Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices

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Executive Summary

There is a continued tragic loss of firefighter and civilian lives, as shown by fire statistics. One significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from the use of ventilation as a firefighter practice on the fire ground. The changing dynamics of residential fires as a result of the changes in home construction materials, contents, size and geometry over the past 30 years compounds our lack of understanding of the effects of ventilation on fire behavior. Positive Pressure Ventilation (PPV) fans were introduced as a technology to increase firefighter safety by controlling the ventilation. However, adequate scientific data is not available for PPV to be used without increasing the risk to firefighters.

This fire research report details the experimental data from cold flow experiments, fuel load characterization experiments and full scale fire experiments. During the project it was identified that the positive pressure attack (PPA) and positive pressure ventilation (PPV) were often used interchangeably. For the purpose of this report they have been defined as PPA for when the fan is utilized prior to fire control and PPV for when the fan is used post fire control.

The information from the full scale tests reviewed with assistance from our technical panel of fire service experts to develop the tactical considerations for the use of PPV fans in residential single family structures. A summary of these tactical considerations are as follows:

Understanding the Basics of Positive Pressure Ventilation/Attack - An understanding of pressure, how pressure creates flow, and the how flow is associated with ventilation is essential to fully understanding PPA and PPV are either effective or in effective in ventilating a residential single family structure.

Horizontal, Vertical and Positive Pressure Attack are different tactics. - No one tactic will work in every scenario. Understanding the fire environment with emphasis on ventilation limited fire dynamics and how fire department operations impact those will ensure the tactic chosen is most effective.

The setback of the fan or development of a cone of air is not as important as the exhaust size. - In the application of PPA a great deal of emphasis has been placed on the flow occurring at the front door. Ensuring the "cone of air" does not equate to most effective flow. An aqueduct size exhaust more important for creating the intended flow.

During PPA, an ongoing assessment of inlet and exhaust flow is imperative to understanding whether or not a fan flow path has been established and if conditions are improving - The fire attack entrance cannot tell you the conditions at the exhaust location(s). Assessing both the inlet, exhaust locations and interior conditions together provide the best assessment of PPA effectiveness.

Positive Pressure Attack is Exhaust Dependant. - For PPA to be effective the pressure created by the fan must be greater than the pressure created by the fire. Although fan size does play a role in the effectiveness of PPA, exhaust size plays a greater role. Providing enough exhaust to reduce the pressure in the fire room below what the fan is capable of producing in the remainder of the structure is essential for safe PPA operations.

An outlet of sufficient size, must be provided, in the fire room to allow for effective PPA. - PPA effectiveness is directly dependent on the ability of the fan to exhaust products of combustion to the exterior. Any exhaust opening created in conjunction with PPA should be located in the fire compartment.

During PPA, creating additional openings not in the fire room will create additional flow paths making PPA ineffective with the potential to draw the fire into all flow paths. - Additional openings not in the fire compartment, will lower the pressure in the adjacent compartments, allowing for more flow from the fire compartment to the remainder of the structure.

The safety of PPA is decreased when the location and extent of the fire is not known with a high degree of certainty. - To ensure the exhaust is provided in the most effective location it is essential to identify the location of the fire. Several indicators are available to aid firefighters in this identification such as heat signatures identified via thermal imaging cameras and smoke/neutral plane conditions.

PPA will not be effective on a fire located in an open concept floor plan or any floor plan with high ceilings. - In order for positive pressure attack to be effective, the fan must be capable of increasing pressure in the adjacent compartments. This forces the products of combustion out of the structure rather than into adjacent compartments. This pressure increase is only possible where the fire is located within a compartment.

The application of water, as quickly as possible, whether from the interior or exterior prior to initiating PPA will increase the likelihood of a successful outcome. - The application of water onto a compartment fire has been shown to slow the growth rate, increasing firefighter and occupant safety while decreasing property loss. This makes rapid hose line deployment a top priority for first arriving crews. Although positive pressure attack can improve the efficiency of a hose stretch, is not a substitute for the application of water on the seat of the fire. This early application of water will aid in the effectiveness of PPA.

PPA is not a replacement for using the reach of your hose stream. - Although PPA can reduce temperatures as crews approach a fire, it is not a replacement for the reach of a hose stream. Applying water as you approach the fire reduces the heat release rate making PPA most effective.

During PPA, extension into void spaces is directly related to the exhaust capabilities of the void space. - In order for fire extension into the void space there must be an entrance (penetration) for the fire and am exit(exhaust) for the products of combustion to leave.

PPA does not negatively affect the survivability of occupants behind a closed door. - Prior research shows the importance of having a closed door between occupants and the fire if they are unable to escape. These PPA experiments reinforced this assessment as temperatures and gas concentrations in the closed or isolated rooms remained tenable while conditions in open compartments exceeded tenability thresholds.

When PPV is used, in single story residential structures, the more openings made in the structure during PPV (Post Knockdown) the more effective it is at ventilating the structure. - The 18 in. gas fan used was capable of moving so much air it could exhaust through more than 5 times the inlet size to most efficiently remove products of combustion. As the number of exhaust points increased the exhaust flow continued to increase. The greater the exhaust flow, the faster the structure was ventilated.

When PPV is used, it is important to assess for extension. - While the fan provides additional visibility after

fire control by exhausting products of combustion out of the structure faster, it also has the potential to hide extension in void spaces. Directing attention to these spaces immediately following knockdown will limit the possibility of extension.

When PPV is used, starting or turning in the fan immediately after fire control will provide the most benefit. - Once water is on the fire and the attack crew has the upper hand, fans will assist with increasing visibility and reducing temperatures to ambient to allow for other fire ground operations like search, rescue and overhaul to happen faster and more efficiently. The use of the fan must be coordinated with interior crews and incident command to ensure

re control has been achieved.

Contents

1 Tactical Considerations

1.1 Understanding the Basics of Positive Pressure

Pressure

Pressure in the fire service is typically thought of in the Units of pounds per square inch (PSI), as this is the standard pressure unit for many of the pump panel gauges on an engine. This however is not the only unit for pressure. The scientific community uses the units of Pascal (Pa). 1Pa is equal to 0.00015PSI. Standard atmospheric pressure, 1atm is equal to 14.7PSI or 101,325Pa. When pressure is discussed in this report it is referring to the differential pressure (ΔP) where the reference pressure is atmospheric pressure. An example of this would be the interior pressure of a house as compared to an the outside pressure. The ΔP could be 5Pa where the pressure inside would be 101,330Pa and the exterior pressure is 101,325Pa.

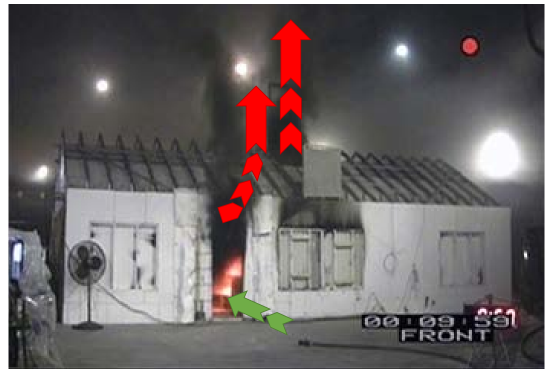
Fire Flows are Caused by Pressure

One by-product of the combustion reaction is heat, most often thought of as "hot gases". The hot gases are made of up the products of combustion mixed with the air in the proximity of the fire. As these gases are heated they expand, becoming less dense. When confined in a compartment or structure, the expanding gases create pressure. When one area of a structure has a different pressure than an adjacent area a flow occurs. The greater the differential pressure the greater the velocity of flow. Pressure always flows from high to low. This flow is the primary method of heat transfer (convention) from one compartment to the next in a structure fire.

Ventilation

The gases and soot produced during a fire are less dense than the density of the ambient air both inside and outside the structure. This makes them buoyant. When fire fighters preform ventilation they are using this buoyancy to their advantage. The less dense fire gases flow out of the structure. As less dense gases flow out of the structure up high, they create a lower pressure inside than outside, drawing in ambient air down low. The flows during both horizontal and vertical ventilation use the buoyancy of the gases in order to reduce temperatures, toxic gas concentrations and given enough time visibility if ordinated with water suppression. Positive pressure ventilation seaks to alter the buoyant flows within the fire.

(a) Flow with Horizontal Ventilation



(b) Flow with Vertical Ventilation

(c) Flow with Positive Pressure Ventilation

Figure 1.1: Comparing Horizontal Vertical and Positive Pressure Ventilation Flows in a Living Room Fire

Positive Pressure Attack/Ventilation

The intent of positive pressure attack or positive pressure attack/ventilation is to alter the flow of the products of combustion within a structure. In theory the fan creates a uni-directional inlet of ambient air which replaces the heat, smoke and toxic gases as they are forced out the unidirectional exhaust. This is accomplished by increasing the pressure in adjacent compartments to force the products of combustion out of intended exhaust locations. Altering flow has the potential to reduce temperatures, gas concentrations all while increasing visibility. The tactic can be employed prior to fire control and is defined as positive pressure attack (PPA) or post fire control defined as positive pressure ventilation (PPV). Figure 1.2 illustrates a possible ventilation profile for PPA on a bedroom fire in a single story structure.

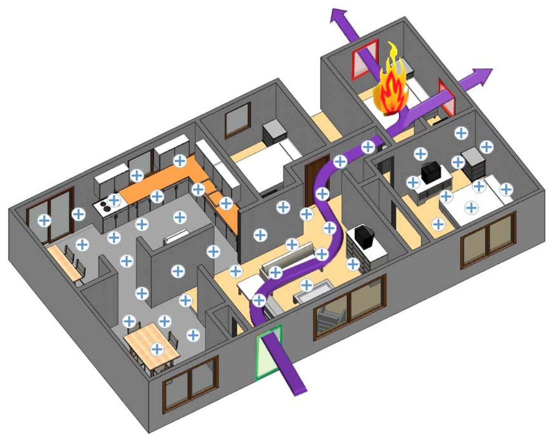
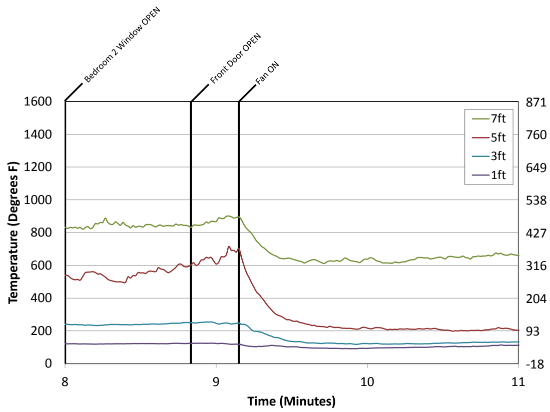
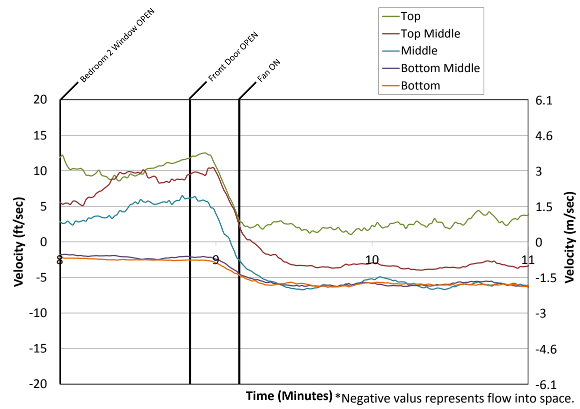


Figure 1.2: Positive Pressure Attack/Ventilation

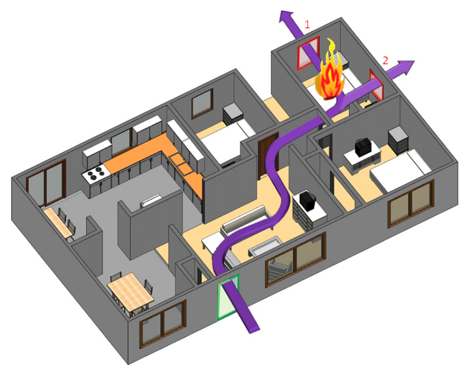
When PPA is employed correctly, using the fan to direct the heat created by the fire out an exhaust opening rather than allowing it to flow back into the structure it is very effective at controlling the temperature. As seen in figure 1.3 the fan is was capable of reducing the temperature in the hallway by directing the majority of the flow out the bedroom 2 windows rather than back into the hallway. This can be confirmed in figure 1.3b where the velocity of the flow coming out of bedroom is reduced once the fan is applied.



(a) Hallway Temperature



(b) Bedroom 2 Doorway Velocity



(c) Ventilation Profile

Figure 1.3: Positive Pressure Attack - Controlling Flows

It is not as effective at increasing visibility because the interior environment is often already charged with smoke, which although diluted by the fan with clean cool air, does not reduce the optical density enough to increase visibility. The area of the structure charged with smoke must be all exhausted through the fire room which requires a substantial amount of time. Figure 1.4 graphically shows the volume which would need to be exhausted through the fire room in a single story ranch home. Although the fan is capable of exhausting the built up smoke, in the research conducted this occurred on the order of 3-5 minutes. It is not recommended nor practical to wait 3-5 minutes prior to applying water to the fire.

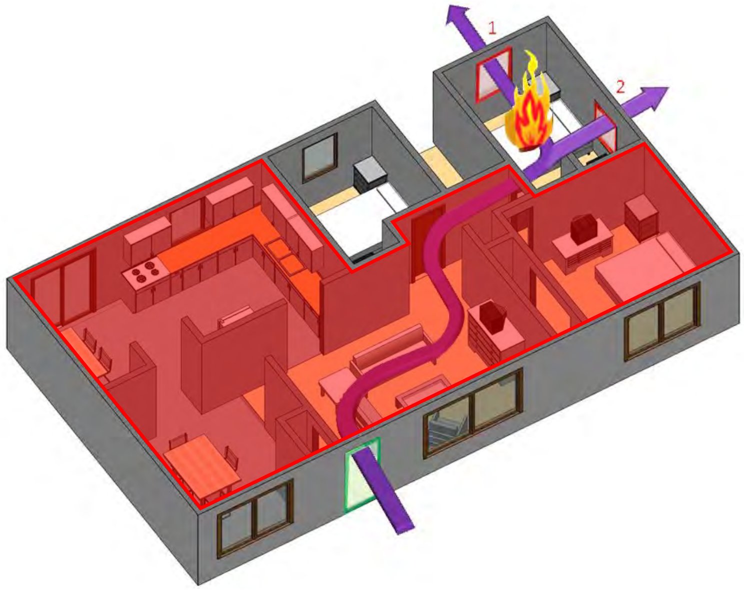


Figure 1.4: Volume of Built-Up Smoke to Exhaust

1.2 Horizontal, Vertical and Positive Pressure Attack are different tactics.

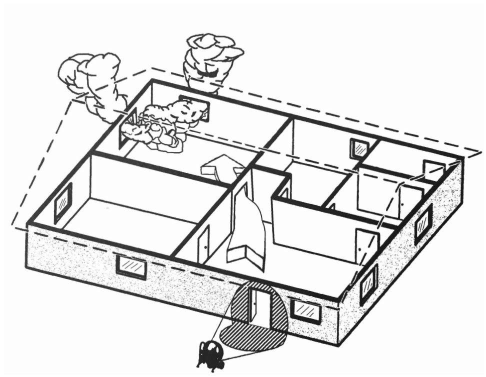
No one tactic will work in every scenario. Understanding the fire environment with emphasis on ventilation limited fire dynamics and how fire department operations impact those will ensure the tactic chosen is most effective.

In a scenario with a bedroom fire isolated from the remainder of the structure with a single doorway and multiple or one large window, positive pressure attack may be the most effective means of controlling the flows within the structure. If the bedroom does not have a large window, utilizing horizontal or vertical ventilation with door control may be the more effective option.

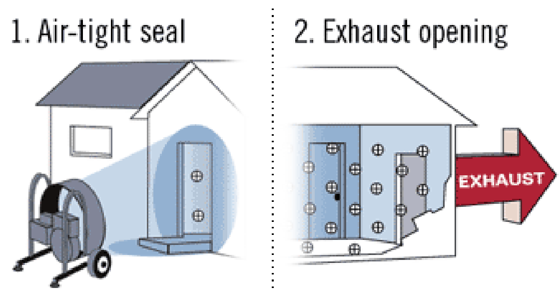
With proper training and education they can all be implemented successfully to improve life safety, property conservation and incident stabilization. Water must be applied in coordination with each of these ventilation tactics for successful outcomes. For example, if in a compartmentalized structure, PPA will transition a ventilation limited compartment fire to flashover faster, however temperatures will be lower in adjacent spaces and return to ambient in those spaces faster with water application.

1.3 The setback of the fan or development of a cone of air is not as important as the exhaust size.

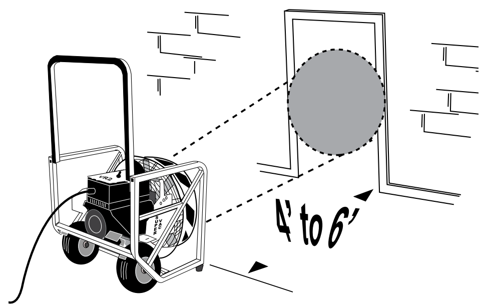
In the application of PPA a great deal of emphasis has been placed on the flow occurring at the front door. It was thought, if a "cone of air" was placed over the door the result would be inflow through the door, pressurizing the structure and forcing all flow out the exhaust openings. Manuals make reference to ensuring PPA effectiveness by evaluating for total inflow at the inlet (Figure 1.5).



(a) Fan Setup [1]



(b) PPA [2]

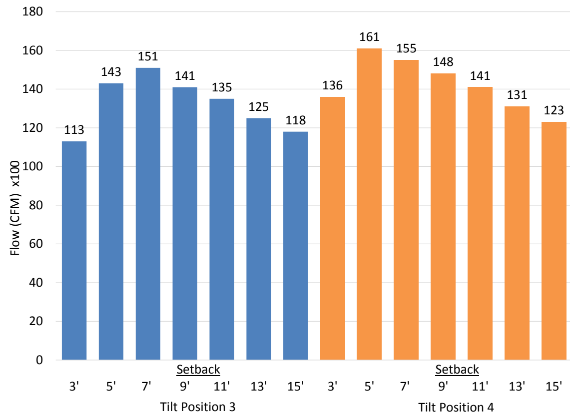


(c) Setback Distance [8]

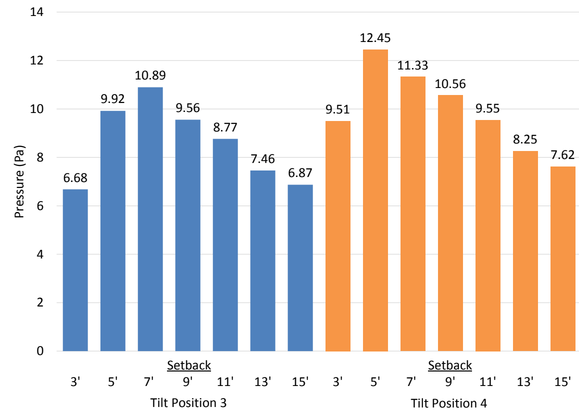
Figure 1.5: Images of "Cone of Air" in Fire Service Literature

Section 1.4 will discuss how the inlet being complete inflow was not noted in any of the fire experiments. The pressure gradient seen when the flows from the fire are opposed by the flow from the fan as illustrated figure 1.7 prevent complete inflow. To effectively counteract the flow from the fire, an airtight seal as indicated in figure 1.5b would be required. This is not possible with a positive pressure fan. Instead of focusing on the flow at the inlet, focus should be on pressure created and exhaust size.

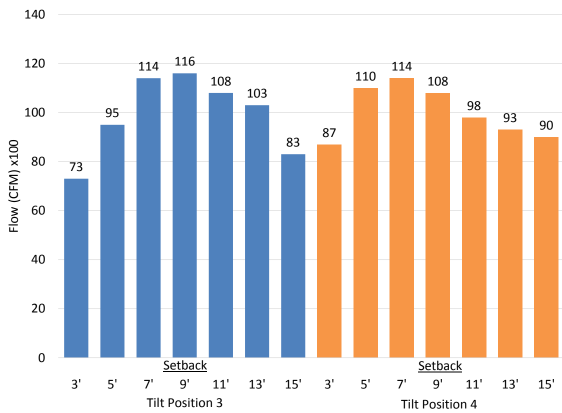
The effectiveness of PPA can be tied directly to the pressure created inside the structure. Flow will always be from a higher pressure to lower pressure. The difference in pressure between compartments determines the direction of flow. The intent of PPA is to increase the pressure in adjacent compartments higher than the fire compartment to prevent the flow of products of combustion from the fire compartment to the remainder of the structure. During the cold flow experiments, the greatest pressure increase in the adjacent compartments occurred when the fan was placed between $5ft$ and $9ft$ from the inlet with the maximum tilt angle. Figure 1.6 shows the results graphically.



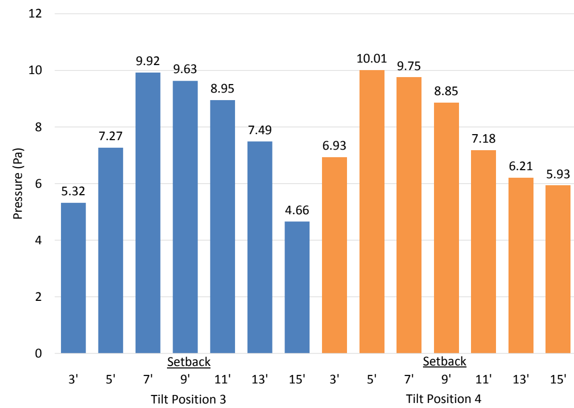
(a) Flow Exiting Bedroom 2 Window



(b) Master Bedrooom Pressure



(c) Flow Exiting Bedroom 3 Window



(d) Family Room Pressure

Figure 1.6: Fan Setback Results

The configuration was independent of structure size however only represents the optimal setback for the fan tested. Departments utilizing PPA should verify the most effective placement for their particular fan to produce the greatest pressure increase in adjacent compartments. This cannot be evaluated solely by developing a ”cone of air”. Much like a pump operator must have an understanding of the pressure required to flow a given nozzle, firefighters need to have an understanding of how much pressure their fan can produce prior to the incident. If the fan is not capable of providing the pressure required to overcome the pressure created by a fire that fan will not be effective for positive pressure attack.

Relatively inexpensive differential pressure sensors can be used to measure the pressure created by the fan. Setting up the fan in cold flow configurations, with a differential pressure sensor reading the interior and exterior pressure, can give help develop an understanding of the capabilities of a particular fan. The fan should be capable of increasing the pressure in the entrance space higher than a fire in a compartment could create.

In addition to creating as much pressure as possible in adjacent compartments, it is imperative the pressure created by the fan not provide additional pressure to the fire room. This is accomplished by providing greater than a 1:1 exhaust to inlet ratio, and understanding how the interior doorway acts a separation to help maintain the pressure in the adjacent spaces. See tactical consideration 1.5 and 1.9 for more information.

1.4 During PPA - An ongoing assessment of inlet and exhaust flow is imperative to understanding whether or not a fan flow path has been established and if conditions are improving

The fire attack entrance cannot tell you the conditions at the exhaust location(s). It is important to watch for changes at fire attack entrance and exhaust as opposed to just a snapshot. "You can not set it and forget it. "This ongoing assessment provides indications as to the effectiveness of the tactic.

When assessing the inlet it is important to understand you cannot achieve a unidirectional flow at the front door. The opposing nature of the exhaust flow from the fire with the flow from the fan results in a non-uniform pressure in the cone of air on the inlet (Figure 1.7).

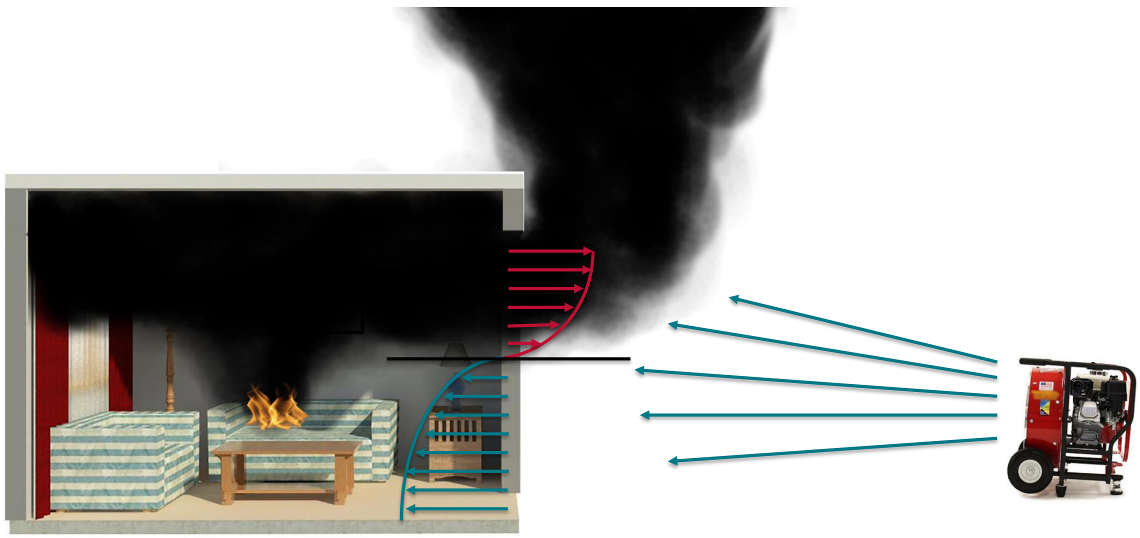
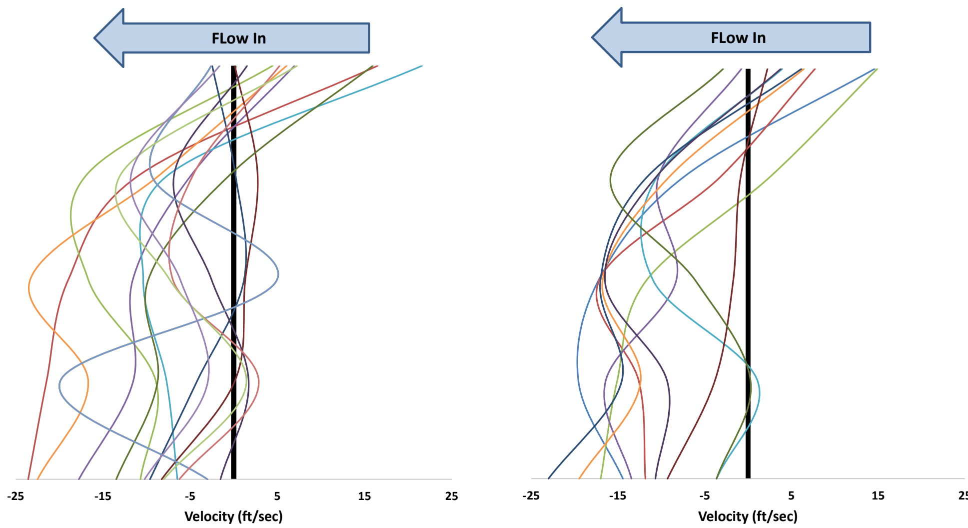


Figure 1.7: Inlet Flows During Positive Pressure Attack

The pressure in the structure is greater than the outside pressure. This, combined with the non-uniform pressure from the fan will result in back flow from the top of the doorway. Figure 1.8 illustrates the front door flow once steady state had been reached for each ventilation configuration tested in the single story and two story structures. The center line is zero flow, any values to the right of the center are outflow and to the left of the line are inflow. Regardless of the exhaust size or location back flow was always seen at the inlet.

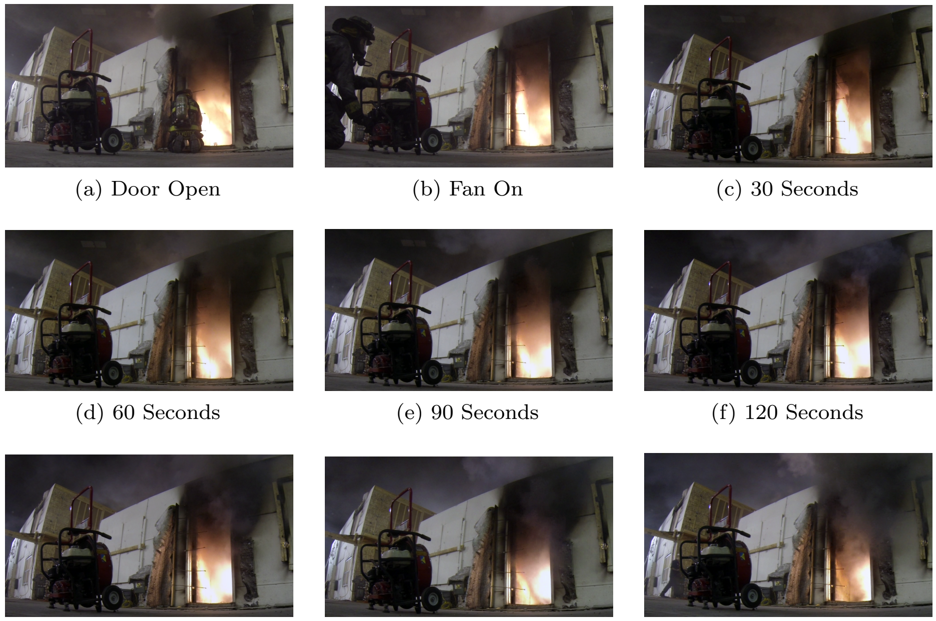


(a) Single Story (b) Two Story

Figure 1.8: Front Door Velocity

If the fire is producing a low HRR because it has decayed due to lack of oxygen or is a small fire such as a trash can or food on the stove, you can get what appears to be flow through the whole doorway. With no smoke in the space, the periodic exhaust seen at the top of the door during ventilation limited fires is not visible. The experiments conducted for this project were room fires with the potential for flash over conditions. They had built up smoke in the entire structure which resulted in the visual flow out the top of the door.

Although backflow at the front door does not indicate the effectiveness of PPA, several other indicators were observed. At the inlet, flow out the top of the door was observed immediately after the door is opened. This is the smoke which has been confined to the compartment the inlet is located in. Once PPA is initiated, if the exhaust is effective, over time this smoke will decrease in volume. Increased smoke volume or darkening color at the attack entrance may indicate that there is too little exhaust. Use both the neutral plane at the attack entrance and at the exhaust to identify progress. A descending neutral plane at the front door indicates the flow moving towards the fan is increasing, potentially indicating the fire is extending or spreading out of the initial fire compartment.



(a) Door Open (b) Fan On (c) 30 Seconds

(d) 60 Seconds (e) 90 Seconds (f) 120 Seconds

(g) 150 Seconds (h) 180 Seconds (i) 210 Seconds

Figure 1.9: Reading the Inlet

When assessing the exhaust locations (s), the impact of PPA will be noticeable within seconds (Figure 1.10). When the exhaust is first created the buoyant flows will result in a neutral plane located somewhere in the window depending on the location of the fire and stage of fire growth. The high pressure hot gases (smoke) will flow out the top of the window above the neutral plane. A gravity flow of cooler ambient air will flow in the bottom below the neutral plane. Once the fan is turned in, the neutral plane should drop to the windowsill and the exhaust should become a unidirectional flow indicating the fan flow path has been established. A neutral plane above the window sill on the exhaust opening while conducting PPA indicates more flow is required or an obstruction exists between the inlet and the exhaust. This indicates either additional actions such as increasing the fan or ensuring now obstruction exists. If increased exhaust vent flow cannot be established within a short period of time crews should stop the fan and consider implementing a different tactic.

(a) Exhaust Without Fan Flow - Pre Flashover

(b) Exhaust With Fan Flow - Pre Flashover

(c) Exhaust Without Fan Flow - Post Flashover

(d) Exhaust With Fan Flow - Post Flashover

Figure 1.10: Reading the Exhaust

In addition to monitoring exterior conditions, interior crews must be monitoring interior conditions. Ineffective PPA has the potential to cause conditions to deteriorate faster than would be noted in horizontal or vertical ventilation. Identifying and reacting to deteriorating conditions becomes even more essential during PPA. With the fan introduced, interior crews should notice a decrease in temperature and increased visibility over time. If this is not the case the structure should be evacuated until the elements required for a successful PPA are re-evaluated.

1.5 Positive Pressure Attack is Exhaust Dependant

For PPA to be effective the pressure created by the fan must be greater than the pressure created by the fire. Although fan size does play a role in the effectiveness of PPA, exhaust size plays a greater role. Providing enough exhaust to reduce the pressure in the fire room below what the fan is capable of producing in the remainder of the structure is essential for safe PPA operations.

A fire in post flashover state, venting to the exterior was seen to produce between 9Pa and 11Pa of pressure in the upper layer 1ft from the ceiling. This means for the fan to prevent flow from the fire compartment to an adjacent compartment, the adjacent compartment needs to be at least 9Pa higher, preferably 11Pa higher.

Table 1.1: Venting - Post Flashover Fire Room Pressure Increase

Experiment Number	δ Pressure (Pa)	Time Period (Min)
6	11.10	7:40 - 8:00
8	9.64	8:50 - 9:08
9	10.56	8:00 - 8:40
10	10.62	6:20 - 6:35
11	10.71	7:55 - 8:10
12	11.27	7:30 - 8:00
Average	10.65	-

Note: Only experiments where post flashover fire venting to the exterior, prior to starting the fan were utilized in this analysis.

With the intent of PPA to direct the flow out of the exhaust vent rather than into the structure, creating the pressure differential is imperative. The greater the differential pressure between the fire room and adjacent spaces, the more effective the PPA will be at keeping fire gases out of the adjacent spaces.

The most effective way to ensure that the pressure from the PPA in the adjacent compartments is higher than the pressure in the fire room is to have the exhaust openings in the fire room be larger than the inlet of the opening to the fire room. For this reason, a great deal of emphasis has been placed on the ideal exhaust to inlet ratio for PPA. The inlet size was thought to be the opening where the fan was placed. The true inlet however is the opening to the fire compartment. In the structures tested the interior doors had $16.7ft^2$ of opening area and the entrance door had $20ft^2$ of opening area. It should be noted that in most structures the front door size is slightly larger than interior doors, however not vastly different sizes, thus the front door can be used as an approximation of the interior door size.

The experiments found PPA most effective when the fire was in a compartment separated from the remainder of the structure (see tactical consideration 1.9). Figure 1.11 illustrates the opening sizes and intended fan flow for several of the experiments conducted. In the structures tested the bedrooms had windows with $15ft^2$ of opening area per window with either one or two windows per bedroom. The bedroom door opening of $16.7ft^2$ provided a limiting point for the flow, making the pressure in the living room and hallway higher than the pressure in the bedroom when the $15ft^2$ window was open. However, because the window opening was smaller than the bedroom door the amount of flow exhausting the bedroom window was less than what was entering the bedroom door making the window the most limiting. This resulted in a pressure increase in the bedroom.

In order to create the intended fan flow the pressure in the fire room must be lower than the pressure in adjacent spaces. As seen in figure 1.12 done under cold flow conditions, when positive pressure attack is utilized the entire volume of the house is more or less at the same pressure with the exception of the room where the exhaust is provided (bedroom 2). The lower pressure in the bedroom creates a flow from the high pressure the adjacent spaces into the lower pressure bedroom and out the low pressure vent. When the single window was open providing an exhaust to inlet ratio of approximately 1:1, the pressure in the exhaust room (bedroom 2) was 1/2 the pressure of the living room. Once the second window as open, the door to the bedroom became the limiting factor for flow in, resulting in no pressure increase in the bedroom.

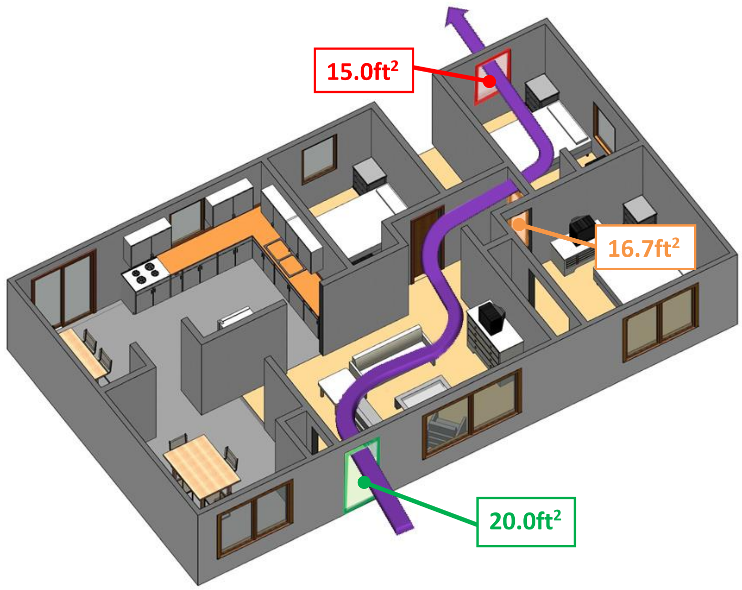
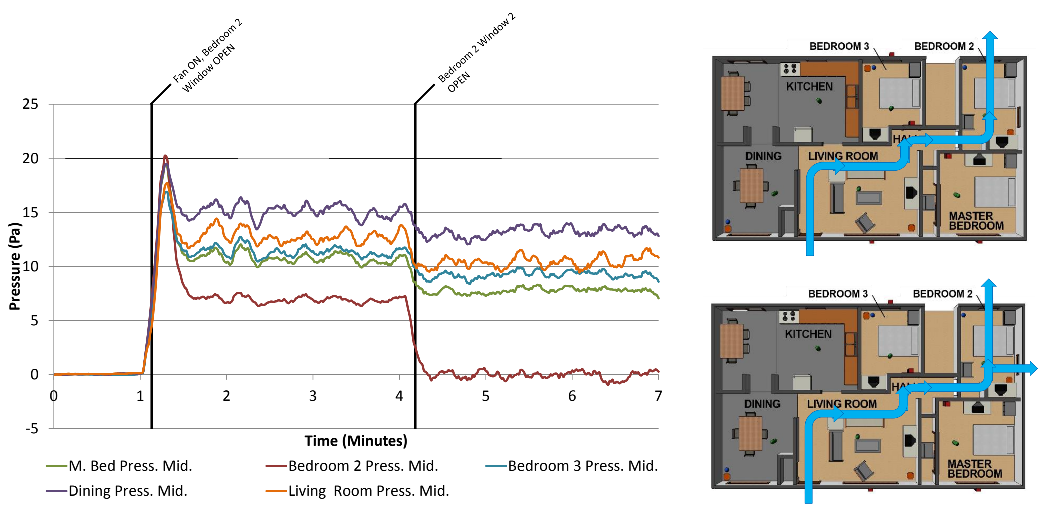


Figure 1.11: Opening Sizes - Single Story Ranch Structure

With this principal in mind, any exhaust to inlet ratio greater than 1:1 will not result in a pressure rise in the fire compartment due to the fan, only what the fire is capable of producing. In the configuration shown, as long as the fan is capable of creating greater than 11Pa of pressure in adjacent spaces, all of the products of combustion being created in the bedroom will exhaust out the bedroom windows.



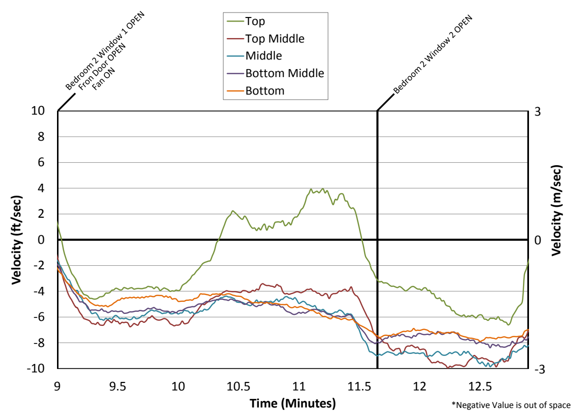
(a) Differential Pressures Within the Structure (b) Ventilation Configuration

Figure 1.12: Single Window vs. Double Window Cold Flow Pressure

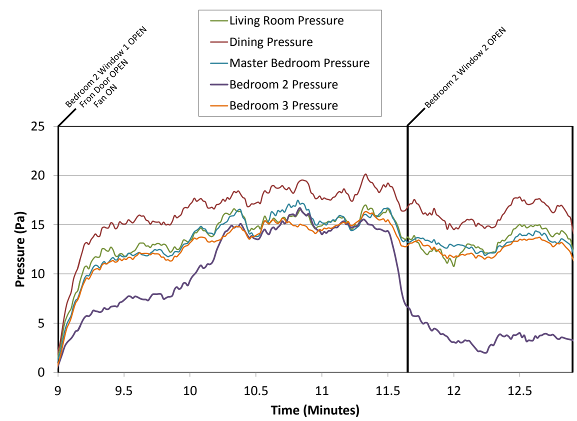
This also applies under fire conditions. If not enough exhaust is provided, the pressure created by the fire and the fan will overwhelm the pressure created by the fan causing the the fire to grow back towards the fan. The solution is to lower the pressure in the fire compartment by 1) create more exhaust openings in the fire compartment or 2) apply water to reduce the pressure created by the fire.

Testing demonstrated a 2:1 exhaust to inlet ratio was much more effective than a 1:1 or less ratio. Although under non-fire conditions the pressure in the bedroom with one window open is less then the remainder of the structure, when fire is introduced it creates additional pressure. As the heat release rate of the fire increases, the pressure in the fire room increases. At the point where the fire room pressure matches the remainder of the structure, combustion products will flow from the fire room into the structure again. This increases temperatures, and transfers smoke and toxic gases from the fire compartment to the remainder of the structure. Figure 1.13b illustrates the increasing pressure as the fire grows (bedroom 2). At 10:15, when the pressure in the fire room (bedroom 2) is equal to the adjacent spaces, hot gas flow exits the top of the bedroom 2 door and flows back into the hall as seen in figure 1.13a. Creating the additional exhaust opening in the fire compartment and reaching a 2:1 ratio of exhaust to inlet results in a decrease of pressure in the fire room and the products of combustion are all exhausted.

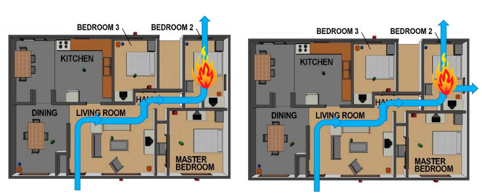
An additional means of reducing the pressure in the fire compartment would be through the application of water. Applying water to the fire reduces the heat release rate of the fire and thus the pressure it can produce. If the fire is not adding pressure to the pressure created by the fan, the pressure difference between the fire compartment and adjacent spaces created by the fan with one exhaust will direct the flow out the exhaust opening rather than back into the structure.



(a) Bedroom 2 Door Flow



(b) Pressure Throughout Structure



(c) Ventilation Configuration

Figure 1.13: Positive Pressure Attack - Single Window Vs Double Window Fire

Earlier research by NIST involved the impact of wind on positive pressure effectiveness. The work concluded positive pressure fans alone are not capable of overcoming the pressure created by the opposing wind condition. An exhaust on the windward side (high pressure side) of the structure will create a hazardous situation and should be avoided. If no other exhaust option is available firefighters should consider another tactic [3].

Proper exhaust size will limit the flow of heat and smoke from the fire compartment to the remainder of the structure. Heat and smoke flowing from the fire room towards the fan has the potential to cause vent point ignition at the fan inlet as seen in Figure 1.14 and 1.15. This is a very dangerous situation for fire fighters, as it indicates untenable conditions within the intended fan flow path, potentially cutting off the primary means of egress for the attack team.

Figure 1.14: Vent Point Ignition of Fan Inlet During Laboratory Experiments

Figure 1.15: Vent Point Ignition of Fan Inlet From Incident Video

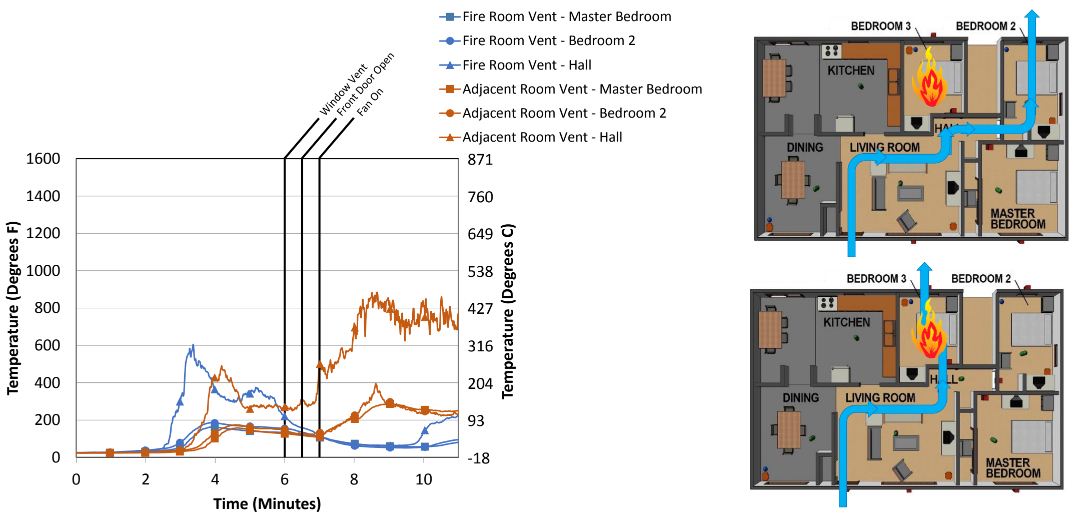
Providing additional exhaust in the fire room will not negatively effect positive pressure attack, it can only aid in ensuring the pressure created from the fire is not able to build and overcome the pressure created by the fan. With a single window often being less square footage than the size of the door to the room, it will be necessary to vent additional windows to achieve the greater than 1:1 ratio.

Many rooms only have one window or the sum of the area the windows in the room is less than the area of the door to the room. This does not mean the tactic of positive pressure attack will be ineffective, just that it will be less effective. An effort should be made to ensure the maximum exhaust ratio is achieved with all exhaust locations being in the fire room. If a minimum of a 1:1 ratio cannot be achieved, firefighters should consider a tactic other than PPA.

Even when the required pressure difference is achieved between the fire room and adjacent spaces, backflow at the inlet where the fan is located will still occur. See tactical consideration 1.4 for a description of why backflow at the inlet is not an indicator of what flows are occurring within the structure and alone cannot identify the effectiveness of a positive pressure attack.

1.6 An outlet of sufficient size, must be provided, in the fire room to allow for effective PPA.

PPA effectiveness is directly dependent on the ability of the fan to exhaust products of combustion to the exterior. Any exhaust opening created in conjunction with PPA should be located in the fire compartment. Exhaust openings not provided in the fire compartment will create unintended flow paths, resulting in the spread of smoke and potentially fire into the room the exhaust is made. For example as shown in figure 1.16 when a vent is opened in the fire room, most of the heat and smoke will be vented out the window resulting in temperatures remaining low in the adjacent rooms. When the exhaust vent is created in an adjacent room it results in temperature increase in that room.

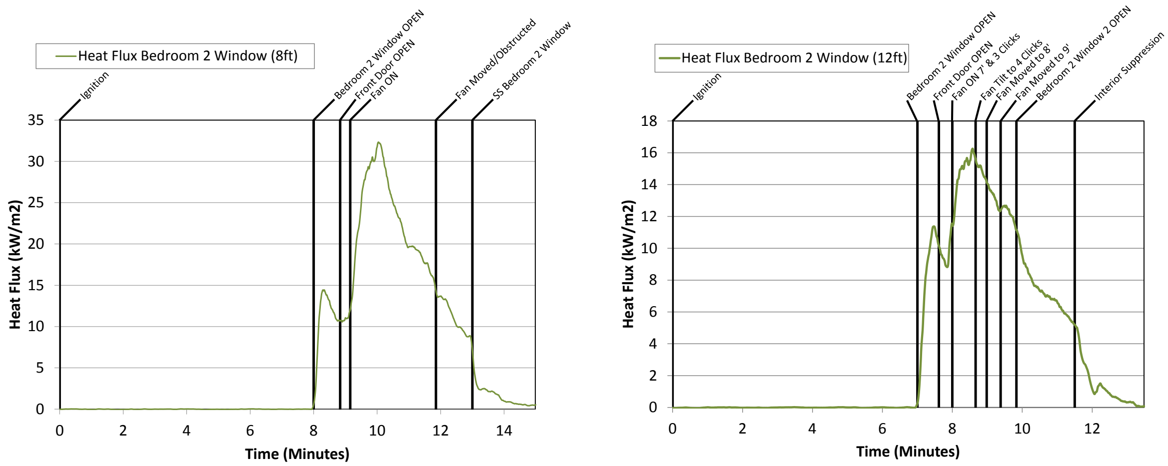


(a) 5ft Temperature in Adjcent Bedrooms & Hallway Comparison

(b) Ventilation Profile - Adjacent vs Fire Room Vent

Figure 1.16: Exhaust Location Comparison with Fire in Bedroom 3

Not only is the location of the exhaust important but also the area or size of the opening. Even when an exhaust opening is located in the fire compartment, if it is not of sufficient size, the effect will be similar to exhaust in an adjacent compartment. The pressure created by the fire combined with the pressure increase in the room due to the fan will exceed the pressure created by the fan in the adjacent space resulting in flow from the fire compartment into adjacent compartments. This results in increased temperatures, decreased visibility and decreased survivability as discussed in tactical consideration 1.5.



(a) Heat Flux from Window at 8ft

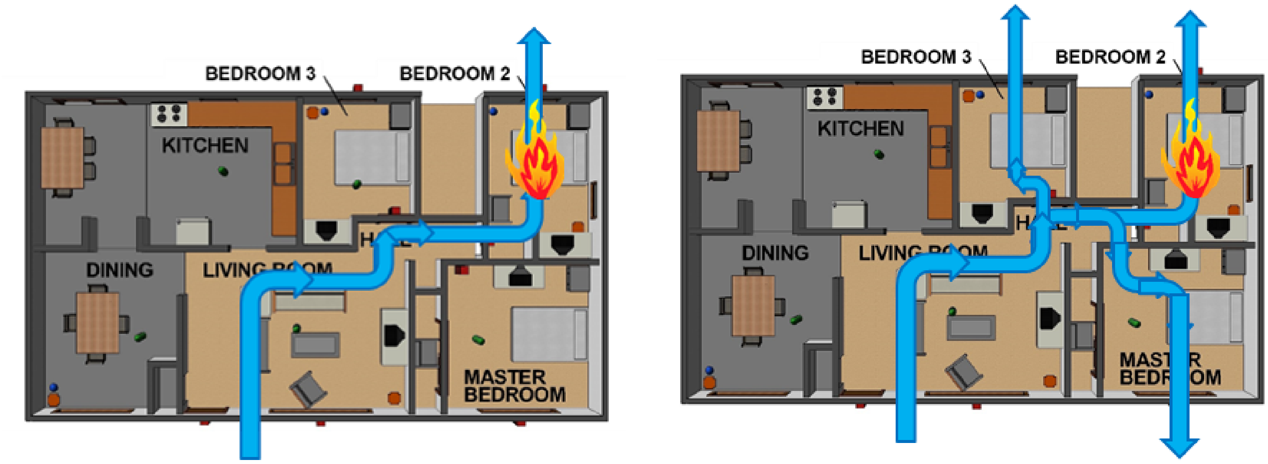
(b) Heat Flux from Window at 12ft

Figure 1.17: Heat Flux from Bedroom 2 Window Vent

As with any ventilation tactic, extension to exposures needs to be a consideration when utilizing PPA. The use of the fan intensifies the volume of fire venting from the exhaust window. As seen in figure 1.17 shows the energy received at 8ft away increases by almost 300% once the fan is introduced. At 12ft the increase is over 150%. Any exhausted created during PPA should be coordinated to limit the exposure potential.

1.7 During PPA - Creating additional openings not in the fire room will create additional flow paths making PPA ineffective with the potential to draw the fire into all flow paths

Additional openings not in the fire compartment, will lower the pressure in the adjacent compartments, allowing for more flow from the fire compartment to the remainder of the structure. An example of this would be ventilating all of the bedroom windows in a ranch home prior to implementing positive pressure attack (Figure 1.18).



(a) Configuration - Single Vent (b) Configuration - Multiple Vents

Figure 1.18: Additional Ventilation Outside the Fire Compartment

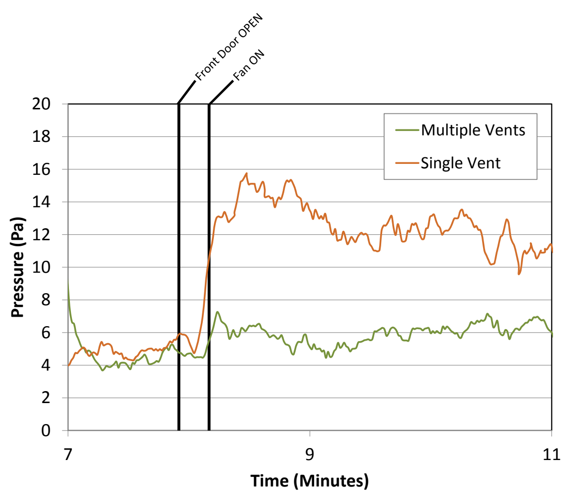
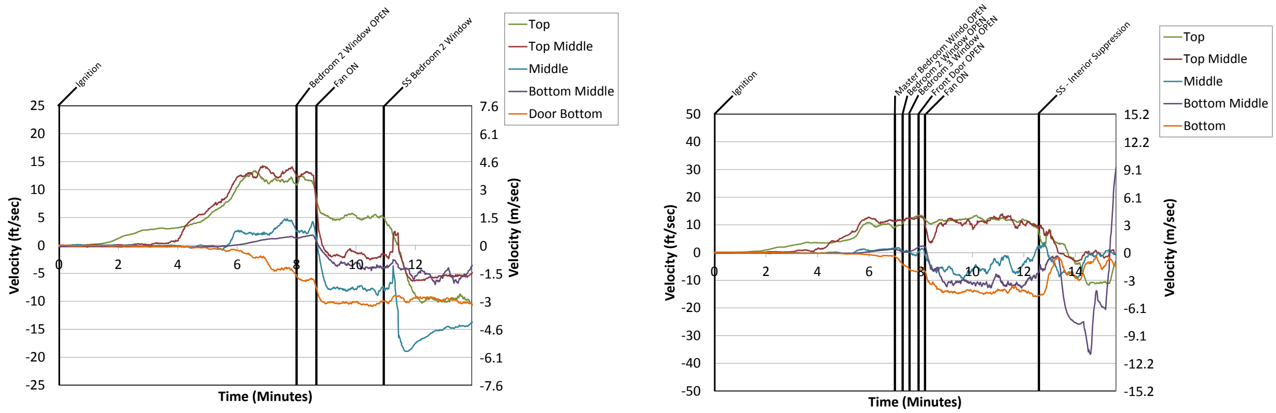


Figure 1.19: Additional Ventilation Openings Reduce Pressure Created by Fan

With four times the additional ventilation openings, the fan cannot maintain the same amount of pressure in the living room. Figure 1.19 shows the fan produced only approximately 1/2 the pressure increase when four times the ventilation openings were provided. The reduction in pressure in the living room resulted in additional fire gas flow from the fire room to surrounding compartments.



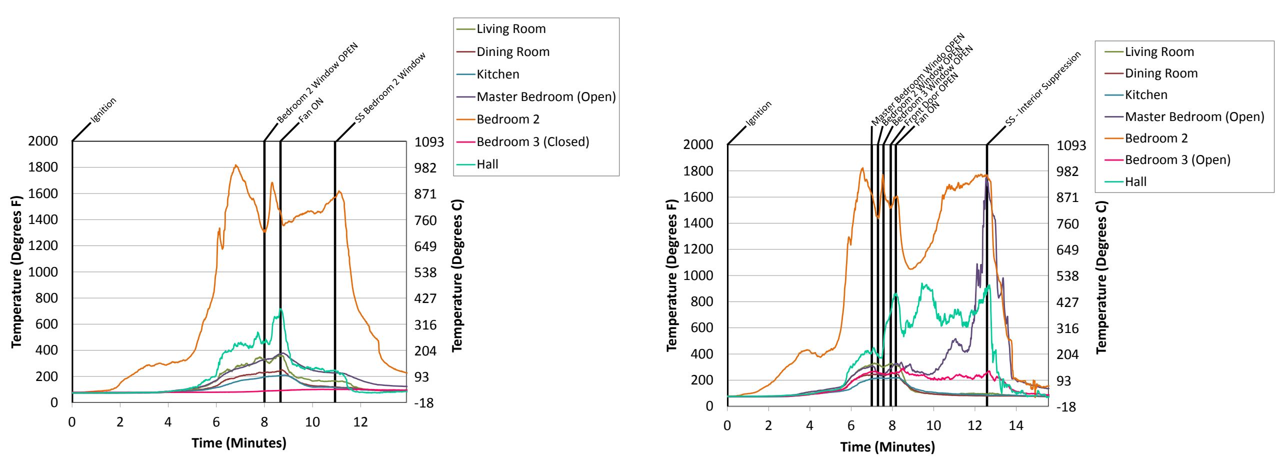
(a) Door Flow Bedroom 2 Door - Single Vent

(b) Door Flow Bedroom 2 Door - Multiple Vents

Figure 1.20: Additional Vents Outside the Fire Compartment Increases Flow to Adjacent Spaces

Figure 1.20 shows the flow exiting the top of the doorway from the fire room (bedroom 2) was more than double that of the single vent. In addition the outflow occurred at both the top and top middle measurement point. This additional flow represents additional products of combustion that in the single vent case would have been exhausted out the ventilation opening, but in the multiple vent case are flowing back into the structure.

The primary mode of heat transport from one compartment to another is convection. This increase in the flow out of the fire compartment results in heat transfer to other rooms in the structure. As seen in figure 1.21 the single vent in the fire room was able to exhaust most of the products of combustion created, reducing temperatures in adjacent spaces. The opposite occurs with additional vents as heat flows into adjacent spaces. The additional heat has the potential to ignite items in other rooms as seen the multiple vent case where the temperature in the master bedroom exceeds that of the hallway.



(a) 5Ft Temperatures - Single Vent

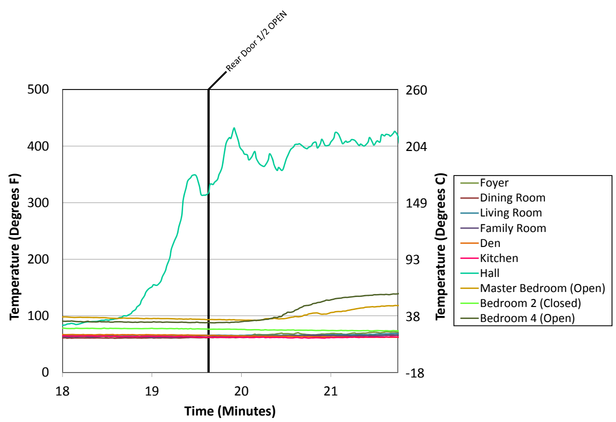
(b) 5Ft Temperatures - Multiple Vents

Figure 1.21: Products of Combustion Spreading to Adjacent Compartments Increase Temperature

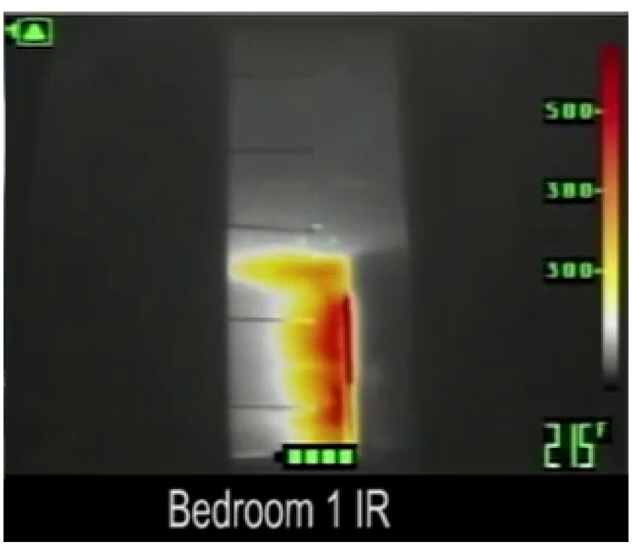
This is also noted in the two story structure where ventilation is provided via a rear door while crews are advancing onto a second floor, compartmented bedroom fire. This could occur as a search crew or additional hose crew enters from the rear while conducting PPA.

Figure 1.22: Two Story Structure Access from Side C

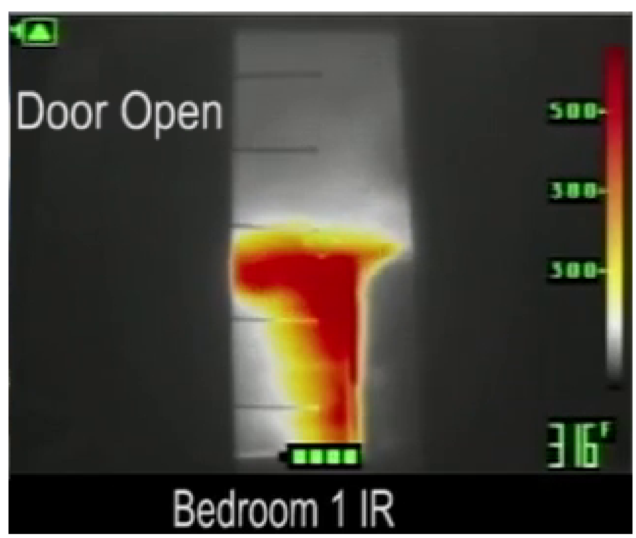
Creating this additional opening is additional ventilation. Opening the rear door decreases the pressure in the family room which allows the pressure created by the fire to overcome the pressure from the fan. The higher pressure fire room now flows into the lower pressure family room. With limited or no visibility this could potentially result in roll over occurring above unsuspecting crews. Controlling or closing the rear door after access would have reversed the flow through the bedroom once again, resulting in lower temperature and increased visibility in the hallway approaching the fire.



(a) 5Ft Temperatures - Additional Opening in Rear



(b) 5 Seconds Prior to Opening Rear Door



(c) 5 Seconds After Opening Rear Door

Figure 1.23: Products of Combustion Spreading to Adjacent Compartments Increase Temperature

This requires additional coordination between crews. Providing any additional openings outside the fire will create additional flow paths which can re-direct heat via convection onto potential victims and interior suppression/search crews.

1.8 The safety of PPA is decreased when the location and extent of the fire is not known with a high degree of certainty.

To ensure the exhaust is provided in the most effective location it is essential to identify the location of the fire. Several tools are available to aid firefighters in this identification. Thermal imaging cameras can be utilized from the exterior to identify heat signatures near windows and doors indicating where the highest temperatures exist in the structure.

In addition understanding how to "read" smoke conditions and evaluate a changing neutral plane will aid in determining the location and extent of the fire. Although smoke density and color can identify the general location of a fire, identifying changes in the neutral plane after creating an opening will aid in understanding the proximity of the opening created to the seat of the fire.

(a) Prior To Opening

(b) 5 Seconds After

(c) 10 Seconds After

(d) 20 Seconds After

Figure 1.24: Fire Room Neutral Plane

Figure 1.24 shows a ventilation opening provided in the fire compartment. The chronological pictures show a change in neutral plane, smoke color and density over the 20 second period shown. The neutral plane drops in the opening as the volume and density increase. In figure 1.25 the opening made shows little to no change in the neutral plan, smoke color or density. This is because the ventilation was not provided in the fire compartment but an adjacent connected compartment. The difference between providing an opening in the fire compartment and not in the fire compartment has to do with the distance the clean air must travel along the flow path to the seat of the fire. If the newly added air has to travel farther to interact with the fire it takes more time to cause identifiable changes in the smoke and consequently the neutral plane.

It is important to remember venting a window is not a temporary action. Once glass is broken it cannot be replaced. Whenever possible a doorway should be used to identify the location of the fire. Closing the door after inspecting the neutral plane will limit the heat release rate of the fire by limiting the available oxygen until crews are in position to implement PPA.

(a) Prior To Opening (b) 5 Seconds After (c) 10 Seconds After (d) 20 Seconds After

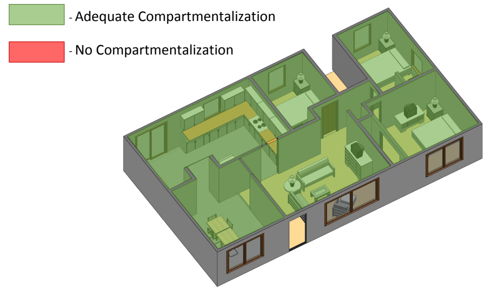
Figure 1.25: Non Fire Room Neutral Plane

If PPA is implemented where the fire location is not known, it must be understood that the points between where the fire is and where the exhaust location is made will become untenable for both trapped occupants and firefighters. Providing an exhaust of adaquet size in the fire compartment can decrease temperatures, increase visibility and tenability. Providing exhaust in an adjacent compartment will create a flow path, rendering the exhausted compartment and other adjacent compartments untenable.

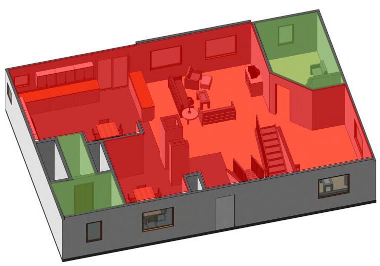
For more information on how ventilation location effects tenability see tactical consideration 1.6.

1.9 PPA will not be effective on a fire located in an open concept floor plan or any floor plan with high ceilings.

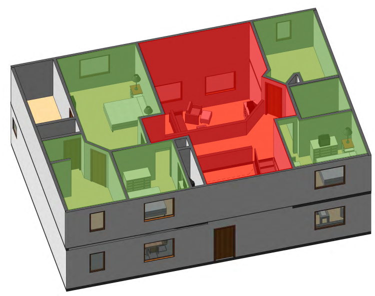
In order for positive pressure attack to be effective, the fan must be capable of increasing pressure in the adjacent compartments. This forces the products of combustion out of the structure rather than into adjacent compartments. This pressure increase is only possible where the fire is located within a compartment.



(a) Single Story



(b) Two Story - First Floor



(c) Two Story - Second Floor

Figure 1.26: Understanding Compartmentalization of Structures

As seen in figure 1.26 the areas in green are provided with compartmentalization and separated from the remainder of the structure. Areas in red are part of the open concept plan where a lack of compartmentalization exists. Fire in the red areas of the structure would not be separated from adjacent compartments by a doorway.

Without a doorway to separate the fire compartment from the remainder of the structure, the pressure increase in adjacent areas cannot be achieved. This causes the fan to create a churning or mixing of the fire gases. High ceilings compound the problem as buoyant gases are carried vertically instead of out of the structure, further mixing the interior environment (1.27). Air added by the fan increases the fire size in an open floor plan. The products of combustion flow from the open areas into adjacent compartments increasing in temperature, reducing visibility and in tenability.

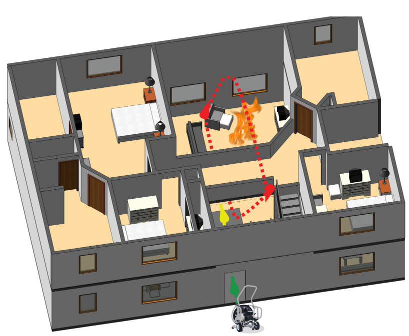
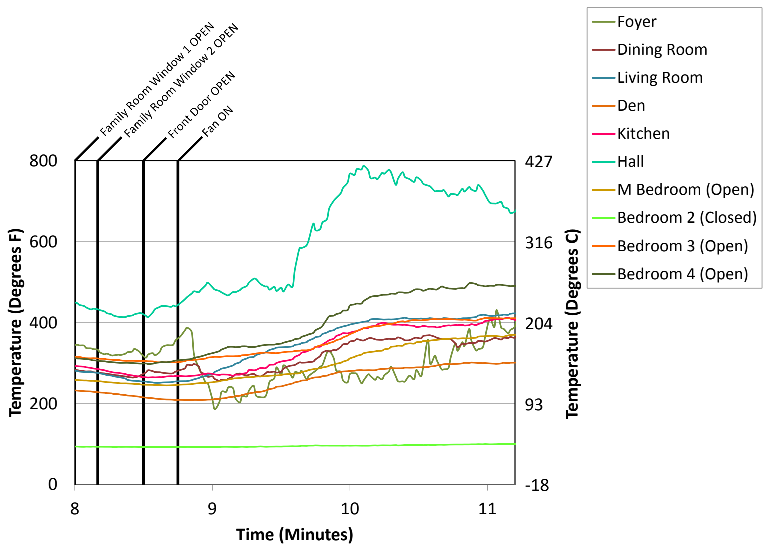
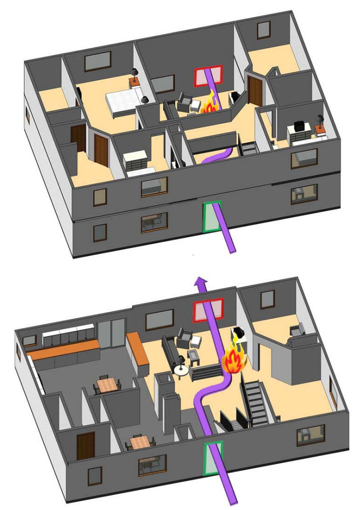


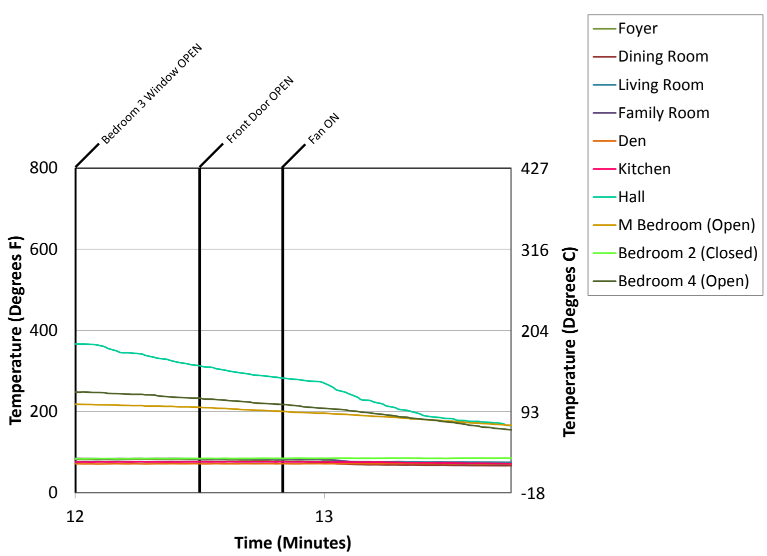
Figure 1.27: Fan Circulating Flow in an Open Concept Floor Plan



(a) Open Plan Fire (Family Room) 5ft Temperatures



(b) Open Plan Fire (Family Room) Ventilation Profile

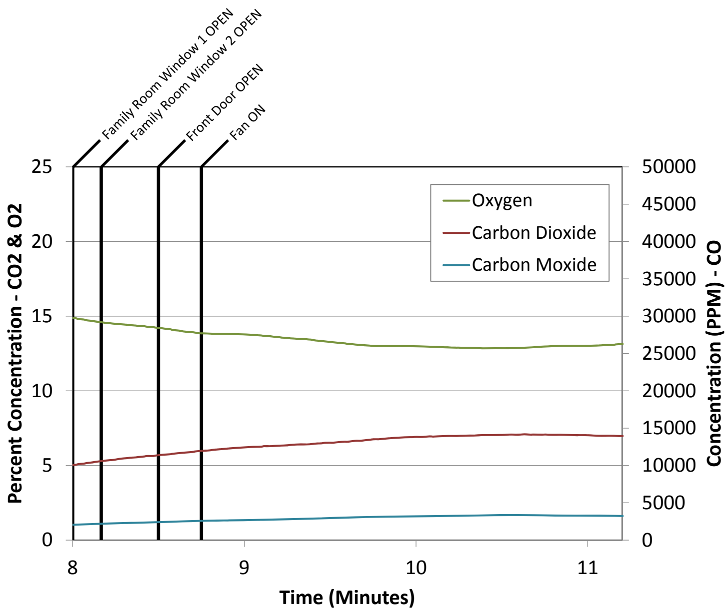


(c) Compartmented Fire (Bedroom 3) 5ft Temperatures

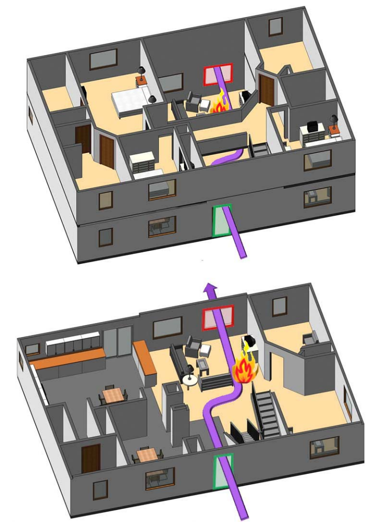
(d) Compartmented Fire (Bedroom 3) Ventilation Profile

Figure 1.28: Two Story Fire in Open Plan versus Compartmented Fire - Temperatures

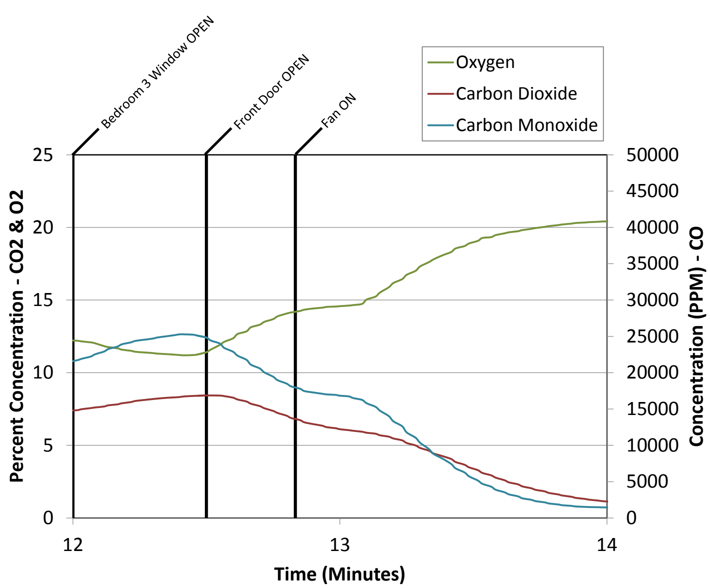
Figure 1.28a shows how the temperatures in a two story open concept structure increase during PPA when the fire is located in the open concept living space. Temperature continue to rise after PPA is initiated. Figure 1.28c shows temperatures in the same structure with a fire in a compartmentalized bedroom decrease After PPA is initiated. Not only do temperatures increase during PPA with a fire in the open plan but figure 1.29 and 1.30 show how gas concentrations and visibility are negatively impacted when the fire in the open plan as compared to the fire in the bedroom.



(a) Open Plan Fire Family Room Gas Concentrations



(b) Open Plan Fire Ventilation Profile



(c) Compartmented Fire Bedroom 3 Gas Concentrations

(d) Compartmented Fire Ventilation Profile

Figure 1.29: Two Story Fire in Open Plan versus Compartmented Fire - Gas Concentrations

(a) Open Plan Fire (Family Room) Fan On

(b) Compartmented Fire (Bed 3) Fan On

(c) Open Plan Fire (Family Room) 30s After Fan On

(d) Compartmented Fire (Bed 3) 30s After Fan On

(e) Open Plan Fire (Family Room) 1min After Fan On

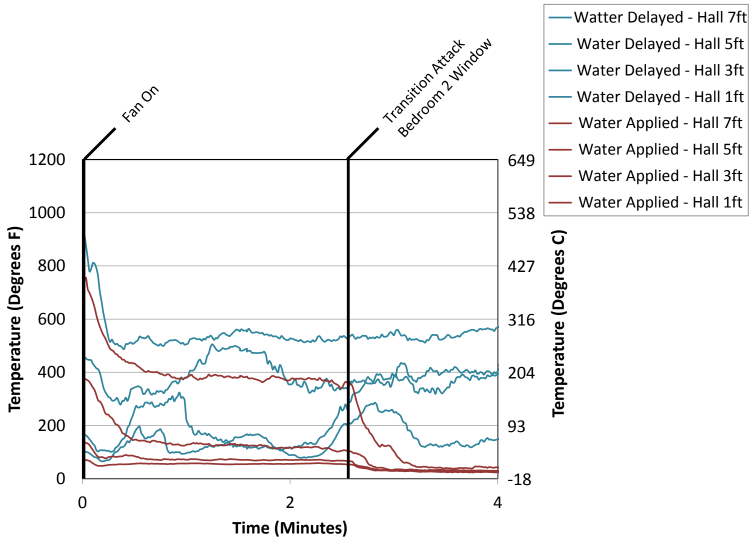
(f) Compartmented Fire (Bed 3) 1min After Fan On

Figure 1.30: Two Story Fire in Open Plan versus Compartmented Fire Visibility

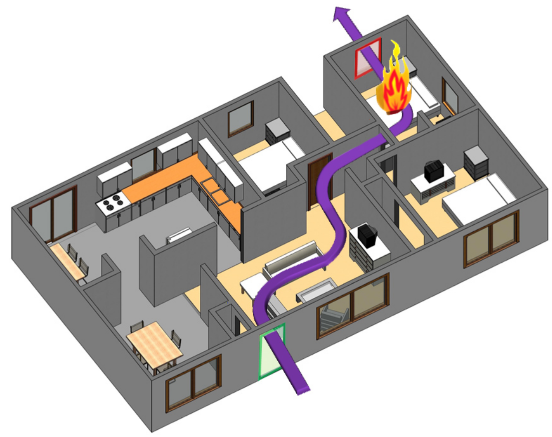
When the same structure has a fire located in a compartment, the fan is capable of increasing the pressure in the adjacent open plan space, preventing the flow of products of combustion from the fire room to the remainder of the structure. As the fan introduces outside air the built up products of combustion are exhausted through the fire room, improving visibility, temperature and tenability.

1.10 The application of water, as quickly as possible, whether from the interior or exterior prior to initiating PPA will increase the likelihood of a successful outcome.

The application of water onto a developing fire has been shown to slow the growth rate, increasing firefighter and occupant safety while decreasing property loss. This makes rapid hose line deployment a top priority for first arriving crews. Although positive pressure attack can improve the efficiency of a hose stretch, is not a substitute for the application of water on the seat of the fire.



(a) Hallway Temperatures



(b) Ventilation Profile

Figure 1.31: Hallway Temperatures - Transitional vs Delayed Attack

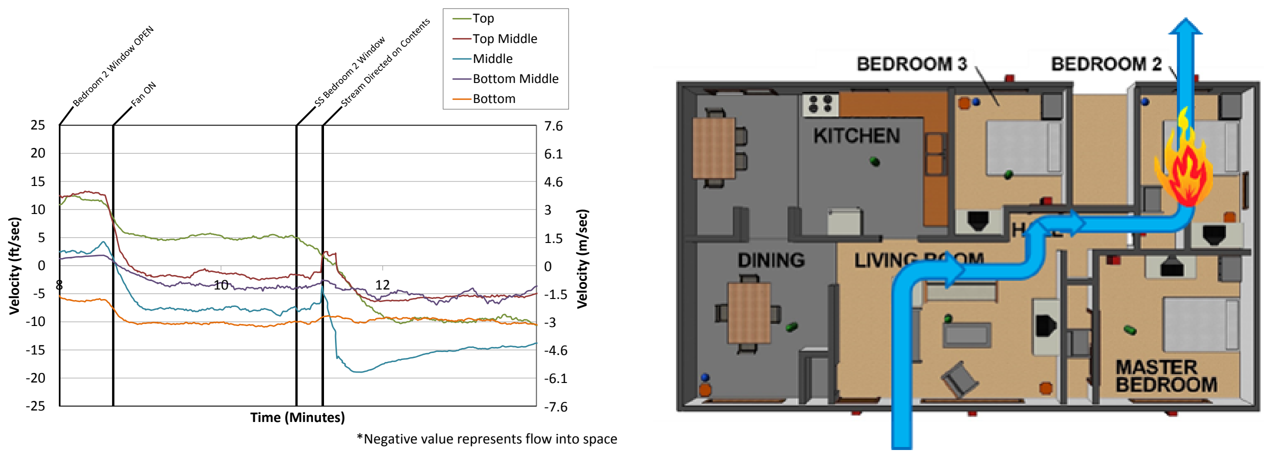
For departments that choose to utilize PPA as their primary fire attack method, training should focus on minimizing the time lapse between the start of the fan and application of water to the fire. If an interior attack is chosen, interior hose advancement should take advantage of the fans ability influence the flow path and reduce temperatures by following the intended fan flow towards the seat of the fire. Figure 1.31 shows that after water has been applied, the temperatures in the hallway decrease to tenable levels for victims. PPA without water application, does not reduce temperatures to tenable levels for victims.

(a) Exterior Application

(b) Interior Application

Figure 1.32: Water Application during Positive Pressure Attack

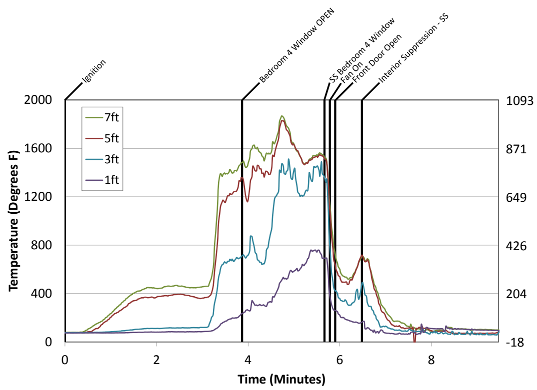
Hence, the effectiveness of PPA, was seen to increase dramatically after water was applied to the fire as seen in figure 1.33. Cooling the upper gas layer reduced the overall heat release rate of the fire, thus reducing the pressure created by the fire. Once water application transitioned the fire from vent limited to fuel limited, the fan was capable of preventing any flow from the fire compartment into the structure, redirecting the smoke, heat and toxic gases out the exhaust vent.



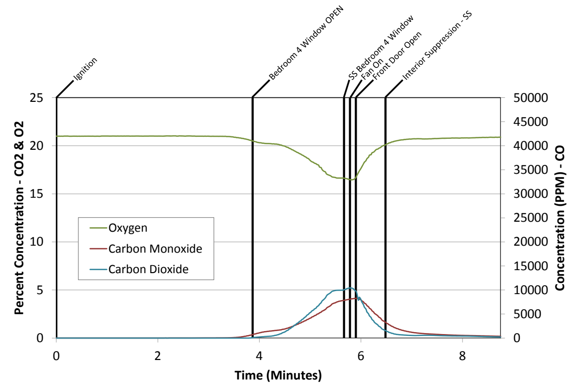
(a) Bedroom 2 Door Velocities (b) Ventilation Configuration

Figure 1.33: Positive Pressure Attack Effectiveness

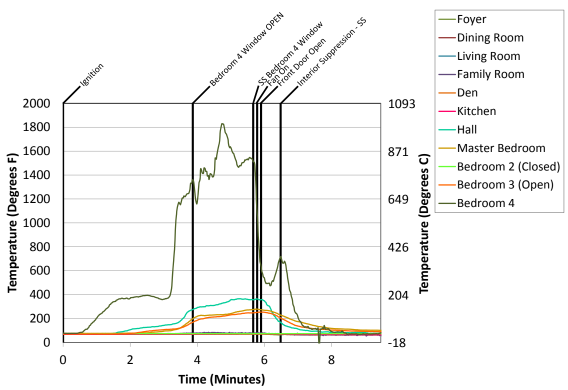
A 5-10 second application of water off the ceiling at a steep angle into the fire compartment from the exterior, reduced the heat release rate of the fire making PPA more effective at exhausting the already created products of combustion. The increased effectiveness of the fan lends to cooler temperatures for the attack crew stretching to the seat of the fire. The short duration between the exterior attack and the interior suppression did not permit much visibility improvement even with the fan as the structure was still charged with smoke. Had the application from the exterior not been followed by a rapid stretch to the interior the bedroom fire would have regrown.



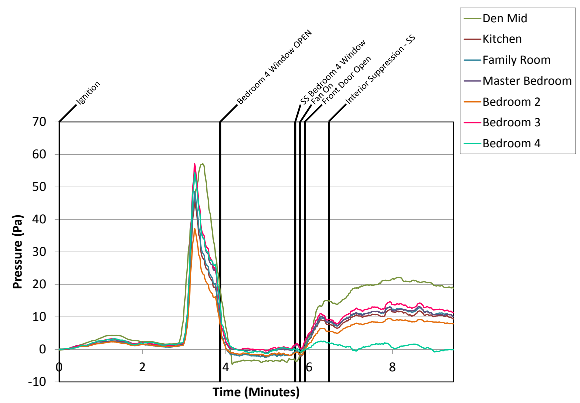
(a) Bedroom Temperatures



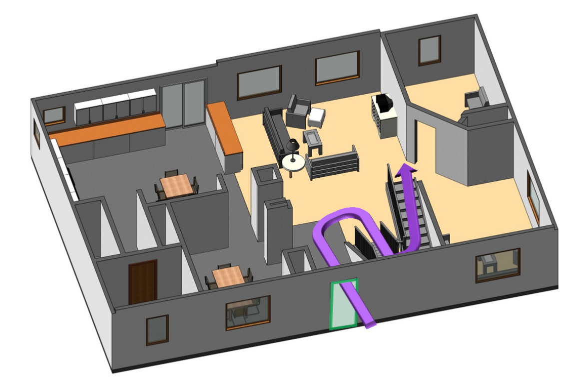
(b) Hallway Gas Concentrations



(c) 5 Ft Temeperatures



(d) Pressure



(e) First Floor Ventilaion Profile

(f) Second Floor Ventilaion Profile

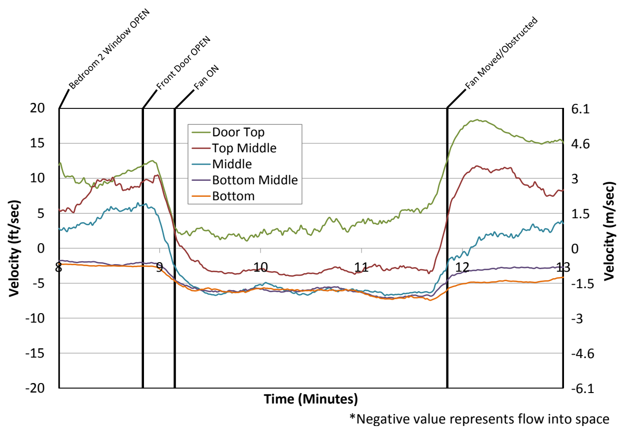
Figure 1.34: Two Story Combined Transition and Positive Pressure Attack

Figure 1.34 shows what occurs when water is applied prior to PPA implementation. The rapid decrease in temperatures, gas concentrations and pressure demonstrated the value of a well coordinated attack. Water application improved conditions regardless of if it was applied via an interior or exterior attack.

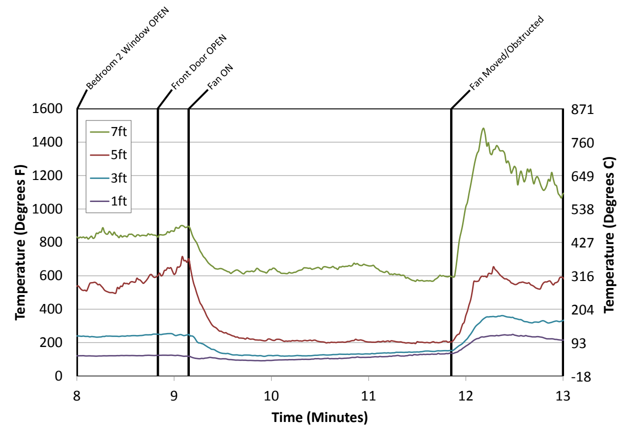
1.11 PPA is not a replacement for using the reach of your hose stream.

PPA can increase visibility and decrease temperatures allowing firefighters get too close to the fire area before putting water on it. When proper exhaust is provided the fan has the capability of redirecting the majority of the flow out the exhaust opening rather than back into the structure over the advancing hose team. If the flow from the fan was cut off for any reason including being obstructed by firefighters in the inlet or along the flow path, the result will be rapid temperature rise and onset of zero visibility. The energy which was being exhausted is now split between the exhaust and the inlet as if the fan was not in place.

Compartment fires are often ventilation-limited. The available oxygen limits the heat release rate as the flow available through a bi-directional flow path is not the most efficient. This has the potential to limit the compartment fire growth pre-flashover resulting in less energy release. When a PPA is utilized the additional flow from the fan will provide additional oxygen which increases the fire size often taking the compartment to flashover. Cutting off or obstructing the flow of the fan results in the energy from a flashed over compartment now being directed out of the compartment towards advancing crews instead of the ventilation limited compartment. The compartment will eventually return to the prior ventilation-limited state if no water is applied.



(a) Bedroom 2 Door Flow



(b) Hallway Temperatures

(c) IR With Fan Flow

(d) IR With Fan Obstructed

(e) Ventilation Configuration

(f) Camera Angle

Figure 1.35: Effect of Removing or Obstructing Fan

Figure 1.35 shows the impact of obstructing or moving the fan. In figure 1.35a the flow from the fire room to the remainder of the structure is reduced with the fan, once the fan is removed the flow is greater than before the fan was applied. The temperature in the halway shows the same pattern in figure 1.35b as the fan reduces temperatures from 800F to 500F in the hallway however once the fan is moved/obstructed it increases to 1400F at the ceiling in the hallway. The IR footage from before and after the fan is obstructed shows the increase in thermal energy.

Using the reach of your stream as you approach the fire from a safe distance will reduce the energy released by the fire. Should the fan become obstructed or shut off while fire fighters are approaching the fire compartment, this upper layer cooling will decrease the thermal assault on the advancing attack crew. Putting water on smoke cools the space, which lowers the temperature, which lowers the pressure which in turn makes PPA more effective.

Using the reach of your stream may be flowing while moving, it may also be the application of water in the direction of the fire to cool prior to advancing. Taking advantage of an open concept floor plans, an attack crew may be capability of applying water to most of the 1st floor from the entrance and most of the 2nd floor bedrooms from the 1st floor. This early application of water, as soon as your stream can reach the fire compartment, will increase the effectiveness of PPA as described in tactical consideration 1.10.

Additionally, firefighters should appreciate the fact that they are a potential impediment to the air flow they are using, especially as they approach the door to a fire room. The same is true for a crew advancing down a narrow hallway. Attack line crews should take advantage of the increased visibility and reduced temperature to make the advance as quickly as possible.

1.12 During PPA - Extension into void spaces when using PPA is directly related to the exhaust capabilities of the void space.

In order for fire extension into the void space there must be an entrance (penetration) for the fire and exit(exhaust) for the products of combustion. An inlet only allows the products of combustion to accumulate and limits oxygen, slowing ignition of objects in that space and thus fire spread. Previous work on fire extension through gypsum walls identified locations such as outlets, switches, lights, and hvac vents as providing a break in the fire barrier[6] [10]. These breaks in the gypsum typically lead to stud or joist bays.

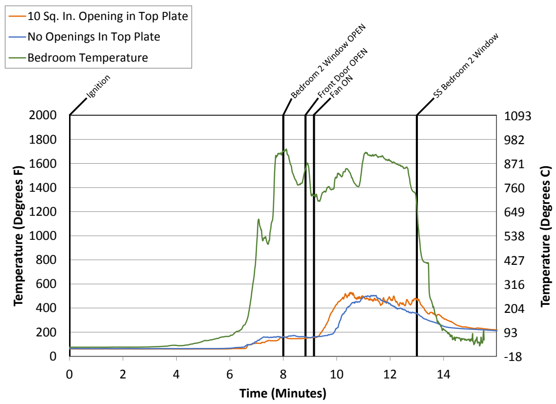
(a) Single Outlet and Switch Rear

(b) Double Outlet and Switch Front

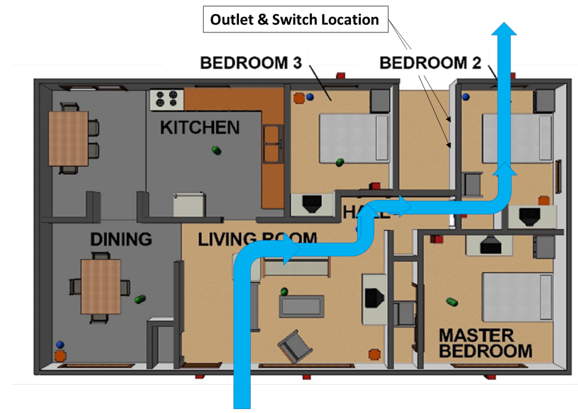
Figure 1.36: Void Space Wall Penetrations

To transfer enough heat into the void space to extend fire, there must be an exhaust provided. Take for an example an outlet and light switch in a stud bay in platform construction (Figure 1.36a). The stud cavity can either be enclosed on all side or have penetrations for lighting, plumbing or HVAC (Figure 1.37b). In the the stud bay that is enclosed, no exhaust was provided. In the case of a bay with plumbing, lighting or HVAC penetrations, limited exhaust is provided as the majority of the hole created to run the utility contains the utility itself.

These two configurations were tested with single outlet and light switches. As seen in Figure 1.37s, during PPA, the room adjacent the void space at reached flash-over and temperatures a the ceiling reached 1700F. The void space reached just over 500F regardless of if it was enclosed or contained small penetrations. The enclosed cavity grew slightly slower but both peaked at the same point and remained relatively steady during the positive pressure attack.



(a) Stud Bay Temperatures



(b) Outlet and Switch Locations

(c) Top Plate Configuration

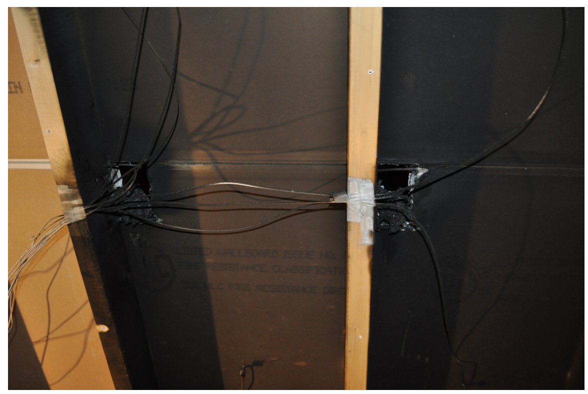
Figure 1.37: Void Space Wall Penetrations

Although the penetration existed in the gypsum and the fire melted the plastic switch/outlet boxes away, the lack of exhaust prevented extension. This caused smoke damage and discoloration of materials however no charing of the wood occurred (Figure 1.38).

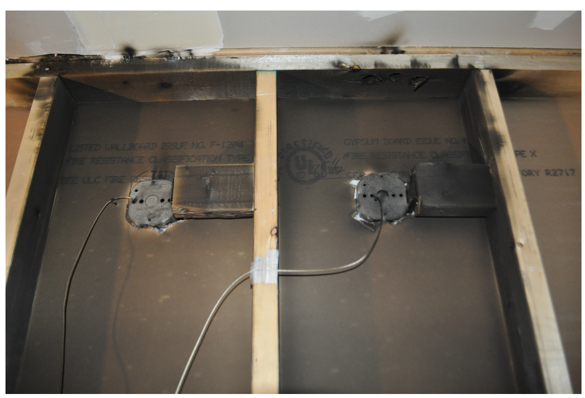
(a) Single Switch & Outlet Front

(b) Single Switch & Outlet Rear Overall

(c) Single Switch & Outlet Rear Bottom



(d) Single Switch & Outlet Rear Middle



(e) Single Switch & Outlet Rear Top

Figure 1.38: Post Fire Wall Images Single Box

During the fire, light gray smoke was noted exiting the holes in the top plate with the pipe penetrations. This would have caused non-thermal damage to any void connected, but would not have led to extension.

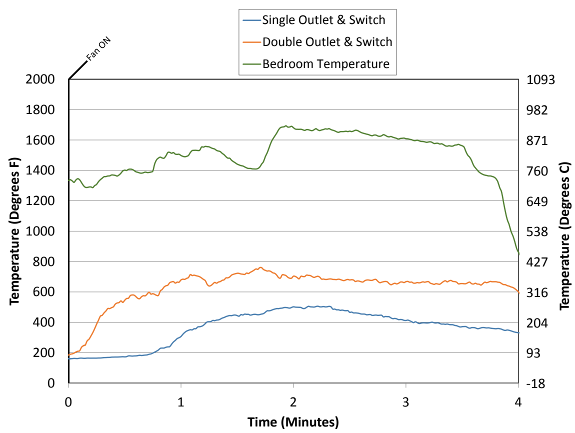
(a) Stud Bay Exhaust No-Fan (b) Stud Bay Exhaust With Fan

Figure 1.39: Stud Bay Exhaust - Single Outlet and Switch - Pipe Penetrations

Increasing the size of the gypsum penetration has little effect on the potential for extension if the exhaust remains the same. For instance a double outlet and switch with no opening above will not result in burning in the study cavity. Temperatures were 200F higher than in the single outlet and switch however even with flashover in the bedroom, post fire inspection of the stud cavity only indicated smoke damage.

(a) Single Switch & Outlet Post Fire Rear

(b) Double Switch & Outlet Post Fire Rear

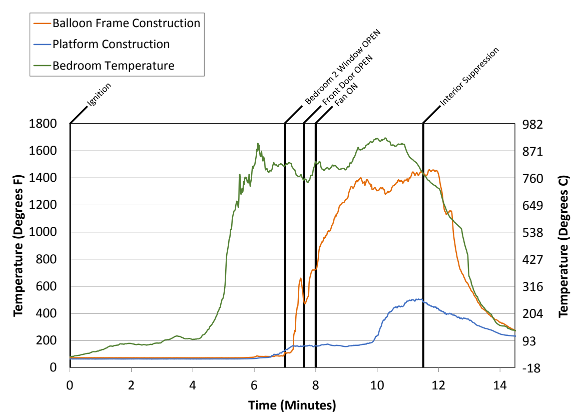


(c) Single Vs. Double Outlet/Switch Comparison (Platform Construction)

If the exhaust size is increased for instance with balloon construction, then combustion can occur in the stud space. There was charing of studs and flames observed from the exhaust point, even before PPA was applied. Temperatures in the stud cavity with balloon frame construction began approaching temperatures in the adjacent compartment.

Figure 1.40: Fire From Simulated Balloon Frame Stud Cavity Prior to PPA

(a) Balloon Fram Construction



(b) Stud Bay Temperatures

(c) Stud Bay Exhaust No-Fan

(d) Stud Bay Exhaust With Fan

Figure 1.41: Balloon Frame Construction Vs Platform

(a) Double Switch & Outlet Rear Overall

(b) Double Switch & Outlet Rear Bottom

(c) Double Switch & Outlet Rear Middle

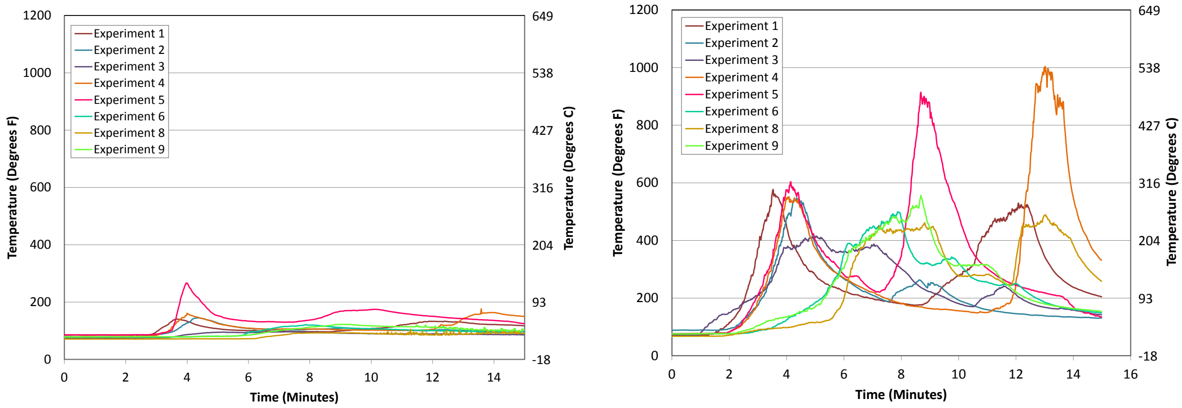
(d) Double Switch & Outlet Rear Top

Figure 1.42: Double Box Post Fire Wall Images - Platform (Left), Balloon (Right)

With the top plate of the wall opened simulating balloon frame construction, fire spread into the void space with and without PPA. PPA allowed for it to occur faster. In structures with openings into the attic space via vents and return air vents (especially with flex ducting), it should be assumed that there will be extension into attic space (especially with PPA). Attic spaces should always be checked with a charged hose line. Click here to access UL FSRIs Attic and Exterior Fire Spread online training program for more information.

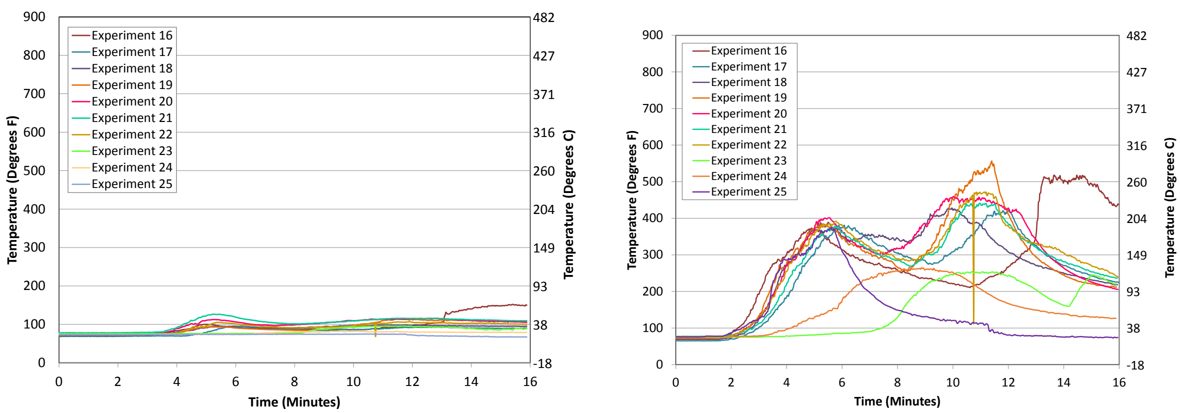
1.13 PPA does not negatively affect the survivability of occupants behind a closed door.

Prior research has shown the importance of having a closed door between occupants and the fire if they are not able to escape [3], [4]. This was emphasized in these experiments where temperatures and gas concentrations in the closed or isolated rooms remained above established tenability criteria where compartments which were not isolated exceeded these threshold values.



(a) Closed Bedroom Ceiling Temperatures Single Story (b) Open Bedroom Ceiling Temperatures Single Story

Figure 1.43: Open versus Closed Bedroom Ceiling Temperatures Single Story

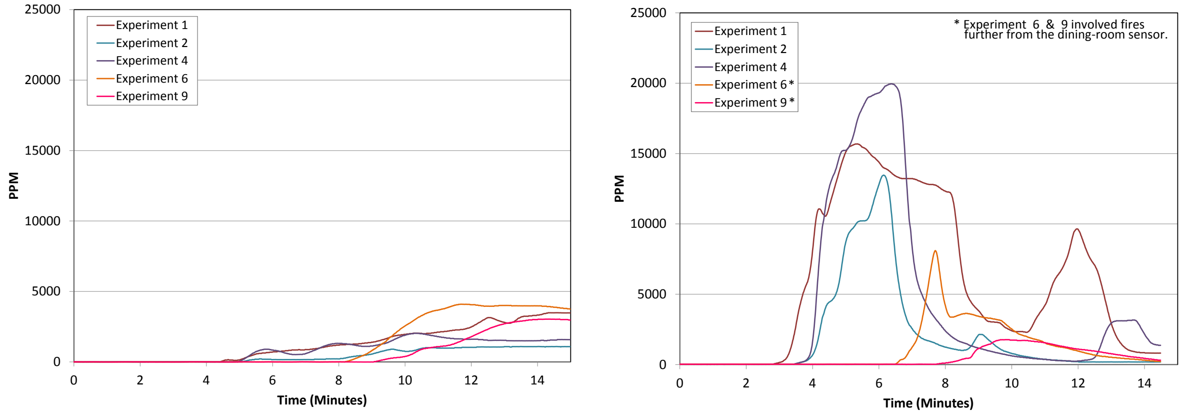


(a) Closed Bedroom Ceiling Temperatures Two Story (b) Open Bedroom Ceiling Temperatures Two Story

Figure 1.44: Open versus Closed Bedroom Ceiling Temperatures Two Story

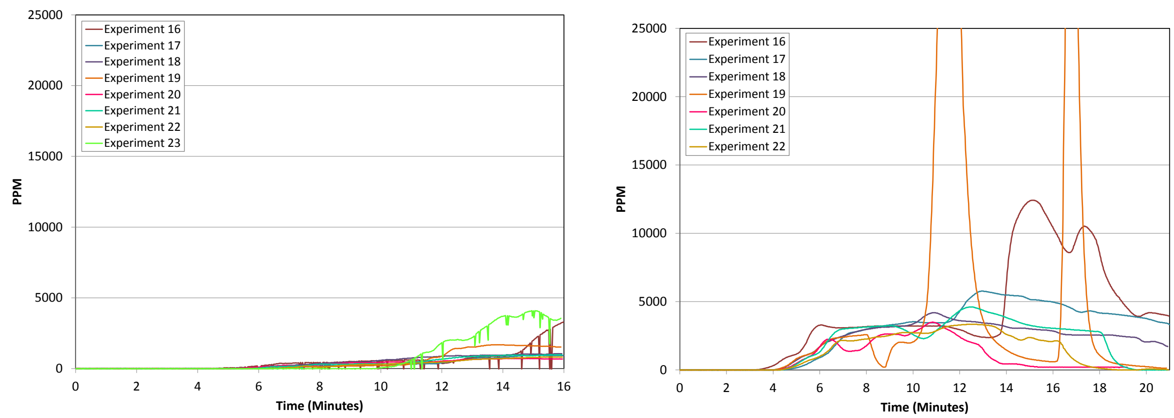
The SFPE Handbook established occupant tenability threshold criteria for temperature of 250F, CO of greater than 5000 PPM for 5 minutes or oxygen level below 12% [7]. Ceiling temperatures in the closed bedroom never exceeded 250F at the ceiling level, where as the open bedroom temperatures exceed that prior to becoming ventilation limited. The two story structure shows the same temperature variations between the open and closed bedroom, with even lower closed bedroom temperatures due to the increased volume of the structure.

In closed bedrooms the CO concentration in both the single story and two story experiments remained below the 5000 PPM threshold. The open area in the single story shows concentrations exceeding the 10000PPM level. Data from the two story closed bedroom shows concentrations remained below the 5000 PPM threshold. Data from the open bedroom in the two story also shows values remained below 5000 PPM for some experiments but not all. In general exposure in the open bedroom was greater in than in the closed bedroom.



(a) Closed Bedroom CO Concentration Single Story (b) Dining Room CO Concentration Single Story

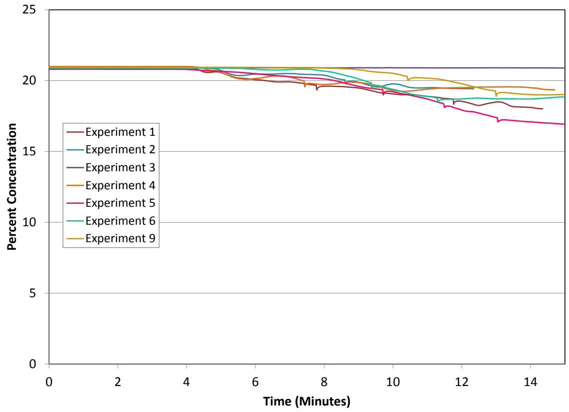
Figure 1.45: Open Area versus Closed Bedroom Carbon Monoxide Concentration Single Story



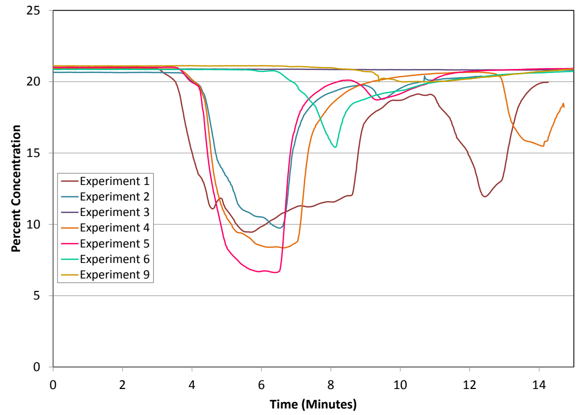
(a) Closed Bedroom CO Concentration Two Story (b) Open Bedroom CO Concentration Two Story

Figure 1.46: Open Bedroom versus Closed Bedroom Carbon Monoxide Concentration Two Story

Oxygen Concentration remained high in the closed bedrooms for both the single story and two story structure. When the room was not isolated from the fire compartment with a closed door the oxygen concentration dropped below the 12% tenability threshold.

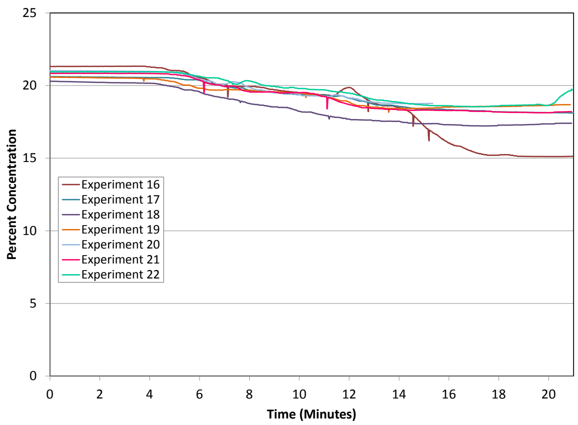


(a) Closed Bedroom Oxygen Concentration Single Story

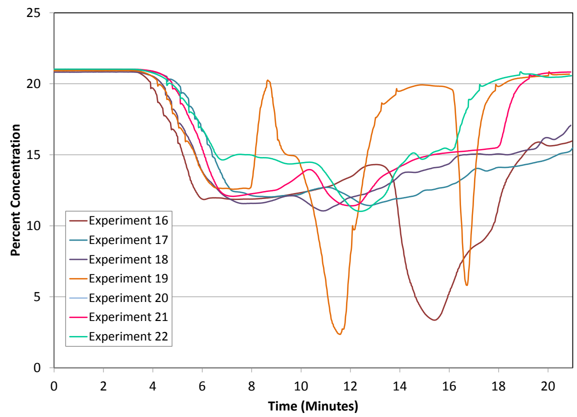


(b) Dining Room Oxygen Concentration Single Story

Figure 1.47: Open Area versus Closed Bedroom Oxygen Concentration Single Story



(a) Closed Bedroom Oxygen Concentration Two Story



(b) Open Bedroom Oxygen Concentration Two Story

Figure 1.48: Open Bedroom versus Closed Bedroom Oxygen Concentration Two Story

Although this analysis only looked at tenability and not lethality, survivability potential of occupants in a closed bedroom or in a compartment isolated from the fire compartment remains higher than those in compartments open to the fire area. The inclusion of a well cordinated positive pressure attack did not negatively impact this increased survivability. The isolation of the compartment prevented the establishment of a flowpath through that space. In any case, the survivability of victims in an isolated compartment (closed bedroom) exceeded the survivability of any potential victims located in an attached (open) compartment.

1.14 When PPV is used post fire control, in single story residential structures, the more openings made in the structure during PPV the more effective it is at ventilating the structure.

The 18 in. gas fan used was capable of moving so much air it could exhaust through more than 5 times the inlet size to most efficiently remove products of combustion. As the number of exhaust points increased the exhaust flow continued to increase.

Ventilation by definition is the *"planned, systematic and coordinated removal of heated air, smoke, gases or other airborne contaminants from a structure, replacing them with cooler and/or fresher air"* [9]. By definition ventilation is changing out the air in the structure, with outside air. If this change occurs faster, conditions will improve faster. In the single story structure, positive pressure ventilation was most effective when multiple openings were provided, (up to 5 times the size of the inlet).

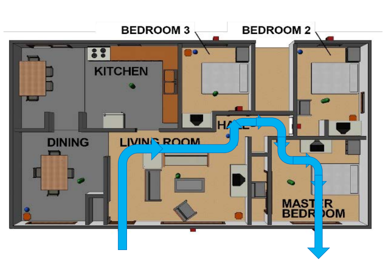
Table 1.2: Single Story Selected Fan Air Changes

Ratio	Flow (CFM)	Air Changes Per Hour	Time for Single Air Change (mm:ss)
5:1	22187.5	154.2	00:23
3:1	18579.8	129.1	00:28
2:1	15979.7	111.0	00:32
1:1	8999.4	62.5	00:58

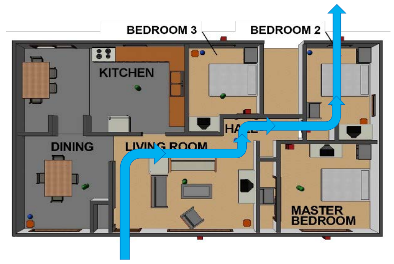
With todays fans flow rates, systematically exhausting smoke one room at a time is not as effective as exhausting several rooms at once. When trying to ventilate one room at a time smoke will be entrained from connected spaces leading to very inefficient smoke removal. All connected spaces will be ventilated at the same time with smoke being forced out only the single opening.

Figure 1.49: Air Entrainment From Connected Spaces

The temperature is gradually reduced throughout the structure during systematic ventilation but it is not until the room itself is ventilated that the temperatures return back to ambient. The elevated temperature is an indication that some of the products of combustion remain. The structures visibility improves gradually throughout but not until the room is ventilated does visibility completely clear.

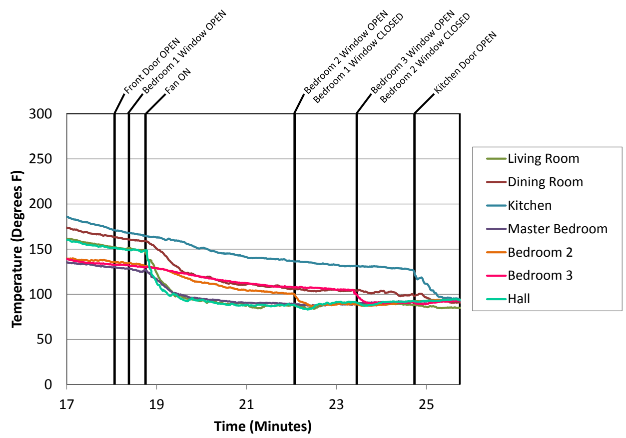


(a) Systematic Bedroom 1



(b) Systematic Bedroom 2

(c) Systematic Bedroom 3



(d) Systematic Ventilation 7Ft Temperatures

(e) Start PPV (00:00)

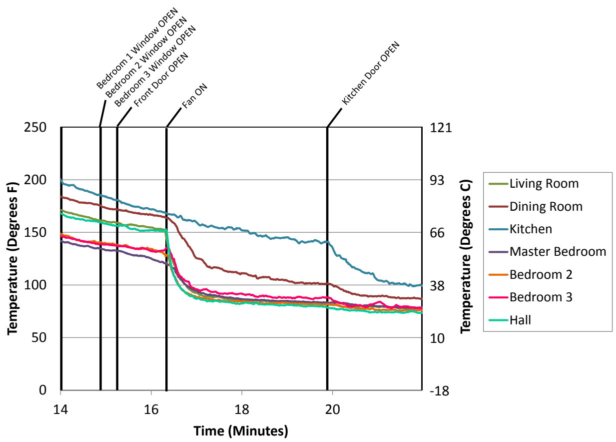
(f) Bedroom 2 Window Open (03:41)

(g) Bedroom 3 Window Open (04:49)

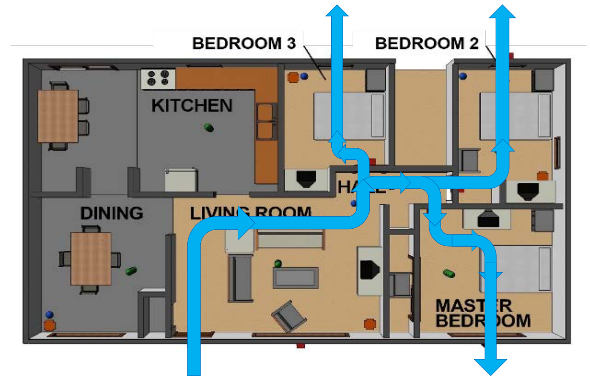
(h) Ventilation Complete (06:06)

Figure 1.50: Systematic Ventilation

Providing additional exhaust during positive pressure ventilation increases the flow though the structure, changing the atmosphere faster. Temperatures return to ambient in all exhausted rooms, with temperatures slowly decreasing in connected spaces as air is entrained. Once flow path is established, temperatures drop.



(a) Non-Systematic Ventilation



(b) Systematic Ventilation 7Ft Temperatures

(c) Start PPV (00:00)

(d) Ventilation Complete (03:41)

Figure 1.51: Non-Systematic Ventilation

Post knock down, the more openings made the more flow the fan can provide and the faster the air is exchanged. More air changes adds to the effectiveness of positive pressure ventilation, as long as the fan is capable of providing the additional flow. Based on cold flow results all of the the fans tested provided this increased flow in the single story structure up to a 5:1 ratio. In the two story structure on average a 4:1 ratio provided the greatest flow.

As with PPA, environmental conditions can impact PPV. Work done by NIST illustrated that wind velocities as little as 10mph can impact both natural and mechanical ventilation [5]. Exhaust vents on the windward (High Pressure) side of the building can become inlets due to the pressure from the wind. In addition a strong cross wind is capable of blocking an exhaust.

1.15 When PPV is used post fire control, it is important to assess for extension.

While the fan provides additional visibility after fire control by exhausting products of combustion out of the structure faster, it also has the potential to hide extension in void spaces. The increased air flow has the potential to accelerate smoldering fires in voids resulting in extension that may have self extinguished in the absence of additional oxygen.

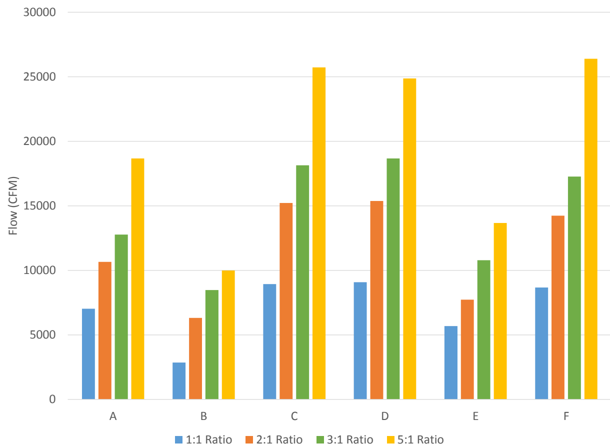
Interior crews should use the increased visibility provided with positive pressure ventilation to evaluate for extension faster. Knowing where to check for extension such as ductwork penetrations, outlets, switches and HVAC return plenums will speed up the overhaul process and limit the chance of a fire in the structure getting ahead of interior crews. Priority should be given to void spaces connected to the fire compartment with an exhaust as described in tactical consideration 1.12. Directing attention to these spaces immediately following knockdown will limit the possibility of extension.

In addition to checking void spaces immediately post knockdown, incident commanders should consider shutting down the fan or closing a door to block fan flow periodically to assess the smoke conditions during overhaul. The fan alters the flows within the structure hiding the possibility of a growing fire. Smoke from a void space that would build up on the interior is exhausted to the exterior. Shutting the fan down or closing the door temporarily will allow interior crews to evaluate if smoke conditions on the interior are changing and incident commanders to evaluate the exterior conditions.

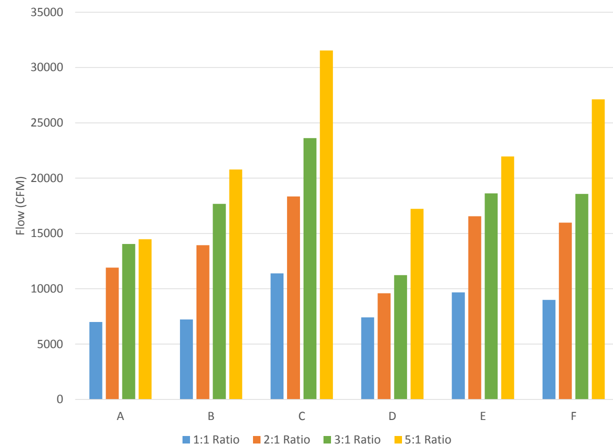
1.16 When PPV is used post fire control, starting or turning in the fan immediately after fire control will provide the most benefit.

Once water is on the fire and the attack crew has the upper hand, fans will assist with increasing visibility and reducing temperatures to ambient to allow for other fireground operations like search, rescue and overhaul to happen faster and more efficiently.

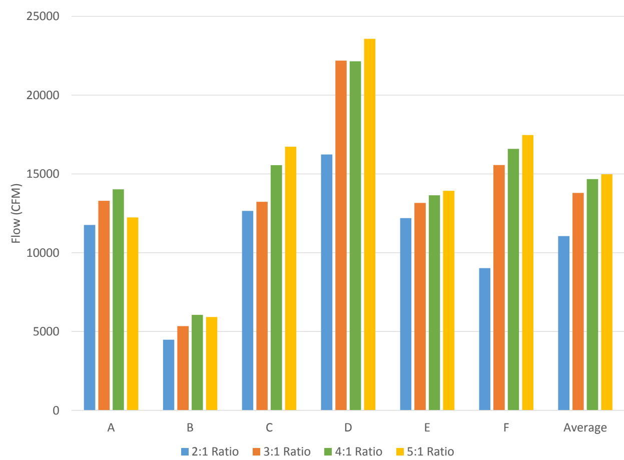
Both horizontal and vertical ventilation take advantage of the buoyancy of fire gases. The buoyancy drives the higher pressure flow out the vent to the exterior which causes a lower pressure inside the structure, drawing in cooler, higher pressure ambient air. If the attack crew has applied water to the fire, bringing it from ventilation limited to fuel limited, the ventilation is effective. The additional oxygen introduced after fire knockdown is not causing the fire to grow [3] [4]. Adding a fan to the buoyant flow will increase the ventilations effectiveness.



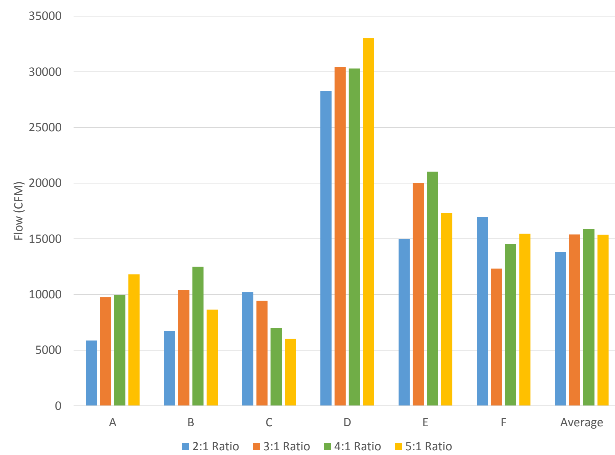
(a) Single Story Exahust Ratio Comparison - Electric



(b) Single Story Exahust Ratio Comparison - Gas



(c) Two Story Exahust Ratio Comparison - Electric



(d) Two Story Exahust Ratio Comparison - Gas

Figure 1.52: Two Story Cold Flow: Exhaust Ratio Comparison Gas Fans - Front Door Inflow

As seen in Figure 1.52a and Figure 1.52b, the single story fans continued to produce more flow the more exhaust openings provided. Even when using an electric fan, the more exhaust openings provided the more flow was achieved. Ratios of up to 5:1 were tested for both the electric and gas fans, with 5:1 producing the most flow in the single story structure.

Figure 1.52c and Figure 1.52d show the ratios tested in the two story structure. The electric fan shows an increase in flow on average as more openings are provided. The gas fan however shows a decrease in flow when 5:1 exhaust ratio is tested vs the 4:1 ratio. The fan is not capable of producing the necessary pressure in the 5:1 ratio of the two story colonial structure. This is due to the larger volume of the two story structure as compared to the single story.

A fan, capable of providing enough CFM for the given exhaust size (up to 5:1 in our single story ranch, up to 4:1 in out two story colonial) used in conjunction with horizontal ventilation will take the bi-directional window vent and make it uni-directional increasing the flow.

As with horizontal ventilation, vertical ventilation would be more effective with the addition of pressure from a fan. The additional pressure would accelerate the rate at which gases are exhausted through a vertical vent, increasing the number of air changes occurring in the structure.

When the fan is applied sooner, more attention needs to be paid to fire extension as discussed in tactical consideration 1.15. Knowing where to check for extension such as ductwork penetrations, outlets, switches and HVAC return plenums will speed up the overhaul process and limit the chance of a fire in the structure getting ahead of interior crews. The use of the fan must be coordinated with interior crews and incident command to ensure fire control has been achieved.