Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Full Scale Experiments

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To assist the design and implementation of the experiments for the Fire Attack study, fire service experts were gathered from across the world with knowledge in fire suppression and the impact of interior and exterior fire streams. The individuals below provided direction for the project, assisting in planing the experiments, witnessing the testing, and developing concrete conclusions. Their tireless support and effort make this project relevant to the fire service across the world.

Fire Service Technical Panel

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Tony Carroll	Washington DC Fire Department
Albert Castillo	Houston Fire Department
Chad Christensen	Los Angeles County Fire Department
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Steve Pegram	Goshen Township Fire and EMS

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List of Acronyms

AFG	Assistance to Firefighters Grant program
DHS	U.S Department of Homeland Security
FEMA	Federal Emergency Management Agency
NFPA	National Fire Protection Association
SB	Smooth Bore
SS	Straight Stream
NF	Narrow Fog
UL FSRI	UL Firefighter Safety Research Institute
USFA	United States Fire Administration

Abstract

As research continues into how fire department interventions affect fire dyanmics in the modern fire environment; questions continue to arise on the impact and implications of interior versus exterior fire attack on both firefighter safety and occupant survivability. Previous research into various types of fire ground ventilation, flow paths, and exterior fire streams has provided the fire service with a more in-depth understanding of fire dynamics in addition to raising questions about certain fire attack methods stemming from differing traditions and myths. This knowledge gap and lack of previous research into the impact of fire streams has driven the need for further research into fire department interventions at structure fires with a focus on hose streams and suppression tactics. Statistics show that both firefighters and building occupants continue to loose their lives due to fire. As such, research into the various methods of fire attack will allow a broader understanding of how firefighter interventions on the fire ground can impact the outcome of both life safety and property protection.

This study will build and expand upon the fire research conducted to date by analyzing how firefighting tactics, specifically suppression methods, affect the thermal exposure and survivability of both firefighters and buidling occupants in addition to impacting fire behavior in structures. The project will be comrprised of 3 parts:

- Part I: Water Distribution.
- Part II: Air Entrainment
- Part III: Full-Scale Residential Fire Experiments.

Contents

Introduction

The purpose of this study is to improve firefighter safety, fireground tactics, and the knowledge of fire dynamics by providing the fire service with credible scientific information, developed from both water flow and full-scale fire testing, in representative single family homes, on the impacts and implications of both interior and exterior fire attack. Part I of the study is aimed at determining where water is distributed within a compartment while Part II of the study attempts to quantify air entrainment in hose streams to provide insidght into how different application methods, nozzle types and patterns, pressures/flows, and stream location and angles move air inside buildings. Parts I and II were conducted without the presence of fire in order to gain a basic understanding of air flow and water flow before Part III of the study was conducted as full-scale fire experiments. The full-scale fire experiments were designed based on the results from Parts I and II of this study.

1 Background

Recent fire service research has highlighted the importance of applying water to the fire as quickly as possible. This tactical consideration has highlighted a knowledge gap and increased the interest in better understanding the impact of water applied as part of an interior attack or exterior attack. Many variables exist in fire attack that impact firefighter effectiveness and victim survivability, stream placement, the timing required to get water on the fire, stream type, stream movement, air entrainment, steam development, hot gas cooling and contraction and position of flow paths. The fire service's most important tool for many years at structure fires is their hose line, however many questions have arisen as more research shows the impact of ventilation, flow paths and exterior fire streams. Whether a fire attack crew chooses to apply water as part of an interior attack or as part of an exterior or transitional attack they need to know what impact their stream has on the fire environment ahead of them. This is difficult on the fire ground because visibility is commonly limited and therefore all of their experience is from behind the nozzle. This results in beliefs about conditions (e.g., temperature), ahead of the nozzle and its impact on victim survivability but knowledge of actual impact has not been researched. Additionally, when the fire is ultimately suppressed that does not mean it was done most effectively, efficiently and safely but the experience gained suggests that it was. Fire service adages such as "donâĂŹt put water on smoke," "you will steam the victims," and "fog nozzles always disrupt the thermal layer" have been passed on from generation to generation with little context or substantiation. Without the context these concepts get treated like rules and can severely limit firefighters understanding of fire suppression.

Fire training curriculum defines 3 fire attack methods, direct attack, indirect attack and combination attack. Direct attack involves the discharge of water directly onto the burning fuel. Indirect attack involves directing the stream toward the ceiling of a compartment in order to generate a large amount of steam in order to cool the compartment. Converting the water to steam displaces oxygen, absorbs the heat of the fire and cools the hot gas layer sufficiently for firefighters to safely enter and make a direct attack. Combination attack extinguishes a fire by using both a direct and indirect attack. Another technique to safely approach a fire that cannot be reached with a direct attack is gas cooling. Gas cooling provides a buffer zone around the attack team but the larger the compartment the less the impact on cooling the hot gas layer. Gas cooling must be a continuous process while advancing toward a shielded fire. Techniques for effective gas cooling and the upper limit of the volume where gas cooling is effective is not well known.

In fire fighter training there is a lot of emphasis on steam generation but little is taught or demonstrated about the mechanics of suppression. Water vaporized in the upper gas layer reduces the total volume of the hot gases and steam. Water vaporized on hot surfaces such as the ceiling does not take much energy from the fire and therefore the volume of steam produced lowers the upper layer and makes conditions less tenable. These concepts are very important when the fire is not able to be directly attacked by applying water on burning fuel but is very difficult to visualize during a fire attack with limited visibility. Many of these fire suppression concepts are difficult to learn and refine because realistic ventilation limited fires are not safely replicated in firefighter training structures. Conditions created by todays fuels with heat release rates and smoke production properties commonly found in our structures are not allowed when following fire service training standards. Therefore the impact of hose streams in concrete training structures or metal containers can be misleading to firefighters resulting in incorrect inferences. This may then lead to inappropriate fire ground tactics with potentially deadly results. Research is needed to better understand the impact of hose streams so that proper messages can be taught in fire service training programs.

There are potentially harmful effects of inappropriate water application regardless of the type of hose stream. Since firefighters today are more aware of the need to cool hot smoke (fuel) in the upper layer, it is essential to understand the capabilities and limitations of each type of stream. The impact of hose stream application as one advances during a fire attack is dependent on a number of factors, principle of which are the flow path and where the steam is produced (in the hot gas layer or on contact with hot surfaces). Continuous application is likely to result in more steam being produced than gas contraction in the hot gas layer. Without ventilation in front of the hose stream, this can result in a reduction in tenability. However, when victims or firefighters are not in the flow path, and ventilation is in front of the hose stream, a combination attack can be quite effective for fully developed fire conditions.

Fire suppression effectiveness and firefighter safety are not achieved by water flow rate alone, but by appropriate use of a given flow rate under specific fire ground conditions. A flow rate must meet the critical flow rate to extinguish a fire depending on the heat release rate and should be higher to reduce the time to extinguishment. Drastically exceeding the critical flow rate has less impact on time to extinguishment but has a significant impact on the total amount of water used. There is little data to support that dramatically exceeding the critical flow rate results in increased firefighter safety. It has been estimated that only 5 to 10 percent of water applied during fire attack contributes to extinguishment. It is difficult for firefighters to realize the the efficiency of various hose stream techniques due to poor visibility on the fireground. However, by developing data in realistic structures, fuel sources, and fire scenarios, important inferences may be developed relative to different hose stream techniques, and use of water.

2 Objectives and Limitations

2.1 Objectives

The purpose of this study was to provide the fire service with scientific based knowledge on the impact of interior and exterior fire attack tactics on firefighter safety and trapped occupants to improve training and decision making on the fire ground. This was accomplished with the completion of the following objectives:

- Improve firefighter safety by increasing knowledge of fire behavior.
- Develop knowledge of water streams applied during an interior and exterior/interior fire attack and its impact on firefighter safety and victim survivability.
- Understand where water goes and how air flows during interior and exterior/interior fire attack utilizing common procedures and what that means to fire dynamics within a structure.
- Gain understanding of the impact of water streams depending on the volume of the fire compartment/structure.
- Advance the understanding of victim survivability in the modern fire environment by working with experts in the use of pig carcasses and rodents.
- Develop and implement a methodology to measure moisture content in the modern fire environmental conditions to answer fire service concerns.
- Bring the 'Science to the Streets' by transferring science based tactical considerations founded on experimental results that can be incorporated into firefighting standard operating procedures.

All five of the Technology & Fire Service Science issues facing the fire service determined during the 2nd National Fire Service Research Symposium [1] were incorporated into this study.

2.2 Limitation and Scope

The fire attack study is not intended to establish which methods of fire attack are more effective when compared to others. More specifically, the study is not intended to dictate tactics or the purchasing of one type of nozzle over another. The purpose is to quantify the amount of air entrainment in nozzles given certain parameters as well as determine where water is distributed within a compartment. This is all without fire involvement in order to provide a baseline understanding before moving forward with the remainder of the study. This baseline knowledge is intended to bridge the gap in the fire service understanding about the use of various nozzles, application patterns, and advancement techniques in specific scenarios. Knowing how hose streams affect air movement and how water is distributed can allow for better decision making capabilities across the fire service when it comes to equipment purchasing and use during an actual emergency incident.

When analyzing the air entrainment and water distribution, equipment from various manufacturers was tested. For the purpose of the study, the companies will be referred to as Manufacturer 1, Manufacturer II, and Manufacturer III. The air entrainment experiments yielded results that showed little to no difference among the various manufacturers. Therefore, a single manufacturer was chosen for the remainder of Part I of the study.

Each and every fire department across the world utilizes different personal protective equipment, firefighting equipment, staffing levels, apparatus, standard operating procedures, and tactics. Additionally, no two fires are identical as well. Thus provides a challenge for researchers when evaluating what can be varied versus held constant during testing. For the purpose of these experiments we utilized the same structure throughout all of the air entrainment experiments. The water distribution testing utilized another structure, which also remained the same for the duration of those experiments. The only component of the firefighting equipment that was varied among the tests was the nozzle, and sometimes the hose line size. The hose line was either 1 3/4 in or 2 1/2 in in diameter and was always 200 ft in length. By creating some aspects that were not varied and by bounding other variables, we ensured that all aspects of the air entrainment and water distribution were examined as a baseline for further future evaluation in different structures with different conditions.

REWRITE SPECIFIC TO FIRE EXPERIMENTS

3 Experimental Configuration

3.1 Test Fixtures

The ranch fire experiments were conducted in two identical structures that were constructed in UL's Large Fire Test Facility in Northbrook, IL. The 1620 ft^2 houses were designed by a residential architectural company to be typical of a single family home constructed in the late-20th century in the United States. The floor plan included 4 bedrooms, a bathroom, a living area, kitchen, and dining room. Three of the bedrooms were left open during the fire experiments, while one bedroom (Bedroom 3) was left closed, to examine the impact of a closed door on fire behavior. The interior of the house had 8' ceilings, and the rooms were separated from each other with walls and doorways. The floor plan of the houses used for these experiments can be seen in Figure 3.1.

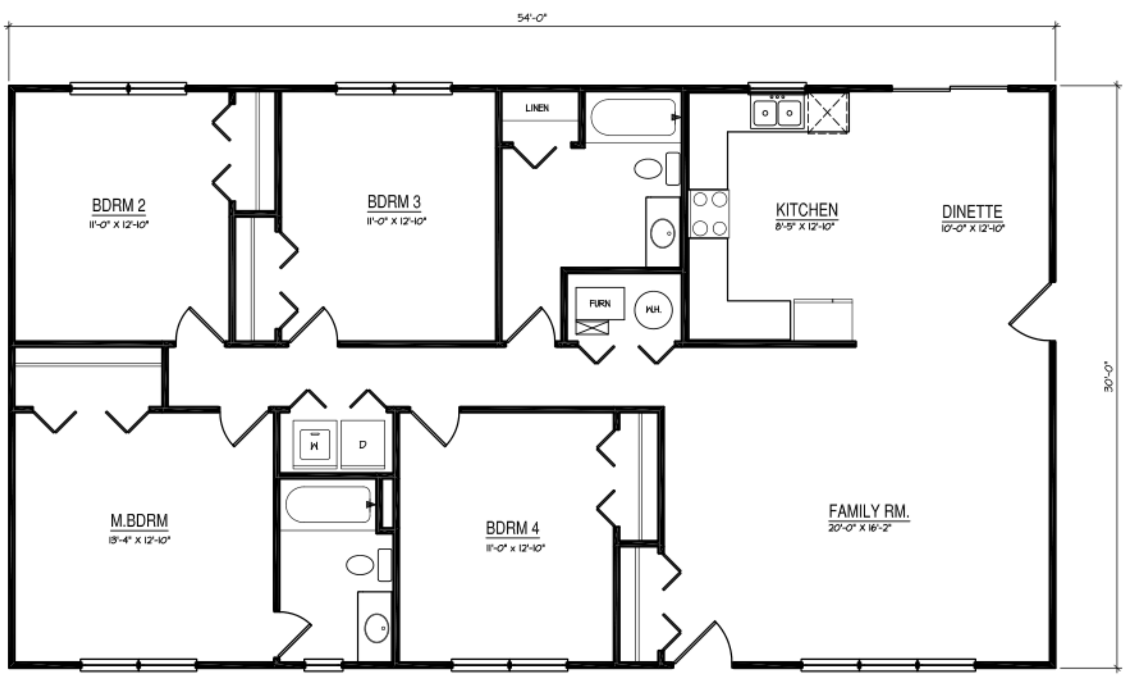

Figure 3.1: Ranch Floor Plan

Since the ranch fire experiments were intended to examine room and contents fires, and not structure fires, the walls of the fire room (Bedroom 1) and hallway were lined with two layers of gypsum board: a surface layer of 1/2" board and a base layer of 5/8" board. The remaining interior surfaces in the structure consisted of 1/2" drywall. The exterior walls were covered with cement board to limit exterior fire spread. In Experiments 1 and 2, the floor close to the fire room and in the kitchen area was composed of cement board. The rest of the house was carpeted. For Experiment 3, the kitchen floor was composed of cement board, while the rest of the house was carpeted. The layout for Experiments 1 and 2 can be seen in Figure **??**, and the layout for Experiment 3 can be seen in Figure 3.2.

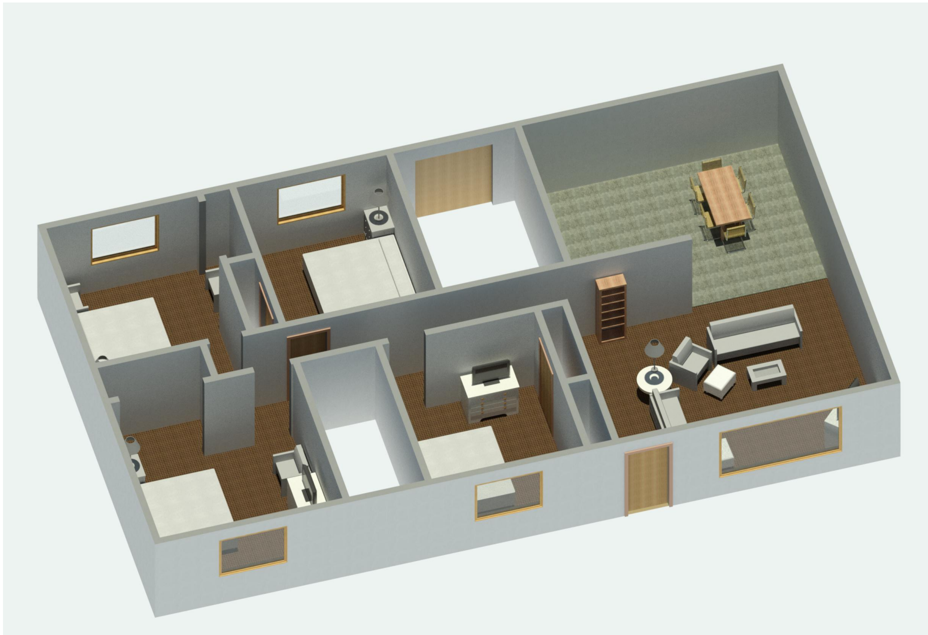

Figure 3.2: Furnished Experiment Layout

3.2 Fuel Loads

In Experiment 1, the only fuel in the fire room was three wooden pallets and 1/3 bale of straw, arranged in a "teepee" formation, as shown in Figure **??**. The middle of the teepee was filled with 13 lbs. of straw. Experiment 2 had an identical configuration of pallets and straw, but also included six 48" x 96" x 7/16' sheets of OSB. Three of these sheets lined the wall behind the fire set, and three lined the ceiling above it, as shown in **??**. In both of the training fuel experiments, the fire was ignited remotely with an electric match in the center of the teepee. In Experiment 3, the fire room was furnished to simulate a typical bedroom in a residential home. The fuel load consisted of a king-sized bed, dresser, TV, nightstand, pillows, 4" foam mattress topper, 3 stuffed chairs (1 Yellow/Green Chair, 1 Red Lined Chair, and 1 Red Swirl Chair), curtains, carpet, and carpet padding. The orientation of the fuel can be seen in Figure 3.3. The fire was ignited remotely with an electric match in the seat cushion of the stuffed armchair at the side of the bed.

Figure 3.3: Experiment 3 Fuel Orientation

The furniture configuration in areas of the house remote from the fire room was identical for all three experiments. Since the furnishings in these areas of the house were remote from the fire, it was assumed that they did not contribute in any significant way to fire growth. Bedroom 2 contained 2 stuffed chairs (1 Striped chair and 1 Red Diamond chair), a king-sized bed, dresser, nightstand, pillows, 4" foam mattress topper, curtains, carpet, and carpet padding. Bedrooms 3 and 4 contained 1 stuffed chair (Yellow/Green Chair), a king-sized bed, dresser, nightstand, pillows, 4" foam mattress topper, curtains, carpet, and carpet padding. The kitchen contained a kitchen table and 6 chairs. The living room contained a bookshelf with shelves line with a 5" foam mattress topper, 2 sofas, 1 stuffed chair (Yellow/Green chair) 2 ottomans, a coffee table, end table, lamp, TV, TV stand, large curtains, carpet, and carpet padding. The weights and dimensions for each elements of the fuel load are listed in Table 3.1.

3.3 Instrumentation

Measurements of temperature, heat flux, pressure, and gas velocity were taken at various locations . For the ranch experiments, the same instrumentation was used throughout the duration of the study. The following describes the instrumentation used and potential uncertainty.

Heat flux measurements were made using a 2.54 cm nominal diameter water-cooled Schmidt-Boelter heat flux gauge (Figure 3.4). The gauges measured the combined radiative and convective heat flux. For these experiments, the dominant form of heat flux is radiative due to the distance of the heat flux gauges from the flames. It should be noted that the convective contribution to the heat flux is dependent upon the surface temperature of the heat flux gauge. The manufacturer gives an

Item	Length (in)	Width (in)	Height (in)	Weight (lbs.)	Material
King Mattress	79	71	10	76	52% Polyurethane Foam, 30% Blended Cotton Batting & 18% Polyester Fiber Batting
King Boxspring	78	35	7	46	59% Fiber Pad, 41% Blended Cotton Batting & Wood Frame
King Headboard	78	24	1	54	Medium Density Fiberboard
Pillow	23.5	17	4	1.5	Filling - All Polyester, Cover - 100% Cotton
Comforter	104	92	1	4.6	Cover - 100% Polyester, Fill - 100% Polyester
Mattress Topper 4 in	78	75	3.875	16.0	Viscoelastic Polyurethane Foam Pad 100%
Mattress Topper 5 in	77.5	76.25	4.625	20.1	Urethane Foam
Sofa Chair (Red Diamond)	35	35	34	69	Polyurethane Foam (Blended Cotton or Polyester when used is less than 10%)
Sofa Chair (Striped)	33	35	33.5	65	Polyurethane Foam 75% Polyester Fiber 25%
Sofa Chair (Yellow/Green)	31.25	31	39	54	Polyester Fiber 75%, Polyurethane Foam 25%, Pillow - Polyurethane Foam 90%, Polyester Batting 10%
Sofa Chair (Red Lines)	34.5	34	32	63	Urethane Foam 100%
Sofa Chair (Red Swirl)	34	34	32	70	Blended Cotton Felt 100%, Cushion - Polyurethane Foam 100%
Night Stand	18	27	23.375	60	Solid Wood
Table Lamp	Base - 5.75, Shade - 14.375	Base - 5.25, Shade - 14.375	31.25	5.9	Glass, Metal & Cloth Shade
Dresser	22.125	36	34.25	120	Wood & Plywood
Curtain (Large)	107	73	0.125	13.7	Flame Retardant & Synthetic Fibers
Curtain (Small)	39	73	0.125	4.5	Flame Retardant & Synthetic Fibers
Sofa	35	77	30.5	255	Polyurethane Foam 50%, Polyester Fiber 50%, & Wood Frame
Coffee Table (Rectangular)	30	18	18.25	24.4	Particleboard & Wood
End Table (Circular)	24.25	24.25	22.125	32.1	Solid Wood
Footstool	19.75	25.5	16	21.3	Upholstery
Bookcase	11.5	24.625	71.25	46	Particleboard
Kitchen Table (Square)	26	26	24.5	29.1	Particleboard & Wood
Straight Chair (Pink)	18	19	33	15.2	Wood & Upholstery
Straight Chair (Blue)	19	19	38.875	14.9	Wood & Upholstery

Table 3.1: Fuel Load Information

uncertainty of Âś3% and results from a study on heat flux calibration found the typical expanded uncertainty to be Âś8% [2].

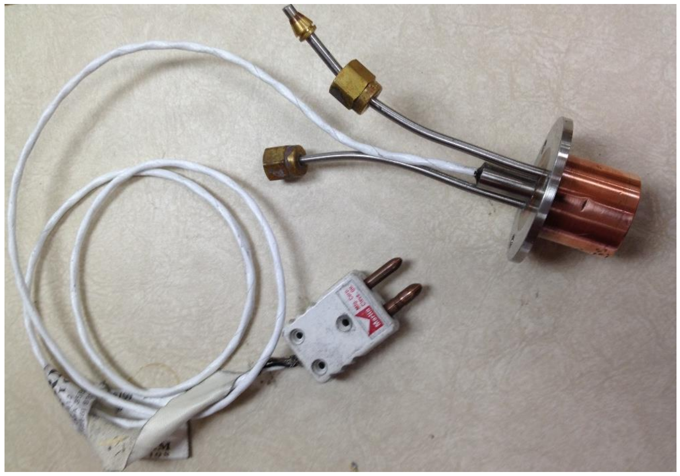

Figure 3.4: Water Cooled Schmidt-Boelter Heat Flux Gauge

Temperatures were recorded using a bare-bead, Chromel-Alumel (Type K) thermocouple with a 0.5 mm nominal diameter (Figure 3.5). The uncertainty given by the manufacturer for the temperature measurements is Âś2.2^0C for temperatures below 293^0C and Âś0.75% for higher temperatures [3]. The thermocouple readings will be lower than the air temperature when the thermocouple is in the flame region, due to radiative losses to the surrounding cooler environment. When the thermocouples are farther from the flame region, the impact of radiation will result in temperature readings higher than the air temperature. Due to the effect of radiative heat transfer to the thermocouples, the expanded uncertainty is approximately Âś15%.

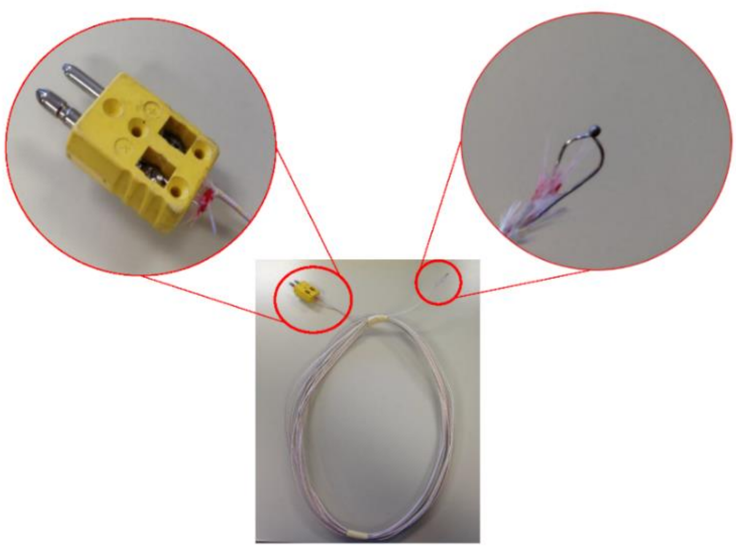

Figure 3.5: Chromel-Alumel (Type K) Thermocouple

To determine the gas velocity, an array of bi-directional probes was utilized in conjunction with differential pressure transducers and inconel thermocouples. The bi-directional probe was constructed of stainless steel and features a ‘high’ side and a ‘low’ side which travel back to a pressure transducer that evaulates the differential pressure from ambient pressure. The iconel thermocouples were placed in-line wtih the bi-directional probes to ensure that the measurements were recorded at the same location. The iconel thermocouple was a 0.063 in. diameter type KSL iconel 600 sheathed grounded junction with a type K, 24 gauge glass/glass insulation lead. The differential pressure transducer was a Setra Model 264 with a range of Âś1.0 in. WC (Âś248.8 Pa). The uncertainty given by the manufacturer is 1% or 1.2 Pa. The configuration had a velocity range of Âś24.2 m/s (Âś54 mph). The pressure transducers were configured in groups of 6, contained in a single plastic box with connections for pressure, temperature and power (Figure **??**a). Five probes were installed in openings where velocity measurements were taken, centered horizontally in the opening (Figure **??**b). Velocity measurement with this configuration was determined to have an uncertainty of Âś18% [4].

Figure 3.6: Bi-Directional Probe

Standard video was obtained through the use of BoschVTC-206F03-4 video cameras (Figure 3.7). Thermal imaging of the front and rear of the structure was taken using ISG Infrasys Elite XR (Figure 3.9). The thermal imaging camera has a fixed emissivity value of 0.9 and was utilized for visual representation of relative conditions, no temperature measurements or analysis were derived using the camera. All cameras were recorded Samsung Model SRD-1680 DN digital video recorder set to 24 frames per second with a quality of “high”.

Figure 3.7: BoschVTC-206F03-4 video camera

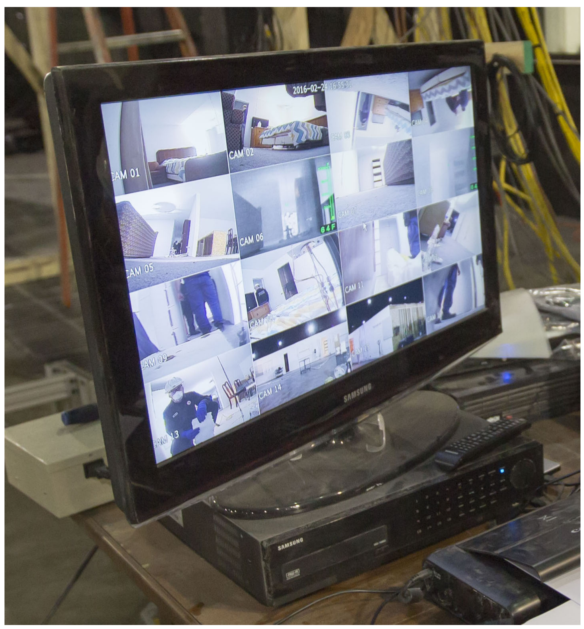

Figure 3.8: Samsung Model SRD-1680 DN Digital Video Recorder with Monitor

Figure 3.9: ISG Elite XR Fire Service Thermal Imaging Camera

Gas samples were analyzed through the use of OxyMat6 and UltraMat23 Siemens gas analyzers. Samples were pulled from the structure through the use of Cole Palmer Model L-79200-30 vacuum/pressure diaphragm pump rated at 0.75CFM via a stainless steel tube. The sample is filtered through a course filter, Solberg Model 842, 2 micron paper filter before running through a condensing trap to remove moisture. The sample then runs through a drying tube dry fine filter, Perma Pure Model FF-250-SG-2.5G with a 1 micron filter FF-250-E-2.5G before splitting into two branches and entering the UltraMat and OxyMat analyzer. The analyzers are calibrated to measure CO from 0-50000PPM, CO2 from 0-20% and O_2 from 0-25%.

(a) Gas Sample Point

(b) Vaccum Pump - Cole Palmber L-79200-30

(c) Course Filter - Solberg 842

(d) Condensing Tube

All data was logged through the use of a national instruments data acquisition system incorporating a SCXI-1001 chassis with 8 SCXI-1102C 32-Channel modules (Figure 3.11). The system is configured for a total of 256 channels capable of reading values between 0-10 volts DC. Values are recorded once a second and translated to quantities of interest through the use of LabVIEW software specifically programmed for use with the system. Data was sampled at 1 hz across all channels.

Figure 3.11: Data Acquisition System

3.4 Measurement Locations

In order to collect the data needed for this analysis, sensors were installed and measurements were recorded throughout each structure. The measurement locations varied dependent on the structure and desired information.

Line Size	Nozzle	Tip (in)	Nozzle Pressure (psi)	Approximate Flow Rate (gpm)
	Smooth Bore	7/8	50	160
	Combination		75	150

Table 3.2: Nozzle Selection

3.5 Equipment Utilized

In order to ensure the data collected and associated results were applicable to the majority of the fire servce, our technical panel was tasked with creating a list of represetative nozzles, specified flows/pressures, and hose line techniques. All of these variables were tested during both the air entrainment and water distribution experiments; however, several other aspects were held constant such as the length of hose used. The nozzles utilized during these experiments can be seen in the table below.

3.6 Tactics Utilized

Shutdown & Move Advancement

Flow & Move Advancement

Transitional Attack

4 Full-Scale Residential Fire Experiments

4.1 Interior

4.1.1 No Ventilation

Experiment	Fire Attack Method	Nozzle	Advancment	Pattern	Ventilation Parameters
1	Interior	Delayed water application with Combination, Shutdown & Move, Straight Stream			Flow path b/n FD and BR1 fire
2	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path b/n FD and BR1 fire
3	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path b/n FD and BR1 fire w/ door control
4	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path b/n FD and BR1 fire w/ coordinated horizontal vent
5	Interior	Combination	Shutdown & Move	Narrow Fog, Near to Far along Hall Centerline	Flow path b/n FD and BR1 fire
6	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path b/n FD and BR1 fire

Figure 4.1: Experiments 1 through 6

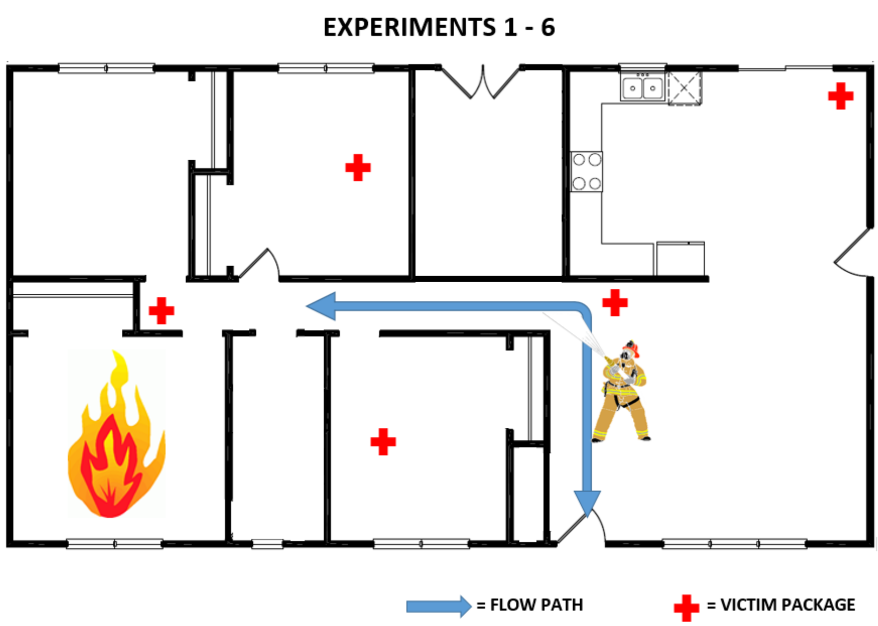

Figure 4.2: Configuration for Experiments 1 through 6

Experiment 1

This experiment is intended to examine the fire dynamics in a typical single-story structure with delayed water application. The fire is ignited in Bedroom 1. The fire develops and eventually becomes ventilation limited. The front door is opened simulating fire department arrival and establishing a flow path between the front door and the bedroom. Once the fire reaches steady state, suppression will be via the front door with a combination nozzle on straight stream. The nozzle will be shutdown for line advancement.

Figure 4.2 shows the configuration of the structure and Table 4.1 shows at what times interventions were performed.

The results of Experiment 1 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.1: Experiment 1 Interventions

Time	Intervention
00:00	Ignition - Bedroom
08:17	Front Door Open
27:47	Attack Team Enters
27:54	Hallway Suppression
42:19	End Experiment

Experiment 2

Experiment 2 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a smooth bore nozzle, flowing while moving. The fire is ignited in bedroom 1. The fire develops and reaches steady state at which point the front door is opened, simulating fire department arrival and establishing a flow path between the front door and the bedroom. An interior fire attack is initiated through the front door, utilizing a smooth bore nozzle, flowing while moving.

Figure 4.2 shows the configuration of the structure and Table 4.2 shows at what times interventions were performed.

The results of Experiment 2 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.2: Experiment 2 Interventions

Time	Intervention
00:00	Ignition - Bedroom
07:05	Front Door Open
07:18	Attack Team Enters
07:23	Burst Suppression
07:36	Hallway Suppression
18:02	End Experiment

Experiment 3

Experiment 3 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a solid stream and the door is controlled immediately following entry. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival, and establishing a flow path between the front door and the bedroom. An interior fire attack is initiated through the front door, utilizing a solid stream pattern. After the attack team enters, the door is closed to the width of the hose line in an effort to limit the amount of fresh air supplied to the fire. The water flow will be shutdown while the hose line is moving.

Figure 4.2 shows the configuration of the structure and Table 4.3 shows at what times interventions were performed.

The results of Experiment 3 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.3: Experiment 3 Interventions

Time	Intervention
00:00	Ignition - Bedroom
08:26	Front Door Open
08:28	Attack Team Enters
08:32	Burst Suppression
08:45	Hallway Suppression
19:09	End Experiment

Experiment 4

Experiment 4 is intended to examine the fire dynamics of a fire in a single-story structure where suppression is conducted with a straight stream pattern. The fire is ignited in bedroom 1. The fire develops and eventually becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing a flow path between the front door and bedroom 1. An interior fire attack is initiated through the front door, utilizing a solid stream pattern. That is flowing while the hose line is moving. Suppression is coordinated with horizontal ventilation of the bedroom 1 window.

Figure 4.2 shows the configuration of the structure and Table 4.4 shows at what times interventions were performed.

The results of Experiment 4 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.4: Experiment 4 Interventions

Time	Intervention
00:00	Ignition - Bedroom
08:25	Front Door Open
08:38	Attack Team Enters
08:43	Burst Suppression
08:43	Bedroom 1 Window Open
08:54	Hallway Suppression
15:23	End Experiment

Experiment 5

Experiment 5 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a narrow fog pattern. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing a flow path between the front door and bedroom 1. An interior fire attack is initiated through the front door, utilizing a narrow fog pattern. Water will be flowing while the hose line is advanced.

Figure 4.2 shows the configuration of the structure and Table 4.5 shows at what times interventions were performed.

The results of Experiment 5 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.5: Experiment 5 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:57	Front Door Open
07:09	Attack Team Enters
07:16	Burst Suppression
07:27	Hallway Suppression
17:54	End Experiment

Experiment 6

Experiment 6 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a solid stream pattern. The fire is ignited in bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing a flow path between the front door and bedroom 1. An interior fire attack is initiated through the front door, utilizing a solid stream pattern. The water flow will be shutdown while the hose line is moving.

Figure 4.2 shows the configuration of the structure and Table 4.6 shows at what times interventions were performed.

The results of Experiment 6 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.6: Experiment 6 Interventions

Time	Intervention
00:00	Ignition - Bedroom
07:58	Front Door Open
08:13	Attack Team Enters
08:18	Burst Suppression
08:27	Hallway Suppression
14:38	End Experiment

4.1.2 Single Room - Single Vent

Experiment	Fire Attack Method	Nozzle	Advancment	Pattern	Ventilation Parameters
7	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
8	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
9	Interior	Combination	Flow & Move	Straight Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
10	Interior	Combination	Shutdown & Move	Straight Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
11	Interior	Combination	Flow & Move	Narrow Fog	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
12	Interior	Delayed water application with Combination, Flow & Move, Straight Stream			Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window

Figure 4.3: Experiments 7 to 12

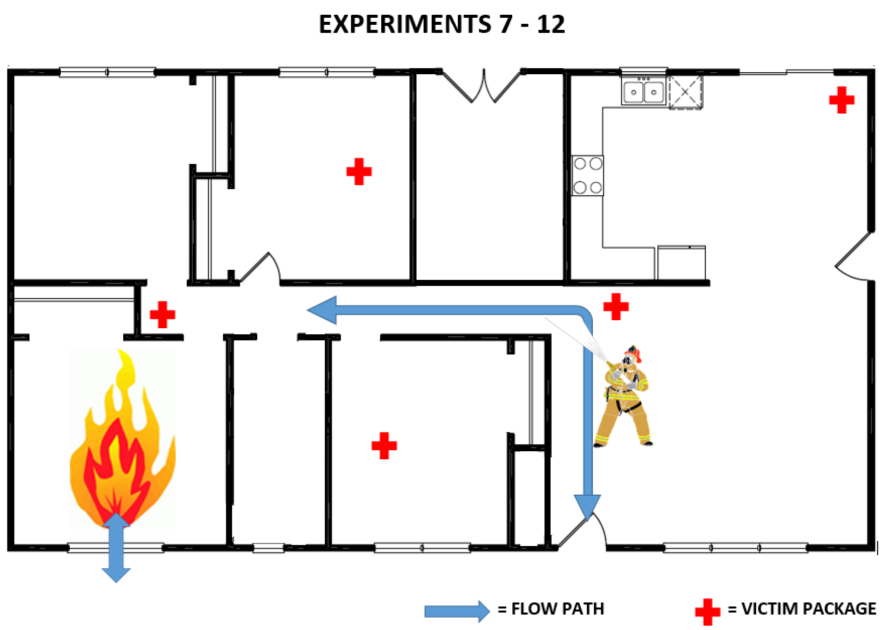

Figure 4.4: Configurations for Experiments 7 to 12

Experiment 7

Experiment 7 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a solid stream pattern. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing two flow paths: One between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack is initiated through the front door, utilizing a solid stream pattern. Water will be flowing while the hose line is advanced.

Figure 4.4 shows the configuration of the structure and Table 4.7 shows at what times interventions were performed.

The results of Experiment 7 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.7: Experiment 7 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:55	Front Door Open
06:07	Attack Team Enters
06:12	Burst Suppression
06:22	Hallway Suppression
12:26	End Experiment

Experiment 8

Experiment 8 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a solid stream pattern. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing two flow paths: One between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack is initiated through the front door, utilizing a solid stream The water flow will be shutdown while the hose line is moving.

Figure 4.4 shows the configuration of the structure and Table 4.8 shows at what times interventions were performed.

The results of Experiment 8 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.8: Experiment 8 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:26	Front Door Open
05:40	Attack Team Enters
05:45	Burst Suppression
05:54	Hallway Suppression
11:57	End Experiment

Experiment 9

Experiment 9 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a straight stream pattern. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing two flow paths: One between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack is initiated through the front door, utilizing a straight stream Water will be flowing while the hose line is advanced.

Figure 4.4 shows the configuration of the structure and Table 4.9 shows at what times interventions were performed.

The results of Experiment 9 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.9: Experiment 9 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:27	Front Door Open
05:38	Attack Team Enters
05:45	Burst Suppression
05:53	Hallway Suppression
11:59	End Experiment

Experiment 10

Experiment 10 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a straight stream. The fire is ignited in the bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing two flow paths: One between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack is initiated through the front door, utilizing a straight stream The water flow will be shutdown while the hose line is moving.

Figure 4.4 shows the configuration of the structure and Table 4.10 shows at what times interventions were performed.

The results of Experiment 10 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.10: Experiment 10 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:27	Front Door Open
05:39	Attack Team Enters
05:45	Burst Suppression
05:54	Hallway Suppression
12:07	End Experiment

Experiment 11

Experiment 11 is intended to examine the fire dynamics in a single-story structure where suppression is conducted with a fog stream pattern. The fire is ignited in bedroom 1. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival and establishing two flow paths: One between the front door and the bedroom fire and the other between the bedroom window and the bedroom fire. An interior fire attack is initiated through the front door, utilizing a narrow fog stream pattern. Water will be flowing while the hose line is advanced.

Figure 4.4 shows the configuration of the structure and Table 4.11 shows at what times interventions were performed.

The results of Experiment 11 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.11: Experiment 11 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:20	Front Door Open
06:32	Attack Team Enters
06:38	Burst Suppression
06:49	Hallway Suppression
12:24	End Experiment

Experiment 12

This experiment is intended to examine the fire dynamics in a typical single-story structure with delayed water application. The fire is ignited in bedroom 1 with the bedroom 1 window open. Once the fire reaches steady state, the front door is opened, simulating fire department arrival. This establishes two flow paths: one between the front door and bedroom 1 and another between the bedroom 1 window and the bedroom. Once the fire reaches steady state again the suppression is initiated via an interior attack with a combination nozzle set to straight stream. The water flow will be shutdown while the hose line is moving.

Figure 4.4 shows the configuration of the structure and Table 4.12 shows at what times interventions were performed.

The results of Experiment 12 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.12: Experiment 12 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:57	Front Door Open
13:29	Attack Team Enters
13:32	Burst Suppression
13:40	Hallway Suppression
28:46	End Experiment

4.1.3 Two Room - Two Vent

Experiment	Fire Attack Method	Nozzle	Advancment	Pattern	Ventilation Parameters
13	Interior	Smooth Bore	Flow & Move	Solid Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window and flow path b/n FD and BR2 and BR2 fire and BR2 window
14	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window and flow path b/n FD and BR2 and BR2 fire and BR2 window
15	Interior	Smooth Bore	Shutdown & Move	Solid Stream	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window and flow path b/n FD and BR2 and BR2 fire and BR2 window w/ door control
16	Interior	Combination	Flow & Move	Narrow Fog	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window and flow path b/n FD and BR2 and BR2 fire and BR2 window
17	Interior	Delayed water application with Combination, Flow & Move, Straight Stream			Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window and flow path b/n FD and BR2 and BR2 fire and BR2 window

Figure 4.5: Experiments 13 to 17

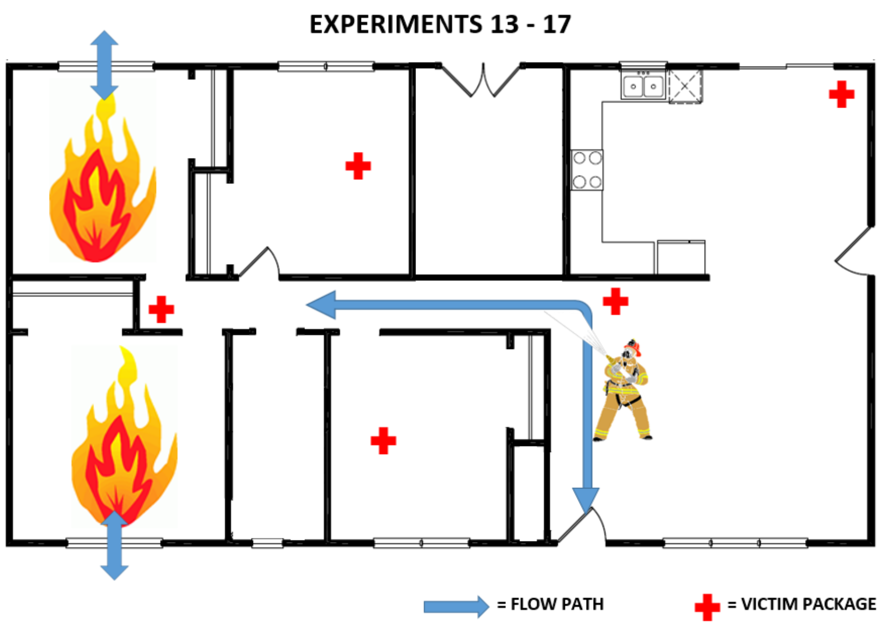

Figure 4.6: Configurations for Experiments 13 to 17

Experiment 13

Experiment 13 is intended to examine a 2-bedroom fire in a single-story structure where suppression is conducted with a solid stream pattern. The fire is ignited simultaneously in bedroom 1 and bedroom 2. The fire develops and becomes ventilation limited. Once this happens, the front door is opened, simulating fire department arrival. These actions create flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack is initiated through the front door, utilizing a solid stream pattern. Water will be flowing while the hose line is advanced.

Figure 4.6 shows the configuration of the structure and Table 4.13 shows at what times interventions were performed.

The results of Experiment 13 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.13: Experiment 13 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:39	Front Door Open
05:52	Attack Team Enters
05:57	Burst Suppression
06:11	Hallway Suppression
12:06	End Experiment

Experiment 14

Experiment 14 is intended to examine a 2-bedroom fire in a single-story structure where suppression is conducted with a solid stream. The fire is ignited simultaneously in the bedroom 1 and bedroom 2. The fire develops and becomes ventilation limited. Once this happens, the front door is opened simulating fire department arrival. These actions create flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack is initiated through the front door, utilizing a solid stream. The water flow will be shutdown while the hose line is moving.

Figure 4.6 shows the configuration of the structure and Table 4.14 shows at what times interventions were performed.

The results of Experiment 14 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.14: Experiment 14 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:26	Front Door Open
06:39	Attack Team Enters
06:43	Burst Suppression
06:50	Hallway Suppression
15:05	End Experiment

Experiment 15

Experiment 15 is intended to examine a 2-bedroom fire in a single-story structure where suppression is conducted with a solid stream pattern. The fire is ignited simultaneously in bedroom 1 and bedroom 2. The fire develops and becomes ventilation limited. Once this happens, the front door is opened simulating fire department arrival. This action create flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack is initiated through the front door, utilizing a solid stream . After the attack team enters, the door is closed to the width of the hose line in an effort to limit the amount of fresh air supplied to the fire. The water flow will be shutdown while the hose line is moving.

Figure 4.6 shows the configuration of the structure and Table 4.15 shows at what times interventions were performed.

The results of Experiment 15 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.15: Experiment 15 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:39	Front Door Open
05:40	Attack Team Enters
05:44	Burst Suppression
05:55	Hallway Suppression
12:06	End Experiment

Experiment 16

Experiment 16 is intended to examine a 2-bedroom fire in a single-story structure where suppression is conducted with a narrow fog stream. The fire is ignited simultaneously in bedroom 1 and bedroom 2. The fire develops and becomes ventilation limited. Once this happens, the front door is opened simulating fire department arrival. These actions create flow paths between the front door and each fire bedroom and between each bedroom window and the fire bedrooms. An interior fire attack is initiated through the front door, utilizing a narrow fog stream. Water will be flowing while the hose line is advanced.

Figure 4.6 shows the configuration of the structure and Table 4.16 shows at what times interventions were performed.

The results of Experiment 16 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.16: Experiment 16 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:23	Front Door Open
05:33	Attack Team Enters
05:37	Burst Suppression
05:54	Hallway Suppression
12:58	End Experiment

Experiment 17

Experiment 17 will examine a fire in a single-story structure where suppression is conducted with a straight stream, shutdown while moving. The fire is ignited in bedroom 1 and bedroom 2. The windows in bedroom 1 and 2 will be open at the start of the experiment. The fire develops and becomes ventilation limited. Once this happens, the front door will be opened, simulating fire department arrival. So at the point of fire attack flow paths exist between the front door and bedroom 1, between the bedroom 1 window and the bedroom1 , between the front door and bedroom 2, and between the bedroom 2 window and bedroom 2.

Figure 4.6 shows the configuration of the structure and Table 4.17 shows at what times interventions were performed.

The results of Experiment 17 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.17: Experiment 17 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:27	Front Door Open
10:32	Attack Team Enters
10:36	Burst Suppression
10:47	Hallway Suppression
23:32	End Experiment

4.2 Exterior

4.2.1 Single Room - Single Vent

Experiment	Fire Attack Method	Nozzle	Advancment	Pattern	Ventilation Parameters
18	Exterior	Smooth Bore	Steep Angle	Solid Stream	Flow path b/n BR1 fire and BR1 window
19	Exterior	Combination	Occlude Opening, Rebuild, Steep Angle to Fog Whip	Narrow Fog, Rebuild, Straight Stream to Fog Whip	Flow path b/n BR1 fire and BR1 window
20	Exterior	Smooth Bore	Steep Angle to Half Bail Whip	Solid Stream to Half Bail Whip	Flow path b/n BR1 fire and BR1 window
21	Exterior	Smooth Bore	Steep Angle to Half Bail Whip	Solid Stream to Half Bail Whip	Flow path b/n FD and BR1 fire and flow path b/n BR1 fire and BR1 window
27	Exterior	Combination	Steep Angle Sweep	Straight Stream	Flow path b/n FD and BR4 fire and flow path b/n BR4 fire and BR4 window

Figure 4.7: Experiments 18 through 21 and 27

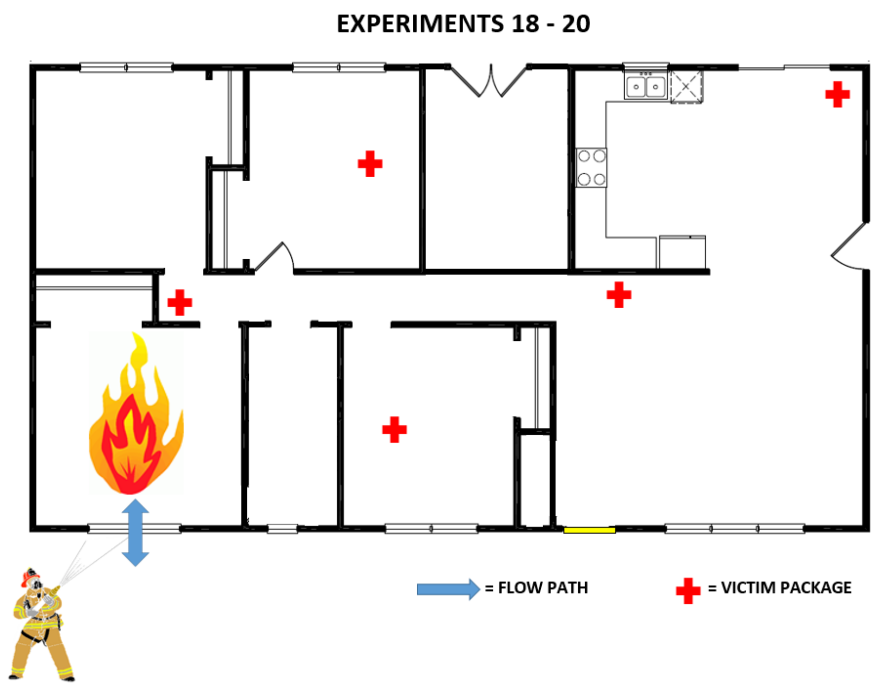

Figure 4.8: Configuration for Experiments 18 through 20.

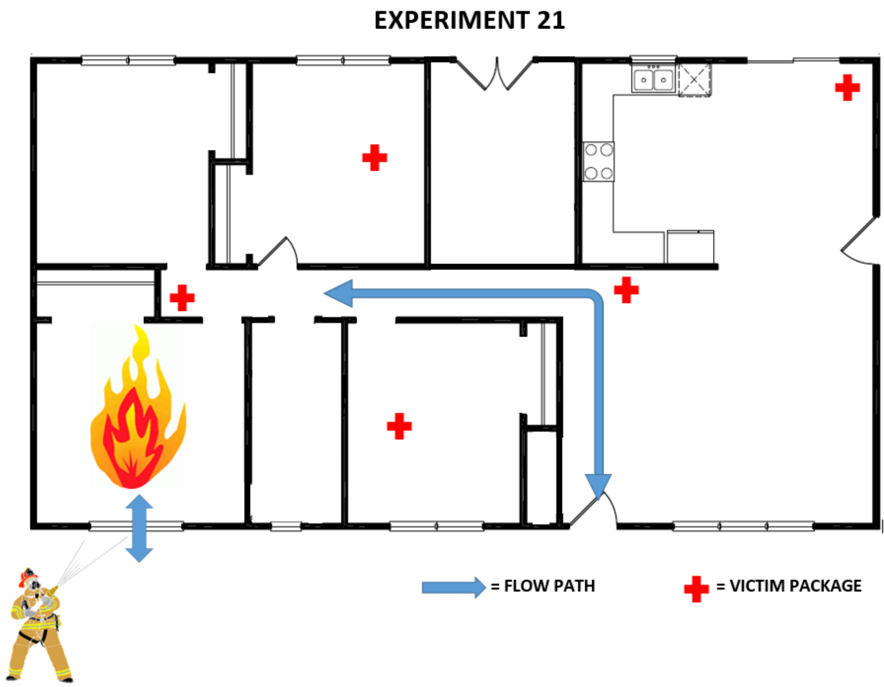

Figure 4.9: Configuration for Experiment 21.

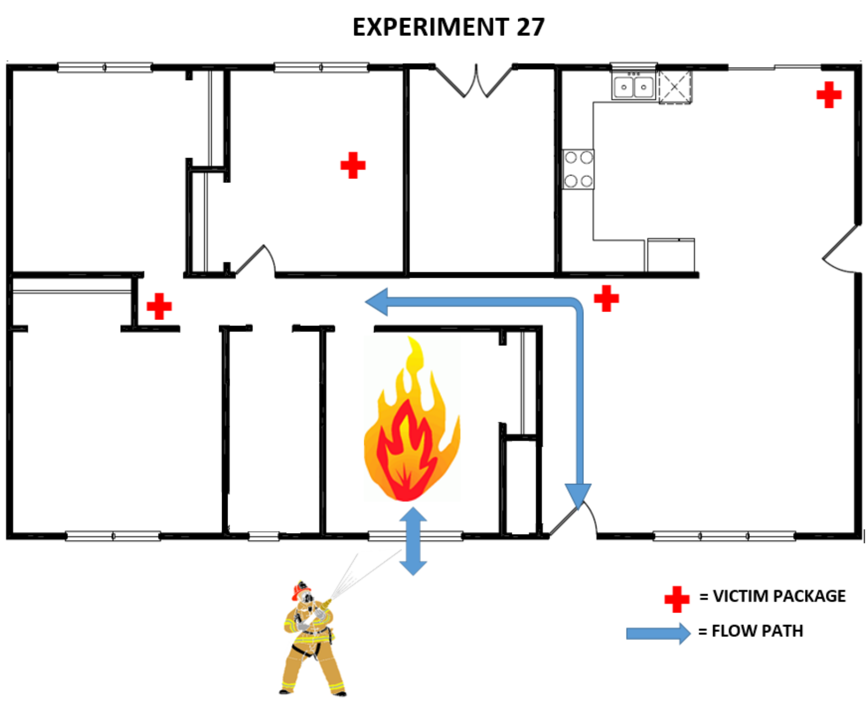

Figure 4.10: Configuration for Experiment 27.

Experiment 18

Experiment 18 is intended to study a bedroom fire in a single-story structure where suppression is initiated from the exterior of the house with a straight stream. The fire is ignited in bedroom 1. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited simulating fire department arrival. Water is applied through the bedroom window, simulating a transitional attack. The exterior fire attack is conducted using a solid stream. Interior attack will be used if needed for extinguishment.

Figure 4.8 shows the configuration of the structure and Table 4.18 shows at what times interventions were performed.

The results of Experiment 18 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.18: Experiment 18 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:24	Exterior Suppression BR1 Window Solid Stream
05:35	Front Door Open
05:42	Attack Team Enters
05:45	Burst Suppression
06:07	Hallway Suppression
12:04	End Experiment

Experiment 19

Experiment 19 is intended to study a bedroom fire in a single-story structure where suppression is initiated from the exterior of the house with a narrow fog stream. The fire is ignited in bedroom 1. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited. Water is applied through the bedroom 1 window, simulating a transitional attack. The exterior fire attack is conducted using a solid stream. Interior attack will be used if needed for extinguishment.

Figure 4.8 shows the configuration of the structure and Table 4.19 shows at what times interventions were performed.

The results of Experiment 19 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.19: Experiment 19 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:24	Exterior Suppression BR1 Window Narrow Fog Stream
08:28	Exterior Suppression BR1 Window Straight Stream
08:58	Front Door Open
09:10	Attack Team Enters
09:34	Room Suppression
14:05	End Experiment

Experiment 20

This experiment is intended to study a bedroom fire in a single-story structure where suppression is initiated from the exterior of the house with a solid stream. The fire is ignited in bedroom 1. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited, the front door is open, simulating fire department arrival. Water is applied through the bedroom 1 window, simulating a transitional attack. The exterior fire attack is conducted using a solid stream. Interior attack will be used if needed for extinguishment.

Figure 4.8 shows the configuration of the structure and Table 4.20 shows at what times interventions were performed.

The results of Experiment 20 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.20: Experiment 20 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:52	Exterior Suppression BR1 Window Solid Stream
07:24	Front Door Open
07:34	Attack Team Enters
08:34	Room Suppression
12:06	End Experiment

Experiment 21

Experiment 21 is intended to study a bedroom fire in a single-story structure where suppression is initiated from the exterior of the house with a solid stream. Before suppression is initiated, the front door is opened, simulating the entry of a search company to look for victims. The fire is ignited in bedroom 1. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited, the front door is open, simulating fire department arrival. Water is applied through the bedroom 1 window, simulating a transitional attack. The exterior fire attack is conducted using a solid stream. Interior attack will be used if needed for extinguishment.

Figure 4.9 shows the configuration of the structure and Table 4.21 shows at what times interventions were performed.

The results of Experiment 21 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.21: Experiment 21 Interventions

Time	Intervention
00:00	Ignition - Bedroom
06:24	Front Door Open
06:44	Exterior Suppression BR1 Window Solid Stream
07:05	Attack Team Enters
07:46	Room Suppression
12:23	End Experiment

Experiment 27

Experiment 27 is intended to simulate a bedroom fire in a single-story structure with exterior suppression. The fire is ignited simultaneously in bedroom 4. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited the front door is opened. After the fire reaches steady state, exterior suppression is initiated using a straight stream pattern sweeping the ceiling. Interior attack will be used for full extinguishment.

Figure 4.10 shows the configuration of the structure and Table 4.22 shows at what times interventions were performed.

The results of Experiment 27 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.22: Experiment 27 Interventions

Time	Intervention
00:00	Ignition - Bedroom
04:10	Front Door Open
06:06	Exterior Suppression BR4 Window Straight Stream
06:19	Attack Team Enters
06:31	Room Suppression
09:09	End Experiment

4.2.2 Two Room - Two Vent

Experiment	Fire Attack Method	Nozzle	Advancment	Pattern	Ventilation Parameters
22	Exterior	Smooth Bore	Steep Angle to Half Bail Whip	Solid Stream to Half Bail Whip	Flow path b/n BR1 fire and BR1 window and flow path b/n BR2 fire and BR2 window
23	Exterior	Combination	Occlude Opening	Narrow Fog	Flow path b/n BR1 fire and BR1 window and flow path b/n BR2 fire and BR2 window
24	Exterior	Combination	Steep Angle to Fog Whip	Straight Stream to Fog Whip	Flow path b/n BR1 fire and BR1 window and flow path b/n BR2 fire and BR2 window

Figure 4.11: Experiments 22 through 24

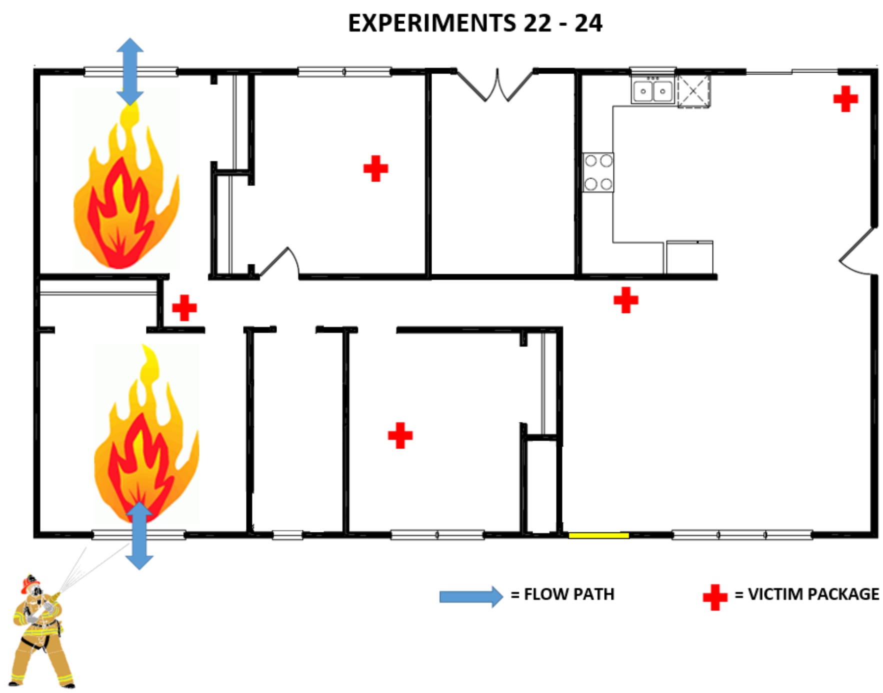

Figure 4.12: Configuration for Experiments 22 through 24.

Experiment 22

Experiment 22 is intended to simulate a 2 bedroom fire in a single-story structure with exterior suppression. The fire is ignited in bedroom 1 and bedroom 2. The windows in bedroom 1 and 2 will be open at the start of the experiment. The fire develops and becomes ventilation limited. So at the point of fire attack flow paths exist between the bedroom 1 window and the bedroom1 , between the front door and bedroom 2, between the bedroom 2 window and bedroom 2. Exterior suppression is then initiated using a solid stream pattern with a steep angle and minimal nozzle movement. Interior attack will follow initial knockdown to complete extinguishment.

Figure 4.12 shows the configuration of the structure and Table 4.23 shows at what times interventions were performed.

The results of Experiment 22 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.23: Experiment 22 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:43	Exterior Suppression BR1 Window Solid Stream
06:07	Front Door Open
06:13	Attack Team Enters
06:15	Burst Suppression
06:24	Hall Suppression
14:25	End Experiment

Experiment 23

Experiment 23 is intended to simulate a 2 bedroom fire in a single-story structure with exterior suppression. The fire is ignited simultaneously in bedroom 1 and bedroom 2. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited, exterior suppression will be initiated using a narrow fog stream pattern. Interior attack will be used for extinguishment.

Figure 4.12 shows the configuration of the structure and Table 4.24 shows at what times interventions were performed.

The results of Experiment 23 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.24: Experiment 23 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:26	Exterior Suppression BR1 Window Narrow Fog Stream
05:41	Front Door Open
05:50	Attack Team Enters
06:01	Hall Suppression
12:05	End Experiment

Experiment 24

Experiment 24 is intended to simulate a 2 bedroom fire in a single-story structure with exterior suppression. The fire is ignited simultaneously in bedroom 1 and bedroom 2. As the fire develops, it transitions to a ventilation limited fire. Soon after the fire becomes ventilation limited, exterior suppression will be initiated using a straight stream pattern followed by content suppression. Interior attack will be used for full extinguishment.

Figure 4.12 shows the configuration of the structure and Table 4.25 shows at what times interventions were performed.

The results of Experiment 24 can be found in Appendix **??**. To view the full experiment video Click Here.

Table 4.25: Experiment 24 Interventions

Time	Intervention
00:00	Ignition - Bedroom
05:28	Exterior Suppression BR1 Window Straight Stream
05:56	Exterior Suppression BR2 Window Straight Stream
06:16	Front Door Open
06:30	Attack Team Enters
07:08	Room Suppression
11:55	End Experiment

5 Experiment Analysis

5.1 Repeatability

The experiments were grouped by the ventilation profile which existed prior to fire department interaction. The three ventilation profiles used were 'No Ventilation', 'Single Vent' and 'Two Vent'. In the 'No Vent' all the openings on the structure were closed until fire department intervention and the fire was located in bedroom 1. In the 'Single Vent' a single window was open in the fire room (Bedroom 1) until fire department intervention. For the 'Two Vent' there were two rooms of fire (Bedroom 1 and Bedroom 2) and both the Bedroom 1 and Bedroom 2 Windows were open prior to fire department intervention. To compare the effectiveness of the various fire service tactics used in the experiments it is important to identify if the experiments are comparable across ventilation profiles.

Each set of experiments in the three ventilation profiles were compared in order to determine repeatability based on ventilation profile and thus the applicability of comparing the experiments. The comparison was done on average thermocouple array temperature. The temperatures in a period 60 seconds prior to fire department intervention were averaged both in time and across the thermocouple array. The following sections will discuss the results for each ventilation profile.

5.1.1 No Ventilation

In the 'No Vent' profile there were six experiments. The average temperate for the time period 60 seconds prior to fire department intervention is shown in Figure5.1. The gray area on the radar plot shows the measurement uncertainty for a thermocouple (+/- %15) at each measurement location based on the average of all experiments. With the exception of Experiment 1 the temperature is very repeatable under the 'No Vent' case. In Experiment 1 the door ot Bedroom 3 was open, where in the other five experiments the door was closed. This accounts for the elevated temperatures in Bedroom 3 and at victim location 3 during experiment 1. All 'No Vent' cases can be directly compared for all temperature measurement locations with the exception of Bedroom 3, where Experiment 1 is the out-lier and will not be used in the analysis.

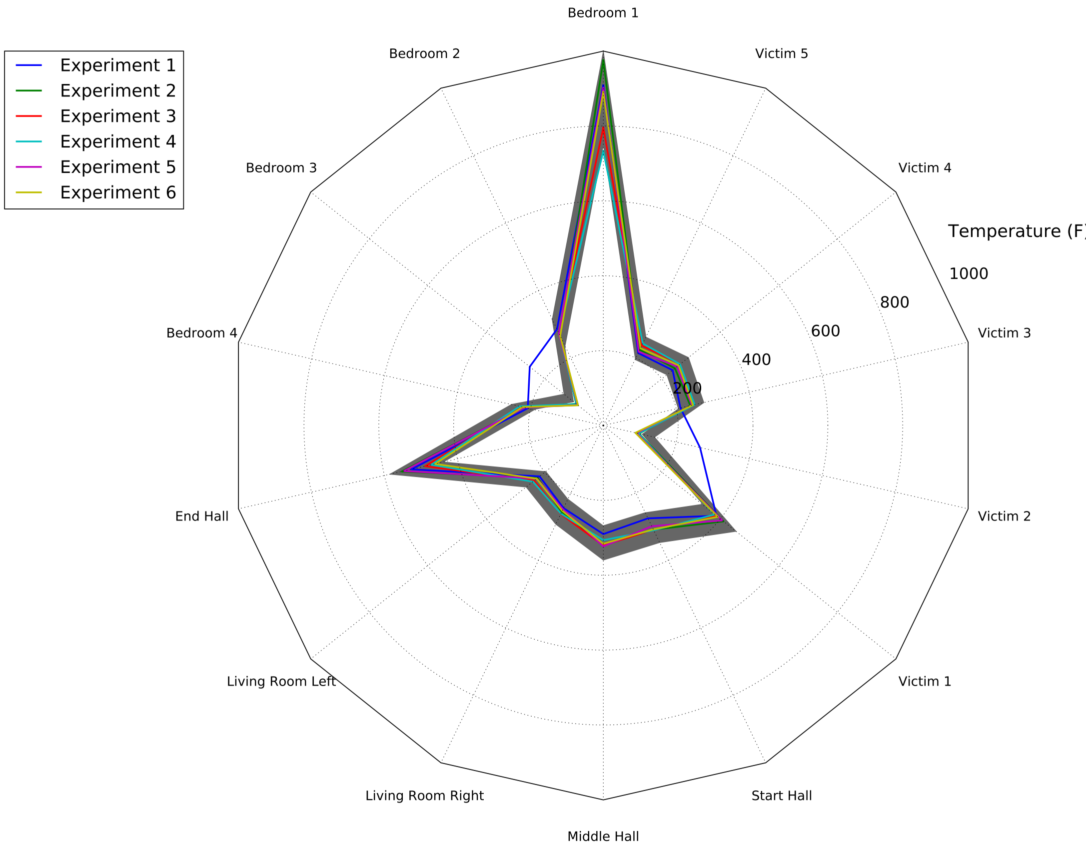

Figure 5.1: Average Thermocouple Array Temperatures - No Ventilation

5.1.2 Single Vent

In the 'Single Vent' profile there were 10 experiments. The average temperature for the time period 60 seconds prior to fire department intervention is shown in Figure 5.2. The gray area on the radar plot shows the measurement uncertainty for a thermocouple (+/- %15) at each measurement location based on the average of all experiments. All experiments were within the uncertainty of the measurement and thus are comparable. All 'Single Vent' cases can be directly compared for all temperature measurement locations.

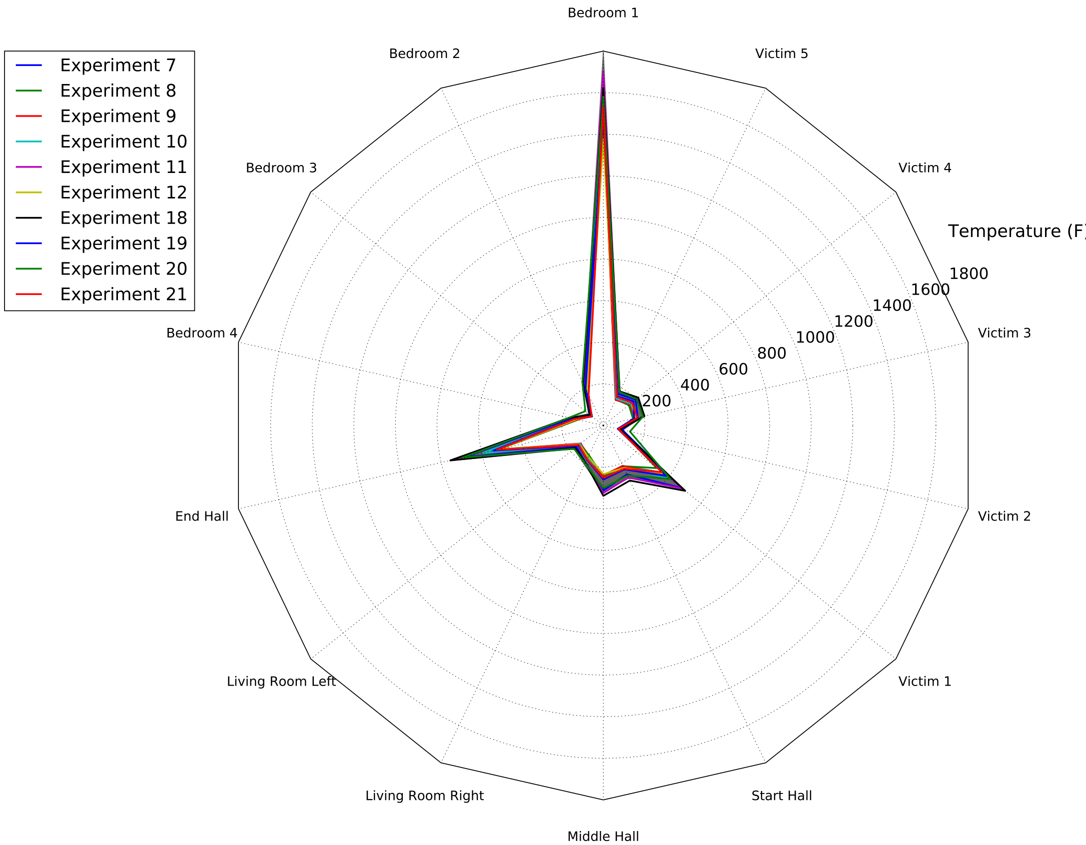

Figure 5.2: Average Thermocouple Array Temperatures - Single Vent

5.1.3 Two Vents

In the 'Two Vent' profile there were 8 experiments. he average temperature for the time period 60 seconds prior to fire department intervention is shown in Figure 5.3. The gray area on the radar plot shows the measurement uncertainty for a thermocouple (+/- %15) at each measurement location based on the average of all experiments. With the two rooms of fire and two ventilation points the repeatability decreased slightly from the other two ventilation profiles. Bedroom 2 grew at a faster rate than Bedroom 1, which reduced in some of the Bedroom 1 temperature averages being outside the measurement uncertainty. However the majority of the other measurement locations were within the measurement uncertainty making all 'Two Vent' cases comparable.

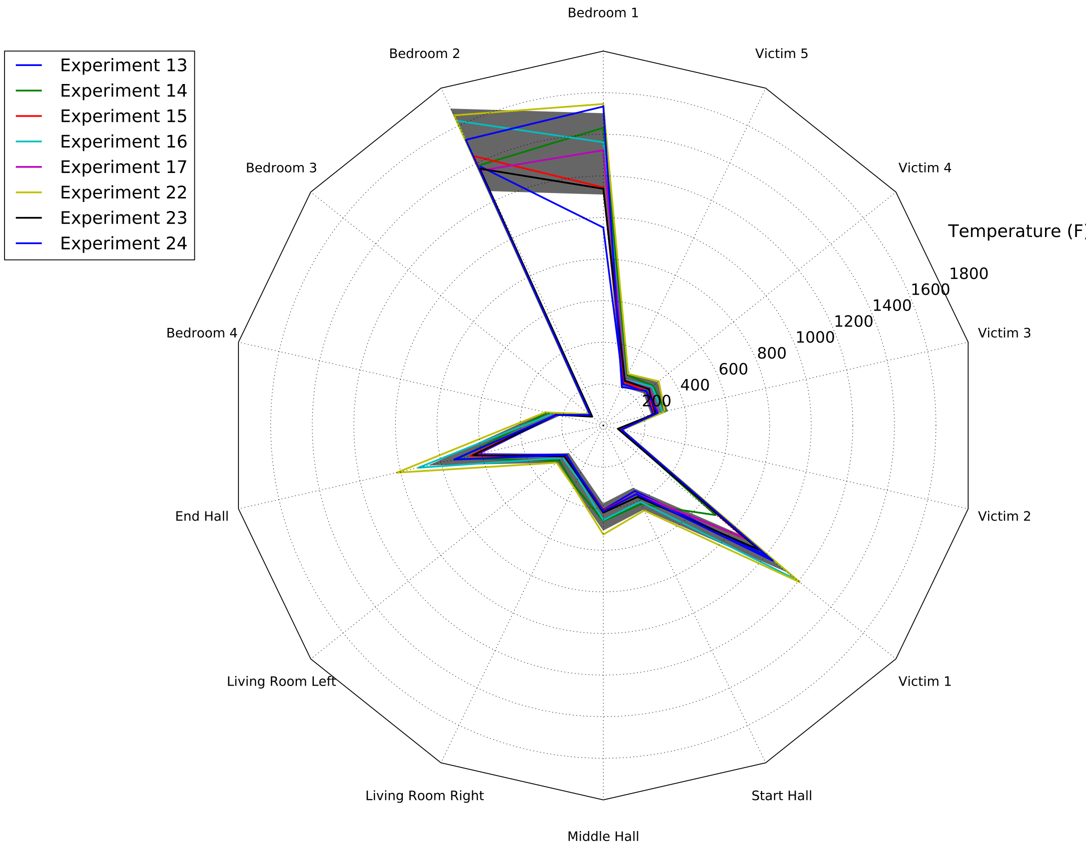

Figure 5.3: Average Thermocouple Array Temperatures - Two Vent

5.2 Effect of Ventilation Profile on Tenability

This section identifies the effect of ventilation profile on the victim tenability (FED) at the four victim locations (Hallway, Bedroom 3, Bedroom 4, and Living room)

5.2.1 Before Fire Department Arrival

This section looks at the specific time period prior to fire department intervention quantifying tenability of the four locations. **Compare 1-6 vs. 7-12 & 18-21 &27 vs. 13-17 & 22-24**

5.2.2 Effect of Fire Department Intervention

This section looks at the difference between fire department intervention and delayed intervention quantifying tenability of the four locations. This will be an average value of all interventions compared to the value with delayed intervention.
Compare 1 vs. 2-6 (No Vent)
Compare 12 vs. 7-11 & 18-21 & 27 (Single Vent)
Compare 17 vs. 13-16 & 22-24 (Two Vent)

5.2.3 Interior vs. Exterior

This section looks at the effect of different fire department tactics on tenability. Specifically the difference in FED from onset of intervention to onset plus longest intervention time. Compare 7-11 vs. 18-21 &27 (Single Vent)
Compare 13-16 vs. 22-24 (Two Vent)

5.3 Effect of Ventilation Profile on Knock back Capability

How does the ventilation and number of rooms of fire effect the ability of the three methods of interior and two methods of exterior attack to knock back the fire.

5.3.1 Interior

Compare 2, 7 , 13 (Flow and move SB)
Compare 6, 8 , 14 (Shutdown and move SB)
Compare 11, 16 (flow and move Fog)

5.3.2 Exterior

Compare 18,20, (just initial hit) vs. 22,24 (just bedroom 1)
Compare 22 (BD1 and interior) vs. 24 (BD1, BD2, and Interior)

5.4 Ability to “Push Fire”

Can you create pressure, thus moving “Products of Combustion”.

5.4.1 Interior

Impact of Advancement Type on Pressure Created

Compare 2(flow and move) vs 6(shutdown and move) [No Vent]
Compare 7(flow and move) vs 8(shutdown and move) [Single Vent]
Compare 13(flow and move) vs 14(shutdown and move) [Two Vent]

Impact of Ventilation Profile on Pressure Created

Compare 2, 7 , 13 (Flow and move SB)
Compare 6, 8 , 14 (Shutdown and move SB)
Compare 11, 16 (flow and move Fog)

5.4.2 Exterior

Compare 20(door closed) vs 21 (front door open)
Compare 19(one room fire) vs 23 (two rooms fire)

5.5 Impact of “Whip” on Regrowth

compare 18 (no whip) vs 20(whip) (front door closed)

5.6 Impact of Door Control

Compare 3 (door control) with 6 (no control)
Compare 14 (no control) with 15 (door control)

5.7 Impact of Water Usage

Overall usage of water, average total amount needed.
Comparison of Fire Size and water used, average amount vs. vent profile.
Water needed to control space vs. water needed for knockdown

6 Tactical Considerations

6.1 Where are Survivable Spaces

A description of how tenability is effected by fire location prior to fire department interaction (Table of tenability broken up by vent configuration). Additionally comparing each delayed suppression case to the earlier cases. GAVIN

6.2 Hose Stream Type has limited effect on knockdown capability.

6.3 Flow & Move vs. Shutdown and Move

6.4 Having a vent ahead changes your need to "Make a Push"

Compare Experiment 4 (coordinated vent) vs. 7 (existing vent)

Compare Experiment 7 (flow and move SB), 9 (flow and move SS) to 11 (flow and move fog)

Compare 13 (flow and move SB), 16 (flow and move Fog)

6.5 Door Control During Interior Suppression slows impact of ventilation

7 Future Research Needs

References

[1] National Fallen Firefighter Foundation. Report of the 2nd national fire service research agenda symposium. Report, National Fire Academy.

[2] William M. Pitts, Annageri V. Murthy, John L. De Ris, Jean-Remy Filtz, Kjell Nygard, Debbie Smith, and Ingrid Wetterlund. Round robbin study of total heat flux gauge calibration at fire laboratories. 41.6:459–475.

[3] *The Temperature Handbook*. Omega Engineering, 7 edition.

[4] L.A Lent and M.E. Schneider. The design and application of bi-directional velocity probes for measurements in large pool fires. 26(4):25–32.

Appendices

.1 Experimental Results

Appendix A   Air Entrainment Figures

Section currently commented out.

Appendix B Water Distribution Figures

Section currently commented out.