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Effect of Positive Pressure Ventilation on a Room Fire

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Abstract

Fire departments may use ventilation blowers or fans to pressurize a structure prior to suppressing a fire. This pressurization or positive pressure ventilation (PPV) tactic can assist in the venting of smoke and high temperature combustion products and make attacking the fire easier than without PPV. However, this tactic also provides additional oxygen to the fire and can increase the rate of heat and energy being released. PPV has not been characterized carefully enough to establish specific guidelines for optimum use. This study examined gas temperatures, gas velocities and total heat release rate in a series of fires in a furnished room. The use of the PPV fan created slightly lower gas temperatures in the fire room and significantly lower gas temperatures in the adjacent corridor. The gas velocities at the window plane were much higher in the PPV case than in the naturally ventilated scenario. This higher velocity improved visibility significantly. PPV caused an increase in heat release rate for 200 seconds following initiation of ventilation but the heat release rate then declined at a faster rate than that of the naturally ventilated experiment.

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Table of Contents

Abstract…. 1
Table of Contents 2
List of Tables 3
List of Figures 3
1.0 Introduction 5
2.0 Overview of Experimental Series 6
2.1 Instrumentation 7
2.2 Fuel Load 7
2.3 Experimental Procedure 8
3.0 Results 8
3.1 Heat Release Rate 9
3.2 Room Gas Temperature 10
3.3 Doorway Gas Temperature 10
3.4 Window Gas Temperature 11
3.5 Corridor Gas Temperature 11
3.6 Room Differential Pressure 11
3.7 Window Gas Velocity 12
3.8 Doorway Gas Velocity 12
3.9 Uncertainty 13
4.0 Discussion 14
5.0 Conclusion 15
6.0 Acknowledgements 16
7.0 References 16

List of Tables

Table 1 - Fire Load Weights 18
Table 2 - Experimental Procedure 18
Table 3 - Observations 19
Table 4 - Estimated Uncertainty in Experimental Data 20

List of Figures

Figure 1 - Two Common PPV Fans 21
Figure 2 - PPV Cone of Air [5] 21
Figure 3 – Experimental Floor Plan 22
Figure 4 – External view of window in closed position 23
Figure 5 – External view of open corridor doorway 24
Figure 6 - Furniture Floor Plan 25
Figure 7 - Instrumentation Floor Plan 26
Figure 8 - Doorway and Window Probe and Thermocouple Locations 27
Figure 9 – View of Doorway from inside the room into Corridor and Window, with Instrumentation 27
Figure 10 - Bidirectional Probe and Thermocouple Combination 28
Figure 11 - Water Cooled Camera 28
Figure 12 - Book Case 29
Figure 13 - Book Case Dimensions 29
Figure 14 - Desk and Monitor 30
Figure 15 - Desk Dimensions 30
Figure 16 - Monitor 31
Figure 17 - Monitor Dimensions 31
Figure 18 - Chair 32
Figure 19 - Chair Dimensions 32
Figure 20 – Bunk Bed 33
Figure 21 – Bunk Bed Dimensions 33
Figure 22 - Ignition Setup 34
Figure 23 - Electrically Activated Matchbook Locations 34
Figure 24 – Exterior View of Doorway to Corridor After the Start of Forced Ventilation (470 s) 35
Figure 25 – Exterior View of Window After the Start of Forced Ventilation (380 s) 35
Figure 26 – Doorway During Natural Ventilation Experiment (645 s) 36
Figure 27 - Window During Natural Ventilation Experiment (470 s) 36
Figure 28 - Heat Release Rate 37
Figure 29 - Heat Release Rate Detail for 200 s Following Peak Output 38
Figure 30 – Total Heat Released 39
Figure 31 - PPV Room Temperatures, Distances Measured From Ceiling. 40
Figure 32 - Natural Ventilation Room Temperatures 41
Figure 33 - PPV Doorway Temperatures 42

Figure 34 - Natural Ventilation Doorway Temperatures 43
Figure 35 - PPV Window Temperatures 44
Figure 36 - Natural Ventilation Window Temperatures 45
Figure 37 - PPV Corridor Temperatures 46
Figure 38 - Natural Ventilation Corridor Temperatures 47
Figure 39 - PPV Room Differential Pressure 48
Figure 40 - Natural Ventilation Room Differential Pressure 49
Figure 41 - PPV Window Velocities 50
Figure 42 - Natural Ventilation Window Velocities 51
Figure 43 - PPV Room Doorway Velocity 52
Figure 44 - Natural Ventilation Room Doorway Velocity 53

1.0 Introduction

In the past positive pressure ventilation (PPV) often has been used by fire departments to ventilate a structure after a fire has been extinguished. Typically this allows fire fighters to complete salvage and overhaul operations in a less hazardous atmosphere. PPV is also being implemented as a tactic during a fire attack. The fan is started in coordination with a ventilation opening during the initial phase of fire attack. This tactic is designed to increase visibility and force heat away from the attack team as they locate and extinguish the fire. PPV has been implemented with some success but also with some difficulty. Positive pressure ventilation has not been carefully characterized in terms of gas temperatures, gas velocities and mass burning rates. Without additional understanding of the impacts or effects caused by PPV, the difficulties associated with PPV have given rise to several issues. When should PPV be used, and just as important, when should it not be used? What is the best location for the fan and where should the exhaust or vent opening be made? Does PPV provide oxygen to the fire and allow for quicker fire growth? What is the consequence if fire fighters or building occupants are between the fire and the exhaust opening? Are there certain types of construction that PPV cannot be used on? These are just a few questions that the fire service has developed based on their experience with PPV.

As early as 1989, questions were posed in fire department training publications as to whether the positive pressure ventilation fans would intensify the fire by introducing additional oxygen. Carlson [1] responds to this question, stating that it is a possibility, but has no evidence or research to substantiate his answer. As part of their "Roundtable" discussion in 1999, Fire Engineering Magazine polled chiefs from around the country to determine if their departments used PPV and to what extent. Many of the polled departments used PPV, but some did not use it offensively with the explanation that the fire intensifying was a concern and this phenomena was not well understood [2]. This study provides experimental data to assist in quantifying the effects that the offensive use of PPV has on a well developed room fire.

In 2001, Mark Yates conducted an investigation and survey of the usage of PPV in the Tyne and Wear Metropolitan Fire Brigade in the United Kingdom, Salt Lake City Fire Department in the United States, and the Aachen Fire Department in Germany [3]. The survey suggested a few reasons for the lack of implementation of PPV. Two of these reasons were the potential for increased damage to structures and insufficient research data and evidence available to support PPV's benefits. This is further evidence that PPV lacks the firm scientific foundation necessary for optimum use for both salvage and overhaul as well as fire suppression operations.

This research used a pair of full-scale experiments to examine how positive pressure ventilation affects the fire environment of a furnished room fire. This work provides a better understanding of the effective use of ventilation and leads to the development of guidelines for the most effective use of positive pressure ventilation. This work is a continuation of previous experiments that examined the flow created by PPV fans and NIST's Fire Dynamic Simulator's ability to model the results [4].

PPV fans are commonly powered with electric or gasoline engines and range in diameter from 0.30 m to 0.91 m (12 in to 36 in) (figure 1). Typically, a positive pressure ventilation fan is placed about 1.8 m to 3.0 m (6 ft to 10 ft) outside the doorway of the structure. It is positioned so that the "cone of air" produced by the fan extends beyond the boundaries of the opening (figure 2). With the doorway within the fan discharge, air pressure inside the structure increases. An exhaust opening in the structure, such as an opening in the roof or an open window, allows the air to escape due to the difference between the inside and outside air pressure. The smoke, heat and other combustion products are pushed out of the structure and replaced with ambient air [5].

2.0 Overview of Experimental Series

A pair of full-scale experiments was performed at NIST's Building and Fire Research Laboratory Large Fire Facility. The facility has interior dimensions, 36.6 m (120.0 ft) long, 18.3 m (60.0 ft) wide and 7.6 m (25.0 ft) high. A room was constructed within the facility under a 6 m x 6 m (20 ft x 20 ft) hood which was instrumented to allow for oxygen depletion calorimetry to measure the heat release rate produced by the fire in the room. The room had interior dimensions of 3.66 m x 4.27 m (12 ft x 14 ft) and a ceiling height of 2.44 m (8 ft) (figure 3). A window was located in the center of the 4.27 m wall (figure 4) and a doorway was located on the center of the 3.66 m wall. The doorway opened to a 1.22 m wide x 2.29 m long (4 ft x 7.5 ft) corridor (figure 5). Another doorway was located at the end of the corridor that was the same size as the doorway to the room. Both doorways were 2.06 m (6.75 ft) tall and 0.91 m (3 ft) wide. The window was 1.2 m (3.9 ft) tall and 0.89 m (2.9 ft) wide and 0.81 m (2.7 ft) above the floor to the sill (figure 3). A 6.1 m (20 ft) wall was constructed between the corridor doorway and room window to the exterior of the room in order to isolate the effects of the fan and not allow recirculation of smoke from the window back through the doorway. All of the walls and the ceiling were framed with 0.038 m x 0.089 m (1.5 in x 3.5 in) pine studs and sheathed with two layers of 0.01 m (0.375 in) gypsum board. The room was furnished with a bunk bed, stuffed chair, book case and desk (figure 6). The floor was covered with carpet and a computer monitor was placed on the desk.

Two experiments were conducted with nearly identical fuel loads, examining the effect of the PPV fan on the room fire. The first experiment utilized a fan to forcibly ventilate the room just after the window was opened. The second experiment was similar to the first experiment except that it was naturally ventilated. The fan used was a 0.75 m (18 in), variable speed, electric positive pressure ventilator. The fan has a depth of 0.48 m, (18.75 in), width of 0.62 m (24.5 in) and height of 0.62 m (24.5 in). It has a maximum speed of 2200 RPM, a power rating of 746 W (1 hp) and a volumetric flow rating of 6.64 m^3/s (14,060 ft^3/min) [6]. The fan was positioned 2.44 m (8 ft) from the open doorway to the corridor at an angle of approximately 15 degrees from horizontal to create the cone of air around the doorway.

2.1 Instrumentation

Temperature measurements were made with 0.5 mm (0.02 in) nominal diameter type K bare bead thermocouples. A vertical thermocouple array was located in the center of the fire room with measurement locations of 0.025 m, 0.30 m, 0.61 m, 0.91 m, 1.22 m, 1.52 m, 1.83 m and 2.13 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the ceiling. The corridor doorway also had a vertical array with measurement locations of 0.025 m, 0.30 m, 0.61 m, 0.91 m, 1.22 m, 1.52 m, 1.83 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft and 6 ft) below the top of the doorway opening. Three thermocouples were located in the room doorway, 0.30 m (1 ft) from the top of the doorway, 0.30 m (1 ft) from the bottom of the doorway and the midpoint of the doorway at 1.02 m (figure 7). Six additional thermocouples were placed in the ventilation window. Three where located 0.30 m (1 ft) in from each side of the window at heights of 0.15 m, 0.61 m and 1.07 m (0.5 ft, 2 ft and 3.5 ft) from the bottom of the window (figures 8, 9).

Gas velocity measurements were recorded in the window and in the fire room doorway using bi-directional probes (figure 10). The doorway had measurement locations of 0.30 m (1 ft) from the top of the doorway, 0.30 m (1 ft) from the bottom of the doorway and the midpoint of the doorway. The ventilation window had six bi-directional probes in the same locations as the thermocouple locations shown in figure 8. Probes were connected to Setra Systems Model 264 differential pressure transducers. Since both in and outflow was expected, each transducer had the capacity to monitor positive and negative pressure differentials. Bi-directional high ranges up to 62 Pa (0.009 PSI) were utilized because of the flow that was expected in the two openings. A set of pressure transducers was also positioned in the rear corner of the room adjacent to the bookcase to examine the differential pressure created at 0.30 m, 1.22 m, 2.13 m (1 ft, 4 ft and 7 ft) from the floor [7].

Video recordings were made of each experiment. Two cameras were positioned on the exterior of the room. One had the view of the ventilation window and the other the open doorway to the corridor. Two water cooled cameras were positioned inside the room (figure 11). One camera was placed just above the floor near the bunk beds viewing the gas flow between the window and doorway. The second interior camera was positioned near the floor viewing the ignition location and flame spread across the bunk beds.

The combustion products were captured by a 6 m x 6 m (20 ft x 20 ft) hood which was instrumented for oxygen consumption calorimetry. Oxygen depletion readings were continuously monitored in order to calculate the total heat release rate of the fire room [8].

2.2 Fuel Load

The fuel load was selected in order to represent a typical bedroom configuration. It was also intended to create a fuel rich atmosphere to make burning dependent on the available oxygen. Both experiments had similar furniture and a total fuel mass that was 250.6 kg and 251.6 kg for experiment 1 and 2, respectively (Table 1). The book case was made of 0.013 m (0.5 in) thick compressed particle board covered with a plastic laminate top

(figures 12, 13). The desk was also made of the compressed particle board with a laminate top, but was 0.038 m (1.5 in) thick (figures 14, 15). The 0.38 m (15 in) nominal size computer monitor on the desk had a plastic shell and a glass face (figures 16, 17). The chair located in the corner had a wood frame; polyurethane cushions and cotton cover (figures 18, 19). Finally, the bunk beds were framed out with 0.038 m x 0.089 m (1.5 in x 3.5 in) pine lumber (figures 20, 21). All of the mattresses were positioned on box springs and were covered with cotton bedding consisting of fitted sheets, blankets, comforters, pillows and pillow cases. The mattresses consisted of a polyester cover, twin innersprings and polyurethane foam. The carpet was polypropylene based and covered the floor wall to wall, but did not extend into the corridor. There was no padding under the carpet, but a 0.01 m (0.375 in) thick sheet of gypsum board was placed under the carpet.

2.3 Experimental Procedure

The fire was ignited using two electrically activated books of matches located in the mattress of the lower bunk, in the corner nearest the center of the room (figure 22). The electric matches consisted of a match book with the cover placed behind the matches, exposing the match heads. Nickel-Chromium wire was spiraled through the match heads and taped to the bottom corners of the match book. A copper wire was connected to each end of the nickel-chromium wire with alligator clips and run to the exterior of the room where they were connected to an igniter box. The igniter box sent current through the wire, heating the wire and, in turn, igniting the matches providing ignition. One of the match books was cut into the mattress and the second was placed under the bedding, directly on top of the mattress to ensure a strong ignition (figure 23).

At the time of ignition, the window was closed and the fire's only source of oxygen beyond the room was through the open room doorway which connected to the corridor via a doorway. The fire was allowed to grow until flashover conditions were reached and the fire became oxygen limited, as determined by the internal video. Once the fire was oxygen limited for a short period of time, the window was opened from the outside of the room to ventilate the fire. Both of the experiments were ventilated 345 s after ignition. In the positive pressure ventilation experiment, the window was opened and 5 s later the fan was turned on to full speed until 1380 s, when the fan was turned off to assess the structure and begin extinguishment. In the naturally ventilated experiment, the window and doorway provided ventilation until the fuel in the room burned to completion. Table 2 provides the timeline of events.

3.0 Results

Cameras at four locations allowed for the visualization of most of the fire growth and the combustion gas flow out of the furnished room. Both experiments experienced very similar fire growth up until the time that the window was opened. In the PPV ventilated experiment, flashover occurred at 275 s and zero visibility at 278 s. In the natural ventilation experiment, flashover occurred at approximately 285 s and zero visibility at 298 s. While the growth was very similar in both experiments, the visibility returned

more rapidly in the PPV experiment. The view from the water cooled camera focused on the corner of the room with the bunk beds showed visibility began to return 181 s after the ventilation in the PPV experiment and 395 s after the ventilation of the naturally ventilated case. Clear visibility inside the room returned to the PPV ventilated experiment 120 s prior to that of the naturally ventilated experiment.

In both experiments, a black smoke flow was observed in the corridor prior to 300 s and flames were not observed in the corridor doorway until the window was ventilated. Within 10 s of opening the window, flames extended out of the corridor doorway. The PPV fan forced all burning out of the corridor and back into the room by 516 s. Once the fan was activated, it took 130 s to completely reverse the flow back into the room. At that point, little or no smoke was seen coming out of the room doorway. Flames were observed in the corridor of the naturally ventilated experiment until 1200 s (figures 24, 26).

The exterior view of the window showed that it took less than 5 s for flames to come out of the window after ventilation in both experiments. The flames in the PPV ventilated experiment extended at least 1.83 m (6 ft) from the window. The flames from the naturally ventilated experiment extended approximately 0.91 m (3 ft) from the outside edge of the window (figures 25, 27). Detailed observations are tabulated in Table 3.

3.1 Heat Release Rate

The maximum heat release rate was 14 MW for the PPV ventilated fire and close to 12 MW for the naturally ventilated fire. Peak heat release rates of both fires occurred approximately 40 s after window ventilation with a spike to their respective maximum. The peak of the PPV experiment occurred 5 s after that of the natural experiment. This corresponded to the 5 s period before the PPV fan was started. Comparing the heat release rate between the time of peak and the time where the two curves intersect showed that the PPV created a higher burning rate by approximately 60 % for about 200 s after the fire reached its maximum output. After the heat release rate spike, the PPV output remained 4 MW above that of the naturally ventilated experiment for 70 s. At the end of those 70 s, the rates converged until 590 s when the naturally ventilated fire had the higher heat release rate. The naturally ventilated fire remained roughly 1 MW above the output of the PPV ventilated fire until the end of the experiment (figures 28, 29). The integral of the heat release rate curve in figure 30 provided the total heat released over the duration of both experiments. The fan caused heat to be released quicker in the PPV experiment, but ultimately both experiments released approximately the same amount of heat.

For fires burning in the open under the laboratory hood, the chemical power measured by the oxygen depletion calorimeter is equal to the heat release rate from the fire as a function of time. However, for a fire within a room, the effluent from the enclosure is a mixed average of the upper layer gases, and does not represent the instantaneous heat release rate of the fire. Prior to ventilation there was a delay in the heat release rate measured due to the room configuration. After the window was opened a majority of the

burning took place on the exterior of the room which allowed for a faster more accurate measure of heat release rate.

3.2 Room Gas Temperature

The gas temperatures measured in the room were similar for both experiments prior to ventilation as each fire grew to an initial peak of approximately 800 ˚C (1470 ˚F). Flashover occurred approximately 270 seconds (s) after ignition and both fires became ventilation limited. Once the fires were ventilation limited, the upper layer temperatures decreased to 700 ˚C (1290 ˚F). When ventilation was started in the experiment with a PPV fan, the upper layer room - gas temperature increased temporarily to 800 ˚C (1470 ˚F), quickly dropped to 550 ˚C (1020 ˚F) and then rapidly increased to the maximum temperature of approximately 980 ˚C (1800 ˚F). The maximum temperature was maintained for a short period of time and then the temperatures in the room steadily decreased to 400 ˚C (750 ˚F) at a rate of 0.8 ˚C /s. At 1200 s into the experiment a piece of the burning bunk bed falling onto the thermocouple leads causing an artificial room temperature increase. The room gas temperatures shown in figure 31 are inaccurate after this point.

The naturally ventilated fire produced a much smoother time evolution of room temperatures. After ventilation, the temperatures rapidly increased to the maximum temperature of 1050 ˚C (1890 ˚F). The temperatures remained around 1000 ˚C (1830 ˚F) for approximately 300 s. Once the temperatures began to decrease the values did so steadily to 500 ˚C (932 ˚F) at a rate of 0.8 ˚C /s. At 1430 s there was a rapid decrease in temperature to 100 ˚C (210 ˚F) as the fuel in the room was nearly consumed (figure 32).

3.3 Doorway Gas Temperature

The temperatures recorded in the upper portion of the doorway to the room were similar to those within the room. For both experiments the temperatures at the top and middle of the doorway were around 600 ˚C (1110 ˚F) while the lower portion of the doorway remained less than 100 ˚C (210 ˚F) prior to window ventilation. This was consistent with the fire drawing a large volume of ambient air into the room at the lower section of the doorway.

After positive pressure ventilation was started, the gas temperatures increased quickly to the peak temperatures of 1000 ˚C (1830 ˚F) at the top, 800 ˚C (1470 ˚F) in the center and 550 ˚C (1020 ˚F) at the bottom of the doorway. Once the fan forced the air into the room, the doorway temperatures began to decline and continued to decrease until the end of the experiment (figure 33). A small increase in temperature occurred at approximately 1380 s which was consistent with the turning off of the fan. The increase is further evidence of the cooling effects of the fan.

The doorway temperatures for the naturally ventilated experiment were higher than those of the PPV experiment for a longer time period. It took approximately 300 s for the maximum temperatures to be reached at the top of the doorway. Both the top and center of the doorway reached a maximum of 1000 ˚C (1830 ˚F). The bottom of the doorway

briefly peaked at 700 ˚C (1290 ˚F) before dropping to 200 ˚C (390 ˚F) as the fire continued to burn. Temperatures slowly declined to 100 ˚C (210 ˚F) over the 700 s after the peak (figure 34).

3.4 Window Gas Temperature

The gas temperatures monitored in the window were significantly different depending on the method of ventilation. The PPV experiment created more uniform gas temperatures in the window due to the unidirectional flow out of the window. Flames and hot gases could be observed coming out of the entire cross sectional area of the window. A bidirectional flow pattern existed in the naturally ventilated fire experiment. Flames could be seen in the entire window for a short period of time and then air entered the lower third of the window for the remainder of the experiment. The gas temperatures in the PPV experiment were all between 900 ˚C (1650 ˚F) and 1100 ˚C (2010 ˚F) while the naturally ventilated experiment had temperatures of 1000 ˚C (1832 ˚F) at the top and 600 ˚C (1110 ˚F) at the bottom of the window. The PPV experiment required 200 s to reach these temperatures while the naturally ventilated experiment took approximately 400 s (figures 35, 36).

3.5 Corridor Gas Temperature

The corridor doorway gas temperatures also showed a significant difference between the two ventilation tactics. Approximately 120 s after the fan was started; the fan was able to reverse the natural tendency for the gas to flow back into the room. This created a unidirectional flow. After ventilation started in the PPV experiment, the gas temperature reached nearly 700 ˚C (1290 ˚F) at the very top of the doorway. Once the fan was turned on, the upper doorway temperatures dropped and all of the other gas temperatures in the doorway never increased above 200 ˚C (390 ˚F). The bottom half of the doorway remained slightly above ambient temperatures of 25 ˚C (77 ˚F). The naturally ventilated gas temperatures were different due to the flow of combustion gases and flames that ventilated out of the corridor doorway. Gas temperatures in the upper third of the doorway were between 600 ˚C (1110 ˚F) and 900 ˚C (1650 ˚F) after ventilation (window opened). The mid doorway temperature rose as high as 400 ˚C (750 ˚F) while the bottom remained around 100 ˚C (210 ˚F). The temperature trends in the corridor were very similar to those of the room doorway (figures 37, 38).

3.6 Room Differential Pressure

Differential pressure readings were taken to examine the static pressure in the room created by the fire and the impact of the PPV fan on this pressure. The interior pressure readings were referenced to the pressure at the same elevation on the outside of the room. Before ignition in the PPV experiment, the fan created uniform pressures at all three elevations of 21 Pa (0.003 PSI). After ignition, the fire created pressures of 34 Pa (0.005 PSI) at the top probe, 14 Pa (0.002 PSI) at the middle probe and -14 Pa (-0.002 PSI) at the lower probe. Once the window was opened and the fan was turned on, these differential pressures became 62 Pa (0.009 PSI), 41 Pa (0.006 PSI) and 21 Pa (0.003 PSI) respectively. These pressures held constant for a period of time when the fire

was at peak and then declined steadily. The naturally ventilated fire created differential pressures of 28 Pa (0.004 PSI) at the top probe, 7 Pa (0.001 PSI) at the middle probe and -14 Pa (-0.002 PSI) at the bottom probe. These differential pressures declined slightly until the fire diminished (figures 39, 40).

3.7 Window Gas Velocity

Before the PPV ventilated experiment, an ambient flow experiment (without a fire) of the fan through the room was conducted. The experiment produced an average velocity of 5 m/s out of the window. For the PPV experiment, velocities on the order of 5 m/s to 20 m/s were measured. The highest velocity occurred just after the window was opened and the fan was turned on. With the fire growing, the velocity increased to 20 m/s and slowly decreased to the fan velocity of 5 m/s as the fire decreased. The naturally ventilated experiment had a bidirectional flow through the window with the highest velocities of 12 m/s at the top of the window. The gas velocity in the middle of the window was about 7 m/s out of the room while the bottom of the window had flow into the room at 2 m/s. It took longer for the maximum velocities to be reached than in the PPV experiment but this was also directly proportional to the growth of the fire (figures 41, 42). In the three minutes following the window being opened, the average gas velocity produced by the PPV experiment was 14 m/s while in the naturally ventilated experiment; the average gas velocity was 5.5 m/s.

3.8 Doorway Gas Velocity

The gas velocities into the room through the doorway were lower than those out through the window. The PPV fan alone created average flow velocities of 3 m/s to 4 m/s as shown in figure 38 for times of -2000 s to -1200 s. The negative time values represent times prior to ignition. Prior to ventilation, there was a 4 m/s to 6 m/s flow out of the top two-thirds of the doorway and a flow into the room in the bottom one-third of the doorway of 2 m/s. After the fan was activated the bottom two-thirds of the doorway flowed into the room and the flow in the upper third of the doorway fluctuated between in and out of the room. Eventually the fan was able to completely move air into the room over the entire doorway cross section. The naturally ventilated experiment began in the same manner as the PPV experiment with bidirectional flow through the doorway. Once ventilation was started, the gas velocities held rather steady until the fire began to decrease with the velocities decreasing as well. The flows into the room may be underestimated due to the orientation of the bi-directional probes. The probes were faced into the room and perpendicular to the corridor which may not have measured the full magnitude of the velocity into the room but were accurate for the flows out of the room (figures 43, 44). The flow out of the room had to pass in the direction of the centerline of the probes yielding a more accurate differential pressure as opposed to the flow into the room that may have passed the bi-directional probe at an angle to the centerline of the probe causing lower differential pressure readings, which correspond to under estimation of the gas velocities.

3.9 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 4. 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. In cases, similar to a developing fire in a compartment, the temperature measurement errors in the lower layer are smaller as the fire develops through flashover, since the effective temperature of the floor and walls are relatively cool. Post-flashover, the potential for measurement error increases as the temperature of the surroundings increase. 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 %.

Total expanded uncertainties associated with oxygen calorimetry techniques is discussed in greater detail by Bryant et al. [8]. This uncertainty was estimated to be 11 % and included components derived from gas concentrations, temperature and gas flows. This estimation is based on the calorimetry system alone and does not account for the uncertainty that exists due to the experimental configuration. There is a delay time for the combustion gases to reach the hood and calorimetry instrumentation. The heat released within the fire room has an additional uncertainty associated with it. This uncertainty varies during the experiment. After the window was opened the uncertainty was minimized due to the majority of the burning occurred outside of the room.

4.0 Discussion

The impact of positive pressure ventilation on the gas temperature, window gas velocity, and mass burning rate has been investigated using different fuel packages and different room/structural configurations. Stott studied typical home furnishings in a single story structure. Svensson utilized fuel fires in three rooms of a larger structure. Ezekoye employed a polyurethane foam fuel in a 4 room residential structure. Different capacity PPV fans were utilized by each study. Instrumentation typically included upper and lower layer gas temperatures and one experimental series included pressure transducers for monitoring gas velocities.

Stott [11] conducted a series of experiments in Preston, U.K. utilizing furnished rooms. These experiments were instrumented with thermocouples but relied upon subjective feedback from the participants that suppressed the fire or watched from outside. These experiments showed that there was a minor temperature elevation after the use of the fan, approximately 10 ˚C (18 ˚F). The experiments also demonstrated that there was no flame extension to the corridor, the temperature decreased and the visibility improved after the initiation of PPV. The report also stated that the fire growth rate was not greatly increased by the fan. The relatively small increase in burning rate as PPV was initiated is consistent with the data collected by this study for a single furnished room.

Svensson [12] of the Swedish Rescue Services Agency also conducted an experimental study of ventilation during fire fighting operations. This experimental setup utilized three rooms on the first floor of a fire training facility. A 0.5 m diameter heptane pool fire was utilized which generated a heat release rate of 0.37 MW. This was a significantly smaller fire (in terms of heat release rate) than the fully furnished rooms in these experiments which released heat at a rate of 11 MW to 14 MW. The smaller heat release rate heptane pool fire generated much lower temperatures, 300 ˚C (570 ˚F), than was monitored in the furnished room, 800 ˚C (1470 ˚F). Svensson did report an increase of 40 % in the burning rate after PPV was initiated. This is comparable to the 60 % increase that was produced in the furnished room in this study. The furnished room had a greater fuel surface area which would have been consistent with the difference in the burning rate. Svensson also reported significantly lower pressure differentials. The larger room size may account for some of this difference but the main reason is likely the smaller fan output. The fan used in Svensson's experiments was rated at approximately one third that of the one used in these experiments. This difference in fan size is also consistent with the smaller flows that were recorded in Svensson's experiments.

Another set of experiments was conducted in the United States by Ezekoye, Lan and Nicks [13] of the University of Texas at Austin. These experiments examined positive pressure attack for heat transport in a house fire. The fuel source chosen for those experiments was 9 kg (19.8 lb) of polyurethane foam, oriented on a rack, capable of generating a peak heat release rate per unit area of 1.2 MW/m^2. This fuel package produced temperatures of 760 ˚C (1400 ˚F) at the ceiling and 200 ˚C (390 ˚F) at the lower levels but did not appear to cause post flashover conditions that were present in the furnished room fire experiments. The fan flow rate was similar to the one used in the furnished room. The mixing which caused higher temperatures in the lower layer are seen in both sets of experiments. Those experiments only reported temperatures so pressure differential, burn rate and gas flow velocity could not be compared.

5.0 Conclusion

As compared to natural ventilation, positive pressure ventilation caused higher fire room temperatures, increased window gas flows and higher pressure differentials for this set of furnished room burns. After the peak heat release rate was reached in both experiments, the temperatures with PPV remained 200 ˚C (360 ˚F) to 400 ˚C (720 ˚F) below the temperatures with natural ventilation for 800 s. The doorway temperatures with PPV peaked 200 s before, but quickly dropped to 200 ˚C (390 ˚F) to 500 ˚C (930 ˚F) below the naturally ventilated temperatures for 900 s following the peak in the PPV experiment. The window gas temperatures generated during the PPV experiment peaked 200 s before gas temperatures at the same location in the naturally ventilated experiment. In the naturally ventilated experiment, gas temperatures in the top two thirds of the window were higher than the PPV experiment, but gas temperatures in the bottom third were lower due to the inflow of air. Once the fan was running, the PPV corridor temperatures were as much as 500 ˚C (930 ˚F) less than comparable temperatures in the naturally ventilated experiment.

The PPV fan alone generated gas velocities of 5 m/s in the window while the naturally ventilated fire generated velocities of nearly 12 m/s. In the experiment with the PPV fan, window gas velocities of nearly 20 m/s were generated, approximately equal to the additive velocities from the fan and the naturally ventilated fire. The fan quickly forced a unidirectional flow out of the window but took a period of time to completely reverse the flow out of the doorway and create a flow into the room. The fan was able to create a more tenable atmosphere as soon as it was turned on by reversing the natural flow out of the corridor, where the fire fighters would be approaching the fire for extinguishment.

The heat release rate of the fire was increased by the fan for the 200 s following the peak heat release rate. This is critical because this is the time window in which the fire department would typically be advancing to extinguish the fire. The peak heat release rate for the two experiments occurred at approximately the same time and the rate with the PPV fan was 2 MW higher. The PPV fan caused a 60 % increase in burning rate during this time of initial fire department attack. This reinforces the importance of selecting a ventilation location close to the seat of the fire that allows for all of the combustion products to be ventilated to the exterior of the structure. The PPV ventilated

experiment forced the flames at least 1.83 m (6 ft) out of the room as compared to the 0.91 m (3 ft) by the naturally ventilated experiment. Flame extension out of the building openings may pose a potential ignition hazard to materials nearby.

While the use of PPV in this particular configuration caused an increase in the room's fire burning rate, it lowered the temperatures in the room, forced all of the combustion products to flow out of the room without affecting the corridor and improved the visibility leading up to and in the room itself. In this experimental configuration a fire fighting team would likely have been able to attack the PPV ventilated fire more easily than the naturally ventilated fire.

This limited data set indicates that coordination of fire fighting crews is essential to carry out positive pressure ventilation in the attack stages of a fire. In this experiment, ideal coordination was simulated as the window was ventilated in the correct location and the fan was initiated s later. Once the fan was turned on, it took approximately 60 s to 90 s for the fire to reach its peak burning rate and the flow was forced away from the entrance. After this transition, the fire remained at a steady burning rate until the fuel was consumed. This would indicate that for the conditions in this experiment fire fighters should delay 60 s to 120 s after ventilation and fan start before advancing towards the fire. This would allow the flows to stabilize, temperatures to decrease and visibility to improve. The burning rate of the fire could become steady at the rate determined by the modified air flow and would be less likely to rapidly change as the fire fighters approach. The time to reach this new steady condition could vary with building layout, fire size and fan capacity.

6.0 Acknowledgements

The authors would like to thank Roy McLane, Andrew Milliken, Jessica Naff, Laurean DeLauter, Ed Hnetkovsky, Jack Lee, Robert Anleitner, Jay McElroy and Alexander Maranghides of the Building and Fire Research Laboratory at NIST for the support they provided during this set of experiments. In addition, the authors express gratitude to the United States Fire Administration, part of the Department of Homeland Security, and Robert McCarthy for their sponsorship and support of this important research program.

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Table 1 - Fire Load Weights

Item	Mass (PPV Experiment) (kg)	Mass (Natural Experiment) (kg)
Bunk Bed Frame	19.15	20.13
Top Mattress	14.60	17.14
Top Box Spring	12.63	13.06
Bottom Mattress	14.98	14.44
Bottom Box Spring	14.21	12.94
Pillows	0.57	0.56
	0.58	0.56
Pillow Cases	0.11	0.10
	0.11	0.10
Fitted Sheets	0.40	0.34
	0.39	0.37
Blankets	1.15	1.19
	1.18	1.22
Comforters	1.54	1.55
	1.59	1.56
Chair	27.13	27.80
Book Case	27.08	26.17
Desk	55.48	55.48
Computer Monitor	17.09	17.90
Carpet	40.66	39.00
Total Weight	250.63	251.61

Table 2 - Experimental Procedure

Time (s)	Natural Ventilation	Positive Pressure Ventilation
0	Ignition	Ignition
345	Window Open	Window Open
350	-	PPV Fan On
* Fire burned until all fuel was exhausted		

Table 3 - Observations

PPV Ventilated Experiment Time (s)	Natural Ventilation Experiment Time (s)	Observation
0	0	Ignition
86	120	Flames touch top bunk box spring
105	120	Black smoke out of corridor
156	180	Flames extend to top bunk
190	220	Top bunk fully involved in flames
190	225	Smoke layer drops to bottom of window
210	240	Bunk bed fully involved in flames
275	285	Flashover
278	298	Zero visibility
270	300	Smoke down to 0.30 m (1 ft) above corridor floor
345	345	Window Open
350	350	Flames out of window
420	460	Flames on corridor floor
-	650	Reduction in smoke out of corridor, increase in flames
480	-	Little - no smoke out of corridor
526	740	Limited visibility returned
645	765	Room clear, everything burning
-	900	Flames out of room but not out of corridor
NA	960	Flames no longer extend out of window
1200	-	Bunk bed falls against thermocouple tree
1230	1230	Burnout
1380	-	Fan is turned off
Note: Times were estimated from the four video camera views		

Table 4 - Estimated Uncertainty in Experimental Data

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Gas Temperature Calibration[16] Radiative Cooling Radiative Heating Repeatability [1] Random [1]	± 1 % - 5 % to + 0 % - 0 % to + 5 % ± 5 % ± 3 %	- 8 % to + 8 %	- 15 % to + 15 %
Differential Pressure Calibration[7] Accuracy[7] Repeatability [1] Random [1]	± 2 % ± 1 % ± 5 % ± 5 %	- 8 % to + 8 %	- 15 % to + 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 %

Notes: 1. Random and repeatability evaluated as Type A, other components as Type B.

Figure 1 - Two Common PPV Fans

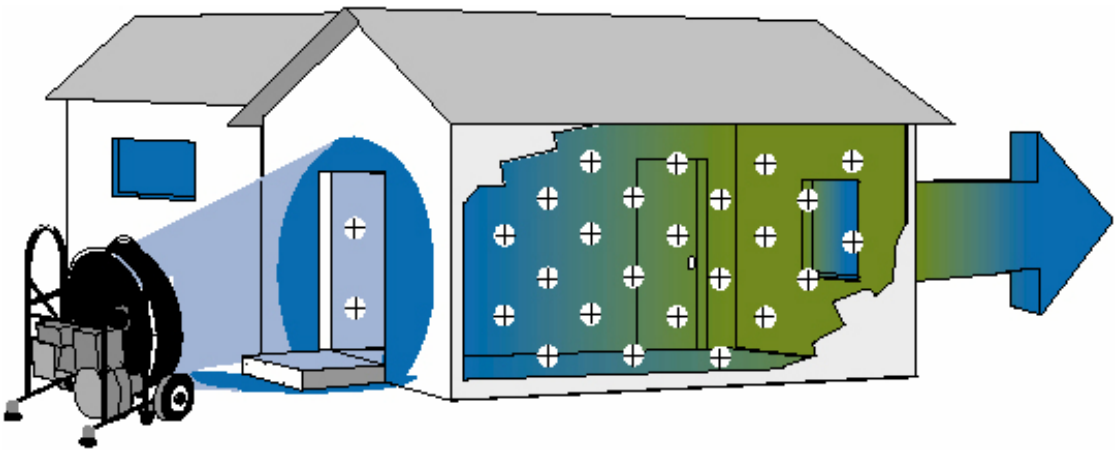

Figure 2 - PPV Cone of Air [5]

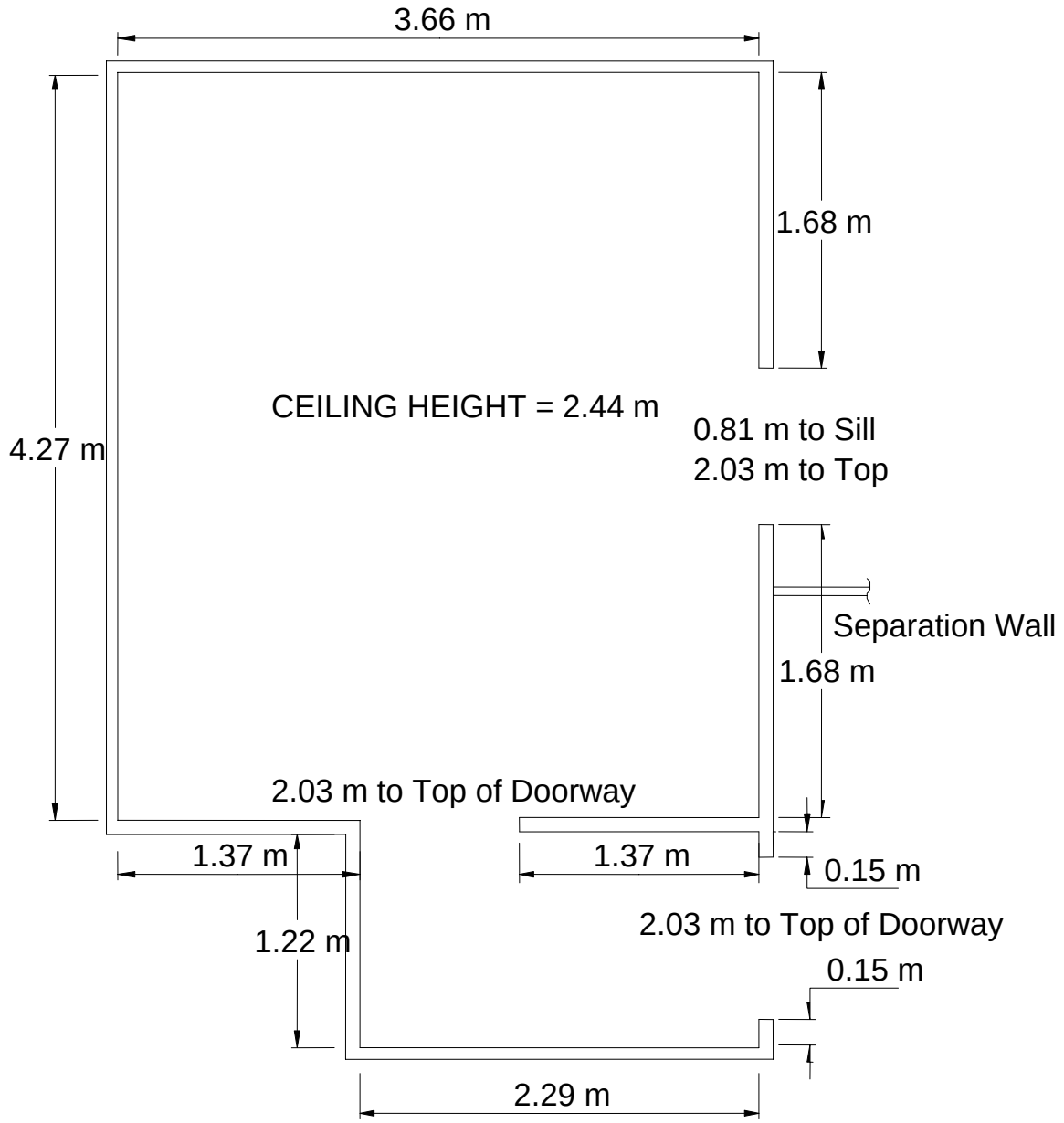

Figure 3 – Experimental Floor Plan

Figure 4 – External view of window in closed position

Figure 5 – External view of open corridor doorway

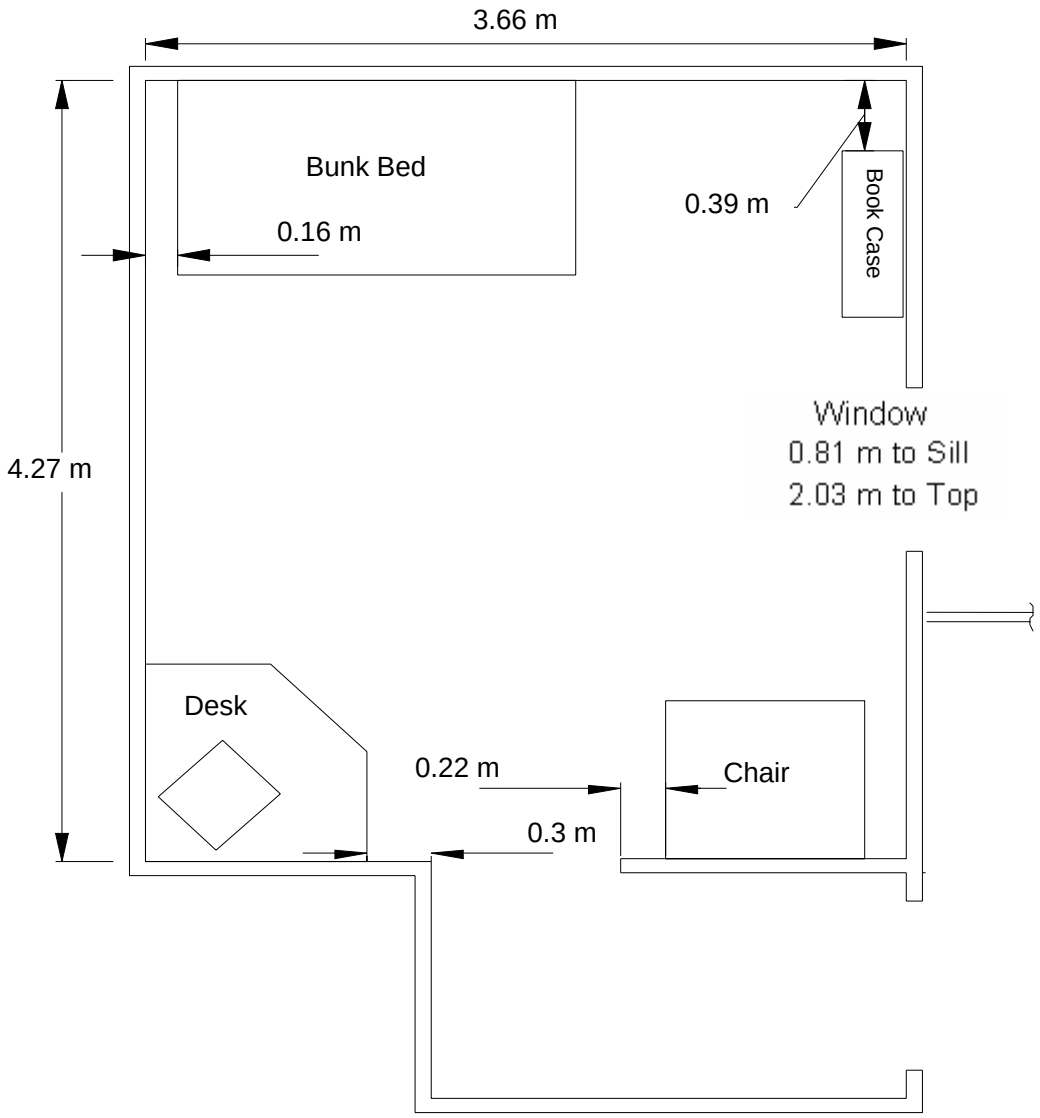

Figure 6 - Furniture Floor Plan

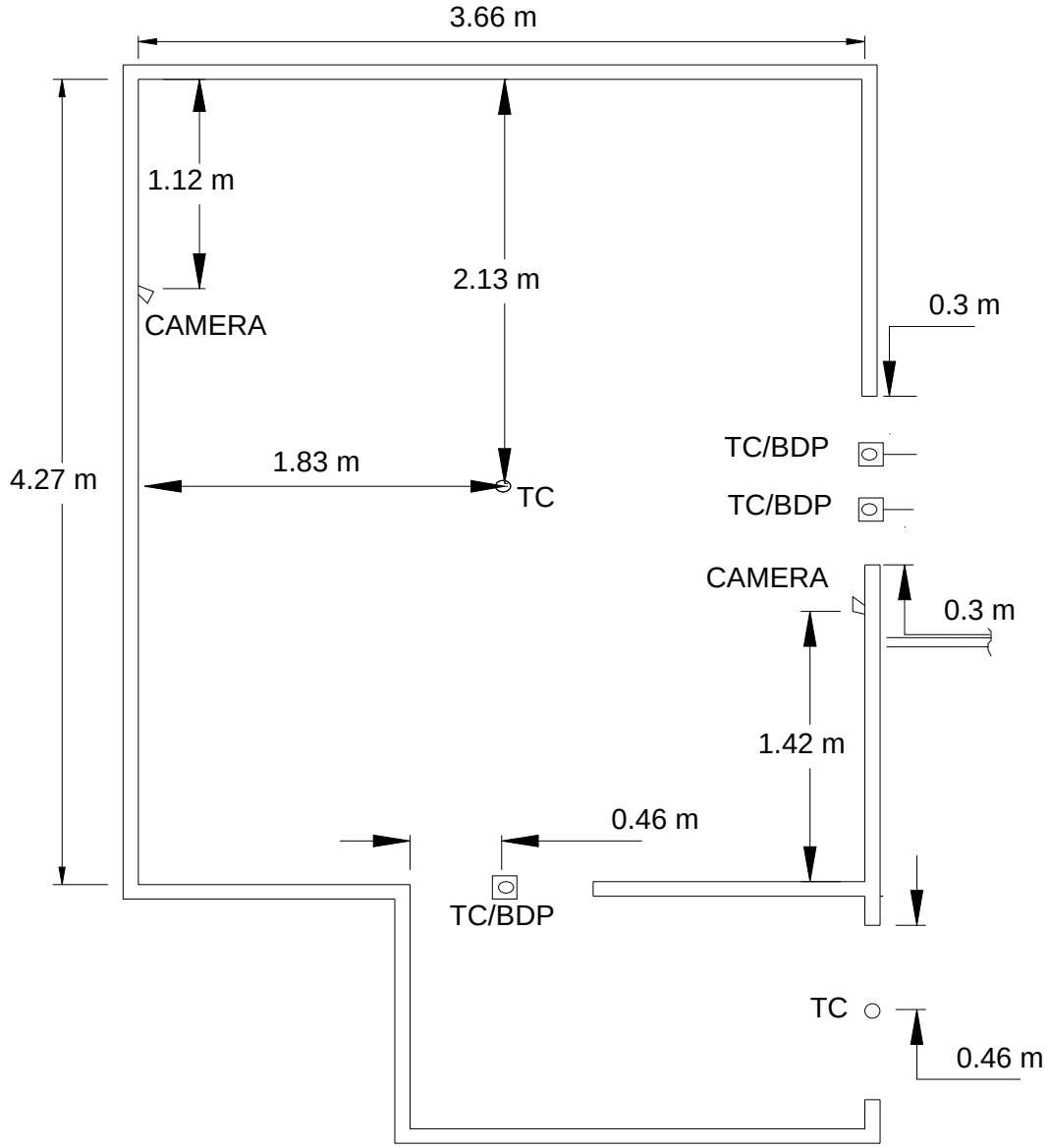

Figure 7 - Instrumentation Floor Plan

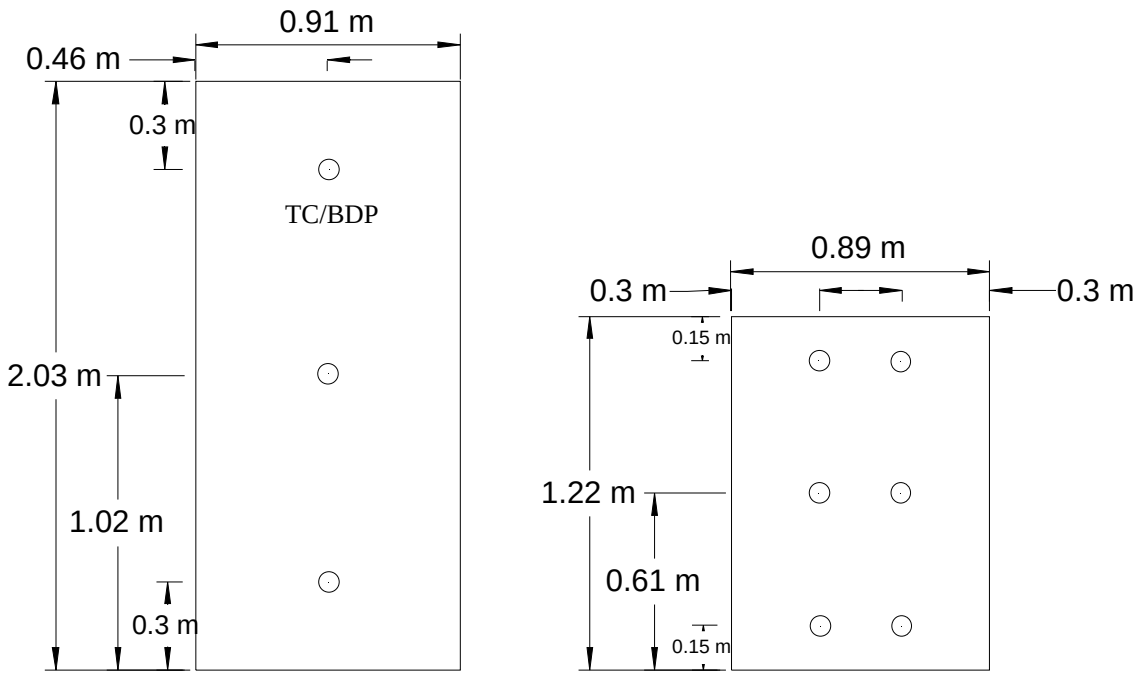

Figure 8 - Doorway and Window Probe and Thermocouple Locations

Figure 9 – View of Doorway from inside the room into Corridor and Window, with Instrumentation

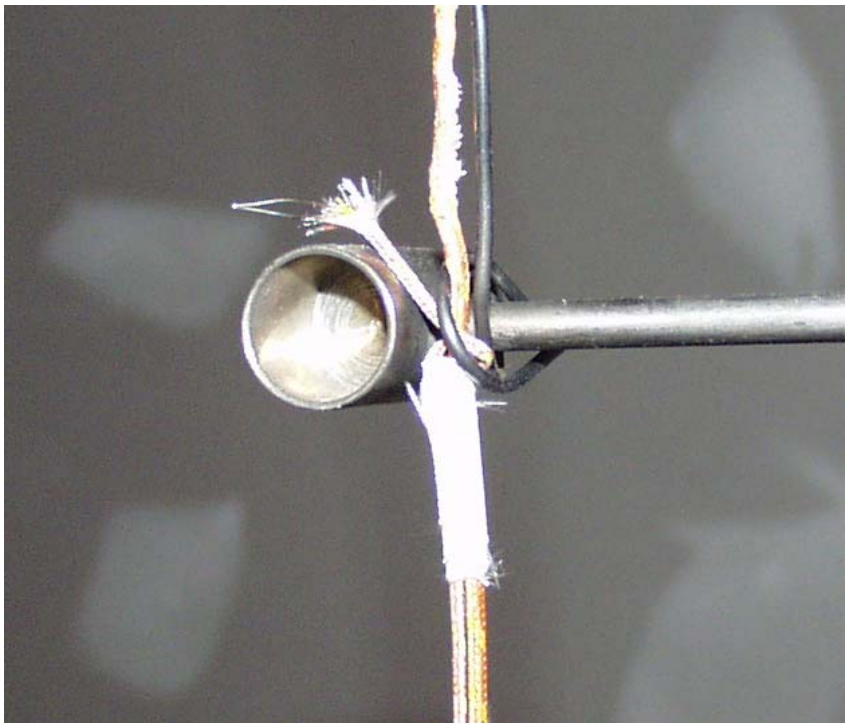

Figure 10 - Bidirectional Probe and Thermocouple Combination

Figure 11 - Water Cooled Camera

Figure 12 - Book Case

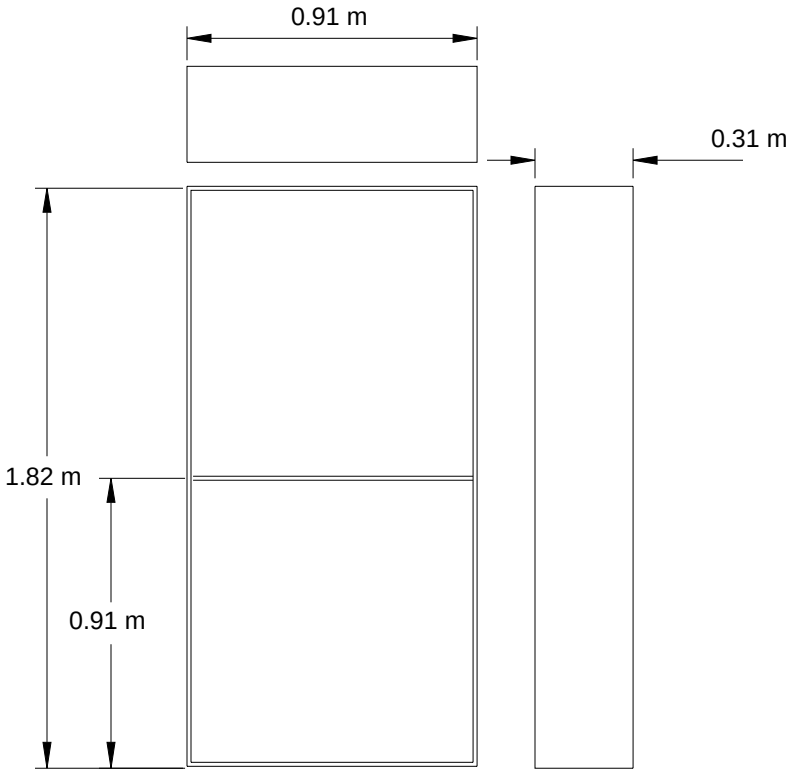

Figure 13 - Book Case Dimensions

Figure 14 - Desk and Monitor

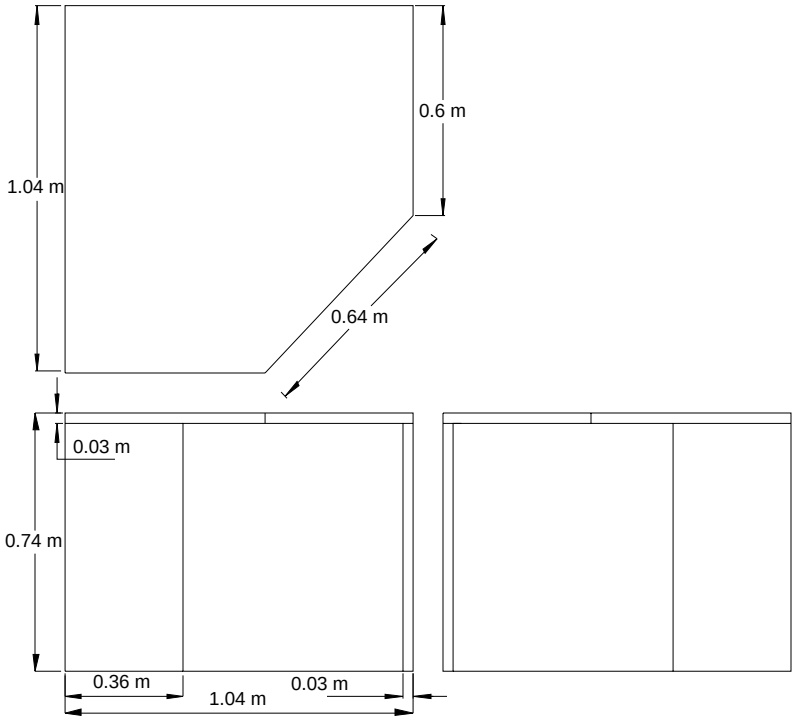

Figure 15 - Desk Dimensions

Figure 16 - Monitor

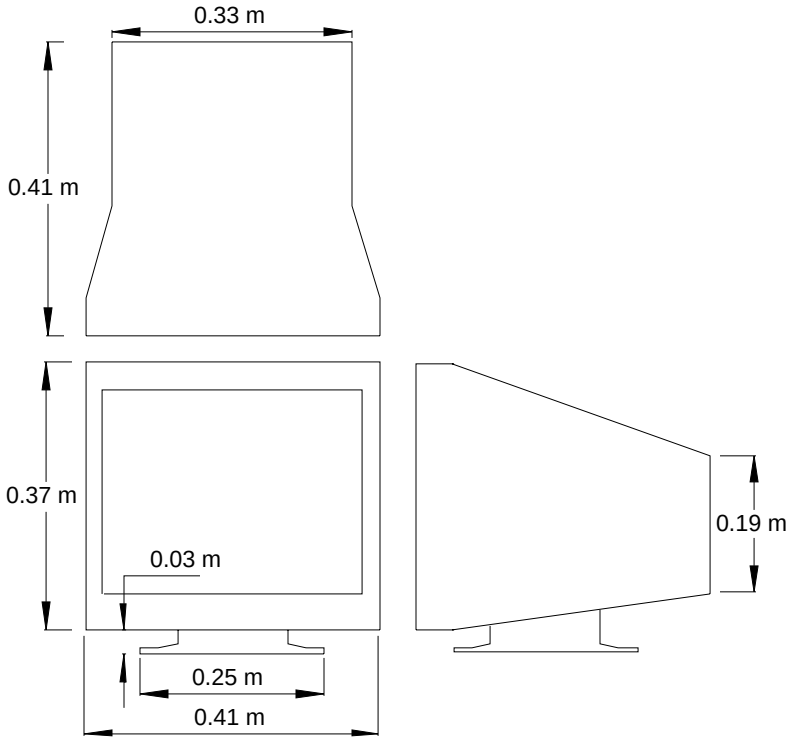

Figure 17 - Monitor Dimensions

Figure 18 - Chair

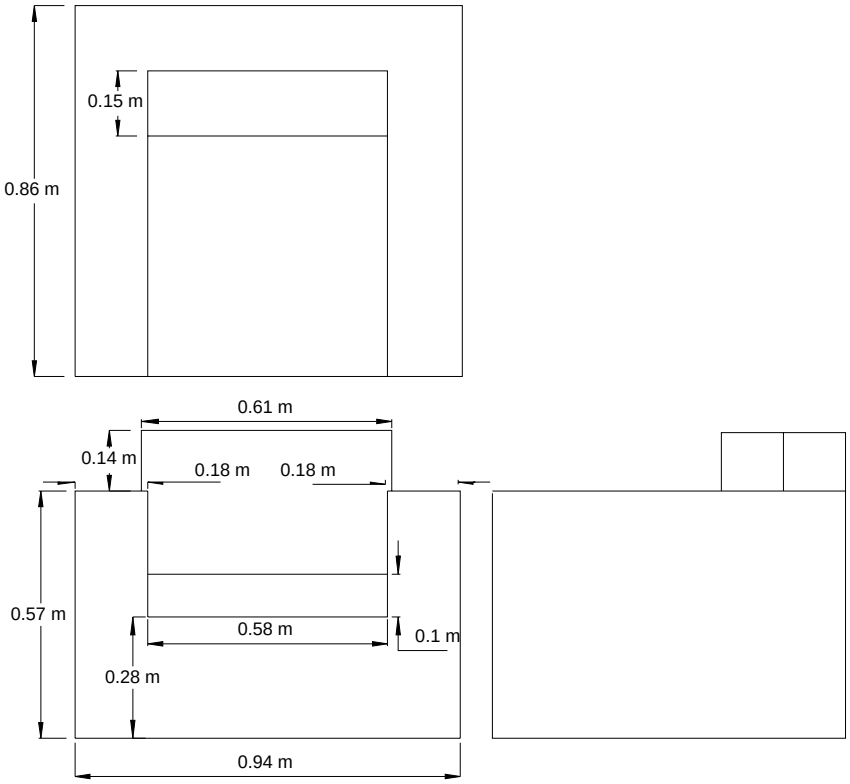

Figure 19 - Chair Dimensions

Figure 20 – Bunk Bed

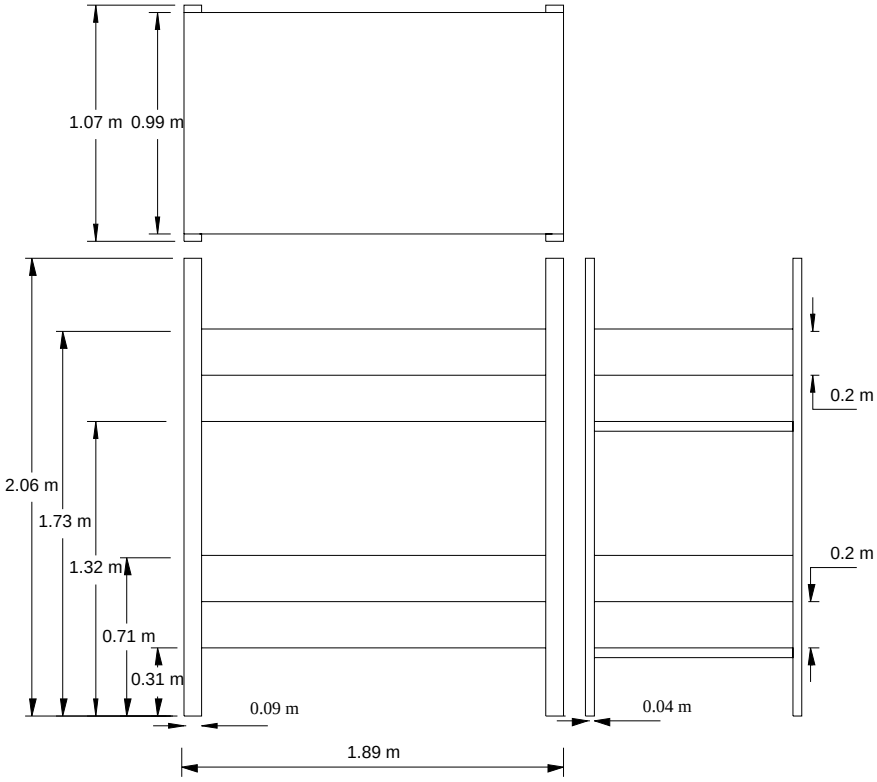

Figure 21 – Bunk Bed Dimensions

Figure 22 - Ignition Setup

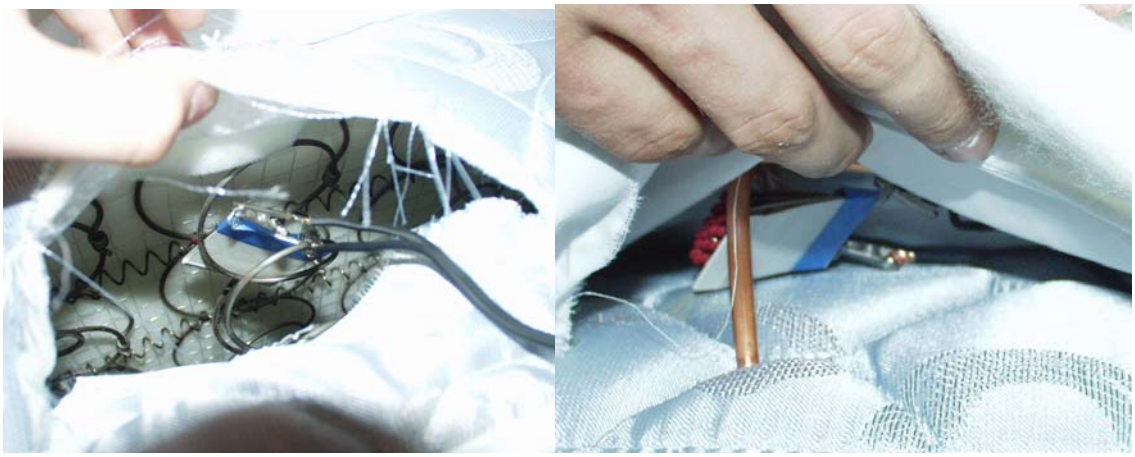

Figure 23 - Electrically Activated Matchbook Locations

Figure 24 – Exterior View of Doorway to Corridor After the Start of Forced Ventilation (470 s)

Figure 25 – Exterior View of Window After the Start of Forced Ventilation (380 s)

Figure 26 – Doorway During Natural Ventilation Experiment (645 s)

Figure 27 - Window During Natural Ventilation Experiment (470 s)

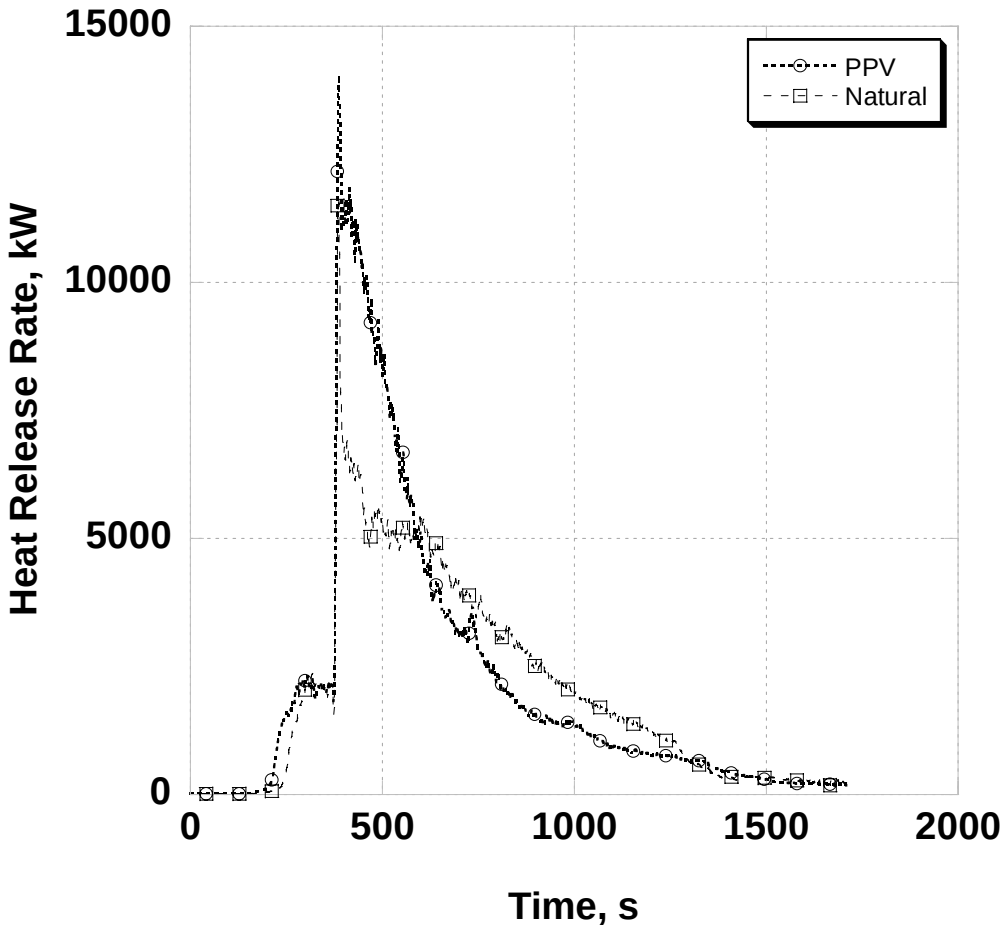

Figure 28 - Heat Release Rate

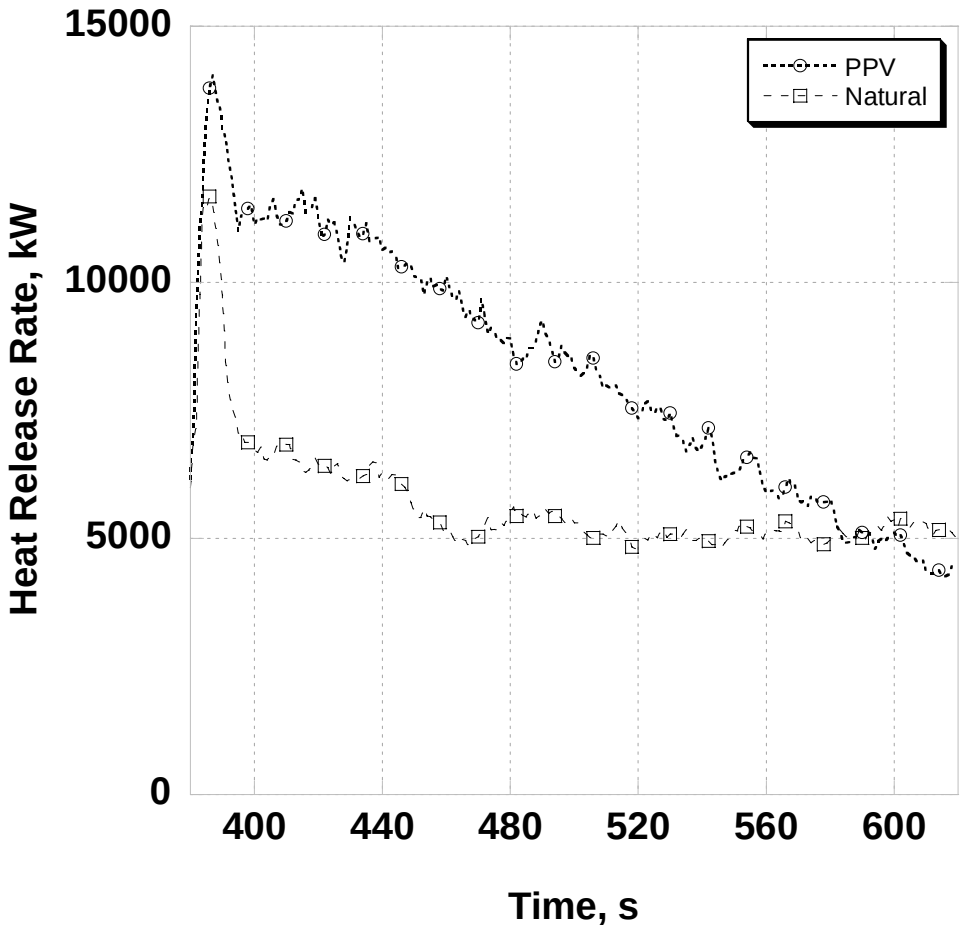

Figure 29 - Heat Release Rate Detail for 200 s Following Peak Output

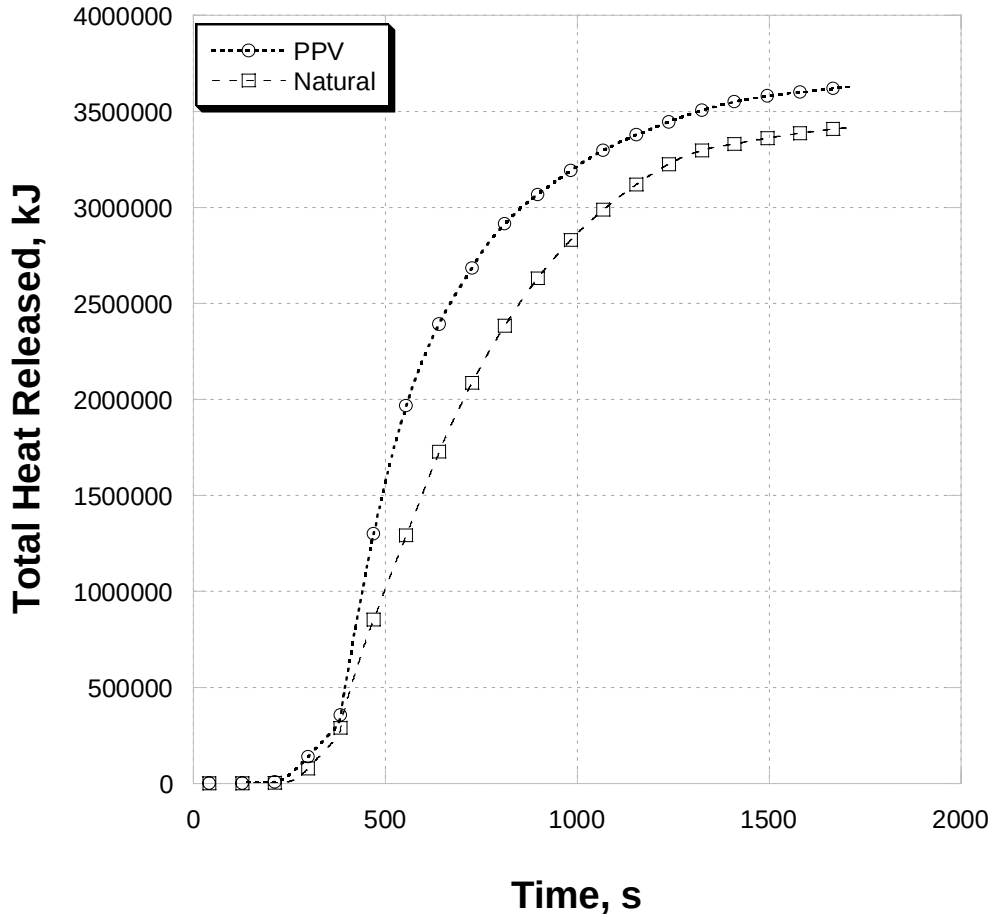

Figure 30 – Total Heat Released

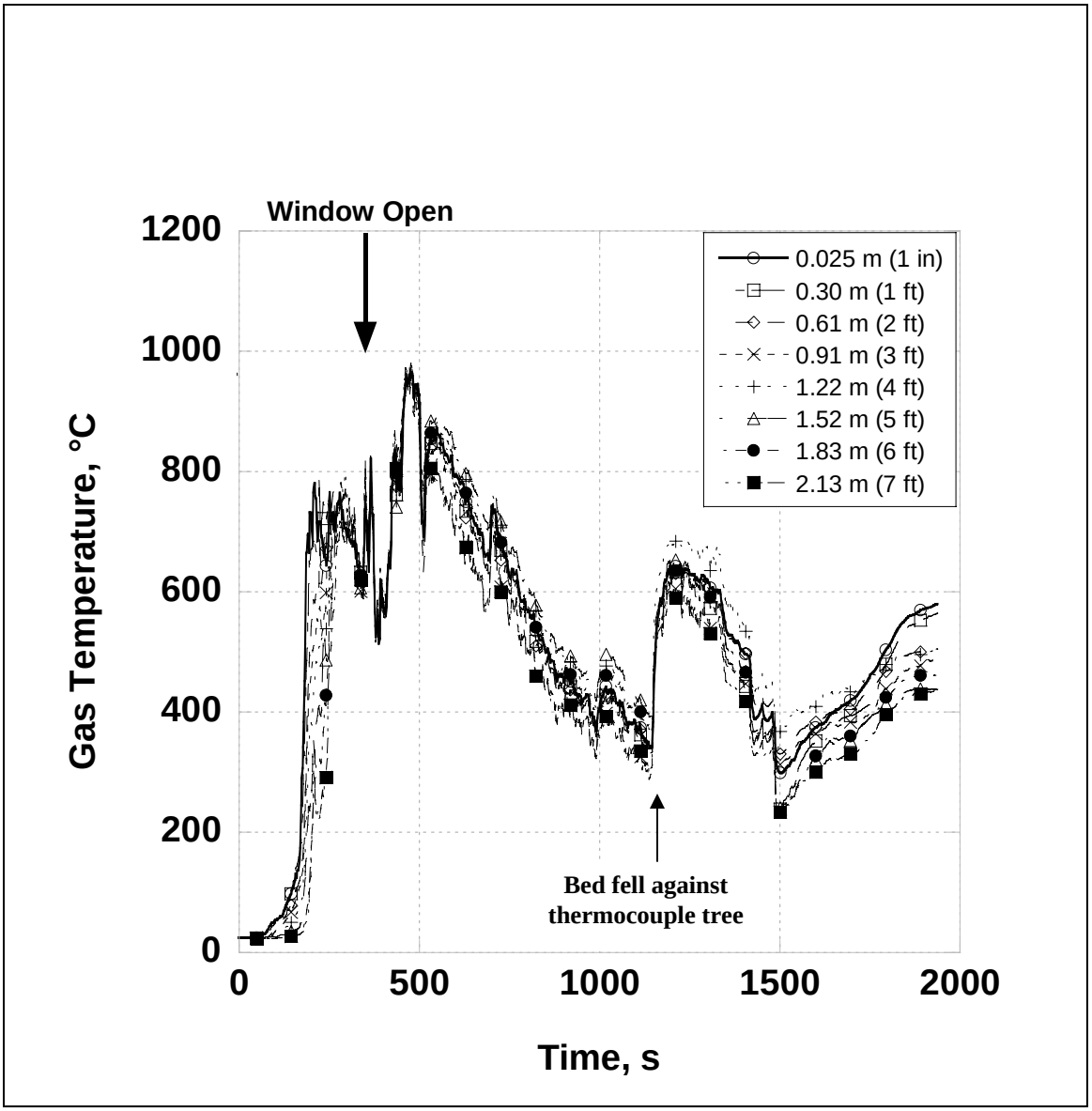

Figure 31 - PPV Room Temperatures, Distances Measured From Ceiling.

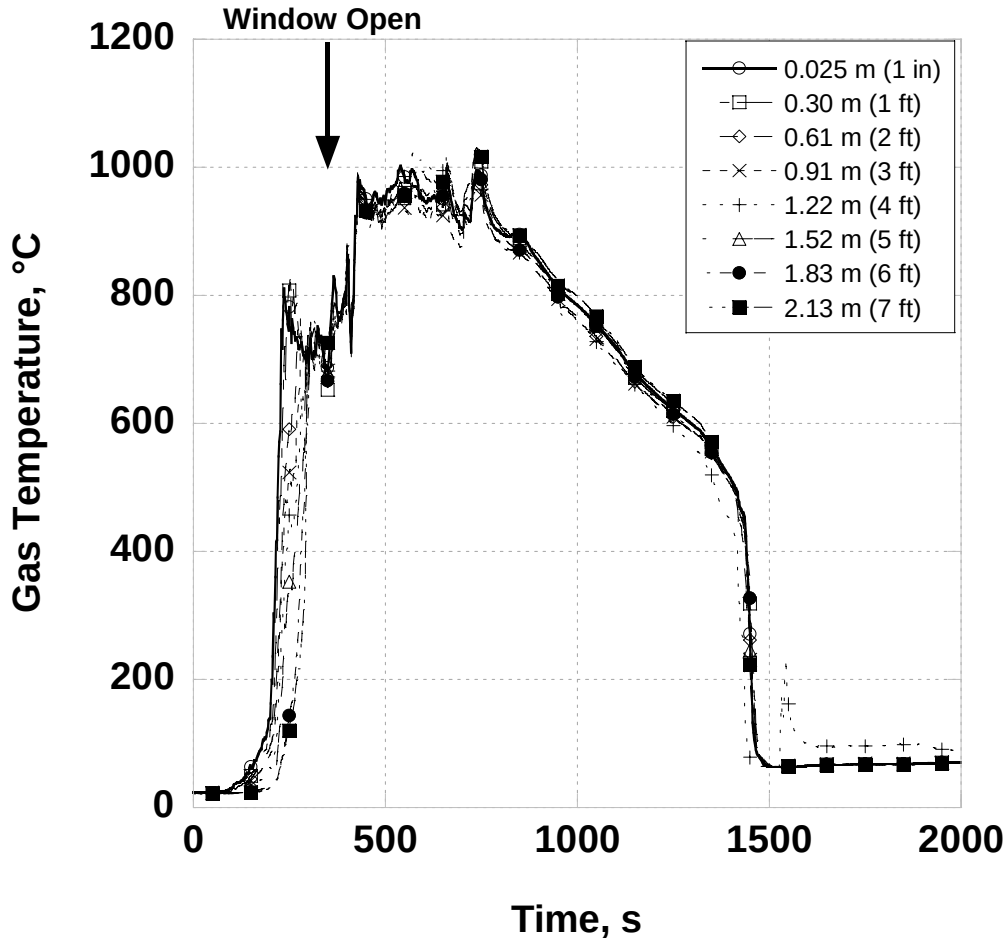

Figure 32 - Natural Ventilation Room Temperatures

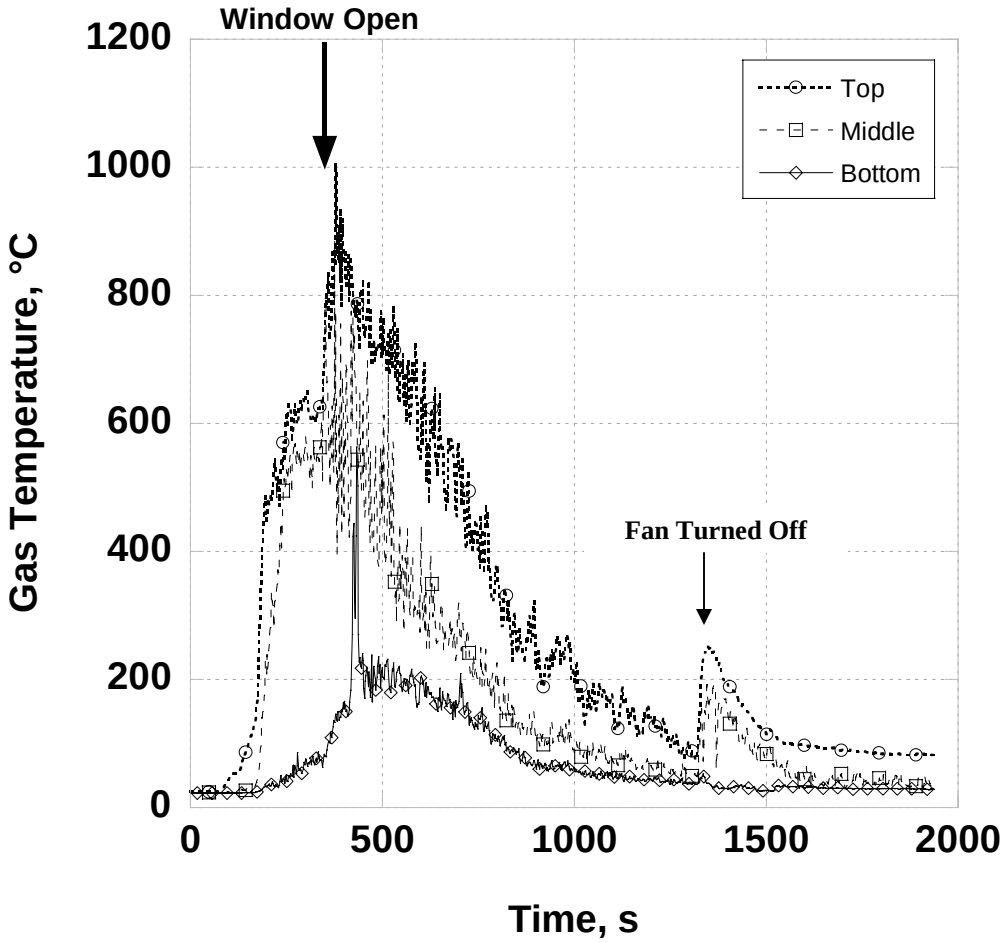

Figure 33 - PPV Doorway Temperatures

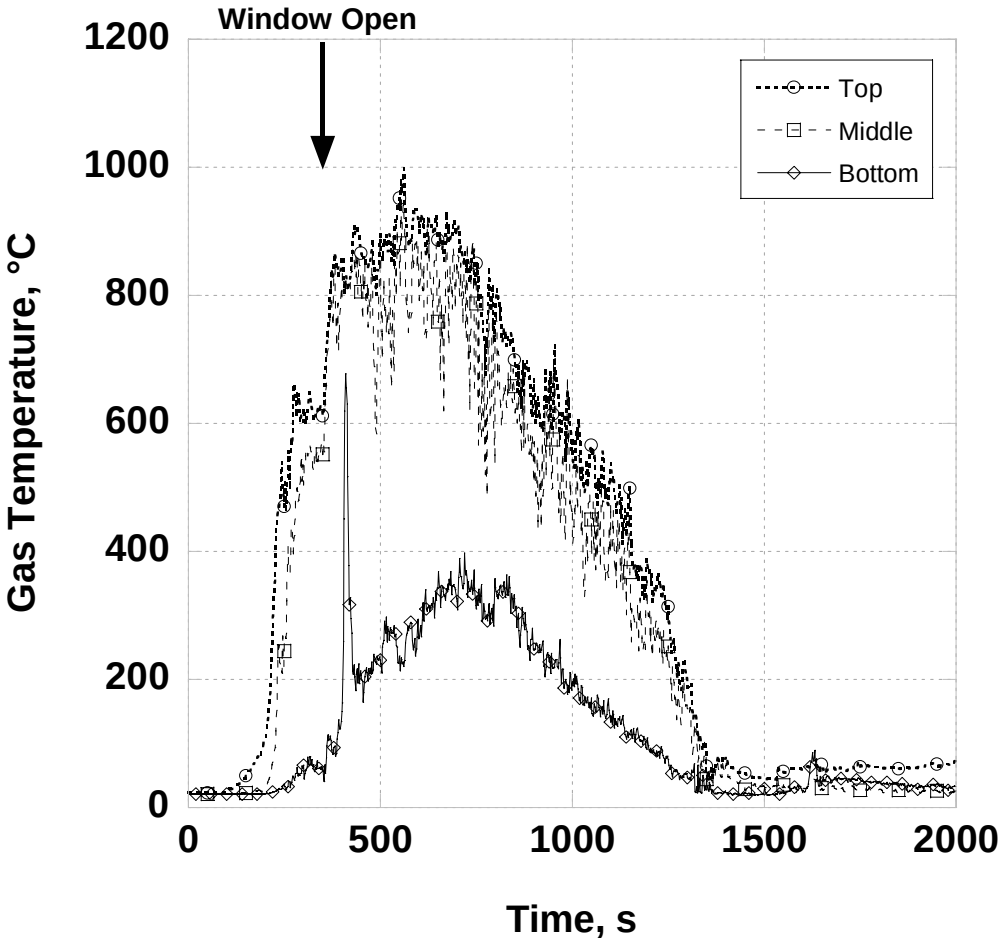

Figure 34 - Natural Ventilation Doorway Temperatures

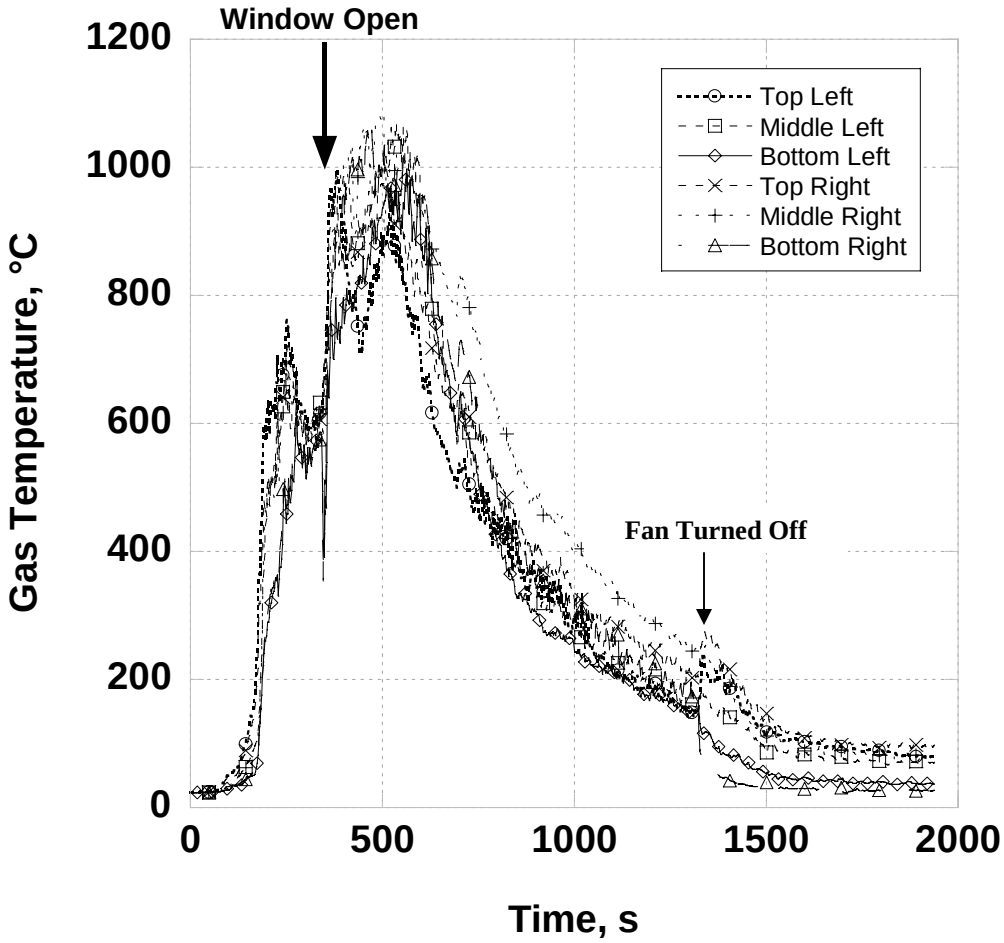

Figure 35 - PPV Window Temperatures

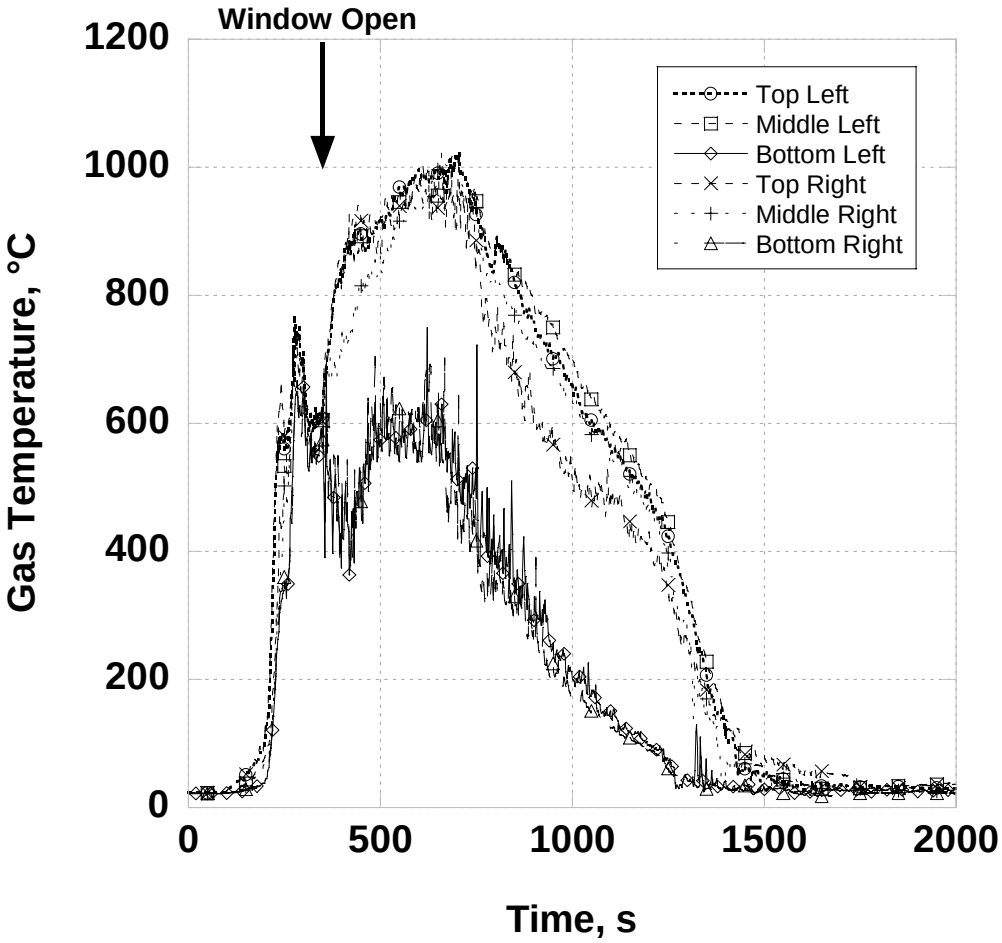

Figure 36 - Natural Ventilation Window Temperatures

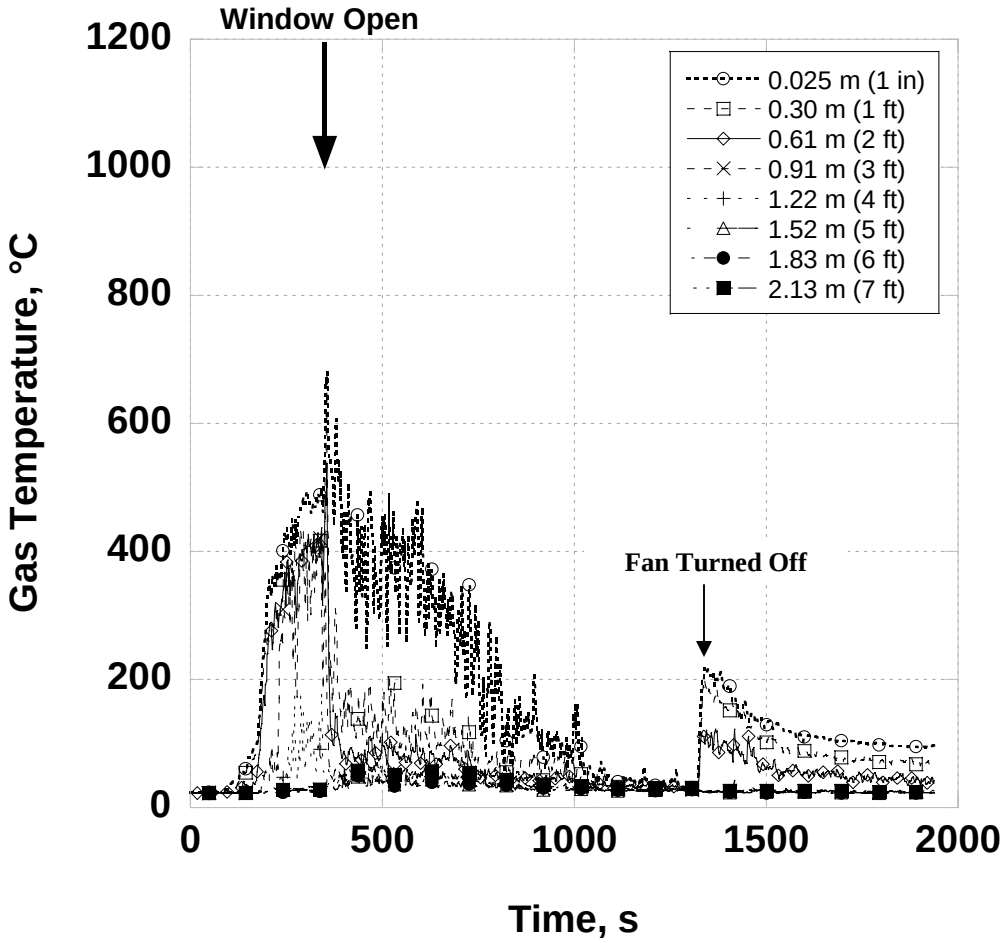

Figure 37 - PPV Corridor Temperatures

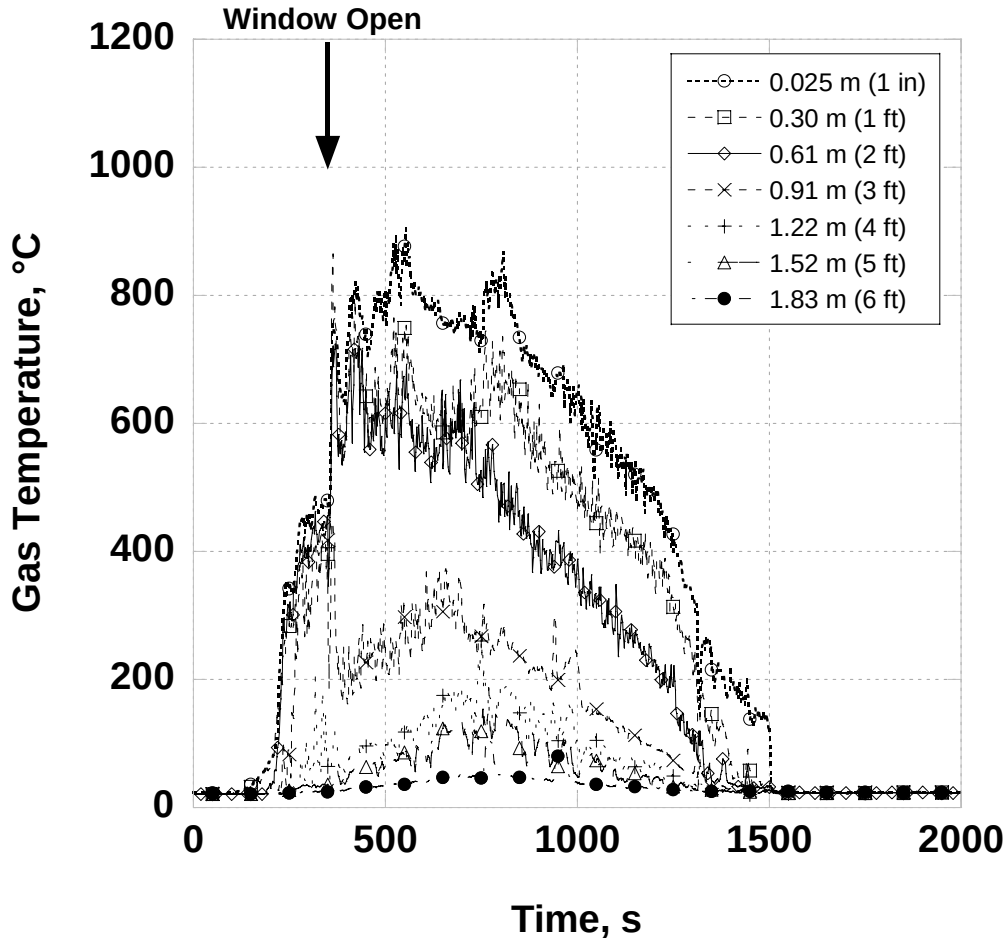

Figure 38 - Natural Ventilation Corridor Temperatures

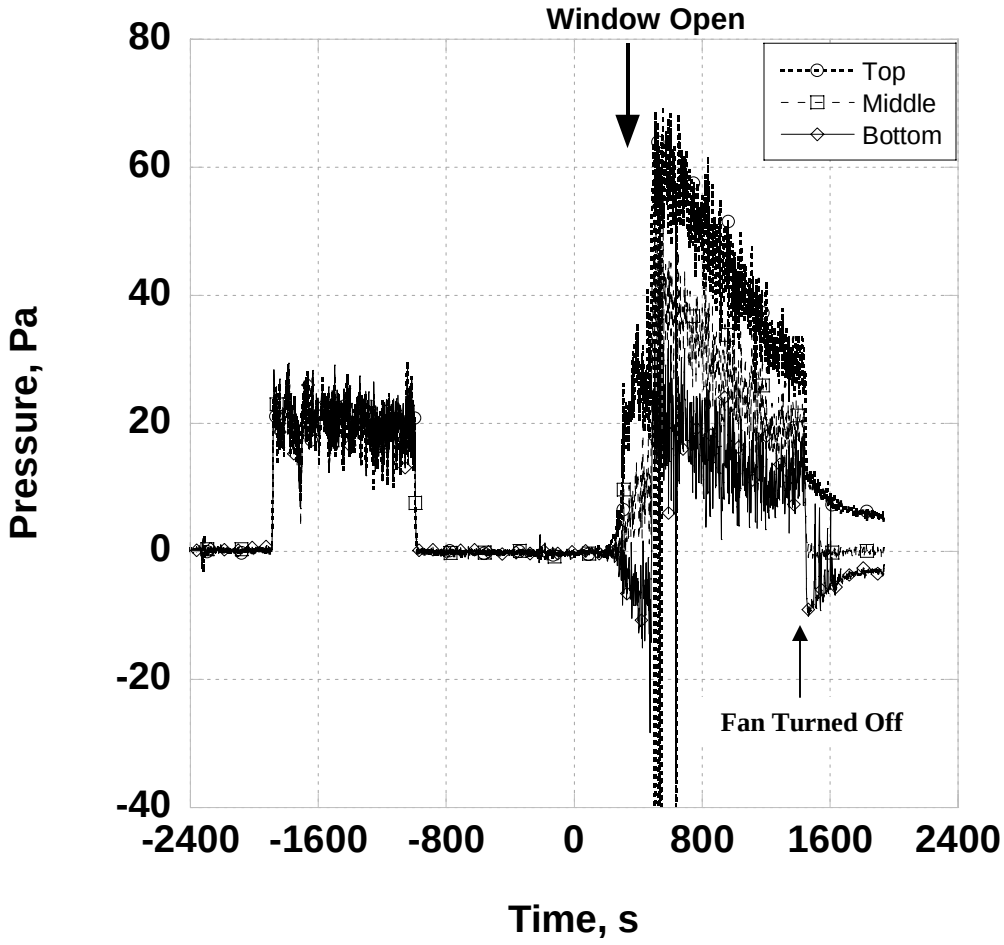

Figure 39 - PPV Room Differential Pressure

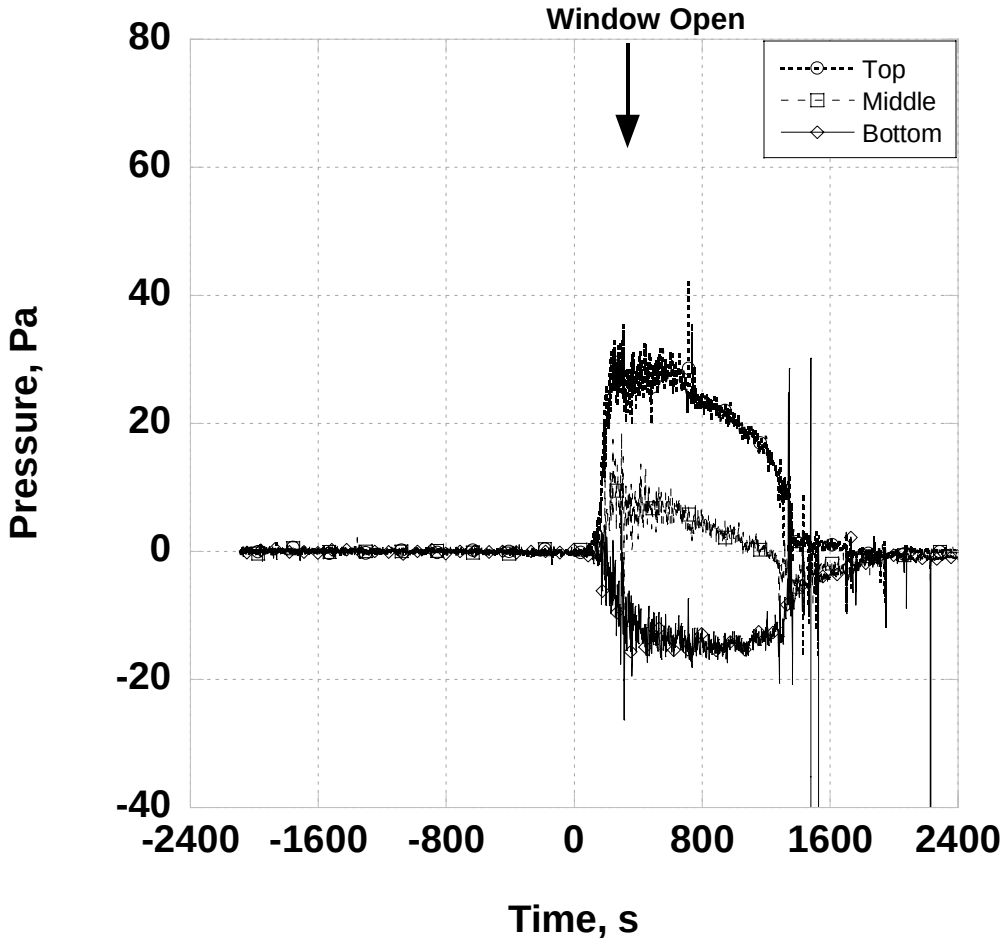

Figure 40 - Natural Ventilation Room Differential Pressure

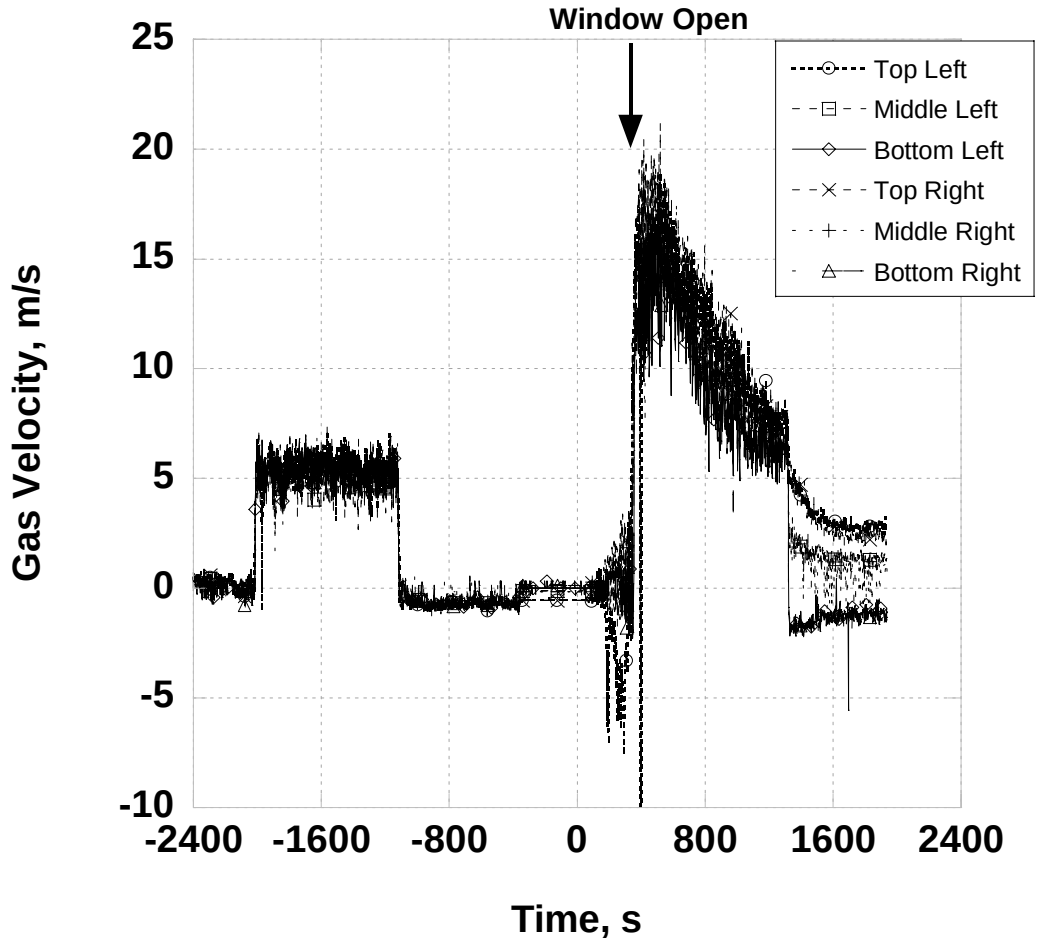

Figure 41 - PPV Window Velocities

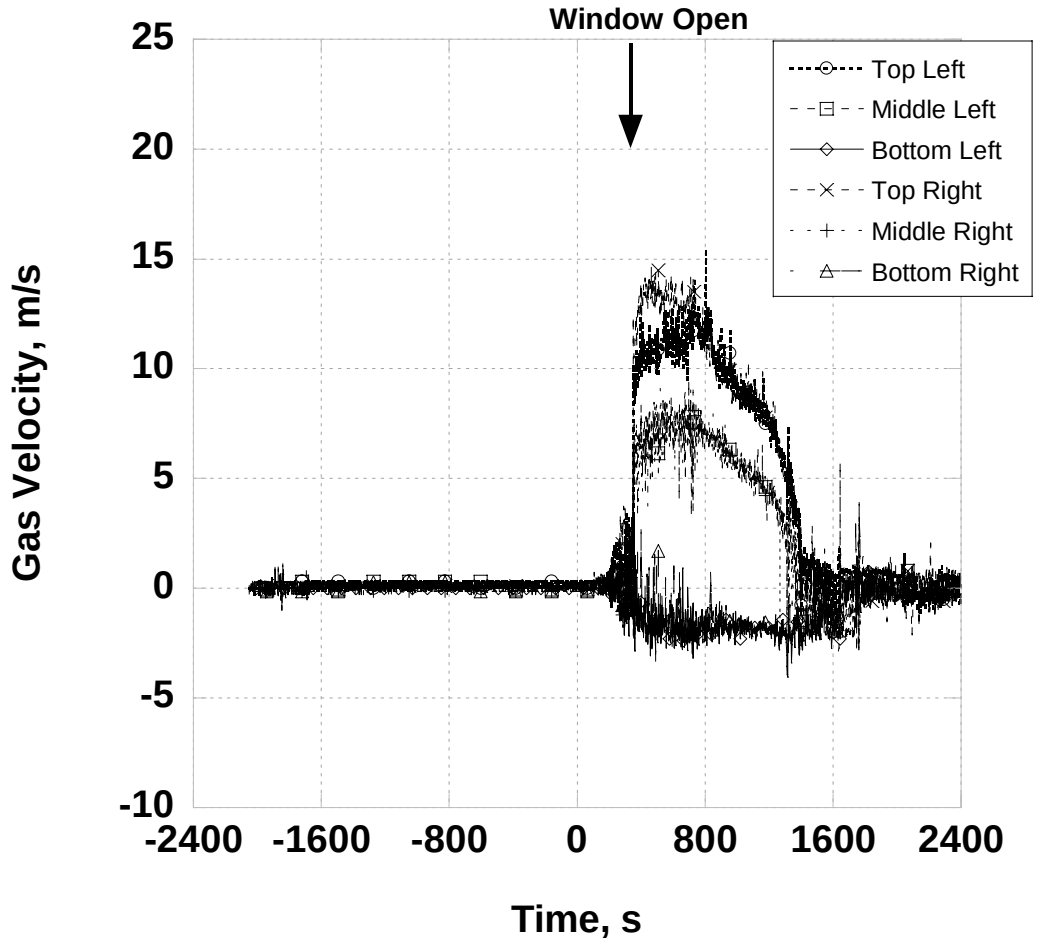

Figure 42 - Natural Ventilation Window Velocities

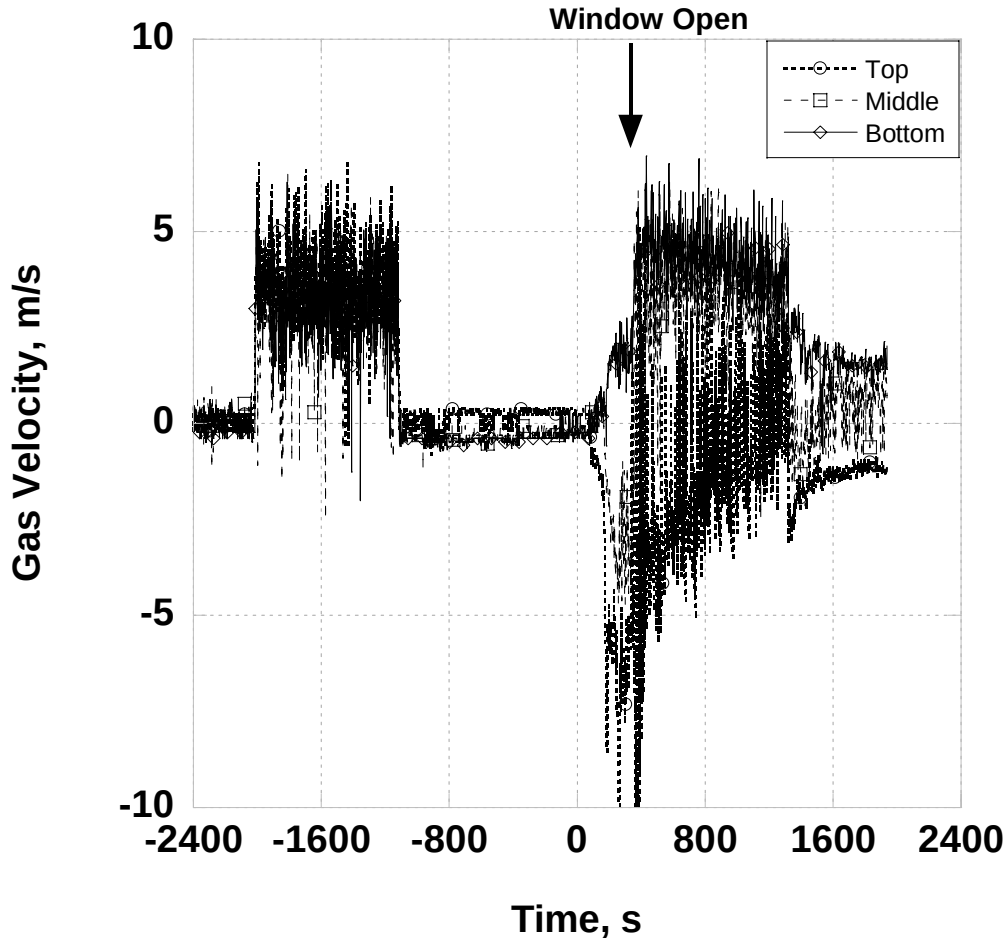

Figure 43 - PPV Room Doorway Velocity

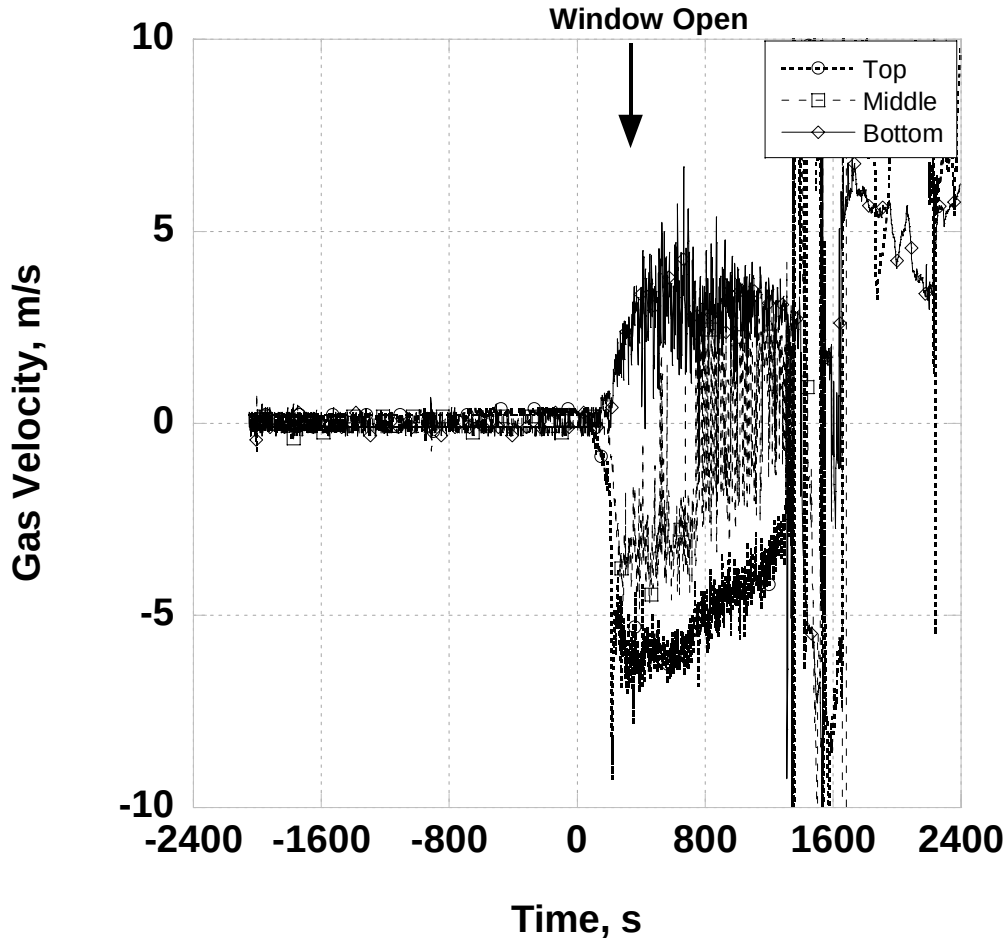

Figure 44 - Natural Ventilation Room Doorway Velocity