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Big Fire, Big Water: An Evaluation of Fire Service Tactics in High-Rise and Standpipe Equipped Structures

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Dedication

The author would like to dedicate this work to Jefferson Parish (LA) Firefighters Danny and Billy Zeigler and all injured and fallen firefighters. Both of these firefighters were severely injured during a fire on February 2, 2019. Both are recovering at the time of this paper's completion. The author would like to wish both a speedy recovery and thank them for their service. It is hoped that this research will help to prevent firefighter injuries and deaths across the world.

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Abbreviations

EKU- Eastern Kentucky University

NFPA- National Fire Protection Association

NIST- National Institute of Standards and Technology

UL- Underwriters Laboratories

FSRI- Firefighter Safety Research Institute

LODD- Line of Duty Death

kJ- Kilojoule

kg- Kilogram

MJ- Megajoule

kW- Kilowatt

MW- Megawatt

UMD- University of Maryland

FDC- Fire Department Connection

PRD- Pressure Reducing Device

PRV- Pressure Reducing Valve

PSI- Pounds Pressure Per Square Inch

IAFF- International Association of Firefighters

HVAC- Heating, Ventilation, and Air Conditioning

USFA- United States Fire Administration

1 Introduction

1.1 Executive Summary

The following report has been compiled to evaluate fire service equipment and tactics, specifically in high-rise environments. This project will first discuss modern fire dynamics and their impact on firefighting operations. This chapter largely reviews established and accepted scientific research. Next, high-rise buildings will be discussed. Fire protection systems including standpipe systems will be examined as well as building geometry, evacuation challenges, and ventilation and other special hazards. The next portion of the report will discuss several case studies that have occurred in the last forty years and their contributions to the fire protection and fire suppression fields. The following chapter will cover fire suppression hose and nozzle selection by the United States fire service. Consideration will be given to friction loss, maneuverability, water pressure, and water flow. This will be followed with findings from empirical testing conducted to compare the water flow, required pressure, and mobility of different hose sizes. Finally, the project will end with conclusions from the testing and other information presented in the proceeding sections.

1.2 Scope and Methods

This project sought to evaluate fire service tactics and equipment popular in the United States fire service. With faster developing and more intense fires, firefighters need to be prepared to more efficiently extinguish fires to ensure firefighter safety. High-rise buildings provide a deadly hazard for both firefighters and occupants. These high-rise buildings are growing more prevalent in America, challenging a greater number of firefighters every day.

Large amounts of scientific research have been conducted in recent years to assist the fire service, but many of these experiments have been conducted in single family homes. For example, one of the most commonly referenced studies is Kerber’s Study on Fire Service Operational timelines in which he discusses the implications of modern fuels and modern building construction on firefighting efforts. A vast majority of firefighters often are called to fires in structures other than high-rise buildings, but firefighters need to be more prepared for fires in these more challenging environments.

This project initially sought to determine why fire departments were using smaller diameter hose lines for fighting fires in high-rise applications. During this process, several fire departments and firefighters stated that they chose to use smaller hose lines because they were more maneuverable than larger hose lines. Fire departments also claimed that they were considering much of the modern fire service research by attempting to get water to the seat of the fire as soon as possible. In order to validate this argument, empirical testing was conducted. Specific details and the data from these tests will be presented in a later section of this report.

With the suggestions of numerous fire service experts, scientific data from numerous experiments, and the aforementioned empirical testing, final conclusions were drawn. These will be discussed in the final section of this report.

2 Fire Behavior Basics

2.1 Overview

In order to discuss considerations for fire service tactics in the modern fire environment, the basics of fire science must be understood. The following sections present the basics of combustion as well as a fire dynamics analysis of the modern fire environment, focusing on high-rise structures.

2.2 The Fire Triangle

In order for the combustion process to occur, fire requires heat, fuel, oxygen, and a sustained chemical reaction. In the urban environment, water is applied to fires in order to remove heat, causing the combustion process to cease. Common tactics to achieve this goal include applying water to the combustion by-product gasses in the upper layer of the compartment, or to the burning surfaces in order to cool the environment and extinguish the fire. The United States fire service often opts for the latter option with a more aggressive frontal attack. This approach seeks to extinguish the burning fuel. Water as an extinguishing agent will be examined shortly.

2.3 Fire Dynamics

2.3.1 Introduction

Fire dynamics is defined as, “the field of study that encompasses how fires start, spread, develop, and extinguish.” (Madrzykowski, 27). While these considerations are generally not given by firefighters operating on the fireground, fire dynamics must be a large part of both fire attack and fire prevention. The ways in which fires burn, or the physics of combustion are always the same despite significantly varied environments. Therefore, fire dynamics provide one of the best ways to prepare to fight a fire. Considerations must also be made for modern fire dynamics.

2.3.2 Modern Fuels vs. Legacy Fuels

Modern fuels are one of the defining characteristics of the modern fire environment. Many furnishings in modern structures are made of synthetic materials. According to Steven Kerber, the director of the Underwriters Laboratory Firefighter Safety Research Institute, “Today more than 95 million kilograms of flexible polyurethane foam are produced in the US, enough to make 140 million sofas." (Kerber 869). This is quite significant for firefighters due to the chemical makeup of the material. While these materials have approximately the same amount of combustible material, the new materials typically weigh significantly less than the older materials and they are also typically much cheaper than legacy materials which makes them more prevalent in modern high-rise construction, all of which are illustrated in Kerber's study.

These materials also have a much higher heat release rate, which is defined as "the rate at which heat energy is generated by burning." (Gorbett, Pharr, Rockwell 299). Heat Release Rate is also key to determining many other important variables in fire dynamics, including quantities such as flame height and upper layer temperatures. Both of these quantities are important in fire growth and development, and it will be discussed in greater detail in later chapters of this report.

To provide some context of the increased heat release rate between these different materials, several studies and tests were conducted. Kerber summarizes an experiment from Babrauskas to discuss these differences. He states, "The cotton padded chair covered in cotton fabric produced a peak heat release rate of 370 kW at 910 s after ignition. The foam padded chair covered in polyolefin fabric produced a peak heat release of 1,990 kW at 260s after ignition. Both chairs had a very similar total heat released 425 MJ for the natural chair and 419 MJ for the synthetic chair." (Kerber 869). With these higher heat release rates, synthetic materials lead to fires that develop much faster and are much more severe, despite releasing nearly the same amount of energy as legacy fuels.

Fire departments and fire service training professionals are realizing this trend and tactics are changing in order to combat this new and more severe threat. Some of the specific tactics and considerations will be discussed in the following section.

2.3.3 New Fire Service Tactics: Ventilation vs. Water on the Fire

In order to combat the increased heat release rates from these new fuels, special considerations must be made by the fire service both during firefighting operations as well as creating standard operating procedures. Much of the modern firefighting research has attempted to address this matter. However, much of this research has been conducted in residential single-family homes. While considerations must be made for high-rise firefighting, much of this research is extremely applicable for developing these new tactics.

A large body of this research shows that the fire service needs to alter their operations and the sequences with which they are conducted on the fireground. With respect to the aforementioned modern fuels, In the same article quoted earlier in this chapter, Kerber argues that the fire service has significantly less time to operate before the fire reaches flashover. Flashover is defined as:

> A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full-room involvement or total involvement of the compartment or enclosed space. (Gorbett, Pharr, Rockwell 298).

This shorter time frame is significant because there are several tasks that must be completed in short order in the first few minutes of any fire attack. Depending on the building and the incident, firefighters must complete tasks such as:

- Evaluating the structural integrity and the extent of the fire
- Setting up a command post
- Securing a water supply
- Stretching hose lines
- Forcing entry, searching for the seat of the fire and possibly trapped victims

- Rescuing any possible victims
- Advancing the hose line to the seat of the fire
- Applying water to the fire
- Throwing ladders to upper floors
- Ventilating windows and the roof
- Protecting any other structures possibly exposed to the fire
- Securing electric and gas utilities
- Setting up crews to rescue other firefighters should they be trapped or injured
- Setting up rehabilitation and medical treatment for fire victims and other firefighters

While some of these tasks are less important than others, they must all be completed quickly and efficiently. Therefore, the fire service must prioritize these tasks so that the most vital ones will be completed as quickly as possible.

Much of the fire service research has also discussed the key tactic of ventilation. Ventilation is done in a variety of ways such as opening windows and doors, cutting holes in the roof, using a fan to push fresh air into the structure, or using a fan to pull air out of the structure. This tactic was first done in order to increase the visibility for occupants, either firefighters or trapped victims, as well as to allow some of the heat and other toxic gasses to escape from the structure. The scientific phenomena that drove the development of this tactic will be discussed in a later section. These goals were achieved, and ventilating structures entered the fire service toolbox. While ventilation still plays an extremely significant role in fire attack, research has shown there are many considerations that must be given to this tactic. Just to name a few of these studies, Underwriters Laboratories Firefighter Safety Research Institute's (UL FSRI) "Analysis of One and Two-Story Single Family Home Fire Dynamics and the impact of

Firefighter Horizontal Ventilation," and "Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction," are some of a few of these studies. Certainly, changes to the fire dynamics of a compartment can have both positive and negative consequences. As previously mentioned, the positives that can come from this are increasing the visibility in the affected areas, decreasing the temperature in the compartment, and reducing the toxic gases that are present in the compartment. However, depending on the method of ventilation, the neutral plane will be affected. The neutral plane is defined as, "the height above which smoke will or can flow out of a compartment. The height of zero pressure difference across a partition." (Gorbett, Pharr, Rockwell 299). This means that when there is a larger area ventilating to the exterior, there is a decrease in pressure inside of the compartment. Therefore, more oxygen can flow into the compartment, which can dramatically increase the fire intensity. A rising neutral plane is normally seen when vertical ventilation is employed, or when holes are cut in the roof of the compartment. When firefighters open windows and doors for ventilation, a "flow path" is created. This phenomena basically intensifies the path that fires travel by increasing the ways in which air travels throughout the structure. Many firefighters have been killed when working in a flow path. The first large Line of Duty Death (LODD) from a flow path related incident was experienced by the New York City Fire Department in a mid-rise senior citizen housing facility. This fire occurred on Vandalia Road in New York City and will be discussed in greater detail in a later chapter. Ventilation is something that is difficult to conduct in a high-rise building for several reasons, which will be discussed later.

However, ventilation tactics were first employed in the traditional furnishing era. While flexible polyurethane foam was being incorporated into furniture on a large scale as early as 1954, it did not become the universal component that it is today until the mid-to late 1960s.

With modern home furnishings, less compartmentation due to open floorplans, and lightweight construction, ventilation conducted incorrectly can severely impact firefighting operations. Traditionally, fires were limited by the amount of fuel rather than the ventilation, but with the advent of modern furnishings, fires are now mainly ventilation limited. Therefore, when ventilation is done and more air is allowed to enter the structure, the fire will only intensify. It has now been determined that ventilation must be coordinated with fire attack, meaning that applying water on the fire must be coordinated with ventilation efforts. Currently, research is being conducted in a variety of structures to determine when to ventilate compared to water application. The results of this research are still pending, but it is incorporating various other projects. More information on this project can be found at ULfirefightersafety.org. A direct link will be included in the bibliography.

While incomplete, this research hypothesizes that the belief that applying water to fire is the best way to cool the fire environment and will slow the growth of the fire and increase the survivability of the environment for trapped occupants will be proven. Much of the research has focused on water application from outside of the fire compartment. While the fire service previously held the belief that applying water from the exterior of the structure would “push” the fire into the unburned and undamaged portions of the compartment, this has largely proved not to be the case. Numerous experiments were conducted to evaluate this belief, and they illustrated that certain water application patterns and certain nozzles entrained more air than others. This air entrainment is what could in fact “push” fire when water is applied in specific ways. In a later section, water application will be discussed through the uses of various types of nozzles. Regardless of the “pushing fire” debate, water application is still extremely significant in fighting fire in the modern fire environment, especially in high-rise buildings.

2.4 Water as an Extinguishing Agent

As this report stated previously, water is the main extinguishing agent used in urban firefighting for a variety of reasons. Water in its liquid form is quite practical as an extinguishing agent as its liquid state allows it to be stored and transported easily, water is generally cheap and accessible in urban areas, and water is not a hazardous material. For firefighting applications, water is also an excellent fire suppression agent as it has a high specific heat. This quantity is defined by Gorbett, Rockwell, and Pharr as, “the amount of heat needed to raise one mass of a substance one degree.” (Gorbett, Pharr, Rockwell 300). This means that the higher the specific heat, the more energy that a substance can absorb before its temperature increases one degree in temperature. Water has a specific heat of approximately 4.181 kilojoules per kilogram degrees kelvin while many other materials such as polyurethane elastomer has a specific heat of 1.800 kilojoules per kilogram degrees kelvin. While this material would not be used to fight fires, it is often seen as a fuel in the modern fire environment, as illustrated above. Both of these values can be found on engineeringtoolbox.com’s “Specific Heat of common Substances” page.

After determining this information, the amount of water and the rate at which it is applied can be considered in order to extinguish a fire. In order to calculate the required flow rate, calculations were completed. These can be found in Appendix A and are summarized here. Assuming that water is found at room temperature, or approximately 20ºC, and water boils at 100ºC, providing a range of 80ºC for water to be increased before it is converted to steam. Therefore, in order to determine how much energy that one kilogram of water can absorb before it is converted to steam, its specific heat can be multiplied by 80. This value equates to approximately 334.48 kilojoules of energy.

Assuming that the fire has reached full room involvement, basically meaning that all combustible materials in the compartment are burning, the heat release rate can be conservatively estimated for both residential and commercial buildings such as offices through previously conducted testing. A residential room such as a bedroom would have a heat release rate of approximately 2 Megawatts (MW). This value is determined from the average peak heat release rate from eight tests catalogued through the University of Maryland's (UMD) Burning Item Database. On the contrary, commercial spaces such as workstations could potentially have a heat release rate of 2.7 MW. This heat release rate is calculated from an average of the four workstation tests that were averaged from the UMD Burning Item Database. However, especially for commercial spaces, this value can be altered by the orientation of the fuel. Therefore, the value for a standard cubicle will be used. This value, as determined by a test conducted by NIST is 6719.7 KW, or 6.72 MW. This value is also the highest one presented for workspaces.

With this information in hand, the rate of water application to extinguish a fire of the presented size can be calculated. These calculations are seen below in Appendix A and they will be summarized here. For the residential scenario, approximately 6 kilograms of water per second would be able to absorb the 2 MW from the smaller residential fire. To place this value into context, a one-and-a-half-inch hose with a 7/8-inch tip nozzle will provide just below double this flow rate, providing approximately 10 kilograms of water per second. However, in a commercial building, a two-and-a-half-inch hose with a one-and-one-quarter-inch smoothbore nozzle will be needed to extinguish this fire. This nozzle will provide 328 GPM at 48 PSI, or approximately 20.312 kg/s. This flow chart is presented in Appendix B.

2.5 Heat Transfer and High-Rise Buildings

In a process known as pyrolysis, heat converts the solid fuels to a fuel vapor, which can then burn. This makes fires in high-rise buildings much more intense, due to heat transfer.

There are three different methods of heat transfer, and all of them are significant in fires. Conduction is the first method of heat transfer that is defined as, “The transfer of energy in the form of heat by direct contact through the excitation of molecules and/or particles driven by a temperature difference.” (Gorbett, Pharr, Rockwell 297). This method of heat transfer can be seen when feeling a hot pan or pot. The metal has absorbed heat from the stove and when touching the exposed portion of the metal, the heat will be transferred to the cooler substance, in this case, skin. This method of heat transfer required some sort of a sold medium. Conduction is a method of heat transfer that does not have a substantial impact on fire intensity or fire growth, other than allowing heat to escape the burning compartment through walls.

Convection is another method of heat transfer, and this method is quite significant in fire development. Convective heat transfer is defined as, “Heat transfer by circulation within a medium such as a gas or a liquid.” (Gorbett, Pharr, Rockwell 297). This method of heat transfer is far more significant than conduction, as it involves fluids such as air. In a fire, a majority of the heat that is released from the fire will rise due to the buoyancy of air. According to Gorbett, Pharr, and Rockwell, “Approximately 70% of the energy liberated from a burning combustible is in the form of convection.” (Gorbett, Pharr, Rockwell 162). This is quite significant in a high-rise building, due to the building geometry, which will be discussed in upcoming sections of this report. As the temperature of the air increases, it becomes less dense, rising to the upper layers of the compartment. The room will then fill with combustion byproducts such as soot and other gasses including toxic gasses. As the upper layer of the room fills with these products, the bottom of the upper layer will descend toward the fire. These materials are then able to escape through windows and doors. As mentioned earlier, this is where the tactic of ventilating a structure originated.

3 High-Rise Building Basics

3.1 Overview

High-Rise firefighting provides numerous challenges to firefighters operating in these environments, and these challenges will be discussed below. The fire protection systems prevalent in these building will be discussed, as will the basic building geometry and other special hazards.

3.2 Fire Protection Systems

3.2.1 Introduction

Fire protection systems are extremely important in high-rise buildings. When these systems fail, or are not property installed, firefighting efforts will be severely hampered, a phenomenon that has been seen in several major high-rise fires.

3.2.2 Sprinkler Systems

Sprinkler systems are required in all new high-rise structures as a result of many historical fires, but there are many high-rise buildings found without sprinkler systems as they were constructed before sprinkler systems were required. Sprinkler systems are usually able to contain fires before the fire department arrives, preventing a major fire that would take several hours to extinguish. Due to the building size, these systems are generally very complicated and are designed during the planning stages and installed during construction. When the system is installed incorrectly, significant damage can be done to the system, causing potential failures.

These systems are to be tested at regular intervals, as prescribed by several standards, including the National Fire Protection Association (NFPA) 25, the Standard for the Testing and Maintenance of Water Based Fire Protection Systems. Sprinkler systems play a major role in the fire protection of large buildings, but they are not the focus of this report.

While not in all buildings, some large buildings rely on fire pumps to supply water and pressure. These systems are supplied from the city water main and then pressurized before being sent up the standpipe riser. A pump can be used for two reasons, to increase the pressure required to overcome the height of the building, or to supply water to the sprinkler system. Sprinkler systems require a certain amount of water and pressure to supply and operate the system, and this must be automatic, meaning that pumps or tanks must be present to supply water. Sprinkler systems cannot be supplied solely by the fire department upon their arrival.

Sprinkler systems are often the main fire protection system found in high-rise buildings, but they are not the most significant for manual firefighting. Sprinkler systems are designed to contain most fires, not extinguish them. In order to provide for manual fire suppression, many large buildings are required to have standpipe systems installed. In many modern buildings, these systems share a riser with the sprinkler system. The systems are therefore much more cost effective, but they become much more complicated. Some of the components of the system will now be discussed below.

3.2.3 Standpipe Systems

As mentioned earlier, standpipe systems are designed to transport water to the upper floors of buildings to facilitate firefighting efforts. These systems are basically piping with fire department hose connections that run from the street level to the lowest and highest points of buildings, typically basements and the roof. In most operations, firefighters use already connected hose lines called “preconnects,” “crosslays,” or “speedlays.” These hose lines allow firefighters to pull a hose line from an engine, stretch and flake the line, and begin fighting fire once the line has been charged with water. In a high-rise fire, firefighters would have to stretch hose lines from an engine to the affected fire area, which can take a very long time and it can also be very exhausting for firefighters. Therefore, these systems are installed to allow firefighters to complete their tasks more efficiently.

Generally, the systems are supplied from a fire department connection, also known as an FDC. These devices can either have two two-and-a-half-inch inlets, or a single five-inch inlet. While it is easier for a single firefighter to establish a supply to the FDC with a single inlet, there is no room for redundancy. While some newer buildings are opting for the single connection option, many older buildings are still equipped with a double inlet option. This “Siamese” connection can allow for two engines to supply the system simultaneously, or it can allow for a troubleshooting option should the first hose become severed by falling glass. Falling glass is something that is a large hazard at high-rise fires, and it will be discussed a later chapter of this report.

These systems are designed for seamless firefighter operation. Firefighters will arrive and then begin to climb the stairs carrying all of the equipment that they will need to fight the fire. Another firefighter, typically the driver of one of the first arriving engine companies, will secure a water supply from a fire hydrant and then supply the FDC from the engine. This allows for a constant flow of pressurized water to flow into the standpipe system and to the firefighters at the tip of the nozzle.

It is important to note that standpipe systems are designed to provide the highest possible volume of water at the lowest pressure. This design is a cost reducing value, as the lower the pressure, than the need for a fire pump may be minimized, if not eliminated. The most important thing for fighting fire is water application, as previously mentioned. However, the fire service places a large emphasis on pressure as opposed to volume of water. While pressure is certainly important, especially to provide the reach and penetration needed for a nozzle crew to be located out of danger, it is not what ultimately extinguishes fires.

However, in the case that the riser is split between the sprinkler system and the standpipe system, a fire pump may supply the system. In the case that the highest standpipe outlet is taller than one hundred and seventy-five feet above ground level, the building must be equipped with pressure reducing devices. This quantity is calculated from the 75 PSI remaining after nozzle operating pressure is considered per NFPA 14. It takes approximately .433 PSI to raise water one foot in elevation. Therefore, the 75 PSI divided by the .433 PSI/foot factor equates to approximately 175 feet. These valves are used to limit the pressure coming from the standpipe. According to NFPA 14, the Standard for the Installation of Standpipe Systems, the outlet pressure of any standpipe outlet can only be 175 PSI maximum. This is defined in NFPA 14.7.2.3.2. This requirement is to limit the nozzle reaction felt by the firefighter on the tip of the nozzle.

Nozzle reaction or kickback can be defined as, “the force exerted on a firefighter or other anchor by a stationary spraying nozzle supplied by a flexible hose. The reaction direction is opposite that of the jet.” (Sunderland, Chun, and Jomaas, 1). This effect is proven by Newton’s Third Law of Motion. This law of physics states, “Whenever one body exerts a force on a second body, the second body exerts an oppositely directed force of equal magnitude on the first body.” (Cutnell and Johnson 94). Therefore, in order for firefighters to maintain their position as well as that of the nozzle, they must exert an equal and opposite force against the nozzle. The higher the nozzle reaction, the quicker firefighters will be fatigued and the quicker that they will consume air from their air packs, exacerbating a logistical challenge that will be discussed in a following section. In addition to fatiguing firefighters, a single firefighter simply cannot control many nozzles. While the types of nozzles will be discussed in detail in a later chapter of this report, it is important to know that some nozzles have lower nozzle reactions than others due to lower operating pressures. This reduced nozzle reaction is important because in addition to the multitude of tasks that were listed previously, many United States fire departments are being forced to reduce their staffing levels due to budgetary constraints.

With this information on the origin nozzle reaction, it is important to identify approximately how much force can be absorbed by one, two, and three firefighters. A study conducted by Paul Grimwood examining this quantity with the London Fire Brigade provides an answer. He found that one firefighter could effectively manage only 266 Newtons, or 60 pounds of force. He also found that a team of two firefighters could manage 333 Newtons or 75 pounds of force and a team of three firefighters could manage 422 Newtons or approximately 95 pounds of force. It should be noted that many firefighters can cope with nozzle reactions above these limits, but these numbers are considerations that are used for firefighters with a median level of training and experience. With these numbers, a flow rate can be determined to ensure that firefighters will not be overwhelmed while attempting to advance and utilize a hose and nozzle while inside of a burning building. This consideration will be discussed in a later chapter on nozzle selection.

Pressure reducing devices are perfect for this task, but they can also create numerous problems in attacking fires. Depending on the device type, the valve may be removable or fixed in position. Some may be adjustable by firefighters in the field while others are set at a certain pressure during the production process. Still other valves are designed to only reduce pressure a certain amount while others are designed to only allow a certain pressure. Understanding these devices is something that is key to high-rise firefighting, but too often it is misunderstood by firefighters. In their haste to perform their duties, firefighters may not notice that a pressure reducing valve (PRV) is present, or they may not adjust the valve to the pressure that is needed. Without noticing this, they may commit to an aggressive fire attack, which can be very dangerous without the proper volume of water to combat the fire or without the pressure to achieve the correct nozzle pattern. Also, depending on the device, increasing the supplied pressure for the water at the supplying engines may not have a significant impact on the fire attack. This has been seen in many different notable fires that will be discussed later.

These systems are also susceptible to other failures. One of the biggest problems that can occur in a standpipe operation is a debris filled system. FDCs are generally equipped with locking caps that only firefighters and fire protection engineers are able to open. However, these caps are often broken or removed. Tampering with these caps is often done either to obtain the caps to sell them as scrap metal as many are made of brass, or even for mischievous purposes. Once these caps are removed, there is the possibility that debris can enter the system though these open connections. Items as simple as leaves and pebbles to soda cans or tennis balls have been found in these systems. The presence of such debris can have serious issues in a fire attack that may require the hose line to be shut down. If a nozzle team has advanced to the seat of the fire and then they lose water supply, they will be in serious danger until water is restored. Firefighters also cannot shut the line down and then attempt to fix any issues in the fire area, so they must retreat to an area of refuge until they can repair the line and push back into the affected area. Such a delay can be deadly for any trapped occupants, or it can lead to a failed fire attack. Methods to overcome this problem will be discussed later in this report.

The particular considerations for fire attack and for standpipe operations will be discussed later when hydraulics are examined. Standpipe systems do solve the problem of time-consuming hose deployment in very tall buildings, there are many other issues that are present in high-rise buildings.

3.3 Building Construction

3.3.1 Introduction

One of the largest hazards when fighting fires in high-rise buildings originates from the design of the building itself. Below, this report will discuss how the large size of high-rise buildings can affect firefighting efforts, as well as the special circumstances that firefighters and building designers must consider.

3.3.2 Building Size

High-rise buildings are becoming more prevalent in the United States, due to several factors. Both residential and commercial high-rise buildings are being built at an ever-increasing rate in order to accommodate the growth of cities. The increasing number of people seeking housing in dense urban areas is driving the increase in residential high-rises. Also, due to the expanding global economy, businesses are hiring vast numbers of employees in order to fulfill important new roles. In addition, these businesses are generally located near similar businesses to facilitate interactions both intercompany and intracompany.

With this increasing demand, buildings are becoming larger and more complex than they ever have been in the past. These larger buildings do greatly complicate firefighting efforts, as previously mentioned. Also, there are numerous tasks that must be normally must be completed in short order by the first arriving firefighters in addition to other tasks that must completed in these environments. The time that it takes firefighters to get into a position where they can complete their tasks will be discussed in the following section of this chapter.

Depending on the size of the building, many high-rise buildings are similar in size to a warehouse. However, unlike a warehouse, these buildings are generally condensed into a single city block. As previously mentioned, the height of these buildings complicates a simple firefighting operation such as water supply operations. This complication will be discussed in much greater detail in later sections of this report.

3.3.3 Building Construction

Due to the orientation of the building, command issues can arise. In a warehouse setting, chiefs and other officers in command of the scene are generally able to have much more situational awareness than they would in a high-rise building. Chiefs would generally be able to perform a 360º survey of the building to determine important information such as the location of entrances and exits, fire progression, and determining other information about the building. In a high-rise building, this important information may be hidden or difficult to determine from the ground. In fact, in some high-rise incidents, there are groups of firefighters who may be assigned to a reconnaissance role in order to supply information for the incident commander to allow him or her to determine the most appropriate course of action.

Due to the size and complexity of the building, many departments assign one crew to perform the task of “lobby control.” This task generally consists of controlling which firefighters ascend the building, occupant evacuation, managing the sprinkler system, managing the fire alarm system, and alerting building occupants through a building loudspeaker. Because a warehouse or a similar large structure will generally not have these systems, firefighters will likely be able to have a direct role in fire suppression operations.

From a scientific perspective, the design of a high-rise building greatly facilitates fire spread. As mentioned in a prior chapter, much of the heat released by the combustion process rises through convective heat transfer. Therefore, the fuel above the fire will be heated and begin the pyrolysis process, increasing the rate of fire spread. There have been numerous recent fires that saw very large fire spread in this manner, including the recent Grenfell Tower Fire in London in 2017. While London firefighters were able to extinguish the fire on the interior of the building, the fire extended to the building's exterior where, out of the reach of firefighters, it spread to consume most of the building. This fire growth was due to the presence of combustible cladding on the exterior of the building. Cladding is a material used on the outside of tall buildings to contain the building's interior temperature, making buildings more energy efficient. While new buildings are required to have noncombustible cladding, there are still many older buildings that were constructed before this requirement was implemented, in the same manner as buildings without sprinkler systems.

As well as the large size, the chemicals found in high-rise buildings can be just as volatile as some that are stored in warehouses. Most people may be used to having the aforementioned synthetic fuels in their homes in the form of chairs and other furniture, but they can release extremely hazardous materials when burned. One of the products of incomplete combustion is Carbon Monoxide. Gorbett, Pharr, and Rockwell state, "CO [Carbon Dioxide] is produced when a fire is undergoing incomplete combustion…. When CO is inhaled, it passes into the bloodstream where it combines with the hemoglobin molecule." (Gorbett, Pharr, and Rockwell, 68). Another colorless and odorless gas that is released when these materials are burned include

Hydrogen Cyanide. While carbon monoxide is mentioned far more often, hydrogen cyanide is much more lethal. With the advent of these plastic based materials, this hazardous material is much more common. The newfound presence of these gases is due to the chemical reactions that take place during the combustion process. As a quick summary, a hydrocarbon reacts with oxygen when energy is added, and carbon dioxide and water are produced. However, these products would only be created in an ideal, laboratory atmosphere. In earth's atmosphere, large quantities of Nitrogen are found, allowing for the formation of new components such as Hydrogen Cyanide, a compound of one Hydrogen molecule, one Carbon molecule, and one Nitrogen molecule, can be created. Carbon Monoxide molecules are also found in these situations due to the incorrect ratio of combustion. These materials are extremely hazardous, requiring the use of respiratory protection for firefighters. Some of the logistical challenges of providing this protection as well as other challenges associated with high-rise firefighting will be discussed in the following section.

3.3.4 Stairs and Other High-Rise Firefighting Logistical Challenges

3.3.4.1 Introduction

As mentioned in the previous section, the sheer size of high-rise buildings makes firefighting in these buildings very difficult. One of the largest reasons for this challenge is due to the heights of the buildings. While already discussed with water supply, in order to arrive at a position where firefighters can perform vital tasks, firefighters may need to exert a high amount of energy and a large amount of time simply climbing the stairs. Firefighters must bring all of their personal protective equipment and all of the supplies that they might need to fight fire with them. Simply carrying protective equipment can weigh upward of eighty pounds, not including hose, nozzles, or hand tools that may be needed to perform lifesaving operations. When all of this equipment is added, firefighters may be carrying well over one hundred and fifty pounds with them.

3.3.4.2 Elevators

Complicating these tasks, firefighters will often not be able to use elevators. While modern elevators have two stages of firefighter operations, firefighters still cannot use these elevators in many situations. Assistant Chief Dave McGrail of the Denver, Colorado, Fire Department lists many of these situations in his book *Fire Department Operations in High-Rise and Standpipe Equipped Buildings*. Chief McGrail lists several of these situations including, water seen in the elevator shaft, fires in the elevator machine rooms, and other hazardous situations. Chief McGrail also lists several considerations that must be made when attempting to use elevators in these buildings. He states that firefighters need to have a firefighter skilled in elevator operation assigned only to operate elevators and they must be equipped with a full complement of forcible entry equipment and fire extinguishers to allow them to escape from an elevator, should they become trapped. Chief McGrail also states that no more than a single crew ride in an elevator. This consideration due to both the size of most elevators, as well as weight requirements.

3.3.4.3 Firefighter Response Using Stairs

Even with all of these safety considerations, firefighters still need to stop the elevator and climb at least one floor before arriving at the fire location, known as the “fire floor.” This recommendation is due in part to both firefighter safety while traveling in an elevator, as well as to allow the officers in charge of fire attack and search and rescue operations to familiarize themselves with the layout of the floor below, as this is generally the same layout as the floor above, especially in commercial buildings. Firefighters can also make their connections to the standpipe system on the landing below the fire and then stretch the line upward to the fire floor, allowing for the hose line to lead firefighters to a safe area of refuge. In addition to having more space for firefighters to prepare the attack line for deployment, when the charged hose line is advanced onto the fire floor, the stairwells will likely fill with smoke and other products of combustion due to the density of these materials, as mentioned previously. The standpipe below will allow firefighters to be guided to an area below this smoke layer, allowing them a safe area should something go wrong during firefighting operations.

Also, the stairwell design can complicate these decisions. If firefighters are faced with a design known as “scissor” stairs, they will have to arrive at two floors below the fire. This type of stair is explained by Chief McGrail with, “Unlike the return-type stair, scissor stairs do not return to the same vertical geographic location at each floor landing. In most scissor stair designs, the stairs exit on the opposite side of the building at each landing.” (McGrail 108). Therefore, in order for firefighters to reach the correct location on the fire floor from that particular stairwell, they must ascend the stairs from two floors below the fire.

With all of this stair climbing, it will take significant longer for firefighters to reach the fire. As stated previously, firefighters are unable to get water on the fire quickly through the use of preconnected hose lines, which will necessitate standpipes. One of the reasons that preconnected hose lines are used as one of the main fire attack packages is due to the speed with which they can be deployed. Firefighters can arrive on the scene, pull a hose from the engine, flake it out, call for water, and begin to flow water. In a high-rise application, firefighters must first climb the stairs and make a hose connection before they can follow the same process. With all of the equipment that firefighters have to carry with them, this can take up to a minute for a firefighter to climb each flight of stairs. This can lead to a substantial amount of time for firefighters to arrive at the scene of the fire. The equipment carried by the firefighters in these applications as well as the potential size of the fire by the time that they arrive at the fire floor will be discussed in the following section.

3.3.4.4 Carrying Equipment

Firefighters must also carry not only the equipment that they would normally use for single family home operations, but they must also carry additional equipment. Again, due to the size of the building, firefighters will have to carry more equipment than normal to support their extended operations. Replacement hose and nozzles, medical equipment, communication equipment, batteries for radios and flashlights, additional tools, longer search ropes, and especially more air cylinders must be carried. While all of this extra equipment is substantial, the most important of these is additional air cylinders. Commonly called air bottles, these are a firefighters' lifeline. These air bottles provide firefighters the ability to survive in otherwise untenable areas due to the toxic gasses. However, these air cylinders only typically hold 3000 psi or 4500 psi of Oxygen. While these are designed to last 30 minutes or 45 minutes, respectively, firefighters often expend air in much less time. This difference is due to the physical toll placed on firefighters, especially operating in these hazardous environments. Firefighters must carry the weight of their equipment, any necessary hand tools, and the weight of a hose line. While the weight of various hose line sizes will be discussed later in this report, it must also be remembered that these tasks are conducted in hot and smoky environments with little to no visibility. In addition to all of these normal circumstances that cause firefighters to expend air faster than normal, in high-rise buildings firefighters often will expend air at a faster rate due to the physical toll taken by climbing the stairs. Such an environment and such a physical toll requires firefighters to carry additional air cylinders with them. When these cylinders are expended, firefighters must return to street level to refill them except for in a few specially equipped buildings. Should all of these cylinders be expended, then the fire attack would surely suffer.

Because of the burden placed on firefighters by carrying all of this equipment, there are often crews that are responsible solely for shuttling equipment. Depending on the size of the building, these firefighters may be responsible for carrying equipment at different heights, or more crews may be assigned. Such a consideration means that these fires are much more manpower intensive, something that many fire departments are lacking. In fact, a report was published in conjunction with the International Association of Firefighters (IAFF) and NIST on high-rise firefighting. This report had firefighters conduct a series of benchmarks to determine how larger crew sizes decreased the time that it would take firefighters to complete a series of tasks. This report held that smaller crews proved detrimental to firefighting efforts, even if the same number of firefighters responded.

While the crew size portion of the study was the focus of the fire departments and the IAFF, NIST focused on fire modeling and fire growth. Because a live-fire evolution was not allowed in order to keep continuity between test replicates, fire modeling had to be conducted to determine fire spread. NIST conducted these tests to evaluate how the longer time that it took for crews to accomplish essential tasks such as getting water on the fire increased the size and intensity of the theoretical fire. This modeling showed fire roughly doubled in size when allowed to burn unchecked, something that is well understood in the fire service. This report shows that it is essential to get water on the fire as quickly as possible. Therefore, when it takes longer for crews to arrive at the fire, the fire will clearly be larger. Of course, the amount of heat released by the fire depends on the growth rate. The report states that depending on the crew sizes, firefighters may arrive when the fire has reached six cubicles rather than two.

As previously mentioned, firefighters must be prepared to encounter large, fast-moving, intense, developed fires in high-rise buildings. The tactics employed must be able to effectively combat the fire as quickly as possible and the equipment must be robust enough to handle the punishment of fireground use while also being light enough to be transported to the emergency by stair-climbing firefighters. In a later chapter, this will be discussed with hose and nozzle selection.

3.3.4.5 Occupant Response Using Stairs

Just as firefighters must climb stairs to ascend to the fire area, occupants must descend these stairs in order to escape from the building. However, in large buildings, it may be impossible to evacuate all trapped occupants. Both occupants and firefighters must work for occupant safety. Rather than evacuating, some occupants may be safer by shelter in place from the fire. Sheltering in place has proved to be one of the best ways to provide for occupant safety during a fire in many cases, especially when a large number of occupants are located a great distance from the fire. However, in other cases, occupants have been killed in very remote locations due to combustion byproducts traveling throughout the building, especially in the MGM Grand Fire in Las Vegas, Nevada. After this fire, many fire departments chose to seek to evacuate all occupants in the case of a high-rise fire. While this may not be advisable, it is sometimes possible for occupants to evacuate the building with the help of the fire department.

The biggest consideration that firefighters need to make when attempting to evacuate trapped occupants from these buildings is getting occupants in stairwells remote from fire attack stairwells. When firefighters make entry onto a fire floor, they will often prop the entry door open to facilitate the hose stretch. This task is required, as it prevents the door from closing on top of the hose line and restricting water from reaching the nozzle, but it does allow combustion byproducts to enter the stairwell and rise throughout the building. In several fires, including the Cook County Administration Building fire, occupants have been killed by the smoke rising through the stairwell. It is also important for firefighters to be aware of the stairwell construction so that they will be able to select which stairs they desire occupants to use for evacuation and which stairwell that they seek to use for fire attacks. The important construction factors for stairwell selection will be discussed in the following section.

In addition to ensure that there are no trapped occupants in the stairwells, firefighters must also ensure that they understand the building's heating, ventilation, and air conditioning system (HVAC). Firefighters have often been taught to turn off the building's entire HVAC system to prevent smoke from traveling through the building. However, stopping the HVAC system can allow smoke and other combustion byproducts to freely travel the building. This result is due to the unpressurized chambers that will allow for these products to travel just as they would naturally. Once firefighters have allowed for this to happen, then it would be very difficult to prevent smoke from traveling to other areas of the building, especially depending on the system design.

It should also be important for firefighters to address the building occupants through loudspeakers. As previously mentioned, one of the "lobby control" tasks to which firefighters may be assigned upon their arrival is this notification role. Firefighters must be able to advise occupants on the events that are happening in the building. If occupants know what is happening in the building, they will likely be more receptive to firefighters' instructions. Occupants must also be well-versed in both evacuation and sheltering-in-place protocols. Many jurisdictions have these fire drills to ensure that occupants know how to evacuate from buildings, but it seems that many occupants are not trained on sheltering-in-place. Building management also seek to have these fire drills in times that will not disturb the tenants of these buildings, especially in business applications. Rather than attempting to minimize their impact on businesses, these drills must maximize their safety benefits.

3.3.4.6 Stair Construction

As mentioned in the prior section, firefighters must be able to select the stairwell that they seek to use for fire attack early in the incident as well as any occupant evacuation stairwell. One of the main considerations for selecting a fire attack stairwell obviously is choosing a stairwell that contains a standpipe system. If the building only contains one stairwell with one standpipe system, then the fire attack stairwell has essentially been chosen for firefighters. However, if the building has two standpipe systems, the decision is made more difficult. Firefighters must be able to choose the stairwell that will be located closest to the fire. This information can be obtained from the fire alarm panel, generally located on the ground floor, or from evacuating occupants. It can be verified by a visual check by truck companies before engine companies begin the fire attack operation. The job roles of each of these types of responding companies will be discussed in final chapter of this report.

Another consideration that must be made is to account for the stairwell(s) that is (are) commonly used by occupants. If occupants are accustomed to use one particular stairwell to evacuate, then that stairwell should not be used for fire attack if at all possible. Firefighters can easily adapt to choose a stairwell upon their arrival. However, occupants who are currently evacuating will be less able to change to another stairwell. Evacuation drills must be conducted with variations in them so that occupants are prepared to evacuate under adverse conditions.

3.3.5 Ventilation and Special Hazards in High-Rise Buildings

3.3.5.1 Introduction

As mentioned previously, one of the main tactics to combat fire is through controlling the ventilation in and out of the compartment. However, in high-rise buildings, this is much more difficult. While HVAC systems were already mentioned in the previous section, this section will focus on more traditional fire service ventilation methods. In addition to the following challenges, it must also be considered that fans used by firefighters to ventilate normal single-family homes will generally be unavailable for fires in high-rise buildings. These fans are not only heavy, making it difficult for firefighters to bring these fans to their needed positions in a high-rise fire, but most of these fans are gas powered or electric powered. Firefighters would either have to fill the building with more dangerous carbon monoxide gas for these gas-powered fans, or they would have to rely on the building's electrical system to supply electric power. In the case of gasoline-powered fans, firefighters would also need to carry large amounts of fuel with them to power these fans.

3.3.5.2 Lack of Ventilation

It is important to remember that the fire service has two main ventilation methods: vertical and horizontal ventilation. Again, vertical ventilation involves cutting holes in the roof or creating openings above the fire and horizontal ventilation involves creating openings on the same level as the fire. While these are used extensively when fighting fires in single family homes, it is much more difficult in commercial and high-rise buildings. Again, this limitation is due to the building construction features.

It is difficult for firefighters to vertically ventilate a high-rise structure, as the fire is rarely on the top floor of the building. While a significant portion of the fires located on the top floor of these buildings are located in mechanical rooms, these fires are generally extinguished easily and do not require additional fire service created ventilation. Fires that are located at lower levels are generally larger, which can require the additional ventilation. The main method of vertical ventilation in high-rise structures involves opening the roof access in stairwells to allow the combustion byproducts to escape through these doors. While this process can be completed with much less destruction than cutting holes in the roof of a structure, it does greatly endanger the occupants sheltering above the fire. This method will also limit fire service access above the floor affected by fire, as firefighters must be breathing supplied air to protect themselves from the environment. In addition to creating a larger logistical challenge, it will also limit how far firefighters can travel above the fire. These challenges have also been seen several times in other historical fires including the One Meridian Plaza Fire and the First Interstate Bank Building fire, both of which will be discussed in the following chapter.

Horizontal ventilation may seem to be a more direct method to ventilate a fire, but it can be just as hazardous for firefighters operating near the fire as well as individuals at the street level. High-rise buildings generally have windows that cannot be opened for building occupant safety. Many of the windows that are present in high-rise buildings are floor to ceiling windows that would completely cover the building’s façade. Therefore, the windows would have to be broken by firefighters to employ horizontal ventilation. At the street level, individuals could be severely injured by falling glass if firefighters would seek to horizontally ventilate mechanically. The area directly below the building would have to be cleared of all people for their own safety. Firefighters would also need to clear a few blocks apart away from the building to protect these individuals in the case of wind carrying glass shards. These reasons alone generally prevent firefighters from using mechanical horizontal ventilation, but there are other natural reasons that this is a difficult tactic, mainly hazards created from the Stack Effect as well as the possibility of wind driven fires.

3.3.5.3 Stack Effect

The stack effect is also another physical effect that must be considered when discussing ventilation in high-rise operations. Chief McGrail defines this phenomenon as, “’the vertical, natural air movement throughout a high-rise building caused by the difference in temperatures between the inside air and the outside air.’” (McGrail 246). He goes on to state that the positive stack effect is a draft from the ground level to the roof and the negative stack effect is a natural air current from the roof to the ground. In warmer climates, the negative stack is induced, meaning that smoke will actually travel downward through the building and vice versa in colder environments. This is due to the temperature gradient between the inside and air outside of the building.

The stack effect impacts ventilation patterns even when the windows are closed. However, when the windows are opened, this pattern becomes much more influential. Furthermore, firefighters sometimes use fans to aid in stairwell pressurization. Many modern stairwells are pressurized by built in fans when the fire alarms are activated, but when doors are opened by fleeing occupants or by firefighters, these built in fans can become overwhelmed. In order to supplement these fans, firefighters can sometimes use fans that they would use for single family homes. However, the stack effect can either assist or reverse this process and cause significant issues for firefighters. If smoke and other combustion byproducts move throughout the building and affect other occupants, firefighters will become overburdened extremely quickly. Rather than evacuating a few floors of the building, firefighters will not be responsible for evacuating the entire building. This task would require far more personnel than simply attacking the fire and evacuating a few floors surrounding the fire. Many fire departments are unable to handle these challenges, which could lead to several injuries and deaths. Overall, the stack effect is something that will limit the fire department's ability to ventilate a high-rise structure. It must be considered before ventilation orders are given as well as in the case of a window failure due to heat or flame impingement.

3.3.5.4 Wind Driven Fires

Wind Impacted Fires are a key safety issue for firefighters not only in high-rise buildings, but in all types of structures. However, as was mentioned in the previous section on the stack effect, the impact of wind is much more severe in high-rise buildings. There have been several documented cases in which firefighters have been severely injured or killed in these events.

One of the most notable of these events was the fire at Vandalia Road in Brooklyn, New York, as previously mentioned. Three firefighters were killed in a fire that occurred in a ten-story apartment complex housing elderly occupants. Firefighters attempted to crawl down the hallway to secure the door of the burning apartment to allow other firefighters to stretch attack lines to the door of the apartment easier. However, these firefighters were caught in a "flow path." This term implies that firefighters and the fire were trapped between two openings, in these cases windows. An open window behind the fire provided oxygen to the fire, which was spreading out of the open apartment door. When firefighters were moving down the hallway, the door to an apartment behind them opened as a victim attempted to escape. While he was doing this, he left his window open, creating a path for the fire to travel. The three firefighters did not stand a chance of survival and were killed instantly. The causes of their deaths were determined to be smoke inhalation and burns. It was determined that the window located behind the fire allowed the wind to enter the compartment and fan the flames. The wind then pushed the fire down the hallway to the newly opened apartment. The opened window in this apartment provided an exhaust point for the fire, allowing the byproducts of combustion to escape the compartment.

This tragic event led to some of the first studies concerning flowpath and wind driven fires. A few years later, studies were done in combination with NIST, UL, and the Fire Department of New York City to study this phenomena and to determine ways to prevent future LODDs. In conjunction with researching wind-driven fires, the research groups also examined different ways to fight high-rise fires, including various wind control devices and different types of nozzles designed to deliver water to the fire from the floor below the fire. These devices have now entered the fire service in serval large cities across the United States. Captain John Ceriello discussed their implementation at the Fire Department Instructor's Conference 2018 in his presentation, "Fighting High-Rise Fires: A Big City Prospective."

3.3.5.5 Lack of Egress Possibilities

One of the most common and most shocking images produced by high-rise fires are from individuals jumping to almost certain death from these buildings. While this study will not examine the psychological justifications for jumping from a burning building in great detail, it is important to note that these individuals are trapped with a limited possibility of escape.

As previously mentioned, the stairwells and elevators are some of the only ways to escape a fire in one of these buildings. However, both building occupants and firefighters are instructed to refrain from the use of elevators in fire situations. This instruction is the result of both firefighter deaths as well as from understanding how elevator sensors work. The sensors that control elevator doors are infrared sensors, meaning that when there is an area of heat in front of the sensor, then the door will remain open. This system has resulted in several deaths of both firefighters and civilians. On the civilian side, the only death that resulted from the First

Interstate Bank Building fire in Los Angeles, California, was a result of this system. While this fire will be discussed in greater detail in following portions of this report, a member of building security used the elevator to evaluate the conditions on one floor of the building after the activation of the fire alarm system. When the elevator door opened, the occupant was met with the smoke and flame accompanying a large fire and he was unable to close the doors. After frantically calling for help from his fellow employees, he succumbed to the fire.

Firefighters more often face these challenges, even on building fire alarm activations. Firefighters are able to place elevators in what is known as a "firefighter's service" condition which equates to recalling the elevators and placing them under the control of the firefighters. One of the ways that this elevator mode changes the controls of the elevator is that it requires firefighters to hold the "Door Open" button until the doors reach their full width, and the sensors that allow for an elevator to be "held" are deactivated. Some of these are due to tragic fires that have occurred in the past. For example, in Memphis, Tennessee, in 1994 six firefighters overcrowded and overloaded an elevator while investigating the source of one of these incidents. The firefighters used the elevator to ascend to the floor involved in fire where they were met with similar conditions to the First Interstate Bank Building fire. One of the firefighters was able to close the doors and escape the fire, but some of his fellow firefighters were not so lucky. This incident is discussed in a NIOSH report on the deceased firefighters. This underscores why elevators are such a hazard in high-rise fires.

While occupant elevators are being developed and other systems such as parachutes are designed to help building occupants to evacuate a high-rise fire, these are not commonly employed. Firefighters and occupants both must use the stairs for building egress. This can be a challenge as there are often only a few stairways in a building due to the lack of everyday use.

However, this is often specified by code, meaning that a building must be able to evacuate a certain amount of people in a certain amount of time. This number is specified in human behavior in fire analyses to ensure that the fire protection systems in buildings can protect occupants long enough to ensure that they will be able to exit the building safely. Such analyses can also determine if occupants should be instructed to evacuate the building or if they should be instructed to shelter in place for protection from the fire, which itself can lead to challenges.

Often in these buildings, occupants on floors remote from the fire may be instructed to shelter in place, but as previously mentioned, these floors can quickly become involved in the incident. The highest fire protection rating in these buildings is generally two hours, meaning that the fire-resistant walls and doors are only rated to prevent fire impingement for two hours. With the immense number of occupants that may be trapped in the building, an immense number of firefighters are needed to facilitate such an evacuation. While these evacuations have occurred in many high-rise fire incidents, the large amount of manpower required to evacuate trapped occupants can severely detract from the fire suppression operations.

To evacuate the residents sheltering in place, firefighters must physically travel to the room to evacuate the occupants. Especially on upper floors, firefighters are unable to use aerial ladders to rescue trapped occupants from the building's exterior. While in low-rise or residential homes, firefighters are able to use even ground ladders to rescue occupants, the height of high-rise buildings negates this option. Occupant evacuation in high-rise fires can truly be a manpower intensive and daunting task for even the largest fire departments.

4 Case Studies

4.1 Overview

In order to determine the ways in which fires are fought today, the fires of the past must be examined. One of the main ways that firefighters and the fire protection community learn are through failures and through notable incidents. Therefore, a comprehensive review of notable high-rise fires in the United States will be presented. These events include the One Meridian Plaza fire, the First Interstate Bank Building fire, and the Clearwater, Florida, Condominium fire. There will also be a brief mention of positive case studies.

4.2 One Meridian Plaza Fire

4.2.1 Introduction

Arguably, the most notable high-rise fire in United States history happened in Philadelphia, Pennsylvania in 1990. This fire resulted in the deaths of three firefighters and the destruction of a major structure in the Philadelphia skyline. This incident can be examined as the "Murphy's Law" of high-rise firefighting in which nearly every system designed to prevent, contain, or suppress a fire was either working improperly or absent from the structure. A technical report published by the United States Fire Administration (USFA) stated, "It was the largest highrise [sic] office building fire in modern American history – completely consuming eight floors of the building – and was controlled only when it reached a floor that was protected by automatic sprinklers." (USFA-TR-049, 1).

4.2.2 Incident Summary

On February 23, 1991, the building located at One Meridian Plaza ignited and burned for over nineteen hours. The fire was detected just after 8:20 PM but the fire department was not notified until just before 8:30 PM. Firefighters arrived to find large amounts of fire on the building's 22nd floor. Two minutes after arrival, crews called for a second alarm, and the first crews took elevators that served the low-rise portions of the building and climbed the stairs from the 11th floor.

The first system failure that occurred was a total electrical power failure due to fire impingement on some of the conduit. The emergency generator did not operate as it was designed and therefore the building was without electrical power for the duration of the incident. This prevented firefighters from using the elevator to transport any equipment.

The initial attack was conducted with one-and-three-quarter inch diameter handlines with automatic nozzles. After several minutes, crews were able to force a door onto the 22nd floor but with insufficient water pressure, firefighters were unable to enter the floor.

Additional alarms were called as crews worked to supply additional pressure to the standpipe system. The upper floors of the building were then exposed to "autoexposure," meaning that the fire was attempting to spread through the exterior of the building. The fire also spread through unprotected vertical shafts such as cable trays and the like.

Due to the water supply issues caused by the pressure PRVs, firefighters were limited to defensive operations while the fire spread to the 23rd and 24th floors. A fifth alarm was summoned while firefighters from Engine 11 were assigned to ascend to the building's roof to open bulkhead doors to allow the fire to vertically ventilate. However, these firefighters radioed that they were disoriented on the 30th floor. While they crew requested to breach a window for ventilation, the captain was reported to be injured. Rescue operations, including using a helicopter to illuminate the floor, were initiated but with no success. A search team was inserted at the roof, but members of this group became disoriented and the operation had to be suspended due to thermal drafts and heavy smoke. The firefighters were eventually located and brought to a medical triage area on the 20th floor, but resuscitation efforts were unsuccessful.

After the missing firefighters were located, firefighters again attempted to overcome the water supply issue by stretching a five-inch supply line up the stairwell to the fire floor. Eventually, three of these hose lines were stretched to supply all of the attack lines operating on the interior of the building. These three supply lines were able to supply all of the handlines that were being used to combat the fire, but the fire had grown to an extent in which it could not be controlled by hose lines.

After approximately 11 hours of firefighting, operations were suspended, and firefighters were withdrawn from the building due to the concern of a possible structural collapse. Firefighters attempted to attack the fire from adjacent buildings using large master stream devices. However, the fire was eventually stopped by sprinkler heads installed on the 30th floor that were supplied from the fire department pumpers that were initially supplying the standpipe system. Only 10 sprinkler heads activated and stopped the spread of the fire.

4.2.3 Lessons Learned

One of the biggest takeaways from this incident, especially as it relates to this report, was the rejection of 100 PSI automatic nozzles and one-and-three-quarter inch handlines. According to the technical report, “The pressure reducing valves in the standpipe outliers provided less than 60 psi discharge pressure, which was insufficient to develop effective fire streams.” (USFA-TR-049 9). Firefighters made several efforts to boost the pressure in the system, but ultimately these were unsuccessful due to the PRVs. The only way that firefighters were able to overcome this challenge was to deploy a large diameter supply hose, a process that took over an hour to complete.

In the technical report, one of the largest considerations on the standpipe system stated, “Code assumptions about fire department standpipe tactics proved invalid.” (USFA-TR-049 17). The report mentions that this standpipe pressure was only required to be approximately 65 PSI rather than the 100 PSI required by the Philadelphia hose and nozzle combination. The report states, “Most fire departments today use 1-3/4 inch and 2-inch hose with fog nozzles for interior attack. These appliances require substantially greater working pressures to achieve effective hose streams.” (USFA-TR-049 17-18). The report goes on to state that PRVs were installed in the building, due to the desire to protect firefighters from excessive nozzle reaction, a force discussed earlier. It discusses that a complete revision of NFPA 14 was suggested in the aftermath of this incident to remedy this potential challenge.

Another major critique resulting from the events at One Meridian Plaza was to ensure that all high-rise buildings were equipped with automatic fire sprinkler systems.

4.3 First Interstate Bank Building

4.3.1 Introduction

The First Interstate Bank Building fire in Los Angeles, California, in 1988 is a cautionary tale about installing and maintaining fire protection systems. This fire grew to such a severe level due to the sprinkler system maintenance that placed the system out of service at the time of the fire. The fire resulted in only one death, nearly fifty injuries, and approximately $50 millions in damage due to the heroic efforts of the Los Angeles City Fire Department members. Nearly half of the department responded to the incident and mounted an offensive attack from four stairwells.

4.3.2 Incident Summary

The fire started on the 12th floor of the building and extended to upper floors of the through the exterior walls of the building. The fire eventually spread to the 16th floor with flames extending nearly 30 feet on the exterior of the structure. The fire burned intensely approximately 90 minutes per floor and took about 45 minutes to spread to the next floor.

Approximately fifteen minutes after the standpipe was drained and the sprinkler system was deactivated, the fire was reported. Within five minutes of department arrival, the officers had requested approximately 200 personnel. Firefighters climbed the stairs to the fire floor per the department's Standard Operating Policy. The first companies to reach the fire area began fire attack from all four stairwells upon the notification of seeing smoke in the stairwell. Firefighters had difficulties advancing these hose lines onto the floor as they were met with heat and smoke. This initial attack used primarily two-inch attack lines and they were supplied by fire department pumpers at street level in addition to the fire pumps that were started after the fire attack began. The fire pumps were restarted by sprinkler contractors who were first rescued and then returned to the building. The engine companies that were supplying the standpipe system also had to be replaced multiple times as they were severed several times due to falling glass. The Incident Commander of the fire also gave approval for firefighters to break any glass they deemed necessary for ventilation.

Upon notice that the fire was expanding on the exterior of the building, crews attempted to push the fire to the perimeter of the floor. Runners were also employed to communicate due to the overtaxed radio system. Approximately 20 handlines were used during the fire attack with firefighters waiting for the fire to impinge on the 16th floor where they could prevent it from spreading. This strategy eventually proved to be successful.

Several occupants remained trapped above the fire and therefore had to be rescued by firefighters and helicopters. These crews were some of the only firefighters at the scene who used 60-minute air cylinders to ensure that the other firefighters did not overexert themselves.

The standpipe system in this building was a single zone system, meaning that only one riser ran the course of the building. It was also determined that the sprinkler system would be activated on higher floors from the 17th floor to the 19th floor so that the fire could be contained if firefighters would not be able to control it. Both the sprinkler and the standpipe systems were fed from an 85,000-gallon reservoir. The 2,000 GPM pumps had the volume of water down to only one-third of the capacity.

The pressure reducing valves in this building regulated the pressure from approximately 585 PSI at the basement down to a manageable level for the firefighters operating in the building. However, there were some errors with these PRVs meaning that there were some valves that allowed for nearly 400 PSI to escape through the system.

It was determined after the incident that firefighters were able to use the 4,000 GPM provided by the standpipe system to supply the one-and-three-quarter, two, and two-and-a-half-inch hose lines that were used to attack the fire.

4.3.3 Lessons Learned

The technical report determined several key lessons from this building, mainly involving the sprinkler system of this building. It reaffirmed that sprinklers were vital for high-rise buildings, but it also determined that non-sprinklered buildings create massive staffing requirements. It also stated that fire departments need to create contingency plans for buildings in which fire protection systems fail.

4.4 Clearwater, Florida, Condominium Fire

4.4.1 Introduction

Clearwater, Florida, firefighters responded to a high-rise condominium fire on June 28, 2002. The fire originated in a kitchen on the fifth floor of an 11-story building. One of the complicating factors in this fire was the delay in fire department notification. Occupants attempted to fight the fire with fire extinguishers and occupant use standpipes before they alerted the fire department. The standpipe riser was also shut down and a fire hydrant in the complex was out of service. Firefighters eventually had to call for a three-alarm compliment to provide enough manpower to successfully extinguish the fire. Despite deviation from established standard department policy, firefighters were able to extinguish the fire through interior and exterior fire attack.

4.4.2 Incident Summary

After residents attempted to use three fire extinguishers as well as the occupant use standpipe, the fire department was alerted of the fire. Upon the arrival of the first engine company, the pump operator attempted to supply the freestanding FDC from the engine. The driver also worked to secure a water supply from the hydrant located directly adjacent to the FDC. While these tasks were performed, firefighters from the first arriving engine as well as the first arriving ambulance ascended to the fifth floor with a one-and-three-quarter inch hose line, various adapters and fittings, and forcible entry tools. Rather than using the stairs, this crew chose to use the elevator to ascend directly to the fifth floor.

When the crew arrived at the fire floor, they encountered a large amount of smoke, but they reported that visibility was still sufficient. They informed other residents to return to their condos while they called for a second alarm assignment. A firefighter than connected to the one-and-a-half-inch standpipe outlet while the rest of the crew continued to look for the seat of the fire.

After the arrival of the first due truck company, the first arriving engine company attempted to stretch a supply line so that the ladder could be used for fire suppression, but the crew then determined that the fire hydrant was out of service, which was previously unknown to the fire department. At this point in the operation, crews inside determined that they would rescue as many occupants as possible but that they would abandon interior firefighting operations. It is believed that the room of origin reached flashover and there was also possibly a rollover in the hallway. These extreme fire events led to the injuries of three firefighters and the death of one of the residents.

Upon the arrival of the next engine company, the first ladder company was supplied with water from a different hydrant. The first squad company also stretched a one-and-three-quarter-inch hose line to assist with fire suppression. The first truck company was used for standpipe operations by providing its ladder pipe as an additional standpipe rise.

At the command level, two additional truck companies were requested as well as a third alarm. The additional alarm was dispatched, but the additional truck companies were not.

4.4.3 Lessons Learned

Many of the recommendations in the wake of this incident discussed communication and command considerations rather than the fire protection systems or fire service tactics. However, in addition to suggesting that firefighters must follow established guidelines set forth by the department, the report does raise some important considerations. One of the main recommendations focuses on using the standpipes located in the stairwells as well as not using elevators to transport firefighters directly to the fire floor.

Another lesson that this report conveys is that an aggressive interior attack should be mounted in order to contain and extinguish fires quickly when staffing is an issue. The report first states that firefighters should mount an aggressive interior extinguish effort. Of this fire in particular the report states, “In this instance, water was not put on the fire for approximately twenty-eight minutes, well after conditions lead to a flashover, which ultimately resulted in two fatalities and ten injuries.” (USFA-TR-148 13). While this report does not critique the fire department’s chose of hose or nozzle, it does state that firefighters should seek to apply water to the fire as soon as possible for firefighter as well as occupant safety.

4.5 Positive Case Studies

4.5.1 Introduction

While case studies detailing the failures of either firefighters or fire protection systems are prevalent, it is much more difficult to locate positive case studies, which could be due to several reasons. The most practical reason is that a large-scale investigation is generally not begun for incidents that have a positive outcome. These federal or state investigations are typically launched where there has been severe injuries or deaths in order to determine where fault lies. However, in positive studies this is not the case. Another reason that these incidents are more difficult to find is that they do not make good news stories. While the media is the predominate source of current event information, it is an entrepreneurial enterprise. Therefore, the media is seeking to increase its viewership so that it may increase its profits. While a high-rise building in the downtown area of any city will draw viewers for the news outlet, a massive fire that firefighters cannot control and that has people hanging out of windows will certainly be more dramatic. A fire that firefighters are easily able to put out in a short time frame with only a limited amount of resources will be substantially less successful.

While there may be few lessons learned from these fires, this report will attempt to illustrate the tactics that were employed in these fires that made the operations successful.

5 Hose and Nozzle Selection

5.1 Overview

Now that tactics have been discussed on a rather broad scale, this chapter will examine the hose and nozzle selection that is key to fire extinguishment. This chapter is applicable to all fire departments, as the information is not unique to high-rise buildings, but the delivery of this information is tailored to standpipe operations. In this chapter, the hydraulic principles of both hose and nozzle characteristics with respect to water flow and pressure will be discussed. This chapter will also focus on the maneuverability of hose lines. Finally, in the nozzle portion of this chapter, the benefits of using a smoothbore nozzle in high-rise buildings will be examined.

5.2 Hose

5.2.1 Introduction

The principle weapon in the any fire department arsenal is hose. In high-rise buildings, attack hose lines are extremely important considerations while supply lines play an equally important but less visible role. This section will relay information on this vital weapon.

5.2.2 Couplings and Hose Diameters

The biggest differentiation between hose is its diameter. Hose lines with a diameter of two-and-a-half inches and smaller are known as attack lines as they are used to directly deliver water to the seat of the fire and hose lines with a diameter of two-and-a-half inches and above are supply lines that are designed to move large volumes of water. This report will mainly focus on attack lines as these are the hose lines that are attached to a standpipe system.

Hose lines that are commonly used for fire attack in high-rise environments include one-and-three-quarter inch hose, two-inch hose, and two-and-a-half-inch hose. While many fire departments also use smaller one-and-half-inch hose, this is typically used for residential and smaller fires rather than fires in commercial buildings and high-rise structures. One-and-a-half-inch hose and one-and-three-quarter inch hose share one-and-a-half inch couplings while two-and-a-half-inch hose has its own couplings. These large couplings contribute to lower pressure loss due to friction loss.

Friction loss is the pressure that is lost due to water traveling. The higher the velocity pressure of the water, also known as the pitot pressure, a quantity that will be discussed later, the higher the friction loss. Smaller diameter hoses also have a large friction loss because more water is in contact with the walls of the hose.

Determining the size of the hose line in a low-rise structure is sometimes the responsibility of the company officer in charge of the company and sometimes the responsibility of the firefighter assigned to the nozzle position. This determination is different from department to department and even from company to company with each department. While it is not important to know who makes this determination, it is important to know that a size determination is made depending on the individual fire. In a large building or in a building showing a large volume of fire upon arrival, firefighters will typically use a large diameter hose line so that they will be able to flow a large volume of water on the fire.

However, in a high-rise building, most fire departments only have one hose size for their high-rise hose packs. Some departments chose to use larger diameter attack hose so that they can provide the large volume of water on a fire, should it be needed, and others choose a smaller hose line so that they will be able to apply water to the fire faster. Both of these are somewhat valid options depending on the area served by the particular department and the particular company's district, as will be discussed in the following chapter.

5.3 Nozzle Selection

5.3.1 Introduction

While choosing a hose size may be somewhat subjective, nozzle selection is far more objective. The following sections will discuss the different in nozzle types and the advantages to different types of nozzles in a high-rise environment.

5.3.2 Nozzle Types

There are four main types of nozzles that are used by United States fire departments. These include, from least to most complex: smoothbore nozzles, fixed gallonage nozzles, and select-a-gallonage nozzles, and automatic pressure nozzles. All nozzles other than a smoothbore nozzle are combination fog nozzles, meaning that they can flow a straight stream or a fog pattern for better vapor conversion.

Smoothbore nozzles on the other hand simply only operate in what is referred to a "solid stream." These nozzles are simply a narrowed tube that allow for water to pass through an opening narrower than the hose diameter. This will create a pressure that will allow the hose stream to reach a distance away from the firefighters as well as providing the ability to penetrate walls and other materials. In order to extinguish fires, water from these nozzles is either applied to the burning surfaces, or the nozzle is moved rapidly to facilitate steam conversion. While these nozzles are very simplistic, the design has been proven for several decades of operation.

The next type of nozzle in terms of simplicity is the fixed or constant gallonage nozzle. This nozzle incorporates many of the design aspects of the smoothbore nozzle, but it includes a stem. This stem creates "chatter" in the stream, creates a turbulent flow of water rather than a laminar flow as seen in a smoothbore nozzle. With the addition of this stem, the pattern can be altered so that the water will be delivered in a cone shape rather than a solid stream. These nozzles will provide a certain amount of water at a certain pressure, depending on the stem that is in the nozzle. Some of these stems are designed to provide 150 gallons per minute when provided 50 PSI, but the nozzles range all the way to 200 gallons per minute at 100 PSI, depending on department and company preference. These nozzles, as with all fog nozzles, are far more effective than smoothbore nozzles when applying foam. These are the simplest fog nozzles used in the fire service.

The next most complex nozzle is a variable flow nozzle. These nozzles are very similar to the fixed gallonage nozzle, except that the stem inside of the nozzle is adjustable. Therefore, the nozzle can provide higher or lower flow rates when provided different pressures. These nozzles typically range from 100 gallons per minute to 200 gallons per minute. While these nozzles may be more versatile than the fixed gallonage nozzle, the nozzle firefighter must relay when the flow is desired to be increased or decreased to the firefighter operating the pump. It is also important to note that when these nozzles are not maintained properly, it is very possible that the gallonage can be changed accidently rather than changing the fog pattern. While these nozzles are more versatile than constant gallonage, there are some additional considerations that must be made.

The most complex nozzles currently used in the fire service are automatic or constant pressure nozzles. These nozzles operate in the same manner as the other fog nozzles, except that the nozzle contains a spring that allows for the stream to retain its reach and stream, regardless of the flow. While this nozzle maintains a steady pressure, it does not maintain a steady flow. Because of the stream appearance and the similar nozzle reaction, firefighters may be tricked into believing that they have a sufficient stream when they are only flowing a small amount of water. The fire service is largely moving away from these nozzles due to this critical problem.

While all of these nozzles have a place in the fire service, there are advantages and disadvantages to using each of these types of nozzles. The following section will discuss the justifications for using a smoothbore nozzle in high-rise firefighting operations.

5.3.3 Advantages of a Smoothbore Nozzle in High-Rise Environments

While this project is applicable for all types of firefighting operations, it examines the special considerations that must be made for high-rise firefighting operations.

While fog nozzles provide the utility of having different stream patterns, smoothbore nozzles are far more beneficial for high-rise operations for numerous reasons. These include: the lower nozzle operating pressure, far superior debris clearance, lighter weight, fewer internal components leading to easier maintenance, more durable, and cheaper purchase cost.

One of the primary reasons to use a smoothbore nozzle with a standpipe system is the lower operating pressure that is necessary because of the lower pressure provided by standpipe systems, especially those equipped with pressure reducing devices. While most combination fog nozzles required 100 PSI for optimal nozzle operation, many smoothbore nozzles can operate well with as low as 50 PSI. This pressure differential is due to the nozzle construction. Smoothbore nozzles have a smaller orifice size, creating a higher velocity due to the acceleration created from the smaller cross-sectional area of the orifice. Fog nozzles on the other hand are designed to create chatter in the stream, which requires turbulence to be created in the stream. This is accomplished through obstructions in the waterway, such as groves in the nozzle shutoff, or various stems and springs. In order to create more turbulence, the water must be moving faster through the nozzle, which requires a higher pressure. Furthermore, there is a lesser degree of water acceleration due to the size of the orifice being a similar size to the coupling at the end of the nozzle.

Another shortfall for combination fog nozzles is the lack of debris clearance within these nozzles. Due to the various appliances and obstructions in the waterway, small objects that would normally be able to pass through a smoothbore nozzle will likely be retained in the fog nozzle. While many fog nozzles have a "flush" function in order to clear debris, it will not be successful in clearing all types of debris that may be found in a standpipe system. For example, open FDCs facilitate various materials to enter the standpipe, especially those in large urban areas. Some common examples of this debris can include: soda cans, tennis balls, cigarettes, rocks, and other rubbish. While a smoothbore nozzle will be unable to clear the larger debris, it is possible that items such as rocks and other smaller materials will be expelled without interruption. In order to clear debris from a fog nozzle, the stream must at least be changed to operate the flush pattern. If this effort is unsuccessful, the fog tip may be removed, depending on the nozzle type. However, if the shutoff and the fog tip are a singular device, then the standpipe valve must be closed so that the nozzle can be removed from the hose line. If a smoothbore nozzle is unable to pass debris normally, then the nozzle can be closed, and the smoothbore tip removed from the shutoff valve where more debris can be removed. As with fog nozzles, if this is unsuccessful, then the fire attack team must retreat and remove the nozzle from the hose line.

It should be stressed that shutting down a hose line is a dangerous situation for firefighters. To provide safety, firefighters must remove the hose line to an area of refuge, likely the stairwell in a high-rise building. This action will allow firefighters to work in a safe location, but it will also take them significantly longer for them to place the hose line back in a useable position. Firefighters should seek to avoid this situation at all costs, which is one of the reasons that using a smoothbore nozzle is a vital consideration when operating in standpipe equipped buildings.

Another more obvious benefit of using a smoothbore nozzle is that these nozzles are generally much lighter than fog nozzles. Due to the lack of internal components, smoothbore nozzles will typically weigh much less than fog nozzles. This differential may only be a few pounds, but when firefighters must climb dozens of flights of stairs, this is critical to ensuring the rapid ascent of firefighters as well as allowing them to be more rested upon arrival at the fire floor. This lighter weight also allows for firefighters to carry a second nozzle with them. Firefighters typically have a high-rise bag to carry with them consisting of various fittings and other appliances that are necessary when making standpipe connections. If the nozzles are light enough, then firefighters can carry a second nozzle with them that can be used in the case of a serious nozzle malfunction.

As mentioned previously, the lack of internal components makes these nozzles easier to maintain. One of the most significant maintenance tasks for smoothbore nozzles is simply to exercise the shutoff valve. Simply opening and closing the bail of the nozzle will ensure that the nozzle can open and close quickly to deliver water quickly and allow for firefighters to reposition the hose line, should it be needed. Fog nozzles on the other hand will need this same maintenance as well as ensuring that the fog tip is also lubricated, the stems are not damaged, and more. High-rise hose and nozzles are typically not used on an everyday basis, so it is imperative that they be both simple to maintain as well as rugged, which smoothbore nozzles are.

While fog nozzles are rather temperamental, smoothbore nozzles are very durable. While a fog nozzle can suffer a broken stem or other serious damage from something as simple as being dropped, smoothbore nozzles can be chipped and dropped from high distances and still function.

Again, this is due to the lack of internal components. Fog nozzles can be damaged when their springs or stems are damaged inside of the nozzle, where a smoothbore nozzle is generally only damaged when the shutoff valve is damaged. Smoothbore nozzles also typically have a rubber bumper on them to protect the removable smoothbore tip, whereas a fog nozzle does not. Overall, smoothbore nozzles are far more durable, which is a key consideration in high-rise firefighting operations.

The final advantage of using smoothbore nozzles that will be discussed is their cheaper purchase cost. As was previously mentioned, smoothbore nozzles are cheaper to maintain as well due to the fewer maintenance procedures that need to be conducted. Again, due to the lack of internal components, the smoothbore nozzle is easier to construct for nozzle manufacturers as well as cheaper. This means that fire departments can afford to equip their firefighters with more nozzles, so that firefighters can be better prepared by bringing a second nozzle when they fight a high-rise fire.

All of these advantages are well documented and well understood in the fire service. However, many fire departments are still using fog nozzles in high-rise environment for some key reasons that will be discussed in a following section.

5.3.4 Nozzle Comparison through Nozzle Reaction

Returning to the topic of nozzle reaction, it is important to note that the lower operating pressures of a smoothbore nozzle are an important way to reduce nozzle reaction. Brian Brush explains in an article, “The only way to alter nozzle reaction is to alter the volume [gallons per minute (gpm)] or the pressure (psi).” (Brush 1). He goes on to state later in the article that when comparing smoothbore nozzles and automatic fog nozzles, “Flowing the same gpm, there is a nozzle reaction difference of 21 pounds at 100 psi; at 150 gpm, the nozzle reaction of 76 pounds is at the working limit of two firefighters." (Brush 2). Again, in an era of lower fire department staffing, this is an important consideration that fire departments must make. This issue is also exacerbated in high-rise structures where it may take longer for firefighters to arrive at the fire floor.

5.3.5 Fire Departments Using Fog Nozzles in High-Rise Buildings

Many fire departments still choose to use fog nozzles in these buildings for several reasons. Some of these reasons include: the additional nozzle pattern options provided by fog nozzles, ability to perform hydraulic ventilation, having a surplus of fog nozzles, believing that smoothbore nozzles are inferior technology, traditional use, or not understanding the standpipe environment. This section will address some of these beliefs.

Fog nozzles do provide nozzle pattern options unlike smoothbores. However, solid streams from smoothbore nozzles can be broken by the movement of the nozzle to facilitate steam conversion. Fog nozzles can also perform hydraulic ventilation more efficiently as they can move a larger amount of air. However, opening the bail of smoothbore nozzles halfway will create a cone that can also move large amounts of air and combustion by products. The traditional method of hydraulic ventilation in the fire service also consists of covering the width of the window with a cone of water. However, this method was disproved recently in a UL FSRI study on air entrainment. This study held that it was more effective to move the stream as more air would be entrained. While hydraulic ventilation is something that should be considered when selecting a nozzle, it can be accomplished by using the correct technique or even through certain appliances such as a stream shaper that are specifically designed for this task.

Some fire departments also choose to use fog nozzles because it is the nozzle of choice for all operations. When fire departments purchase nozzles, they may simply purchase one type of nozzle to fulfill all of their needs. This “one size fits all” solution is certainly not the best and should be evaluated, especially when considering that the one-and-three-quarter-inch and automatic nozzle is a fire attack packaged that is better suited for trash or vehicle fires than structure fires. However, the lack of purchasing specialized nozzles for various tasks is also influenced by the final point discussed in this section.

The belief that smoothbore nozzles are also antiquated technology is also one that is prevalent in the fire service. There are some firefighters that believe that because the nozzle is not capable of other nozzle patterns, smoothbore nozzles should no longer be used in the fire service. However, the simplicity of this design is one of the reasons that the smoothbore has enjoyed such a long tenure in the fire service. These nozzles apply basic hydraulic principles rather than complex hardware that is found in combination fog nozzles. These nozzles have been dethroned as the most common nozzle in the fire service, but a large amount of fire departments are returning to smoothbore nozzles for these reasons.

As mentioned previously, the fire service embraces numerous traditions. While smoothbore nozzles were the traditional nozzle of choice in the fire service, many fire officers now choose fog nozzles. Many of these fire officers began their career during the 1980s, when fog nozzles were making their entry into the fire service. In fact, this period was known as the “fog frenzy.” Furthermore, many training drills that firefighting recruits endure involves them advancing two attack lines equipped with fog nozzles toward devices resembling Christmas trees that release propane gas. The objective of this drill is to use the stream of the fog nozzles to cool the ambient air so that the crews can advance toward the device to close the propane valve. While this objective is to demonstrate the protective ability of fog nozzles, the instances of propane tree fires are quite rare, meaning that this drill is stressed far more than it should be.

The final reason for using fog nozzles in a standpipe fire attack is that fire department policy writers may not understand the standpipe environment. While the criteria for standpipe systems, and even the suggested equipment is readily available in NFPA documents, these documents are rarely referenced by many fire departments. Some departments even hold the belief that NFPA stands for “Not for Practical Application,” rather than examining the standards that are presented by NFPA committees. Other firefighters also feel that they may have a better grasp on the information than the technical expert committees that formulate these documents. While this may be true in a few cases, it is generally false.

These are some of the reasons that the fire service choses to use fog nozzles even in high-rise buildings. While all of these different types of nozzles have very important applications in the fire service, the place for fog nozzles is not in high-rise buildings. While they provide more capabilities on many fires, there are many disadvantages to using these in high-rise buildings. Smoothbore nozzles should be used in high-rise buildings as often as possible for the reasons listed above.

6 Empirical Testing Data

6.1 Overview

In order to validate some of the information that was presented previously, empirical testing was conducted. This testing was conducted both to evaluate the flows comparing one-and-three-quarter-inch hose with two-and-a-half-inch hose. These tests were formatted with the goal of comparing the deployment times with the flows as well. The instrumentation that was used to evaluate this criteria, the parameters for the testing, and the data for the tests are all described below.

6.2 Testing Instrumentation

Various types of instrumentation were used to evaluate the deployment times and maneuverability of these hose lines. To measure the flow rate, an in-line pitot gage was coupled to the discharge of the engine. This gage read in PSI and was then included into a computer spreadsheet to calculate the gallons per minute flowed by the hose lines. Additionally, a stopwatch was used to measure the time that it took to flow a predetermined amount of water. A measuring wheel was also used to mark critical benchmarks which were noted with tape for the firefighting crew. Video and numerical data were taken from these tests. This data is presented below in the appendices.

6.3 Test Parameters

Several considerations were made to standardize these tests. First, the two firefighters that were involved in the hose line advance maintained the same positions on the hose line. Therefore, the firefighter operating the nozzle remained at the nozzle for each evolution and the firefighter assigned to the backup position remained in that position. The same operator remained at the pump panel for all evolutions to ensure that the crews were receiving the same pressure at all points throughout the experiments. The videographer and the data recorder also remained in their respective positions for all portions of the tests.

Three replicates of each test were run in order to establish a baseline while also examining any outliers. The two-and-a-half inch replicates were completed first, for several reasons. Two-and-a-half-inch hose is strongly supported in fire service publications, so it was deemed important to examine the benefits of this larger hose line. It was also determined that researchers could determine the flow that this hose size would provide so that the one-and-three-quarter inch hose could be estimated. This hose size was also chosen so that firefighters would be better rested for these early replicates that would be more physically demanding.

The one-and-three-quarter inch diameter hose was equipped with a 15/16-inch diameter smoothbore nozzle. This nozzle was chosen for its common use on this diameter hose line. This was also one of the few smoothbore nozzles that could be located at EKU. The two-and-a-half-inch diameter hose line was equipped with a 1 1/4-inch diameter nozzle for its superior flow and its use on this hose diameter.

Each test used three fifty-foot-long sections of hose. This hose was folded in a configuration known as the Denver hose load. Images of this hose pack can be seen in the appendix. This hose pack was chosen for its ease of deployment in the testing situation as well as its common use in the United States fire service. The same three sections of each hose diameter were used for all tests, but their orders were randomly rotated, meaning that the nozzle section during the first replicate of a certain test may next become the middle section and the last section could become the nozzle section. The following section will discuss the physical procedures done during each replicate.

The following table shows the order in which these replicates were conducted.

Testing Order	Hose Diameter Replicate Number
1.	2.5” Replicate #1
2.	2.5” Replicate #2
3.	2.5” Replicate #3
4.	1.75” Replicate #1
5.	1.75” Replicate #2
6.	1.75” Replicate #3

6.4 Testing Procedure

During each replicate of the tests, firefighters were wearing full turnout gear, with the exception of an air pack. The third firefighter in the evolution who doubled as the data recorder remained at the engine and therefore only wore a turnout coat and gloves. The two nozzle firefighters began the tests by coupling the nozzle, middle, and last sections together. The backup firefighter was also responsible for connecting the last hose section to the discharge equipped with the in-line pitot gauge. Once all of the hose packs were connected, the firefighters would advance away from the engine to a predetermined seventy-five feet. The nozzle firefighter took the nozzle with him to this point while the backup man grabbed the middle section of the middle hose pack and brought it to the seventy-five-foot mark. When the nozzle team approached the seventy-five-foot mark, the data recorder made sure to remove any folds that remained by the engine to ensure that there would be no kinks in the hose line. At this point, the nozzle firefighter called for the pump operator to fill the hose line with water. The pump operator was instructed to charge the hose line to a residual pressure of 60 PSI. The nozzle firefighter then opened the nozzle to remove any residual air from the stream and ensure that the hose line was filled with water. The firefighters then advanced the hose line twenty-five feet where they would drop to their knees to simulate advancing the hose line through a hot and smoky environment. For the final twenty-five feet, the firefighters then advanced the hose line while flowing water. The firefighters were instructed to advance the nozzle with the bail fully open to allow for the greatest amount of water to flow. However, it was expected that they would be unable to advance the two-and-a-half hose line with the bail fully open, so they were instructed to advance the line with the bail only halfway open to reduce the nozzle reaction. At the final mark of one hundred and fifty feet away from the pump, the firefighters were instructed to remain stationary and flow until the order was given from the data recorder to conclude the test.

Between replicates, the firefighters were instructed to relax and rest before the next replicate began. The data recorder and the videographer first “walked” the hose lines to empty them of water and then rolled them to remove any more water and air from the hose line before they were refolded into their Denver load configuration. The hose lines were then carried to the engine and placed so that the nozzle section was facing away from the engine and the female coupling of the last pack was placed closest to the engine to facilitate the hose stretch. The firefighters were then asked if they were rested and ready to begin the test. Once they were ready, all participants took their positions and prepared for the test to begin. After ensuring that all participants were prepared to carry out their duties and ready for the test to begin, the data recorder counted down and initiated the test and started the stopwatch.

6.5 1.75” Testing

This section and the following sections will only broadly describe the findings of the tests. They will not provide all relevant data, which can be found in the appendices. Rather, this section will describe the findings that will be discussed in the upcoming chapter which will describe the conclusions drawn from the literature review and this testing.

The three replicates utilizing one-and-three-quarter inch hose was actually conducted after the two-and-a-half-inch hose replicates, but they are discussed first due to their prevalence in the United States fire service.

This test did prove that one-and-three-quarter inch hose can be deployed rather quickly. Firefighters were able to reach the final point of the evolution in approximately ninety seconds for all three replicates. Despite being instructed not to run, during one replicate, a firefighter took much longer on making all of the coupling connections, so he ran to the seventy-five-foot mark to try and correct this error. Overall, the crews were consistently making their connections around thirty seconds after the test began and were able to advance the line and were flowing water between eighty and one hundred seconds.

In approximately five hundred seconds in each of these tests, the one-and-three-quarter inch hose line was able to flow approximately 670 gallons. This was an average value of all three replicates. For more information and more specific data, see Appendix D.

6.6 2.5" Testing

The two-and-a-half-inch hose data is included below in Appendix E. In summary, firefighters who were not nearly as familiar with this line were able to deploy it on an average of 10 seconds later than the one-and-three-quarter inch hose. The advantage of placing the one-and-three-quarter inch hose was negated in approximately thirty seconds on average. This hose line was able to flow approximately 1302 gallons of water in the same five hundred allotted seconds.

6.7 Testing Limitations

This testing was completed to evaluate deployment times for one-and-three-quarter-inch and two-and-a-half-inch hose. It did not seek to evaluate the maneuverability of these hose lines or the manpower required to use these hose lines in a fire environment. This testing also did not simulate crews advancing from a standpipe system.

Due to time and budgetary constraints, only three replicates of this test were attempted. It was determined that the firefighters should remain in the same positions for each of the evolutions so that they could be compared with the other replicates and possible variables were eliminated. If given more time for these experiments, it is desired that three to five replicates be completed for a series of firefighters to ensure that the skills and abilities of firefighters of different backgrounds be evaluated.

If conducted again, it is also important that these tests would be conducted to evaluate crew size as well as maneuvering around objects. It would also be important to measure nozzle reaction faced by firefighters operating this hose line.

Again, conducting these tests in an actual high-rise building would be extremely beneficial, but due to budgetary constraints, this is not a realistic goal. However, it would allow for some of the maneuverability challenges, such as stairwells, to be evaluated in addition to some of the hydraulic challenges of overcoming building elevation.

7 Conclusions

7.1 Overview

Now that it has been proven why these considerations are so important and the data has been presented, conclusions will be drawn from the established literature as well as from the physical testing that was conducted.

7.2 Hose and Nozzle Use

As stated earlier, the main focus of this report was to determine the correct hose and nozzle to be used for high-rise fire attack. Through a literature review as well as the testing discussed in the previous chapter, the conclusions are drawn below.

7.2.1 Hose Line Justification

Despite the physical testing that was employed for this report, hose line selection remains somewhat subjective. Fire departments should use the data presented in the appendices as well as the other discussion presented above to choose the fire attack package that best fits their district as well as their firefighters. If a fire department is expecting to encounter structures that are more difficult to navigate, it should consider a smaller hose for increased maneuverability.

This report was able to disprove the belief that it takes too much time to deploy a two-and-a-half-inch hose line, as the two firefighters were able to deploy the line in an average of only ten seconds longer than it took to deploy the smaller one-and-three-quarter-inch hose line. While this is only a small sample of data, it shows that this argument should be examined further.

The empirical testing was unfortunately unable to examine any two-inch hose. This diameter hose line is becoming increasingly common in the fire service, especially in high-rise applications. The two-inch hose is becoming more common because it is able to provide a very similar maneuverability to one-and-three-quarter-inch hose while providing a flow similar to that of a two-and-a-half-inch hose. Therefore, the two-inch hose may be an ideal choice for a high-rise fire attack hose, but this project was unable to quantify two-inch deployment times or flow.

7.2.2 Nozzle Justification

Smoothbore nozzles should be used in high-rise fire attack for all of the reasons listed above. Fog nozzles were not examined in this report due to the numerous benefits of using a smoothbore nozzle. In addition to significantly reducing potential problems with water application, the operation of these nozzles is much easier. Because these nozzles do not have as many functions as fog nozzles, it is also easier to calculate the flow provided by these nozzles. Being able to easily obtain this information is vital for firefighters in the challenging high-rise environments encountered by firefighters.

While it may be smart for fire departments to include a fog nozzle in their high-rise appliance bags to be used for overhaul or hydraulic ventilation operations after a majority of the fire has been extinguished, smoothbore nozzles are the only nozzles that should be used for fire attack from standpipe systems.

7.3 Fire Service Tactics: Engine Companies vs. Truck Companies

While various fire service traditions have been mentioned throughout the course of this paper, one of the most common is the distinction between different companies. In most fire departments, the terms fire engine and fire truck are not interchangeable. Fire apparatus that carry hoses, water, and other appliances are known as fire engines while trucks that carry tall aerial ladders and other equipment are known as fire trucks. While there are other types of apparatus such as rescue squads, water tenders, and other specialized apparatus, engine and truck companies are the most common. There are also apparatus that carry both large aerial devices as well as water, but these apparatus are generally used as truck companies, depending on the fire department's policies.

Because of the water and equipment carried by engine companies, they are responsible for applying water to the fire while truck companies are responsible for a myriad of other tasks including ventilation and search and rescue to name a few. While all of these truck company tasks are important, these tasks are done to support engine companies. Due to the difficulty of putting hose lines into position in a fire environment, tasks such as finding the fire for the engine companies are typically done by truck companies.

In high-rise buildings, staffing becomes an important issue, as mentioned previously. Many fire service instructors have stated that it may take as many as eight firefighters to put a single hose line in service. While most crews carry four or fewer personnel, this can equate to two companies needed to put one hose line in service. Rather than waiting for a second engine company to arrive, the fire service should examine using truck companies to facilitate an initial hose stretch. While truck company tasks are important, the most efficient manner to protect life and property in high-rise fires is to extinguish the fire, as mentioned in prior chapters. Many fire departments have gone to systems that involve pairing two engine companies and one truck company together to form a “fire attack group.” This tactic should be considered by other fire departments. Training exercises should be conducted before these tactics are utilized on an actual working incident, but they may prove to be extremely beneficial.

While policy could easily be adapted by fire departments simply by altering the wording in some of their policies and procedures, it is in staunch opposition to tradition. For example, many fire departments steeped in tradition greatly dissuade members on truck companies from touching hose lines. This sentiment has led to significant problems on the fire scenes when truck crews have walked past a kinked hose line, resulting in significant problems for crews.

Overall, truck companies need to recognize that their tasks, while important, are all to support engine company operations. Therefore, if an engine company is experiencing difficulties, or is unable to conduct their basic tasks, truck crews should readily assist.

7.4 A Final Note on Purpose

It should be noted that this report should not be viewed as the final word on high-rise fire attack. Rather, this is to provide firefighters another tool in their toolbox. Firefighters need to be able to understand their environments and their equipment. It is this lack of understanding of the fire environment and equipment that often leads to firefighter injuries and deaths.

Especially in high-rise buildings, the difficulty of extinguishing these fires increases exponentially as does the importance of suppressing the fire. Firefighters cannot operate in their normal roles during these fires, as the environment is radically different from single family dwellings.

This report remains valid for firefighters who do not have high-rise buildings in their response area, due to its use of basic hydraulic principles. As mentioned previously, this study sought to examine high-rise buildings due to the considerations that must be made when fighting fires from standpipe systems. These systems can be a perfect resource for firefighters, but it can also greatly complicate the intricate high-rise fire environment.

It is the hope of this report that firefighters, fire protection engineers, and fire protection system designers and installers will be able to understand the vital roles that many of these fire protection systems have in the environment. When this knowledge is coupled with building-specific information, firefighters will be able to save more lives and property while remaining safer themselves.

7.5 Potential Future Studies

As stated in a previous section of this chapter, two-inch hose should be examined. This hose may prove to be the perfect choice for high-rise environments due to its maneuverability, but it also suffers from a lower flow than the two-and-a-half-inch hose.

Future tests could also examine how easily these hoses are deployed when there are objects in the way. For lower staffing levels, crews will need to be more efficient when they advance hose lines. Due to the increased difficulty of this evolution, it would likely take crews longer to stretch the larger diameter hose lines due to the weight of the hose lines. This delay could increase the usefulness of smaller diameter hose lines.

Many fire departments will continue to use fog nozzles, despite results drawn in in this paper or established best practices. Therefore, these tests could be repeated again to evaluate the use of fog nozzles in these types of structures and with these fire protection systems.

Finally, it would be quite valuable to repeat these tests in more realistic environments. The testing ground could change to include burn buildings, mid-rise, or high-rise buildings. These tests could also be run in a live fire environment. While this test would include substantially more instrumentation so that the volume of fire extinguished by these attack lines would be measured, it would provide a plethora of practically applicable data. However, this data could be skewed by an infinite number of variables including the nozzle pattern employed by firefighters. It would also be quite difficult to obtain structures in which to conduct these live fire tests.

Overall, there is much more work that can be conducted in these areas. More information is needed so that firefighters can make important decisions both in critical planning stages as well as during an incident. This research only answers a very small portion of this discussion, but it is a vital one when fire departments are attempting to determine the best way to apply water in these environments to extinguish fires to accomplish the goals of safeguarding life and property.

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9 Appendices

9.1 Appendix A: Required Water Flow Calculations

Energy absorbed by 1 Kg of Water

$$\left(\frac{4.181\ KJ}{KgK}\right)(80K) = 334.48\frac{KJ}{Kg}$$

Residential Occupancy

Water needed to absorb all energy

$$2MW = \frac{2000KJ/s}{334.48\ KJ/Kg} = 5.98\frac{Kg}{s}$$

7/8” nozzle, common for 1 ½” hose lines

$$\dot{m} = 161\ gpm\ (from\ Elkhart\ Brass\ @50\ PSI)$$

$$\frac{161\ gallons}{1\ minute}\left(\frac{1\ min}{60\ s}\right)\left(\frac{3.78\ L}{1\ gallon}\right)\left(\frac{1\ Kg}{1L}\right) = 10.143\ \frac{Kg}{s}$$

Commercial Occupancy

Water application rate

$$6.72\ MW = \frac{6719.7\ KJ/s}{224.48\ KJ/Kg} = 20.09\frac{Kg}{s}$$

1 ¼” Nozzle, common for 2 ½” hose lines

$$\dot{m} = 322\ gpm\ (from\ Elkhart\ Brass\ @46\ PSI)$$

$$\frac{322\ gallons}{1\ minute}\left(\frac{1\ min}{60\ s}\right)\left(\frac{3.78\ L}{1\ gallon}\right)\left(\frac{1\ Kg}{1L}\right) = 20.3125\frac{Kg}{s}$$

9.1 Appendix B: Elkhart Brass Flow Chart

TECHNICAL DATA

SMOOTH BORE DISCHARGE

DISCHARGE OF SMOOTH BORE NOZZLES/TIPS

Nozzle Pressure in psi*	Nozzle Diameter In Inches																				
	1/4"	3/8"	7/16"	1/2"	5/8"	3/4"	7/8"	15/16"	1"	1 1/16"	1 1/8"	1 3/16"	1 1/4"	1 3/8"	1 1/2"	1 5/8"	1 3/4"	1 7/8"	2"	2 1/4"	2 1/2"	3"
	Gallons Per Minute																					
20	8	19	25	33	52	75	102	117	133	150	168	187	208	251	299	351	407	467	531	672	830	1195
22	9	20	27	35	54	78	107	122	139	157	176	196	218	263	313	368	427	490	557	705	871	1254
24	9	20	28	36	57	82	111	128	145	164	184	205	227	275	327	384	446	512	582	737	909	1309
26	9	21	29	38	59	85	116	133	151	171	192	214	237	286	341	400	464	532	606	767	947	1363
28	10	22	30	39	61	88	120	138	157	177	199	222	246	297	354	415	481	553	629	796	982	1414
30	10	23	31	41	64	92	125	143	163	184	206	229	254	308	366	430	498	572	651	824	1017	1464
32	11	24	32	42	66	95	129	148	168	190	213	237	263	318	378	444	515	591	672	851	1050	1512
34	11	24	33	43	68	97	133	152	173	196	219	244	271	327	390	457	530	609	693	877	1082	1559
36	11	25	34	45	70	100	136	157	178	201	226	251	278	337	401	471	546	626	713	902	1114	1604
38	11	26	35	46	72	103	140	161	183	207	232	258	286	346	412	483	561	644	732	927	1144	1648
40	12	26	36	47	73	106	144	165	188	212	238	265	293	355	423	496	575	660	751	951	1174	1691
42	12	27	37	48	75	108	147	169	192	217	244	271	301	364	433	508	589	677	770	974	1203	1732
44	12	28	38	49	77	111	151	173	197	222	249	278	308	372	443	520	603	693	788	997	1231	1773
46	13	28	39	50	79	113	154	177	201	227	255	284	315	381	453	532	617	708	806	1020	1259	1813
48	13	29	39	51	80	116	158	181	206	232	260	290	322	389	463	543	630	723	823	1042	1286	1852
50	13	30	40	53	82	118	161	185	210	237	266	296	328	397	473	555	643	738	840	1063	1313	1890
52	13	30	41	54	84	120	164	188	214	242	271	302	335	405	482	566	656	753	857	1084	1339	1928
54	14	31	42	55	85	123	167	192	218	246	276	308	341	413	491	576	668	767	873	1105	1364	1964
56	14	31	43	56	87	125	170	195	222	251	281	313	347	420	500	587	681	781	889	1125	1389	2000
58	14	32	43	57	88	127	173	199	226	255	286	319	353	428	509	597	693	795	905	1145	1414	2036
60	14	32	44	58	90	129	176	202	230	260	291	324	359	435	518	607	705	809	920	1165	1438	2070
62	15	33	45	58	91	132	179	206	234	264	296	330	365	442	526	618	716	822	935	1184	1462	2105
64	15	33	45	59	93	134	182	209	238	268	301	335	371	449	535	627	728	835	950	1203	1485	2138
66	15	34	46	60	94	136	185	212	241	272	305	340	377	456	543	637	739	848	965	1221	1508	2172
68	15	34	47	61	96	138	188	215	245	276	310	345	383	463	551	647	750	861	980	1240	1531	2204
70	16	35	48	62	97	140	190	218	248	281	314	350	388	470	559	656	761	874	994	1258	1553	2236
72	16	35	48	63	98	142	193	221	252	284	319	355	394	476	567	665	772	886	1008	1276	1575	2268
74	16	36	49	64	100	144	196	225	255	288	323	360	399	483	575	675	782	898	1022	1293	1597	2299
76	16	36	50	65	101	146	198	228	259	292	328	365	405	490	583	684	793	910	1036	1311	1618	2330
78	16	37	50	66	102	148	201	231	262	296	332	370	410	496	590	693	803	922	1049	1328	1639	2361
80	17	37	51	66	104	149	203	233	266	300	336	375	415	502	598	701	814	934	1063	1345	1660	2391
82	17	38	51	67	105	151	206	236	269	304	340	379	420	508	605	710	824	946	1076	1362	1681	2421
84	17	38	52	68	106	153	208	239	272	307	345	384	425	515	612	719	834	957	1089	1378	1701	2450
86	17	39	53	69	108	155	211	242	275	311	349	388	430	521	620	727	843	968	1102	1394	1721	2479
88	17	39	53	70	109	157	213	245	279	315	353	393	435	527	627	736	853	979	1114	1410	1741	2507
90	18	40	54	70	110	158	216	248	282	318	357	397	440	533	634	744	863	991	1127	1426	1761	2536
92	18	40	55	71	111	160	218	250	285	322	361	402	445	539	641	752	872	1002	1139	1442	1780	2564
94	18	40	55	72	112	162	220	253	288	325	364	406	450	544	648	760	882	1012	1152	1458	1800	2592
96	18	41	56	73	114	164	223	256	291	329	368	410	455	550	655	768	891	1023	1164	1473	1819	2619
98	18	41	56	74	115	165	225	258	294	332	372	415	459	556	662	776	900	1034	1176	1488	1838	2646
100	19	42	57	74	116	167	227	261	297	335	376	419	464	562	668	784	910	1044	1188	1504	1856	2673
105	19	43	58	76	119	171	233	267	304	344	385	429	476	575	685	804	932	1070	1217	1541	1902	2739
110	19	44	60	78	122	175	238	274	311	352	394	439	487	589	701	823	954	1095	1246	1577	1947	2803
115	20	45	61	80	124	179	244	280	318	360	403	449	498	602	717	841	975	1120	1274	1612	1991	2866
120	20	46	62	81	127	183	249	286	325	367	412	459	508	615	732	859	996	1144	1301	1647	2033	2928
125	21	47	64	83	130	187	254	292	332	375	420	468	519	628	747	877	1017	1167	1328	1681	2075	2989
130	21	48	65	85	132	190	259	298	339	382	429	478	529	640	762	894	1037	1191	1355	1714	2116	3048
135	22	49	66	86	135	194	264	303	345	390	437	487	539	652	776	911	1057	1213	1380	1747	2157	3106
140	22	49	67	88	137	198	269	309	351	397	445	496	549	664	791	928	1076	1235	1406	1779	2196	3163
145	22	50	68	89	140	201	274	314	358	404	453	504	559	676	805	944	1095	1257	1431	1811	2235	3219
150	23	51	70	91	142	205	278	320	364	411	460	513	568	688	818	961	1114	1279	1455	1841	2273	3274
175	25	55	75	98	153	221	301	345	393	444	497	554	614	743	884	1037	1203	1381	1572	1989	2456	3536
200	26	59	80	105	164	236	322	369	420	474	532	592	656	794	945	1109	1286	1477	1680	2126	2625	3780

* Nozzle pressure measured by pitot tube and gauge.

FORMULA FOR DISCHARGE OF SMOOTH BORE NOZZLES:

$$GPM = 29.71\, d^2 \sqrt{NP}$$

GPM = Gallons per minute

29.71 = Constant

d = Diameter of nozzle orifice (inches)

NP = Nozzle pressure (psi) measured by pitot tube and gauge

9.2 Appendix C: Water Weight Calculations

$$A = \frac{\pi d^2}{4}$$
$$V = A * l$$
$$Weight = V * 7.48\ \frac{gal}{ft^3} * 8.345\ \frac{lb}{gal}$$

1.5” Hose

$$A = \frac{\pi .125ft^2}{4} = .01227\ ft^2$$
$$V = .01227ft^2 * 50\ ft = .6134ft^3$$
$$Weight = .6134ft^3 * 7.48\ \frac{gal}{ft^3} * 8.345\ \frac{lb}{gal} = 38.300\ lb$$

1.5” Hose= 38.300 lb per 50’, 114.902 lb per 150’

1.75” Hose

$$A = \frac{\pi .145ft^2}{4} = .01670\ ft^2$$
$$V = .01670ft^2 * 50\ ft = .8352ft^3$$
$$Weight = .8352ft^3 * 7.48\ \frac{gal}{ft^3} * 8.345\ \frac{lb}{gal} = 52.100\ lb$$

1.75” Hose= 52.100 lb per 50’, 156.301 lb per 150’

2” Hose

$$A = \frac{\pi .166ft^2}{4} = .02182\ ft^2$$
$$V = .02182ft^2 * 50\ ft = 1.0908ft^3$$
$$Weight = 1.0908ft^3 * 7.48\ \frac{gal}{ft^3} * 8.345\ \frac{lb}{gal} = 68.090\ lb$$

2” Hose= 68.090 lb per 50’, 204.270 lb per 150’

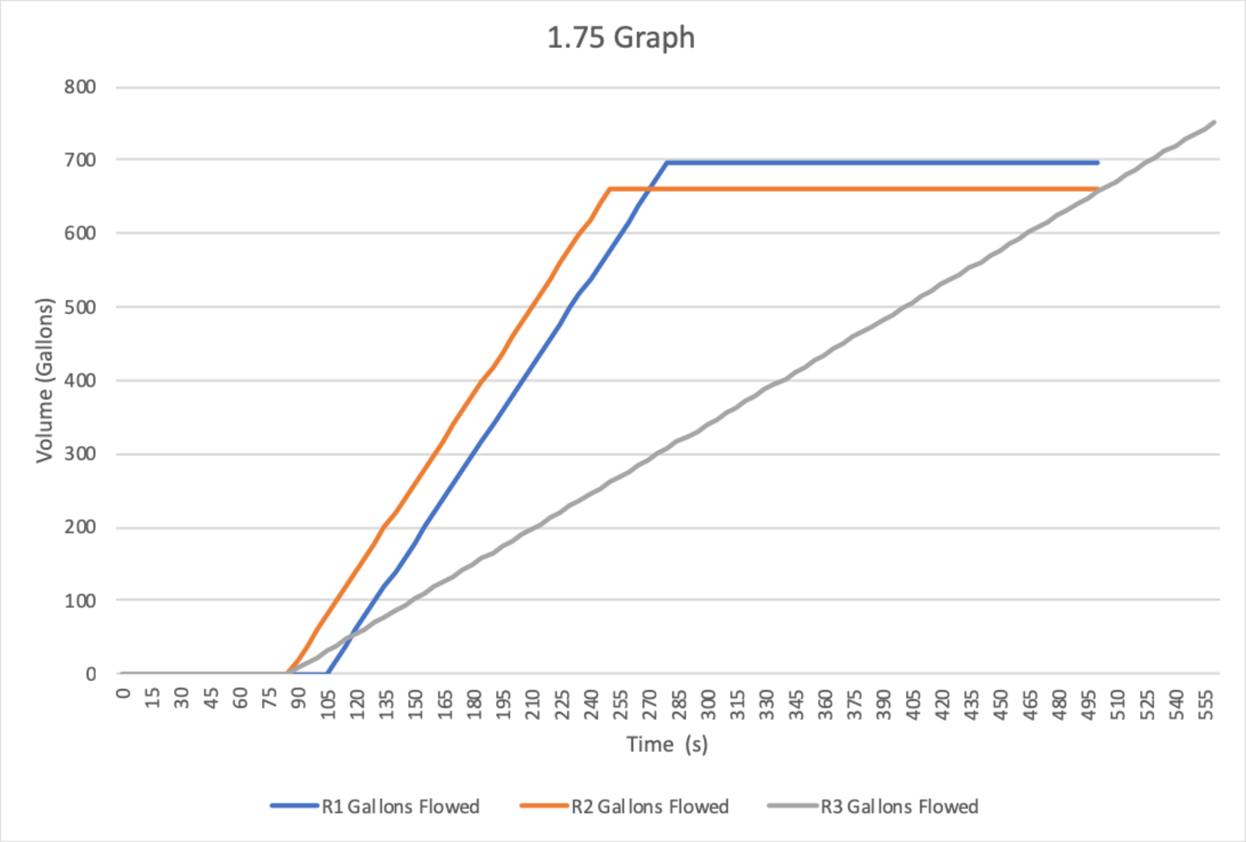
2.5” Hose

$$A = \frac{\pi .208ft^2}{4} = .0341\ ft^2$$
$$V = .0341ft^2 * 50\ ft = 1.7044ft^3$$
$$Weight = 1.7044ft^3 * 7.48\ \frac{gal}{ft^3} * 8.345\ \frac{lb}{gal} = 106.391\ lb$$

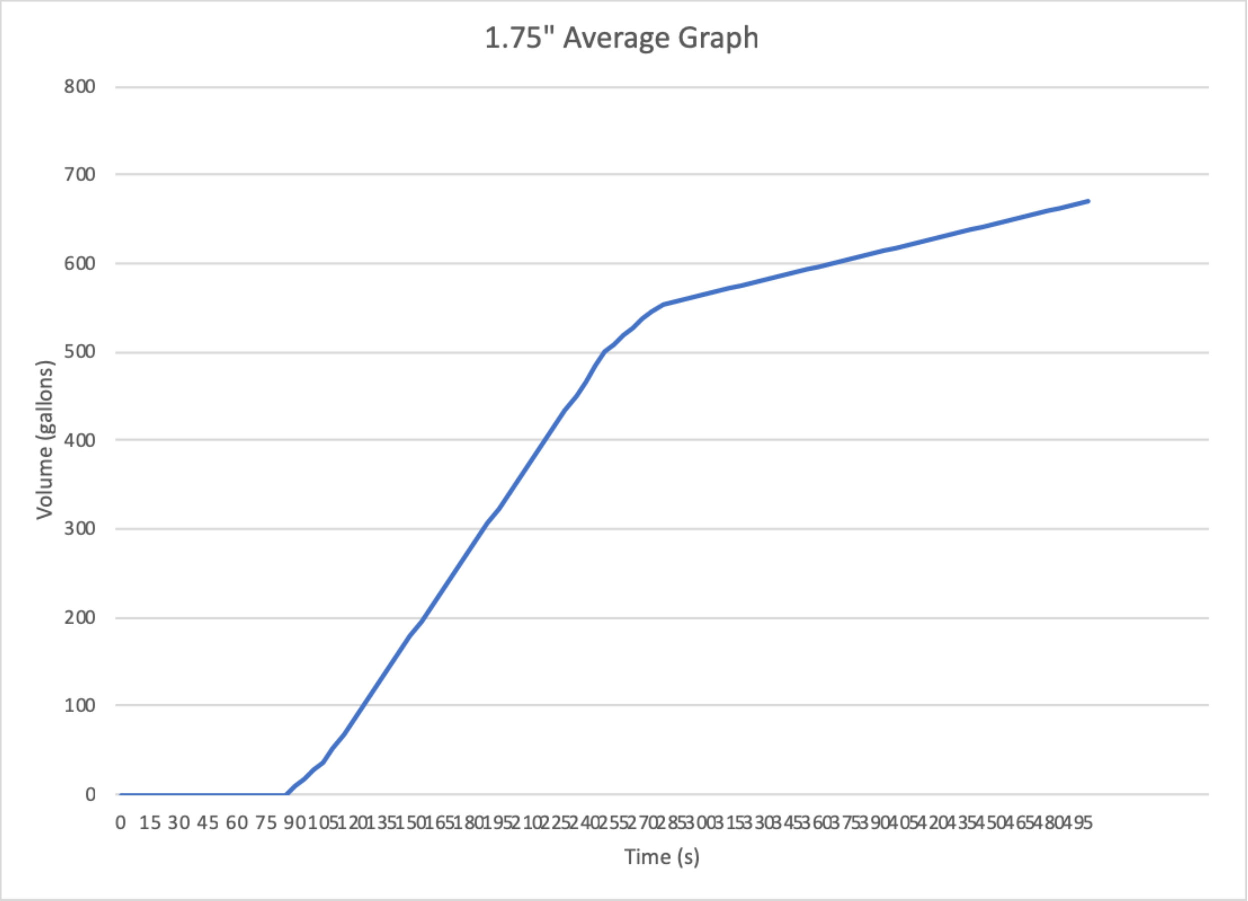
2.5” Hose= 106.39 lb per 50’, 319.173 lb per 150’

9.3 Appendix D: 1.75” Data

9.3.1 Individual Graph



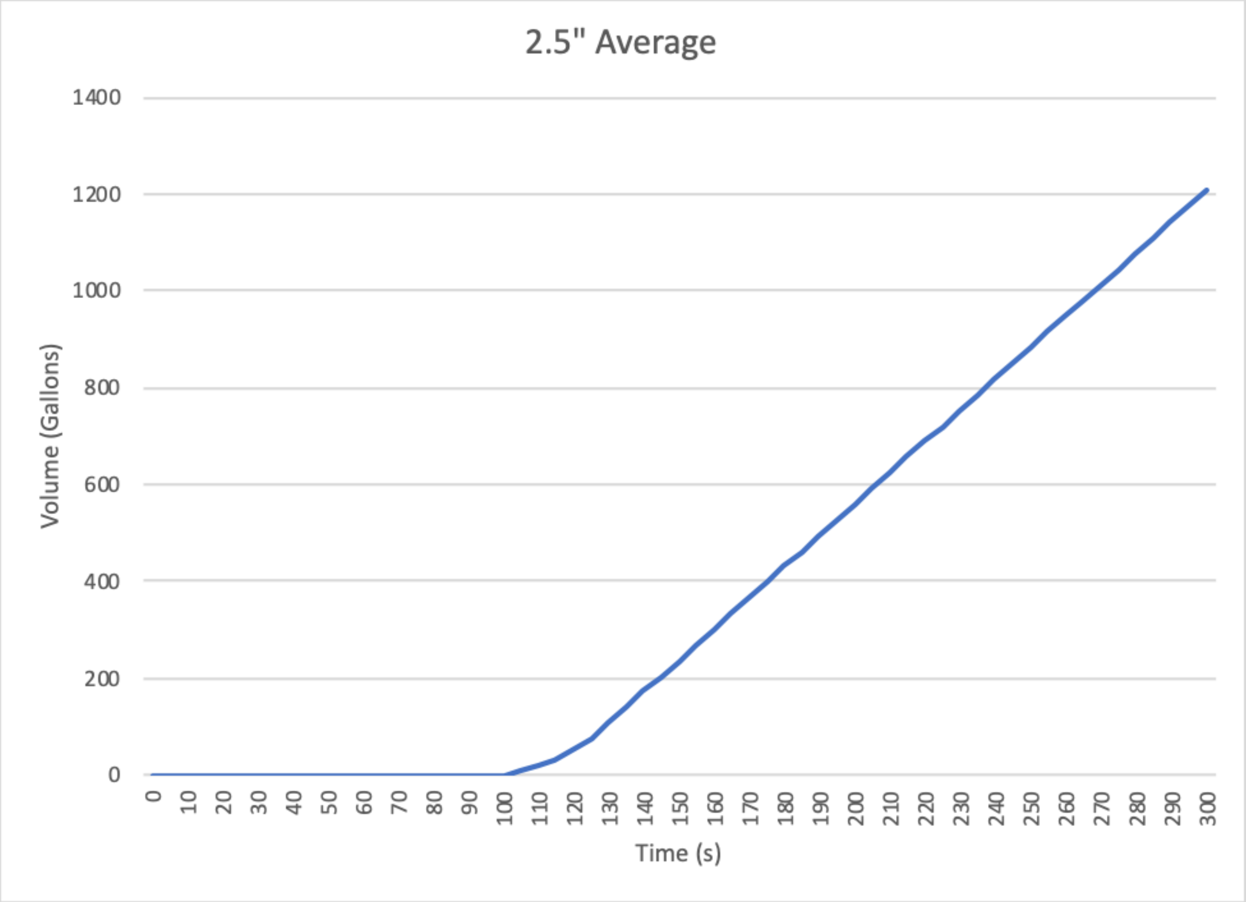
9.3.2 Average Graph



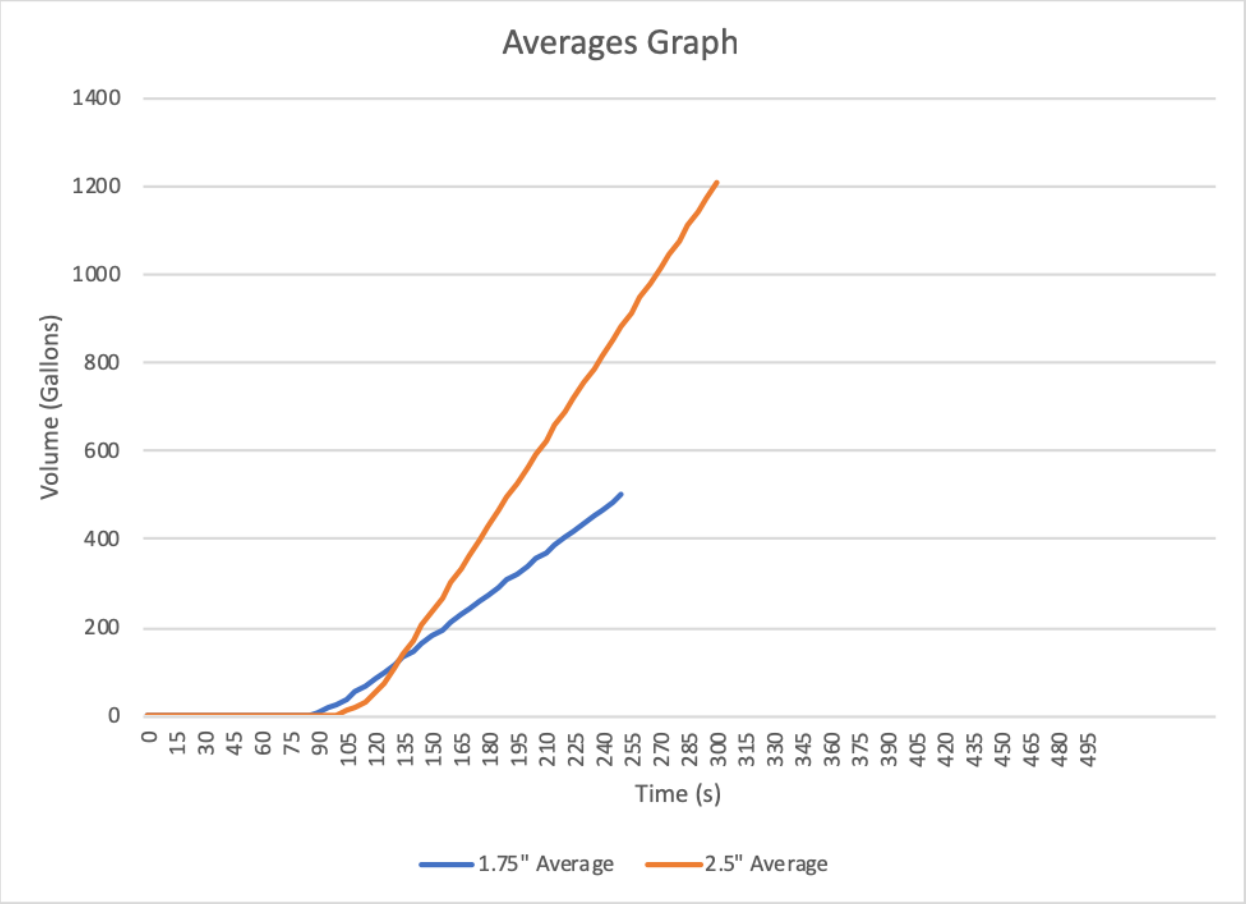
9.4 Appendix E: 2.5” Data

9.4.1 Individual Graph

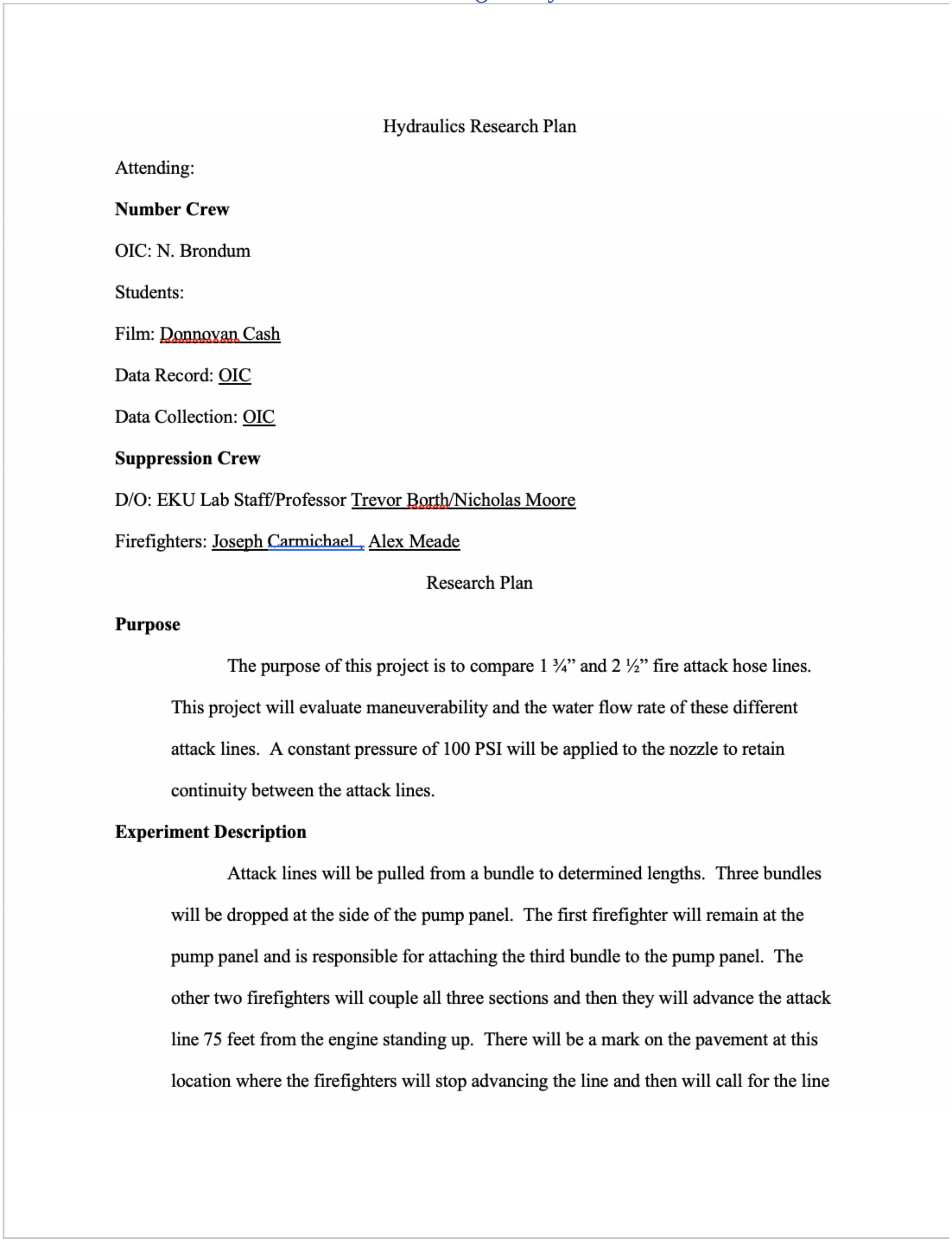
9.4.2 Average Graph



9.5 Appendix F: Average Comparison Graph



9.6 Testing Safety Plan



Hydraulics Research Plan

Attending:

Number Crew

OIC: N. Brondum

Students:

Film: Donnovan Cash

Data Record: OIC

Data Collection: OIC

Suppression Crew

D/O: EKU Lab Staff/Professor Trevor Borth/Nicholas Moore

Firefighters: Joseph Carmichael , Alex Meade

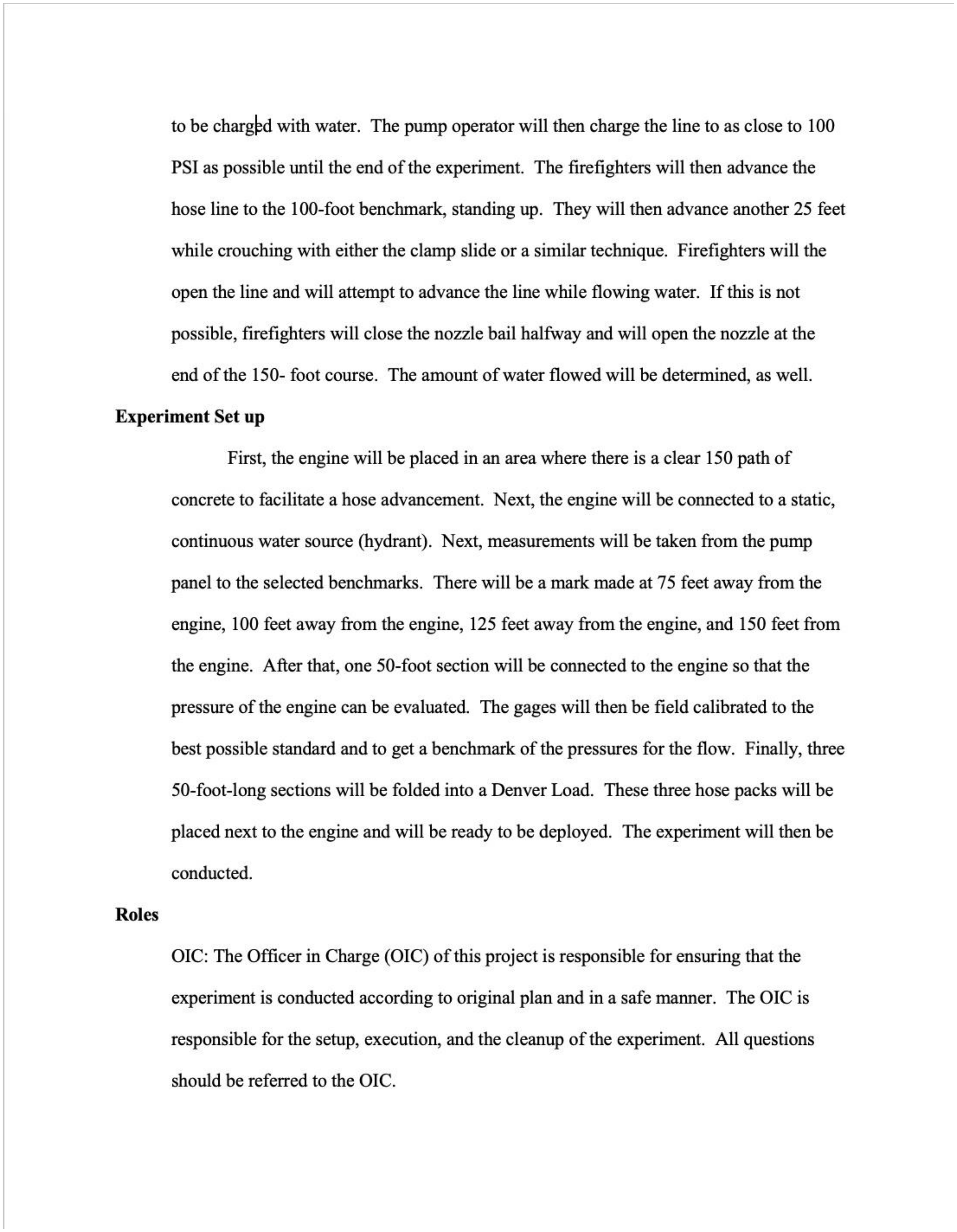
Research Plan

Purpose

The purpose of this project is to compare 1 ¾" and 2 ½" fire attack hose lines. This project will evaluate maneuverability and the water flow rate of these different attack lines. A constant pressure of 100 PSI will be applied to the nozzle to retain continuity between the attack lines.

Experiment Description

Attack lines will be pulled from a bundle to determined lengths. Three bundles will be dropped at the side of the pump panel. The first firefighter will remain at the pump panel and is responsible for attaching the third bundle to the pump panel. The other two firefighters will couple all three sections and then they will advance the attack line 75 feet from the engine standing up. There will be a mark on the pavement at this location where the firefighters will stop advancing the line and then will call for the line



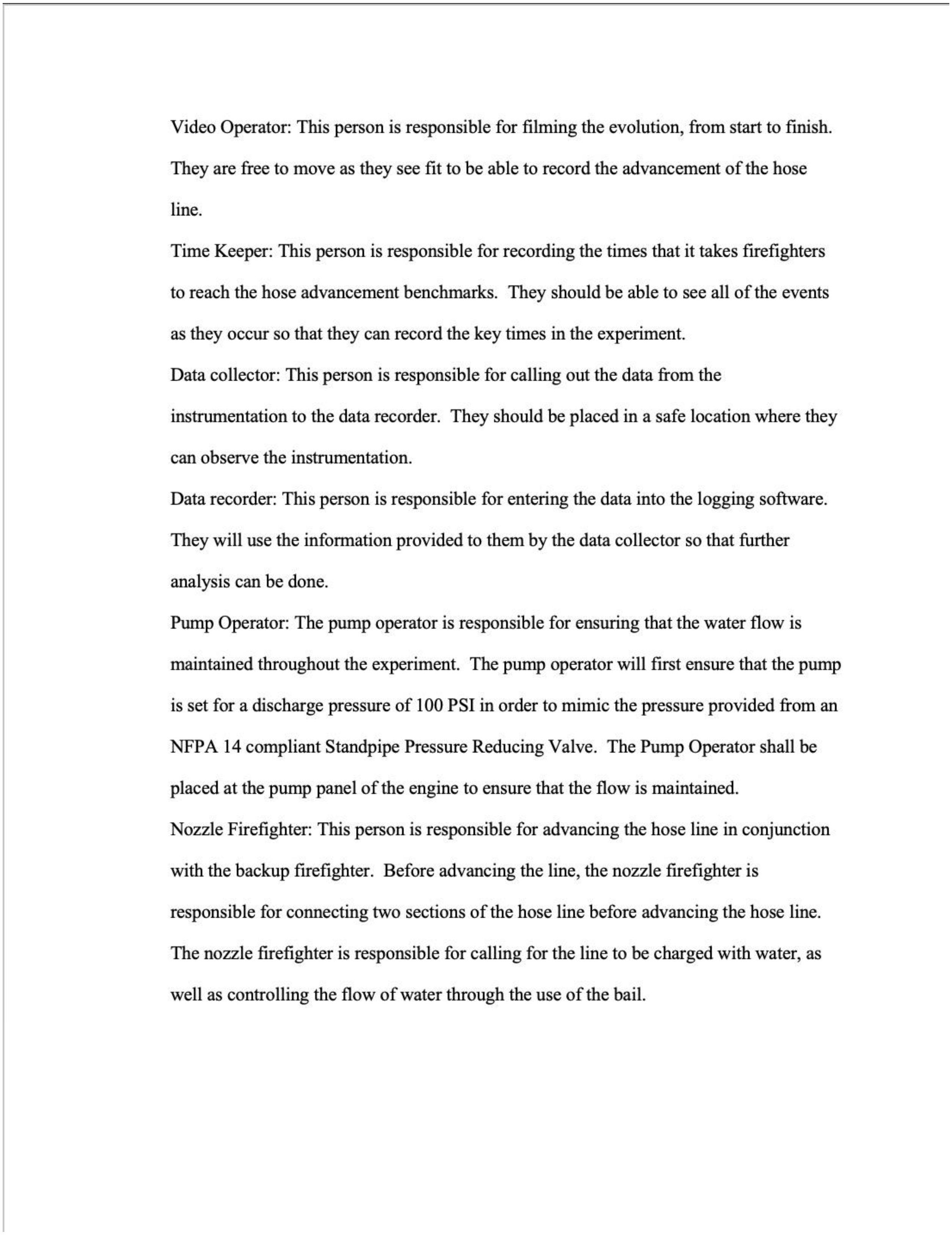
to be charged with water. The pump operator will then charge the line to as close to 100 PSI as possible until the end of the experiment. The firefighters will then advance the hose line to the 100-foot benchmark, standing up. They will then advance another 25 feet while crouching with either the clamp slide or a similar technique. Firefighters will the open the line and will attempt to advance the line while flowing water. If this is not possible, firefighters will close the nozzle bail halfway and will open the nozzle at the end of the 150- foot course. The amount of water flowed will be determined, as well.

Experiment Set up

First, the engine will be placed in an area where there is a clear 150 path of concrete to facilitate a hose advancement. Next, the engine will be connected to a static, continuous water source (hydrant). Next, measurements will be taken from the pump panel to the selected benchmarks. There will be a mark made at 75 feet away from the engine, 100 feet away from the engine, 125 feet away from the engine, and 150 feet from the engine. After that, one 50-foot section will be connected to the engine so that the pressure of the engine can be evaluated. The gages will then be field calibrated to the best possible standard and to get a benchmark of the pressures for the flow. Finally, three 50-foot-long sections will be folded into a Denver Load. These three hose packs will be placed next to the engine and will be ready to be deployed. The experiment will then be conducted.

Roles

OIC: The Officer in Charge (OIC) of this project is responsible for ensuring that the experiment is conducted according to original plan and in a safe manner. The OIC is responsible for the setup, execution, and the cleanup of the experiment. All questions should be referred to the OIC.



Video Operator: This person is responsible for filming the evolution, from start to finish. They are free to move as they see fit to be able to record the advancement of the hose line.

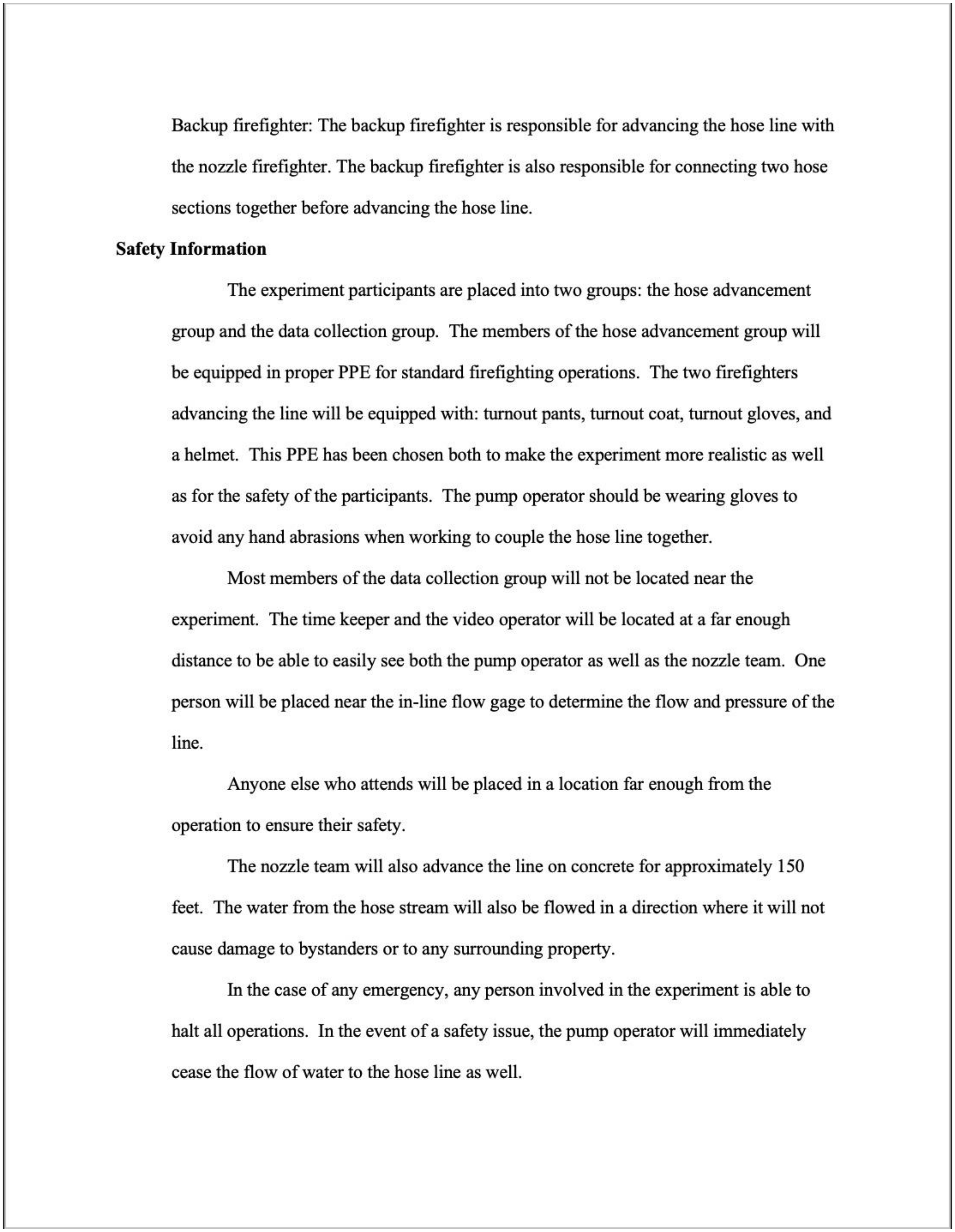
Time Keeper: This person is responsible for recording the times that it takes firefighters to reach the hose advancement benchmarks. They should be able to see all of the events as they occur so that they can record the key times in the experiment.

Data collector: This person is responsible for calling out the data from the instrumentation to the data recorder. They should be placed in a safe location where they can observe the instrumentation.

Data recorder: This person is responsible for entering the data into the logging software. They will use the information provided to them by the data collector so that further analysis can be done.

Pump Operator: The pump operator is responsible for ensuring that the water flow is maintained throughout the experiment. The pump operator will first ensure that the pump is set for a discharge pressure of 100 PSI in order to mimic the pressure provided from an NFPA 14 compliant Standpipe Pressure Reducing Valve. The Pump Operator shall be placed at the pump panel of the engine to ensure that the flow is maintained.

Nozzle Firefighter: This person is responsible for advancing the hose line in conjunction with the backup firefighter. Before advancing the line, the nozzle firefighter is responsible for connecting two sections of the hose line before advancing the hose line. The nozzle firefighter is responsible for calling for the line to be charged with water, as well as controlling the flow of water through the use of the bail.



Backup firefighter: The backup firefighter is responsible for advancing the hose line with the nozzle firefighter. The backup firefighter is also responsible for connecting two hose sections together before advancing the hose line.

Safety Information

The experiment participants are placed into two groups: the hose advancement group and the data collection group. The members of the hose advancement group will be equipped in proper PPE for standard firefighting operations. The two firefighters advancing the line will be equipped with: turnout pants, turnout coat, turnout gloves, and a helmet. This PPE has been chosen both to make the experiment more realistic as well as for the safety of the participants. The pump operator should be wearing gloves to avoid any hand abrasions when working to couple the hose line together.

Most members of the data collection group will not be located near the experiment. The time keeper and the video operator will be located at a far enough distance to be able to easily see both the pump operator as well as the nozzle team. One person will be placed near the in-line flow gage to determine the flow and pressure of the line.

Anyone else who attends will be placed in a location far enough from the operation to ensure their safety.

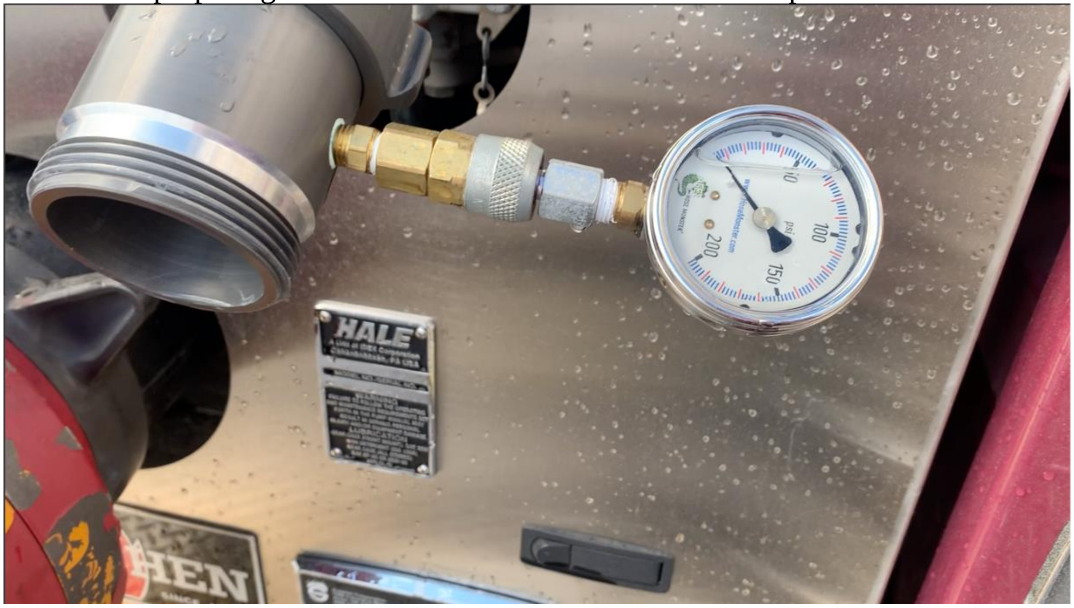
The nozzle team will also advance the line on concrete for approximately 150 feet. The water from the hose stream will also be flowed in a direction where it will not cause damage to bystanders or to any surrounding property.

In the case of any emergency, any person involved in the experiment is able to halt all operations. In the event of a safety issue, the pump operator will immediately cease the flow of water to the hose line as well.

9.7 Testing Hose and Nozzle Systems Images

9.7.1 General Images

Researcher preparing two-and-a-half-inch hose for another replicate.



In-Line Pitot Gage used to measure pressure to determine flow.

9.7.2 In-Progress Images

Firefighters making their initial connections on a one-and-three-quarter-inch replicate.

Firefighters advancing two-and-a-half-inch hose dry while standing.

Firefighters advancing charged two-and-a-hal- inch hose while standing.

Firefighters advancing two-and-a-half-inch hose while crawling.

Firefighters attempt to advance a two-and-a-half-inch hose while flowing.

Firefighters flow the two-and-a-half hose after advancing it.

9.7.3 Hose Bundles

One-and-three-quarter-inch hose bundles before being deployed.

Three fifty-foot long sections of hose in the Denver Load prepared for the next replicate.