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Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction

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1. Introduction

There is a continued tragic loss of firefighters' and civilian lives, as shown by fire statistics. It is believed that one significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from natural ventilation and use of ventilation as a firefighter practice on the fire ground. The changing dynamics of residential fires as a result of the changes in construction materials, building contents and building size and geometry over the past 50 years add complexity to the influence of ventilation on fire behavior. UL conducted a series of 15 full-scale residential structure fires to examine this change in fire behavior and the impact of firefighter ventilation tactics.

NFPA estimates[1] that from 2003-2007, U.S. fire departments responded to an average of 378,600 residential fires annually. These fires caused an estimated annual average of 2,850 civilian deaths and 13,090 civilian injuries. More than 70% of the reported home fires and 84% of the fatal home fire injuries occurred in one- or two- family dwellings, with the remainder in apartments or similar properties. For the 2001-2004 period, there were an estimated annual average 38,500 firefighter fire ground injuries in the U.S.[2] The rate for traumatic firefighter deaths when occurring outside structures or from cardiac arrest has declined, while at the same time, firefighter deaths occurring inside structures has continued to climb over the past 30 years.[3] Ventilation is believed to be one significant factor that is contributing to this continued climb in firefighter deaths.

Ventilation is frequently used as a firefighting tactic to control and fight fires. In firefighting, ventilation refers to the tactic of creating a draft with an opening above or opposite the entry point so that heat and smoke will be released, permitting the firefighters to locate and attack the fire. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. If a fire is not properly ventilated, not only will it be much harder to fight, but it could also build up enough smoke to create a back draft or smoke explosion, or enough heat to create flashover. However, poorly placed or timed ventilation may increase the air supply to the fire, causing it to rapidly grow and spread. Used improperly, ventilation can cause the fire to grow in intensity and potentially endanger the lives of fire fighters who are between the fire and the ventilation opening.

While no known studies compile statistics on ventilation induced fire injuries and fatalities, the following are examples of recent ventilation induced fires that resulted in fire fighter injuries and fatalities.

1) A NIOSH fatality investigation report, 98-FO7 involved "offensive entry (that) was not coordinated with ventilation that was complete and effective" that resulted in a firefighter fatality[4];

2) A January 27, 2000 Texas residential fire resulted in one firefighter death as a result of venting through the front door causing "a thermal heat column"[5];

3) A February 29, 2008 duplex fire resulted in 1 firefighter death and 1 resident death as a result of, among other factors, "lack of coordinated ventilation". NIOSH report conclusion states "This contributory factor (tactical ventilation) points to the need for training on the influence of tactical operations (particularly ventilation) on fire behavior".[6] ;

4) A November 20, 2008 residential fire in Prince Georges County, Maryland resulted in "two firefighters involved in this incident were seriously injured. The crew from the truck company donned their PPE and SCBA and entered the structure to begin ventilation by removing windows. As additional arriving firefighters stretched another hoseline into position, flashover occurred."[7];

5) NIOSH fatality investigation report F2007-29 reports of a fire in a residential structure and states "...Horizontal and vertical ventilation was conducted and a powered positive pressure ventilation fan was utilized at the front door but little smoke was pushed out. Minutes later, heavy dark smoke pushed out of the front door.... Two victims (firefighters) died of smoke inhalation and thermal injuries.";

6) While not a residential fire, the Charleston, SC fire on June 18, 2008 that resulted in 9 firefighter deaths reported that misuse of ventilation was one contributing factor. The recent NIOSH report on this event stated "A vent opening made between the fire fighter or victims and their path of egress could be fatal if the fire is pulled to their location or cuts off their path of egress"[8];

7) Most recently a residential fire in Homewood, IL claimed the life of a young firefighter and injured another. The NIOSH fatality investigation report, F2010-10 recommends, "Fire departments should ensure that fire fighters and officers have a sound understanding of fire behavior and the ability to recognize indicators of fire development and the potential for extreme fire behavior, and, Fire departments should ensure that incident commanders and fire fighters understand the influence of ventilation on fire behavior and effectively coordinate ventilation with suppression techniques to release smoke and heat.[9]"

An alliance of the Department of Homeland Security, International Association of Fire Chiefs and the International Association of Fire Fighters created a website, www.firefighternearmiss.com, to track fire fighter near miss incidents. The National Fire Fighter Near-Miss Reporting System is a voluntary, confidential, non-punitive and secure reporting system with the goal of improving fire fighter safety. Submitted reports are reviewed by fire service professionals. Identifying descriptions are removed to protect people's identities. The report is then posted on the web site for other fire fighters to use as a learning tool. Countless reports indicate that ventilation, rapid fire progression and flashover are responsible for near miss situations. Some excerpts of the reports include:

- "While progressing further into the living area, the temperature of the room, which was about 350 degrees F, rapidly climbed to approximately 800 degrees. Smoke conditions rapidly darkened, and we proceeded to immediately exit the structure. Heat conditions worsened and I began to feel burning on my arms, legs and neck. I turned around and noticed a wall of orange flame as the room began to flash. The firefighter and I made it to the hallway and rapidly exited the structure.[10]"

- "We tracked the sound to a door that was leading to a converted garage with 15 foot ceilings. The windows were blackened, giving us a clear indication that there were possible backdraft conditions in that room. I called on the radio for ventilation to be coordinated with our fire attack. Command sent crews to the wrong set of windows.

When we opened the door and began to advance, I noticed that the entire room was burning around us. Just as I was ordering crews to retreat and regroup, a wall of flame came rushing toward us and the force of the flame knocked three 225 pound men flat on their backs. We were fortunate to be retreating when the flashover occurred. Although we all suffered minor first and second degree burns, it could have been a lot worse.[11]"

- "On arrival at a two-story house fire, we found heavy smoke coming from the 2nd. floor of the house and no visible fire. We entered with a 1 3/4" line, using the stairway. We went to the second floor to do a primary search and search for a confined fire. We advised command that we needed ventilation and a back-up on the second floor. Suddenly, smoke and heat conditions increased, and we were driven down to the landing of the stairway. My officer then told me to take the landing window out, which I did without thinking. Suddenly an explosive event occurred that knocked us down the stairway to the first floor followed by a large fire ball.[12]"

- "Arrive on scene of a 2 story 3000 square foot residential structure...Ventilation needed to take place. The ventilation occurred at the rear of the structure. I opened the front door and the smoke was rapidly being sucked back into the building. I was on my knees and looking inside the door to see what I could see. I decided to crawl inside to see where the fire was coming from. As I got to a couch that was about 8 foot inside the door, I stopped as heavy embers of fire were dropping on the floor. I found the smoke had lightened and I could see the roof. All I saw was fire. The gas vapor at the highest level of the structure was burning. I immediately retreated to the exterior of the structure through the doorway. As I turned from the front porch and looked back at the door, the fire was lapping out of the front door about 12 feet. The second line was deployed to knock that fire down and give me a chance to get farther away from the structure. When I regained my position, both hand lines were deployed at the door and the front window. The entire living room was on fire from flashover.[13]"

- "We backed out, advised the IC of the situation, and requested ventilation be performed. Two large windows were broken out behind the wood stove in the same room. The smoke layer lifted 3-4 feet. We advanced again inside just past our earlier position when the entire home flashed over. My nozzle man disappeared in flames except for his feet. I could barely see the doorway we entered but was otherwise surrounded by fire. I began dragging my partner by the feet back to the door. Initially he was resistant to this due to the fact he had rolled to his back and opened the nozzle without any apparent effect on the fire. The backup crew assisted as we exited the door. They saw that the fire had blown out the windows on our side and was impinging on both hose lines in the breezeway leading to the door connecting to the garage.[14]"

As fire grows from the initial ignited item to other objects in the room of fire origin, it may become ventilation controlled depending on how well the fire compartment (i.e., home) is sealed. During this incipient stage both the fire growth and power (heat release rate) are limited by available ventilation. If the compartment is tightly sealed, the fire may ultimately self-extinguish due to insufficient oxygen. However, if ventilation is increased, either through tactical action of firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window) or human action (e.g., door opened) heat release will increase, potentially resulting in ventilation induced flashover conditions. These ventilation induced fire conditions are sometimes unexpectedly swift providing little time for firefighters to react and respond.

Compounding the problem with ventilation is the changing dynamics of residential fires due to the changes in contemporary home construction including recently developed building materials and construction practices, contents, size and geometry of new homes. Many contemporary homes are larger than older homes built before 1980. Based on United States Census data homes have increased in average square footage from approximately 1600 ft^2 in 1973 to over 2500 ft^2 in 2008[15]. Newer homes tend to incorporate open floor plans, with large spaces that can contribute to rapid fire spread. The challenge of rapid fire spread is exacerbated by the use of building contents that have changed significantly in recent years, contributing to the decrease in time to untenable (life threatening) conditions. Changes include: a) the increased use of more flammable synthetic materials such as plastics and textiles, b) the increased quantity of combustible materials and c) the use of goods with unknown composition and uncertain flammability behavior.

2. Objectives and Technical Plan

The objectives of this research study are to:

- Improve firefighter safety by providing an enhanced understanding of ventilation (naturally induced and as a firefighting tactic) in residential structures.
- Demonstrate the impact on fire behavior of changes in residential construction such as those created by window types and furnishings.
- Develop tactical considerations based on the experimental results that can be incorporated into firefighting standard operating guidelines.

The objectives were accomplished through the technical plan depicted in Figure 1. The literature review was conducted to determine the gaps in research and to develop the details of the panel furnace window and door experiments, heat release rate experiment and the modern and legacy room fire experiments. The results of the panel furnace window and door experiments and the heat release rate experiment were used to develop the timeline and fuel load for the full-scale house experiments. All of the experiments were documented for the technical report and the technical report is the basis for the web based outreach program and the dissemination of the results to the key stakeholders such as the Department of Homeland Security, the fire service and other organizations in the fire protection community.

4. Previous Literature

Prior to the start of the experimentation three topics were researched for previous studies that have been conducted, window failure, ventilation research and fire service ventiation publications.

4.1. Research on Window Failure

There have been quite a few studies done on the failure of windows. Many of these studies had very different objectives such as windows exposed to room fires, windows exposed to outside fires, glass cracking temperatures, glass fall out temperatures, thick glass windows, multi-glazed windows, radiant exposure of windows, small-scale windows, vinyl, aluminum and wood frame windows, floating glass experiments, speacial types of glass, etc. An analysis was done by Vytenis Babrauskas in 2005[16] that compiled 21 studies on glass breakage in fires. He highlights the challenges with the lack of repeatability as it pertains to glass fall out. Similar to the house experiments, glass breakage is not important if there is never glass fallout to provide oxygen to the ventilation limited fire.

Many of the studies used 4 mm to 6 mm glass which is representative of commercial applications[17,18,19,20,21]. This study utilized residential windows with glass thicknesses of 2.2 mm to 2.9 mm. Another topic that was researched was wildland fire exposure to the outside of the windows[22,23]. Two studies examined the impact of frame type[24,25]. The first study states that they had vinyl frame failure prior to the falling-out of the glazing which was not witnessed in these experiments. The only studies that utilized double glazing were also studies that utilized thick glass so their conclusions provide little importance to our needs.

The Building Research Institute of Japan[26] conducted a series of experiments on 3 mm thick window glass in a large muffle furnace. They concluded that the mean temperature of glass breaking and falling out was 340 °C (640 °F) with a standard deviation of 50 °C (120 °F).

This review concludes that factors such as window size, frame type, glass thickness, glass defects and vertical tremperature gradiant may all be expected to have an effect on glass fall-out. This study will examine many of these variables in Section 0.

Another series of experiments was conducted in 2009[27] to try to develop inputs for FDS for glass breakage and fall-out. The experiments utilized 6 mm thick glass in a compartment fire with up to a 680 kW fire and concluded that glass fall-out temperature was around 450 °C (840 °F).

An article by a fire chief in 1992[28] examines the impact of "Energy Efficient Windows" to firefighting. He explains that the negative impacts include that they keep the heat and smoke in the fire building, they are difficult to break and they severly limit firefighter egress. The author states that the windows allow for faster flashover times and pose a real problem for the fire service. A second article by a fire chief in 2008[29] restates many of the previous articles concerns. The first concern is the interference with the size-up process. Heat inside the structure is masked by the windows. The article also identifies that energy efficient windows are harder to break and harder to clean out for safe passage.

4.2. Research on Ventilation

There has been some research on ventilation but no studies on full-scale houses that examined horizontal ventilation for the fire service. To date most scientific studies focus on a single room or a couple rooms. Some studies have been done in full-scale fire training structures or single fires have been examined in acquired structures. Additional ventilation studies are done with computer models and have no supporting experiments.

Six studies were found that address fire service ventilation. The first was "Experimental Study of Fire Ventilation During Fire Fighting Operations," by Svensson in 2001[30]. This study compared natural ventilation to positive pressure ventilation in a simulated 3 room apartment in a concrete fire training faility. Fifteeen tests were conducted using a pan of heptane as the fuel source. The tests show an increased burning rate with ventilation but all of the conclusions focused on the use of positive pressure ventilation. It is concluded that coordination of different measures at the fire scene is crucial.

The second study was ""Exploratory Experiments on Backdraft in a Full Residential Scale Compartment, " by Fleischmann in 1995.[31] This study utilizes a single room to try to create backdraft conditions as the result of fire service ventilation operations. The fuel used for the experiments was methane and 18 experiments were conducted. They conclude that they were able to replicate small scale experiments but there were no conclusions about ventilation procedures.

Another study was conducted to examine backdraft conditions titled, "Some Theoretical and Practical Aspects on Fire-Fighting Tactics in a Backdraft Situation", by Gojkovic in 2001. No experiments were conducted but SOFIE computational fluid dynamics (CFD) models were run to examine underventilated fires and the impact of firefighter operations. Four tactics were examined, search and rescue, natural ventilation, positive pressure ventilation and use of the cutting extinguisher. They conclude that the choice of tactic depends on whether or not there are people left in the building, the risks one is willing to take and what resources are available.

A second study utilizing CFD modeling was conducted by Saber titled, "CFD simulation for fully-developed fires in a room under different ventilation conditions."[32] This study examined the impact of different ventilation scenarios on heat release rate, fuel total mass loss, temperature, airflow distribution, and fire duration in a single room with a sofa. Ventilation was provided by a door and window. These openings were varied in size and location during the 11 configurations. The study concludes that when the door and window were on the same wall the window size was not significant but when on opposite walls the window size had a significant impact on fire behavior. Additionally, the results showed that the location of the fire load in the room had a significant effect on the fire characteristics. There were no tactical conclusions for the fire service.

The next study, "Effect of Positive Pressure Ventilation on a Room Fire," by Kerber completed in 2005[33], was a comparison of natural and positive pressure ventilation (PPV) in a bedroom with attached hallway. Examining the natural experiment only, when the window was ventilated the heat release rate increased from approximately 2 MW to 12 MW in seconds. After ventilation, the temperatures rapidly increased from 800 °C (1470 °F) to the maximum temperature of 1050 °C (1890 °F). While most of the conclusions deal with the use of PPV the study does highlight the rapid change in conditions and the need for firefighting crews to be coordinated.

The final study by the same authoras the previous study, "Full-Scale Evaluation of Positive Pressure Ventilation In a Fire Fighter Training Building" was completed in 2006[34]. This study also was focused on PPV but half of the experiments were naturally ventilated. The fire training building the experiments were conducted in was to simulate a two story house. The fuel was wooden pallets and straw and the fires were all ventilation limited prior to ventilation. Fourteen different ventilation configurations were examined including, near the seat of the fire, remote from the seat of the fire and several different fire locations. The data suggested that natural ventilation created lower temperatures and the low elevations in the rooms. In these tests the fire did transition back to a fuel limited fire rather quickly because of the heat absorption of the concrete walls of the fire training building and the wood product fuel load. The study concludes that the growth of the fire after ventilation was influenced by the path the outside air traveled to provide oxygen to the fire. When the ventilation window was in proximity of the fire, usually in the correct ventilation scenarios as defined in the report, the initial fire growth was more rapid in the naturally ventilated tests. The average rate of temperature increase for the naturally ventilated tests was 1.91 °C/s (3.44 °F/s).

4.3. Fire Service Ventilation Publications

There are several fire service training publications and many fire service magaine articles that address ventilation. Most of the training publications are based on the criteria put forth by NFPA 1001, the standard for "Fire Fighter Professional Qualifications."[35] This standard outlines the requisite knowledge needed by the firefighter should include: Perform horizontal ventilation on a structure operating as part of a team, given an assignment, personal protective equipment, ventilation tools, equipment, and ladders, so that the ventilation openings are free of obstructions, tools are used as designed, ladders are correctly placed, ventilation devices are correctly placed, and the structure is cleared of smoke. Additional knowledge is needed on the principles, advantages, limitations, and effects of horizontal, mechanical, and hydraulic ventilation; safety considerations when venting a structure; fire behavior in a structure; the products of combustion found in a structure fire; the signs, causes, effects, and prevention of backdrafts; and the relationship of oxygen concentration to life safety and fire growth.

There are three main publications that provide firefighters with the requisite knowledge outlined above. Each of them teaches ventilation differently and each of them has their own definition of what ventilation is. International Fire Service Training Association (IFSTA) defines ventilation as, "Systematic removal of heated air, smoke, and airborne contaminants from a structure and replacing them with fresh air." Jones and Bartlett define ventilation as, "The process of removing smoke, heat, and toxic gases from a burning structure and replacing them with clean air." Delmar defines ventilation as, "the planned, methodical, and systematic removal of pressure, heat, smoke, gases, and in some cases, even flame from an enclosed area through predetermined paths." All of these definitions are generally the same, with subtle differences. One point to highlight is the inclusion of words that hint at coordination such as, systematic, process, planned, and methodical. The other important point is the mention of fresh air and clean air in the first two definitions and no mention in the third definition. The ability of air to enter during ventilation is a significant component of ventilation. Each of these publishers also generates their own training material based on the opinions, experience and practical knowledge of the committees or authors that get assembled to write them. Unfortunately, there have not been a lot of experiments done to answer many of the topics that need to be covered to meet the NFPA 1001 standard.

Of the many fire service magazine articles on ventilation, ten of them will be included in this literature review because of their relevance to horizontal ventilation and fire behavior. Much like the training books described above these articles are written based on the experience or opinion of the author. The difference in this case is that the article is written by a single author and not a committee of fire fighters.

The first of these magazine articles is Vincent Dunn's "The Danger of Outside Venting."[36] This Fire Engineering Magazine article from 1989 is written by a retired Deputy Chief of the Fire Department of New York. He had 42 years as a member of FDNY with 26 years as a chief officer. He has written numerous books and countless articles, all based on the knowledge he gained through his experiences.

In his article he describes a fire where a firefighter assigned to ventilate the rear of a two story house is met by a mother in the front yard that is panicked saying her baby is in the bedroom next to the kitchen. The firefighter ventilates the bedroom window, crawls in and saves the baby. After this dramatic story that ends in heroism Chief Dunn goes on to teach the importance of ventilation. He says, "outside venting shows that it requires knowledge, skill and determination." To prove his point he describes the hazards of operating alone, dangers around the perimeter of the structure, dangers of working off of ground ladders, dangers of window removal, the possibility of being cut off from egress by flames such as those on a fire escape and the hazards of entering the structure to search after ventilating. After these topics he defines flashover and says that signs of flashover are high temperatures in smoke filled rooms or intermittent flames at the ceiling of the room. He suggests taking your glove off, raise it to check for heat and if it is too hot to raise then flashover is possible. Dunn mentions that flashover creates temperatures of 1000 F to 1500 F and that "tests" show that skin has extreme pain at 280 F to 320 F. He says that due to the speed a firefighter can crawl, he can only be in the structure 5 to 10 feet and safely escape a flashover.

This article is typical of ventilation articles in that it explains a lot about how to ventilate and what to look out for when doing so but does not talk about why a firefighter would ventilate and what impact it would have on the conditions in the structure. It mentions flashover but does not say why flashover could occur. This highlights a significant gap in the knowledge of the US fire service. As a general rule firefighters are taught practical knowledge with little scientific foundation to support their training. Another important question that should be asked by the reader which is often not is, how valid is the knowledge in this article to me? No one would question that Chief Dunn does not have significant experience or practical knowledge, but how does his experience relate to the reader as far as available resources, types of structures, or training level. Very few places have the resources, structures or training of FDNY so is Chief Dunn's knowledge always applicable and what hazards does that cause? There are not one set of tactics or rules of thumb that apply to all fires but all fires do have to follow the rules of physics.

A second article by Comstock and Maxwell, "Firefighters' 10 Deadly Sins of the Fireground"[37] contains a discussion of 3 critical issues which are relevant to this research. "Ignoring Size-up" is the first issue which discusses the importance of looking at the type of structure, especially modern construction techniques as they may provide information about fire spread and length of time a fire has been burning. "Ignoring changing fire conditions" is the next relevant issue. The authors highlight roll-over and flameover and the importance of understanding that smoke can ignite when mixing with air. The third issue is "Ventilating late or not at all." This supports that ventilation needs to be studied and understood. It goes on to say that ventilation helps trapped occupants and helps advance the hoseline but does not mention the ability of ventilation to increase the size of the fire. Coordinating ventilation is mentioned as waiting for the hoseline to be in place.

A Fire Engineering Magazine article titled "First Due Without a Clue: Don't Let it Happen to You"[38] also discussed construction and horizontal ventilation. The authors say that the use of thermal pane windows contributes greatly to the development of flashover conditions by not allowing heat to exit the building. They reference the NFPA code on fire investigation to highlight the changes in heat release rate of natural material chair (290 to 370 kW) and newer polyurethane foam padded chair (1350 to 1990 kW). They use this information and relate it to other contents such as upholstered furniture, mattresses and electronics to make up the "ingredients for a fire scene disaster." They go on to say, "proper, well-timed venting techniques will greatly reduce the chances for flashover and backdraft. By using these, we can aggressively and more safely perform our interior attack and searches, and any trapped occupants will have increased survival time." However they don't define what proper or well-timed means.

In August 2008, Battalion Chief Ed Hartin had an article, "Flashover Fundamentals"[39] published in Fire Rescue Magazine. This article points out many of the questions we aim to answer with our study. He states, "For many years firefighters have been taught that ventilation reduces the potential for flashover...When a fire is ventilation controlled, heat release rate is limited by the available oxygen. Under ventilation-controlled conditions, increased air supply (ventilation) results in increased heat release rate and establishes a path for fire travel, which may result in flashover." He reviews several case studies that discuss this phenomena and provides guidance to identify the ventilation profile of the structures. He explains how changes in ventilation will impact that profile. Chief Hartin advises that controlling the air track will limit the potential for flashover and that an access point is also a ventilation opening.

The fifth article included in this review is "Getting the Most from Horizontal Ventilation" by Wolfe, published in Fire Engineering Magazine in 2009[40]. Wolfe compares vertical ventilation with horizontal ventilation. He argues that without preexisting openings in the roof such as skylights or scuttles that vertical ventilation takes too long and the focus should be on using horizontal ventilation to relieve interior crews and save the occupants. The coordination of crews is highlighted, "knowing when the attack team has a charged hoseline in place and is ready for ventilation will ease the operation and prevent any premature actions by the attack or ventilation team." The author concludes that horizontal ventilation hasn't been used to its fullest potential and that operations can be made safer and less destructive if used. There is no mention in this article about the impact of improper timed or located ventilation. No attention is given to the air entering the structure in this analysis.

"Gone With the Wind? Ventilation Fundamentals" was an article published in National Fire and Rescue Magazine in 2001[41]. It highlights the need to understand "systematic" ventilation by knowing the location of the fire, type of building construction, occupancy and pre-fire plan. The author, Peltier, emphasizes that for operations to be carried out effectively, there must be a person specifically in charge of the ventilation crew and the command to vent should be coordinated and come from the incident commander. Another important point is made in that "check to make sure there is a charged hoseline in place before the opening operation takes place." Peltier describes horizontal ventilation as letting smoke and hot gases out but never talks about the fresh air allowed into the structure and its potential effects.

FDNY Lieutenant Tom Donnely wrote an article, "Primary Ventilation: A Review" in Fire Engineering Magazine in 2007[42]. He focuses on the hazard that single family dwelling fires pose and that horizontal ventilation coupled with an aggressive search should be the primary firefighting tactics. He emphasizes communication and coordination as keys to a safe operation and that venting is done for 2 reasons:

- Venting for fire is done to "facilitate the movement of the hoseline attack into the fire area. We do this by releasing the products of combustion – heat and the highly flammable, toxic gases and smoke – to decrease the flame spread to reduce the possibility of flashover, backdraft or smoke explosion."
- Venting for life is defined as, "during an aggressive search effort, we vent to improve conditions for known life hazard while knowing that we may escalate the fire condition."

Another Fire Engineering Magazine article by a FDNY firefighter, Tom Brennan, was published in 2006[43]. The article titled, "Still Talking in the Kitchen…" focuses on the tactics associated with the most well-trained operations that support aggressive structural firefighting. Brennan mentions horizontal ventilation and that a mistake that is rarely detected or talked about is venting without a plan basd on size-up factors and interior aggressive offensive operations. He also describes two types of ventilation, accounting for human life and ensuring effective firefighting. "Venting for life is to open anything that will keep the interior search going-or allow entry and search of areas behind the fire before water or fans start." "Venting horizontally for fire control is to open the fire floor methodically depending on the fire location, movement of the handline, wind conditions and auto-exposure. This usually means, where the fire is going to be pushed by the nozzle, the flanks of the enclosure that the nozzle is trying to pass through and at the side that the nozzle entered from, if necessary."

The ninth fire service article is titled "Ventilation in Wood-Frame Structures" by Buffalo Fire Department Captain Peter Kertzie[44]. He shares that putting water on the fire is the most important task but ventilation makes that easier. He goes on to say that venting too early does not occur often because hoselines are put in place quickly and venting too late is dangerous and irresponsible. He adds that random breaking of windows is not right and "systematic" ventilation is what is needed. This should be based on sound firefighting essentials, fire and weather conditions, standard operating procedures, and the use of trained and experienced firefighters. Another point made is that smoke removal gets confused with ventilation and the two should be thought of as being very different. Kertzie says, " the goal of ventilation is to poke a big enough hole in the structure to let out as much heat, smoke and steam as possible." He compares ventilation to opening a bag of popcorn. The caveat he provides is that ventilation must be carried out simultaneously with the advancement of charged hoselines to save life and property. While the author mentions coordination he does not mention the fact that the fire can get larger due to the addition of air to the fire.

The final article, "When to Break the Windows" by John Carlin, Volunteer Safety Officer, was published in Fire Engineering Magazine in 2001[45]. He explains there are many types of ventilation but horizontal is the most effective on house fires, easiest to perform and least time consuming. Carlin explains that he had adverse fire conditions in a number of fires because of lack of ventilation; they were "cooked like lobsters." They learned that "beginning the ventilation process by simply breaking the right window at the right time resulted in a much more positive outcome." Again the coordination of ventilation is emphasized. He goes on to say that the window closest to the fire or in the fire area should be broken. Further the crew will have to have a charged hoseline and be ready to advance into the fire area and that premature ventilation can cause problems that are detrimental to the outcome of the firefight by increasing the intensity of the fire or pull the fire into uninvolved areas. Carlin advises, "flames can be drawn to open windows. Therefore, if you break a window in an unburned area, you can pull the fire to that area, causing greater damage." He warns, "if the hoseline crew does not have adequate water or is not advancing into the fire area, do not break the window." Also, "remember that a building on fire is not a green light to randomly smash every window in sight."

From this literature search the following gaps were identified:

- Window failure data for residential windows is lacking.
- The ventilation research fell short on creating experiments that give the fire service the necessary details to ventilate intelligently.
- The fire service publications provide a lot of practical knowledge about ventilation but there are many holes to be filled, especially what is the role of the air allowed into the house during ventilation on fire growth.
- How ventilation differs in different types of houses and different house geometries.

5. Panel Furnace Window and Door Experiments

Fire performance experiments were conducted to identify and quantify the self-ventilation performance of windows, comparing legacy to modern, in a fire event prior to fire service arrival. An additional experiment was conducted to examine interior door performance. The object of this investigation was to evaluate the reaction to fire of six different window assemblies and three different door assemblies, by means of fire endurance experiments with the furnace temperatures controlled in accordance with the time-temperature curve presented in the Standard, "Fire Tests of Window Assemblies," UL 9, 8th Edition dated July 2, 2009 for windows or "Positive Pressure Fire Tests of Door Assemblies," UL 10C, 2nd Edition dated January 26, 2009 for doors. Window performance measurements included: extent of and mechanism of failure indicated by time of initial glass breakage and size of opening; catastrophic frame failure; and other fire performance characteristics of varying window structures comparing legacy and modern windows. Each window had thermocouples inside and outside the furnace, in the center of the panes as well as near the frame. Heat flux was measured at the face of the window inside the furnace and 1 m (3 ft) back from the window outside the furnace.

Different window construction parameters assessed include: 1) wood frame and vinyl frame construction; 2) single and multi-pane designs and 3) single and multi-glazed designs. Different door construction parameters assessed include: 1) Hollow and solid core construction; and 2) different wood types. This data demonstrates and compares window and interior door performance parameters between legacy and modern window and door types. Modern windows are defined as windows that are able to be easily purchased new and that are typically found in houses constructed post the year 2000. The legacy windows used in these experiments were purchased used and are meant to be representative of windows that would be found on houses built between the years 1950 and 1970. These results were used to design specific ventilation parameters for the full-scale house fire experiments.

9. Tactical Considerations

Bringing together the results of these experiments or all experiments for the fire service, to understand how they may impact tactics on the fire ground is crucial to the safety of the fire service. All of the changes to the fire environment that have occurred over the past few decades make it essential for the fire service to reevaluate their tactics on a regular basis. This section will attempt to bring the science to the street. Many of the topics examined in this section can be attributed to the projects technical panel which consisted of fire service leaders from around the world.

Before you read this section it is very important to understand this information and these considerations as they pertain to the types of structures used in these experiments. Another important factor to keep in your mind is the capabilities and resources available to your particular department. If your department has 3 person staffing on an engine and your mutual aid is 20 minutes away you should look at these considerations differently that if your department has 6 person staffing and you expect 4 engines and 2 trucks on the scene in 10 minutes. There are no two fires that are the same and not every scenario has one answer that is correct every time, most of the time it depends on a number of variables. Even in these controlled experiments with the same house and fuel load there are differences in how the fire develops. These tactical considerations are not meant to be rules but to be concepts to think about, and if they pertain to you by all means adapt them to your operations.

9.1. Stages of fire development

A key element to fire behavior training is the fire growth curve that is used to demonstrate where the different stages occur in relation to each other. The basic fire growth curve shows fire ignition followed by the growth stage, flashover, fully developed stage and finally the decay stage (Figure 476). This curve can be misleading. If an item like a sofa was placed in a large room or outside, where plenty of oxygen is available, then the growth curve will look like Figure 476. A more realistic explanation of the modern fire environment where there is usually not enough oxygen available would be ignition followed by a growth stage, decay stage, ventilation (either by the fire service or by an opening created by the fire like window failure), a second growth stage, flashover, fully developed stage and finally the decay stage. Figure 477 depicts what this would look like. Taking an average of all of the fire room ceiling temperatures for both houses shows the shape of the time-temperature curve for all of the ventilation scenarios (Figure 478).

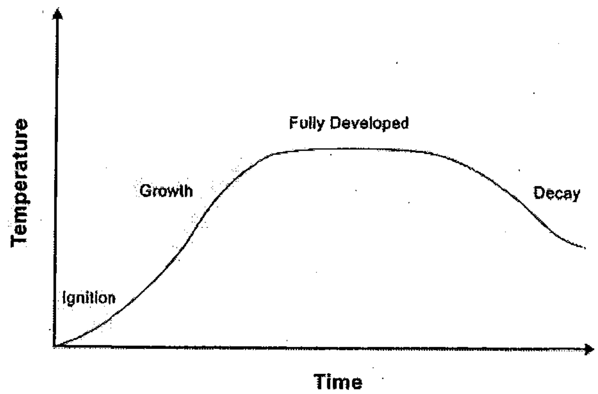

Figure 476. Basic fire growth curve

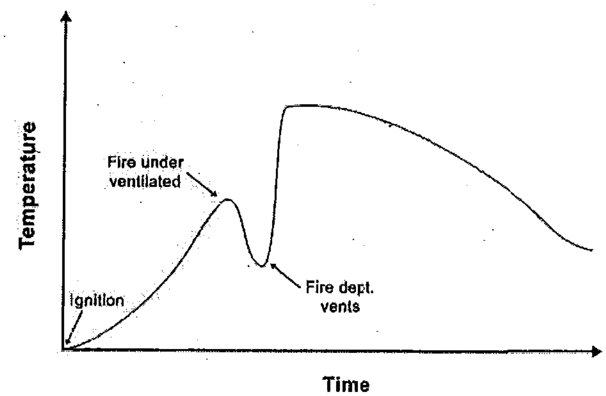

Figure 477. Compartment fire growth curve

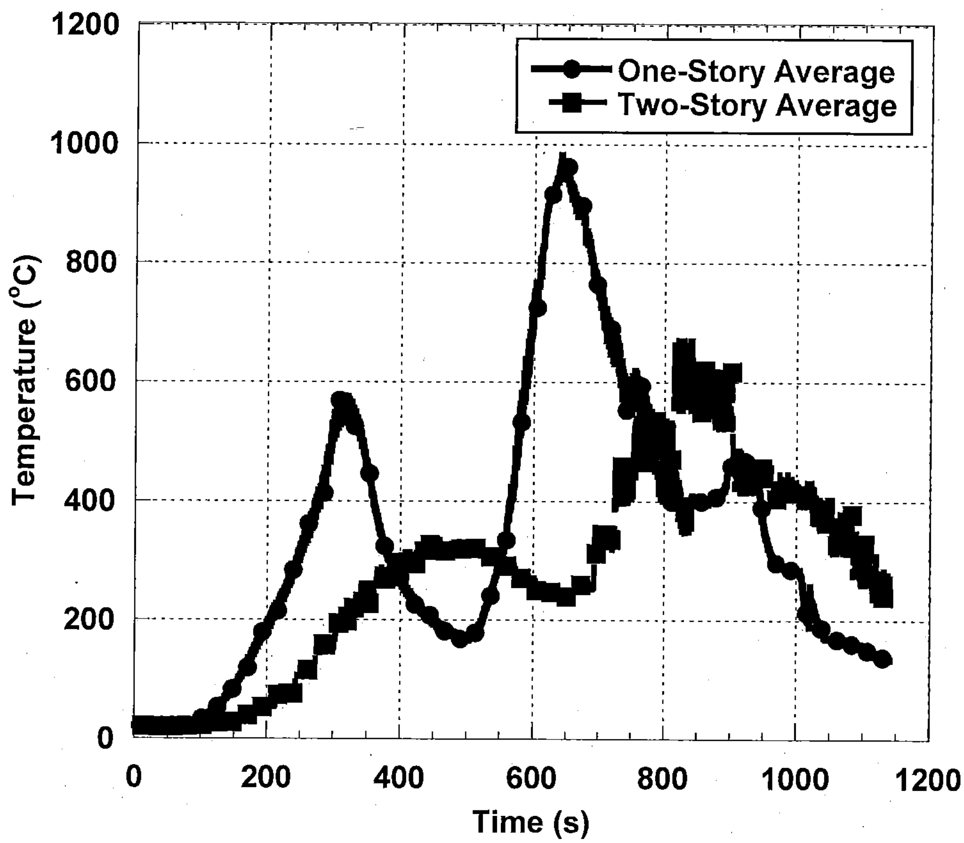

Figure 478. Average fire room ceiling temperature for each house

9.2. Forcing the front door is ventilation

In most cases, when ventilation is taught to new firefighters it is defined by the removal of heat and smoke from a structure. International Fire Service Training Association (IFSTA) defines ventilation as, "Systematic removal of heated air, smoke, and airborne contaminants from a structure and replacing them with fresh air."[52] The problem is that proper respect is not given to the fact that as an opening is made, air is able to enter the structure and provide the missing piece of the fire triangle to a ventilation limited fire. Many firefighters do not think of opening the front door as ventilation, but rather as forced entry for access to search and attack the fire. While entry is necessary, one must also realize that air is being feeding the fire and there is little time before either the fire gets extinguished or it grows until a untenable condition exists, jeopardizing the safety of everyone in the structure.

Examining fire room temperatures at 5 ft above the floor in both houses during the experiments where only the front door was opened shows the increase in temperature following ventilation (Figure 479). In the one story experiment (Experiment 1) the temperature was 180 °C (360 °F) at ventilation (480 s), exceeded the firefighter tenability threshold of 260 °C (500 °F) at 550 s and reached 600 °C (1110 °F) at 650 s. In the two story experiment (Experiment 2) the temperature was 220 °C (430 °F) at ventilation (600 s), exceeded the firefighter tenability threshold of 260 °C (500 °F) at 680 s and reached 600 °C (1110 °F) at 780 s. Both of these experiments show that opening the front door needs to be thought of as ventilation as well as an access point. This necessary tactic also needs to be coordinated with the rest of the operations on the fireground. A simple action of pulling the front door closed after forcing entry until access is ready to be made as part of the coordinated attack will limit the air to the fire and slow the potential rapid fire progression.

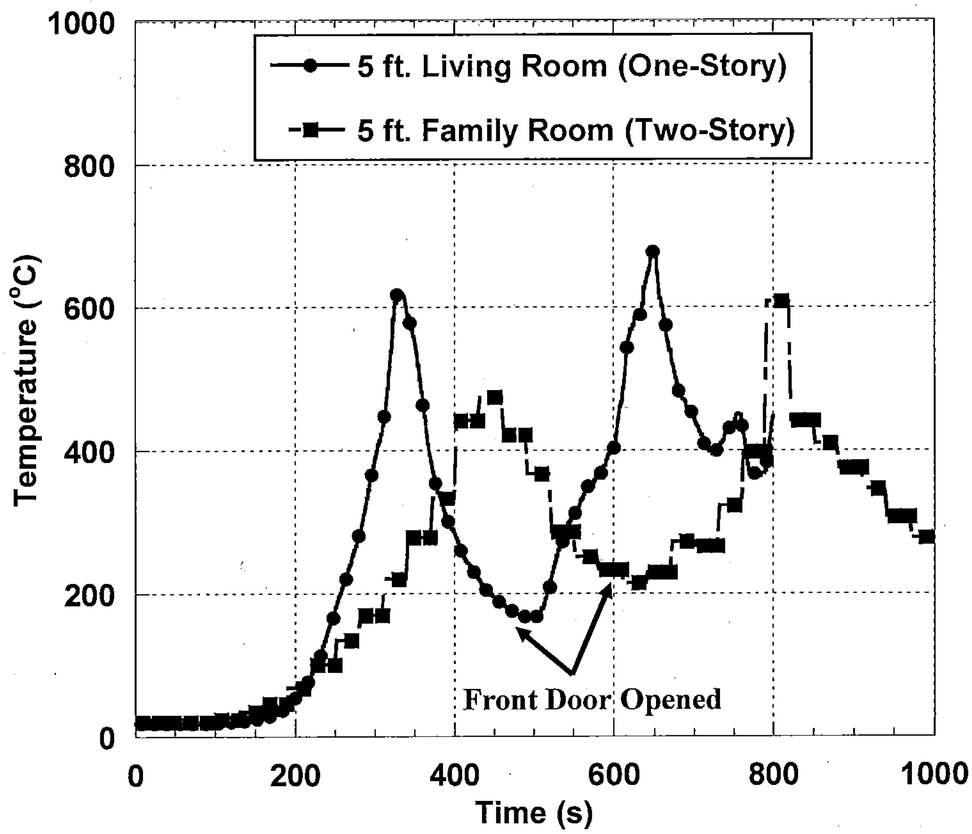

Figure 479. Living/Family room temperatures during front door only ventilation experiments

9.3. No smoke showing

During the experiments it was observed that prior to ventilation smoke stopped coming out of the gaps in the structures. As the fire became ventilation limited the temperatures decreased rapidly and significantly. While this drop was occurring the pressure in the structure would also be decreasing as temperature and pressure created by the fire are dependent on each other. While the pressure was decreasing, smoke would completely stop coming out of the cracks in the structure. Figure 480 shows the temperature in the living room prior to ventilation. As the fire grows, smoke is visible coming from around the windows and the door. As the temperature peaks and then declines, there is no longer smoke visible from the front of the one-story house. The same phenomenon was seen in the two-story house. Figure 481 shows the temperature in the family room and images of the rear of the two-story house during the growth of the fire until it became ventilation limited and decayed. Smoke is visible coming from the windows at 390 seconds but no smoke is visible at 510 seconds.

Tactically, this could be very important for the initial crews sizing up a fire. With no smoke showing from the structure complacency could easily set in. It is important to consider that little or no smoke showing does not mean that conditions are safer than having fire showing. Smoke conditions need to be used to try to determine the conditions inside the structure but this should be done with extreme caution because smoke is not always an indicator of what is happening in the structure. With the modern fire environment and response times being what they are, consider that the fire is most likely in the initial decay stage of the fire growth curve and not the incipient stage.

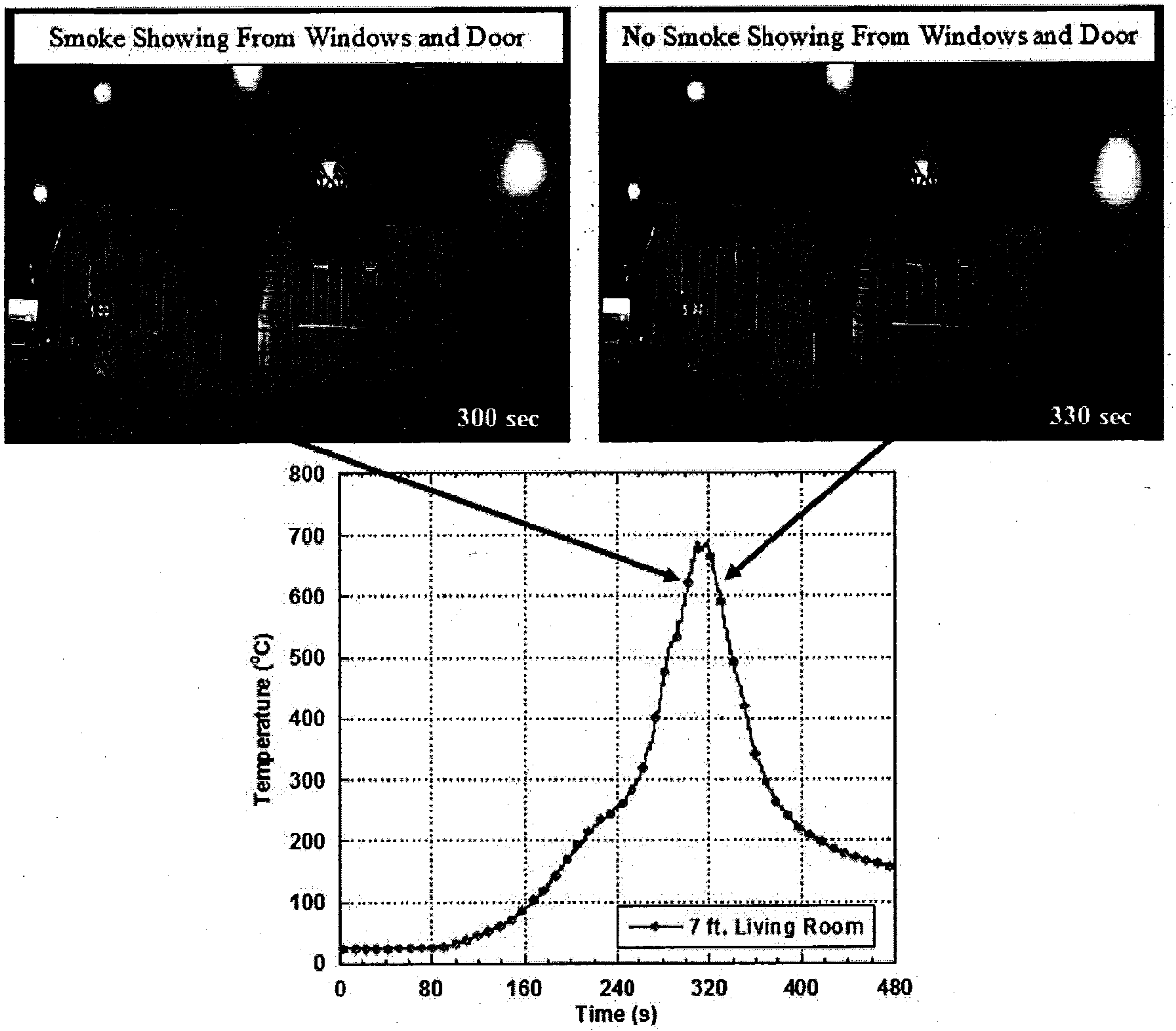

Figure 480. Experiment 5 size-up comparison, smoke vs. no smoke showing

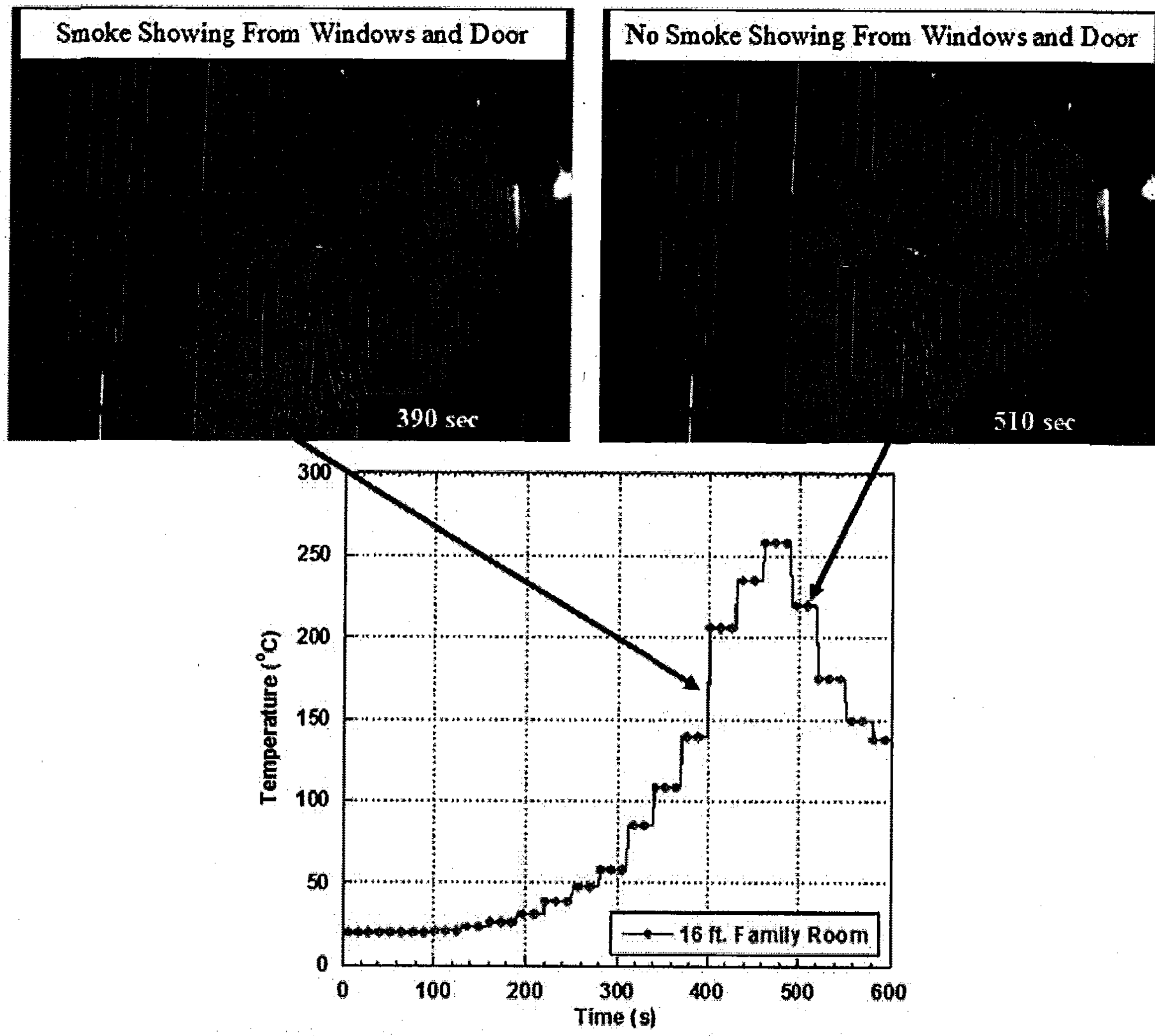

Figure 481. Experiment 2 size-up comparison, smoke vs. no smoke showing

9.4. Coordination

There are many fire service publications that say that fire attack should be coordinated and there is a very good reason for that. As shown in previous sections, if air is added to the fire and water is not applied in the appropriate time frame the fire gets larger and the hazard to firefighters increases. Examining the times to untenability provides the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation openings because the temperatures in the house are going to be higher at the time of the additional openings.

When to make the ventilation opening is another consideration for a coordinated fire attack. This question will be answered independently on every fire because no two fires are the same. Respect needs to be given to the time it is going to take the hoseline to get to the seat of the fire. If it is a ranch house like the one used in these experiments then it probably won't take long to get to the seat of the fire. This means you may want to ventilate once the attack line is charged at the front door. In larger structures like the 2-story house or a commercial structure it may be safer to delay ventilation until the engine advises they are prepared to put water on the fire. Making ventilation openings before water can be applied to the seat of the fire could lead to rapid fire progression and life threatening situations.

Figure 482 through Figure 489 describe a hypothetical search operation during a fire in the one-story house. The red line in Figure 482 shows their search pattern and timeline of the search. The search team forces open the front door at 8:00 (See Figure 483 and Figure 484 for conditions). They see the amount of smoke coming out of the doorway and they put on their SCBA face pieces. While they are doing this the ventilation team vents the front window at 8:15. The search team then makes entry and begins to search the living room. They see fire on the sofas in the middle of the room but conditions are still tenable for them. They skip the bedrooms and decide to search the left side of the house. They enter the kitchen at 9:00 (See Figure 485 and Figure 486 for conditions) and search it quickly and move into the dining room at 9:30. They make their way around the dining room and make it back to the entrance to the living room at 10:00 (See Figure 487 and Figure 488 for conditions). This shows that 2 minutes is not a lot of time to operate inside a structure and those conditions can go from tenable for a search to untenable very quickly. Figure 489 shows the temperatures at crawling height (3 ft above the floor) for the rooms being searched. This depicts that the rooms were tenable while they were being searched but once the firefighters circle back toward the living room it is untenable and they must find another way out, which at that point the dining room and kitchen become untenable so the only option is to bail out of a window.

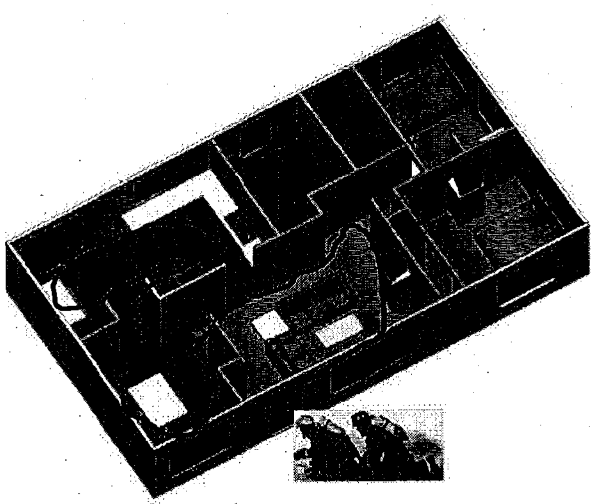

Figure 482. Search team path

<u>Hypothetical Search Team Operation</u>
8:00 – Team forces front door
8:00 – 8:20 - Team puts on SCBA masks
8:15 – Ventilation team vents the front window
8:20 – 8:30 - Team enters to start search
8:30 – 9:00 – Team searches living room
9:00 – 9:30 – Team searches kitchen
9:30 – 10:00 – Team searches dining room

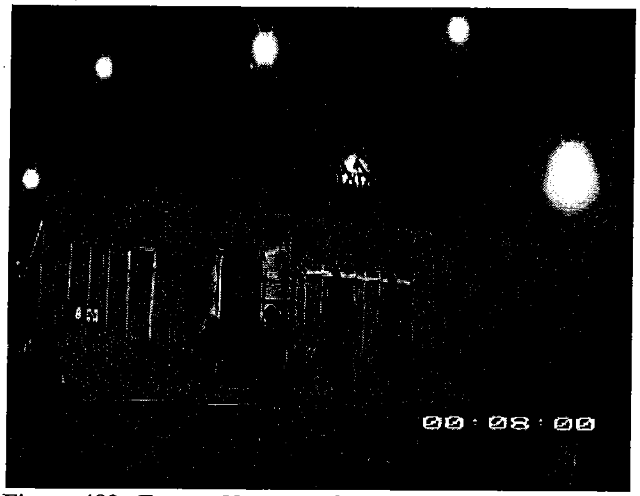

Figure 483. Front of house at 8:00

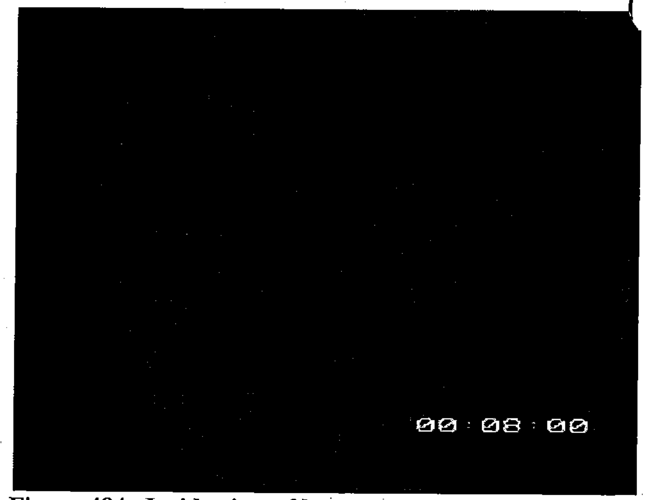

Figure 484. Inside view of house at 8:00

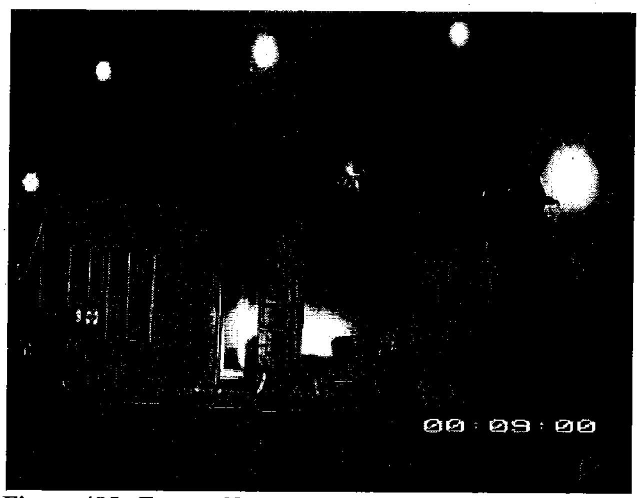

Figure 485. Front of house at 9:00

Figure 486. Inside view of house at 9:00

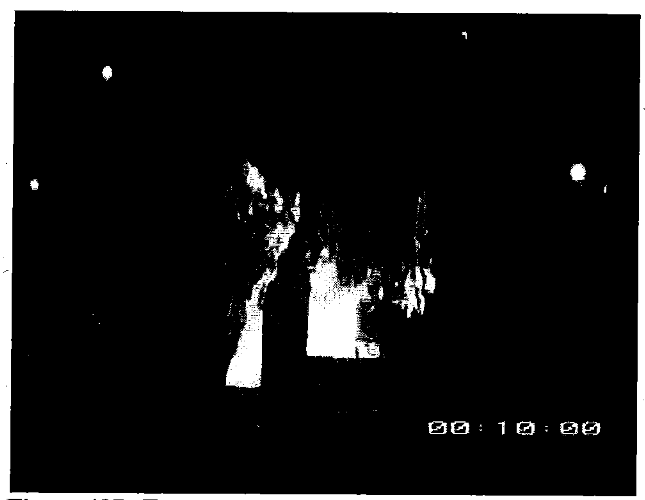

Figure 487. Fornt of house at 10:00

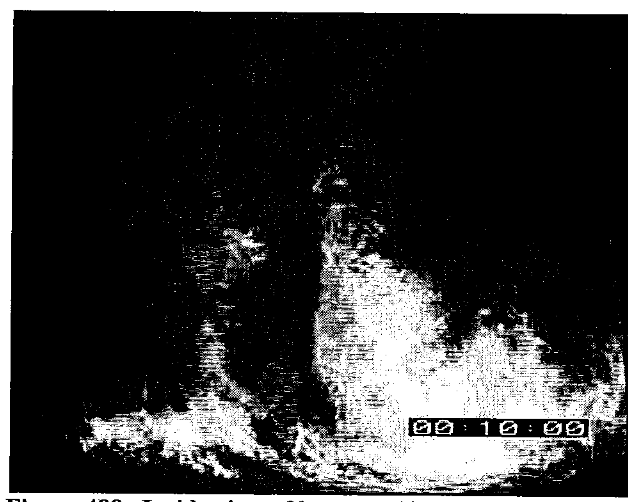

Figure 488. Inside view of house at 10:00

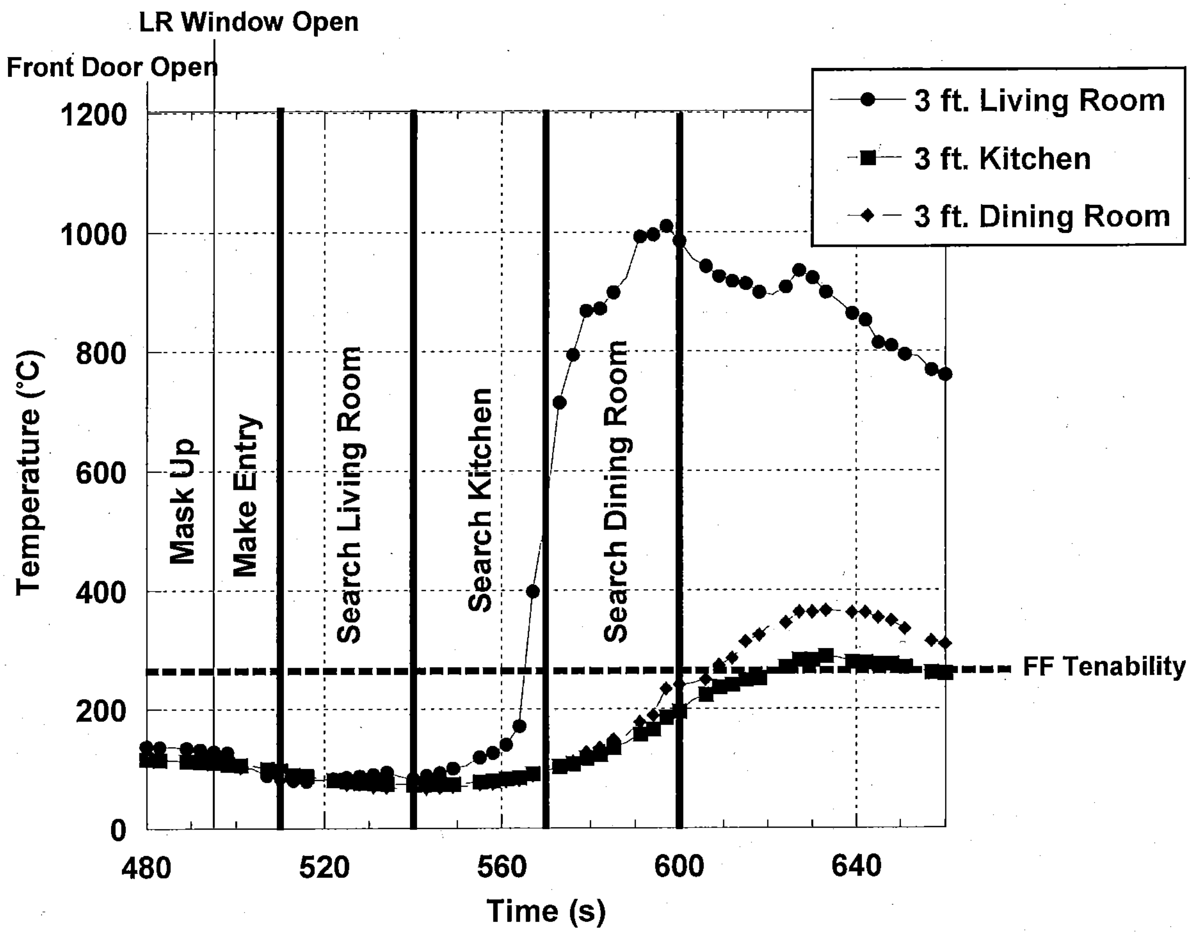

Figure 489. Search Room Temperatures at 3 ft.

9.5. Smoke tunneling and rapid air movement in through front door

In today's fire environment there is more smoke generated due to the increased usage of synthetic materials[53]. In all of these experiments the smoke layer reached the floor prior to ventilation leaving zero visibility in the houses. After ventilation this smoke layer did not repeatedly lift above the floor throughout the house. A better way of describing the impact of ventilation on the smoke was a temporary tunnel as air rushed in through the ventilation opening. Higher smoke release rates and heat release rates have decreased the desired smoke lifting that is traditionally the intent of ventilation. If visibility is increased then search and fire attack are easier to accomplish. It appeared that as the fire received air it produced more smoke than was being ventilated out of the house and therefore not lifting the smoke layer.

It is possible to get an idea of what may be happening inside the structure by observing the flows at the front door after it is opened. In these experiments there was an obvious flow in through the front door toward the fire location. The average velocity through the bottom of the front door for all of the experiments where the door was opened was 1.5 m/s (3.4 mph). There was also a tunneling effect that resulted from the in rush of air through the front door. Figure 490 and Figure 491 show this effect during Experiment 10. An image was captured from the video camera inside the front door 5 seconds before ventilation and 5 seconds after ventilation. Another similar example was captured during Experiment 13 in Figure 492 and Figure 493.

Without the impact of wind this could indicate there is a ventilation limited fire inside and precautions should be taken. Slowing down and ensuring a charged hoseline with the crew is a good primary precaution. In some cases the smoke lifted above the floor in adjacent rooms to the fire but rarely in remote rooms such as the bedrooms. The lifting usually went away once the fire room transitioned to flashover.

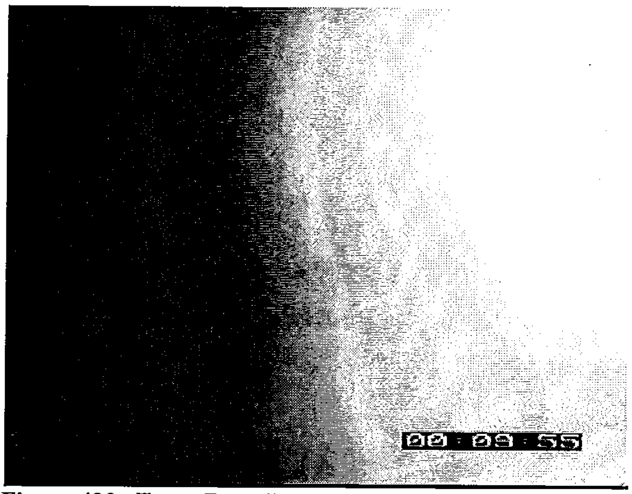

Figure 490. Front Door Image from Experiment 10, 5 seconds before Ventilation

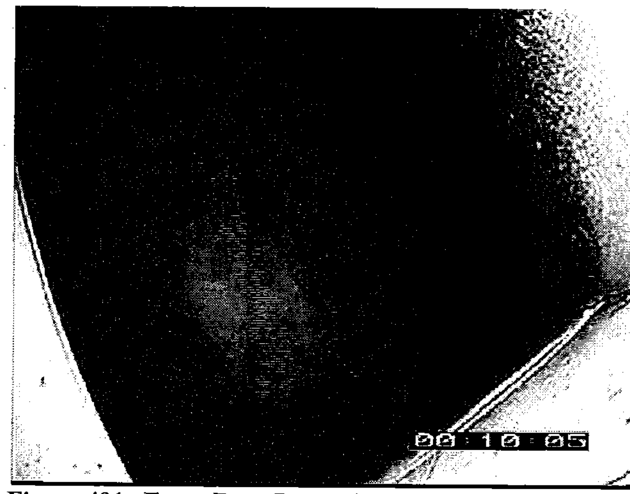

Figure 491. Front Door Image from Experiment 10, 5 seconds after Ventilation

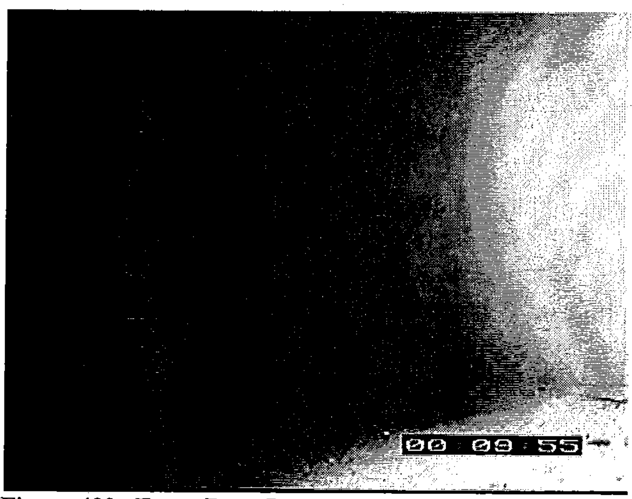

Figure 492. Front Door Image from Experiment 13, 5 seconds before Ventilation

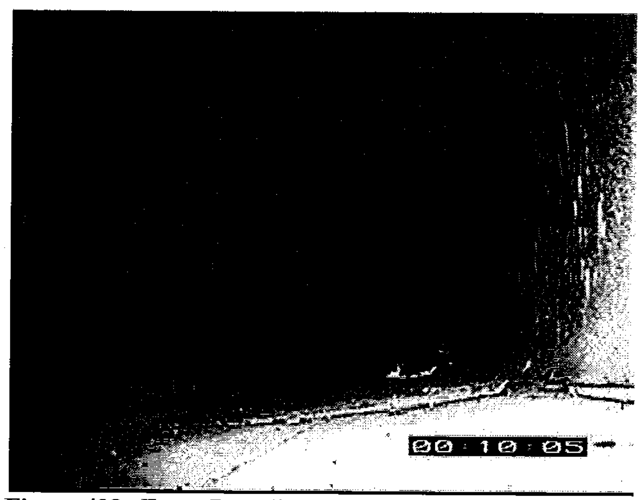

Figure 493. Front Door Image from Experiment 13, 5 seconds after Ventilation

9.6. Vent Enter Search (VES)

VES is a tactic used by many fire departments. It can be described as ventilating a window, entering the window, searching that room and exiting out of the same window entered. These experiments show the ability of a closed door to protect a room from fire conditions even with an open window. They also show how conditions can worsen as a window is ventilated remote from the fire, creating a flow path from the window to the fire. A primary objective of VES is to close the door of the room ventilated to isolate the flow path to the fire and not allow the air from the open window to make it to the underventilated fire. This can be thought of as Vent Enter Isolate Search. While one may be able to search the room quickly and exit, the new flow path created by this tactic if not isolated could cause an unintended interior condition crews are not expecting.

During Experiment 8 the second floor bedroom (Bedroom 3) was ventilated. This tactic could represent a firefighter conducting a VES operation of the bedroom without closing the door to the bedroom. Figure 494 shows the bedroom temperatures versus time with arrows indicating tenability thresholds. If a VES operation were conducted in this bedroom temperatures would increase significantly. The temperature 1 ft above the floor was approximately 60 °C (140 °F) at ventilation and increased to the occupant tenability limit in 2 minutes and to the firefighter tenability threshold in 3 minutes. If the door had been closed the temperatures would not have increased much above 60 °C (140 °F) based on the peak temperature of Bedroom2 (the adjacent bedroom) that had the door closed.

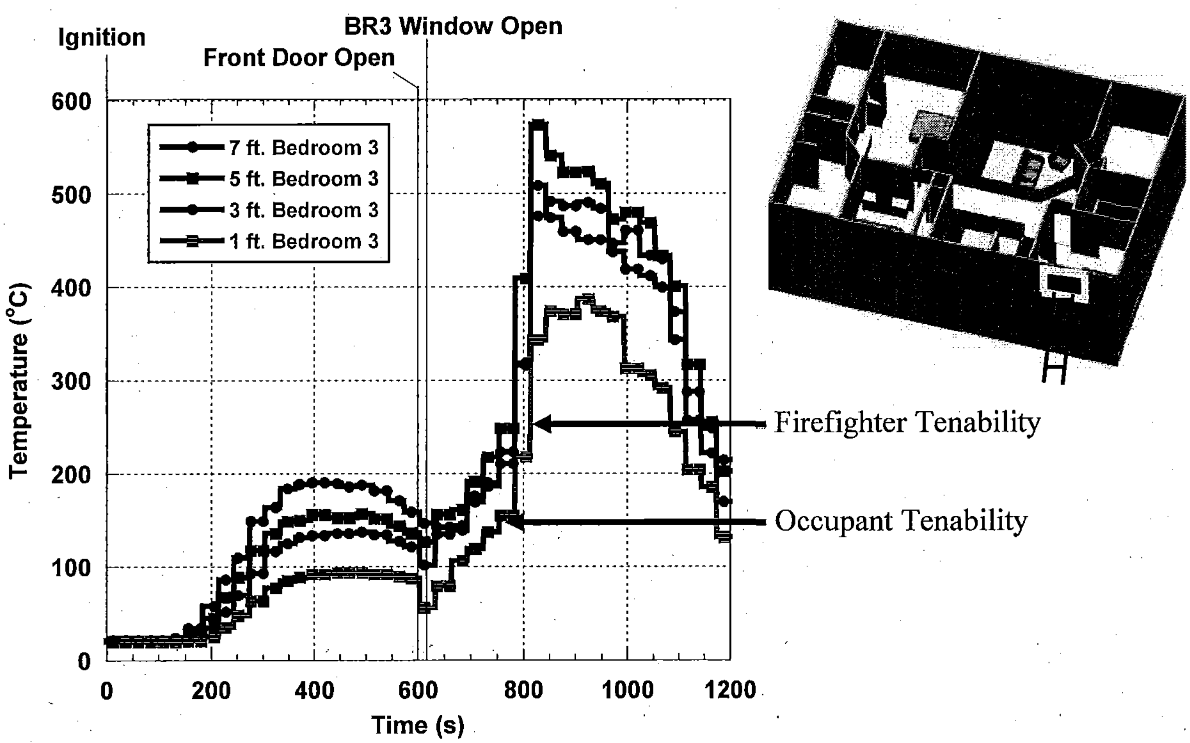

Figure 494. VES bedroom temperatures

In Experiment 14 the window to the closed bedroom, Bedroom 3, was opened at 8:42 (Figure 495). This could simulate conducting a VES with a closed bedroom or what would happen when the door was closed. Figure 496 and Figure 497 show the same view one minute and two minutes after ventilation respectively. During each of these pictures there is a fully developed fire right outside the door to the bedroom and the smoke layer is lifted and conditions improved in the bedroom for the duration of the experiment. This further highlights the importance of closing the door during VES operations. The image of the rear of the house also shows thick black smoke ventilating out of Bedroom 2 which has an open bedroom door. Closing a door between a firefighter and a fire during emergency conditions is also a good way to buy more time to be rescued.

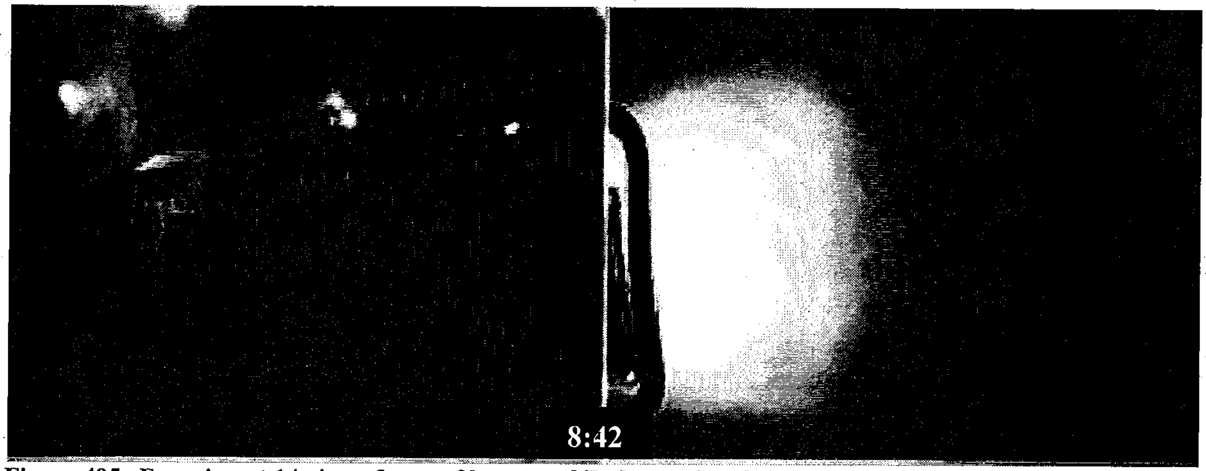

Figure 495. Experiment 14 view of rear of house and Bedroom 3 at 8:42

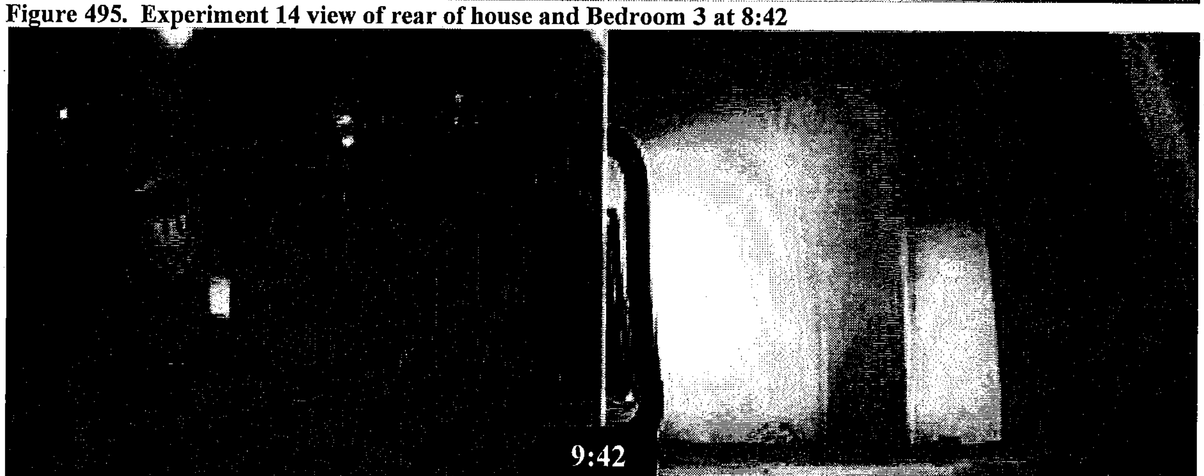

Figure 496. Experiment 14 view of rear of house and Bedroom 3 at 9:42

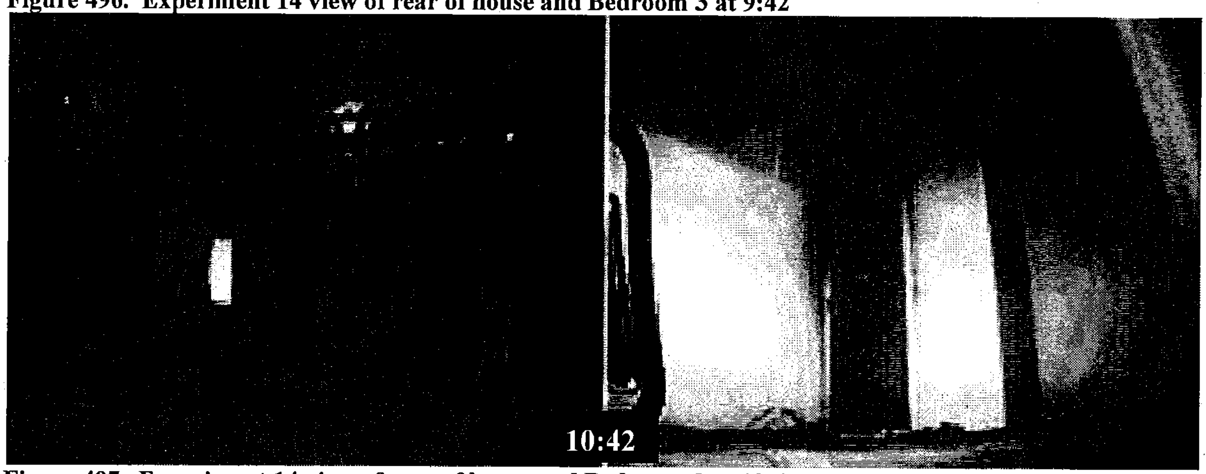

Figure 497. Experiment 14 view of rear of house and Bedroom 3 at 10:42

9.7. Flow paths

Many fire departments teach their search crews to "ventilate as they go." The reasoning is that the procedure may create cooler and clearer conditions throughout the structure. Experiments 14 and 15 show this is not the case if water is not applied to the fire. Figure 498 shows the flow paths created between the seat of the fire and the 4 open windows. The living room temperature from ventilating the door and 4 windows is compared to ventilating the front door and only 1 window near the seat of the fire (Figure 499). Opening more windows created faster fire growth and flashover approximately 40 seconds faster. Figure 500 shows the flow path from the same ventilation scenario in the two-story house. In this experiment, opening multiple windows also created faster fire growth and flashover conditions approximately 80 seconds faster (Figure 501). Every new ventilation opening provides a new flow path to the fire and vice versa. This could create very dangerous conditions when there is a ventilation limited fire. Adding many openings does not confuse the fire or create cooler temperatures for a longer period of time.

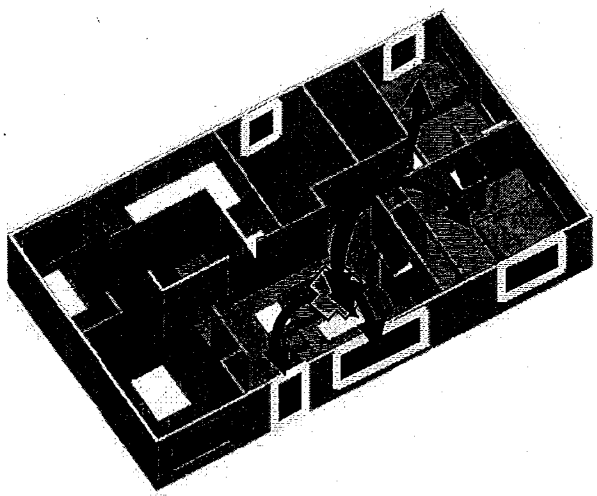

Figure 498. Experiment 14 flow paths

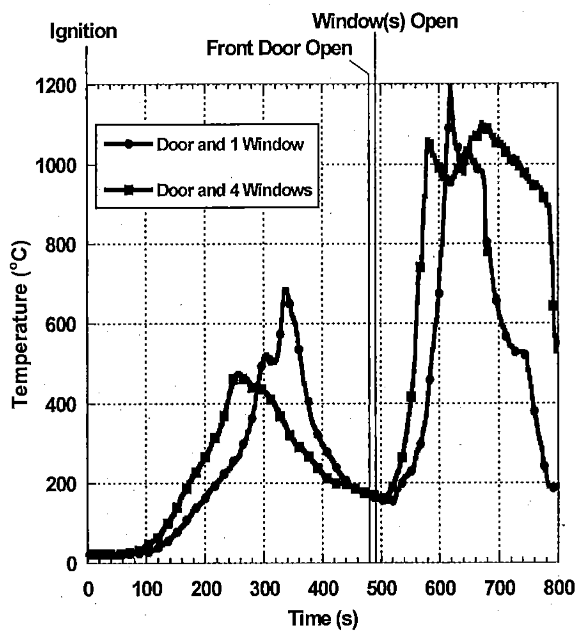

Figure 499. One-Story 1 window versus 4 windows

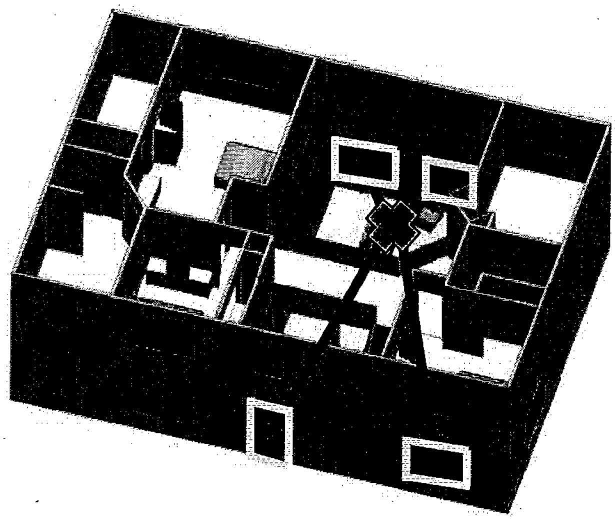

Figure 500. Experiment 15 flow paths

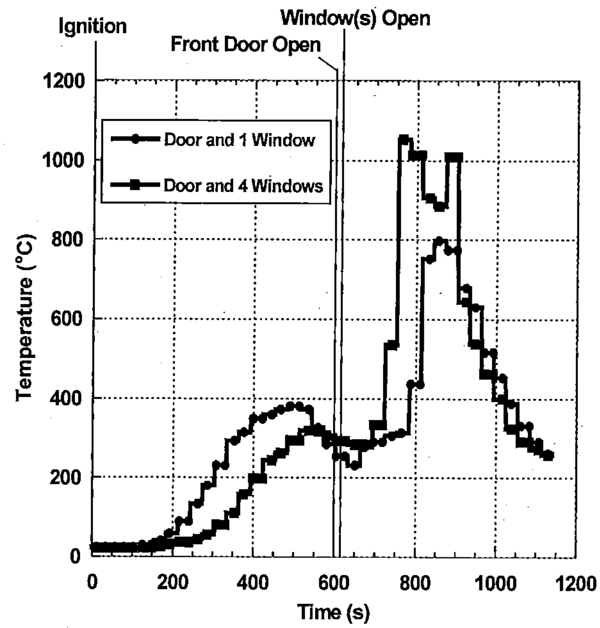

Figure 501. Two-Story 1 window versus 4 windows

9.8. Can you vent enough?

Another firefighter hypothesis is that opening enough ventilation locations will transform a ventilation limited fire to a fuel limited fire. Figure 502 shows the temperatures 1 ft above the floor in the living room for each of the different ventilation scenarios. In all four scenarios the living room transitions to flashover. The orange curve represents the scenario where the door and 4 windows were opened and this is also the scenario where flashover occurred the fastest. During this experiment there was 102 square feet of ventilation openings (Table 38). All four scenarios also remained ventilation limited throughout the experiment, until suppression took place. The two-story house behaved very similar to the one-story house in that the scenario with the front door and 4 additional windows transitioned to flashover the fastest (Figure 503). During this experiment there was 159 square feet of ventilation openings. In the heat release rate experiment in Section 7 there was 70 square feet open on the front of the room and the fire was ventilation limited. In both of the house experiments, with significantly more ventilation area, the fire still burned at the openings indication a ventilation limited fire and not a fuel limited fire.

Table 38. Experimental Ventilation Area

Experiment #	Structure	Ventilation Parameters	Ventilation Area (ft^2)
1	1-Story	Front Door	19.1
2	2-Story	Front Door	19.1
3	1-Story	Front Door + Living Room Window (Window near seat of the fire)	61.2
4	2-Story	Front Door + Family Room Window (Window near seat of the fire)	61.2
5	1-Story	Living Room Window Only	42.1
6	2-Story	Family Room Window Only	42.1
7	1-Story	Front Door + Bedroom 2 Window (Window remote from fire)	32.5
8	2-Story	Front Door + Bedroom 3 Window (Window remote from fire)	61.2
9	1-Story	Front Door + Living Room Window (Repeat Exp. 3)	61.2
10	2-Story	Front Door + Family Room Window (Repeat Exp. 4)	61.2
11	2-Story	Front Door + Family Room Window (Repeat Exp. 4)	61.2
12	1-Story	Front Door + Living Room Window (Repeat Exp. 3)	61.2
13	2-Story	Front Door + Upper Family Room Window	61.2
14	1-Story	Front Door + 4 Windows (LR, BR1, BR2, BR3)	102.4
15	2-Story	Front Door + 4 Windows (LR, Den, FR1, FR2)	158.8

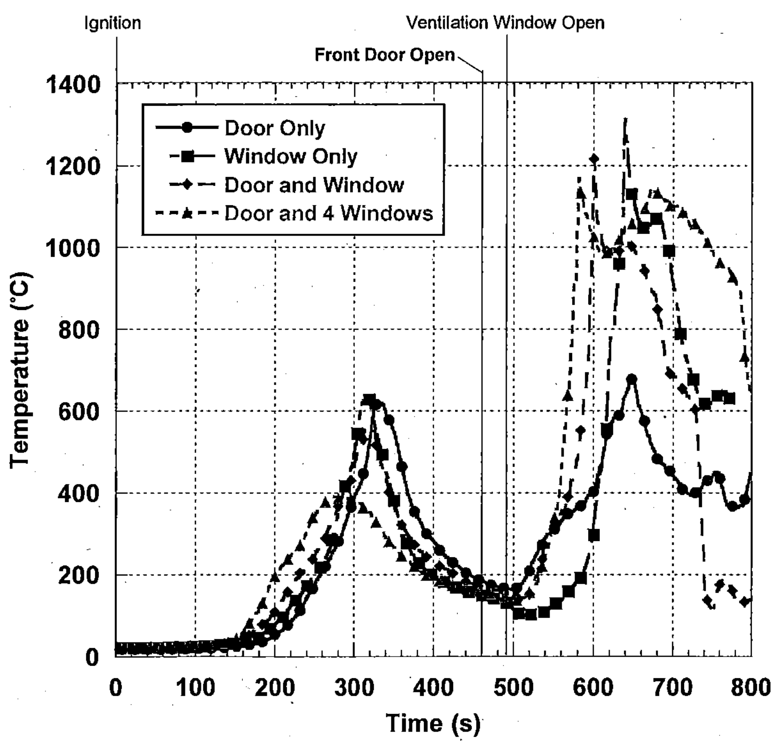

Figure 502. One-story comparison of different ventilation areas

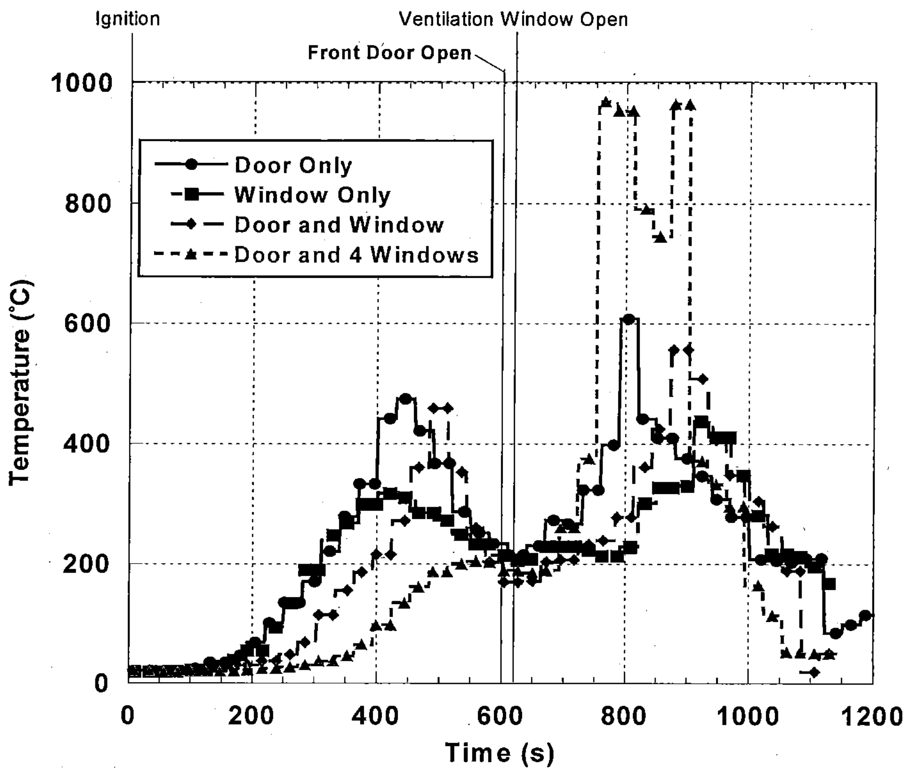

Figure 503. Two-story comparison of different ventilation areas

9.9. Impact of shut door on victim tenability and firefighter tenability

When it comes to rescuing occupants, the fire service makes risk based decisions on the tenability of occupants. They assume personal risk if it may save someone in the house. During the experimental design it was decided to have one closed bedroom in each house for every experiment. This allowed for the comparison of tenability of two side by side bedrooms, one with an open door and another with the door closed assuming the occupant already had a closed door or the closed it when they discovered there was a fire in the house.

In the one-story house there was a thermocouple tree in the closed bedroom (Bedroom 3) and one in the hallway right outside the closed bedroom. Figure 504 shows the ceiling (worst case scenario) temperatures during Experiment 14 in both of these locations for comparison. In the hallway the temperature reached 900 °C (1650 °F) while the Bedroom remained below 125 °C (260 °F). Large variances in temperature were observed in every experiment. The oxygen concentrations were also compared from inside the closed bedroom at 5 ft. above the floor, in the adjacent open bedroom and outside the room in the living room at 5 ft. above the floor (Figure 505). The living room and open bedroom had oxygen concentrations decline to 10% while the closed bedroom did not decline below 19.5%. The closed bedroom conditions were tenable while the open bedroom was not.

A comparison can also be made in the two-story house. Bedroom 2 had a closed door and the adjacent Bedroom 3 was open. There is also a thermocouple tree on the second floor hallway landing right outside the two bedrooms. Figure 506 compares the temperatures at these 3 locations. The second floor hallway temperature reaches 825 °C (1520 °F) and the open bedroom reaches 430 °C (810 °F) while the closed bedroom remains below 100 °C (210 °F).

Conditions in every experiment for the closed bedroom remained tenable for temperature and oxygen concentration thresholds. This means that the act of closing a door between the occupant and the fire or a firefighter and the fire can increase the chance of survival. During firefighter operations if a firefighter is searching ahead of a hoseline or becomes separated from their crew, and conditions deteriorate then an option would be to get in a room with a closed door until the fire is knocked down or escape out of the room's window with more time provided by the closed door.

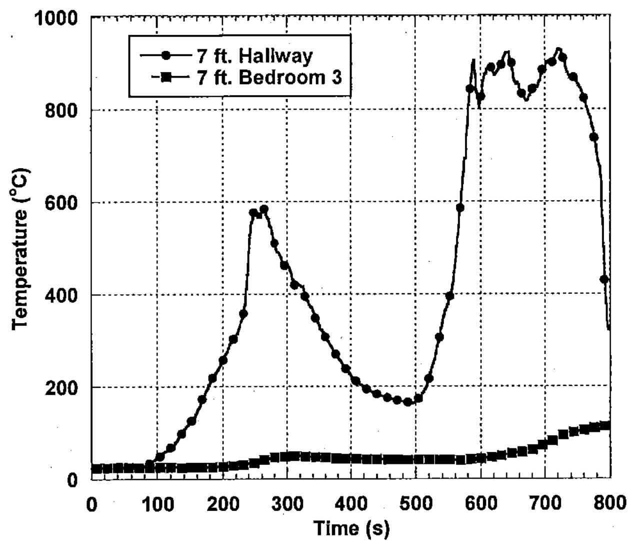

Figure 504. Experiment 14 Hallway and Bedroom 3 Temperatures with Door Closed

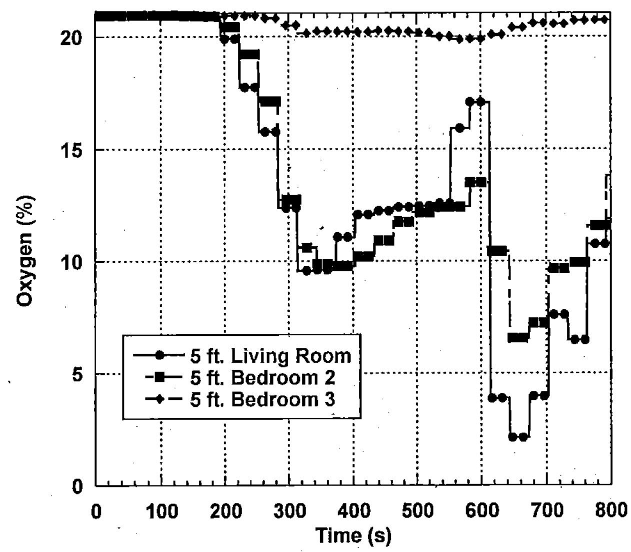

Figure 505. Experiment 14 Hallway, Bedroom 3 and Bedroom 2 Oxygen Concentration with Door Closed

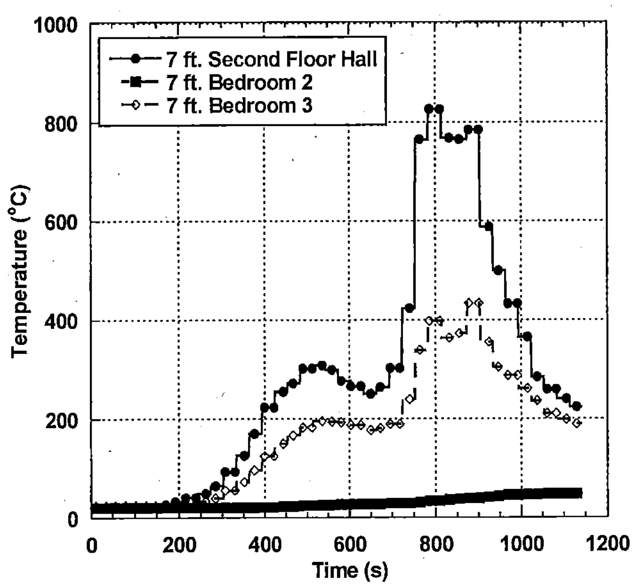

Figure 506. Experiment 15 Temperatures on the 2nd Floor Hallway and in Bedroom 2 with the door closed

9.10. Potential impact of open window already on flashover time

All of these experiments were designed to examine the first ventilation actions by an arriving crew when there are no ventilation openings. It is possible that the fire will break a window prior to fire department arrival or that a door or window was left open by the occupant while exiting. It is important to understand that an already open ventilation location provides air to the fire, allowing it to sustain or grow. In the experiments where multiple ventilation locations were made it was not possible to create fuel limited fires. The fire responded to the additional air provided. That means that even with a ventilation location open the fire is still ventilation limited and will respond just as fast or faster to any additional air. It is more likely that the fire will respond faster because the already open ventilation location is allowing the fire to maintain a higher temperature than if everything was closed. In these cases rapid fire progression is highly probable and coordination of fire attack with ventilation becomes even more important.

The closest experiment to demonstrate this phenomenon was Experiment 1. The fire was ventilated at 480 seconds by opening the front door. The fire produced its peak temperatures of 725 °C (1340 °F) at approximately 660 seconds (Figure 507). The fire was allowed to grow and then two 10 second bursts of water were flowed into the front door. At 857 seconds one half of the living room window was opened (Figure 508). This caused the living room to transition to flashover in approximately 30 seconds and peak above 1300 °C (2370 °F) (Figure 509 and Figure 510).

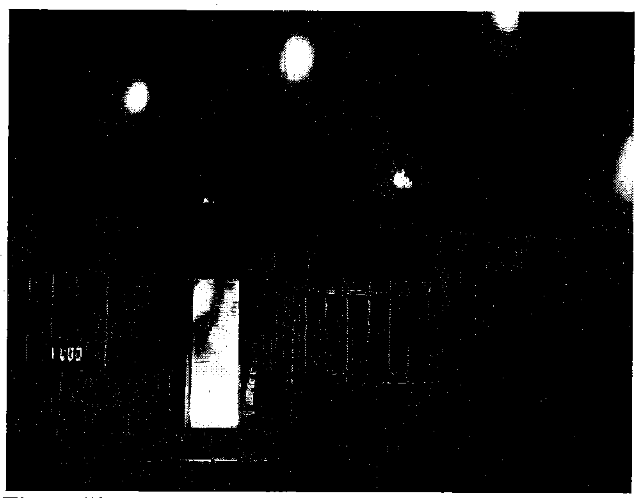

Figure 507. Peak fire conditions with front door open

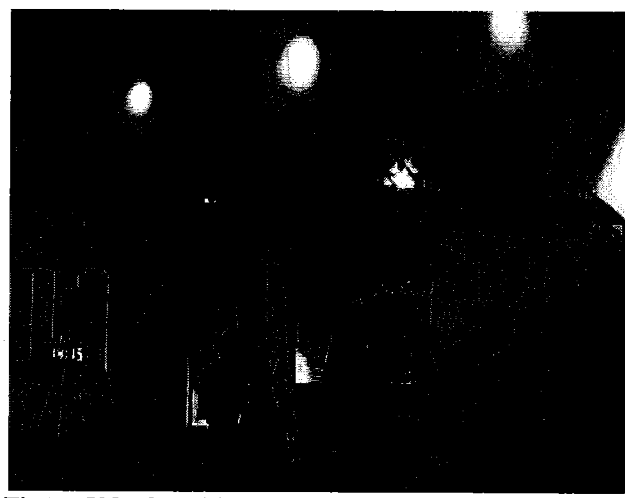

Figure 508. Conditions at time of window opening (14:15)

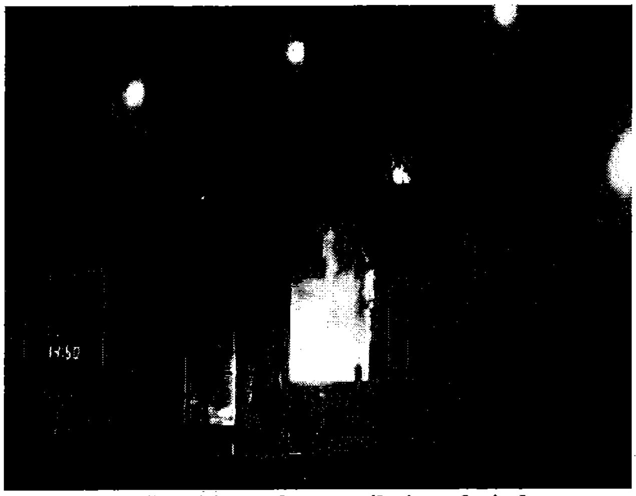

Figure 509. Conditions after ventilation of window (14:50)

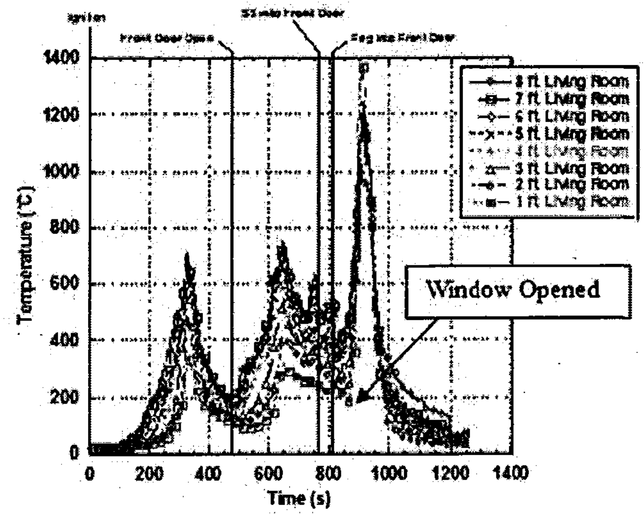

Figure 510. Living room temperatures for Experiment 1

9.11. Pushing Fire

With the changes that have occurred in the fire environment and the speed at which fires grow there have been questions posed about the validity to the belief that fire can be "pushed" with a hose stream. Pushing fire could occur as a result of three potential mechanisms. Once a hose stream is directed into an opening with fire or hot gases exiting, the pressure from the stream, airflow created by the stream or steam expansion could create conditions in the house that are worse downstream. It was not the focus of this research to examine this problem but since these fires were knocked down by external water application, the data can be analyzed to look at the possibility of pushing fire.

In each experiment, the fire was allowed to grow to approximately peak burning rate before water was introduced through the opening. In order to examine the impact of the water, temperatures were examined in each room, 30 seconds before water application, during the 10 seconds of water application and 30 seconds after water application. Figure 511 through Figure 527 show the temperature versus time for every water application, for every experiment, and for every room. The water application duration is identified by the time interval between the two black vertical lines. In Experiment 1 and Experiment 13 both types of streams were used. The stream was directed toward the ceiling to cool the ceiling and was not directed directly onto any burning fuel which is why there is no dramatic cooling seen in the graphs. Examining the graphs from the 15 experiments, there is no evidence of "pushing fire". Temperatures tend to decrease and any temperature increase after water application was minimal. There were also no temperature spikes in any of the rooms, especially the rooms adjacent to the fire room. It appears that in most cases the fire was slowed down by the water application and that external water application had no negative impacts to occupant survivability.

While room temperatures were not influenced by the use of the fog stream, there was an impact on visibility or the disruption of the thermal layer in Experiment 14 and 15. Two key factors for this were the air entrainment on the stream and the presence of a flow path. The flow from the nozzle caused steam formation and that steam flowed through the flow path created by the open door and windows. Figure 528 and Figure 529 show an example of this thermal layer disruption in the two-story house. The first quad view shows the front, rear, front door and living room views from the video just before the fog nozzle was operated. The second quad view was captured 10 seconds after the first and the visibility has greatly decreased because of the flow of gases out of the front door and living room windows. Figure 530 and Figure 531 show this same phenomenon in the one-story house during Experiment 14. The first two pictures show the front of the house and the master bedroom just prior to fog stream application. The second two pictures were captured 10 seconds later and the gases from the water application are forced into the bedroom in the flow path with the open window. This did not occur with the use of the straight stream water application but the fog stream was more effective at cooling during these experiments. While steam was "pushed" along the flow path there was no fire "pushed"..

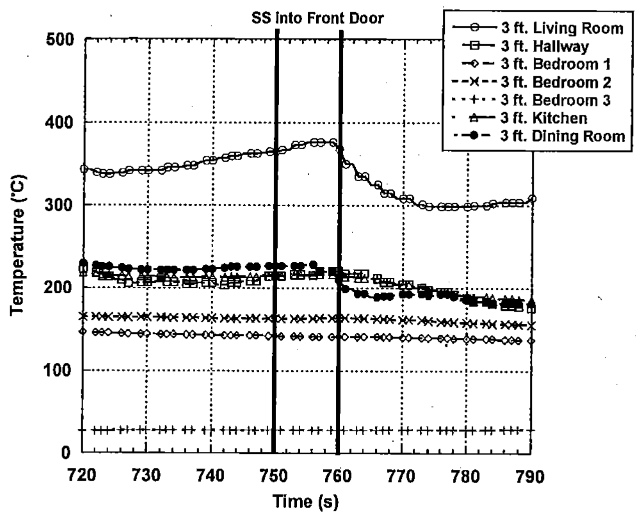

Figure 511. Experiment 1 Straight Stream

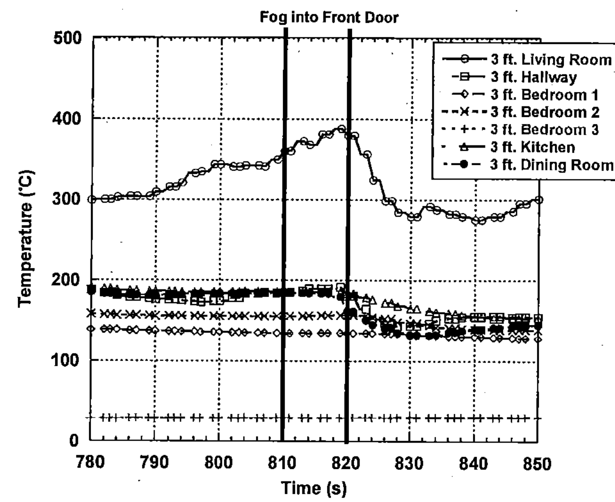

Figure 512. Experiment 1 Fog Stream

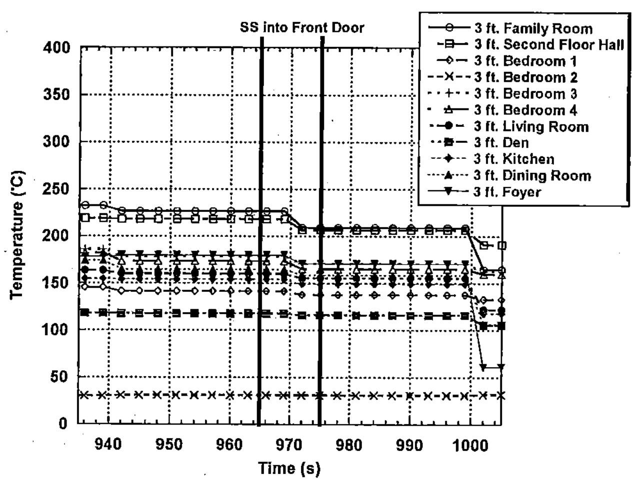

Figure 513. Experiment 2 Straight Stream

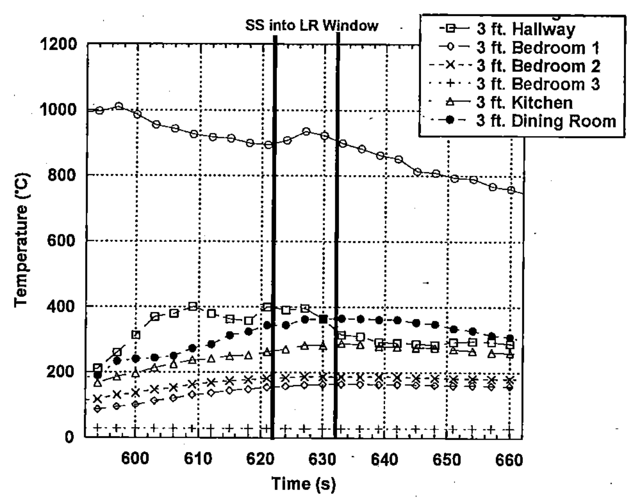

Figure 514. Experiment 3 Straight Stream

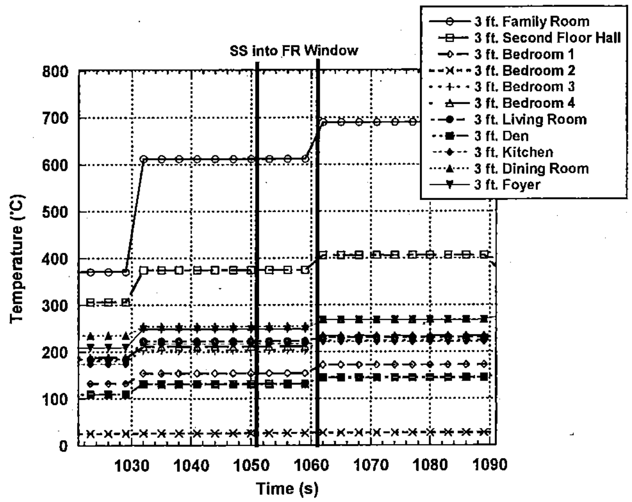

Figure 515. Experiment 4 Straight Stream

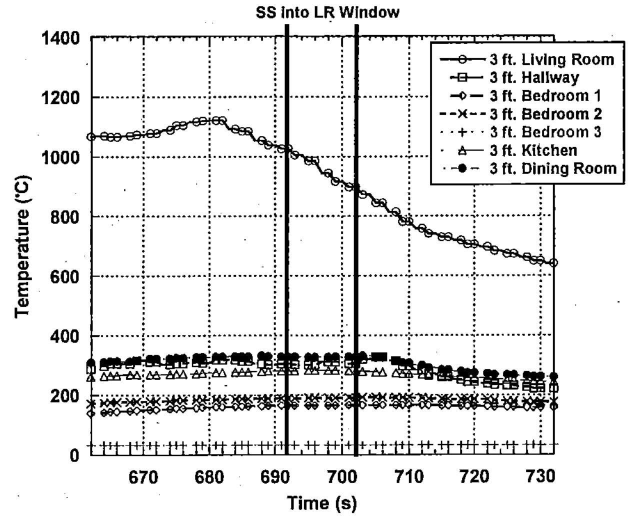

Figure 516. Experiment 5 Straight Stream

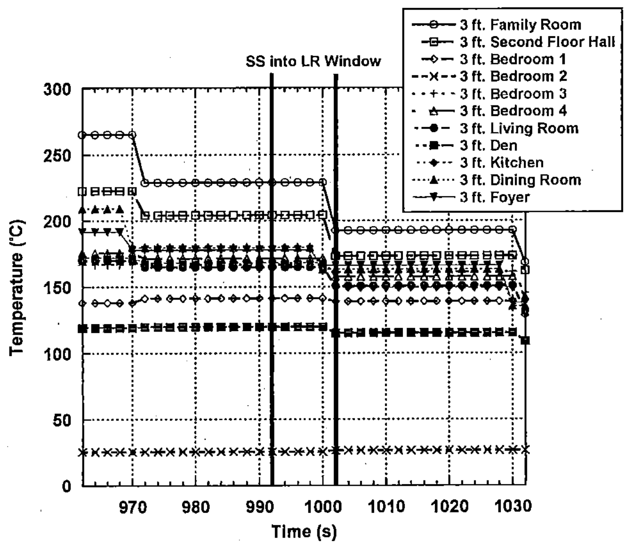

Figure 517. Experiment 6 Straight Stream

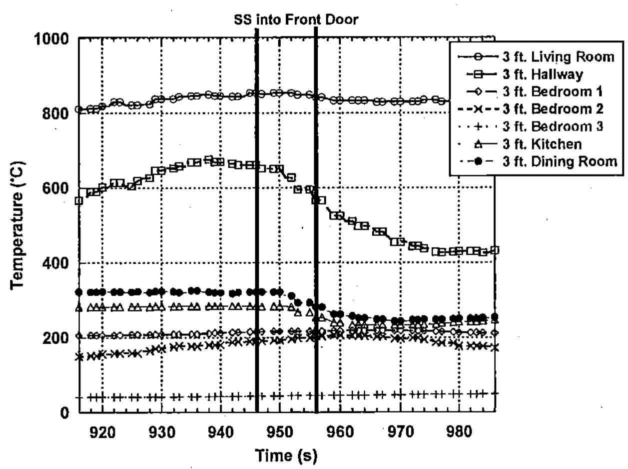

Figure 518. Experiment 7 Straight Stream

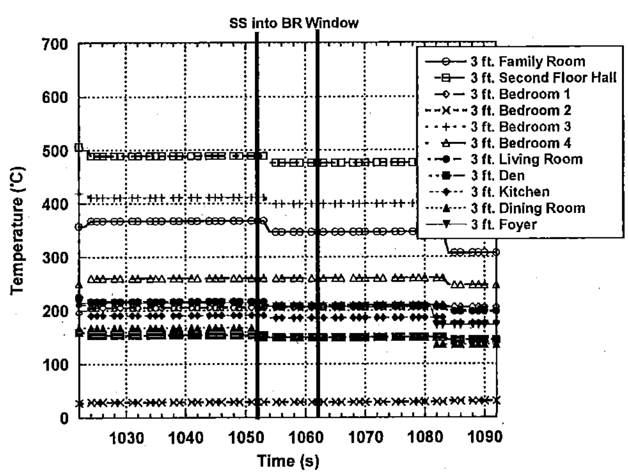

Figure 519. Experiment 8 Straight Stream

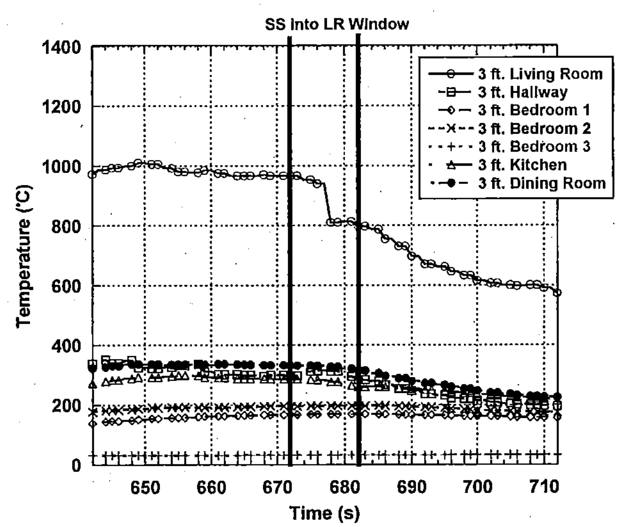

Figure 520. Experiment 9 Straight Stream

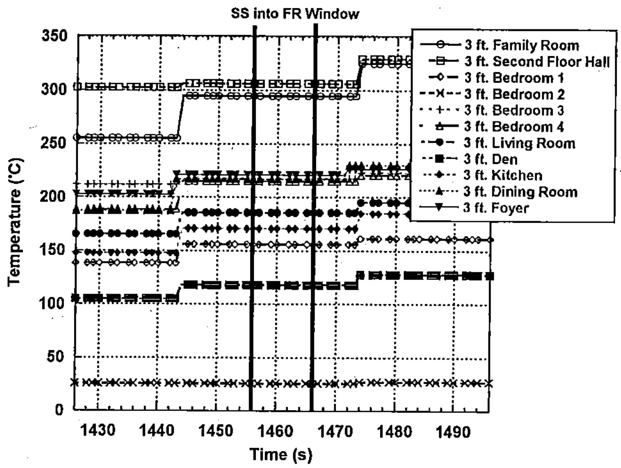

Figure 521. Experiment 10 Straight Stream

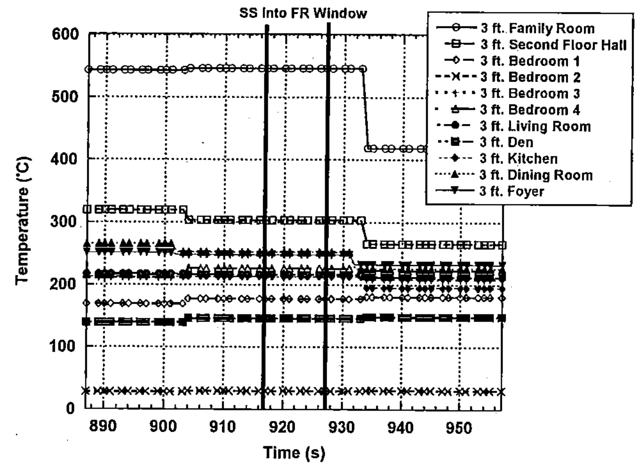

Figure 522. Experiment 11 Straight Stream

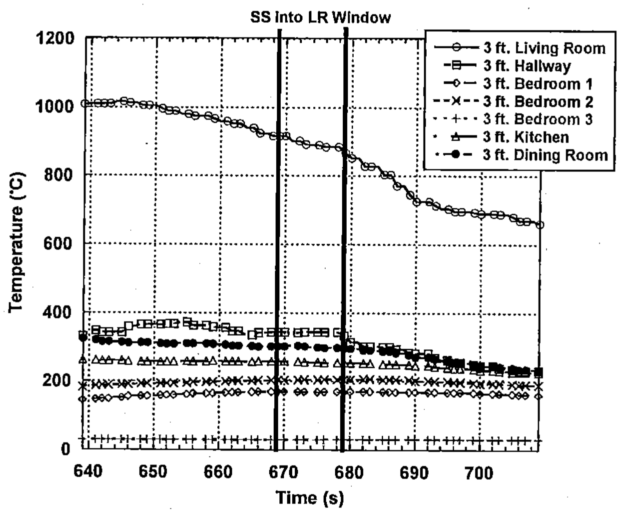

Figure 523. Experiment 12 Straight Stream

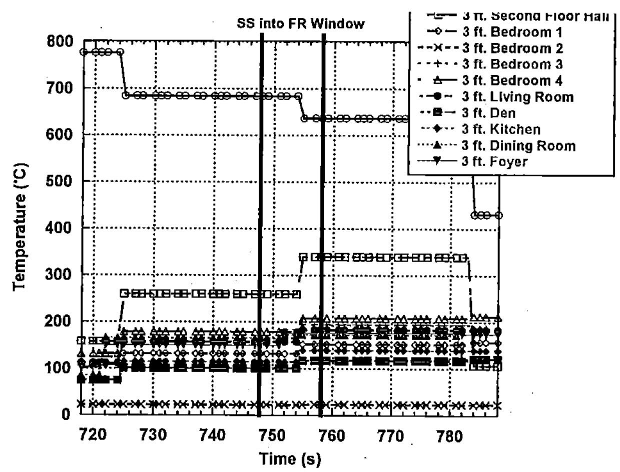

Figure 524. Experiment 13 Straight Stream

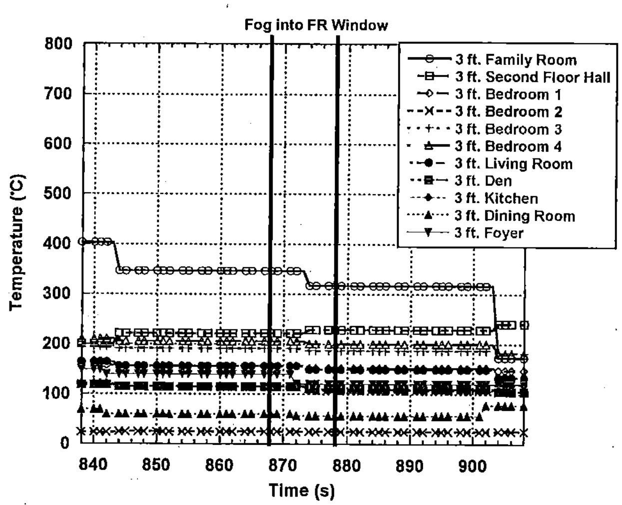

Figure 525. Experiment 13 Fog Stream

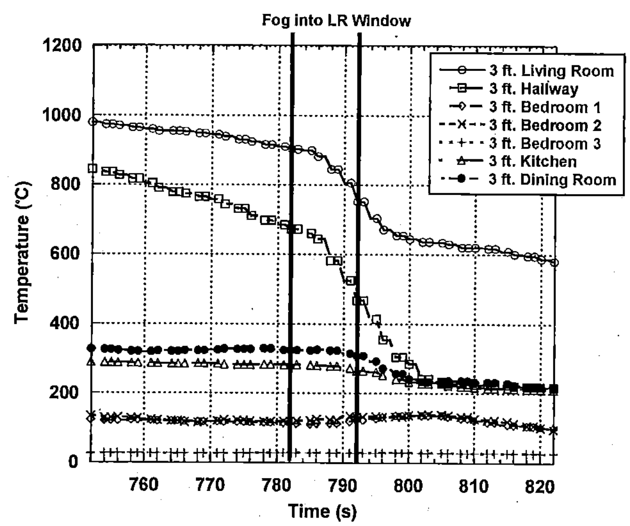

Figure 526. Experiment 14 Fog Stream

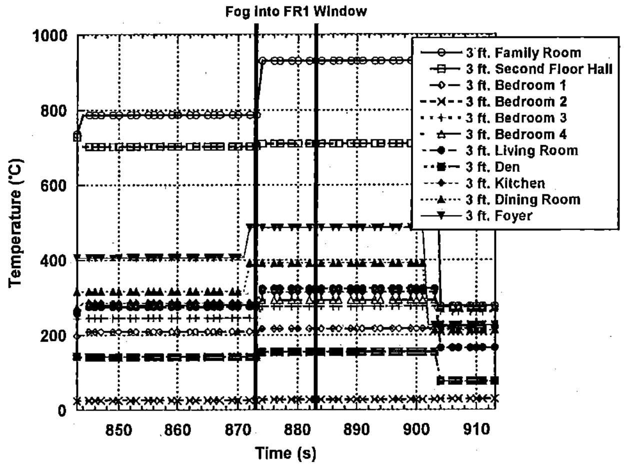

Figure 527. Experiment 15 Fog Stream

Figure 528. Two-story house before fog stream application (Experiment 15)

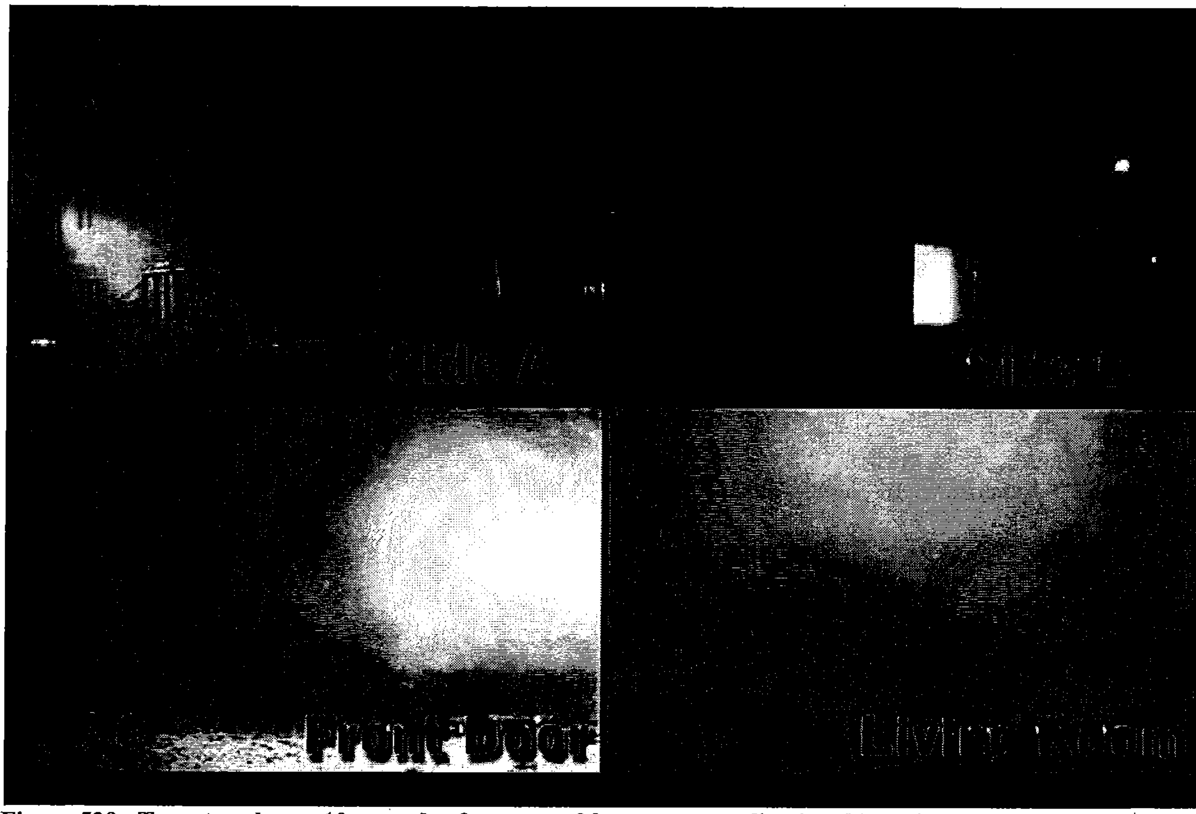

Figure 529. Two-story house 10 seconds after start of fog stream application (Experiment 15)

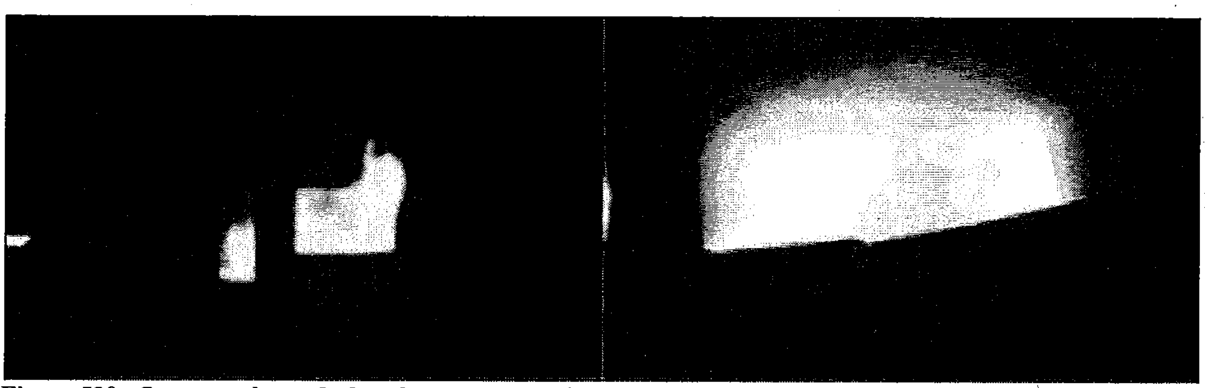

Figure 530. One-story house before fog stream application, Front, left and Bedroom 1, right (Experiment 15)

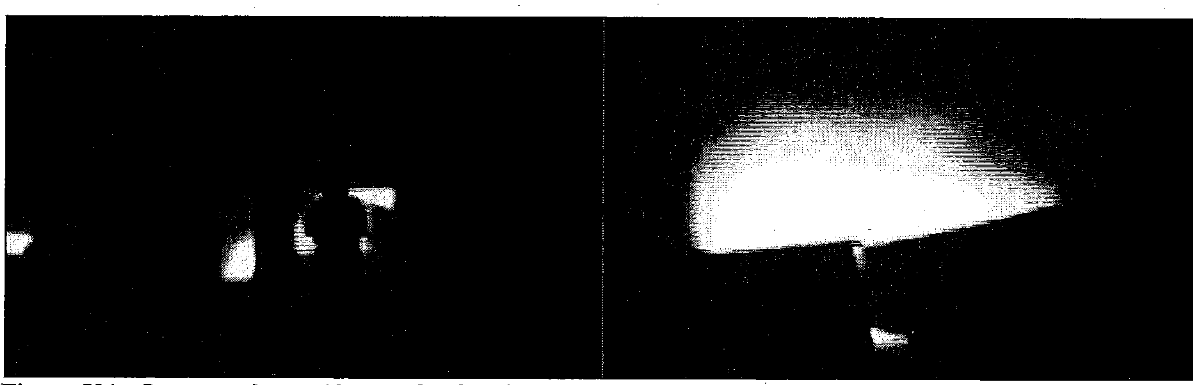

Figure 531. One-story house 10 seconds after fog stream application (Experiment 14)

9.12. No damage to surrounding rooms

Just as the fire triangle depicts, fire needs oxygen to burn. A condition that existed in every experiment was that the fire (living room or family room) grew until oxygen was reduced below levels to sustain it. This means that it decreased the oxygen in the entire house by lowering the oxygen in surrounding rooms and the more remote bedrooms until combustion was not possible. In most cases surrounding rooms such as the dining room and kitchen had no fire in them even when the fire room was fully involved in flames and was ventilating out of the structure. There was not enough oxygen in the structure to burn so there was some pyrolysis or melting because of high temperatures, but there was no burning in the adjacent rooms. The only time this did not hold was when remote windows were ventilated. Doing this created a flow path for oxygen to come from another part of the house and ignite rooms in the flow path but not outside the flow path. This is a good demonstration as to why ventilating near the seat of the fire is ideal. The fully developed fire conditions were localized by ventilating near the seat of the fire.

Examining the video of the interior conditions in the houses as compared to the exterior conditions highlighted the flame locations and extent of fire extension within the houses. Figure 532 shows the video views from Experiment 3. At 10 minutes after ignition, flames were extending out of the entire front door and living room window. The view in the bottom right is the view from the kitchen into the living room, and the flames are filling the entire doorway and intermittently flowing in through the top of the door but are not filling the kitchen due to lack of oxygen. During all of the experiments the appliances, cabinets, kitchen table and chairs melted a little bit but never became involved in the fire. If the kitchen door or windows were ventilated this would change and the flow path would allow for burning of the combustibles in the kitchen.

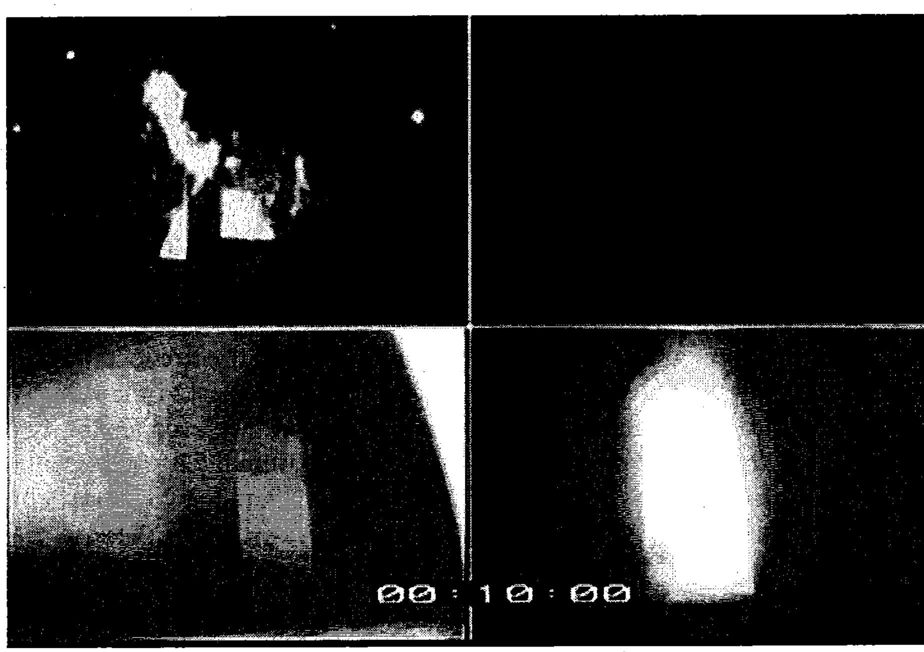

Figure 532. Experiment 3 at 10:00 showing flame extension.

10. Summary of Findings:

There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, more open floor plans and volumes and increased synthetic fuel loads. UL conducted a series of 15 full-scale residential structure fires to examine this change in fire behavior and the impact of firefighter ventilation tactics. This fire research project developed the empirical data that is needed to quantify the fire behavior associated with these scenarios and result in immediately developing the necessary firefighting ventilation practices to reduce firefighter death and injury.

The increased use of synthetic materials in the home has created faster flashover times. The two experiments demonstrated flashover times of less than 4 minutes with modern furnishings as compared to more than 29 minutes with legacy furnishings. This difference has a substantial impact on occupant and firefighter safety.

Tenability in these two homes was limited for occupants but the possibility of savable lives, especially behind closed doors should be considered by the fire service in their risk analysis. Also, emphasis should be placed on closing doors when the fire service is educating the public. Tenability for firefighters can also be quantified for these experiments. Firefighters had 100 seconds in the one-story house and 200 seconds in the two-story house after ventilation before water would have to be applied to remove the hazard or the firefighter would have to exit the house. These numbers should be considered conservative as the fire were allowed to become ventilation limited and decrease to a low temperature without becoming extinguished.

A significant portion of the 100 second and 200 second time to firefighter untenability is fresh air being entrained into the ventilation limited fire. In many of the experiments the time from the beginning of temperature escalation until untenability was less than 10 seconds. This provides little warning that the fire is going to flashover and highlights the need to understand that ventilation opening are not only allowing hot gases to escape but fresh air to enter.

Several ventilation comparisons could be made from the experimental series. First, the more ventilation openings that were made the faster the fire room transitioned to flashover. This shows that even in these modestly furnished homes fuel is not the limiting factor and that more air will create more burning and less tenability. Ventilating near the seat of the fire localized the combustion and temperatures within the house. Ventilating remote from the seat of the fire created a flow path which expanded the area available to burn and further decreased tenability within the homes. Allowing air into a ventilation limited fire low and letting the hot gases out high can create prime conditions for a flashover, even in a large volume like the two-story family room. More efficient ventilation can mean more efficient air entrainment which can lead to faster flashover times if water is not applied in the shorter tenability window.

Several tactical considerations were able to be developed with the assistance of the technical panel of fire service leaders. In summary, the stages of fire development change when a fire becomes ventilation limited. It is common with today's fire environment to have a decay period prior to flashover which emphasizes the importance of ventilation. Forcing entry has to be thought of as ventilation as well. While forcing entry is necessary to fight the fire it must also trigger the thought that air is being fed to the fire and the clock is ticking before either the fire gets extinguished or it grows until an untenable condition exists jeopardizing the safety of everyone in the structure. A common event during the experiments was that once the fire became ventilation limited the smoke being forced out of the gaps of the houses greatly diminished or stopped all together. No smoke showing during size-up should increase awareness of the potential conditions inside. Once the front door is opened attention should be given to the flow through the front door. A rapid in rush of air or a tunneling effect could indicate a ventilation limited fire.

During a VES operation primary importance should be given to closing the door to the room. This eliminates the impact of the open vent and increases tenability for potential occupants and firefighters while the smoke ventilates from the now isolated room. Every new ventilation opening provides a new flow path to the fire and vice versa. This could create very dangerous conditions when there is a ventilation limited fire. Conditions in every experiment for the closed bedroom remained tenable for temperature and oxygen concentration thresholds. This means that the act of closing a door between the occupant and the fire or a firefighter and the fire can increase the chance of survivability. During firefighter operations if a firefighter is searching ahead of a hoseline or becomes separated from his crew and conditions deteriorate then a good choice of actions would be to get in a room with a closed door until the fire is knocked down or escape out of the room's window with more time provided by the closed door.

All of these experiments were designed to examine the first ventilation actions by an arriving crew when there are no ventilation openings. It is possible that the fire will fail a window prior to fire department arrival or that a door or window was left open by the occupant while exiting. It is important to understand that an already open ventilation location is providing air to the fire, allowing it to sustain or grow. In the experiments where multiple ventilation locations were made it was not possible to create fuel limited fires. The fire responded to all the additional air provided. That means that even with a ventilation location open the fire is still ventilation limited and will respond just as fast or faster to any additional air. It is more likely that the fire will respond faster because the already open ventilation location is allowing the fire to maintain a higher temperature than if everything was closed. In these cases rapid fire progression if highly probable and coordination of fire attack with ventilation is paramount.

If you add air to the fire and don't apply water in the appropriate time frame the fire gets larger and safety decreases. Examining the times to untenability gives the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation opening because the temperatures in the house are going to be higher. Coordination of fire attack crew is essential for a positive outcome in today's fire environment.

This research study developed empirical fire experiment data to demonstrate fire behavior resulting from varied ignition locations and ventilation opening locations in legacy residential structures compared to modern residential structures. The data will be used to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic that will result in mitigation of the firefighter injury and death risk associated with improper use of ventilation.

11. Future Research Needs:

These experiments were the first of their kind and there are countless experiments that could be done in two full-scale houses, especially the 2-story house. Other full-scale house experiments were done in an acquired structure and did not allow for repeatability or examination of multiple variables. There are several variable changes that could be done to further validate the conclusions from this series of experiments.

The first variable that could be altered is the fire location. These experiments focused on living room or family room fires. Additional experiments with fires in the kitchen or bedrooms would allow for analysis of fire spread from these locations. Additionally, changing fuel loading could provide some further insight. These experiments were realistically loaded but more experiments could examine the upper bound of fuel loading which may further emphasize the impact of ventilation.

Future experiments should also consider creating a ventilation point after one already exists from the fire creating one of its own by failing a window or a door being left open by an escaping occupant or a window left open on a warm day. This will also show the importance of ventilation. With an opening the fire will still be ventilation limited but will not be as starved for oxygen. This will allow the fire to respond to the ventilation faster demonstrating a very dangerous yet common situation.

There are also two more types of ventilation in addition to horizontal ventilation that are frequently used by the fire service that did not fit into the scope of this project but should be analyzed in a similar manner. These are vertical ventilation and positive pressure ventilation. Very little research has been conducted on these tactics used in a house.

12. Acknowledgements:

Without the financial support of the Department of Homeland Security's Assistance to Firefighters Grant Program's Fire Prevention and Safety Grants this research would not be possible, in particular the staff members Dave Evans, Kathy Patterson, Ellen Sogolow and Maggie Wilson.

Appendix A: Firefighter Reference Scales for the Results Sections

This section includes tables with reference values that firefighters can use to assist with putting the results in the following sections into perspective. Table 39 provides a set of temperatures commonly experienced during firefighting operations and information on the human and equipment response. Table 40 provides common symptoms from carbon monoxide exposures of a given duration to a particular concentration. There are number of variables that could cause an individual to respond differently.

Table 39. Firefighter Temperature Reference Table

Temperature	Response
37 °C (98.6 °F)	Normal human oral/body temperature [1]
44 °C (111 °F)	Human skin begins to feel pain [2]
48 °C (118 °F)	Human skin receives a first degree burn injury [2]
55 °C (131 °F)	Human skin receives a second degree burn injury [2]
62 °C (140 °F)	A phase where burned human tissue becomes numb [2]
72 °C (162 °F)	Human skin is instantly destroyed [2]
100 °C (212 °F)	Water boils and produces steam [3]
140 °C (284 °F)	Glass transition temperature of polycarbonate [4]
230 °C (446 °F)	Melting temperature of polycarbonate [5]
250 °C (482 °F)	Charring of natural cotton begins [6]
>300 °C (>572 °F)	Charring of modern protective clothing fabrics begins [6]
>600 °C (1112 °F)	Temperatures inside a post-flashover room fire [7, 8]

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8 Drysdale, D., "An Introduction to Fire Dynamics", 2nd Edition, John Wiley & Sons, New York, 1999.

Table 40. Carbon Monoxide Firefighter Reference Table [1, 2, 3]

Concentration	Common Symptoms	Duration of Exposure
35 ppm (0.0035 %)	None	<= 8 hours
150 ppm (0.0150 %)	Mild headache	2 – 3 hours
400 ppm (0.04 %)	Headache/nausea	1 – 2 hours
800 ppm (0.08 %)	Headache/nausea/dizziness Progressing to unconsciousness	45 minutes 2 hours
6400 ppm (0.64 %)	Headache/nausea/dizziness	1 – 2 minutes
12800 ppm (1.28%)	Immediately dangerous to life and health (IDLH)	1 – 2 minutes

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1. Delagi, Robert, “A CO Emergency: Whose Call Is It, Anyway?”, *Fire Engineering Magazine*, October 2007.
2. Henry CR, Satran D, Lindgren B, Adkinson C, Nicholson CI, Henry TD, MD (2006). "Myocardial Injury and Long-term Mortality Following Moderate to Severe Carbon Monoxide Poisoning". *JAMA* **295**: 398-402.
3. Raub JA, Mathieu-Nolf M, Hampson NB, Thom SR. (2000). "Carbon monoxide poisoning-a public health perspective". *Toxicology* **145** (1): 1-14.