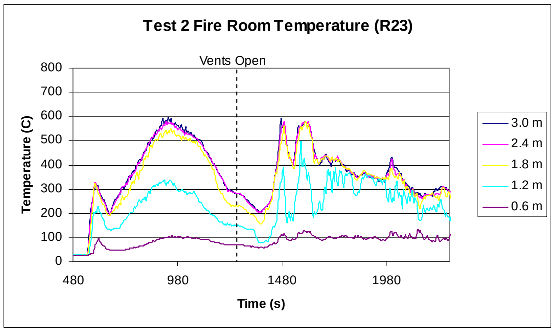
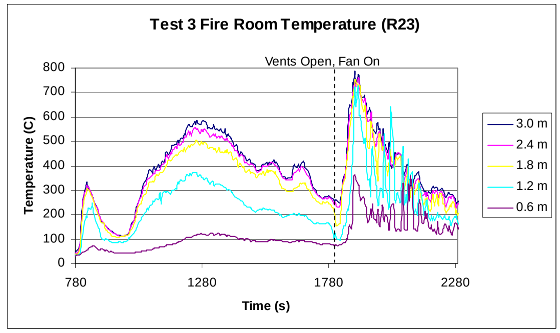


Figure A-43. Test 2 Temperature



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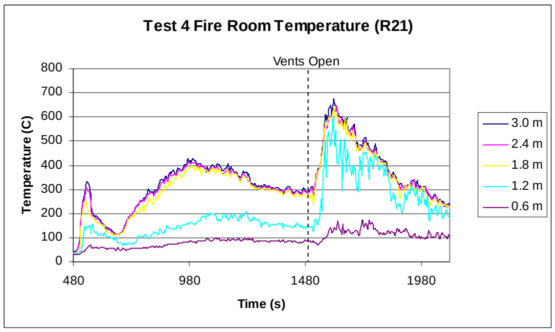

Figure A-45. Test 4 Temperature

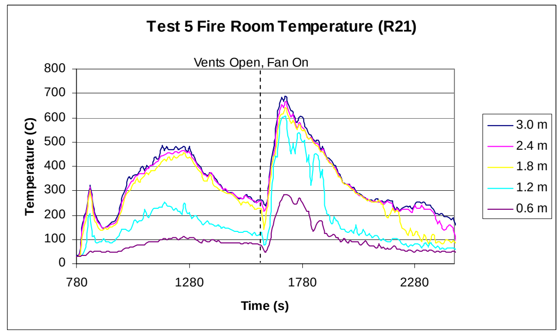

Figure A-46 - Test 5 Temperature

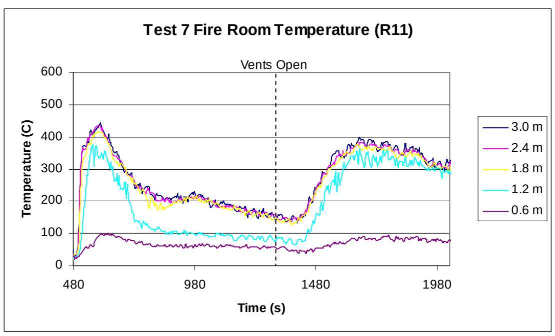

Figure A-47. Test 7 Temperature

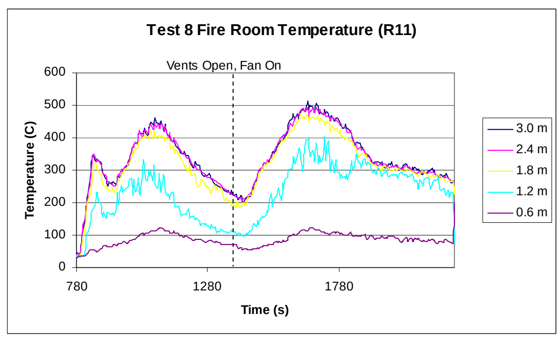

Figure A-48. Test 8 Temperature

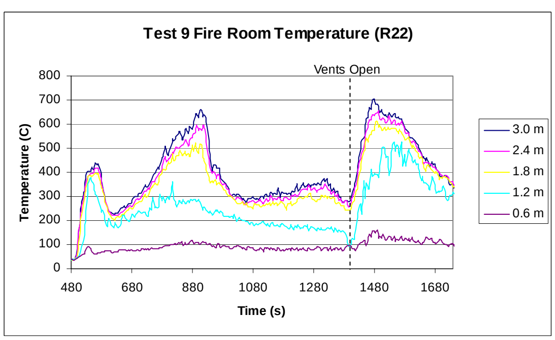

Figure A-49. Test 9 Temperature

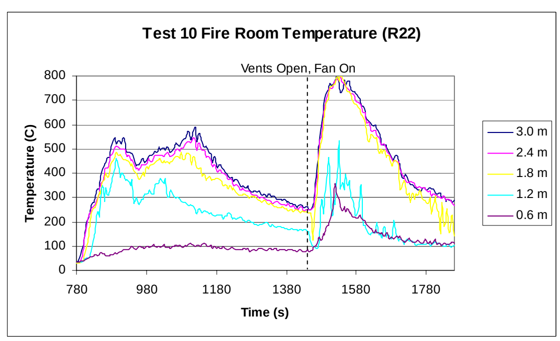

Figure A-50. Test 10 Temperature

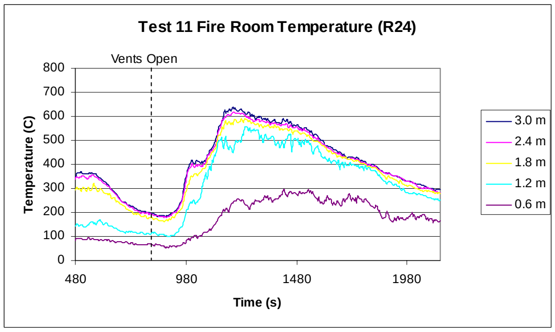

Figure A-51. Test 11 Temperature

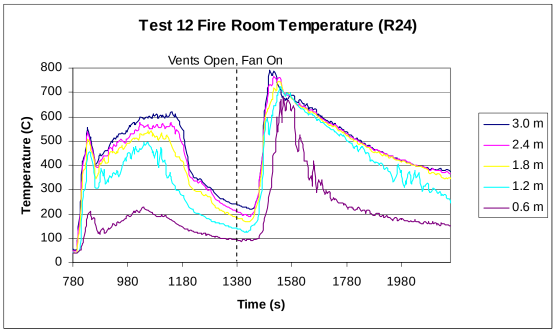

Figure A-52. Test 12 Temperature

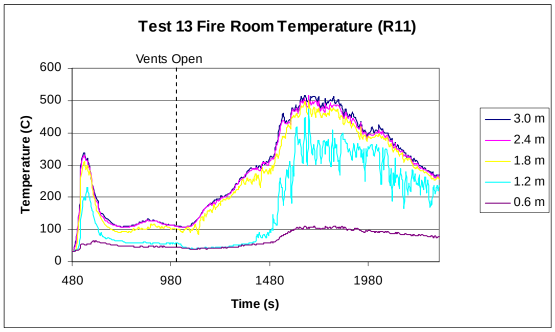

Figure A-53. Test 13 Temperature

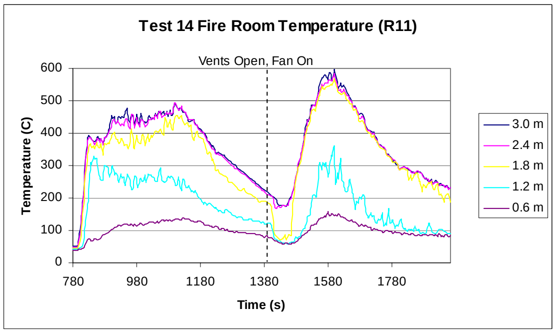

Figure A-54. Test 14 Temperature

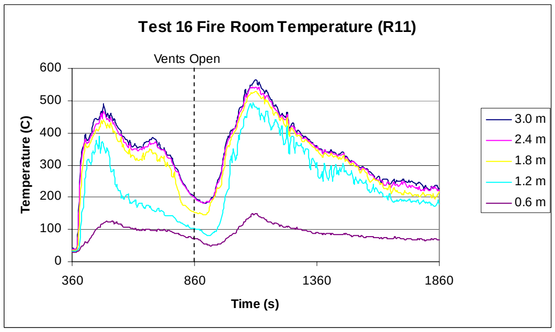

Figure A-55. Test 16 Temperature

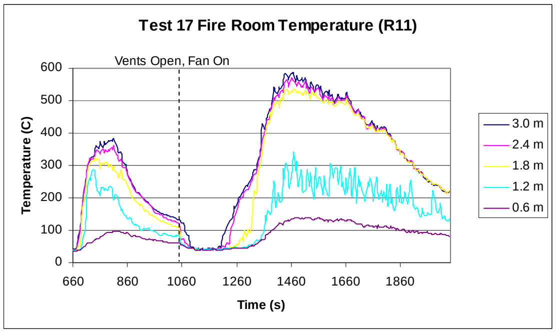

Figure A-56. Test 17 Temperature

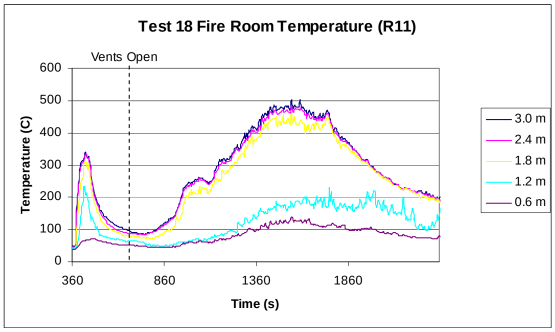

Figure A-57. Test 18 Temperature

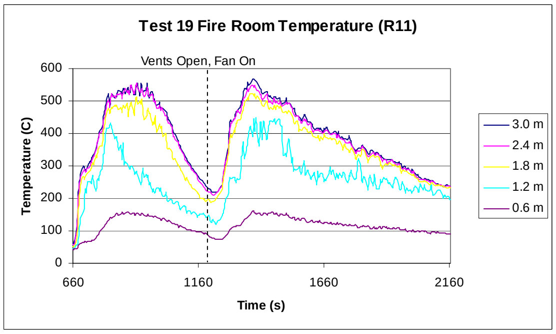

Figure A-58. Test 19 Temperature

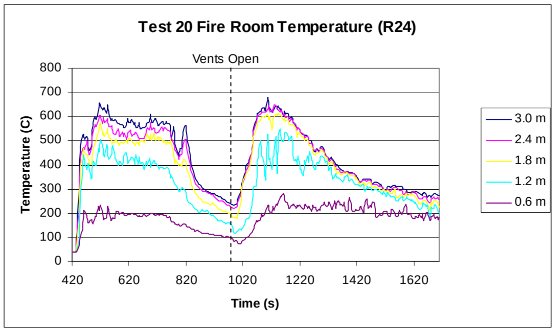

Figure A-59. Test 20 Temperature

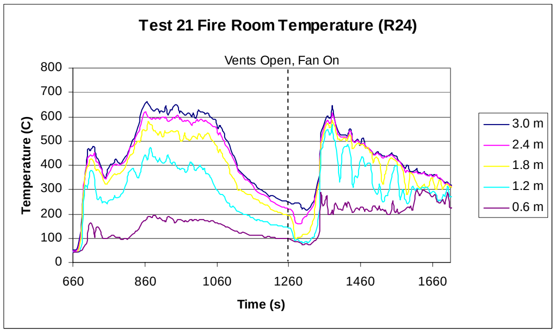

Figure A-60. Test 21 Temperature

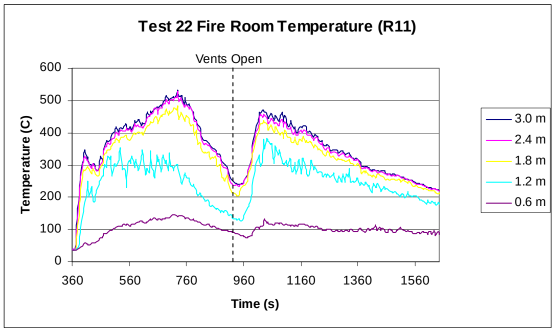

Figure A-61. Test 22 Temperature

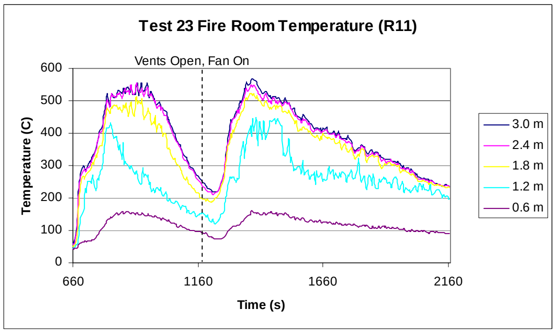

Figure A-62. Test 23 Temperature

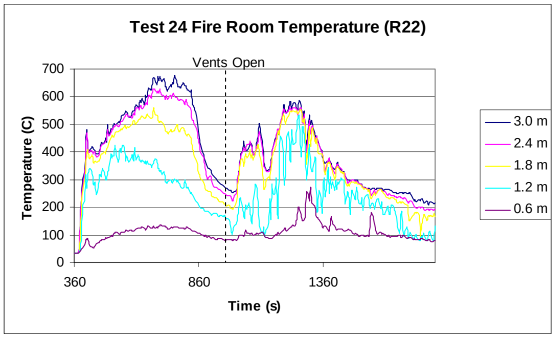

Figure A-63. Test 24 Temperature

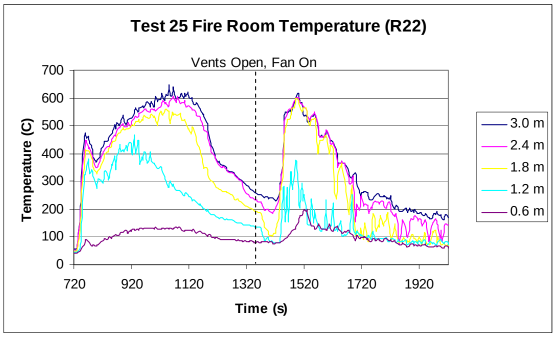

Figure A-64. Test 25 Temperature

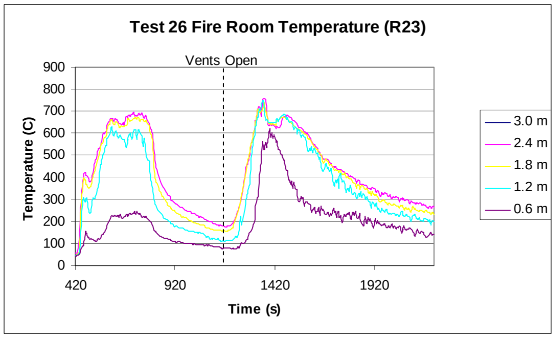

Figure A-65. Test 26 Temperature

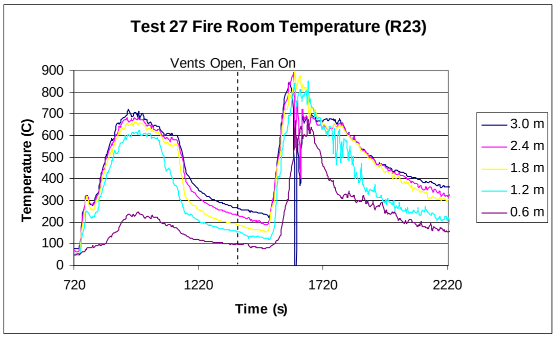

Figure A-66. Test 27 Temperature

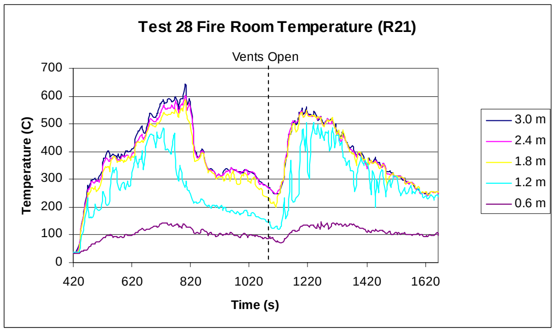

Figure A-67. Test 28 Temperature

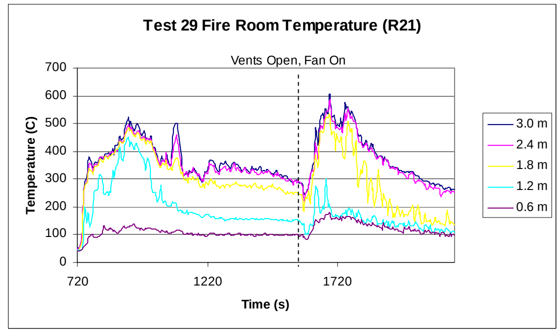

Figure A-68. Test 29 Temperature

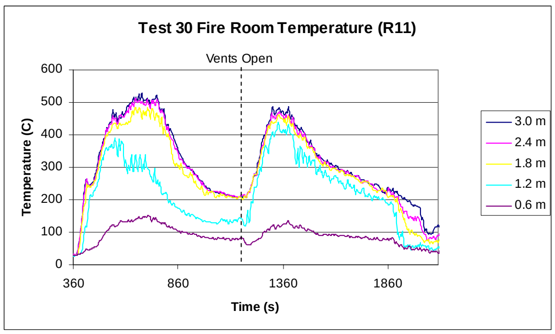

Figure A-69. Test 30 Temperature

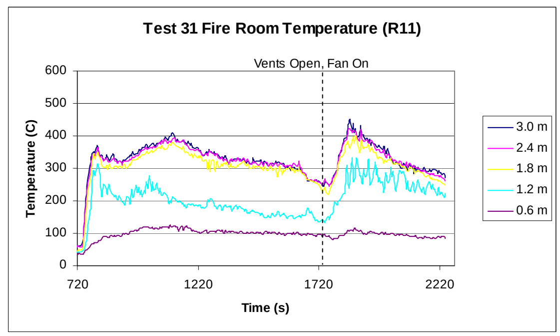

Figure A-70. Test 31 Temperature

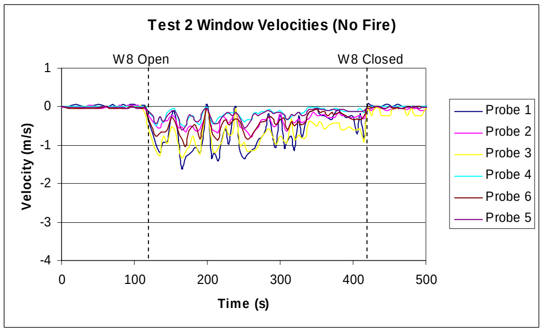

Figure A-71. Test 2 Pretest Window Velocities

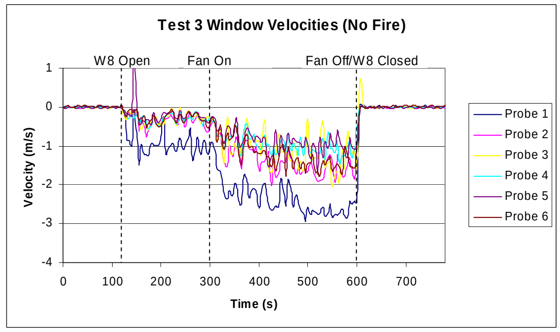

Figure A-72. Test 3 Pretest Window Velocities

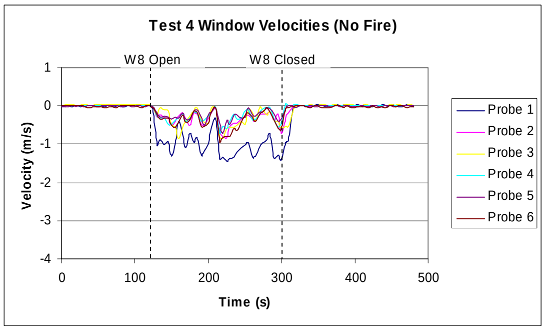

Figure A-73. Test 4 Pretest Window Velocities

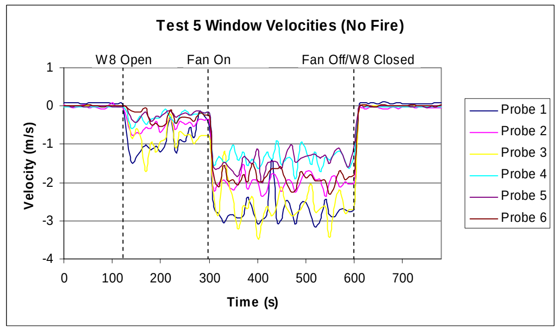

Figure A-74. Test 5 Pretest Window Velocities

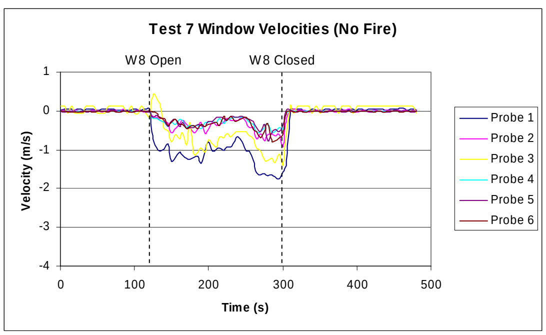

Figure A-75. Test 7 Pretest Window Velocities

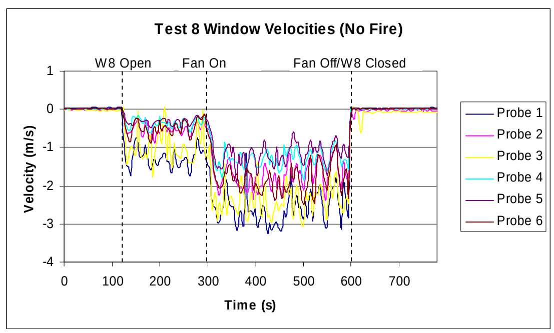

Figure A-76. Test 8 Pretest Window Velocities

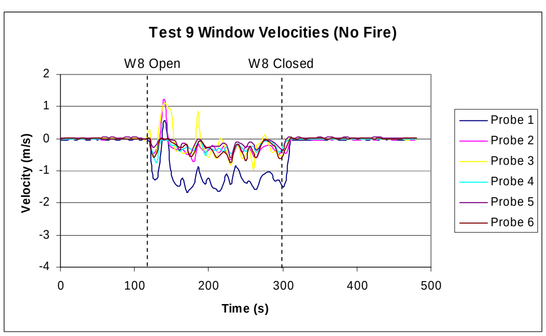

Figure A-77. Test 9 Pretest Window Velocities

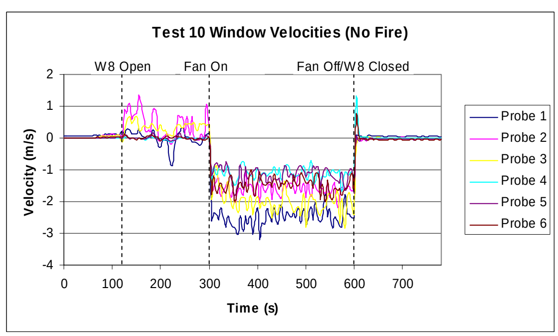

Figure A-78. Test 10 Pretest Window Velocities

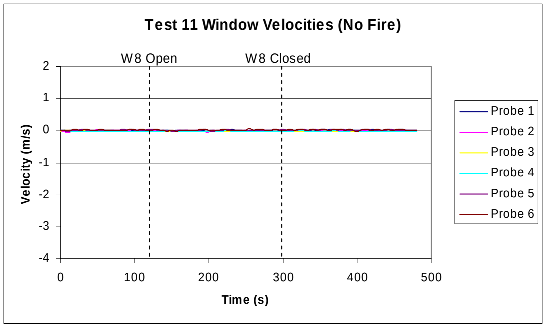

Figure A-79. Test 11 Pretest Window Velocities

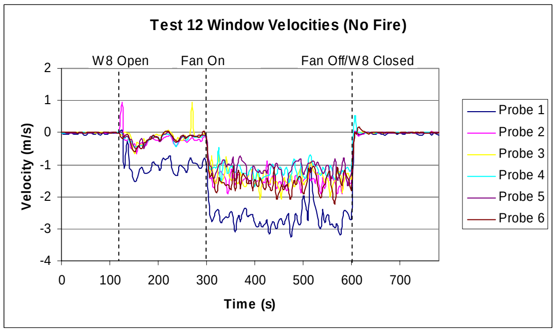

Figure A-80. Test 12 Pretest Window Velocities

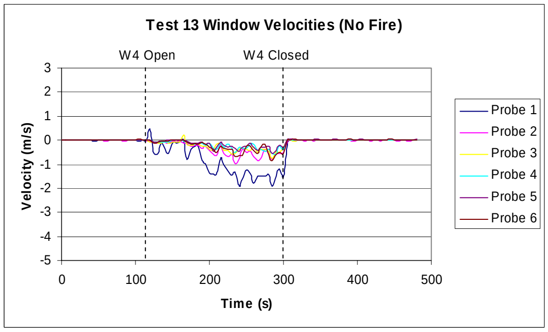

Figure A-81. Test 13 Pretest Window Velocities

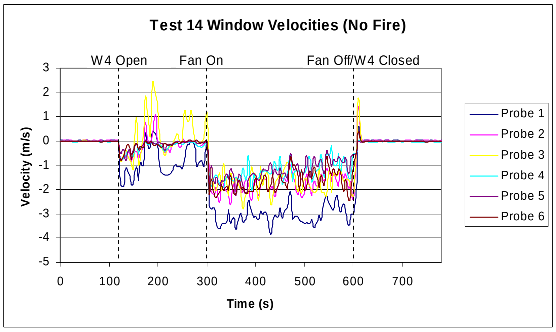

Figure A-82. Test 14 Pretest Window Velocities

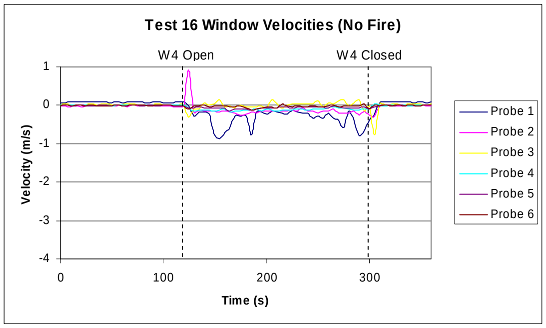

Figure A-83. Test 16 Pretest Window Velocities

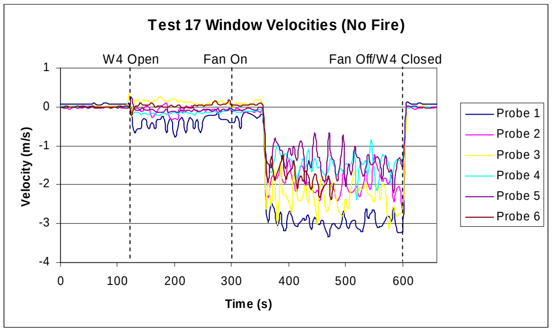

Figure A-84. Test 17 Pretest Window Velocities

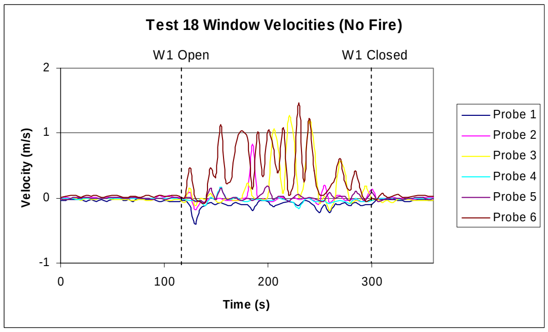

Figure A-85. Test 18 Pretest Window Velocities

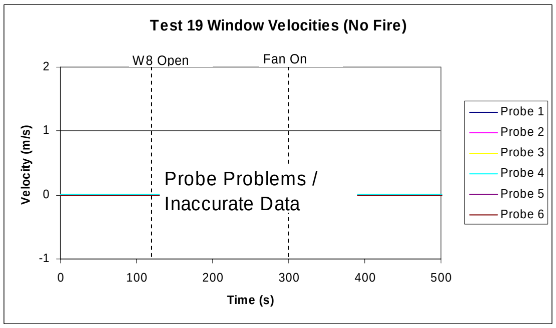

Figure A-86. Test 19 Pretest Window Velocities

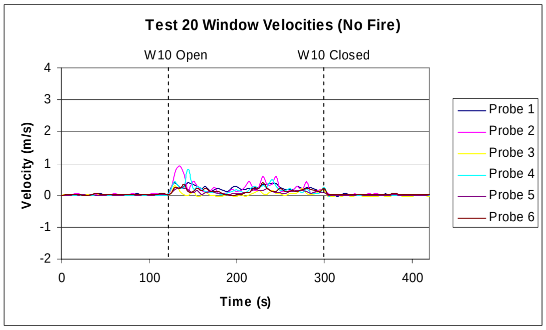

Figure A-87. Test 20 Pretest Window Velocities

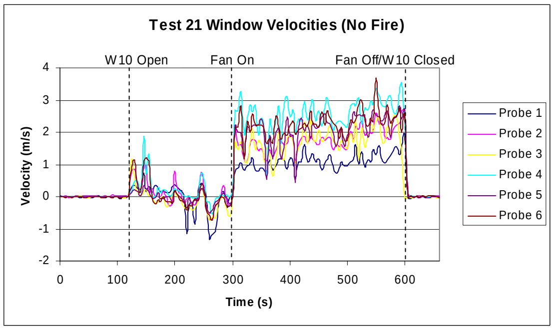

Figure A-88. Test 21 Pretest Window Velocities

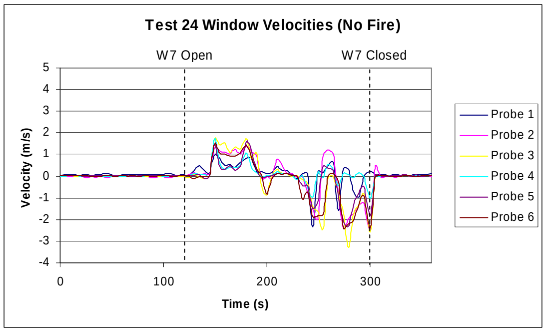

Figure A-89. Test 24 Pretest Window Velocities

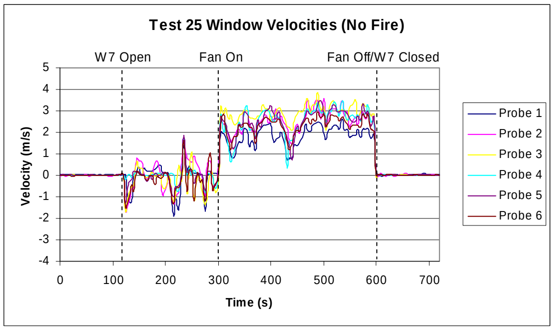

Figure A-90. Test 25 Pretest Window Velocities

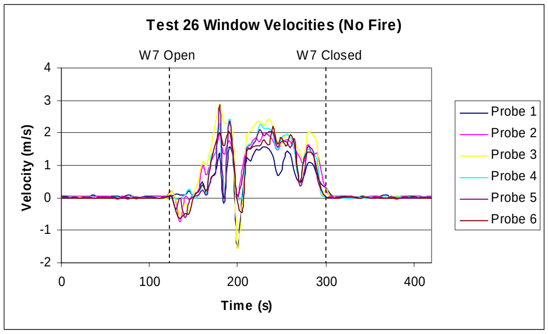

Figure A-91. Test 26 Pretest Window Velocities

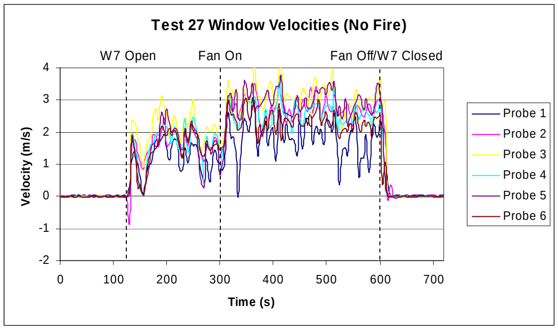

Figure A-92. Test 27 Pretest Window Velocities

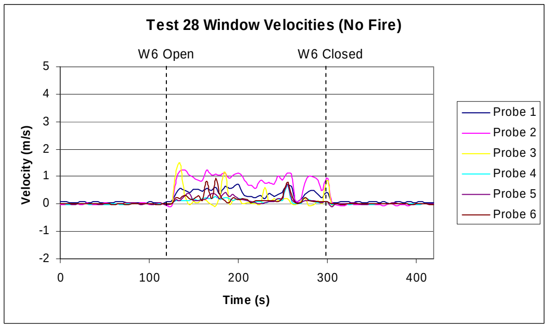

Figure A-93. Test 28 Pretest Window Velocities

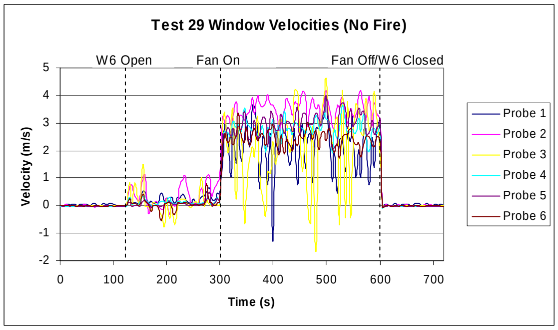

Figure A-94. Test 29 Pretest Window Velocities

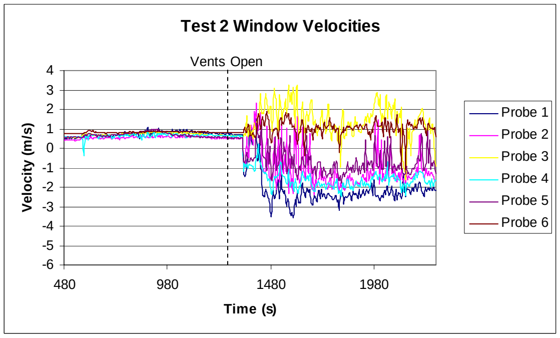

Figure A-95. Test 2 Window Velocities

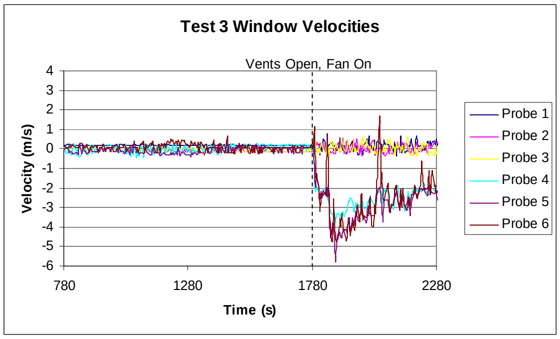

Figure A-96. Test 3 Window Velocities

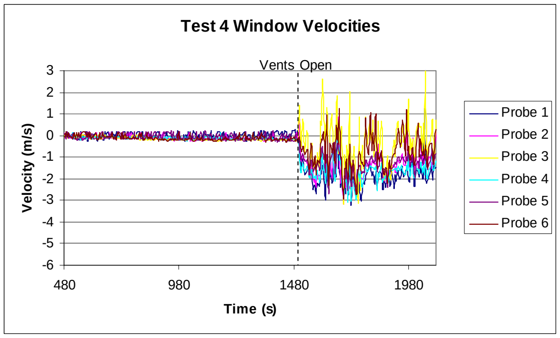

Figure A-97. Test 4 Window Velocities

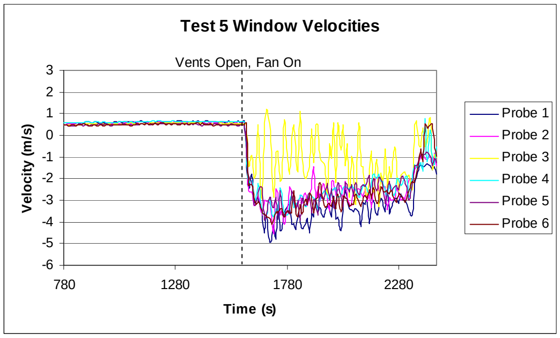

Figure A-98. Test 5 Window Velocities

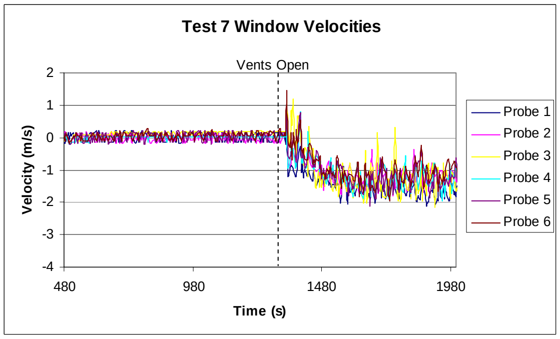

Figure A-99. Test 7 Window Velocities

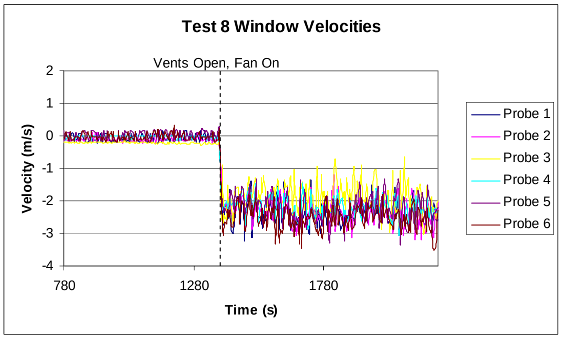

Figure A-100. Test 8 Window Velocities

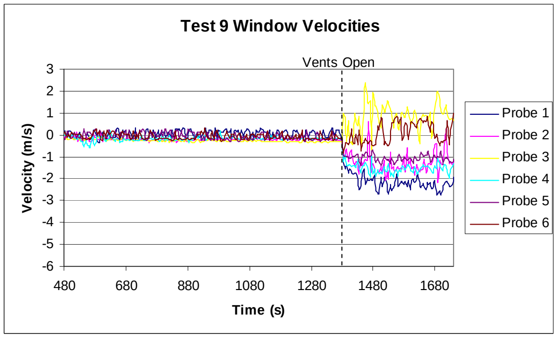

Figure A-101. Test 9 Window Velocities

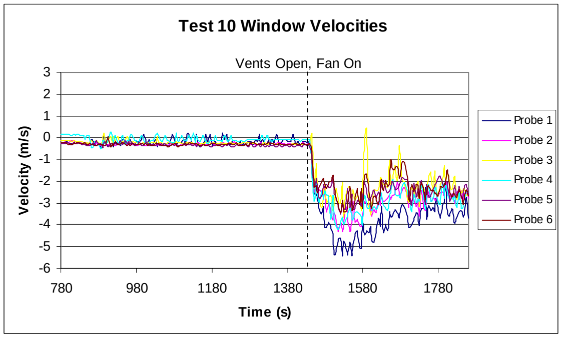

Figure A-102. Test 10 Window Velocities

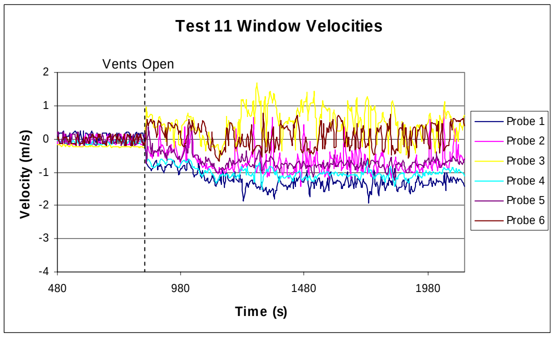

Figure A-103. Test 11 Window Velocities

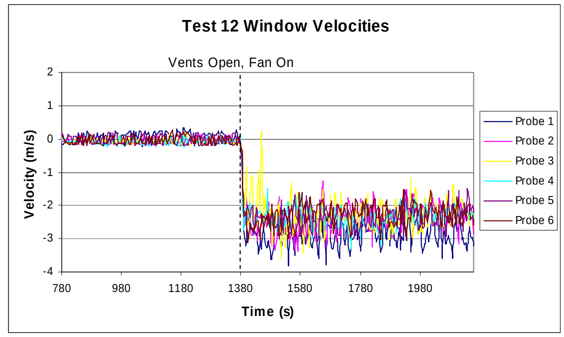

Figure A-104. Test 12 Window Velocities

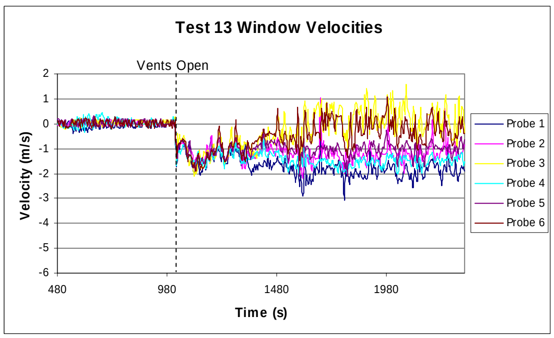

Figure A-105. Test 13 Window Velocities

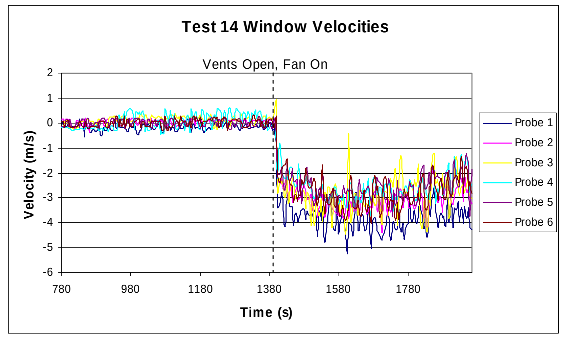

Figure A-106. Test 14 Window Velocities

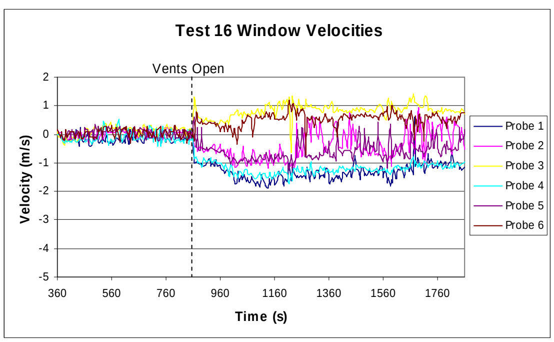

Figure A-107. Test 16 Window Velocities

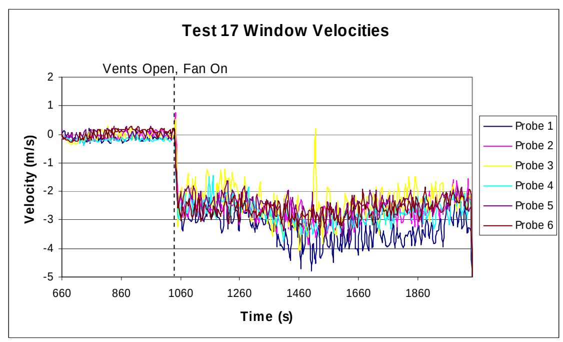

Figure A-108. Test 17 Window Velocities

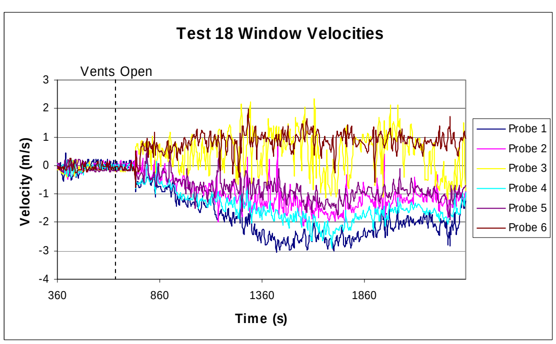

Figure A-109. Test 18 Window Velocities

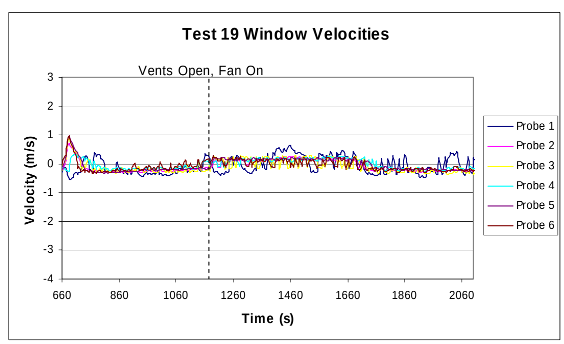

Figure A-110. Test 19 Window Velocities

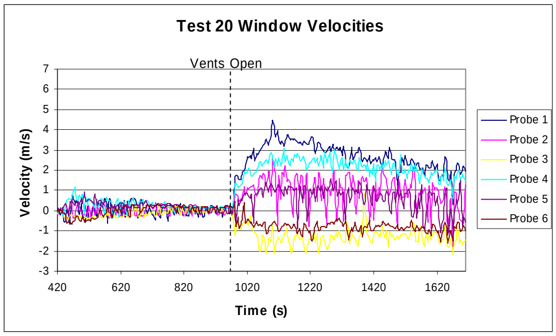

Figure A-111. Test 20 Window Velocities

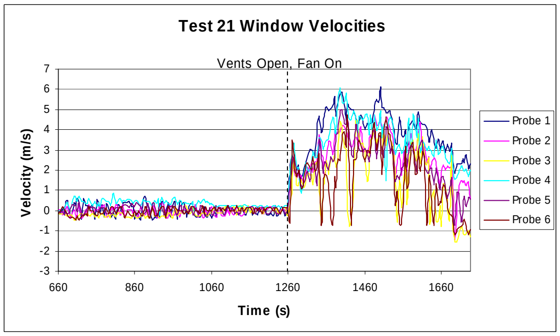

Figure A-112. Test 21 Window Velocities

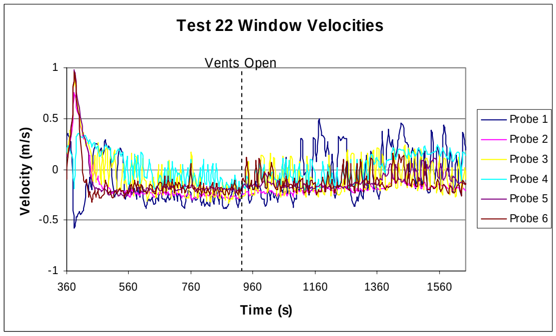

Figure A-113. Test 22 Window Velocities

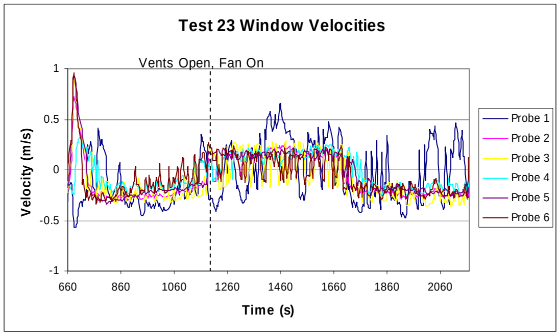

Figure A-114. Test 23 Window Velocities

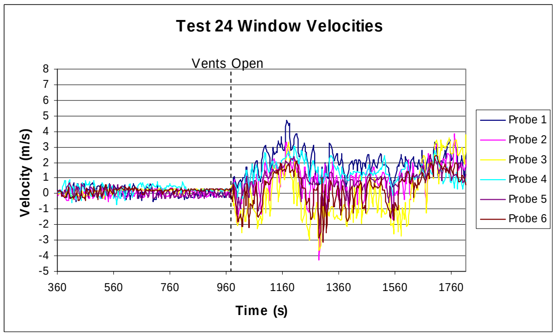

Figure A-115. Test 24 Window Velocities

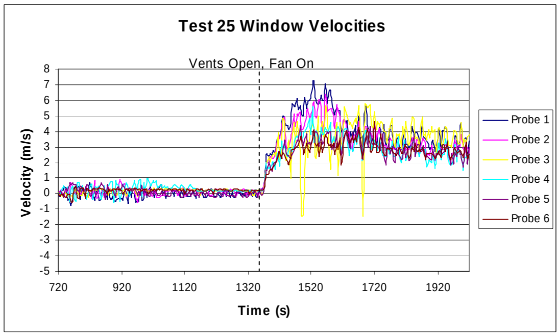

Figure A-116. Test 25 Window Velocities

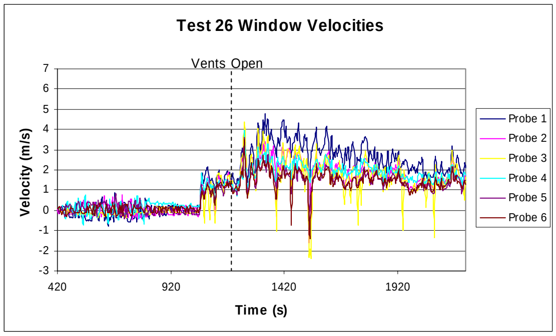

Figure A-117. Test 26 Window Velocities

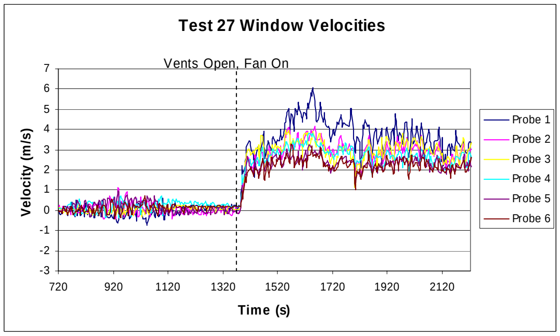

Figure A-118. Test 27 Window Velocities

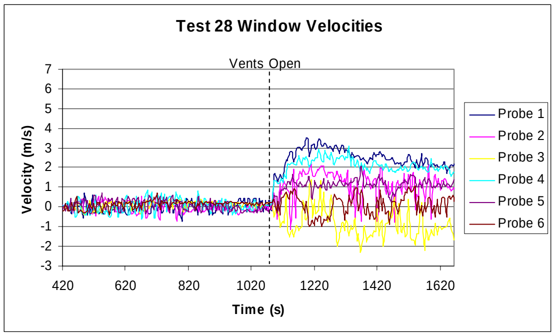

Figure A-119. Test 28 Window Velocities

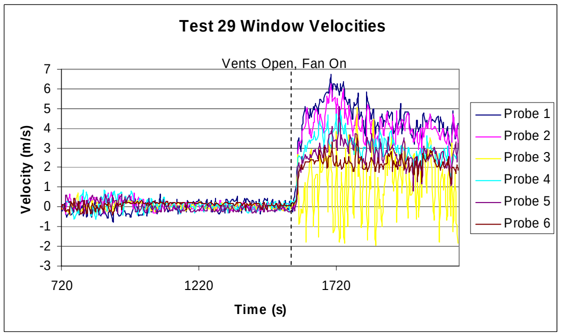

Figure A-120. Test 29 Window Velocities

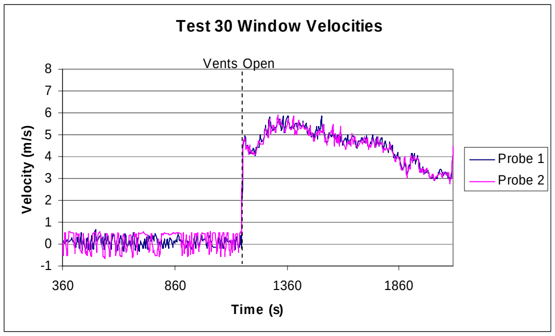

Figure A-121. Test 30 Window Velocities

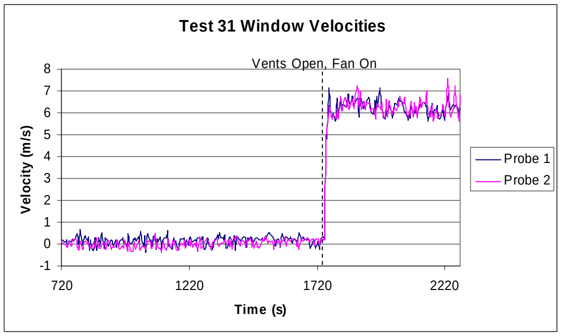

Figure A-122. Test 31 Window Velocities

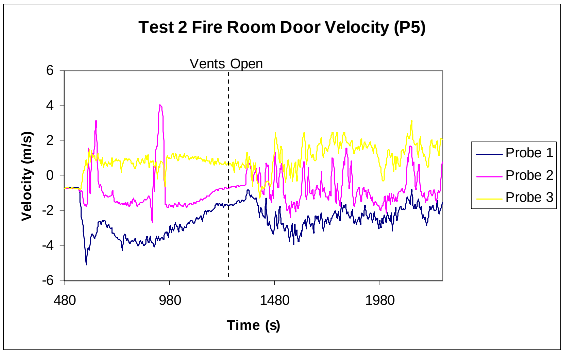

Figure A-123. Test 2 Door Velocity (P5)

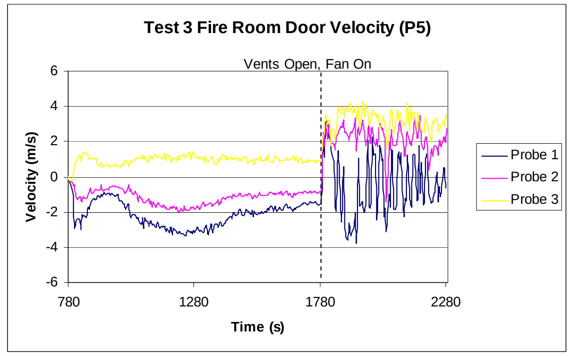

Figure A-124. Test 3 Door Velocity (P5)

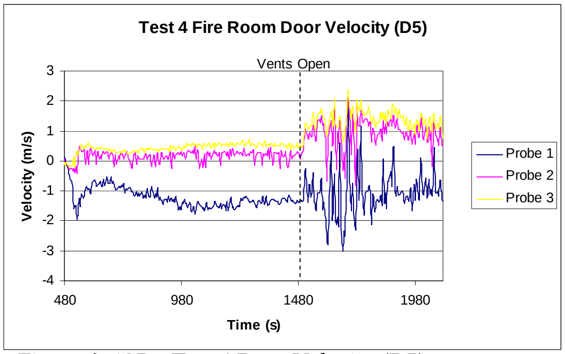

Figure A-125. Test 4 Door Velocity (D5)

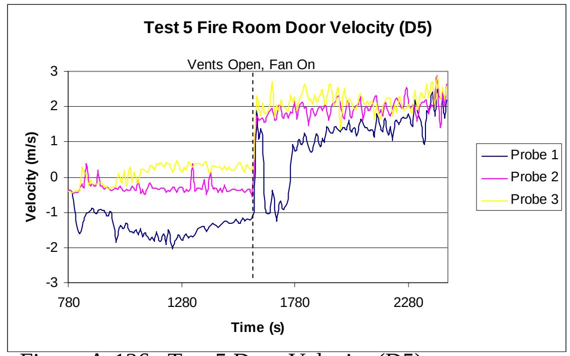

Figure A-126. Test 5 Door Velocity (D5)

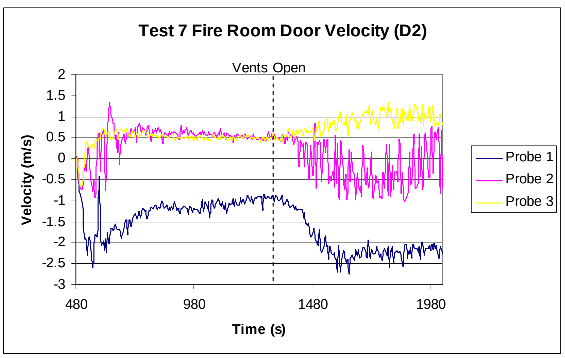

Figure A-127. Test 7 Door Velocity (D2)

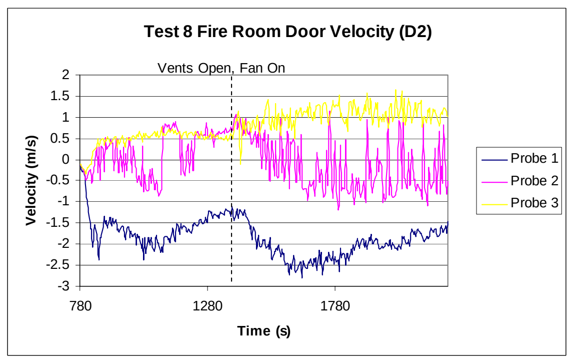

Figure A-128. Test 8 Door Velocity (D2)

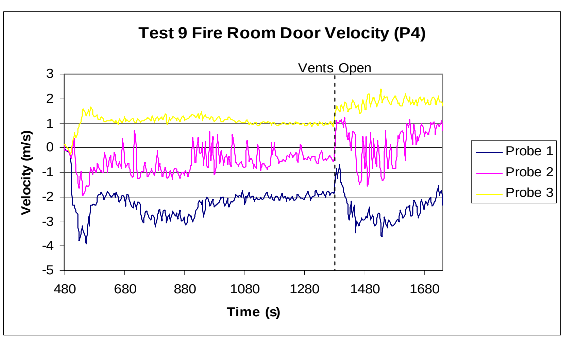

Figure A-129. Test 9 Door Velocity (P4)

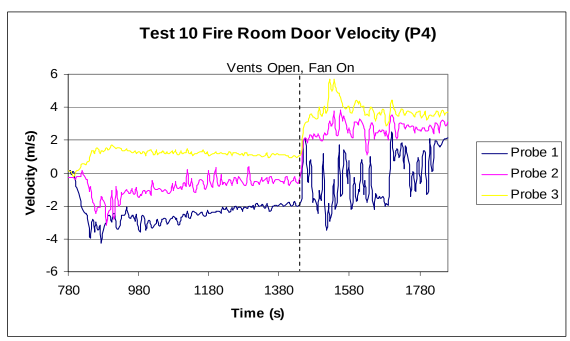

Figure A-130. Test 10 Door Velocity (P4)

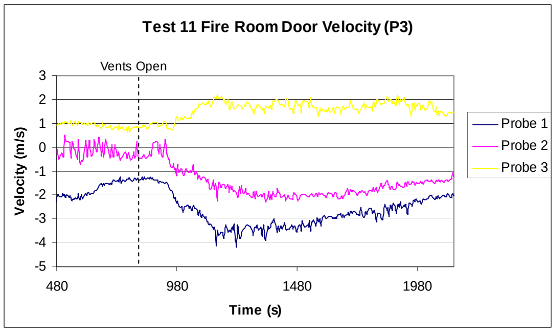

Figure A-131. Test 11 Door Velocity (P3)

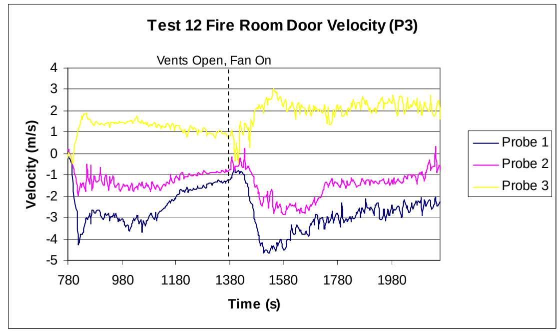

Figure A-132. Test 12 Door Velocity (P3)

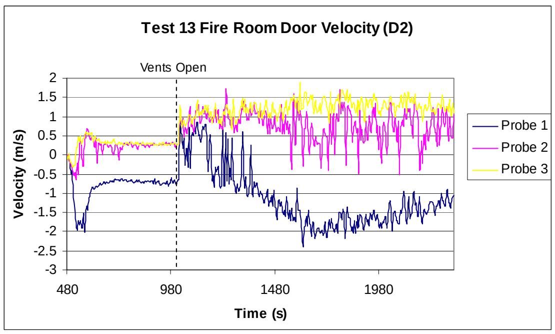

Figure A-133. Test 13 Door Velocity (D2)

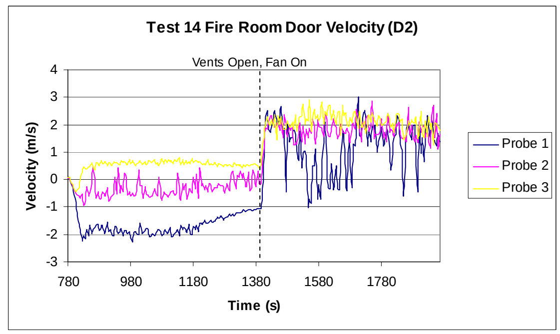

Figure A-134. Test 14 Door Velocity (D2)

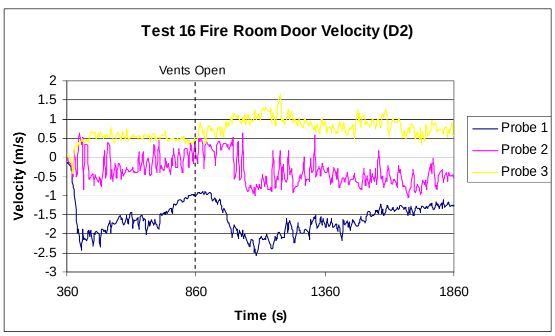

Figure A-135. Test 16 Door Velocity (D2)

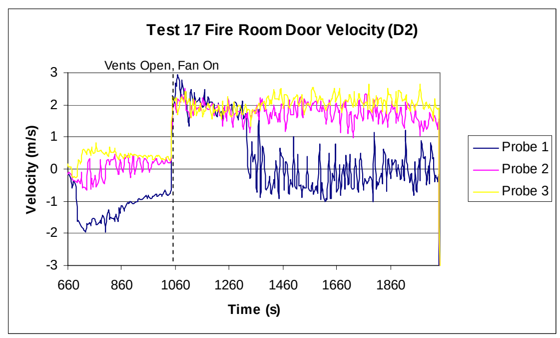

Figure A-136. Test 17 Door Velocity (D2)

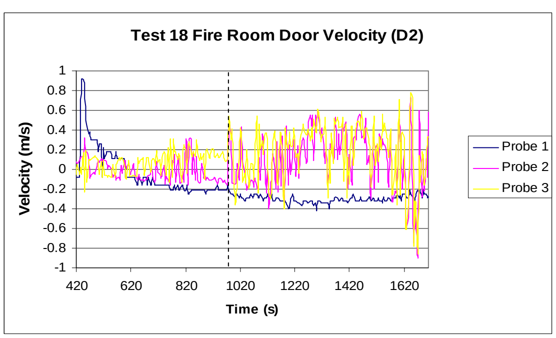

Figure A-137. Test 18 Door Velocity (D2)

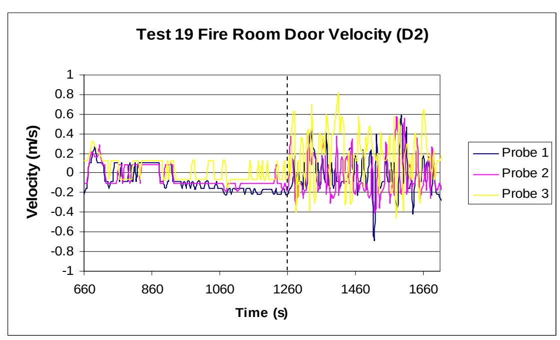

Figure A-138. Test 19 Door Velocity (D2)

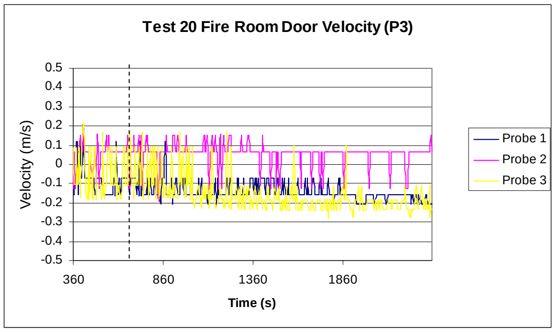

Figure A-139. Test 20 Door Velocity (P3)

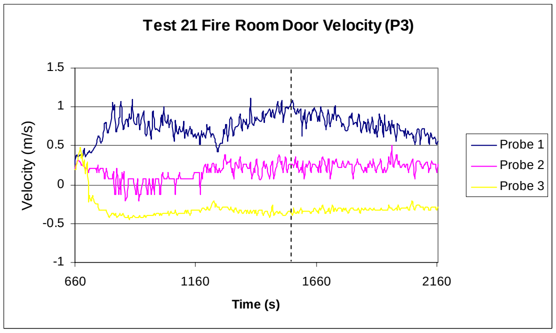

Figure A-140. Test 21 Door Velocity (P3)

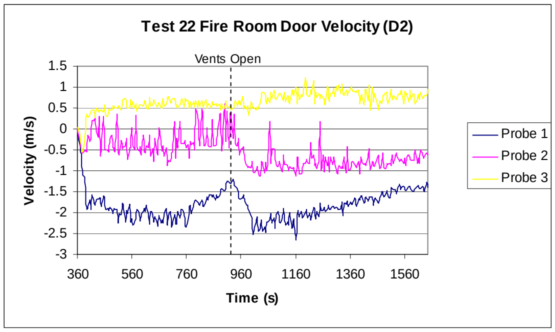

Figure A-141. Test 22 Door Velocity (D2)

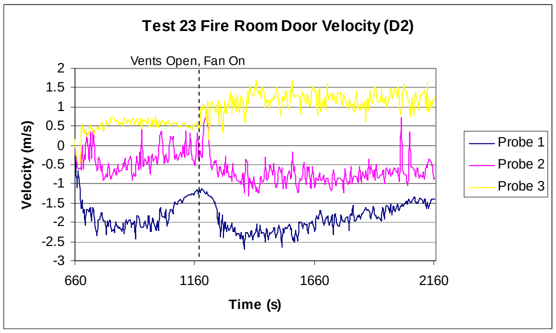

Figure A-142. Test 23 Door Velocity (D2)

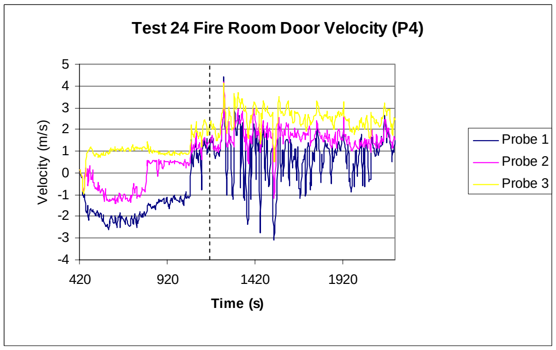

Figure A-143. Test 24 Door Velocity (P4)

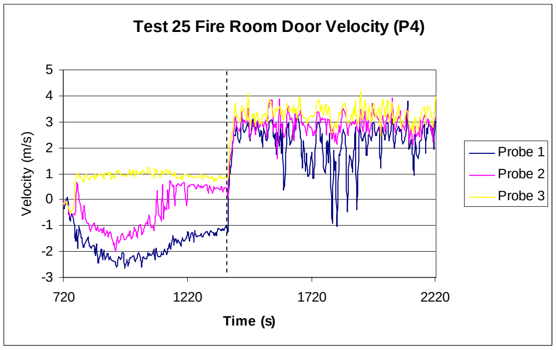

Figure A-144. Test 25 Door Velocity (P4)

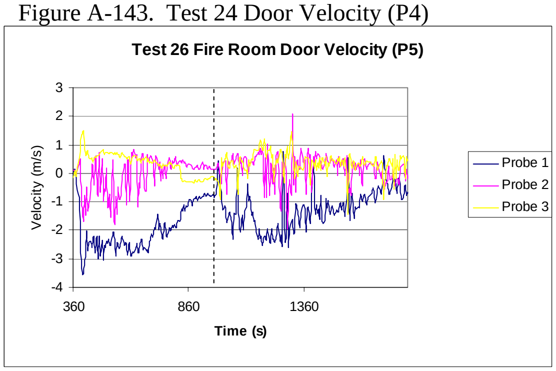

Figure A-145. Test 26 Door Velocity (P5)

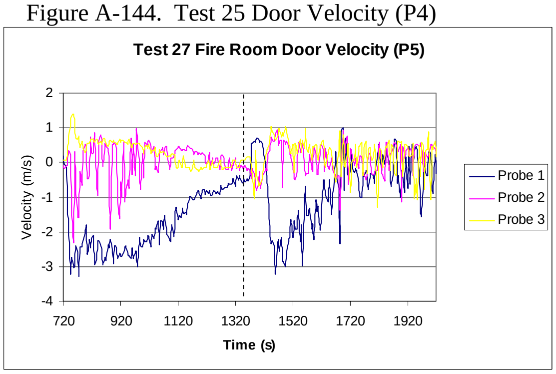

Figure A-146. Test 27 Door Velocity (P5)

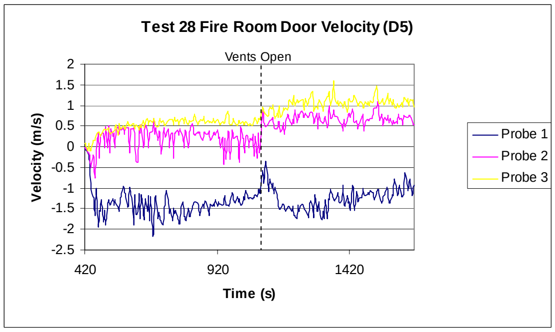

Figure A-147. Test 28 Door Velocity (D5)

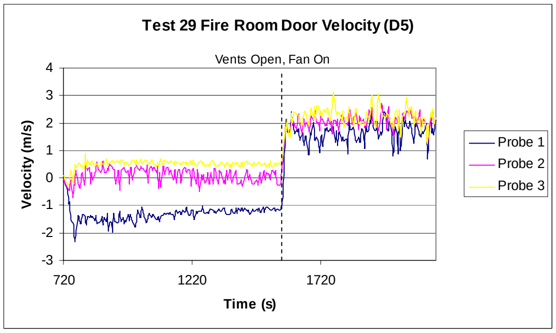

Figure A-148. Test 29 Door Velocity (D5)

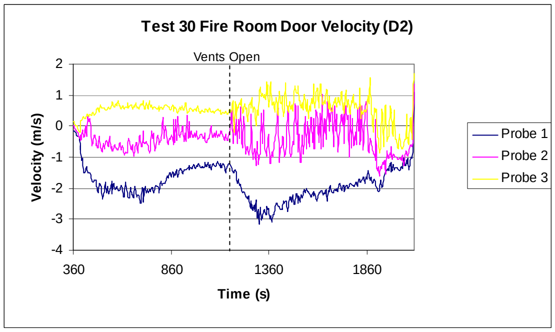

Figure A-149. Test 30 Door Velocity (D2)

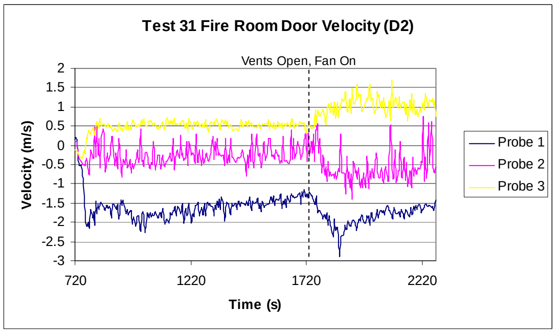

Figure A-150. Test 31 Door Velocity (D2)

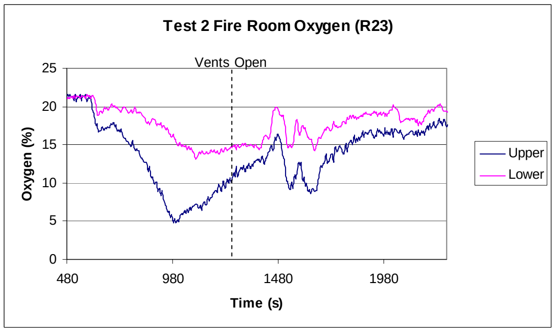

Figure A-151. Test 2 Fire Room Oxygen

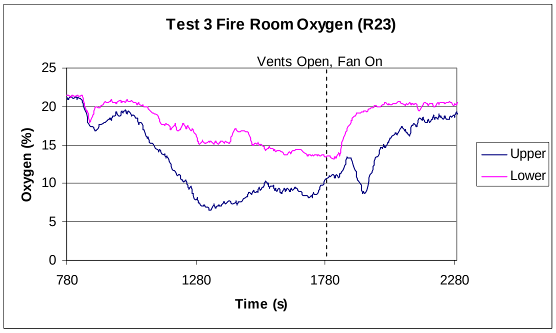

Figure A-152. Test 3 Fire Room Oxygen

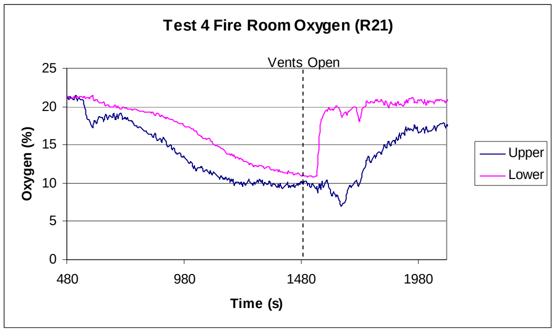

Figure A-153. Test 4 Fire Room Oxygen

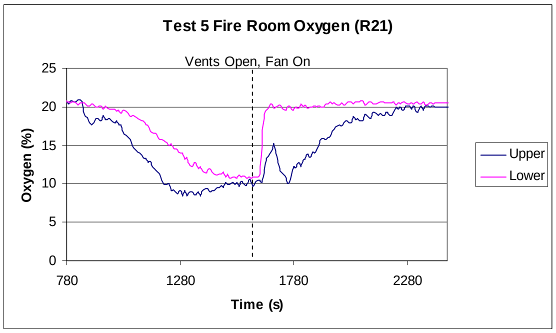

Figure A-154. Test 5 Fire Room Oxygen

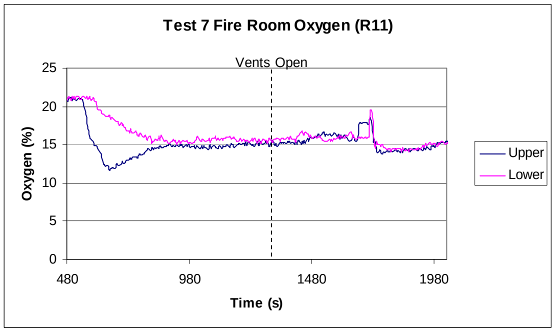

Figure A-155. Test 7 Fire Room Oxygen

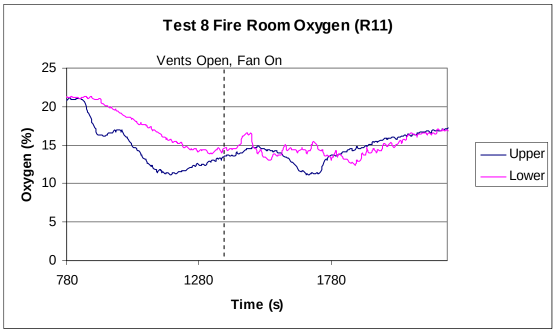

Figure A-156. Test 8 Fire Room Oxygen

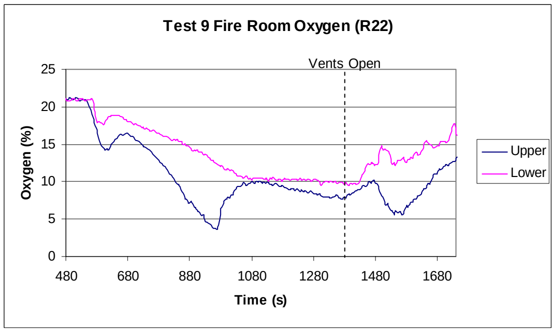

Figure A-157. Test 9 Fire Room Oxygen

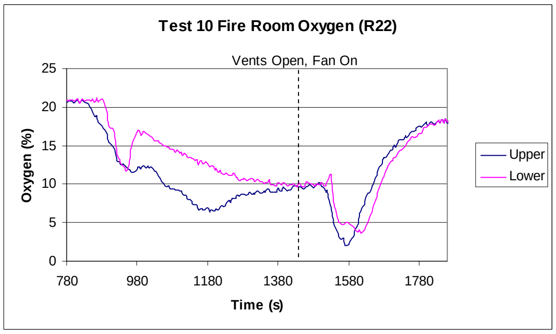

Figure A-158. Test 10 Fire Room Oxygen

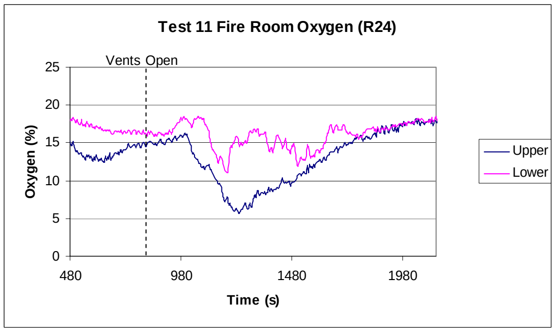

Figure A-159. Test 11 Fire Room Oxygen

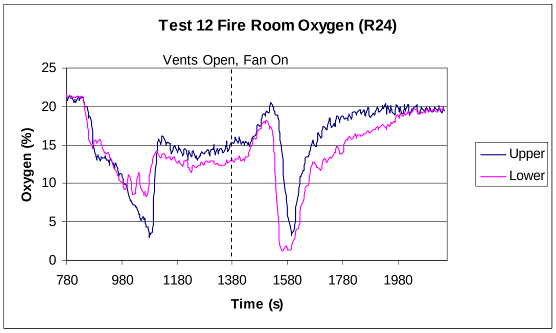

Figure A-160. Test 12 Fire Room Oxygen

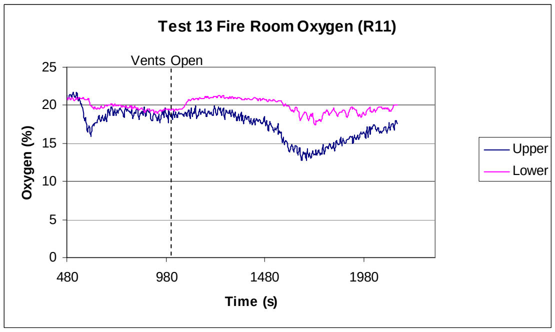

Figure A-161. Test 13 Fire Room Oxygen

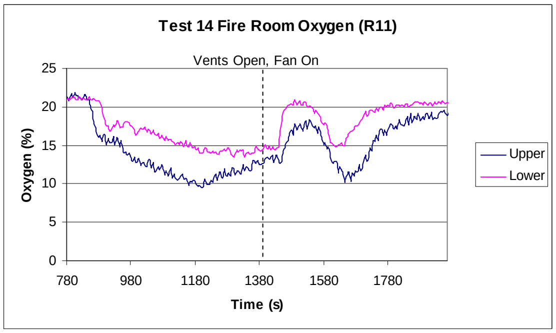

Figure A-162. Test 14 Fire Room Oxygen

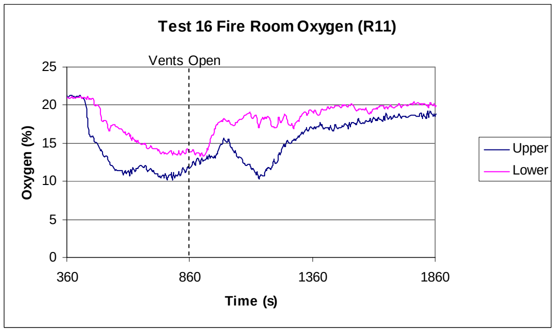

Figure A-163. Test 16 Fire Room Oxygen

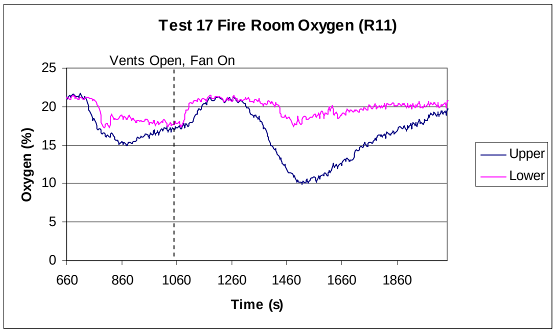

Figure A-164. Test 17 Fire Room Oxygen

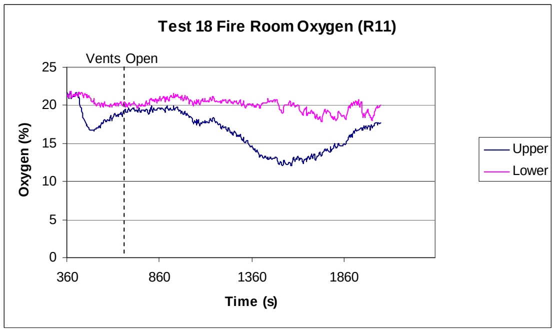

Figure A-165. Test 18 Fire Room Oxygen

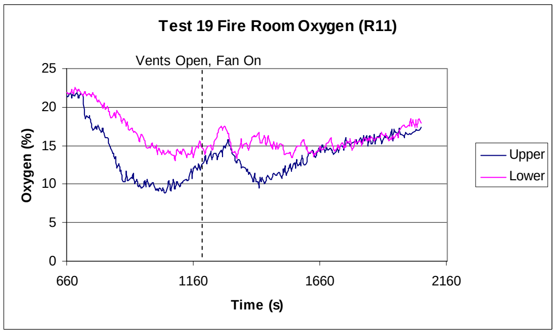

Figure A-166. Test 19 Fire Room Oxygen

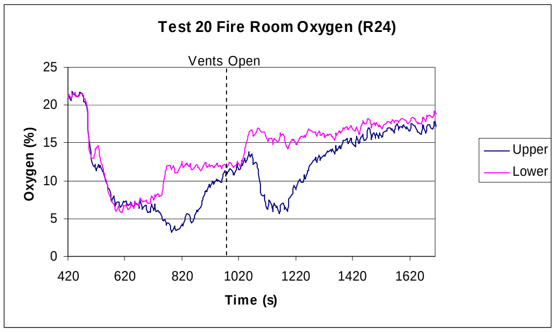

Figure A-167. Test 20 Fire Room Oxygen

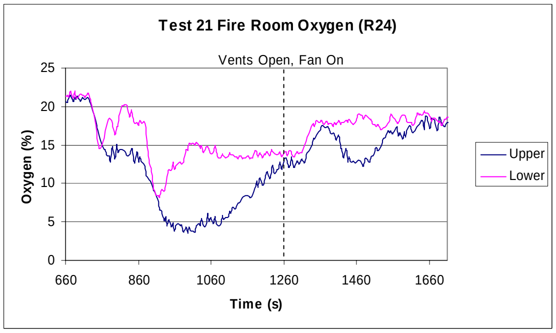

Figure A-168. Test 21 Fire Room Oxygen

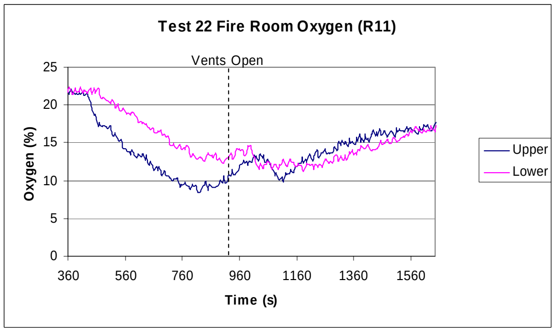

Figure A-169. Test 22 Fire Room Oxygen

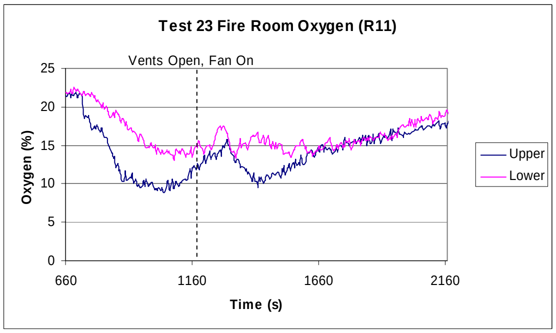

Figure A-170. Test 23 Fire Room Oxygen

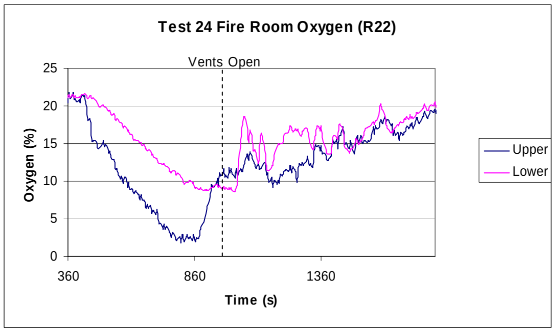

Figure A-171. Test 24 Fire Room Oxygen

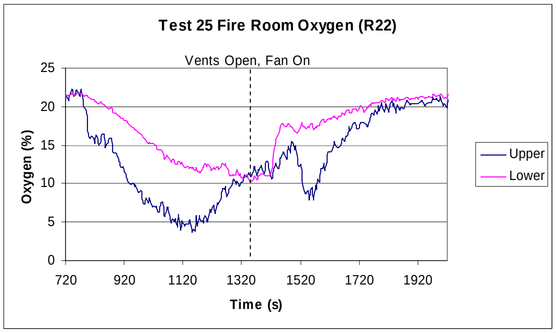

Figure A-172. Test 25 Fire Room Oxygen

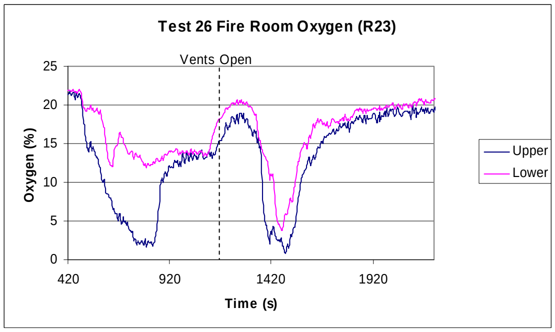

Figure A-173. Test 26 Fire Room Oxygen

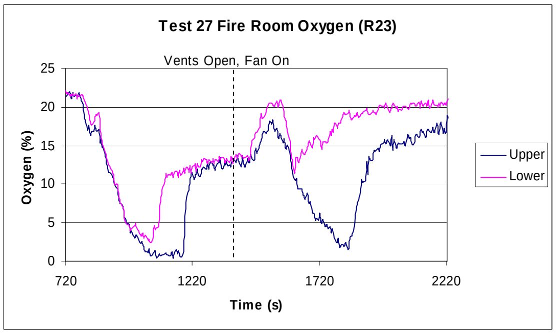

Figure A-174. Test 27 Fire Room Oxygen

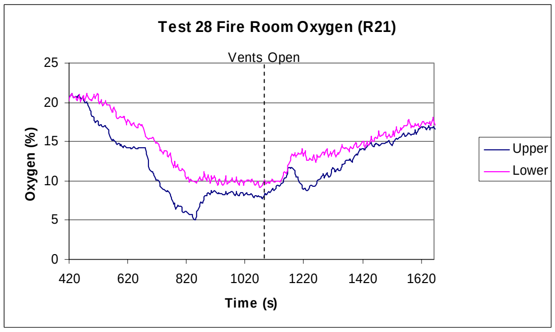

Figure A-175. Test 28 Fire Room Oxygen

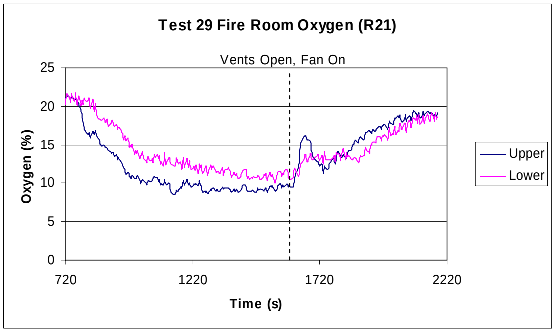

Figure A-176. Test 29 Fire Room Oxygen

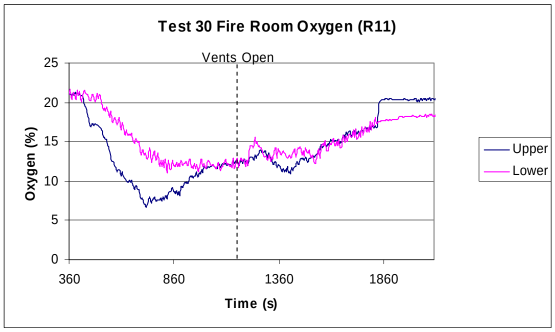

Figure A-177. Test 30 Fire Room Oxygen

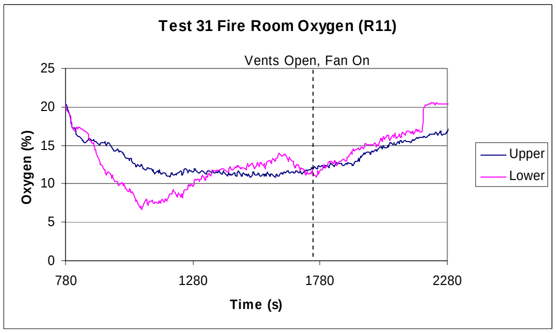

Figure A-178. Test 31 Fire Room Oxygen

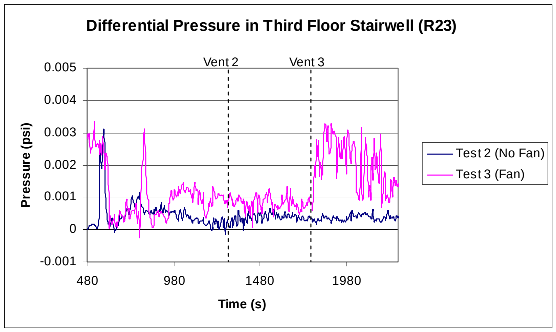

Figure A-179. Configuration 1 Differential Pressure

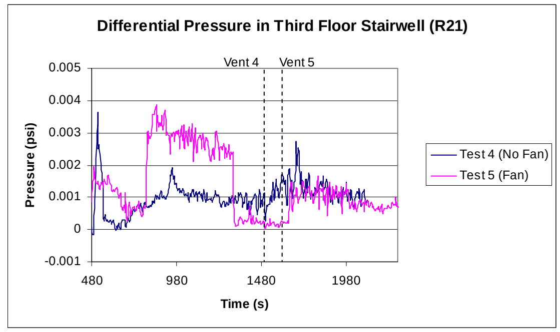

Figure A-180. Configuration 2 Differential Pressure

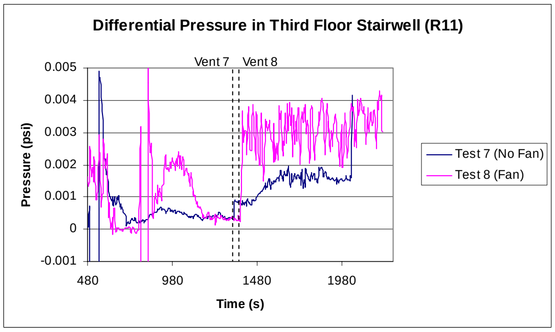

Figure A-181. Configuration 3 Differential Pressure

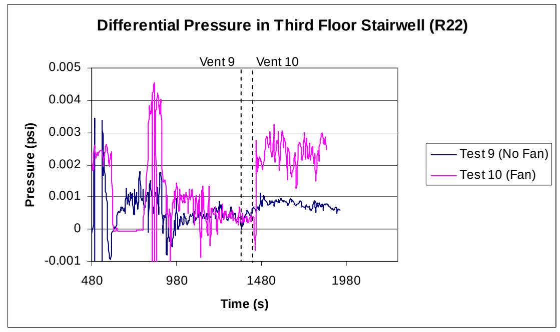

Figure A-182. Configuration 4 Differential Pressure

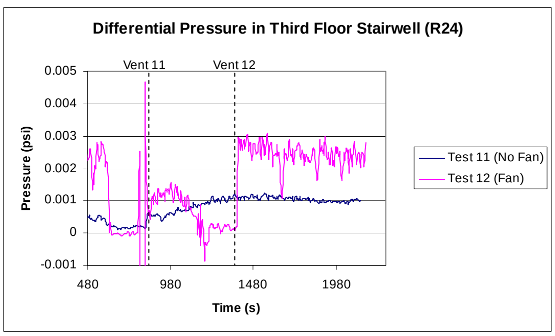

Figure A-183. Configuration 5 Differential Pressure

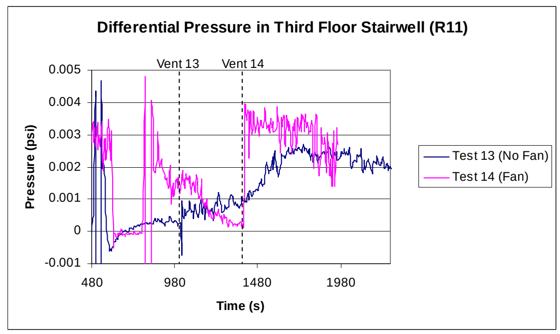

Figure A-184. Configuration 6 Differential Pressure

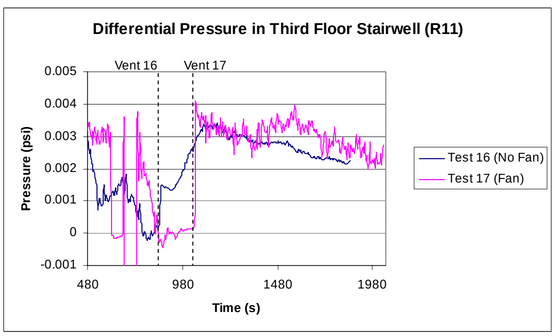

Figure A-185. Configuration 7 Differential Pressure

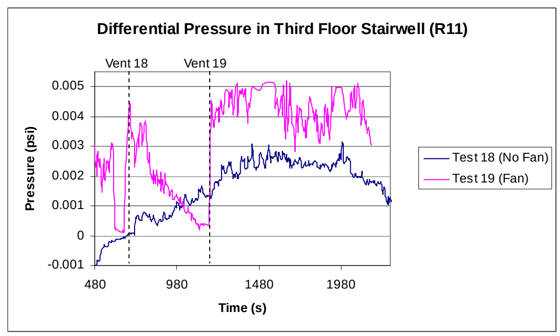

Figure A-186. Configuration 8 Differential Pressure

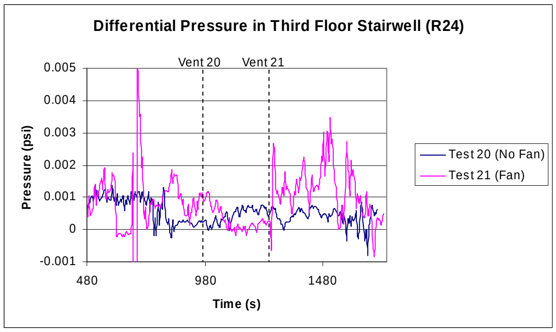

Figure A-187. Configuration 9 Differential Pressure

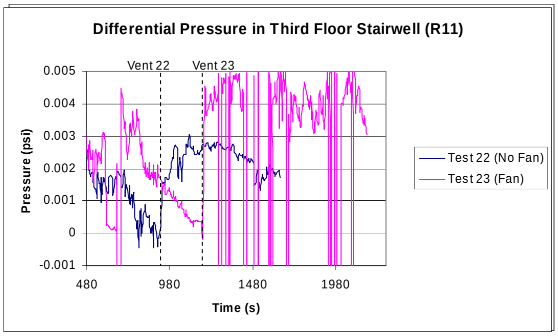

Figure A-188. Configuration 10 Differential Pressure

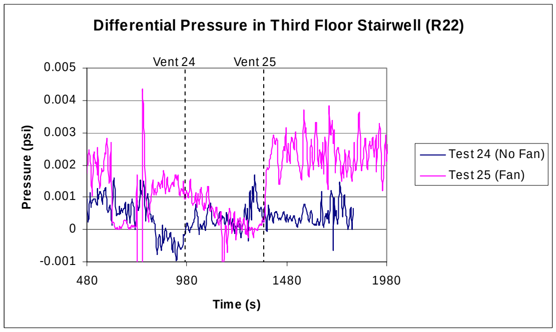

Figure A-189. Configuration 11 Differential Pressure

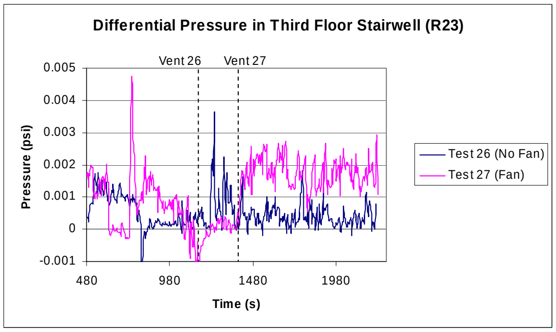

Figure A-190. Configuration 12 Differential Pressure

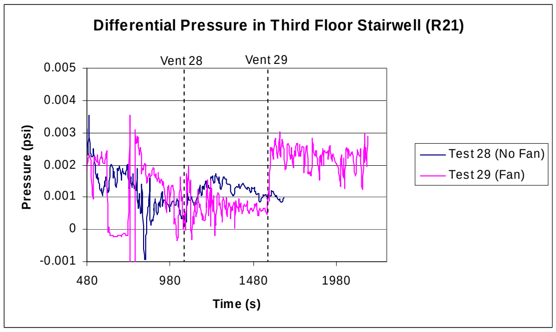

Figure A-191. Configuration 13 Differential Pressure

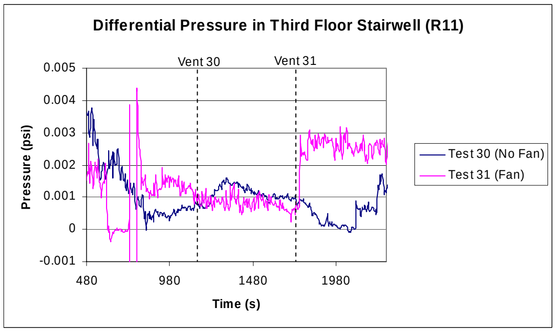

Figure A-192. Configuration 14 Differential Pressure