


Study of the Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival

Part I: Air Entrainment and Water Distribution

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In order to better design and implement the experiments for the Fire Attack study, UL - FSRI has gathered a group of fire service experts from across the world with knowledge in fire suppression and the impact of interior and exterior fire streams. The individuals below provided direction for the project, assisting in planing the experiments, witnessing the testing, and developing concrete conclusions. Their tireless support and effort make this project relevant to the fire service across the world.

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Chad Green	Anchorage Fire Department
Chad Christensen	Los Angeles County Fire Department
Dennis Legear	Oakland Fire Department
Tony Carroll	Washington DC Fire Department
Jordan Mohr	Sedgwick County Fire District 1
Samuel Hittle	Wichita Fire Department
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Matt Carrigan	Montgomery County Fire and Rescue Service
Kelly Hanink	Eden Prairie Fire Department
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Jerry Knapp	West Haverstraw (NY) Fire Department
Ray McCormack	Fire Department of New York
Jacob Hoffman	Toledo Fire/Rescue Department
Steve Pegram	Goshen Township Fire and EMS
Danny Doyle	Pittsburgh Fire Department
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John McDonough	New South Wales Fire Department
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Fire Service Technical Panel

Abstract

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

This study will build and expand upon the fire research conducted to date by analyzing how firefighting tactics, specifically suppression methods, affect the thermal exposure and survivability of both firefighters and buidling occupants in addition to impacting fire behavior in structures. The purpose of this study is to improve firefighter safety, fireground tactics, and the knowledge of fire dynamics by providing the fire service with credible scientific information, developed from both water flow and full-scale fire testing, in representative single family homes. The project will be comprised of 3 parts:

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

This report details the results and analysis from the air entrainment and water distribution experiments. These tests were conducted without the presence of fire in order to gain a basic understanding of air flow and water flow before Parts II and III of the study were conducted as full-scale fire experiments. Each test was designed to quantify the air entrainment in hose streams and determine where water is distributed within compartments by evaluating the differences caused by various application methods, hose stream types, nozzle movements, pressures/flow rates, and stream locations and elevation angles. Over 150 tests were conducted in Part I of the overall study. Results from these experiment series were analyzed and reviewed with assistance from our technical panel. These results were summarized and can be seen below:

Air Entrainment -

- Air entrainment is dependent on hose stream type. (smooth bore, straight stream, fog)
- Air entrainment is dependent on structure size, compartmentation, and ventilation configurations.
- Increases in nozzle movement increase overall air entrainment.
- Different nozzle movement patterns have little effect on overall air entrainment. (O, T, Z, inverted U)
- Air entrainment, either into or out of the structure, is dependent on the horizontal distance of the nozzle to the ventilation opening.

Water Distribution -

- Water distribution is dependent on hose stream type. (smooth bore, straight stream, fog)
- Water distrubtion is dependent on stream elevation angle within a compartment.
- Varying water pressure at the nozzle and flow rate can affect the total amount of water applied to a given area; however, the distribution location can remain constant.
- Deflecting the hose stream off the ceiling or opposite wall of a compartment can coat the surfaces while applying little water to the center of the room.

Contents

1 Background

Recent fire service research has highlighted the importance of applying water to the fire as quickly as possible. This tactical consideration has highlighted a knowledge gap and increased the interest in better understanding the impact of water applied as part of an interior or exterior attack. Many variables exist in fire attack that impact firefighter effectiveness and victim survivability including stream placement, the time required to get water on the fire, stream type, stream movement, air entrainment, steam development, hot gas cooling and contraction, and position of flow paths. The most important firefighting tool for many years at structure fires has been their hoseline; however, many questions have arisen as more research shows the impact of ventilation, flow paths, and exterior fire streams. Whether a fire attack crew chooses to apply water as part of an interior attack or as part of an exterior or "transitional attack," they need to know what impact their stream has on the fire environment ahead of them. This is difficult on the fire ground because visibility is commonly limited and therefore most experience and first-hand accounts are from behind the nozzle. This results in beliefs about conditions (e.g. temperature) ahead of the nozzle team and the impact of their tactics on victim survivability; but knowledge of the actual impact has yet been researched. Additionally, when the fire is ultimately suppressed, there is no assurance the attack was conducted in the most effective, efficient, and safe manner even if the experience gained suggests that it was. Fire service adages such as "dont put water on smoke," "you will steam the victims," and "fog nozzles always disrupt the thermal layer" have been passed on from generation to generation with little context or substantiation. Without the context, these concepts get treated like rules and can severely limit firefighters understanding of fire suppression.

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

The water distribution experiments from the

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

2 Objectives and Technical Plan

2.1 Objectives

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

- Improve firefighter safety by increasing knowledge of fire suppression.
- Develop knowledge of hose streams applied during an interior and exterior fire attack and its impact on firefighter safety and victim survivability.
- Understand where water goes and how air flows during interior and exterior fire attack utilizing common equipment, practices, and tactics.
- Gain understanding of the impact of water streams depending on the volume of the fire compartment/structure.
- Bring the 'Science to the Streets' by transferring science based conclusions founded on experimental results that can be incorporated into firefighting standard operating procedures.

2.2 Technical Plan

Part I to the study consisted of the following tasks.

- **Task 1 - Design of Experiments**

  Task 1 is the design of the experiments. In this task, UL - FSRI's project engineers will work closely with the technical panel to ensure fire service concerns are addressed and that the results will be of great benefit to the end users. All experimental variables, equipment, personnel, infrastructure, and other resources will be evaluated to determine the best set of experiments to get the most for the investment and provide the largest return to the fire service community. Variables such as types of nozzles, flow rates, nozzle pressures, hose stream types, stream elevation angles, ventilation parameters, and timing of tactics will be discussed and selected.

- **Task 2 - Test Fixture Design**

  Task 2 is the design of the test fixtures to be used in the experiments. There will be a separate main test fixture for each test series. The air entrainment experiments will be utilizing an exisiting structure at the Delaware County Emergency Services Training Facility repurposed for this study and the water distribution structure will be constructed within a lab space inside UL's Large Fire Facility. The structures and compartments incorporated into this study are representative in both size and construction type of the structures utilized in the full-scale fire experiments for Parts II and III of the study. These fixtures are similar in construction type and size to the structures built for the three previous ventilation research grants and will therefore allow continuity of previous results to expand our knowledge. Additional test fixture details are provided in the detailed report below.

- **Task 3 - Conduct Experiments**

  Task 3A: Water Flow Mapping (Interior and Exterior Applications)

  Methodology: Conduct a series of experiments in a compartment constructed to determine where water goes once discharged from fire department nozzles during a simulated interior fire attack and exterior fire attack. The ability to suppress a fire safely and efficiently is dependent on how much water absorbs energy from the fire and what surfaces are cooled. A combination of water mapping techniques that are commonly used for characterizing sprinkler sprays will be utilized to determine flow distribution. The compartment will be of similar size to the fire rooms in the full-scale fire experiments so that the results can be linked.

  Water will be flowed utilizing common fire department nozzles with 3 hose stream types (combination nozzle in straight stream, combination nozzle in narrow fog, and a smooth bore nozzle). Different nozzle techniques that are commonly taught to firefighters and utilized in practice will be evaluated such as circular motions, various patterns, flowing off the ceiling, and flowing ahead. Common flow rates for each nozzle will be used during the experiments. We will also construct a prop to aid in water delivery to distribute the water in a repeatable manner that would be done by firefighters in the field. Several experiments will be done to also examine repeatability.

  Measurements: The actual delivered density apparatus (described later) will be used to determine water distribution.

Task 3B: Air Flow and Pressure Experiments

Methodology: Conduct air flow and pressure experiments in specific test fixtures prior to the introduction of any fire. Different hose streams and nozzle movement techniques entrain different amounts of air which can greatly impact fire dynamics, firefighter safety, and victim survivability. The same nozzles, hose stream types, and nozzle movement techniques from the water distribution experiments will be used and the amount of air flow generated in the structure will be measured. Different flow paths will also be established to see their impact such as having a ventilation point ahead of the hoseline when compared to having no ventilation opening ahead. We will also examine air movement generated by both 1 3/4 in. and 2 1/2 in. hoselines in addition to flows from portable and master-stream devices.

Measurements: During each of these experiments, velocities will be measured with bidirectional probes attached to differential pressure transducers.

- **Task 4 - Data Compilation and Analysis**

Task 4 is the compilation and analysis that will be conducted by UL - FSRI engineers to make the data usable by the fire service community. The data will be organized in graphs that will be reviewed by the technical panel in preparation for the final report. The focus of the analysis will be to quantify air entrainment in hose streams and the location of where water is distributed during suppression. In addition, conclusions will be developed in conjunction with the fire service technical panel supported by data and subsequent analysis.

- **Task 5 - Develop Final Project Report**

Task 5 is the development of the final report that details all of the experiments and results. The report will be provided to DHS and made publicly available via UL - FSRI's website for the fire service, www.ULfirefightersafety.com to serve as a reference for future research. The conclusions developed with the technical advisory panel will be a focus within the report. A fire service summary report at the conclusion of the remainder of the study will also be written and disseminated to include critical information for firefighter safety.

2.3 Limitation and Scope

The purpose is to quantify the amount of air entrainment in hose streams given certain parameters as well as determine where water is distributed within a compartment. This is all without fire involvement in order to provide a baseline understanding before moving forward with the remainder of the study. This baseline knowledge is intended to bridge the gap in the fire service understanding about the use of various nozzles, hose stream types, nozzle movements, and advancement techniques in specific scenarios. Knowing how hose streams affect air movement and how water is distributed can allow for better decision making capabilities across the fire service when it comes to use during an actual emergency incident.

When analyzing the air entrainment and water distribution, equipment from various manufacturers was tested. For the purpose of the study, the companies will be referred to as Manufacturer 1, Manufacturer II, and Manufacturer III. The air entrainment experiments yielded results that showed little to no difference among the various manufacturers. Therefore, a single manufacturer was chosen for the remainder of Part I of the study. More specifically, Part I of the study is not intended to purchasing of one type of nozzle over another.

The intent of the air entrainment experiments was to determine how much air hose streams entrain. This involved several components:

- Does the hose stream type (smooth bore versus straight stream versus narrow fog) effect air entrainment?
- Does the amount of air entrainment vary dependent on manufacturer given set flow rates/pressures?
- How do different building geometries, compartment layouts, and ventilation configurations effect air entrainment?
- Do various nozzle movements effect air entrainment (fixed, sweeping, O, T, Z, inverted U)?
- Does the distance from a ventilation opening effect the air entrainment?

Additionally, the intent of the water distribution experiments was to determine where water goes within a compartment. In order to answer this question, the tests considered the following:

- Does interior versus exterior attack effect water distribution?
- Does the hose stream type (smooth bore versus straight stream versus narrow fog) effect water distribution?
- Does the hose stream elevation angle effect water distribution?
- Does adjusting the flow rates/pressures of the nozzles effect water distribution?
- Do various nozzle movements effect water distribution (fixed, sweeping, O)?
- How does a first floor exterior attack effect the water distribution when compared to a second floor exterior attack?

For the purpose of these experiments we utilized the same structure throughout all of the air entrainment experiments. The water distribution testing utilized another structure, which also remained the same for the duration of those experiments. The only component of the firefighting equipment that was varied among the tests was the nozzle, and sometimes the hoseline size. The hoseline diameter was either 1 3/4 in. or 2 1/2 in. and was always 200 ft. in length. By creating some aspects that were not varied and by bounding other variables, we ensured that all aspects of the air entrainment and water distribution were examined as a baseline for further future evaluation in different structures with different conditions.

3 Previous Literature

At the start of the study, a literature review was performed to identify and analyze the following:

- Previous research in the field of air entrainment, water distribution, and fire suppression.
- Both past and current fire suppression tactics.
- Knowledge gaps in fire suppression operations. (choice of tactics, myths, traditions, etc.)

The following section outlines some of the material as it relates to the fire attack study. The literature review encompassed past research work, various articles in fire service publications, fire service training manuals, as well as fire department standard operating procedures to highlight some of the critical areas of information which drove the project at hand.

3.1 Literature Overview

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Hose, nozzles and water have been used by the fire service for hundreds of years. Despite their frequent use, there has been little scientific research conducted on the effective use of these tools for fire suppression. It is common in the fire service to find discussions about which nozzle is better or which flow rate is required for what sized fire but this is based on experience and usually not science.

In 1950 Chief Lloyd Layman presented a paper titled Little Drops of Water at the Fire Department Instructors Conference. He introduced what he called indirect method of attack to suppress interior building fires by using the heat absorbing properties of expanding and condensing steam, produced in great quantities by fog streams. The conclusions were based on Coast Guard experiments that Layman was in charge of conducting at the Coast Guard Firefighting School at Fort McHenry in Baltimore, MD. Layman continued his experiments after he returned to his position as fire chief in Parkersburg, WV where he applied his tactic in building fires. This research had a very large impact on the fire service and their suppression techniques to this day.

Throughout the 1950s a National Committee began conducting experiments to collect data on the growth and behavior of interior fires and how to most effectively suppress them. Keith Royer and Bill Nelson were members of this committee, and as the heads of the firemanship training program at the Iowa State Universitys Engineering Extension, they collected and analyzed data from hundreds of experimental fires. Through this research the fire service was taught about fire behavior and how to suppress fire with a combination fire attack. They examined the amount of heat generated by common fuels, the heat absorbing capacity of water, the impact of compartment volume during suppression and they developed the Iowa formula. The Iowa formula or critical rate of flow formula is still used today and it determines the amount of water needed to control a fire in the largest open space within a structure by dividing the cubic foot volume of the space by 100.

While the physics of fire development has not changed over time, the fire environment for specifically the single family home has evolved. Several factors including home size, geometry, contents and construction materials have changed significantly over the past 50 or more years. Each of these factors has impacted firefighter and occupant safety. Faster fire propagation, shorter times to flashover, rapid changes in fire dynamics and shorter escape times all impact fire service suppression techniques and effectiveness. Many of the variables in Royer and Nelsons analysis have changed and more research is needed to see how suppression techniques used in the 1950s with 1950s fuel loads and firefighting tools translates to todays firefighter safety and effectiveness.

Beginning in 1994, the Naval Research Laboratory carried out a series of full-scale fire experiments to compare straight stream attack versus fog pattern attack. These experiments were conducted on the Navy ship ex-USS Shadwell with a fire volume of approximately 110 m^3. In these experiments one 60 degree fog pattern was applied at a 45 degree angle into the smoke layer. They examined cooling effects, steam generation and thermal layer disruption. Their experiments examined shielded and non-shielded fires and concluded that using fog to cool the upper layer was more effective and safer than straight stream attack when the fire could not be attacked directly and the firefighters heart rates and body temperatures were lower utilizing the fog attack.

In 1998 NIST conducted a series of experiments to demonstrate the suppression effectiveness of water-based firefighting agents. This was a step toward creating test procedures to determine suppression effectiveness to develop a standardized test method for evaluating the fire fighting effectiveness of water and other agents. This study provides preliminary data upon which firefighting effectiveness test may be developed by it suggests additional research on application technique, tests reflective of the complexities found in firefighting and experiments involving structural-fire suppression.

In 2002, The National Research Council of Canada conducted a literature search on 3D water fog techniques for firefighting. It discusses the impact of water fog characteristics associated with properties of the nozzle (e,g,, droplet size, momentum, flow rate, spray angle and pattern) and discharge techniques (e.g., discharge angle, and discharge duration related to the burts) on performance of the 3D water fog technique are discussed. This technique is to supplement a direct attack by controlling the environment the firefighters are in until they are in a position to apply water directly to the fire. Opponents of flowing water into smoke have concerns that include: (i) effectiveness of controlling the fire, compared to traditional straight stream attack; (ii) possible disruption of the thermal balance; (iii) possible generation of a large amount of hot steam that produces burn injuries to firefighters; and (iv) the performance of this technique is complex and requires extensive training. Advocates of this technique have attempted to respond to these concerns but very limited experimental studies have been undertaken do to complexity of the problems. Application techniques and fire conditions on the the performance of fog technique is not well studied and therefore there are little guidelines and adoption will be greatly limited.

Several theoretical studies had been conducted that examine droplet size and their ability to suppress fire gases. For example, when droplet diameter is reduced from 1000 nanometers to 100 nanometers the total surface area increases 10 times from 6 m2 to 60 m2 for 1 liter of water. Since these smaller droplets evaporate sooner, others have examined the lifetime of the droplet to determine how far it can travel based on temperature of the surrounding gases and droplet size. Further complicating this theory is that droplets all have an impact on each other as they turn to steam. Residence time can be further reduced compared to an individual droplet, because leading droplets impart forward momentum to the surrounding gas, reducing the air drag on the following droplets and resulting in better penetration. In 2010, the University of Maryland examined spray characteristics from fire hose nozzles. They examined the breakup of a smooth bore nozzle utilizing techniques such as shadowgraphy and a patternator and concluded that more research was needed to fully understand the water spray from fire hose nozzles.

In 2000, Lund University examined the demand for extinguishing media in manual firefighting. They examined critical flow rates required to suppress fires by reviewing available literature and conducted a series of experiments that examined suppression of wood pallets at a fire training academy. They examined the five ways that water can be applied during fire extiguishment, on hot gases, on flames, on burning fuel, on fuel that is not yet burning and on hot surfaces. They highlight that what is most effective against the fire is not necessarily best for the firefighters since there are other constraints during firefighting operations such as limited air supply and multiple priorities. The optimum flow rate corresponds to an optimum control time, a control time that gives the lowest total demand for resources. Most of the current data for optimum water flow rate include experiments utilizing wood cribs or pallets, but not todays synthetic fuel loads in actual structures. These studies also did not investigate the effect of flow paths or the impact of steam generation on firefighters or victims.

In 2003, a fire service group at the Rockland County (NY) Fire Training Center conducted a series of tests in their concrete training building. They measured the amount of air moved by solid bore and combination nozzles using common fire ground methods. They concluded that air volumes moved by smooth bore nozzles and combination nozzles in the straight stream setting are very similar if not the same, and that combination nozzles in the fog pattern move significant amounts of air which can over pressurize the fire area and send steam over the attack crew even with a ventilation opening opposite the attack crew. These tests were performed either with no fire or with a training fire but which are very different than actual fire conditions. Their tests do provide a good range of airflows that can be expected in our experiments. The authors state, Our nozzle testing program was not as controlled and as precise as we would have liked. They also did not have measurement devices that were able to accurately measure air flows from a fog pattern.

The Firefighting Technology Group at NIST has a current project that is examining hose streams. This project examines a variety of fire fighting hose stream characteristics related to flow, distribution and thermal impact from both solid and fog stream nozzles. A series of real scale, laboratory based experiments have been started to look specifically at the water discharge and distribution characteristics, the impact of hose streams on a hot gas layer in a compartment, the impact of hose streams on gas flows through multi-compartment structures, and the suppression effectiveness on burning piles of wooden pallets. The proposed project will build on their results by utilizing real-scale structures with common residential fuels and making additional measurements to better characterize the impact of flow path, nozzle technique and steam generation on fire dynamics, firefighter exposure and occupant survivability.

3.2 Fire Service Publications

[MIKE]

3.3 Fire Service Training Manuals

[MIKE]

3.4 Research Work

[MIKE]

4 Air Entrainment Experiments

4.1 Test Setup

4.1.1 Structures

The air entrainment testing was conducted at the Delaware County Emergency Services Training Center in Sharon Hill, PA. A two-story purpose built strucutre was constructed several years ago for the use during previous research work conducted by both NIST and UL.

Figure 4.1: Delaware County, PA Fire Test Structure

The two-story concrete structure was built on a concrete slab as shown in Fig. 4.1. It was designed to simulate a representative residential structure. The outer wall of the structure was composed of interlocking concrete blocks 2 ft. wide, 2 ft. high, and 4 ft. long. The interior dimensions of the structure was 20 ft. wide, 36 ft. long, and 8 ft. high. The joints and gaps between the blocks were filled with high temperature insulation.

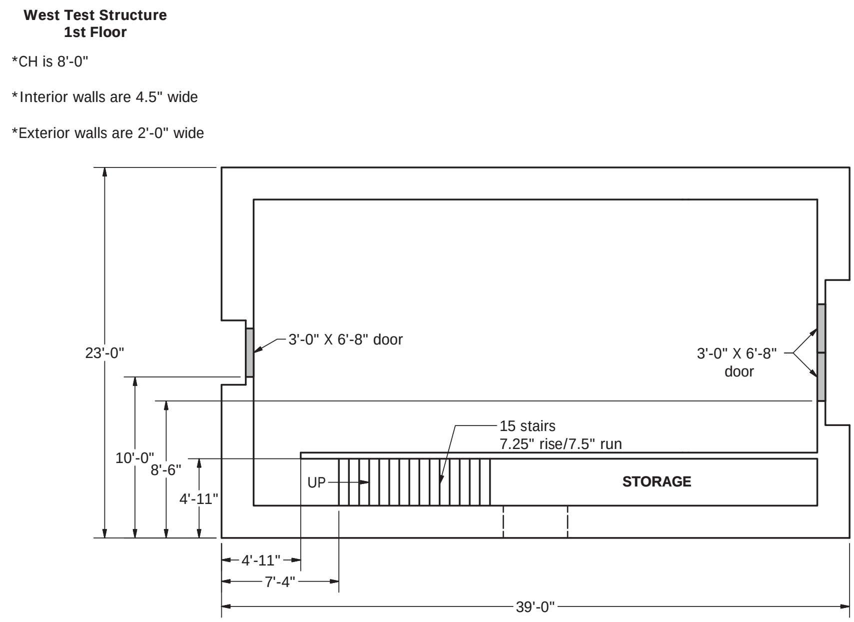


Figure 4.2: Delaware County, PA Fire Test Structure First Floor

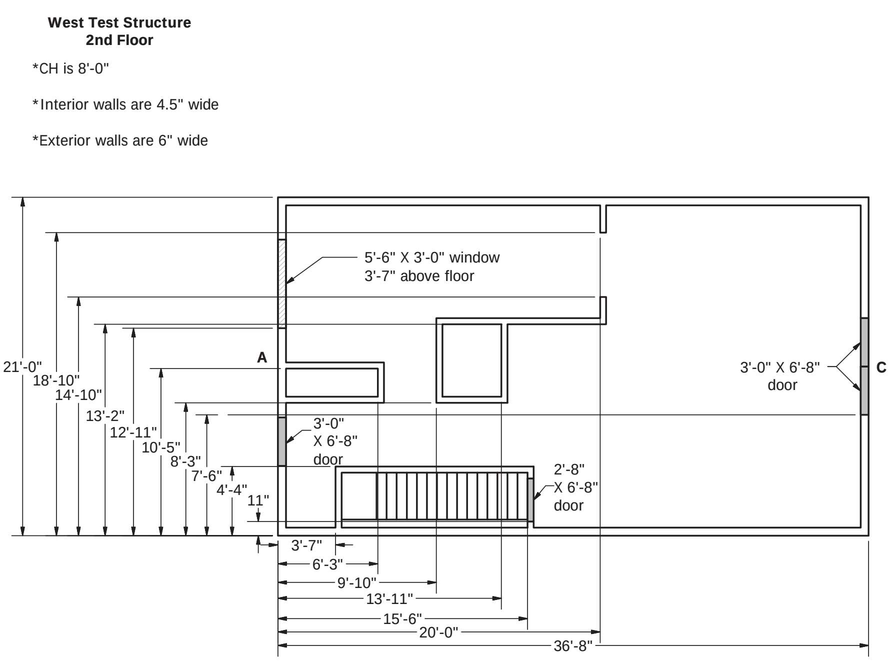


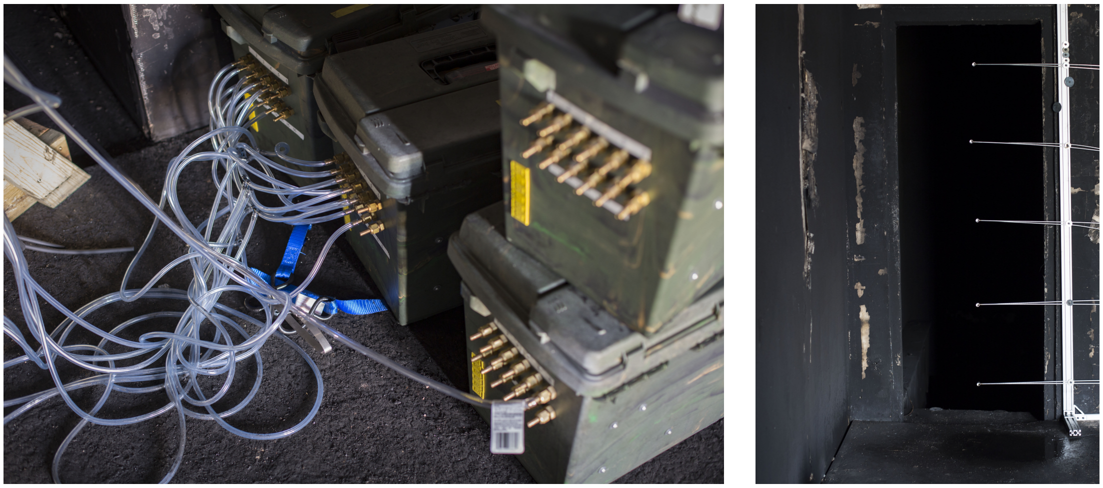
Figure 4.3: Delaware County, PA Fire Test Structure Second Floor

The interior walls of the first floor were framed with steel studs set to 16 in. centers and track and were lined with 0.5 in. thick cement board. The walls were composed of 0.6 in. Type X gypsum board. Additionally, the ceiling was composed of two layers of 0.5 in. thick cement board. The first floor ceiling support of the structure was composed of wood truss joist I-beams (TJIs) with a 11.75 in. depth. Each TJI was composed of laminated veneer lumber flanges with a cross section of 1.13 in. x 1.75 in. and an 0.43 in. thick oriented strand board web. Tongue and groove oriented strand board of 0.72 in. thickness was screwed to the top of the TJIs. The second floor of the two story structure was built on the wood ceiling support described above and was connected to the first floor by a stairwell. The walls of the second floor were wood frame with nominal 2 in. by 4 in. studs set to 16 in. centers. The interior walls were protected by 0.6 in. fire rated gypsum board, 0.6 in. durarock board, and a second layer of 0.6 in. fire rated gypsum board. The exterior walls were protected with 0.4 in. oriented strand board and 0.3 in. fiber cement lap siding.

The interior layout of the structure can be seen in the dimensioned floor plans above. The interior dimensions of the first and second floors of the structure were 19 ft. by 35.1 ft. and 20 ft. by 35.8 ft., respectively. The stairs connecting the two floors of the structure started 5.3 ft. off the South wall with a width of 4 ft. off the East wall and contained a 7.25 in. rise and 7.5 in. run. The exterior doorways of each structure and the stairwell doorway on the second level of the structure all contained steel doors that were opened or closed at certain instances during tests to change the ventilation configuration within the structure. All other doorways in the structures did not contain a door. If it was determined that these doors needed closed during a test, a sheet of either gypsum board or oriented strand board was used to cover the opening and remainded as such until the conclusion of the given test.

4.1.2 Instrumentation

To determine the amount of air entrained in hose streams, gas velocity was obtained through the use of an array of bi-directional probes in conjunction with differential pressure transducers and inconel thermocouples. The bi-directional probe was constructed of stainless steel and features a 'high' side and a 'low' side in which gases travel, through tubing, back to a pressure transducer that evaulates the differential pressure from ambient pressure. The iconel thermocouples were placed in-line wtih the bi-directional probes to ensure that the measurements were recorded at the same location. The iconel thermocouple was a 0.063 in. diameter type KSL iconel 600 sheathed grounded junction with a type K, 24 gauge glass/glass insulation lead. The differential pressure transducer was a Setra Model 264 with a range of +/- 0.5 in. WC (+/- 124.5 Pa.). The uncertainty given by the manufacturer is 1% or 1.2 Pa. The configuration had a velocity range of +/- 24.2 m/s (+/- 54 mph). The pressure transducers were configured in groups of six, contained in a single plastic box with connections for pressure, temperature, and power (Figure 4.4a). Five probes were installed in openings where velocity measurements were taken, centered horizontally in the opening (Figure 4.4b). The opening in which the bi-directional probes were placed is 2 ft. 8 in. by 6 ft. 8 in. The probes were placed in the center of the doorway horizontally and spaced evenly vertically. Velocity measurement with this configuration was determined to have an uncertainty of +/- 5% [**BDPInPoolFires**].



(a) Pressure Transducer Box (b) Bi-Directional Probe Array

Figure 4.4: Gas Velocity Measurements

All data was logged through the use of a National Instruments data acquisition system incorporating a SCXI-1001 chassis with 8 SCXI-1102C 32-Channel modules (Figure 4.5). The system is configured for a total of 256 channels capable of reading values between 0-10 volts DC. Values are recorded once a second and translated to quantities of interest through the use of LabVIEW software specifically programmed for use with the system.

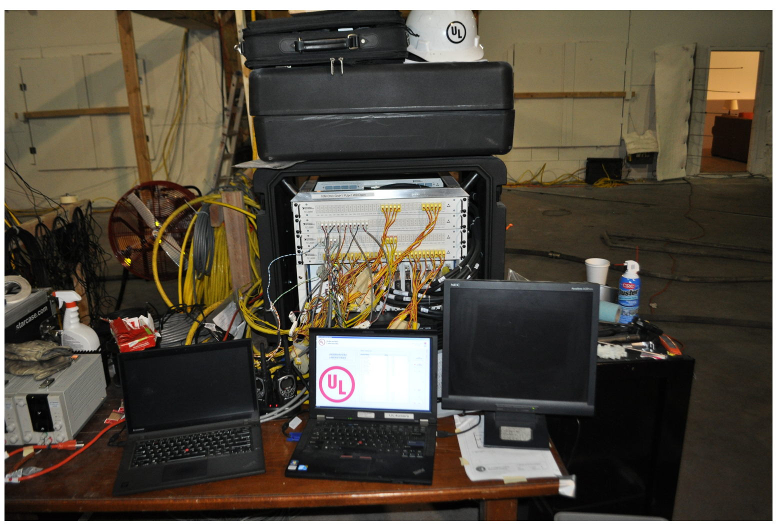


Figure 4.5: Data Acquisition System

4.1.3 Measurement Locations

When examining the amount of air entrainment caused by variations in hose stream types, several challenges arose in determining the location to measure the gas velocity in the structure. Because the experiments were conducted in an outdoor fixture, considering environmental factors such as wind was critical; especially when quantifying the amount of air moved by hose streams. Additionally, the instrumentation used in data collection requires a dry environment to maintain the smallest level of uncertainty and remain operational. In order to combat these challenges, it was determined that the best way to acquire flow data would be to utilize the structure in such a way that there would be an inlet for replacement air, a measurement location, and an exhaust for both the hose streams and air moved.

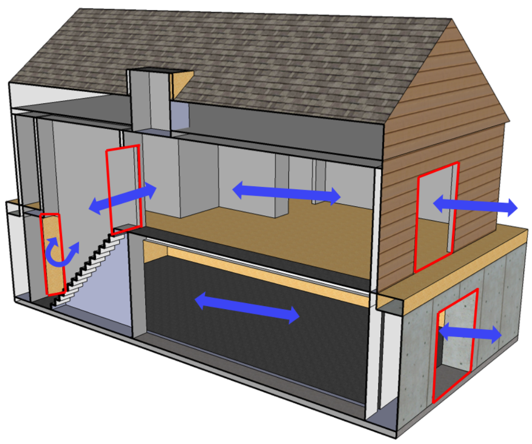


Figure 4.6: Air Entrainment Flowpath

By placing the inlet and exhaust on the same side of the building, we can ensure that any presence of wind does not affect the pressure or air flow within the building. Therefore, the interior environment was consistent throughout the flow path as to not affect the measurements taken. The measurement location was placed in the inlet portion of the flow path in order to keep the instrumentation dry and out of the reach of a hose stream. With the exception of the predetermined inlet and outlet, the remainder of the ventilation openings in the structure remained closed throughout the duration of testing. This ensures that the air entrained by the nozzle is drawn from the inlet location and passes through the measurement location seen in Figure 4.7.

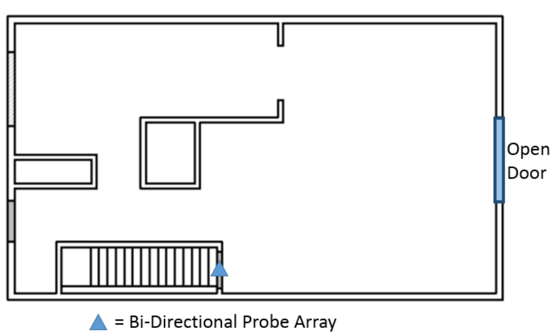


Figure 4.7: Measurement Location (Second Floor)

4.1.4 Equipment Used

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

Line Size	Nozzle	Tip (in)	Nozzle Pressure (psi)	Approximate Flow Rate (gpm)
1 3/4 in.	Smooth Bore	1	50	210
	Smooth Bore	15/16	50	180
	Smooth Bore	7/8	50	150
	Fog		100	100
	Fog		100	150
	Fog		75	150
	Fog		50	150
2 1/2 in.	Smooth Bore	1 1/8	50	260
	Smooth Bore	1 1/4	50	320
	Fog		100	250
	Fog		75	250
	Fog		50	250
Portable Monitor	Smooth Bore	1 3/8	80	500
	Fog		75	500
Master Stream	Smooth Bore	1 1/2	80	600
	Smooth Bore	1 3/4	80	800
	Fog		100	500-1000

Table 4.1: Nozzle Selection

When determining how to create a test setup that would involve the repetition of nozzle movements and patterns, it was vital to ensure human fatigue of the nozzle operator would not affect the results. Thus, the UL - FSRI engineers designed a nozzle prop to serve as the 'backup' firefighter by supporting the hoseline and nearly eliminating any potential nozzle reaction and fatigue.

Figure 4.8: Nozzle Prop

The hose was affixed to the prop with ‘C’ clamps and locking nuts to ensure the hose did not move during a given experiment. The prop served as support for both 1.5 in. and 2.5 in. hoseline sizes. The distance from the nozzle to the ventilation opening was measured from the tip of the nozzle, and not the base of the prop, and thus the measurements between the experiments were consistent.

Figure 4.9: Nozzle Prop in Use

4.2 Experiments Conducted

The experiments to determine the amount of air entrained by hose streams consisted of several test series to gain a wholelistic view of how varying different components, either with the structure or equipment utilized, affected the end result.

Prior to determining the parameters for the test series' below, several preliminary experiments were conducted in order to provide insight into several key components including the setback distance from the nozzle to the ventilation opening, the hose stream type, and various nozzle movements.

- **Setback Distance**

  Two experiments were conducted on the interior of the structure utilizing a 1.5 in. combination nozzle with a flow rate of 150 gpm. to determine the effects of altering the setback distance of the nozzle to the ventilation opening on the overall air entrainment in the hose stream. The first of the two tests examined setback distances of 3, 6, 9, 12, and 15 feet from the open double door at a pressure of 50 psi. The second test examined the same setback distances at a nozzle pressure of 100 psi.

- **Hose Stream Type**

  To gain an initial look into the hose stream type, a fixed setback distance of 3 ft. was chosen and the nozzle was varied to a wide fog pattern (nearly occluding the ventilation opening), a narrow fog pattern (roughly 30 deg.), and a straight stream pattern. This provided preliminary information that aided in the test setup for the remainder of the experiments. The nozzle used during this test was a 1.5 in. combination nozzle with a flow rate of 150 gpm and a pressure of 100 psi.

- **Nozzle Movements**

  Because there are numerous nozzle movements that firefighters can employ during suppression operations, it was vital that the UL - FSRI team identify any differences in air entrainment prior to conducting the remainder of the study. This would provide information into whether or not the various nozzle movements would all be tests or if some could be eliminated due to similarities in results. These tests were conducted with a fixed setback distance of 18 ft. from the ventilation opening and utilized both a 1.5 in. combination nozzle with a flow rate of 150 gpm and a pressure of 100 psi and a 1.5" smooth bore nozzle with a 1" tip flowing 210 gpm at a pressure of 50 psi.

- **Manufacturer Comparison**

  Similar to the issue above with various nozzle movements, fire departments across the world used nozzles made from different manufacturers. To provide some insight into the accuracy of manufacturer ratings of flow rate and pressure in addition to air entrainment, several experiments were conducted to determine the differences in nozzle manufacturers. These experiments were all conducted with both a 1.5 in. combination nozzle and a 1.5" smooth bore nozzle. This would provide information into the differences in air entrainment between nozzles with similar flow rates and pressures made by different manufacturers.

4.2.1 Total Air Entrainment Comparison

The first test series of the air entrainment experiments looked at the differences in total entrainment given a single nozzle manufacturer with varying flow rates and pressures. These tests were conducted from both the interior and exterior of the structure at a setback distance of 18 ft. from the ventilation opening.

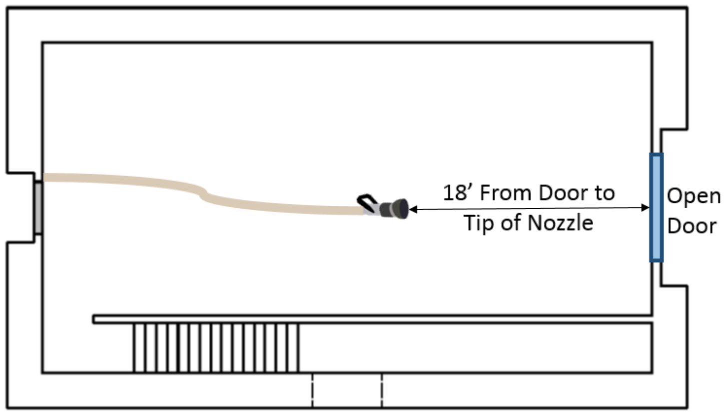


Figure 4.10: First Floor Setup - Total Entrainment Interior Tests

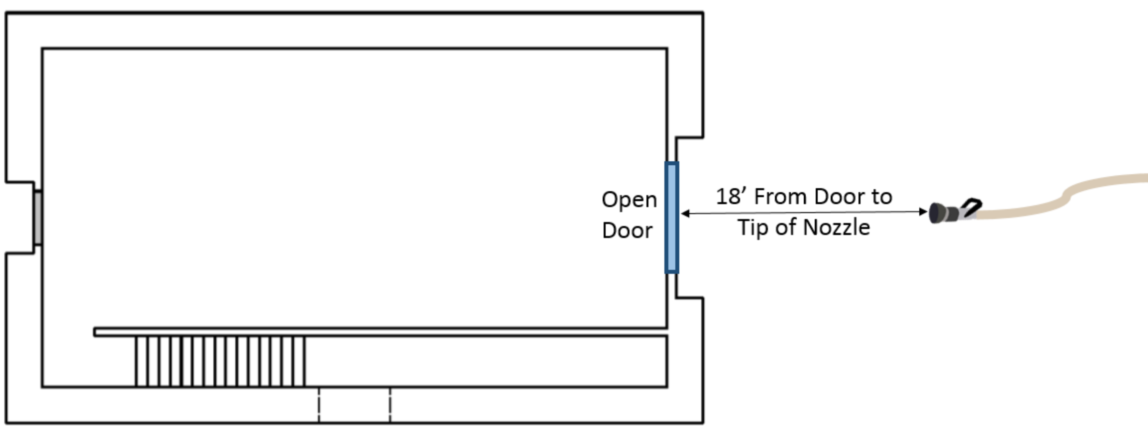


Figure 4.11: First Floor Setup - Total Entrainment Exterior Tests

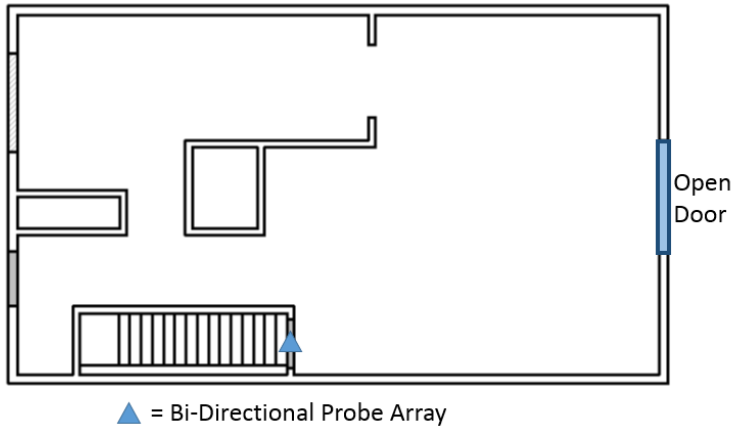


Figure 4.12: Second Floor Measurement Location

Location	Nozzle Size	Manufacturer	Nozzle Type	Tip Size	Flow Rate	Pressure
Interior	1.5	MF1	Combination		95	100
Interior	1.5	MF1	Combination		150	50
Interior	1.5	MF1	Combination		150	75
Interior	1.5	MF1	Combination		150	100
Interior	1.5	MF1	Smooth Bore	7/8	150	50
Interior	1.5	MF1	Smooth Bore	15/16	180	50
Interior	1.5	MF1	Smooth Bore	1	210	50
Interior	2.5	MF1	Combination		250	50
Interior	2.5	MF1	Combination		250	75
Interior	2.5	MF1	Combination		250	100
Interior	2.5	MF1	Smooth Bore	1 1/8	260	50
Interior	2.5	MF1	Smooth Bore	1 1/4	320	50
Interior	MS	MF1	Combination		500	100
Interior	MS	MF1	Combination		750	100
Interior	MS	MF1	Smooth Bore	1 1/2	600	80
Interior	MS	MF1	Smooth Bore	1 3/4	800	80
Interior	PM	MF1	Combination		500	80
Interior	PM	MF1	Smooth Bore	1 3/8	480	80
Exterior	1.5	MF1	Combination		150	75
Exterior	1.5	MF1	Smooth Bore	15/16	180	50
Exterior	2.5	MF1	Combination		250	75
Exterior	2.5	MF1	Smooth Bore	1 1/4	320	50
Exterior	PM	MF1	Combination		500	75
Exterior	PM	MF1	Smooth Bore	1 3/8	500	80

Table 4.2: Total Air Entrainment Experiments

4.2.2 Ventilation Configuration

The second series of tests conducted to analyze air entrainment in hose streams involved varying the ventilation configurations within the flow path. The inlet and exhaust of the flow path were varied between both different sized doors and windows to show its effect on overall air entrainment. The tests were conducted from both the interior and the exterior of the structure with a fixed setback distance of 18 ft. from the ventilation opening. The measurement location during these experiments remained the same as that used during the total air entrainment experiments with the instrumentation remaining in the doorway at the top of the stairs on the second floor.

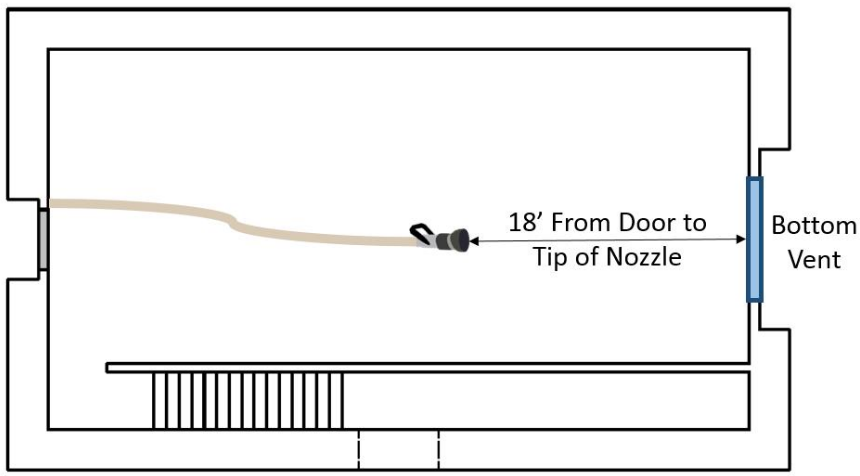


Figure 4.13: First Floor Ventilation Configuration Interior

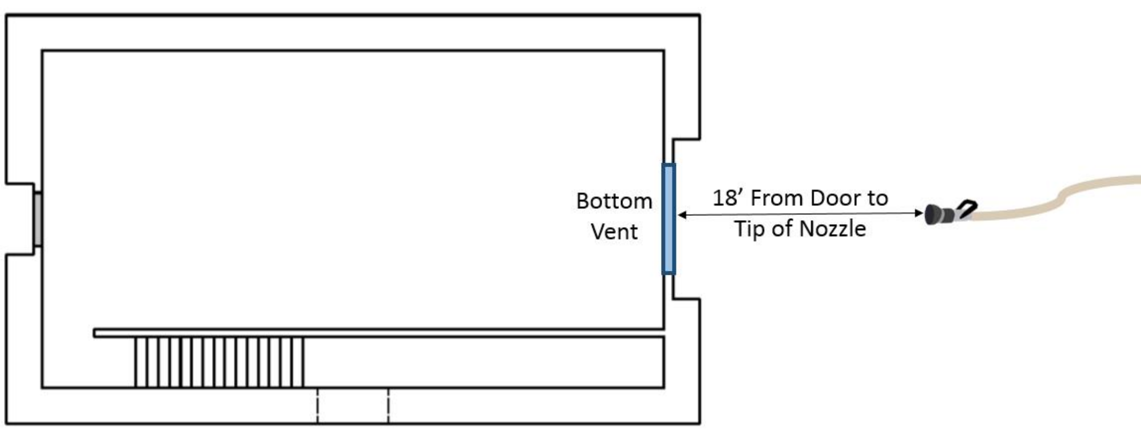


Figure 4.14: First Floor Ventilation Configuration Exterior

Location	Top Vent	Bottom Vent	Nozzle Size	Nozzle Type	Tip Size	Flow Rate	Pressure
Interior	Controlled Door	Single Window	1.5	Combination		150	75
Interior	Double Door	Double Door	1.5	Combination		150	75
Interior	Double Door	Single Door	1.5	Combination		150	75
Interior	Double Door	Single Window	1.5	Combination		150	75
Interior	No Opening	Double Door	1.5	Combination		150	75
Interior	No Opening	Single Door	1.5	Combination		150	75
Interior	No Opening	Single Window	1.5	Combination		150	75
Interior	Single Door	Double Door	1.5	Combination		150	75
Interior	Single Door	Single Door	1.5	Combination		150	75
Interior	Single Door	Double Window	1.5	Combination		150	75
Interior	Single Door	Single Window	1.5	Combination		150	75
Interior	Controlled Door	Single Window	1.5	Smooth Bore	15/16	180	50
Interior	Double Door	Single Window	1.5	Smooth Bore	15/16	180	50
Interior	Single Door	Double Window	1.5	Smooth Bore	15/16	180	50
Interior	Single Door	Single Window	1.5	Smooth Bore	15/16	180	50
Exterior	Double Door	Double Door	1.5	Combination		150	75
Exterior	Double Door	Single Door	1.5	Combination		150	75
Exterior	No Opening	Double Door	1.5	Combination		150	75
Exterior	No Opening	Single Door	1.5	Combination		150	75
Exterior	No Opening	Single Window	1.5	Combination		150	75
Exterior	Single Door	Double Door	1.5	Combination		150	75
Exterior	Single Door	Single Door	1.5	Combination		150	75
Exterior	Single Door	Double Window	1.5	Combination		150	75
Exterior	Single Door	Single Window	1.5	Combination		150	75
Exterior	Single Window	Double Window	1.5	Combination		150	75
Exterior	Single Window	Single Door	1.5	Combination		150	75
Exterior	No Opening	Single Window	1.5	Smooth Bore	15/16	180	50
Exterior	Single Door	Double Window	1.5	Smooth Bore	15/16	180	50
Exterior	Single Door	Single Window	1.5	Smooth Bore	15/16	180	50
Exterior	Single Window	Single Door	2.5	Combination		250	75
Exterior	Single Door	Single Window	2.5	Combination		250	75
Exterior	Single Window	Single Door	2.5	Smooth Bore	1 1/4	320	50
Exterior	Single Door	Single Window	2.5	Smooth Bore	1 1/4	320	50
Exterior	Single Window	Single Door	PM	Combination		500	80
Exterior	Single Door	Single Window	PM	Combination		500	80
Exterior	Single Window	Single Door	PM	Smooth Bore	1 3/8	500	80
Exterior	Single Door	Single Window	PM	Smooth Bore	1 3/8	500	80
Transitional	Single Window	Single Window	1.5	Combination		150	75
Transitional	No Opening	Single Window	1.5	Combination		150	75
Transitional	Single Door	Single Window	1.5	Combination		150	75
Transitional	Single Window	Single Window	1.5	Smooth Bore	15/16	180	50
Transitional	No Opening	Single Window	1.5	Smooth Bore	15/16	180	50
Transitional	Single Door	Single Window	1.5	Smooth Bore	15/16	180	50

Table 4.3: Ventilation Configuration Experiments

4.2.3 Room Configuration

The last test series of the air entrainment experiments involved reconfiguring the first floor of the structure to analyze how compartmentation and varying building geometries affect the end result. The air entrainment from various attacks, both fixed and advancements were studied. Additionally, the tests were conducted from both the interior and exterior of the structure. The nozzles utilized during these experiments included both a 1.5 in. combination nozzle and a 1.5 in. smooth bore nozzle with a 15/16 in. tip.

The dimensioned drawing below shows the changes to the first floor of the structure. A wall was constructed to create a room adjacent to the bottom ventilation opening. Attached to the room via a standard 2 ft. 6 in. by 6 ft. 8 in. doorway was a 16 ft. by 4 ft. hallway. This allowed for the team to study entrainment in a structure configuration most comparable to residential single family homes.

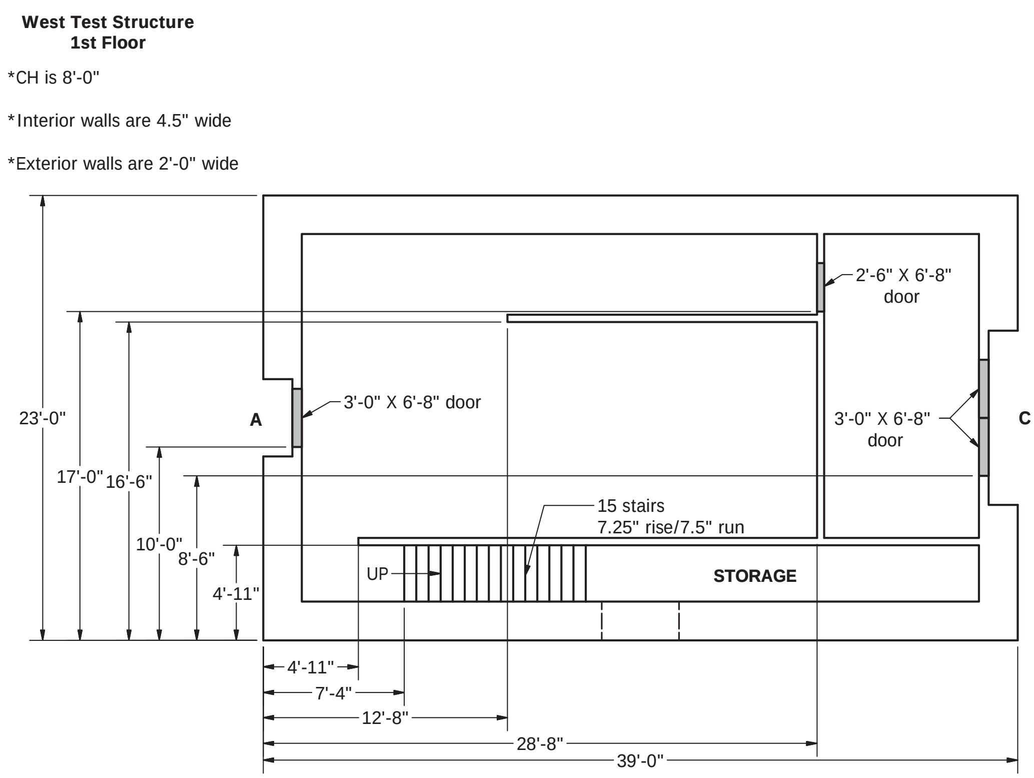


Figure 4.15: First Floor Alterations Room Configuration

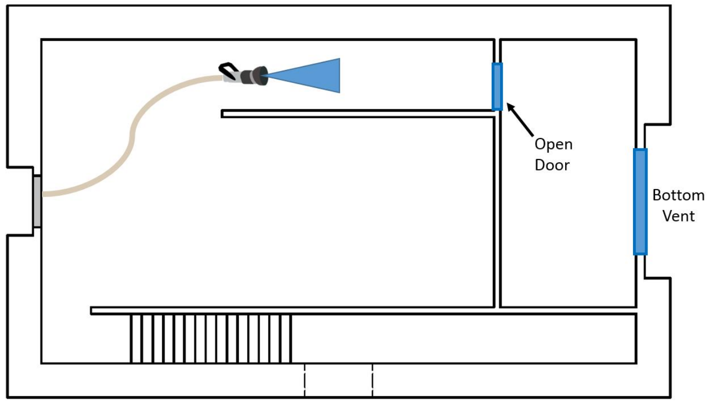


Figure 4.16: First Floor Room Configuration, Interior Experiments

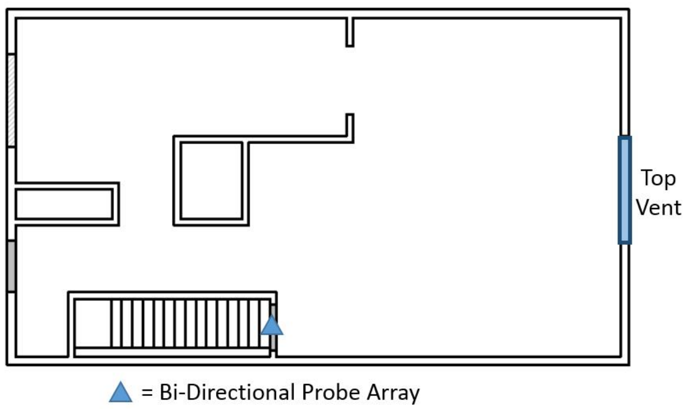


Figure 4.17: Second Floor Room Configuration

Location	Nozzle Size	Nozzle Type	Tip Size	Flow Rate	Pressure
Interior	1.5	Smooth Bore	15/16	180	50
Interior	1.5	Smooth Bore	15/16	180	50
Interior	1.5	Smooth Bore	15/16	180	50
Interior	1.5	Combination		150	50
Interior	1.5	Combination		150	50
Interior	1.5	Combination		150	50
Interior	1.5	Combination		150	75
Exterior	1.5	Combination		150	50

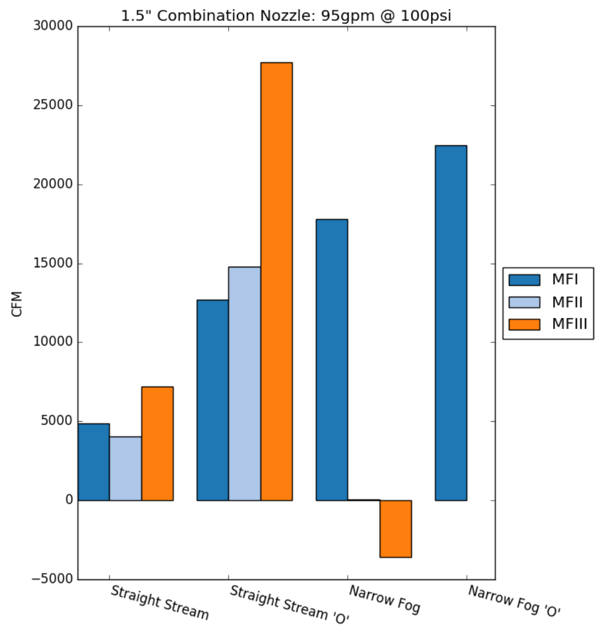
Table 4.4: Room Configuration Experiments

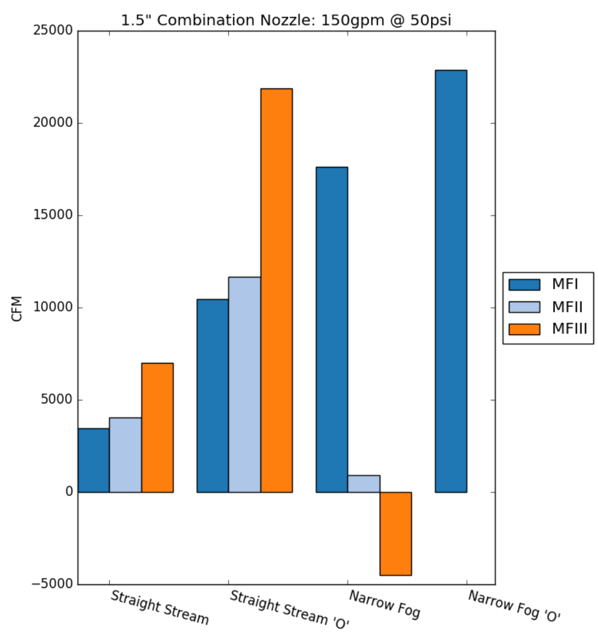
4.3 Analysis & Results

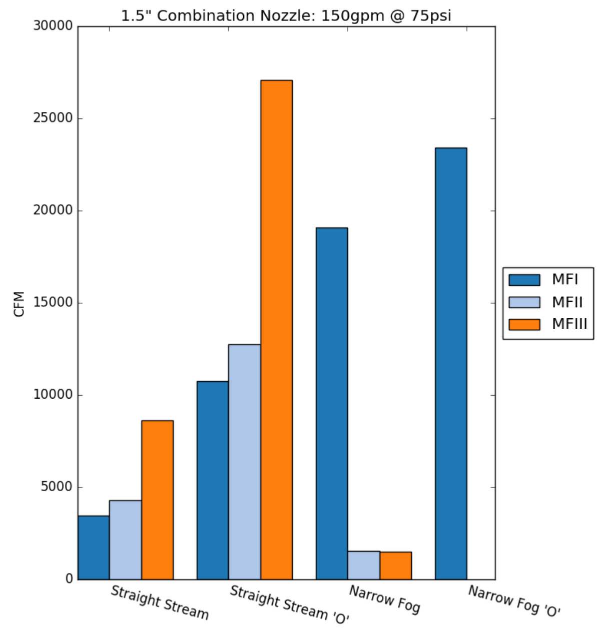
Manufacturer Comparison The table below shows the tests that were conducted to compare similar nozzles from differing manufacturers. Within each of these tests, the air entraiment from various hose stream types was determined.

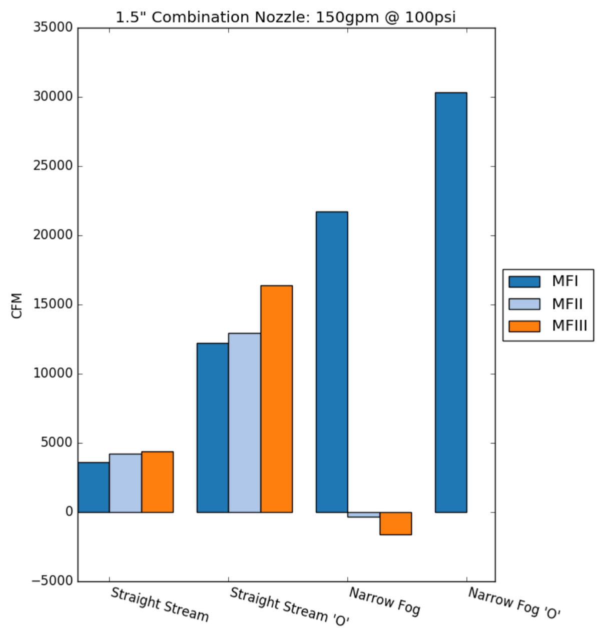
Location	Nozzle Size	Manufacturer	Nozzle Type	Tip Size	Flow Rate	Pressure
Interior	1.5	MF3	Combination		95	100
Interior	1.5	MF3	Combination		150	50
Interior	1.5	MF3	Combination		150	75
Interior	1.5	MF3	Combination		150	100
Interior	1.5	MF3	Smooth Bore	7/8	150	50
Interior	1.5	MF3	Smooth Bore	15/16	180	50
Interior	1.5	MF3	Smooth Bore	1	210	50
Interior	1.5	MF2	Combination		95	100
Interior	1.5	MF2	Combination		150	50
Interior	1.5	MF2	Combination		150	75
Interior	1.5	MF2	Combination		150	100
Interior	1.5	MF2	Smooth Bore	7/8	150	50
Interior	1.5	MF2	Smooth Bore	15/16	180	50
Interior	1.5	MF2	Smooth Bore	1	210	50
Interior	1.5	MF1	Combination		95	100
Interior	1.5	MF1	Combination		150	50
Interior	1.5	MF1	Combination		150	75
Interior	1.5	MF1	Combination		150	100
Interior	1.5	MF1	Smooth Bore	7/8	150	50
Interior	1.5	MF1	Smooth Bore	15/16	180	50
Interior	1.5	MF1	Smooth Bore	1	210	50

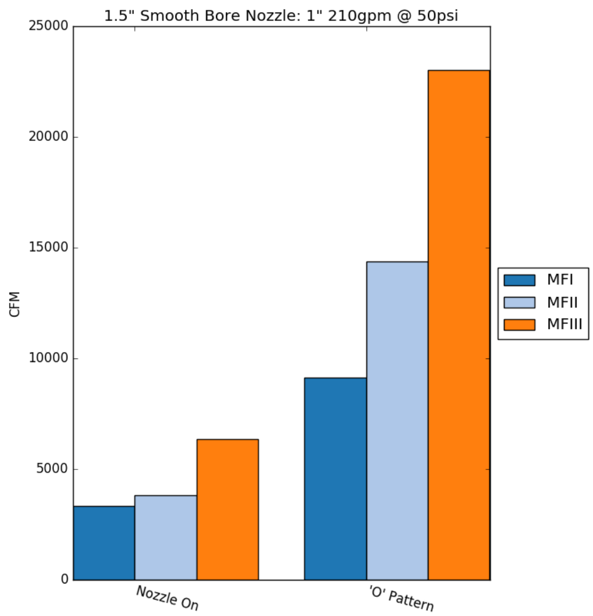
Table 4.5: Manufacturer Comparison Experiments

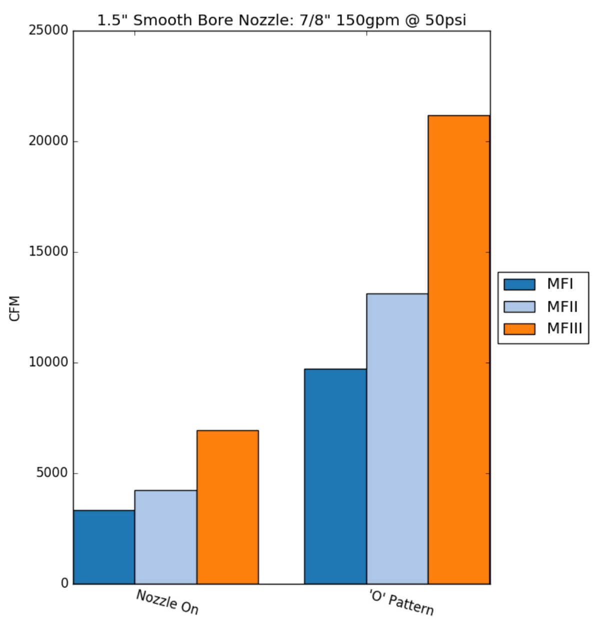

1.5" Combination Nozzle: 95gpm @ 100psi
30000
25000
20000
15000
10000
5000
0
−5000
CFM
MFI
MFII
MFIII
Straight Stream
Straight Stream 'O'
Narrow Fog
Narrow Fog 'O'

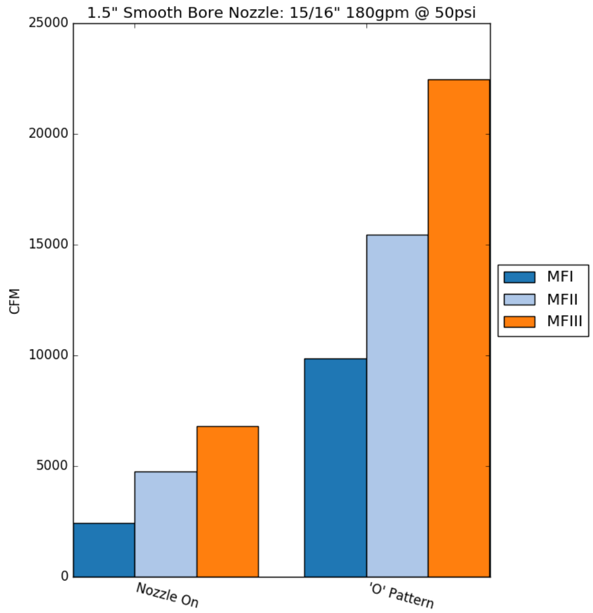

1.5" Combination Nozzle: 150gpm @ 50psi
25000
20000
15000
10000
5000
0
−5000
CFM
MFI
MFII
MFIII
Straight Stream
Straight Stream 'O'
Narrow Fog
Narrow Fog 'O'


1.5" Combination Nozzle: 150gpm @ 75psi
CFM
30000
25000
20000
15000
10000
5000
0
Straight Stream
Straight Stream 'O'
Narrow Fog
Narrow Fog 'O'
MFI
MFII
MFIII


1.5" Combination Nozzle: 150gpm @ 100psi
CFM
35000
30000
25000
20000
15000
10000
5000
0
−5000
Straight Stream
Straight Stream 'O'
Narrow Fog
Narrow Fog 'O'
MFI
MFII
MFIII


1.5" Smooth Bore Nozzle: 1" 210gpm @ 50psi
25000
20000
15000
10000
5000
0
CFM
Nozzle On
'O' Pattern
MFI
MFII
MFIII


1.5" Smooth Bore Nozzle: 7/8" 150gpm @ 50psi
25000
20000
15000
10000
5000
0
CFM
Nozzle On
'O' Pattern
MFI
MFII
MFIII


1.5" Smooth Bore Nozzle: 15/16" 180gpm @ 50psi
25000
20000
15000
10000
5000
0
CFM
Nozzle On
'O' Pattern
MFI
MFII
MFIII

Air entrainment is dependent on hose stream type. (smooth bore, straight stream, fog)

The intial opening occlusion was conducted to determine how varying the hose stream type from a single nozzle can effect the air entrainment at a given setback distance. This test showed that given a fixed setback distance, a combination nozzle flowing a common flow rate of 150 gpm at a pressure of 50 psi had increasing air entrainment with an increase in the angle of the pattern. As the pattern became wider, approaching the size of the ventilation opening, the air entrainment increased, with straight stream experiencing the smallest airflow.

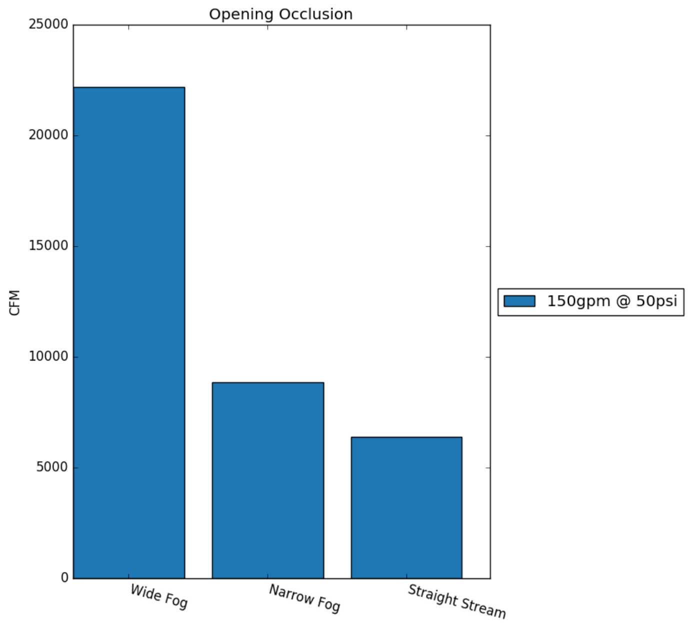


Figure 4.18: Varying air entrainment in varying hose stream types utilizing a 1.5” combination nozzle with a flow rate of 150gpm at 50 psi.

Varying the hose stream type was analyzed in various other experiments as well. These were conducted with a interior fixed setback distance of 18 ft. and utilized 1.5” nozzles.

Hose Stream Type	Flow Rate (GPM)	Pressure (PSI)	Air Entrainment (CFM)
Straight Stream	150	50	3440
Straight Stream ‘O’	150	50	10441
Narrow Fog	150	50	17645
Narrow Fog ‘O’	150	50	22873
Smooth Bore	150	50	3319
Smooth Bore ‘O’	150	50	9738

Table 4.6: Hose stream type comparison for interior 1.5” nozzles.

Air entrainment is dependent on structure size, compartmentation, and ventilation configurations.

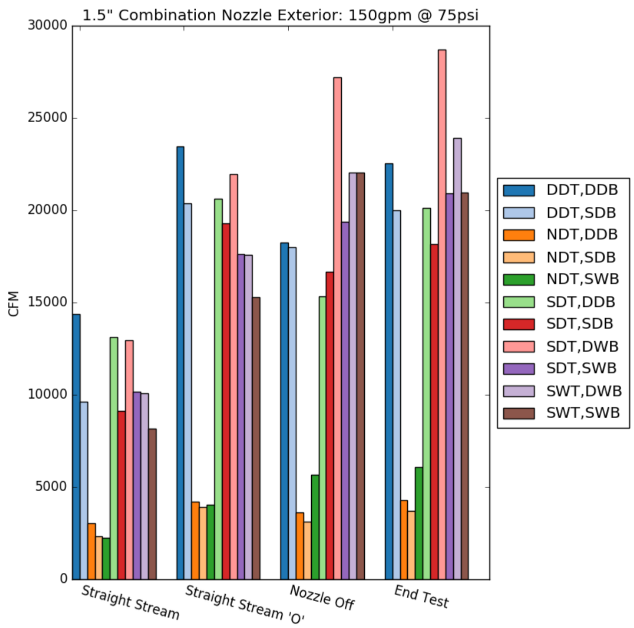


Figure 4.19: Figure showing various vent configuration of an exterior 1.5" combination nozzle.

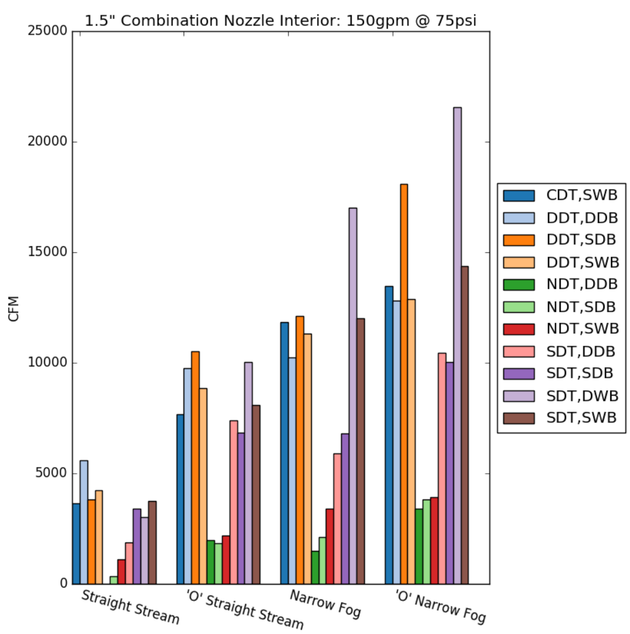


Figure 4.20: Figure showing various vent configuration of an interior 1.5" combination nozzle.

Increases in nozzle movement increase overall air entrainment A single test was conducted to determine the differences in air entrainment when a given 1.5 in. smooth bore nozzle of fixed flow rate of 210 gpm and pressure of 50 psi was utilized with a 'O' pattern at different rotation speeds. Using a metronome, the 'O' pattern was applied at 50, 100, and 150 revolutions per minute. This test was conducted at the fixed interior setback distance of 18 ft. from the tip of the nozzle to the ventilation opening.

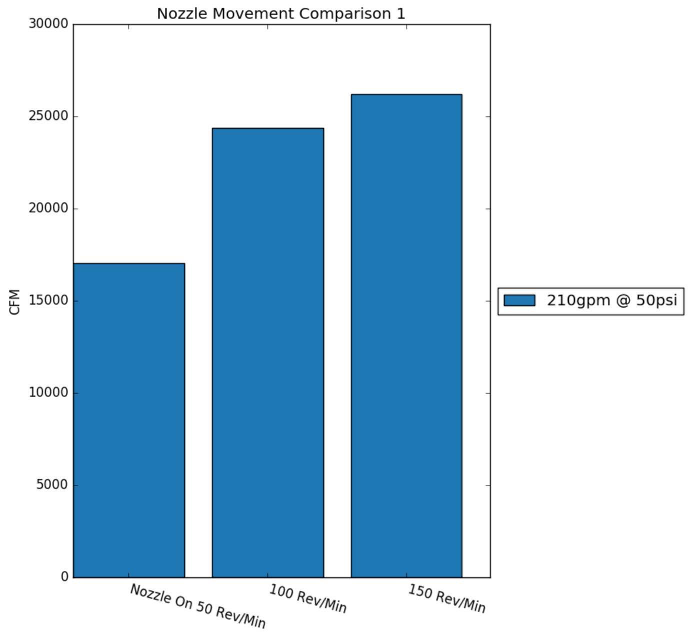


Figure 4.21: Figure showing various rotation speeds of an 'O' pattern for an interior 1.5" smooth bore nozzle with a 1" tip.

As shown in the figure above, an increase in the rotation speed while applying a specified pattern yeilded an increase in the air entrainment seen within the stream.

Differing nozzle movement patterns have little effect on overall air entrainment.

Various tests were conducted to determine how different nozzle movements effect the overall air entrainment. Common nozzle movements seen in the fire service today are the ‘O’, ‘Z’, and ‘n’ patterns. Differences in these were examined utilizing nozzles of various flow rates and pressures for both 1.5 in. combination as well as 1.5 in. smooth bore nozzles from the interior of the structure at a fixed setback distance of 18 ft. The results show that there is less than a +/- 1000 CFM difference between the patterns across the various nozzle types and settings.

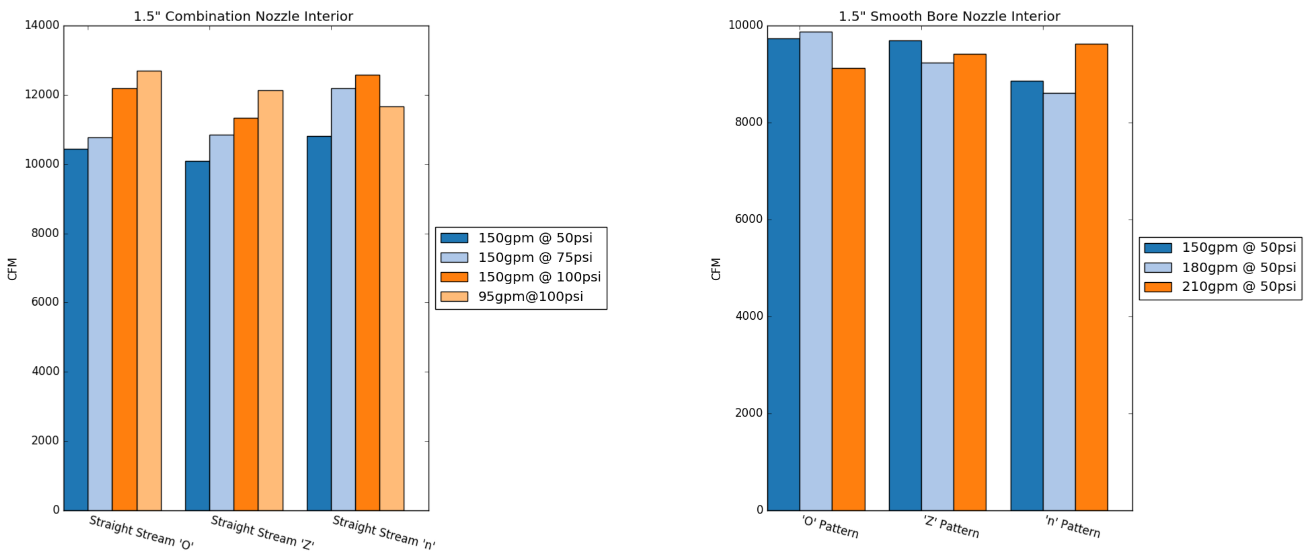


Figure 4.22: Figures showing air entrainment given various nozzle movements for interior 1.5” nozzles.

A test was also conducted to determine if a standard utilized nozzle movement in an ‘O’ pattern would differ from a ‘Spray and Pray’ technique in which the nozzle operator moves the hose stream across the ventilation opening as fast as possible with no discerible pattern. Once again, the results showed little to no difference in the air entrainment.

Because the results very clearly showed little to no difference in air entrainment from varying nozzle movements across multiple nozzle types and settings, a single nozzle movement pattern (‘O’) was utilized for the remainder of the experiments conducted.

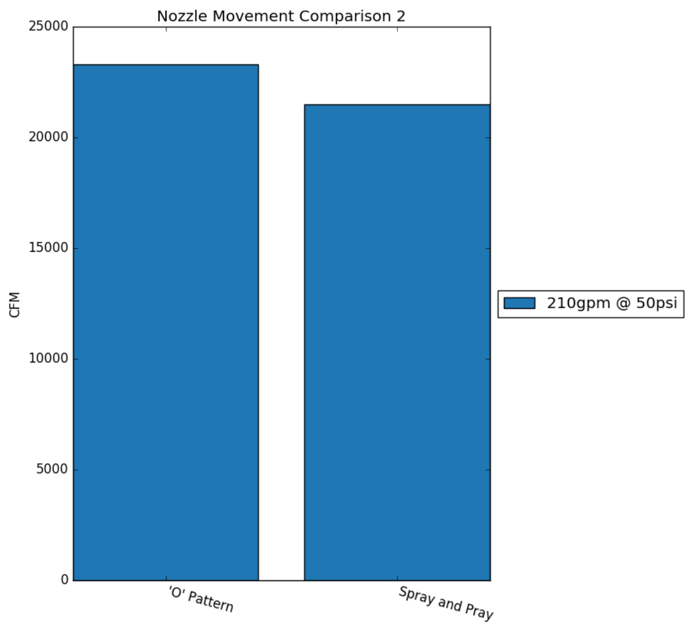


Figure 4.23: Figure showing common pattern compared to no discernible pattern for an interior 1.5" smooth bore nozzle with a 1" tip.

Air entrainment is dependent on the distance of the nozzle to the ventilation opening.

One of the preliminary experiments conducted was the setback comparison tests in which a 1.5 in. combination nozzle at two different pressures (100 psi and 50 psi) was utilized in a fixed pattern at varying distances from the ventilation opening. The nozzle was moved back from the opening at intervals 3, 6, 9, 12, and 15 ft. to see the effect on air entrainment in the hose stream.

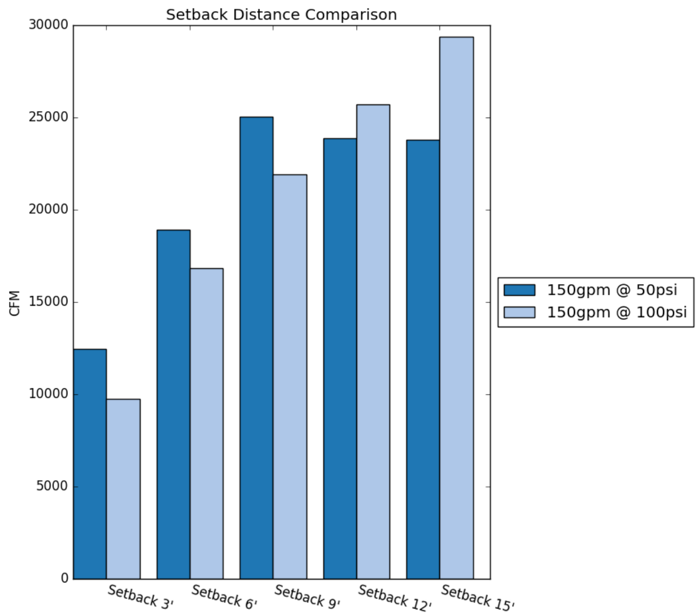


Figure 4.24: 1.5" Combination Nozzle, Setback Distance Comparison

With a fixed nozzle movement, the tests showed that increasing the distance between the tip of the nozzle and the ventilation opening increased the entrainment in the hose stream. The further the nozzle from the vent allowed for a more broken and 'wider' stream, which in turn, encompassed more of the opening.

5 Water Distribution Experiments

The experiments to determine the distribution of water within a compartment consisted of several test series to gain a wholelistic view of how varying different components, either with the structure or equipment utilized, affected the end result.

5.1 Test Setup

5.1.1 Structures

Testing for the water distribution experiments was conducted at the UL - Headquarters in Northbrook, IL. A purpose built compartment with a small attached hallway and moveable staircase was constructed to sit atop the ADD apparatus.

Figure 5.1: Water Distribution Test Structure and ADD Apparatus

The elevated compartment was build on an existing concrete slab located in one of the rooms within the UL large fire lab. It was designed to simulate a room of size commonly found in residential structures. The size and orientation of the ADD apparatus dictated the overall size of the compartment which measured 15 ft 4 in. by 10 ft 5 in. finished interior dimensions. The compartment was wood frame construction with 2 in. by 4 in. studs and track set to 16 in. centers with a interior height measuring 8 ft 1 1/8 in. rough. The walls and ceiling were lined with 1/2 in. durarock cement board atop 1/2 in. plywood. The ceiling joists were 2 in. by 6 in. set to 16 in. on center.

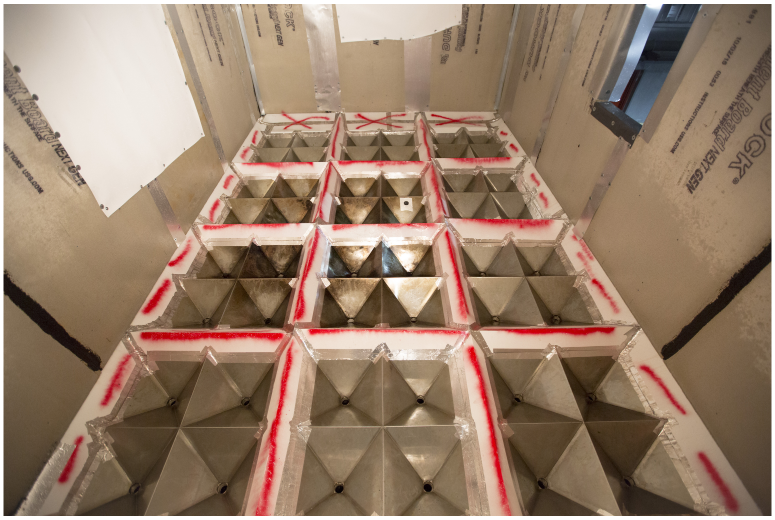


Figure 5.2: ADD Interior Layout with Flashing

There was no floor constructed in the compartment as the top of the ADD aparatus served as such. The gaps between the collection bins were covered by flashing which was folded to divert the water evenly in each bin to ensure adequate distribution results. The gaps between the outer collection bins and the walls of the structure were also covered with flashing to ensure all water directed into the structure was collected in the appropriate bins. The interior layout of the structure and use of flashing can be seen in Figure 5.2.

The compartment featured two ventilation openings, one doorway measuring 3 ft by 6 ft 8 in. which opens to the interior hallway, and one window measuring 2 ft by 4 ft which opens to the exterior of the compartment. A moveable staircase and landing was constructed to provide access to either the interior hallway of the compartment or provide a simulation of a first floor exterior attack. The dimensions of the both the staircase and overall compartment can be seen in the dimensioned drawings below.

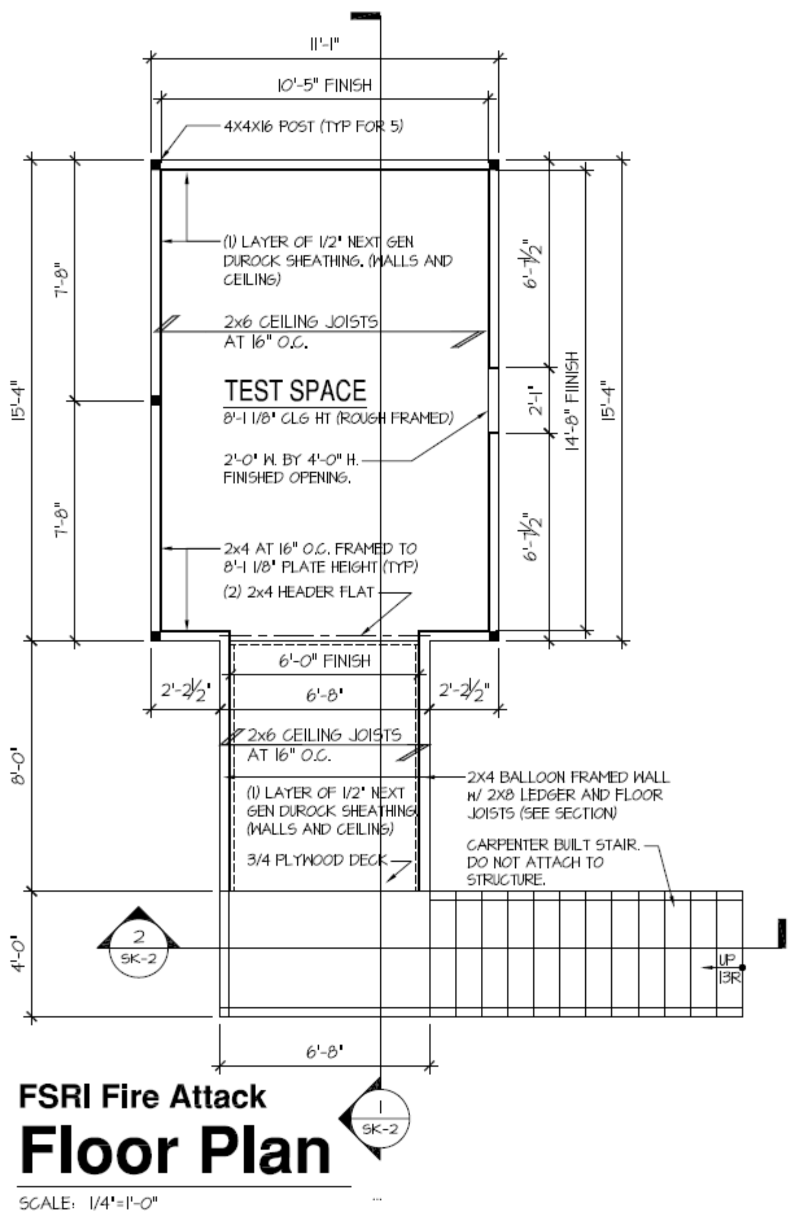
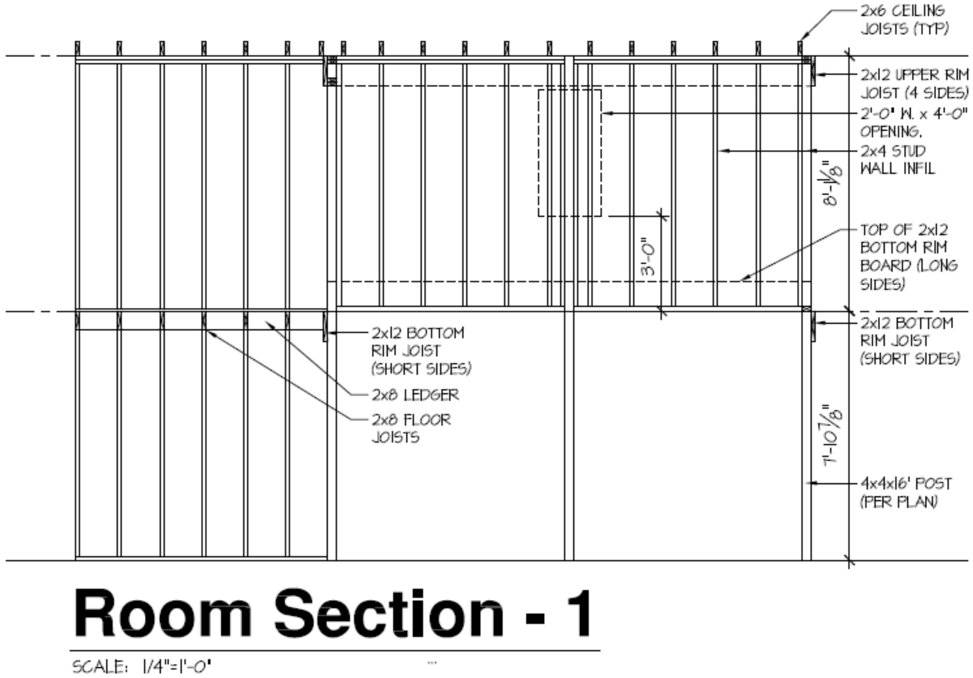


Figure 5.3: ADD Top View



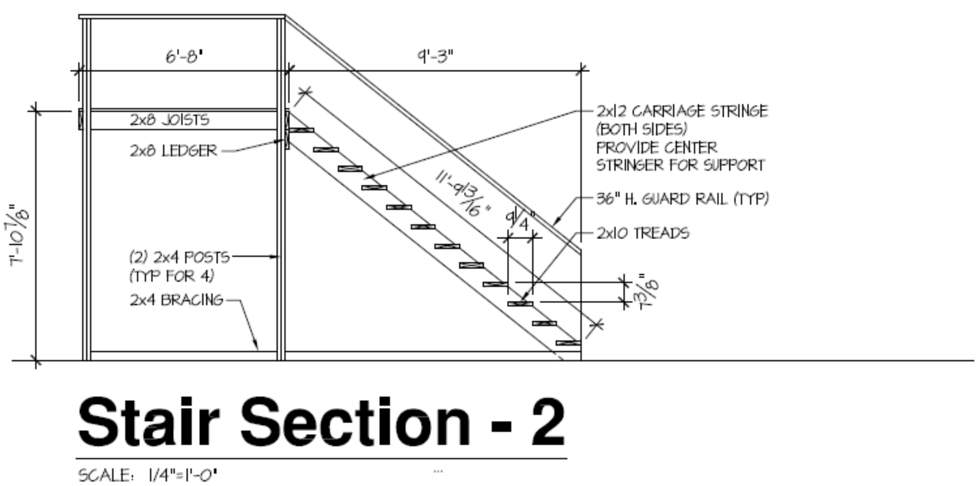


Figure 5.4: ADD Side View

5.1.2 Instrumentation

In order to obtain the results for Part I of this study, sensors were installed in the test fixtures to record measurements throughout the experiments. The instrumentation used varied between the air entrainment and the water distribution testing. The instrtuments, and associated uncertainty, used for each test series is outlined below.

UL operates a fire sprinkler spray density measurement instrument known as the Actual Delivered Density (ADD) apparatus. The first prototype of the apparatus was built at Factory Mutual in mid-1980s, in order to enable manufacturers to design sprinklers that are effective at ever-increasing commodity storage heights [1, 2]. The UL ADD apparatus, constructed in 2003, represents the 3rd generation design within the sprinkler industry.

The concept of the ADD measurement is to simulate the top surface of an array of high storage commodity, and measure the flux of water on this top surface as a result of the spray pattern discharged by one or more sprinklers. The ADD apparatus is designed to perform these measurements while simulating different sized rack storage fires (500 kW to 2.5 MW, in increments of 500 kW). This allows for insight into the effect of a real fire plume on sprinkler spray distribution. Typically, the ADD apparatus is used to simulate commodity underneath one, between two, or between four fire sprinklers. For sprinkler manufacturers, the ADD apparatus can be used as a screening tool for new automatic sprinkler designs. The fire capabilities were not utilized during any of the water distribution experiments.

The UL ADD apparatus is comprised of one main array and two satellite arrays of heavy steel framework. The main array consists of 32 water barrels and water pan collection assemblies while each satellite array contains 8 barrels and collection assemblies. All barrels are of 30-gallon capacity and are connected by a 2-inch diameter hose to a 20 inch by 20 inch inverted square pyramid shaped stainless steel water collection pan above. In total, there are 48 total collection pans/barrels. Differential pressure transducers connect to the bottom of each water collection barrel via flexible tubing. The water level in a given barrel is determined by the head pressure measured by the transducer. The water collection rate is calculated based the change in head pressure over time. As Figure 5.5 shows, collection assemblies are arranged into 2x2 arrays so that each group of 4 collection assemblies represents one pallet load of commodity.

(a) Collection Barrels

(b) Collection Pans

Figure 5.6: ADD Collection Assembly

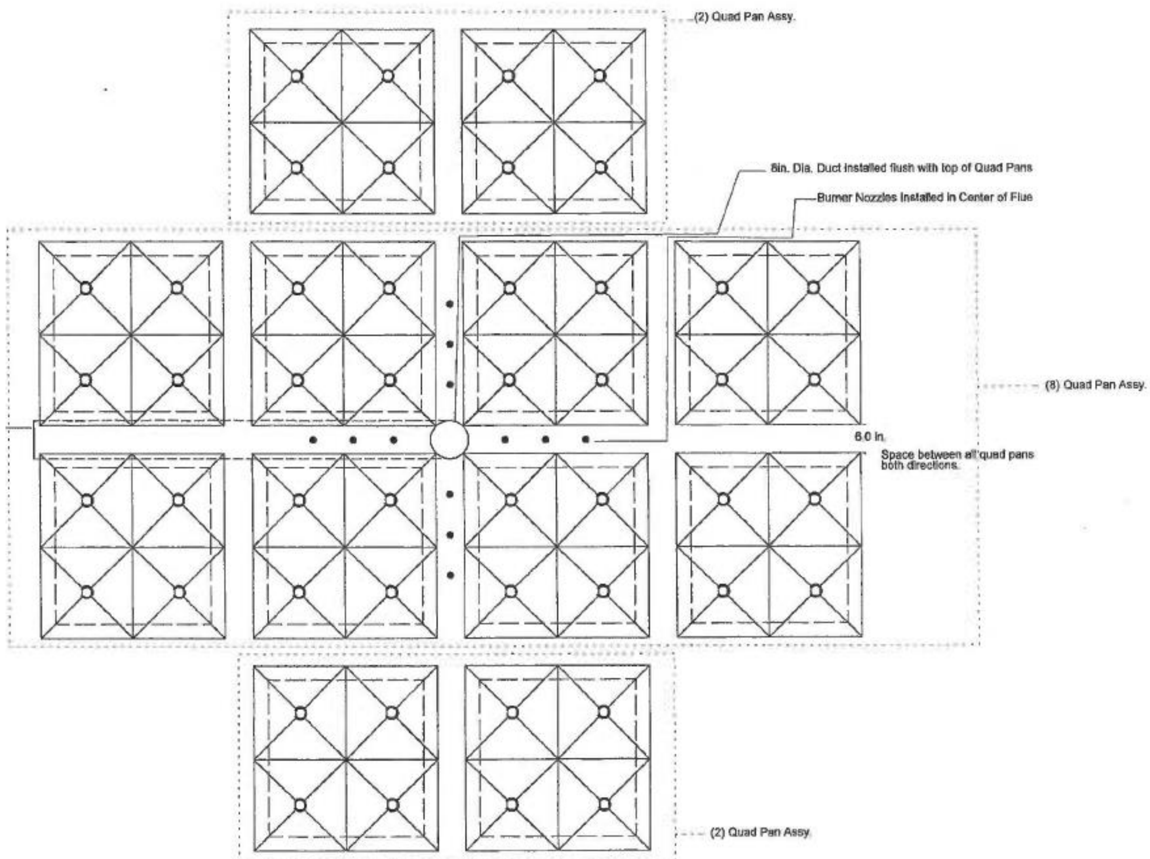


Figure 5.5: Top-down schematic view of the ADD apparatus

Each collection barrel is also connected to a pneumatic drain valve which can be actuated to automatically drain each barrel at the conclusion of each experiment. Figure 5.5 also shows flue spaces, as well as an 8 inch duct in the center of the array, which enable the entrainment necessary to simulate a rack-storage fire. A blower supplies air to the center duct to simulate the momentum of the plume of a fire that has reached the top of a rack storage array. Within the center flue spaces of the main array, 12 spray nozzles are angled toward the center to provide the heptane spray used to simulate the commodity fire. Each of the three arrays contains a pipe network and water spray nozzles for cooling the underside of the water collection pans. Cooling is providing during fire simulation to prevent measurement error due to the evaporation of collected water from the hot steel pans, and to prevent absorbed thermal energy from damaging the steel pans.

In December of 2015, data was collected in order to estimate the uncertainty associated with the water distribution experiments performed using the ADD apparatus. Each water collection assembly was filled to capacity while recording pressure transducer measurements as well as data from a calibrated turbine flowmeter (with less than 1 % measurement uncertainty). Although the design of each water collection assembly is the same, the measurement performance across the entire apparatus varied in terms of bias and precision. Overall, the water collection assemblies reported volume with a bias of 0.5 gallons less than the volume calculated using the flow meter and with a precision of +/- 2.4 gallons. Using the same data, it is estimated that the real-time (1 Hz) flowrate calculated by the ADD apparatus reported 0.1 gpm less than the turbine flow meter, and with a precision +/- 0.4 gpm.

The recorded data was used to compute a total amount of water in a given bin with the units of gallons.

5.1.3 Measurement Locations

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

The Actual Delivered Density apparatus, described above, was utilized to measure the amount and dsitribution of water flowed into the compartment constructed specifically for this testing. By placing the ADD apparatus beneath the compartment, all of the water flowed was collected and measured. The collection bins were numbered according to their location within the apparatus which allowed a 3D map of the water flow to show the distribution.

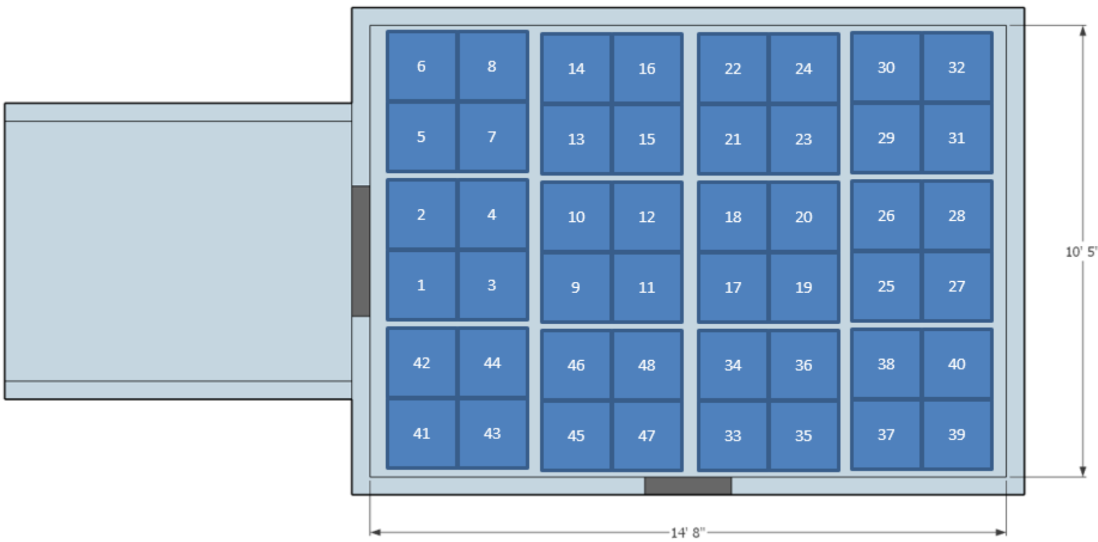


Figure 5.7: Bin Numbers and Locations

Line Size	Nozzle	Tip (in)	Nozzle Pressure (psi)	Approximate Flow Rate (gpm)
1 3/4 in.	Smooth Bore	1	50	210
	Smooth Bore	15/16	50	180
	Smooth Bore	7/8	50	150
	Fog		100	100
	Fog		100	150
	Fog		75	150
	Fog		50	150
2 1/2 in.	Smooth Bore	1 1/8	50	260
	Smooth Bore	1 1/4	50	320
	Fog		100	250
	Fog		75	250
	Fog		50	250
Portable Monitor	Smooth Bore	1 3/8	80	500
	Fog		75	500
Master Stream	Smooth Bore	1 1/2	80	600
	Smooth Bore	1 3/4	80	800
	Fog		100	500-1000

Table 5.1: Nozzle Selection

5.1.4 Equipment Used

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

5.2 Experiments Conducted

The water distribution experiments incorporated both interior and exterior fire attack utilizing the various nozzles and configurations chosen by the technical panel.

The interior testing was simulating a fire on the same floor as the attack crew in which the suppression operations were conducted from an adjoining room/hallway. At this position, the nozzle type as well as nozzle direction and application pattern were varied to determine the water distribution within the compartment. The nozzle directions and associated terminology can be seen in Figure 5.8.

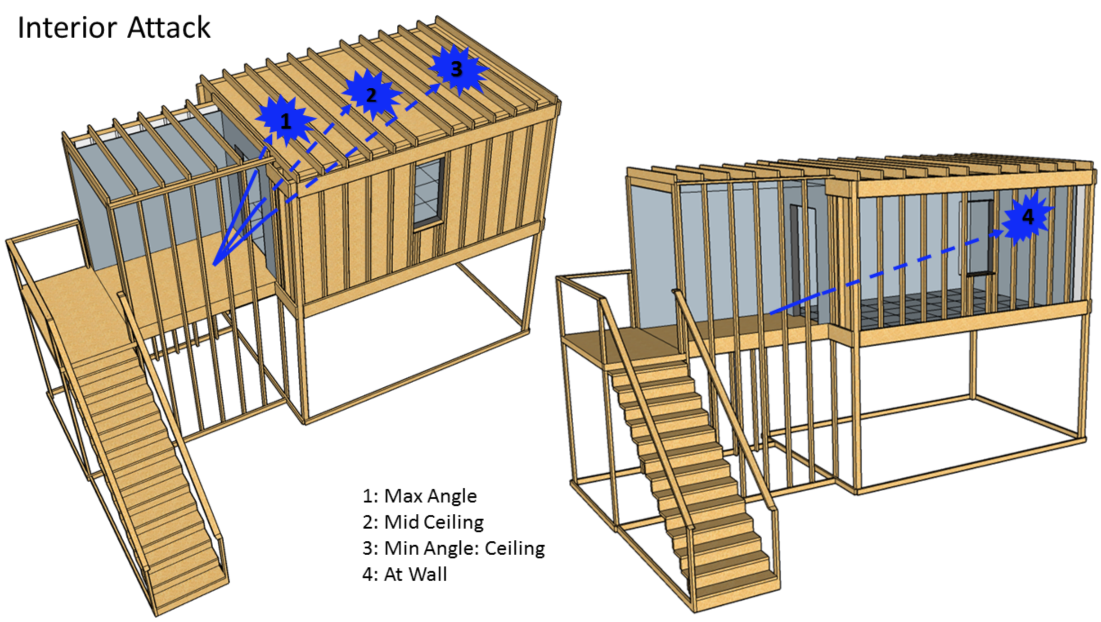


Figure 5.8: Nozzle Direction, Interior Attack

Nozzle Position	Nozzle Pattern	Nozzle Direction	Nozzle Type	Nozzle Pressure (psi)	Flow Rate (gpm)
At Room Entrance	Fixed	Mid Ceiling	Straight Stream	100	125
At Room Entrance	O	Mid Ceiling	Straight Stream	100	125
At Room Entrance	Z	Mid Ceiling	Straight Stream	100	125
At Room Entrance	T	Mid Ceiling	Straight Stream	100	125
At Room Entrance	Inverted U	Mid Ceiling	Straight Stream	100	125
At Room Entrance	Fixed	Mid Ceiling	Fog	100	125
At Room Entrance	Fixed	Mid Ceiling	Straight Stream	100	150
At Room Entrance	O	Mid Ceiling	Straight Stream	100	150
At Room Entrance	Fixed	Mid Ceiling	Fog	100	150
At Room Entrance	O	Mid Ceiling	Fog	100	150
At Room Entrance	Fixed	Mid Ceiling	Straight Stream	75	150
At Room Entrance	O	Mid Ceiling	Straight Stream	75	150
At Room Entrance	Fixed	Mid Ceiling	Fog	75	150
At Room Entrance	O	Mid Ceiling	Fog	75	150
At Room Entrance	Fixed	Mid Ceiling	Straight Stream	50	150
At Room Entrance	O	Mid Ceiling	Straight Stream	50	150
At Room Entrance	Fixed	Mid Ceiling	Fog	50	150
At Room Entrance	O	Mid Ceiling	Fog	50	150
At Room Entrance	Fixed	At Wall	15/16 Smooth Bore	50	180
At Room Entrance	O	At Wall	15/16 Smooth Bore	50	180
At Room Entrance	Fixed	Mid Ceiling	15/16 Smooth Bore	50	180
At Room Entrance	O	Mid Ceiling	15/16 Smooth Bore	50	180
At Room Entrance	Fixed	Max Angle	15/16 Smooth Bore	50	180
At Room Entrance	O	Max Angle	15/16 Smooth Bore	50	180
At Room Entrance	Fixed	At Wall	Straight Stream	100	150
At Room Entrance	O	At Wall	Straight Stream	100	150
At Room Entrance	Fixed	Max Angle	Straight Stream	100	150
At Room Entrance	O	Max Angle	Straight Stream	100	150
At Room Entrance	O	Mid Ceiling	Fog	100	125
At Hall Entrance	O	At Wall	Straight Stream	100	150
At Hall Entrance	Z	At Wall	Straight Stream	100	150
At Hall Entrance	Pulsing	At Ceiling	Straight Stream	100	150

Table 5.2: Interior Fire Attack Distribution Experiments

The exterior testing included both an attack from the fire floor as well as the floor below. These were referred to as first floor and second floor attacks for the purpose of this testing. The construction of the compartment featured a moveable staircase to allow for the variation between first floor and second floor suppression. The exterior testing simulated a single room of fire in which a transitional, or exterior attack, was made by suppression crews. As done in the interior testing, both the nozzle type as well as the nozzle direction and application pattern were varied for comparison. The differences in first floor and second floor attacks can been seen in Figures 5.9 and 5.10.

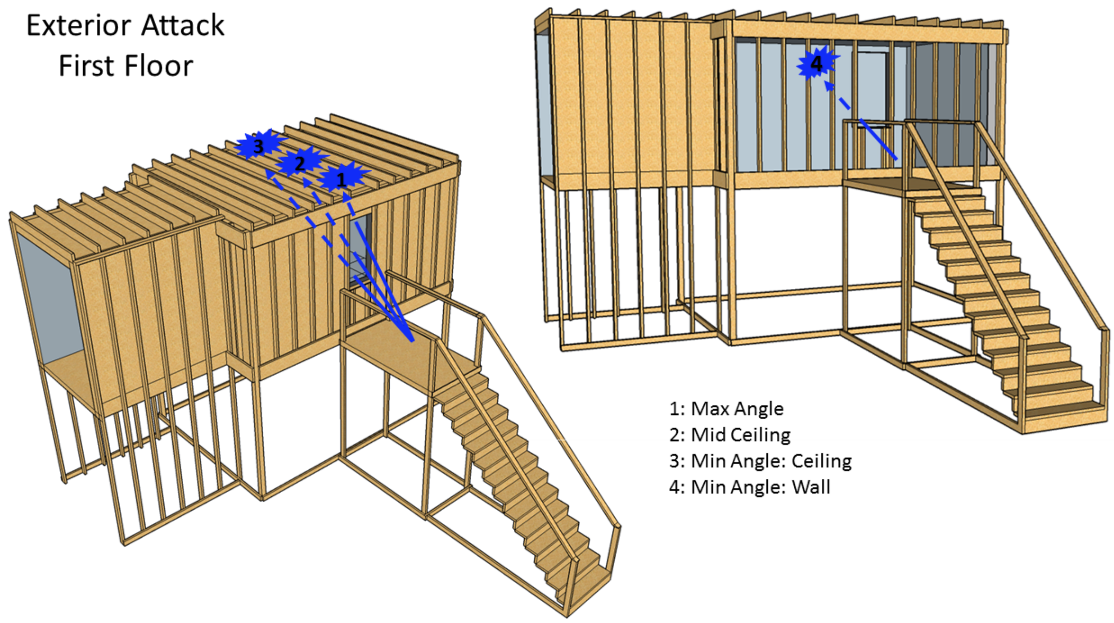


Figure 5.9: Nozzle Direction, Exterior 1st Floor Attack

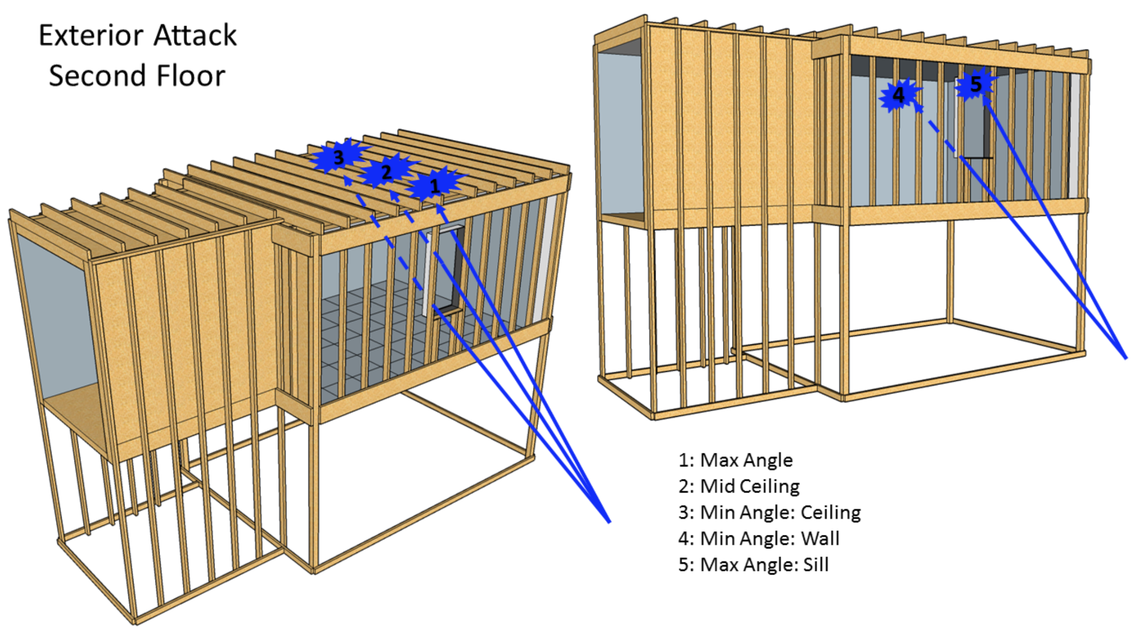


Figure 5.10: Nozzle Direction, Exterior 2nd Floor Attack

Nozzle Position	Nozzle Pattern	Nozzle Direction	Nozzle Type	Nozzle Pressure (psi)	Flow Rate (gpm)
Second Floor	Fixed	Max Angle	15/16 Smooth Bore	50	180
Second Floor	Sweeping	Max Angle	15/16 Smooth Bore	50	180
Second Floor	Fixed	Mid Ceiling	15/16 Smooth Bore	50	180
Second Floor	Fixed	Min Angle: Ceiling	15/16 Smooth Bore	50	180
Second Floor	Fixed	Min Angle: Wall	15/16 Smooth Bore	50	180
Second Floor	Fixed	Max Angle	7/8 Smooth Bore	50	150
Second Floor	Fixed	Max Angle	1 Smooth Bore	50	210
Second Floor	Fixed	Max Angle	Straight Stream	100	150
Second Floor	Sweeping	Max Angle	Straight Stream	100	150
Second Floor	Wide Sweep	Max Angle	Straight Stream	100	150
Second Floor	Fixed	Max Angle: Sill	Straight Stream	100	150
Second Floor	Fixed	Mid Ceiling	Straight Stream	100	150
Second Floor	Fixed	Min Angle: Ceiling	Straight Stream	100	150
Second Floor	Fixed	Min Angle: Wall	Straight Stream	100	150
Second Floor	Fixed	Max Angle	Fog	100	150
Second Floor	Comb (Fixed then O)	Max Angle	Fog	100	150
First Floor	Fixed	Max Angle	15/16 Smooth Bore	50	180
First Floor	Sweeping	Max Angle	15/16 Smooth Bore	50	180
First Floor	Fixed	Mid Ceiling	15/16 Smooth Bore	50	180
First Floor	Fixed	Min Angle: Ceiling	15/16 Smooth Bore	50	180
First Floor	Fixed	Min Angle: Wall	15/16 Smooth Bore	50	180
First Floor	Fixed	At Wall	15/16 Smooth Bore	50	180
First Floor	Fixed	Max Angle	7/8 Smooth Bore	50	150
First Floor	Fixed	Max Angle	1 Smooth Bore	50	210
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Sweeping	Max Angle	Straight Stream	100	150
First Floor	Wide Sweep	Max Angle	Straight Stream	100	150
First Floor	Fixed	Mid Ceiling	Straight Stream	100	150
First Floor	Fixed	Min Angle: Ceiling	Straight Stream	100	150
First Floor	Fixed	Min Angle: Wall	Straight Stream	100	150
First Floor	Fixed	At Wall	Straight Stream	100	150
First Floor	Fixed	Max Angle	Fog	100	150
First Floor	Comb (SS then Fog O)	Max Angle	Fog	100	150
First Floor	Fixed	Max Angle	Straight Stream	100	250
First Floor	Fixed	Min Angle: Ceiling	Straight Stream	100	250
First Floor	Fixed	Max Angle	1 1/4 Smooth Bore	50	260
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Fixed	Max Angle	Straight Stream	100	150
First Floor	Fixed	Max Angle	15/16 Smooth Bore	50	180
First Floor	Fixed	Max Angle	15/16 Smooth Bore	30	150
First Floor	Fixed	Max Angle	15/16 Smooth Bore	15	130
First Floor	Fixed	Max Angle	15/16 Smooth Bore	10	100
First Floor	Fixed	Max Angle	Straight Stream	50	150
First Floor	Fixed	Max Angle	Straight Stream	75	60
First Floor	Fixed	Max Angle	Straight Stream	50	185
First Floor	Fixed	Max Angle	Straight Stream	25	130

Table 5.3: Exterior Fire Attack Distribution Experiments

5.3 Analysis & Results

The results from the water distribution testing yielded several tactical considerations for suppression operations on the fireground. These are outlined below along with examples from the results. There are several key points to keep in mind when viewing the analysis.

The experiments conducted for water distribution were approximately 1 minute in length. This was dictated by the size of the collection barrels in the ADD apparatus. Each collection barrel was a total of 30 gallons. At the start of each test, there was a predetermined amount of water in the bottom of the barrel to ensure the sensors were able to record the intial water received during the testing. This 'predetermined' amount of water was recorded prior to the start of the test and was subtracted from the final total so that the end results were not affected by the measurement technique.

Because of these limitations, the results were only plotted to 20 gallons to minimize uncertainty. Additionally, various bins in various tests only received a final total of a couple gallons or less, and thus, appending the charts to 20 gallons, allows the viewer to more easily see these results. Please keep in mind that the intent of the testing was to determine the location of where water is going within the compartment and not necessarily the total quantity of water that reached a given area. As such, focus on the overall distribution and not the amount of water to a given area.

5.3.1 Repeatability

It should be noted that several tests were conducted to determine the repeatability of the experiments to ensure accuracy in the results as well as several tests utilizing 'live-fire' in order to detemine the applicability of this testing to the remainder of the study.

Four tests utilizing a straight stream nozzle flowing 150 gpm at 100 psi from the exterior first floor position directed into the structure with a maximum angle were conducted to determine the variance in results.

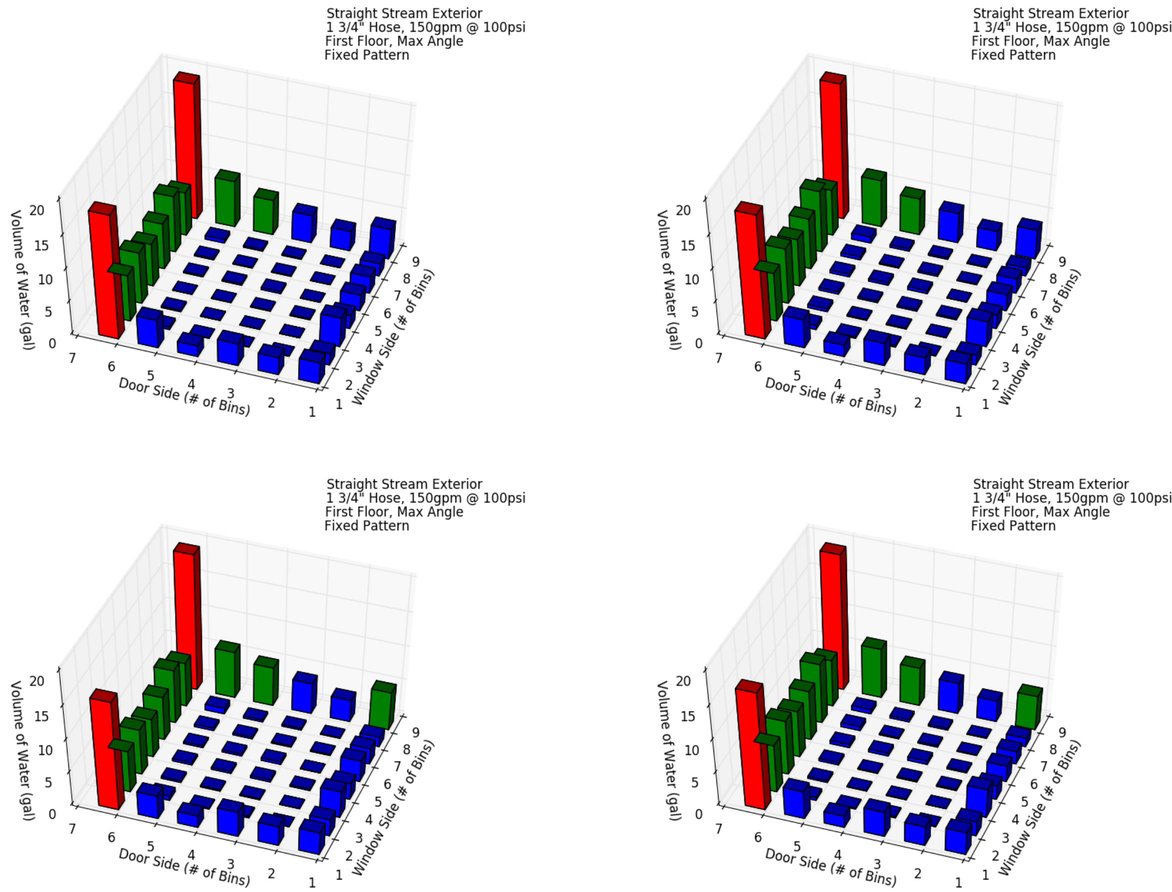


Figure 5.11: Figures showing repeatability in test results.

From these results, it is clear that the differences between the tests were minimal and thus determined that the measurement technique was repeatable.

Water distribution is dependent on nozzle type (smooth bore, straight stream, fog).

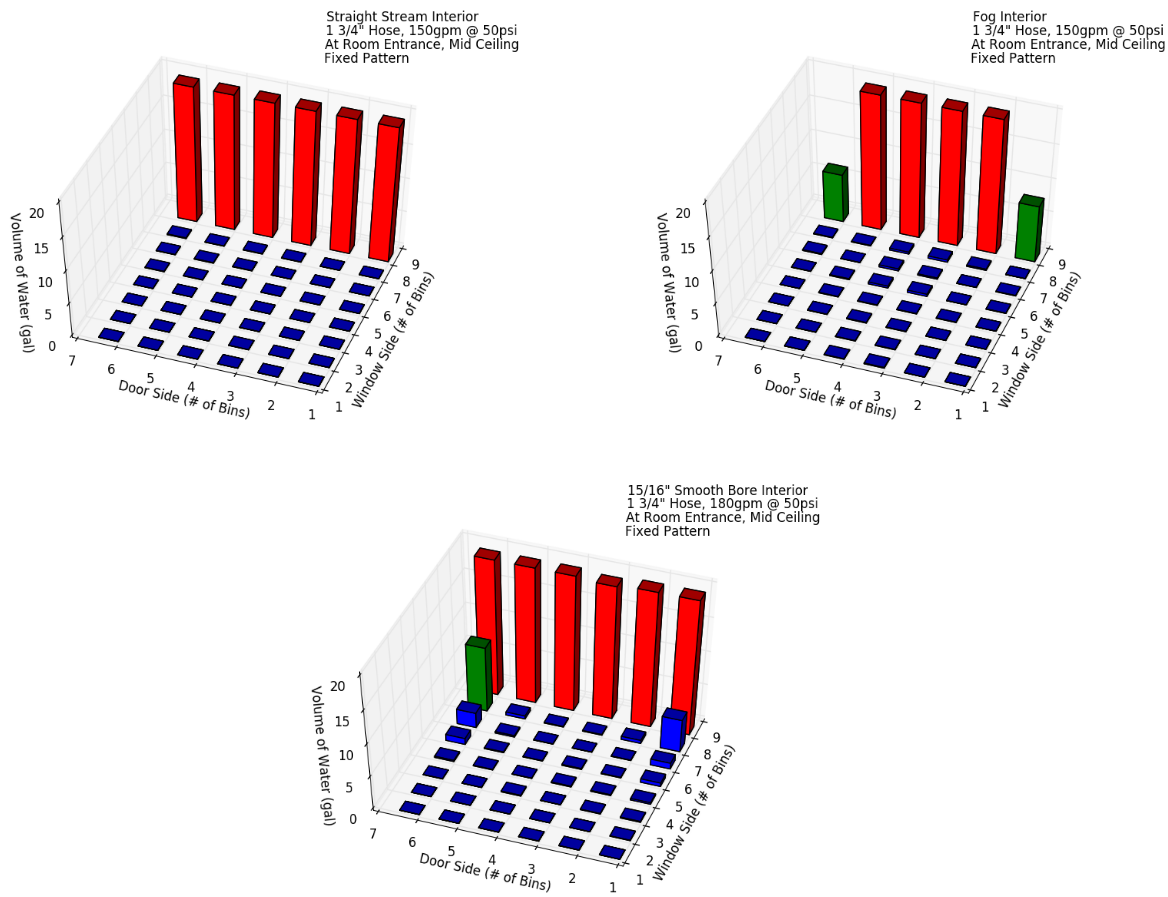


Figure 5.12: Figures showing distribution differences in varying nozzle types during an interior attack with a fixed pattern.

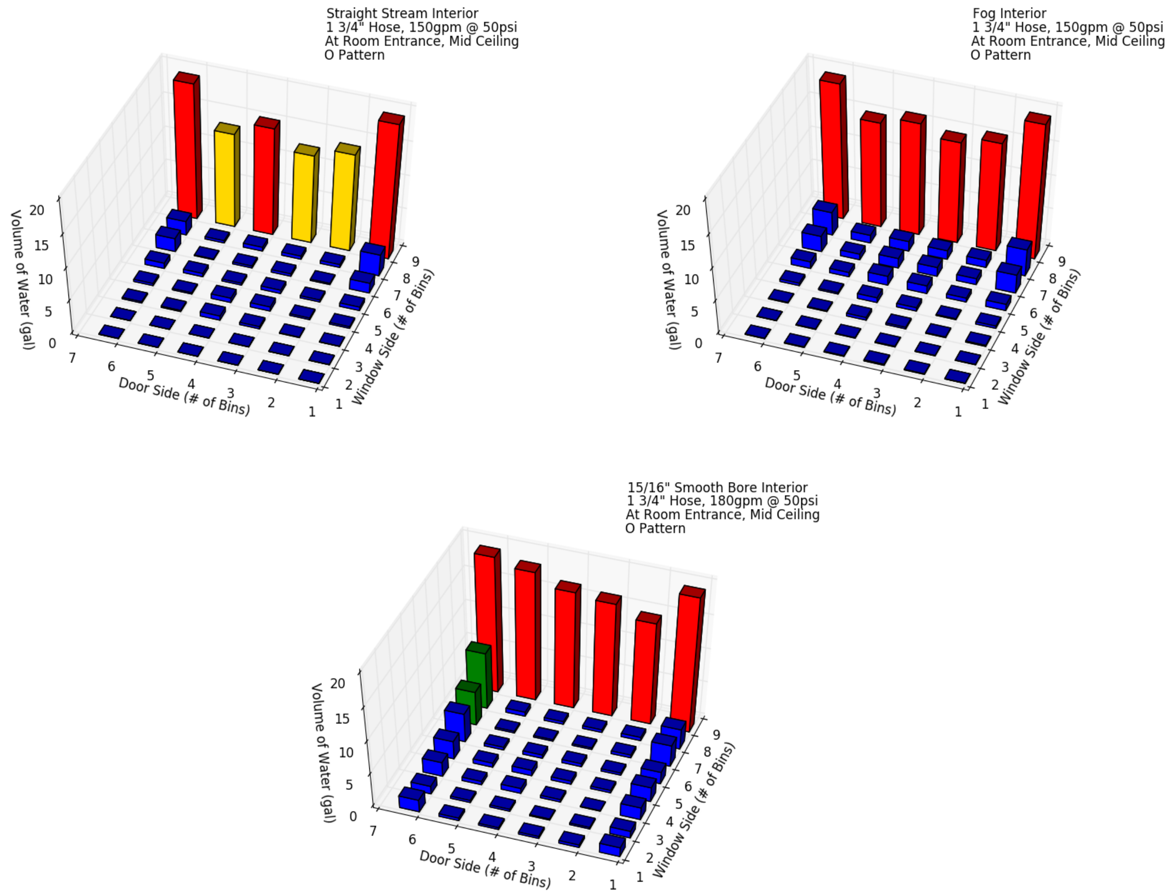


Figure 5.13: Figures showing distribution differences in varying nozzle types during an interior attack with an 'O' pattern.

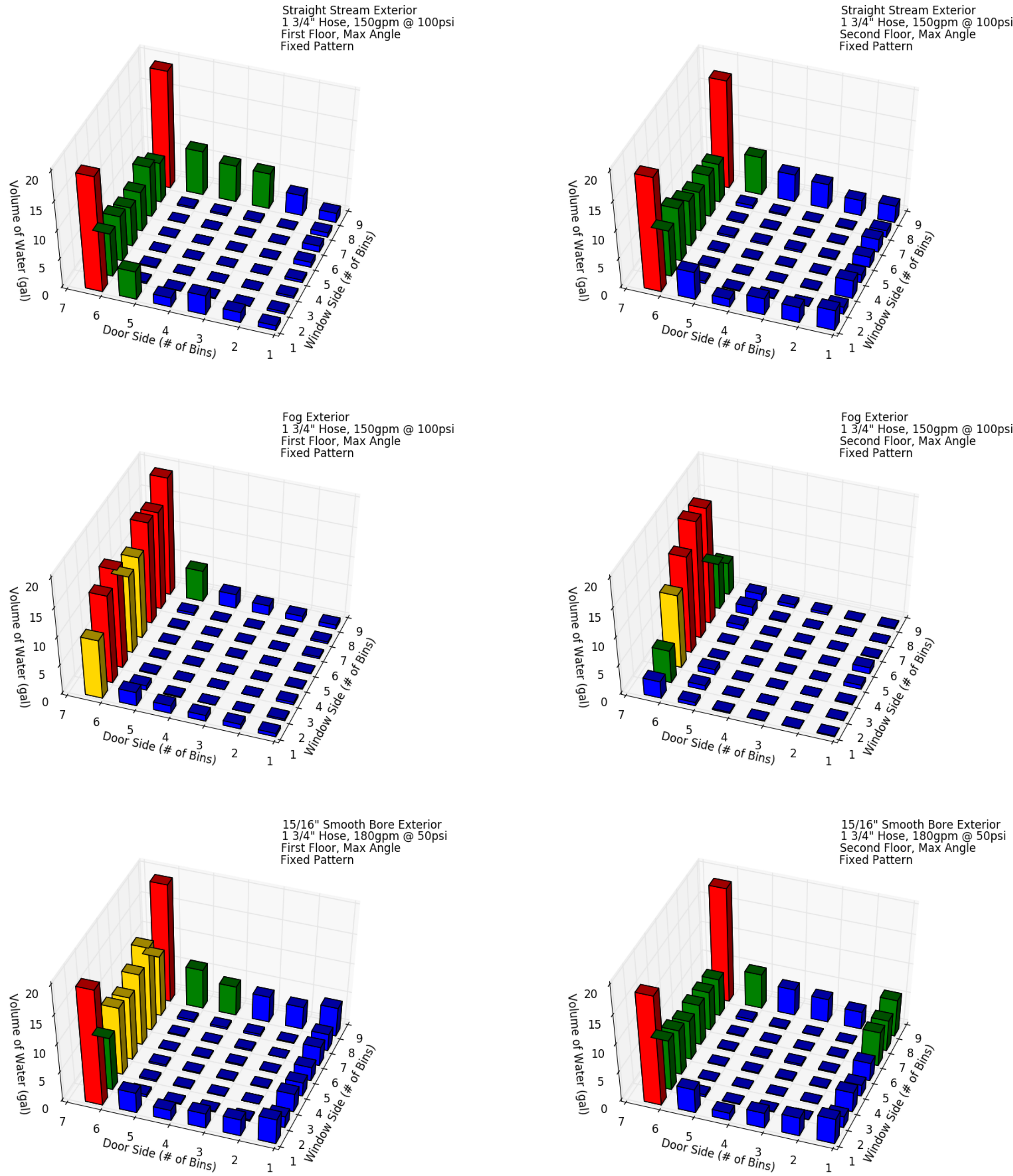


Figure 5.14: Figures showing distribution differences in varying nozzle types during an exterior attack with a fixed pattern.

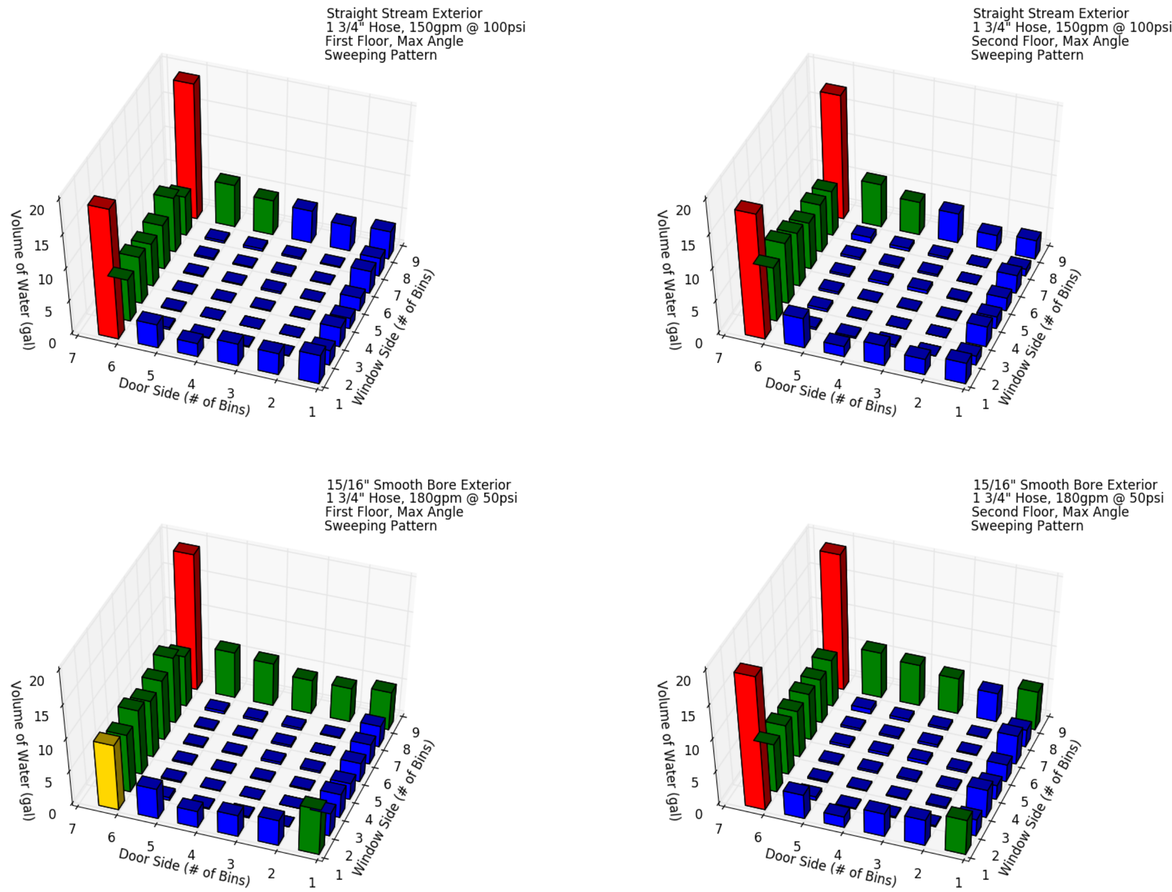
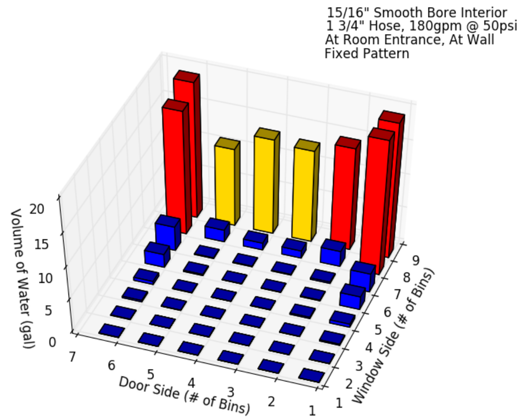
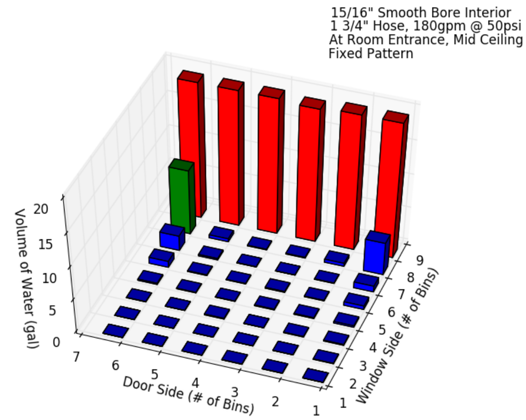


Figure 5.15: Figures showing distribution differences in varying nozzle types during an exterior attack with a sweeping pattern.

Water distrubtion is dependent on stream direction within a compartment (max angle, mid ceiling, min angle).





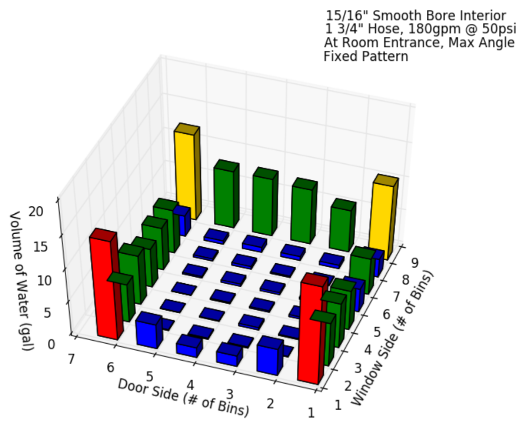


Figure 5.16: Figures showing distribution differences in varying nozzle directions during smooth bore attack with a fixed pattern.

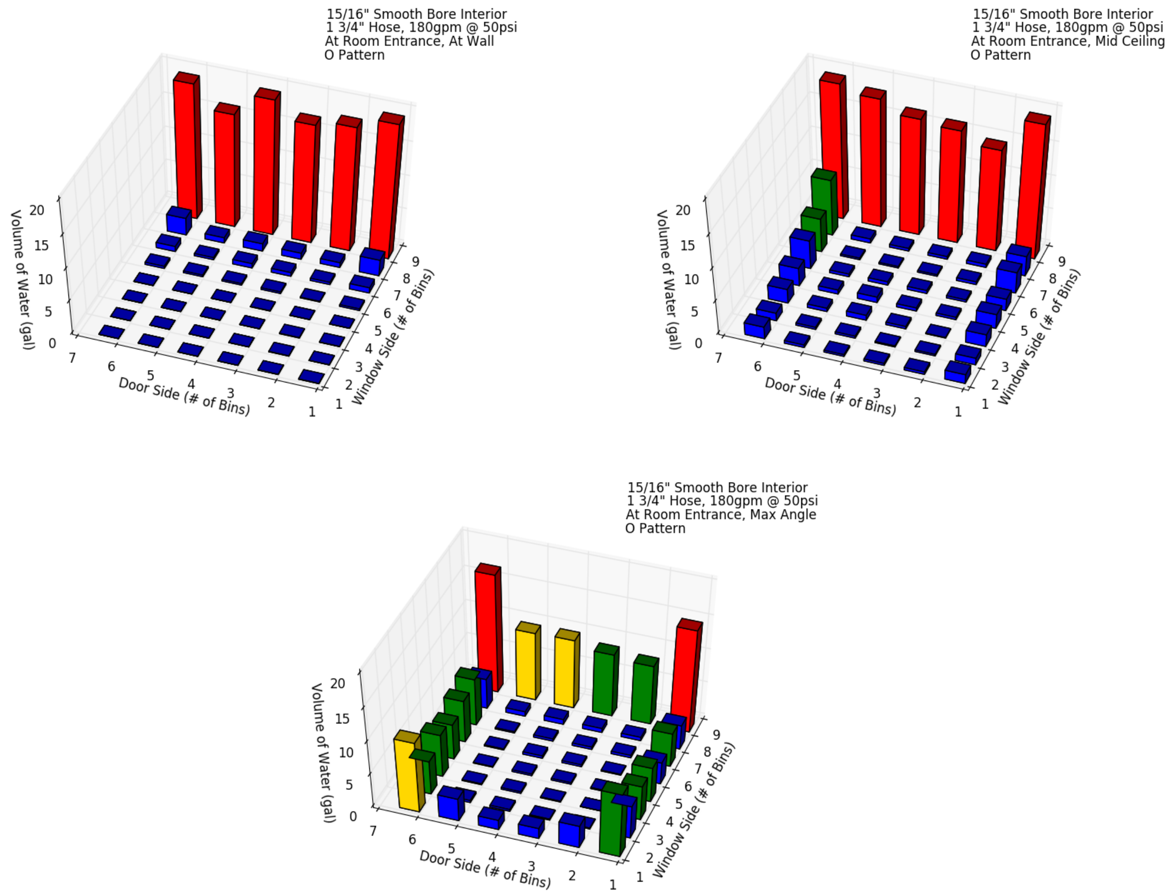


Figure 5.17: Figures showing distribution differences in varying nozzle directions during smooth bore attack with an ‘O’ pattern.

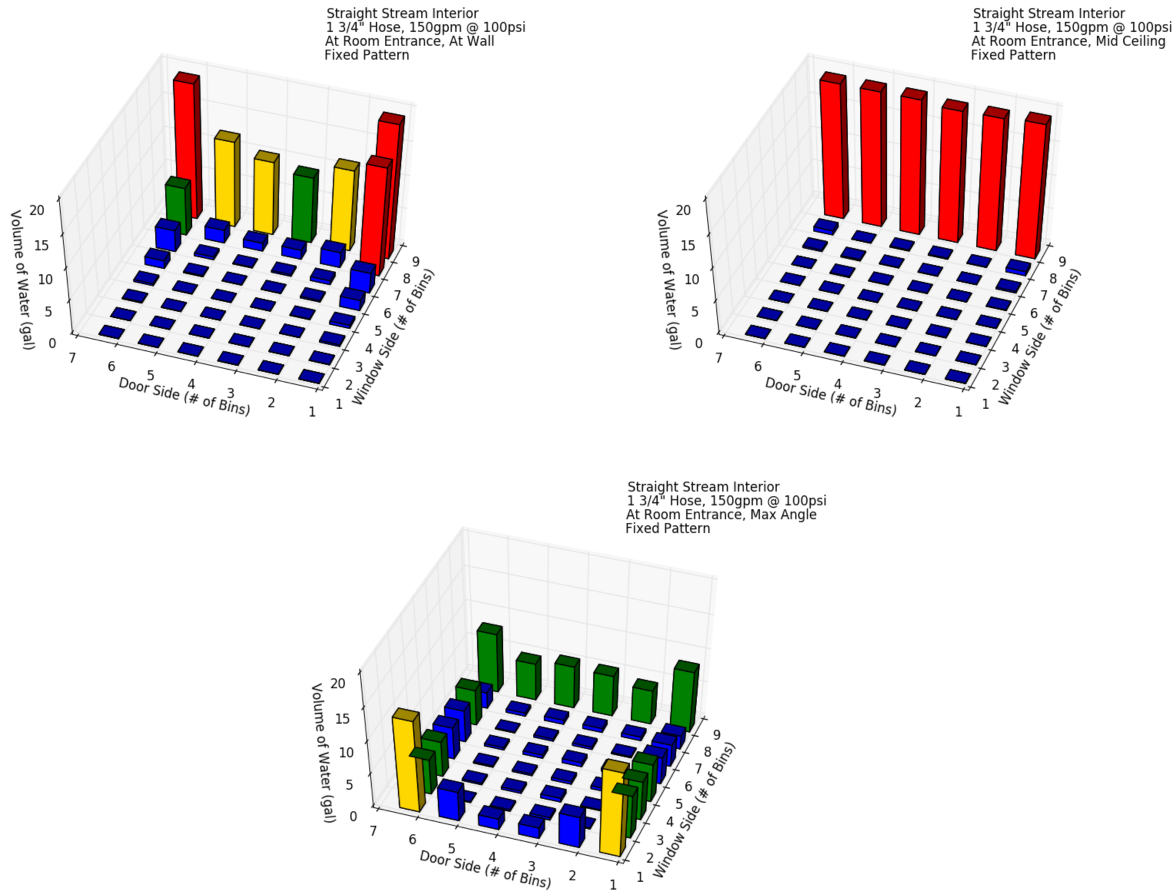


Figure 5.18: Figures showing distribution differences in varying nozzle directions during a straight stream attack with a fixed pattern.

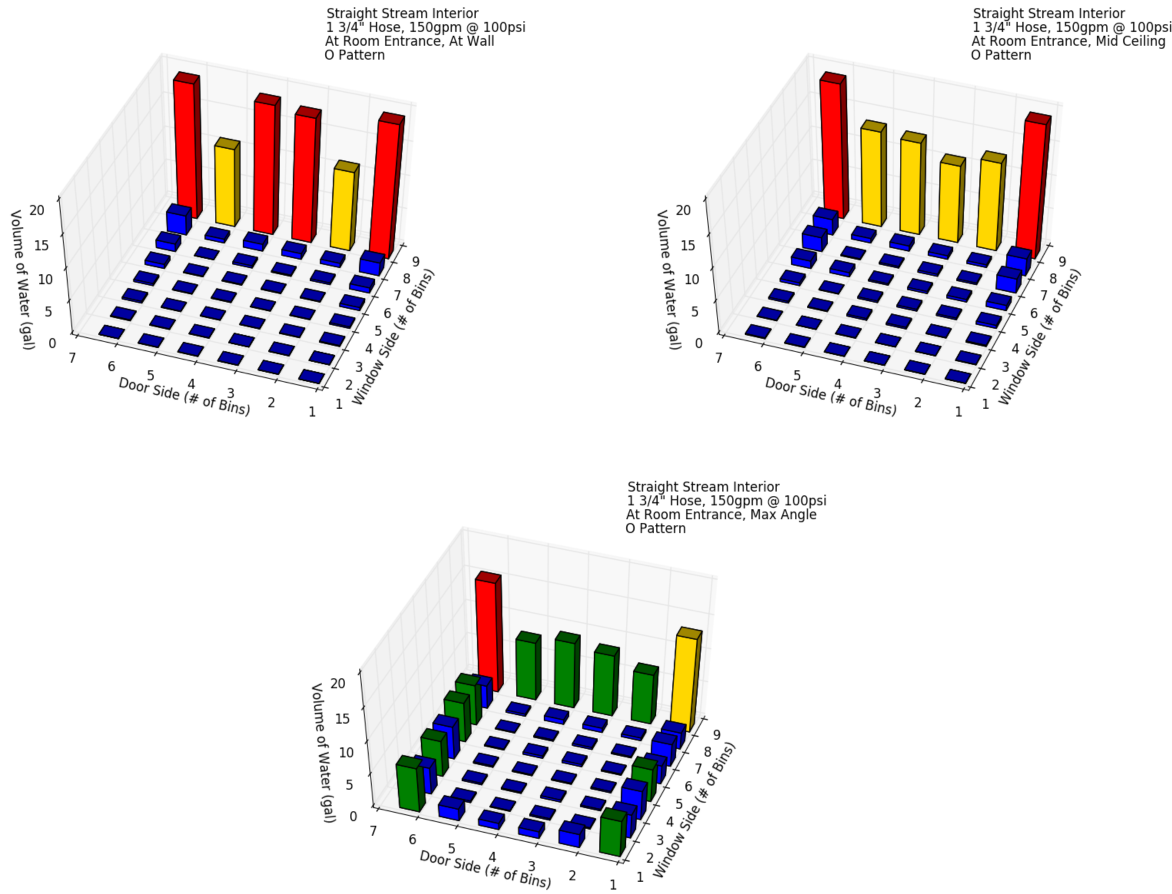


Figure 5.19: Figures showing distribution differences in varying nozzle directions during a straight stream attack with an ‘O’ pattern.

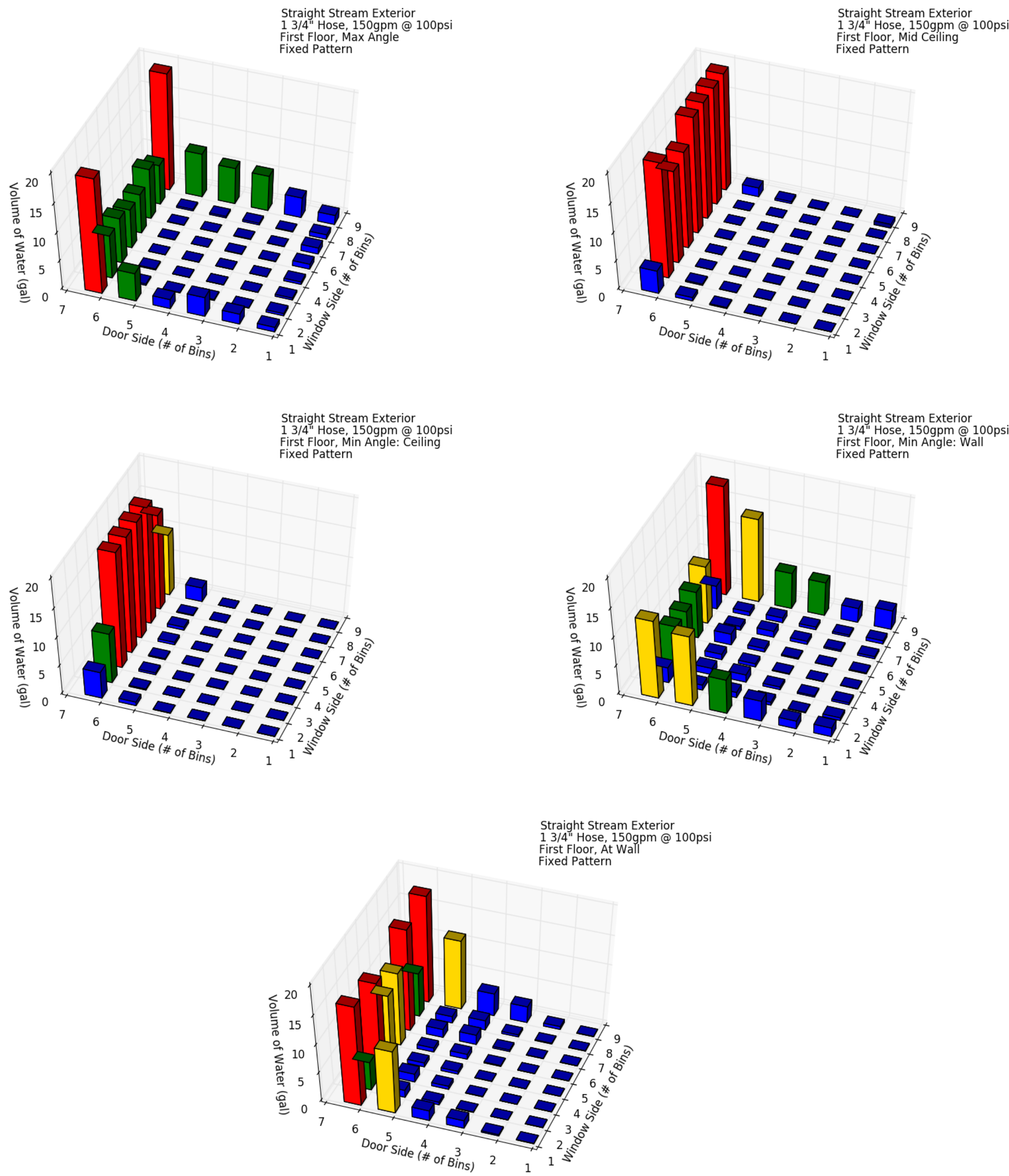


Figure 5.20: Figures showing distribution differences in varying nozzle directions during an exterior first floor attack with a SS fixed pattern.

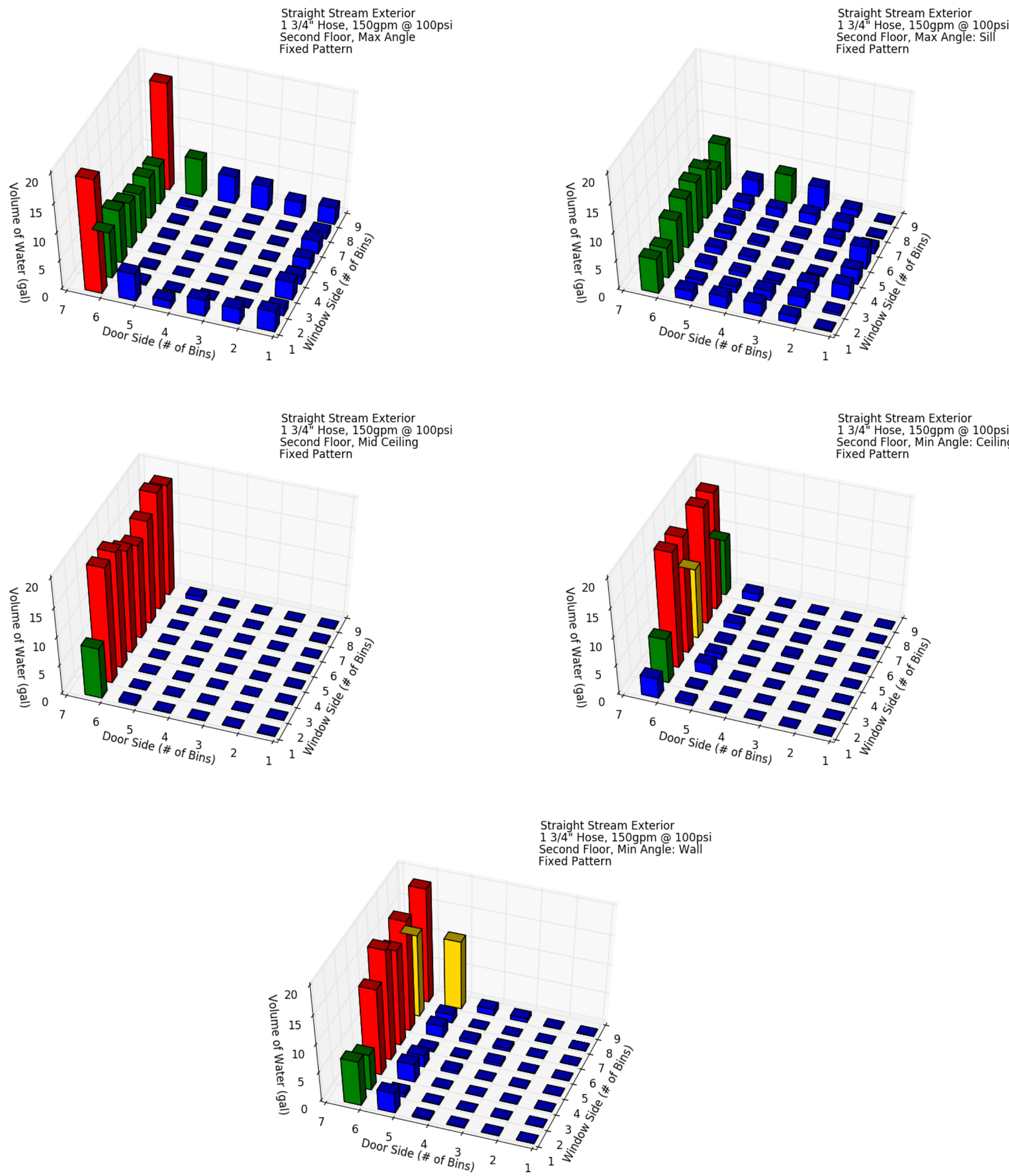


Figure 5.21: Figures showing distribution differences in varying nozzle directions during an exterior second floor attack with a SS fixed pattern.

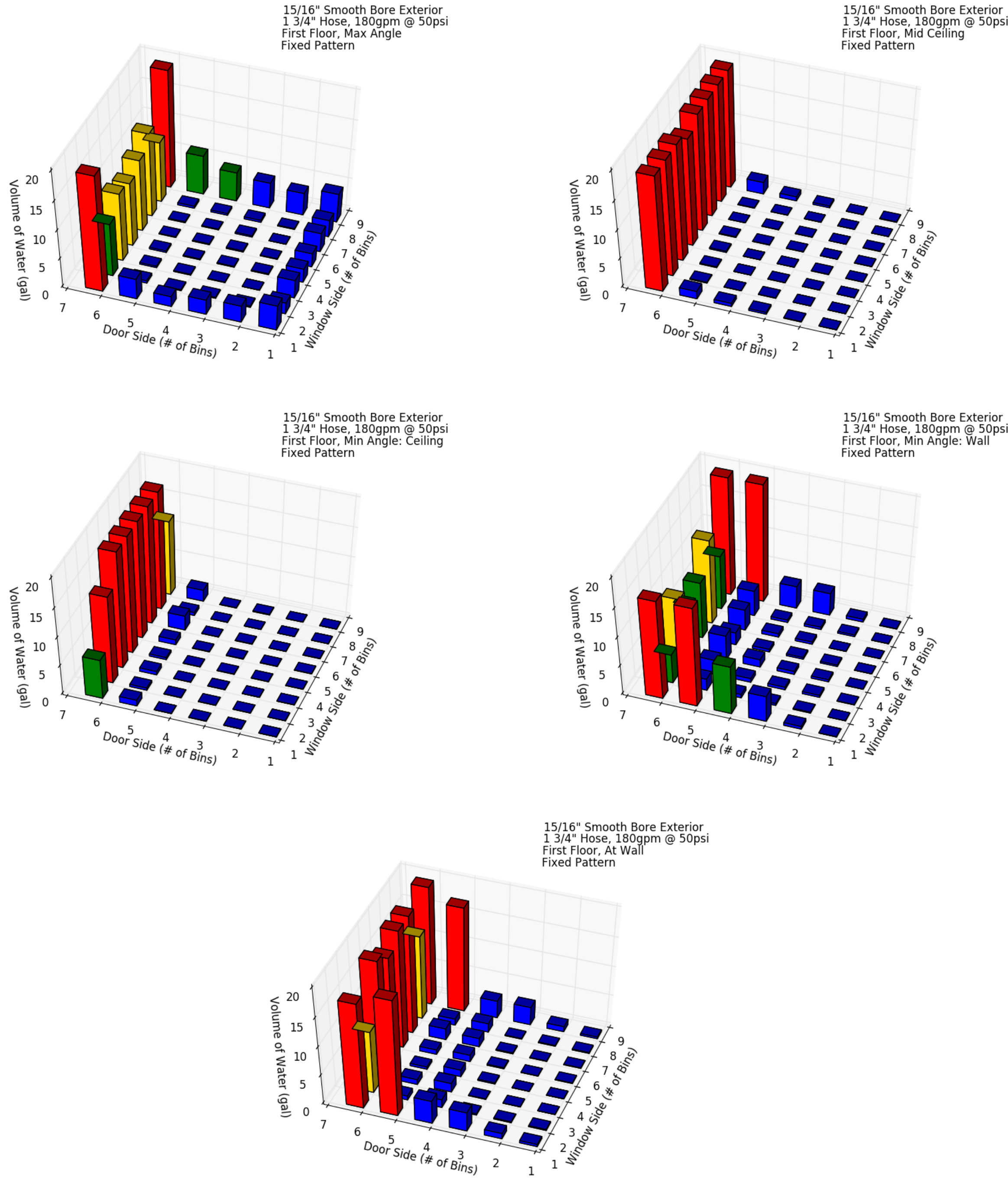


Figure 5.22: Figures showing distribution differences in varying nozzle directions during an exterior first floor attack with a SB fixed pattern.

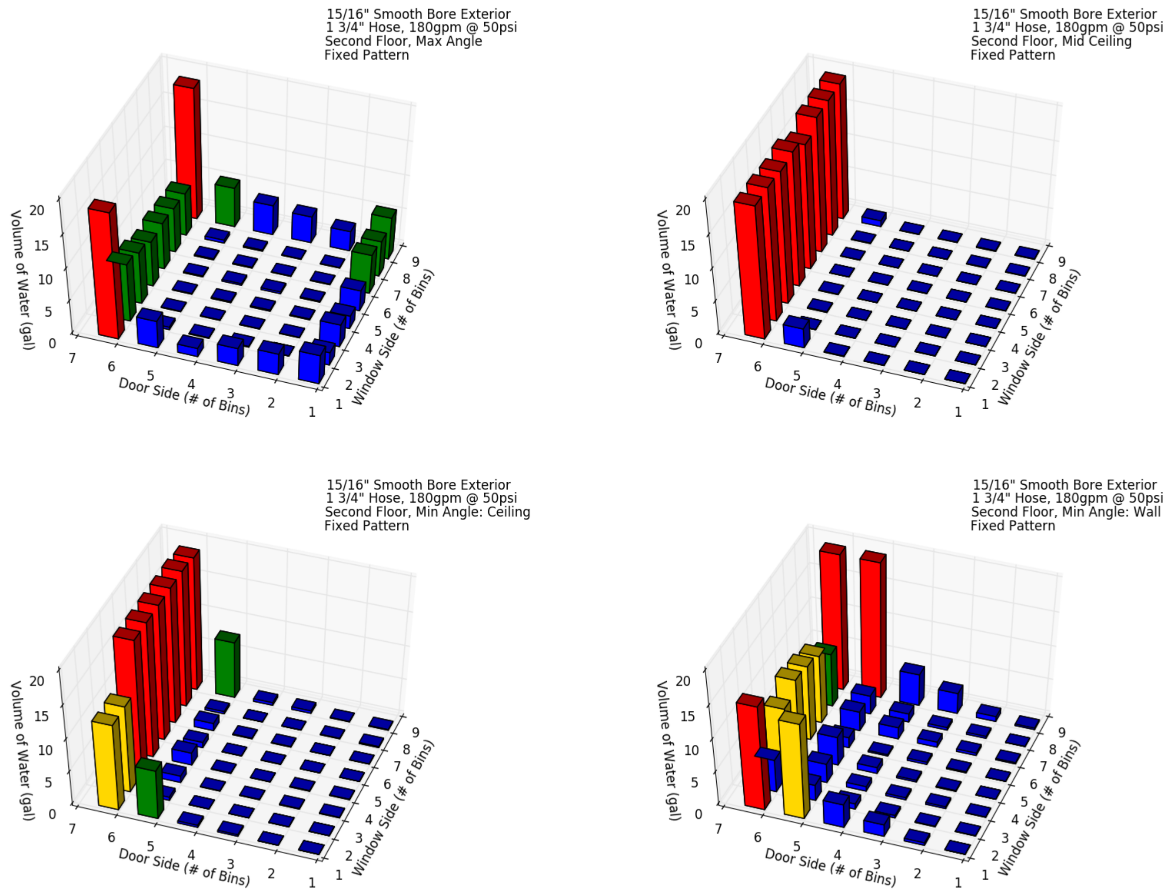


Figure 5.23: Figures showing distribution differences in varying nozzle directions during an exterior second floor attack with a SB fixed pattern.

Varying nozzle pressure and flow can affect the amount of water applied to a given area while the distribution remains somewhat constant.

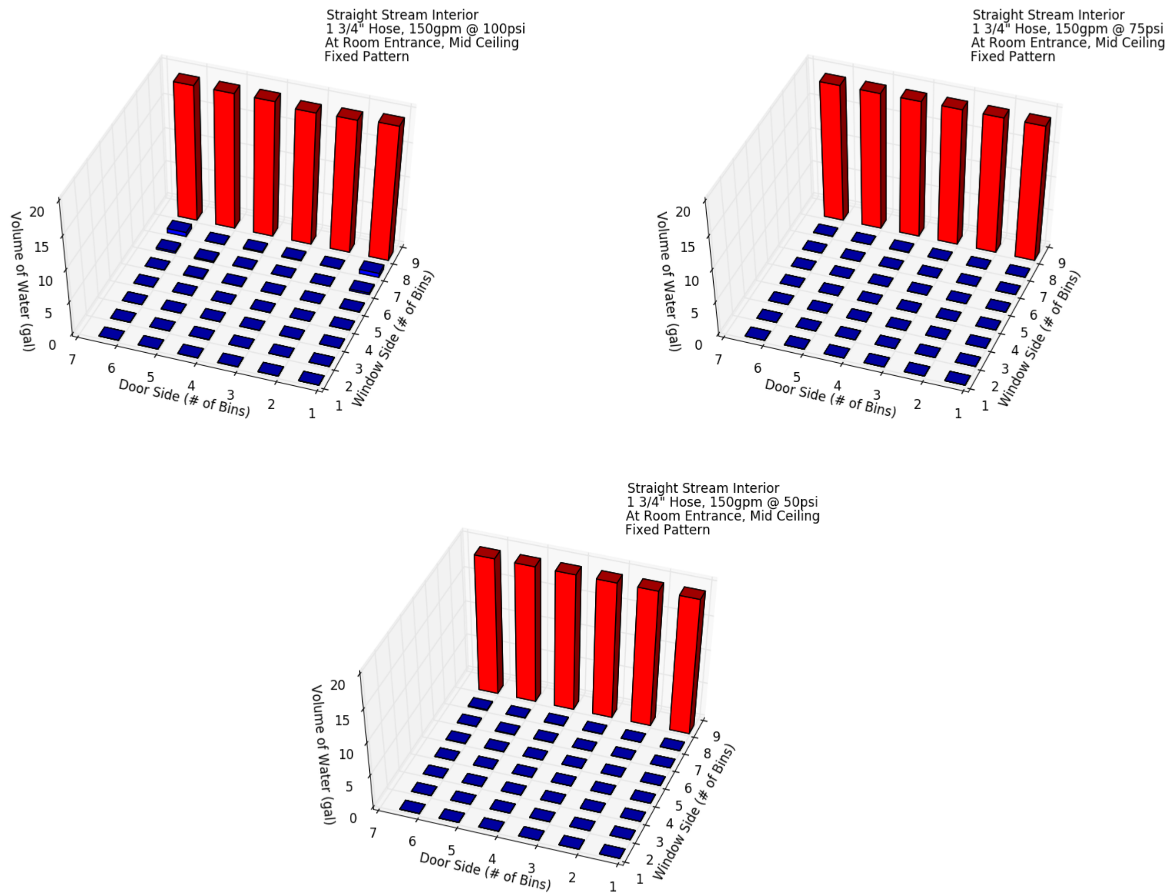


Figure 5.24: Figures showing distribution differences in varying nozzle pressures during a straight stream attack with a fixed pattern.

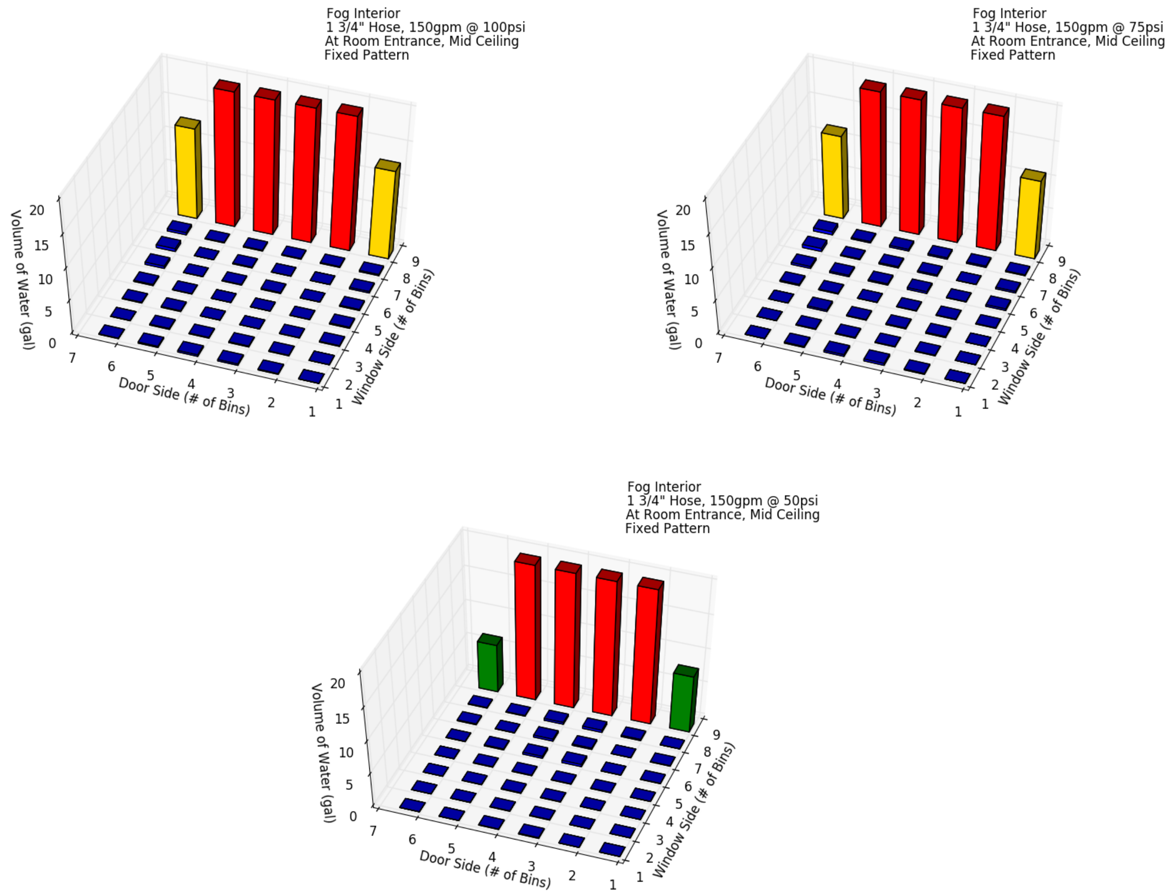


Figure 5.25: Figures showing distribution differences in varying nozzle pressures during a fog attack with a fixed pattern.

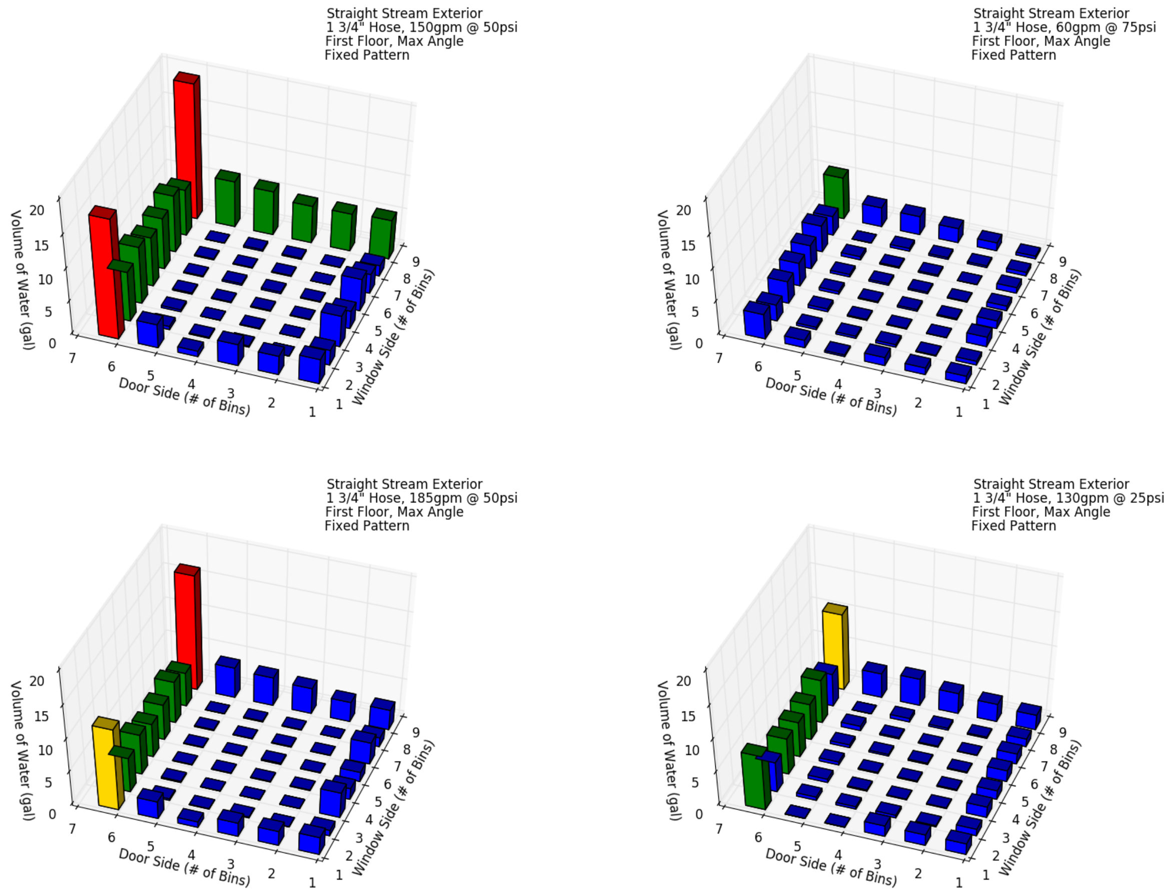


Figure 5.26: Figures showing distribution differences in varying nozzle pressures during an exterior first floor straight stream attack with a fixed pattern.

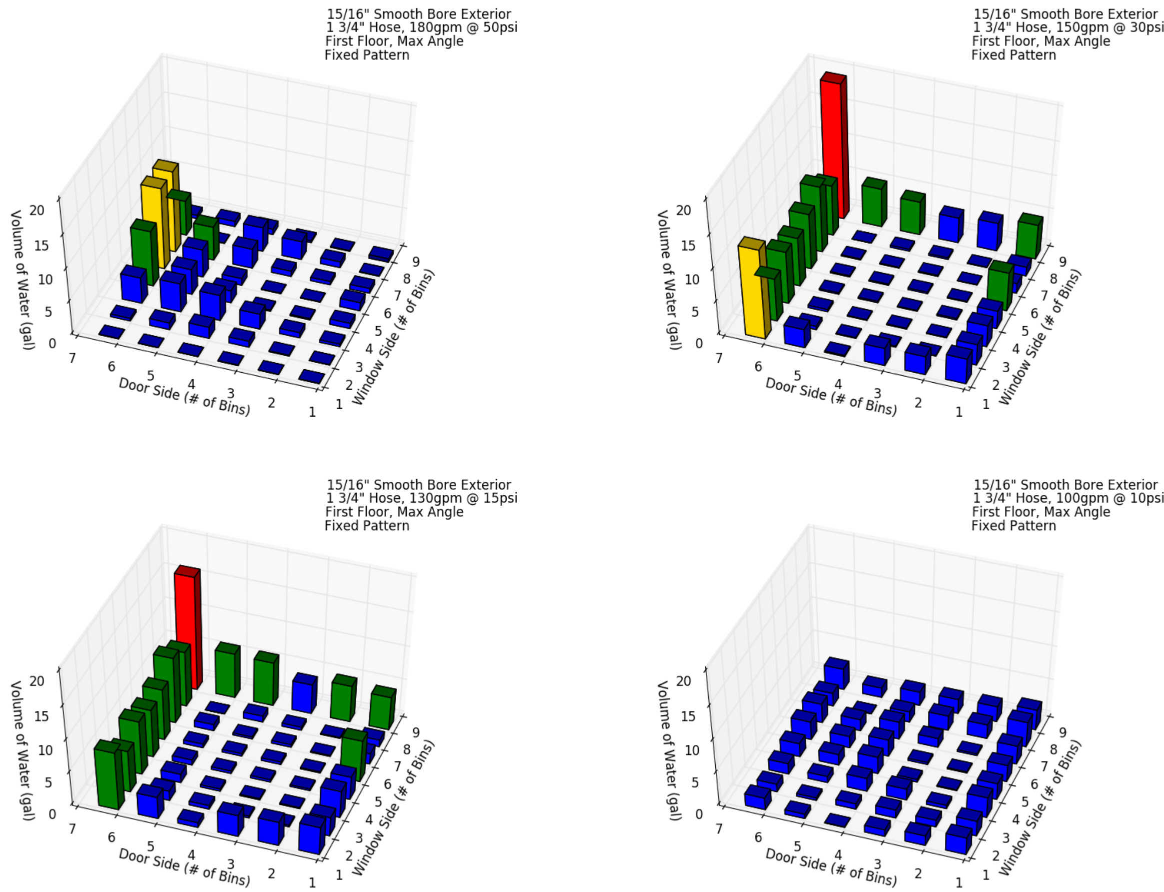


Figure 5.27: Figures showing distribution differences in varying nozzle pressures during an exterior first floor smooth bore attack with a fixed pattern.

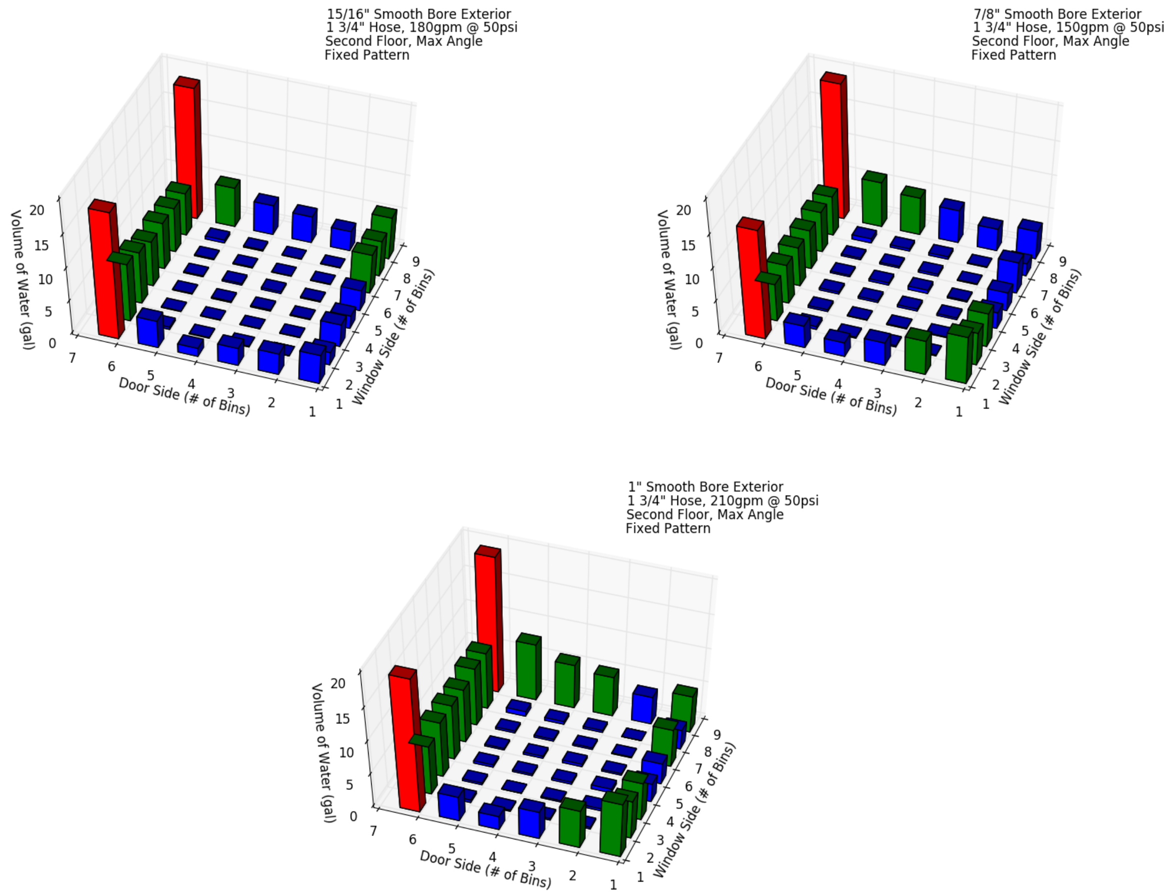


Figure 5.28: Figures showing distribution differences in varying nozzle flow rates by increasing the tip size during an exterior second floor smooth bore attack with a fixed pattern.

Applying water from the exterior or from a distance via the interior will adequately coat the surfaces of a compartment (walls and ceiling) while applying little water to the center of the room.

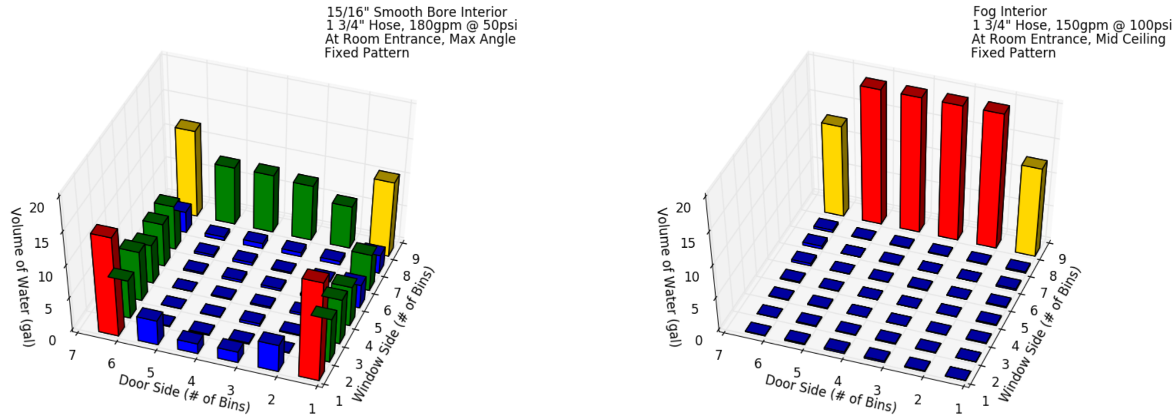


Figure 5.29: Figures showing lack of adequate coverage to the center of the room from an interior attack.

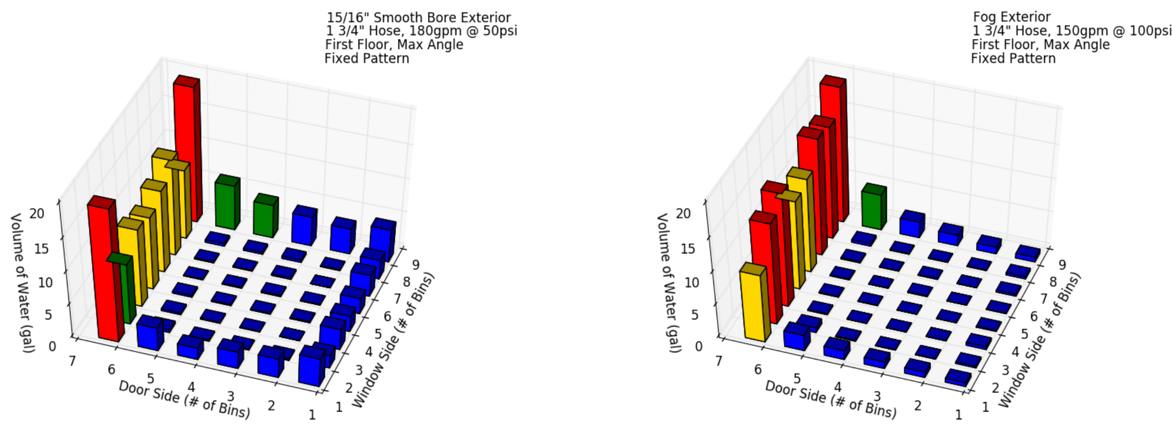


Figure 5.30: Figures showing lack of adequate coverage to the center of the room from an exterior attack.

From both the fire tests as well as the non-fire tests, it is evident that little to no water makes it into the center of the room given an attack featuring the nozzle directed at either the ceiling or the side walls of the compartment.

6 Future Research Needs

Part I of the Fire Attack Study was intended to provide preliminary results and insight into the amount of air entrained by hose streams using differing nozzles and configurations in addition to determining where water is distributed within compartments. These tests have built upon the work conducted by Knapp et. all of the Rockland County, NY Fire Training Academy who conducted early experiments to attempt to quantify the amount of air entrained by suppression operations. Because the testing scope was limied to certain geometries for both air entrainment and water distribution, a future study analyzing different sized structures (including a varying ceiling height and design) in addition to differing compartmentation versus open concepts would be beneficial to further the understanding.

7 Summary

Appendices

A Experimental Results

Air Entrainment Figures

Section currently commented out.

Water Distribution Figures

.1 Second Floor Exterior Tests

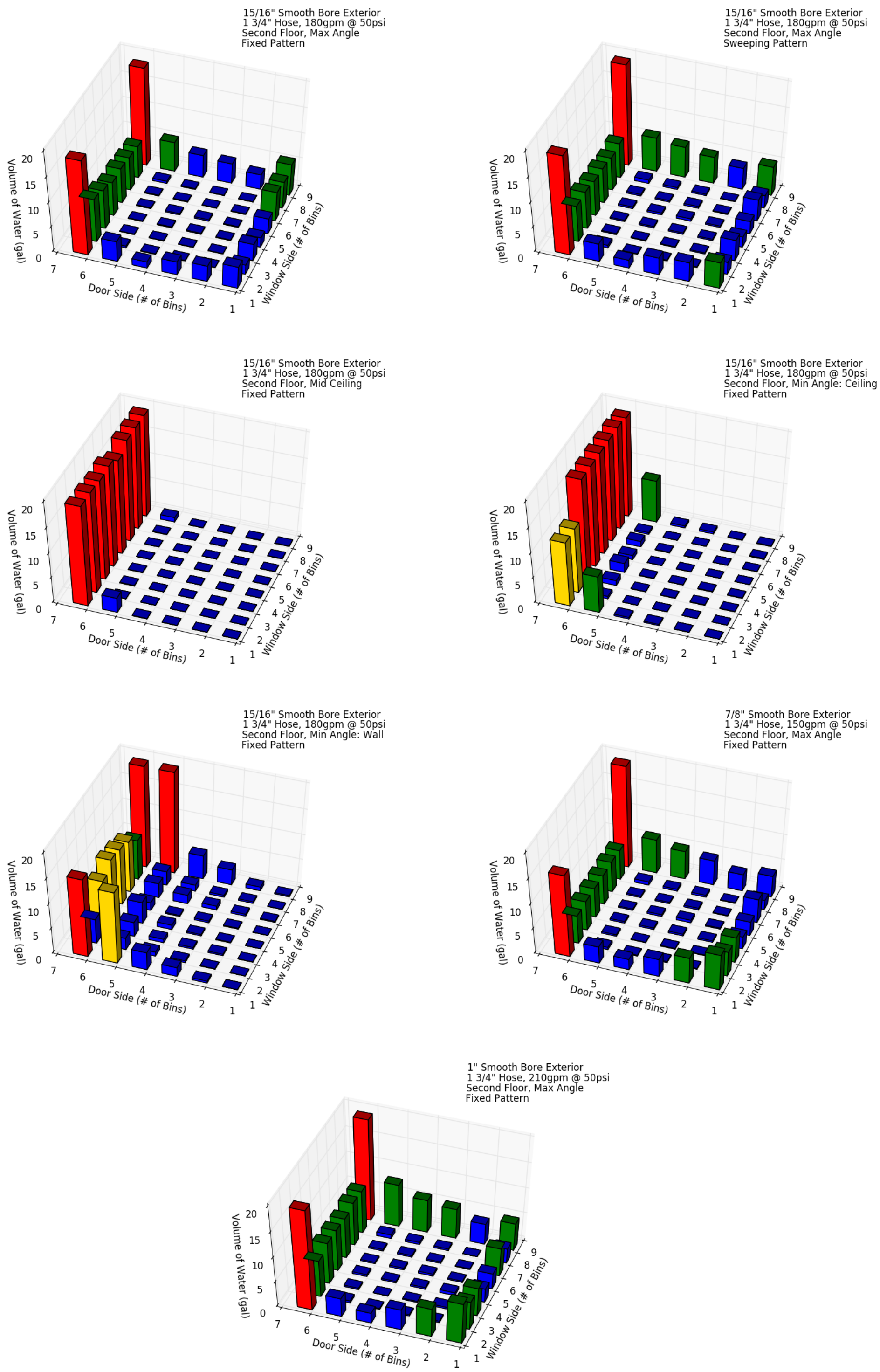


Figure .1: Smooth Bore Second Floor Exterior

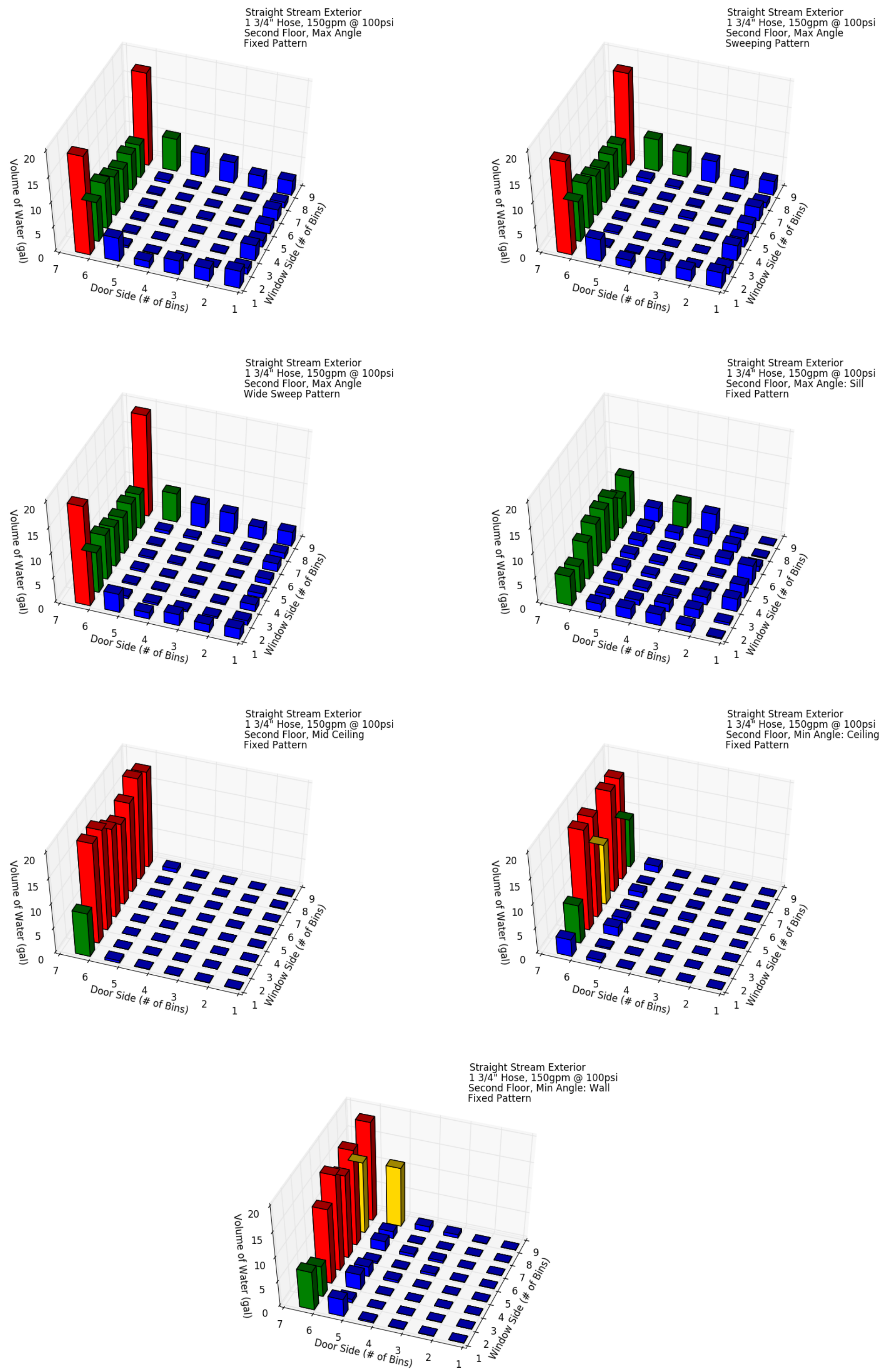
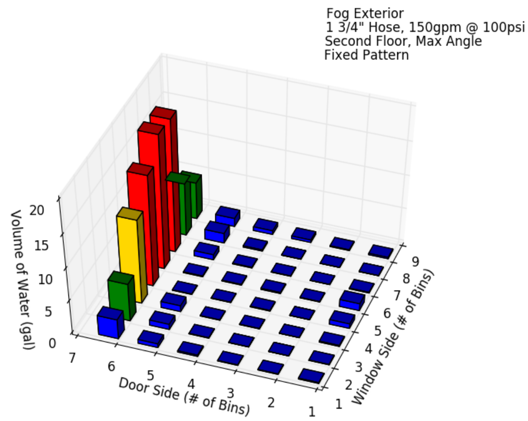


Figure .2: Straight Stream Second Floor Exterior



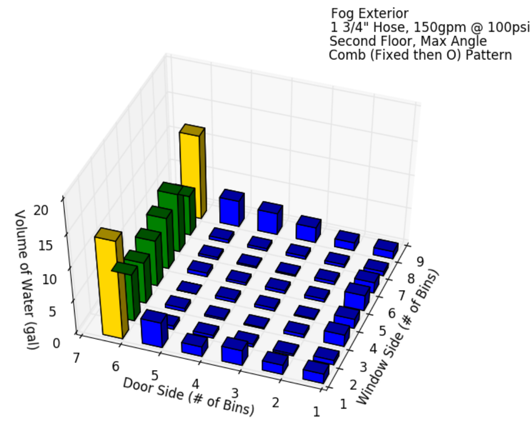


Figure .3: Fog Stream Second Floor Exterior

.2 First Floor Exterior Tests

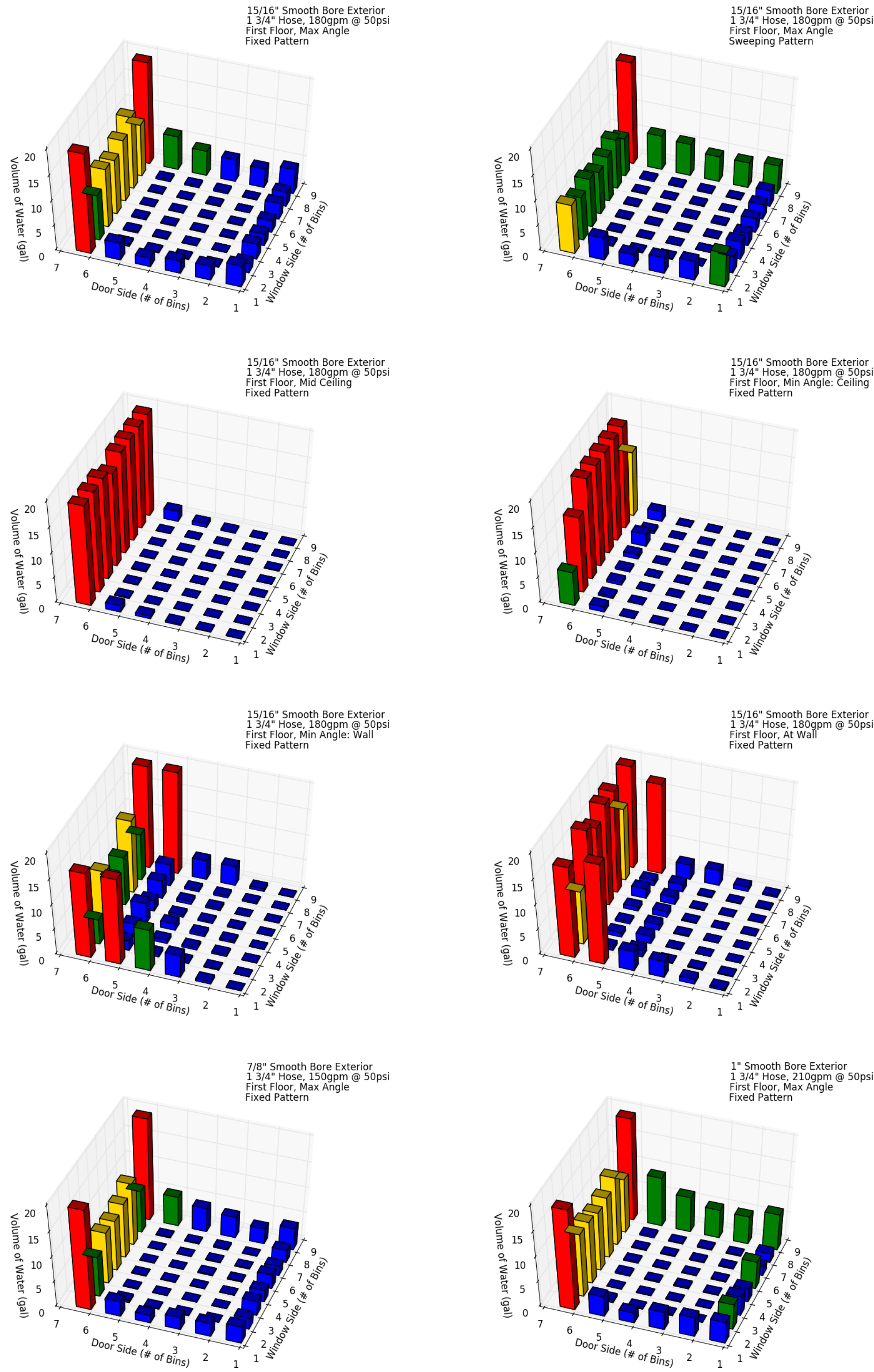


Figure .4: Smooth Bore First Floor Exterior

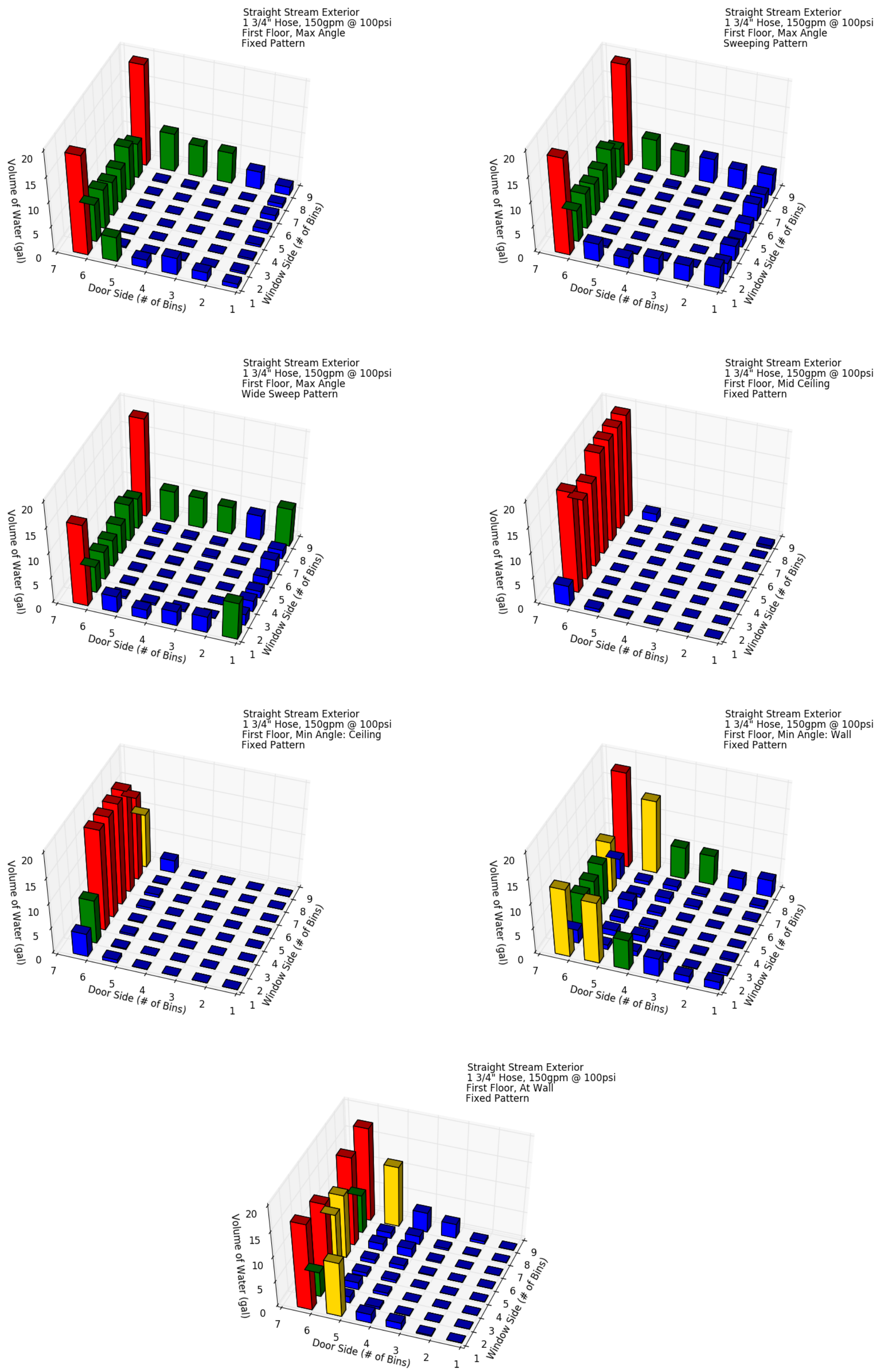


Figure .5: Straight Stream First Floor Exterior

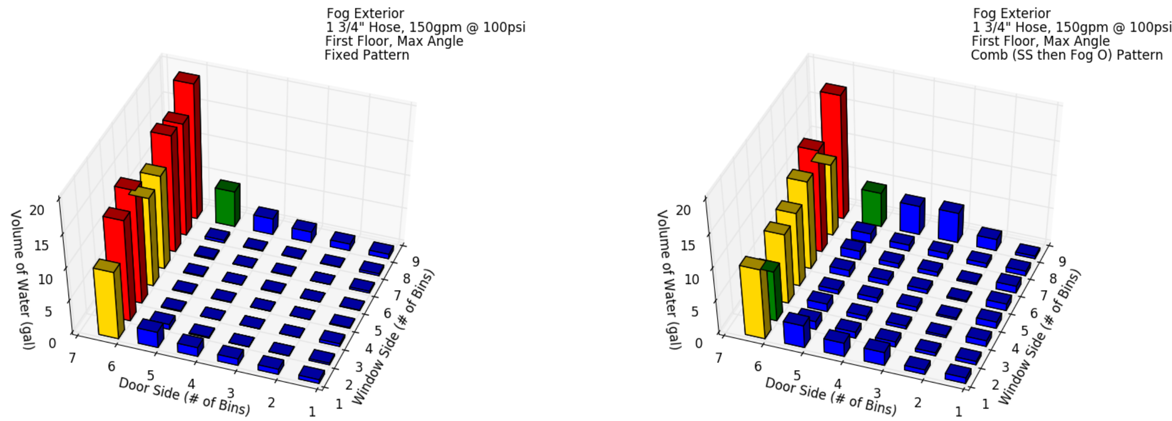


Figure .6: Fog Stream First Floor Exterior

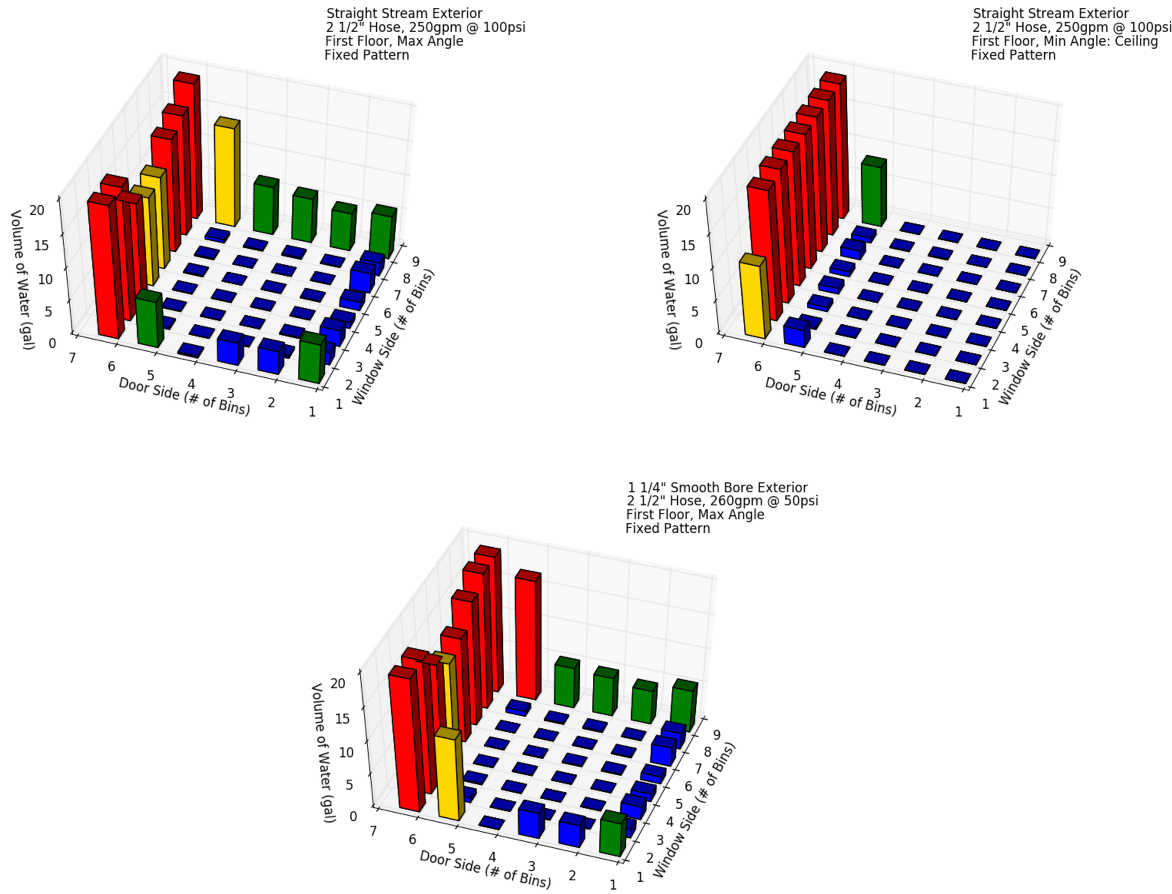


Figure .7: Straight Stream vs. Smooth Bore, 2 1/2 Hose, First Floor, Exterior

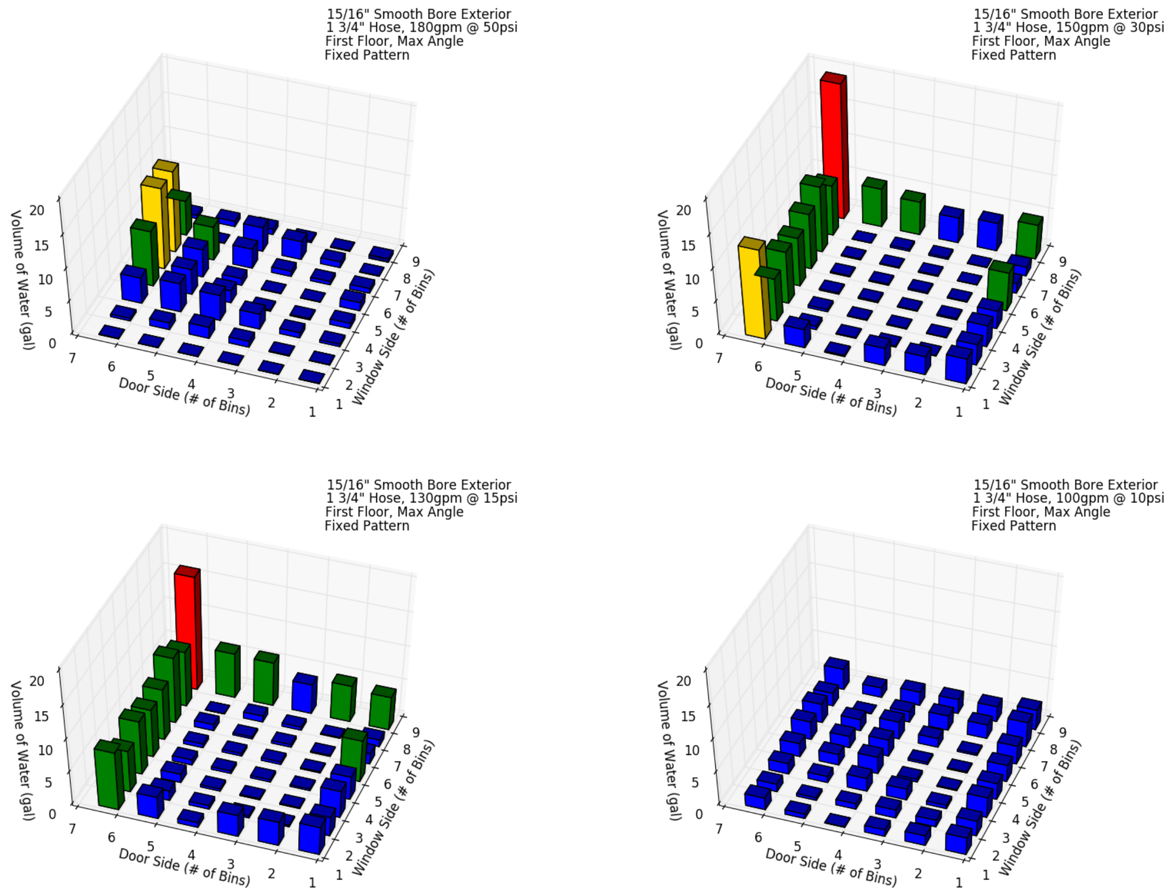


Figure .8: Smooth Bore Adjusted Pressures/Varied Flow Rates, First Floor Exterior

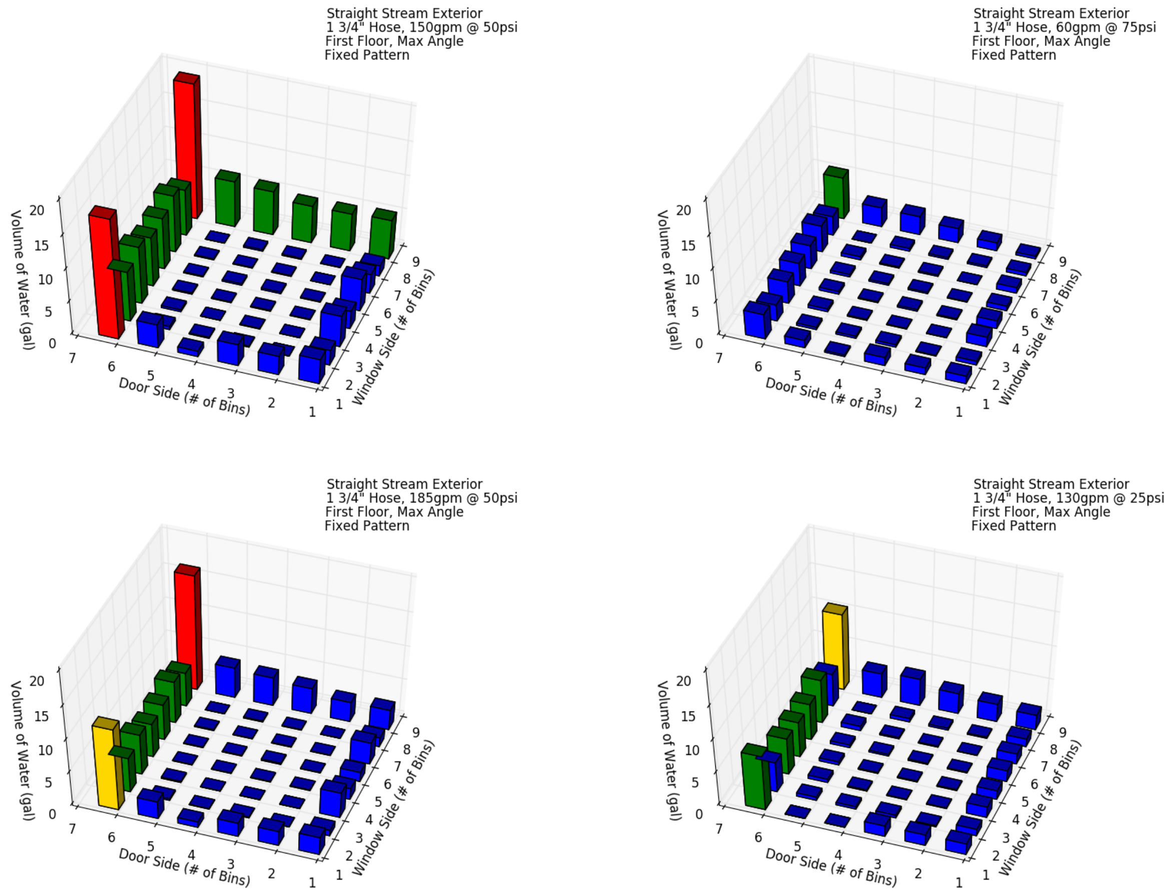
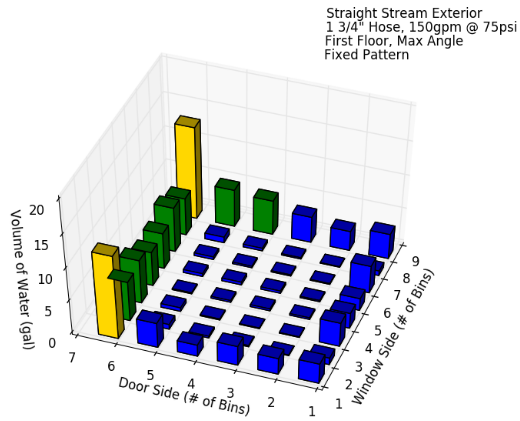
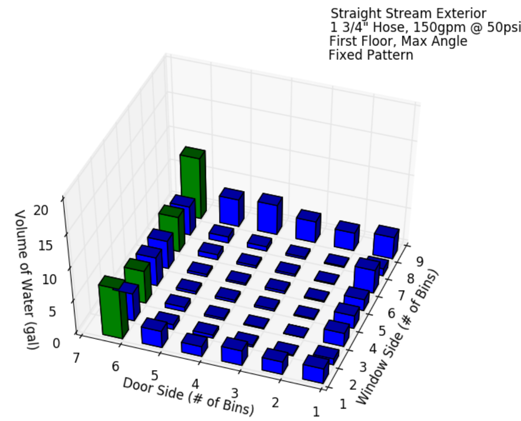


Figure .9: Straight Stream Adjusted Pressures/Varied Flow Rates, First Floor Exterior





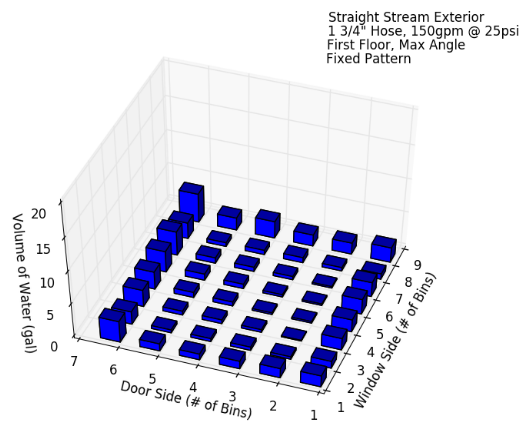


Figure .10: Straight Stream Adjusted Pressures/Constant Flow Rates, First Floor Exterior

.3 Interior Tests

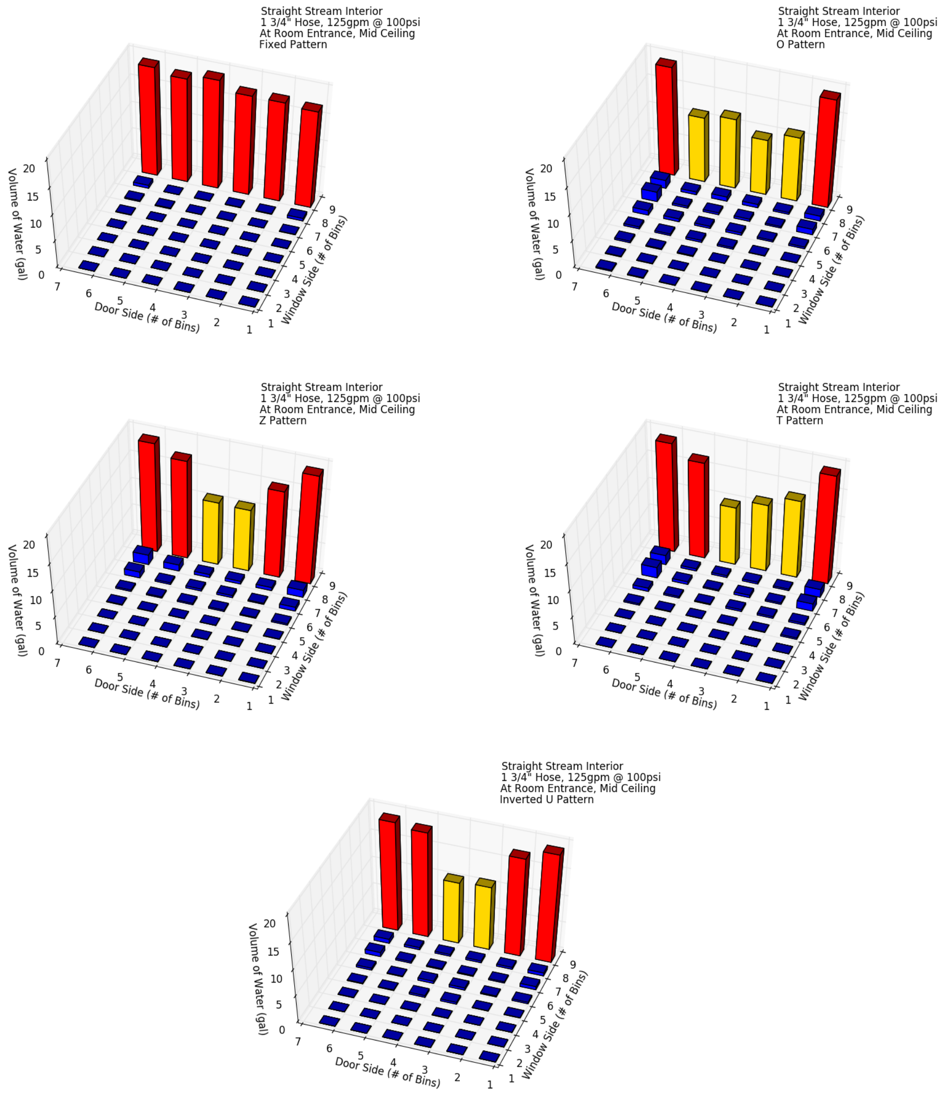


Figure .11: Straight Stream Varied Nozzle Movements, First Floor Interior

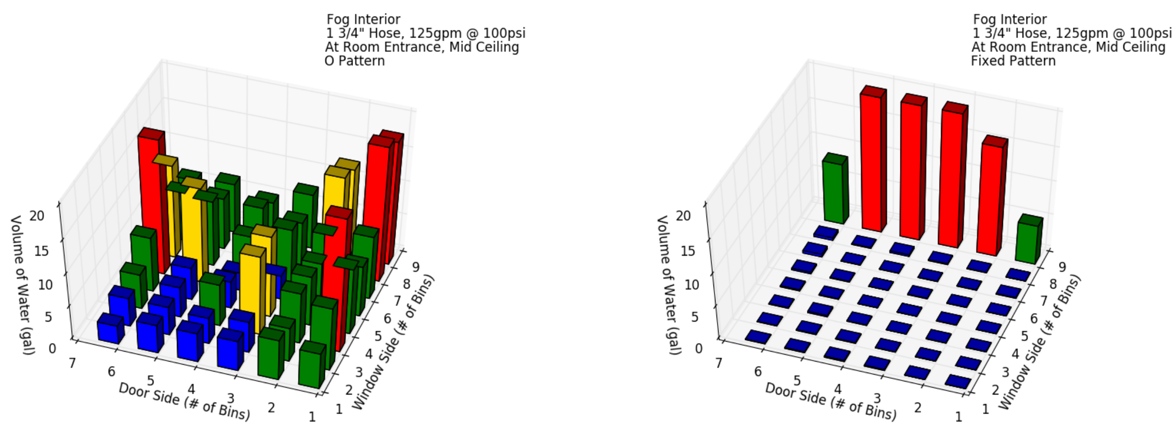


Figure .12: Fog Stream Fixed vs. Moving, First Floor Interior

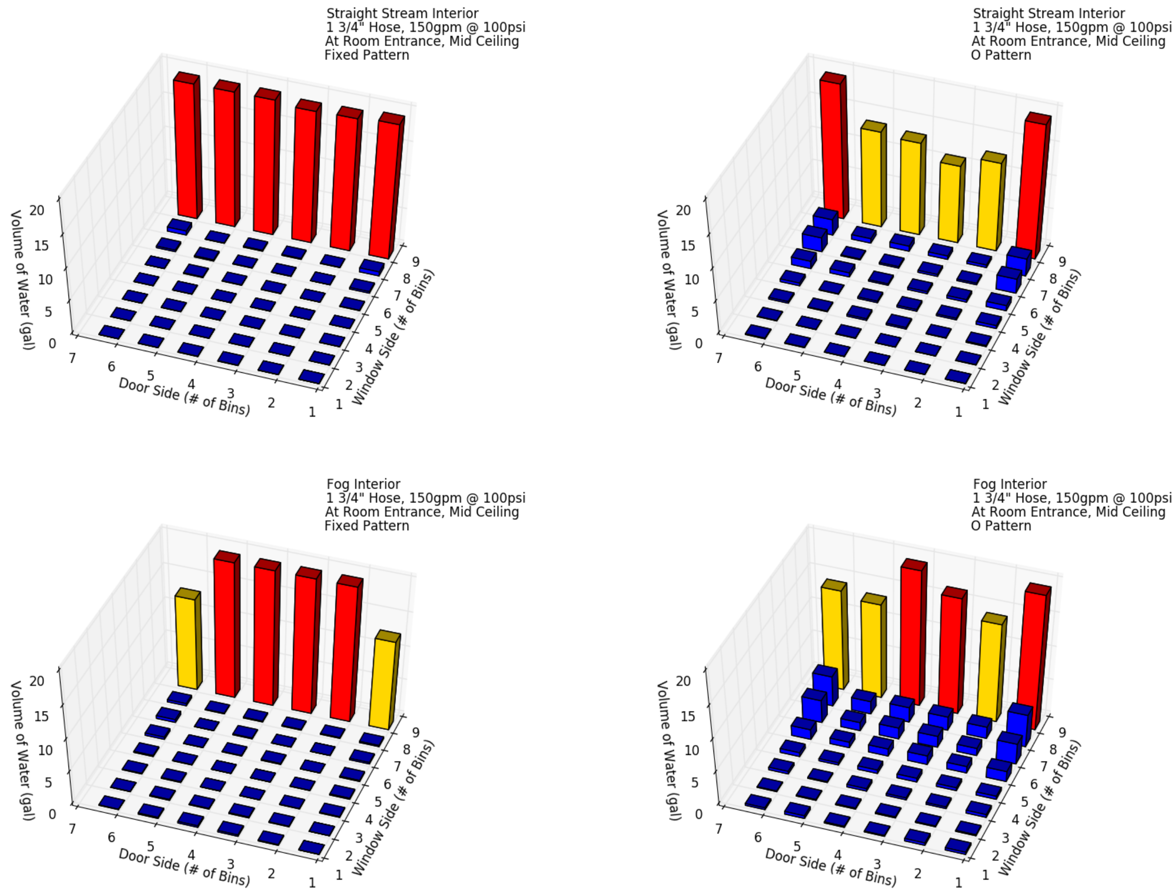


Figure .13: Straight Stream vs. Fog 100 psi, First Floor Interior

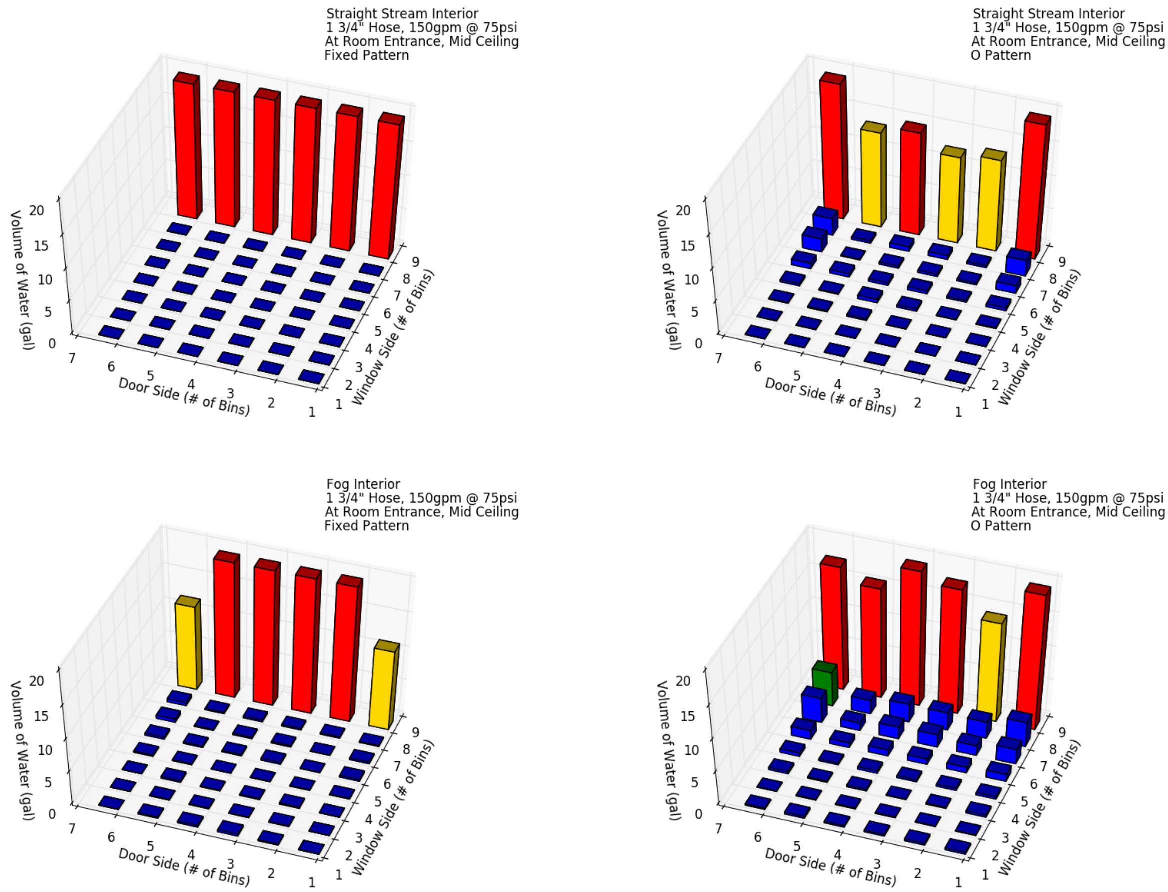


Figure .14: Straight Stream vs. Fog 75 psi, First Floor Interior

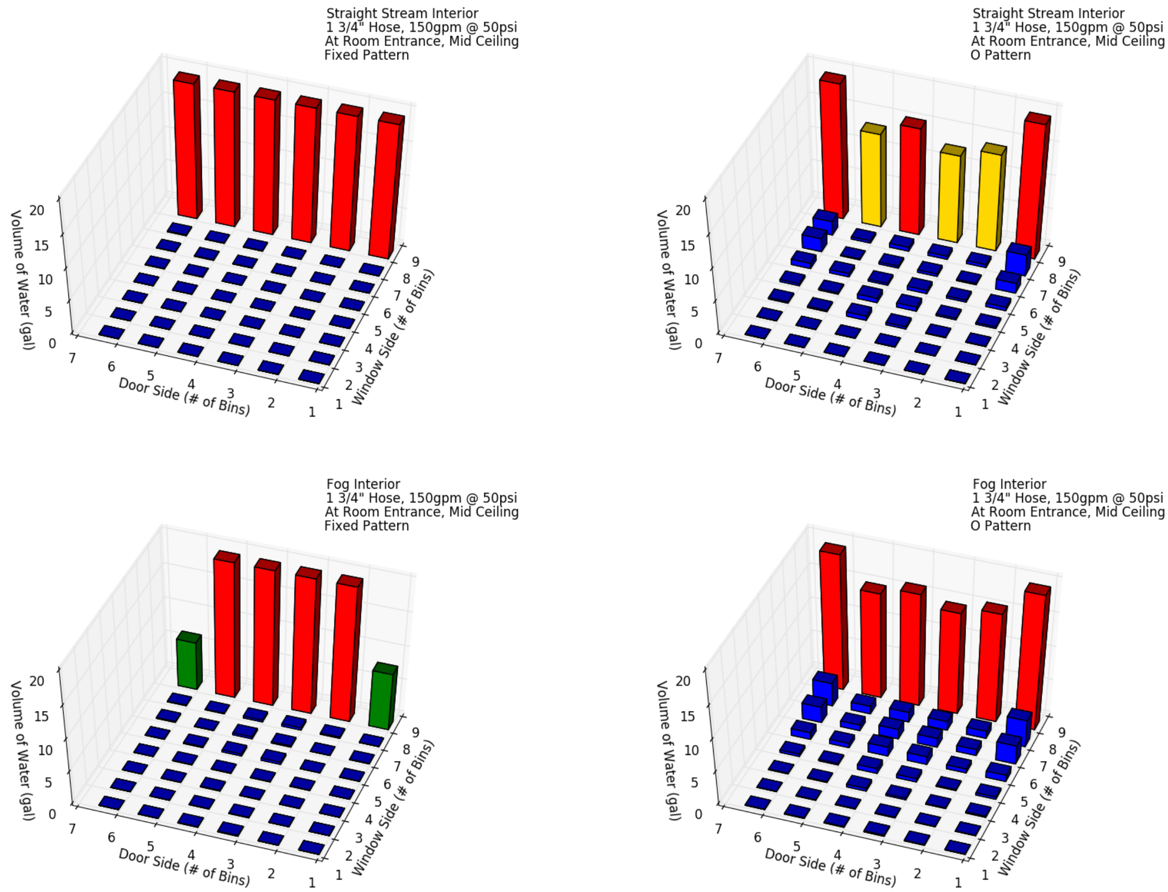


Figure .15: Straight Stream vs. Fog 50 psi, First Floor Interior

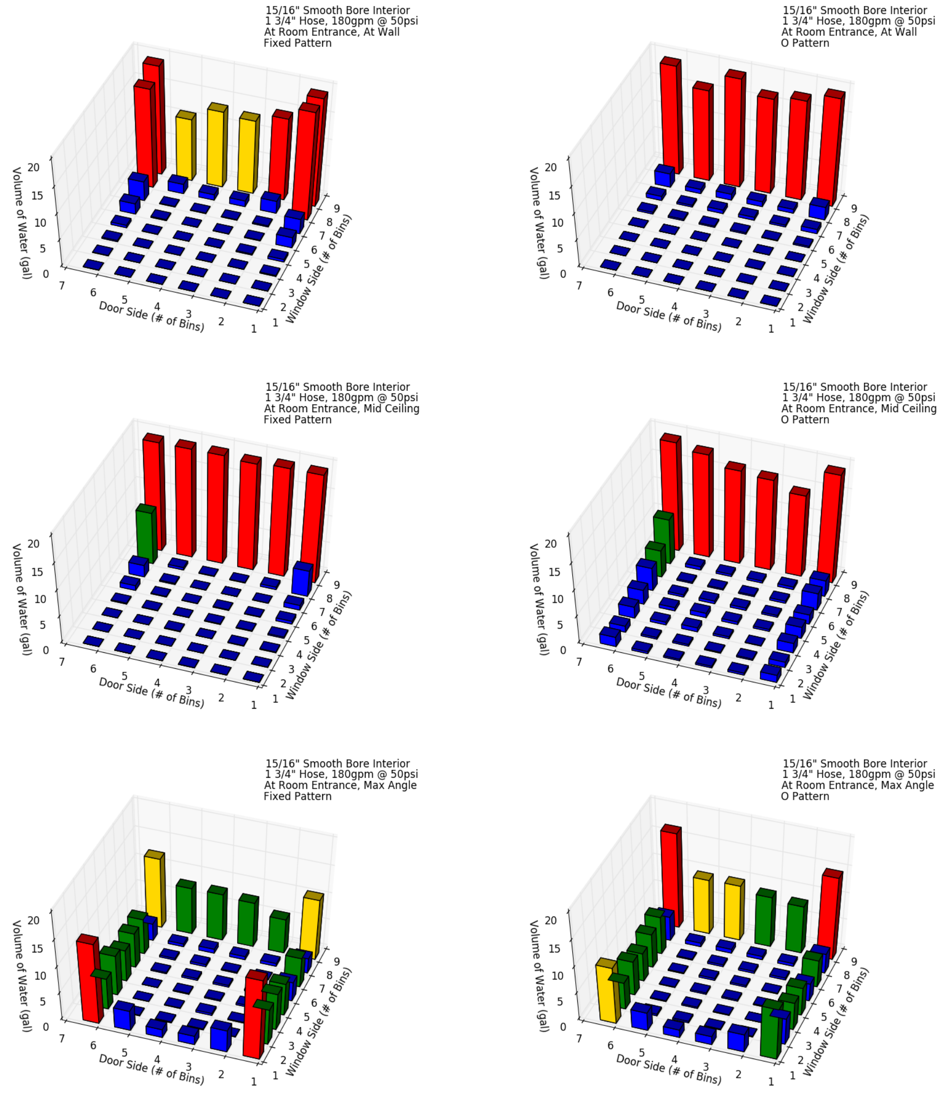


Figure .16: Smooth Bore Varied Elevation Angle, First Floor Interior

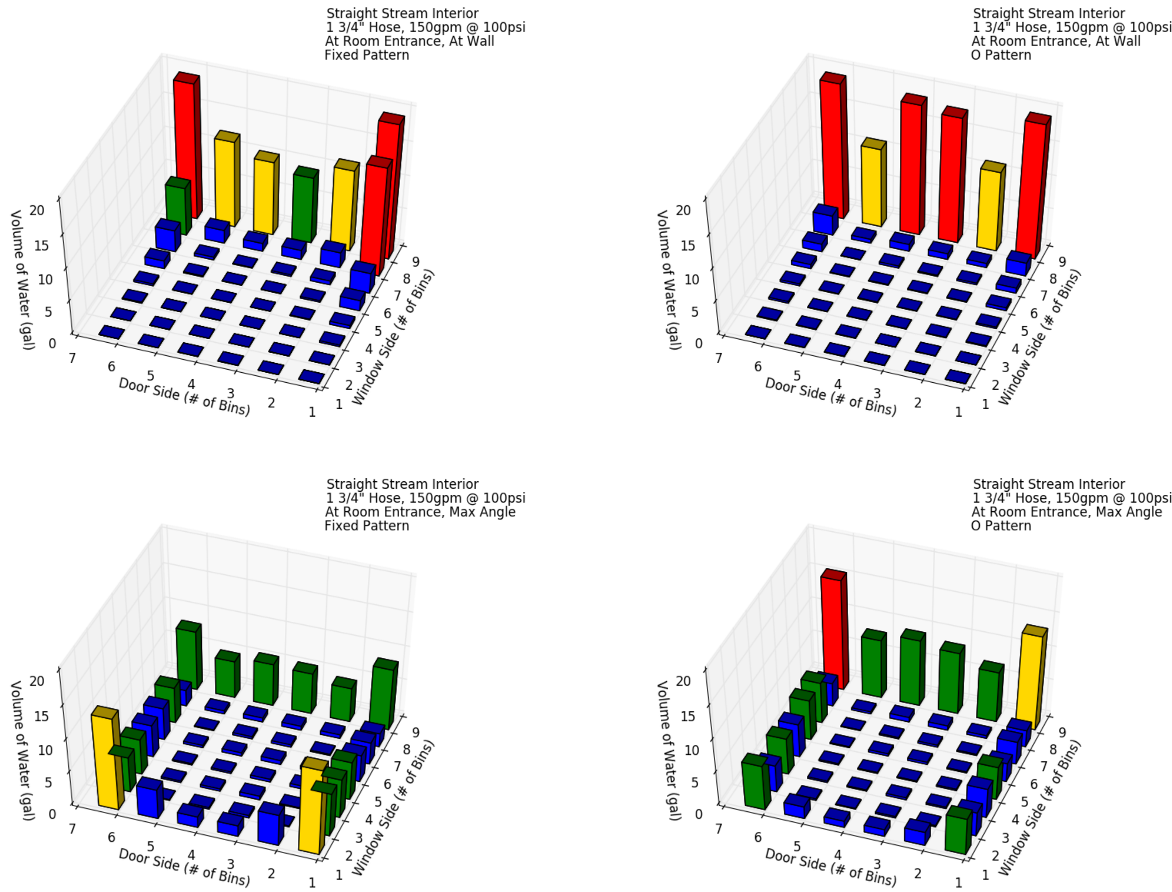


Figure .17: Straight Stream Varied Elevation Angle, First Floor Interior