Residential Flashover Prevention with Reduced Water Flow: Phase 1

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List of Abbreviations

ANOVA	Analysis of Variance
DHS	U.S. Department Of Homeland Security
ESTC	Emergency Services Training Center
FEMA	Federal Emergency Management Agency
FMRC	Factory Mutual Research Corporation
gpm	gallons per minute
HRR	heat release rate
IDLH	immediately dangerous to life or health
kg	kilogram
kW	kilowatt
lb	pound
lpm	liters per minute
min	minute
mm	millimeter
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
RTI	response time index
UL	Underwriters Laboratories
UL FSRI	UL Firefighter Safety Research Institute
USFA	U.S. Fire Administration

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Abstract

This study was designed to be an initial step to investigate the potential of low flow nozzles as part of a retrofit flashover prevention system in residential homes with limited water supplies. Not all homes have water supplies that can meet the needs of a residential sprinkler system. Current alternatives, such as including a supplemental tank and pump, increase the cost of the system. These homes could benefit from an effective fire safety system with lower water supply requirements.

The experiments in this study were conducted in a steel test structure which consisted of a fire room attached to a hallway in an L-shaped configuration. Three types of experiments were conducted to evaluate nozzles at different flow rates and under different fire conditions. The performance of the nozzles was compared to the performance of a commercially available residential sprinkler. The first set of experiments measured the distribution of the water spray from each of the nozzles and the sprinkler. The water spray measurements were made without the presence of a fire. The other two sets of experiments were fire experiments. The first set of fire experiments were designed to measure the ability of a water spray to cool a hot gas layer generated by a gas burner fire. The fire source was a propane burner which provided a steady and repeatable flow of heat into the test structure. Two water spray locations were examined, in the fire room and in the middle of the hallway. In each position, the burner was shielded from the water spray. The results showed that for equivalent conditions, the nozzle provided greater gas cooling than the sprinkler. The tests were conducted with a fire size of approximately 110 kW, and water flow rates in the range of 11 lpm (3 gpm) and 19 lpm (5 gpm).

The second set of fire experiments used an upholstered sofa as the initial source of the fire with the water spray located in the same room. As a result of the compartment size and water spray distribution, the nozzle flowing water at 23 lpm (6 gpm) provided more effective suppression of the fire than the sprinkler flowing 34 lpm (9 gpm) did. The nozzle was similarly effective with the ignition location moved 1.0 m (3.2 ft) further away. However, the nozzle failed to suppress the fire with a reduced water flow rate of 11 lpm (3 gpm).

The results of this limited study demonstrate the potential of low flow nozzles, directly flowing water on to the fuel surface, with the goal of preventing flashover. Additional research is needed to examine larger room sizes, fully furnished rooms, and shielded fires to determine the feasibility of a reduced water flow flashover prevention system.

1 Introduction

Automatic residential fire sprinkler systems, designed and installed in accordance with NFPA 13D, Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes [1] have been shown to save lives and property. The purpose of the standard is "...to provide a sprinkler system that aids in the detection and control of residential fires and thus provides improved protection against injury and life loss." The purpose continues that, a sprinkler system shall be designed and installed in accordance with NFPA 13D to prevent flashover in the room of fire origin, where sprinklered, and to improve the chance for occupants to escape or be evacuated [1].

According to the NFPA, the civilian death rate in homes with fire sprinklers was 81% lower than in homes without an automatic suppression system. A similar comparison was made on both civilian and firefighter injury rates, in the homes with fire sprinklers the injury rates were 27% and 67% lower respectively [2].

The U.S. Census Bureau conducted an American Housing Survey in 2011 which included questions regarding the Health and Safety Characteristics of a home. The survey contained a section on Safety Equipment. In this section the question was asked; is there a sprinkler system inside the home? NFPA tabulated the data from the American Housing Survey to show, based on occupied units, that approximately 1% of manufactured homes, 2% of single-family detached homes, and 8% of single-family attached homes had residential sprinkler systems [2].

While the life safety benefits are clear based on fire incident data, the American Housing Survey data shows the trend that the majority of single family homes in the United States are not sprinklered. Their are many reasons for this but a key reason is that more than half of the housing stock existed prior to the adoption of the first edition of NFPA 13D in 1975 [3]. Retrofitting a sprinkler system in an existing home can be more expensive than installing a system in a new home, with costs depending on a number of factors specific to each individual home [4]. This raises the question, is there another approach to water based, residential fire suppression systems that could be used to enable retrofit in the existing housing stock? When considering a fire suppression system for residential retrofit, challenges such as the available water supply may need to be overcome.

In an effort to examine, or perhaps re-examine, the options for a reduced water flow, residential flashover prevention system, these scoping experiments were conducted to examine the mechanism of fire control used for residential fires.

1.1 Objective

The objective of this study was to begin an investigation of flashover prevention methods for residential homes with limited water supplies. In particular, the study focused on the cooling of fire gases and the use of low flow spray nozzles in place of residential sprinklers. The spray nozzles provided an evenly distributed conical pattern of water, as opposed to a sprinkler which distributes water primarily near the edges of its spray radius to limit fire growth/spread.

1.2 Technical Approach

Based on findings from the literature review, three series of full-scale experiments were designed. The first set of experiments measured the distribution of the water spray from each of the nozzles and the sprinkler. The water spray measurements were made without the presence of a fire. The other two sets of experiments were fire experiments which examined the ability of a water spray to cool a hot gas layer flow, and the ability of a water spray to suppress a fire started on an upholstered sofa.

UL 1626 tenability criteria was used as a measure of success in providing protection for occupants. UL 1626 defines limits for the conditions in a residence to be maintained by a sprinkler system such that the residence is tenable for occupants. The criteria of primary relevance to this study are as follows:

(a) The maximum temperature 76 mm (3 in) from the ceiling at [the room center and/or the nearest sprinkler] shall not exceed 316 °C (600 °F).

(b) The maximum temperature 1.6 m (5.25 ft) above the floor shall not exceed 93 °C (200 °F).

(c) The temperature at the location described in (b) shall not exceed 54 °C (130 °F) for more than any continuous 2-minute period.

Gas concentrations of O_2, CO, and CO_2 were measured as an additional component of tenability. UL 1626 does not state limits on gas concentrations for tenability, however, concentrations of CO above 0.012% and CO_2 above 4% are considered immediately dangerous to life or health (IDLH) for a 30 minute exposure [5].

The data from the experiments was analyzed to determine the cooling effectiveness of the water spray systems and the potential impact on maintaining tenable conditions.

2 Literature Review

The objective of the literature review was to examine previous research that may aide in designing the experiments for this project. Research has been conducted on gas cooling with respect to water spray systems. As part of the development and evolution of the residential sprinkler system, researchers examined potential innovations such as the Manufactured Home Sprinkler System which consisted of limited-water, residential style sprinklers and a 100 gallon self-contained water supply to suppress residential fires. The final piece of the literature review focuses on residential water supplies to determine the range of flow rates and pressures typically available.

2.1 Cooling of Fire Gases

Fire suppression and gas cooling studies were examined to determine the amount or application rate of water needed to control a residential fire or prevent flashover in order to provide time for individuals not intimate with the fire to safely exit the structure or be rescued.

USFA sponsored a research program which examined the effectiveness of residential sprinkler systems with reduced water supplies [6]. The research program included water distribution tests for a variety of sprinklers, flow rates, and room configurations. The minimum flow rates required to meet the requirements of UL 1626 were reported, and provide a range between 15 lpm (4 gpm) and 76 lpm (20 gpm). Another series of tests examined the water distribution density with and without a 500 kW heptane fire present in the room. The results were summarized in terms of efficiency, defined as the ratio of collected water density to the design density of the sprinkler. The highest efficiencies were observed when discharging at design densities ranging from 1.63 mm/min (0.04 gpm/ft^2) to 3.26 mm/min (0.08 gpm/ft^2).

Subsequent studies conducted as part of the USFA sprinkler research program focused on strategies to reduce the necessary water supply for residential sprinkler systems, and included an investigation of prototype sprinklers and nozzles [7]. The sprinklers and nozzles were subjected to wall wetting, distribution, and fire performance tests. The sprinklers and nozzles met UL 1626 criteria for wall wetting, perimeter and floor collection at flow rates as low 11 lpm (3 gpm), but the flow rates had to be increased to 30 lpm (8 gpm) during preliminary fire tests to provide viable control of the fires. The spray densities associated with these flow rates cannot be determined from the data provided. This result indicates that there exists a lower bound to flow rates (in this case, between 11 lpm (3 gpm) and 30 lpm (8 gpm)) below which the capability of a sprinkler/nozzle to control a residential fire is drastically reduced.

Blanchard et al. conducted a study to evaluate the impact of three different water spray systems on a smoke layer in a corridor [8]. The experimental setup was designed to isolate the fire source from the water sprays, thereby limiting the scope of the findings to only the interaction between the water sprays and the smoke layer. The water spray systems were a sprinkler system which was used at two different operating pressures, and a water mist system. Table 2.1 summarizes the flow characteristics and gas cooling capabilities of each spray system tested. The difference in temperature response between the sprinkler at 41 lpm (11 gpm) versus at 91 lpm (24 gpm) indicates the existence of a strong relationship between flow rate and gas cooling performance. All three systems maintained tenability in the corridor during operation according to UL 1626 criteria. The study emphasized the importance of opacity measurements to track smoke presence and concentration as a means to complete the information obtained from temperature alone.

Table 2.1: Summary of water spray performance in study conducted by Blanchard et al. [8]. The temperature response is measured 2.0 m above the ground and 2.5 m away from the water spray, opposite of the fire.

Water Spray	Pressure [bar (psi)]	Flow Rate [lpm (gpm)]	Temperature Response [°C]
Water mist system	85 (1232)	25 (7)	-80
Low pressure sprinkler	0.3 (3.9)	41 (11)	-50
High pressure sprinkler	1.3 (18.9)	91 (24)	-90

NIST sponsored an investigation of residential sprinkler performance that included 22 sprinklered fire tests with flow rates between 61 lpm (16 gpm) and 79 lpm (21 gpm). The findings showed that the sprinkler system less reliably controlled the fire when the fire source was located between two sprinklers, rather than in a corner [9].

2.2 Residential Sprinkler Systems for Reduced Water Supplies

The testing and development of residential sprinkler systems with reduced water supplies was investigated. The majority of the research in this area has been conducted by either Underwriters Laboratories as part of the USFA sponsored sprinkler research project, or by the Factory Mutual Research Corporation. The state-of-the-art and history of residential sprinklers has been reviewed in a more general context in a report by Madrzykowski and Fleming, and by Bryan in the National Fire Protection Agency's book, Automatic Sprinkler and Standpipe Systems [10, 11].

The USFA sponsored residential sprinkler research program developed and tested systems to reduce the total amount and flow rate of water necessary for sprinklers to control fires in one and two family dwellings and in mobile homes [6, 7, 12–14]. The systems and strategies considered by the research program are as follows: a 100 gallon, self-contained, water supply unit; prototype sprinklers designed for low flows; the Manufactured Home Sprinkler System (MHSS) that combines the water supply unit and the prototype sprinklers; interconnecting a 30 gallon water heater with the MHSS; and using water additives such as Class A foams, wetting agents, antifreeze solutions, and combinations of each. The studies found these methods to be viable options for reducing the flow rates and total water supply necessary to operate a sprinkler for the extent of its operation time (10 minutes).

Bill and Kung, of FMRC, investigated the suppression capability of limited water supply sprinklers in mobile homes [15]. A preliminary test series was conducted to evaluate reduced sprinkler spacing – a strategy intended to allow the first sprinklers to actuate when the fire is smaller and a low flow sprinkler would be sufficient to control the fire. The results of these tests showed that a reduction in sprinkler spacing from 12 ft to 8 ft would reduce the heat release of a fire at sprinkler actuation by about 50% for the chosen scenario. Bill and Kung then conducted a series of eight full-scale fire tests using the reduced sprinkler spacing and under the constraint of a 100 gallon total water supply. These tests demonstrated that a single sprinkler flowing at 38 lpm (10 gpm) could maintain room tenability for a ten-minute operation time, under most conditions. Under severe fire scenarios multiple sprinkler actuation occurred which maintained room tenability, but for a shorter duration due to the increased total flow rate.

2.3 Residential Water Flow Rates

Studies were reviewed that provided data characterizing the water supply flow rates for residential homes. Milke and Bryan developed techniques to evaluate and alleviate water supply deficiencies in residential sprinkler systems for one- and two-family dwellings [16, 17]. Data on the available water supply was obtained from Washington Suburban Sanitary Commission (WSSC) who performed water flow tests in the Maryland suburbs of Washington D.C. This data was supplemented by performing water flow rate tests from garden hose outlets of 22 different residences in the Baltimore-Washington, D.C. area, yielding an average flow rate and standard deviation of 23.50 ± 4.85 lpm (6.20 ± 1.28 gpm). The USFA sponsored residential sprinkler research program included a survey of mobile home water supplies [6]. Three sites in northern Illinois were sampled, and the maximum flow rates available ranged from 15 lpm (4 gpm) to 56.0 lpm (14.8 gpm). Although these sample sizes are limited, they are sufficient to provide a preliminary benchmark for the flow rate expected to be available for a residential sprinkler system.

3 Experimental Methods

All of the experiments described in this report were conducted at full scale in a steel training prop at the Delaware County Emergency Services Training Center in Sharon Hill, Pennsylvania. The layout of the steel test structure was an L-shape, with a fire room and adjoining hallway. Ports for water sprays were installed in both the fire room and the hallway, centered to the respective rooms. In the hallway the nozzle or sprinkler was located 3.1 m (10.2 ft) from the entry door and 0.6 m (2.0 ft) from either wall. In the fire room the nozzle or sprinkler was located 2.3 m (7.5 ft) from the window wall and 1.15 m (3.8 ft) from the back wall.

Three sets of experiments were conducted. The first set were water distribution tests intended to characterize the spray patterns of the different water sprays. The second set of experiments examined the ability of a low flow spray nozzle to cool a hot gas layer flow produced by a propane burner. The third set of experiments evaluated the performance of low flow spray nozzles in a furnished room fire.

3.1 Experimental Structure

The structure was constructed from two adjoining shipping containers, with walls and ceiling composed entirely of 6 mm (0.25 in) thick corrugated steel. A layer of 13 mm (0.5 in) thick cement board covered the wood floor. Figure 3.1 shows an exterior view of the test structure, and Figure 3.2 provides the dimensioned floor plan of the test structure. The test structure was arranged in an L-shape, with a fire room and an adjoining hallway. The interior dimensions of the fire room were 4.6 m (14.9 ft) wide by 2.4 m (7.8 ft) long. The hallway was 1.2 m (3.8 ft) wide by 6.2 m (20.2 ft) long. The ceiling height throughout the structure was 2.4 m (7.8 ft), except for the door lintel between the fire room and hallway which was 2.0 m (6.7 ft) high. The width of the door between the fire room and the hallway was 0.8 m (2.5 ft).

Two exterior openings were present in the test structure. One opening was the doorway serving as the entrance to the structure, at the opposite end of the hallway from the fire room. It remained open during all of the experiments. The dimensions of the doorway were 0.8 m (2.5 ft) wide by 2.0 m (6.7 ft) tall. The second opening was a ventilation duct through the window in the fire room, whose purpose was to supply fresh air to the seat of the fire. The remaining area of the window was sealed shut during all of the experiments. The ventilation duct had a constant cross-sectional area with dimensions of 0.7 m (26 in) by 0.2 m (8 in). The opening of the ventilation duct in the interior of the structure was 0.3 m (1 ft) above the floor of the fire room and parallel to the floor. Its position within the fire room is provided by Figure 3.2, and it is pictured in the background in Figures 3.4 and 3.5.

Figure 3.1: Exterior view of the test structure.

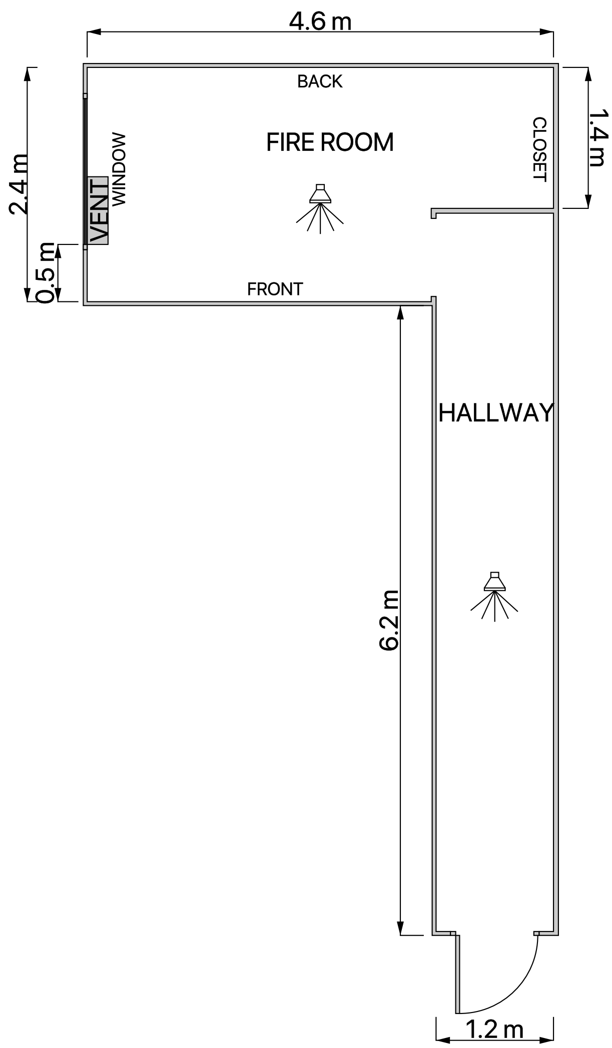


Figure 3.2: Plan view of the test structure including major dimensions.

3.2 Instrumentation

The structure was instrumented for gas temperature, gas concentration,, heat flux, and water flow measurements. Instruments utilized during these experiments included thermocouples, gas analyzers (oxygen, carbon dioxide, and carbon monoxide), Schmidt-Boelter gauges, and a water flow meter.

Gas temperatures were measured with 1.6 mm (0.0625 in) inconel sheathed thermocouples (sheathed thermocouples allow the instrumentation to be placed in areas where suppression may occur to minimize the affect the water had on the measurement). Small-diameter thermocouples were used during these experiments to limit the impact of radiative heating and cooling. The total expanded uncertainty associated with the temperature measurements from these experiments is estimated to be ± 15% as reported by researchers at NIST [18, 19].

Total heat flux measurements were made with water-cooled Schmidt-Boelter gauges. The heat flux gauges were oriented vertically and horizontally at multiple locations within the structure. Results from an international study on total heat flux gauge calibration and response demonstrated that the uncertainty of a Schmidt-Boelter gauge is typically ± 8% [20].

Gas concentration sampling ports were installed at two locations within the structure. The sampling ports consisted of 3/8 in. stainless steel tubing within the structure. Once outside the structure, the sample was filtered through a coarse, 2 micron paper filter before being drawn through a condensing trap to remove moisture. At the condensate trap exit, the sample line transitioned from stainless steel to polyethylene tubing for flexibility. Upstream of the analyzer the sample passed through a fine, 1 micron filter. To minimize transport time through the system, samples were pulled from the structure through the use of vacuum/pressure diaphragm pump rated at 0.75 CFM. Gas samples were analyzed through the use of oxygen (paramagnetic alternating pressure) and combination carbon monoxide/carbon dioxide (non-dispersive infrared) analyzers. The gas sampling instruments used throughout the series of tests discussed in this report have demonstrated a relative expanded uncertainty of ± 1% when compared to span gas volume fractions [21]. Given the non-uniformities and movement of the fire gas environment and the limited set of sampling points in these experiments, an estimated uncertainty of ± 12% is applied to the results [22].

Water flow rate was measured with a 0.23 m (0.75 in) diameter turbine flow meter. The wetted components of the meter are composed of PVC. Flow rate is measured indirectly via the rotational speed of a paddle-wheel that is induced by fluid flow. A built-in display provides the flow rate proportional to the rotational speed of the paddle-wheel. The manufacturer reports a ± 3.0% calibration uncertainty for the accuracy of the measurement [23].

For experiments with the propane burner, a mass flow meter was used to measure the propane flow rate. Section 3.3 describes how the heat release rate of the burner was estimated based on the propane flow rate. According to the manufacturer, the accuracy of the flow meter is ± (0.8% of reading + 0.2% of full scale) [24].

All numerical data was recorded with a purpose-built data acquisition systems with specifically programmed software. Temperatures were recorded using specific hardware with built-in cold-junction compensation and raw voltage values were translated to quantities of interest through post-processing software specifically programmed for use with the systems. Data were sampled at 1 Hz and 1.5 Hz depending upon the system used.

3.2.1 Measurement Locations

One thermocouple array, two gas concentration sampling ports, and one heat flux gauge were in the fire room. The thermocouple array consisted of eight, 1.6 mm (0.0625 in) inconel sheathed thermocouples with the top thermocouple placed 2.5 cm (1 in) below the ceiling. The remaining seven thermocouples were spaced in 30.5 cm (1 ft) intervals below the ceiling such that the bottom thermocouple was 2.1 m (7 ft) below the ceiling. The thermocouple array was positioned 0.6 m (2 ft) perpendicular to the entrance of the fire room and centered with the door frame of the entrance. The gas concentration sampling ports composed of 9.5 mm (0.375 in) stainless steel tubes were positioned in the same location as the thermocouple array, at heights of 0.9 m (3 ft) and 1.5 m (5 ft) from the floor. The heat flux gauge was installed 1.5 m (5 ft) above the ground, against the front wall of the fire room, 0.5 m (19 in) away from the entrance of the fire room. It was oriented horizontally, facing the back wall of the fire room. Figure 3.3 shows the location of the instrumentation within the test structure. All of the instruments in the fire room are grouped under the label, Position 1, in Figure 3.3 and in the results.

The instrumentation in the hallway included two thermocouple arrays, two gas concentration ports, and two heat flux gauges. The instrumentation in the hallway are grouped in two locations – at one-quarter and three-quarters the length of the hallway, and centered with the width of the hallway. The location closer to the fire room is referred to as Position 2, and the location further from the fire room is referred to as Position 3. One thermocouple array was placed at each of the positions in the hallway. Each thermocouple array had eight thermocouples. The first was 2.5 cm (1 in.) below the ceiling, and the remaining seven thermocouples were spaced in 30.5 cm (1 ft) intervals below the ceiling such that the bottom thermocouple was 2.1 m (7 ft) below the ceiling.

Two gas concentration ports and two heat flux gauges were installed at Position 3. The gas concentration ports were installed at heights of 0.9 m (3 ft) and 1.5 m (5 ft) from the floor. The heat flux gauges were both installed at a height of 1.5 m (5 ft) from the floor. One heat flux gauge was oriented horizontally, facing towards the fire room. The other heat flux gauge was oriented vertically, facing the ceiling. Both heat flux gauges were 22.5 cm (8.9 in) off center of the hallway, and the vertical heat flux gauge was offset 10.2 cm (4.0 in) above and behind the horizontal heat flux gauge.

The water flow to the sprinkler and nozzles was measured with an in-line turbine flow meter installed downstream of the water pump.

For the propane burner experiments the flow of propane was controlled and measured with a mass flow meter which was installed in-line between the propane tanks and the burner. Standard video and fire service thermal imaging cameras were installed inside of the structure to capture information about the fire dynamics of the experiments. To ensure video capture even if the cameras experience thermal failure, the cameras were hardwired to a digital video recorder that was outside of the structure. The positioning of the cameras is shown in Figure 3.3. The camera installed in the front wall of the fire room was not included in the propane burner experiments.

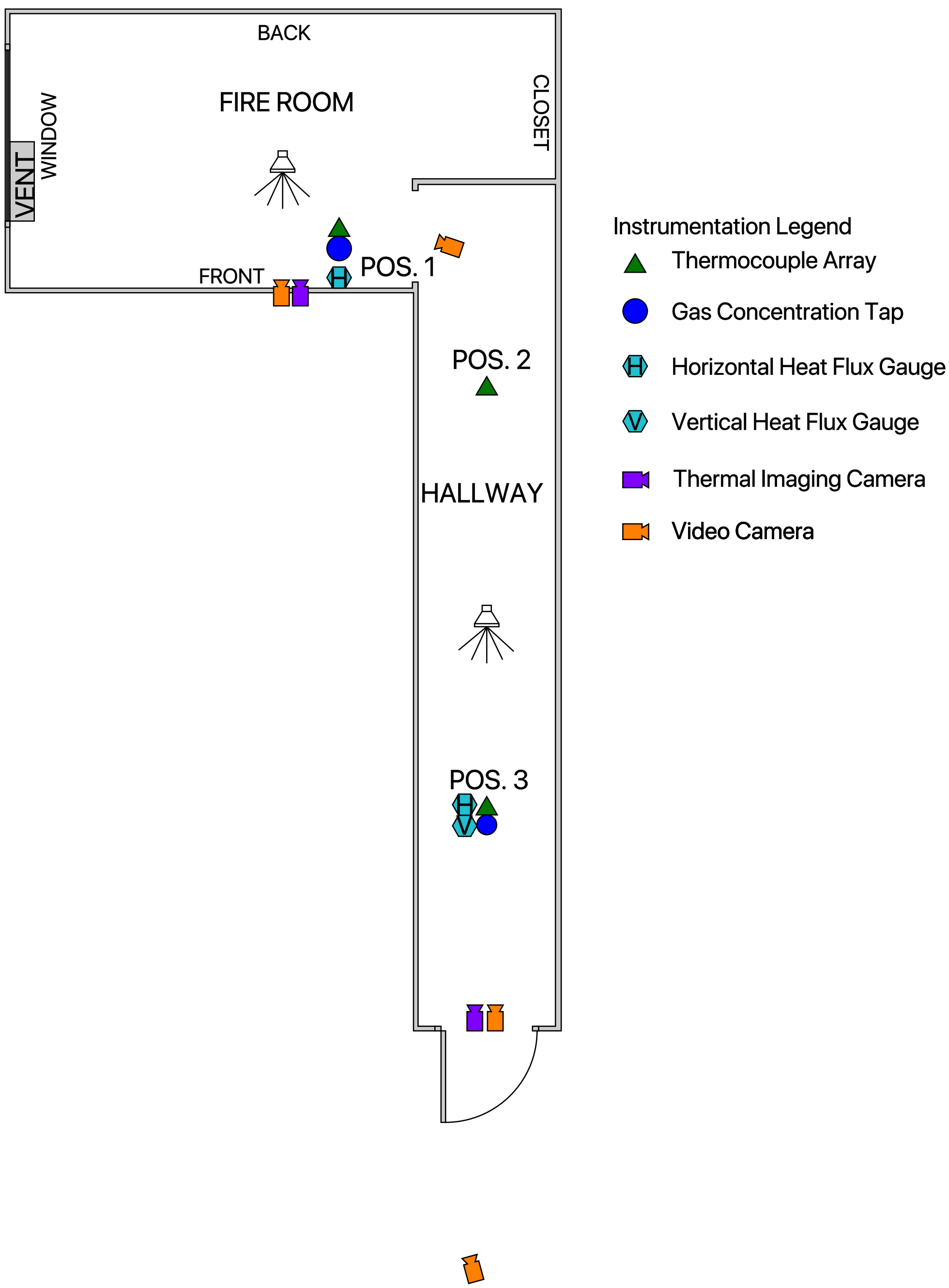


Figure 3.3: Instrumentation locations in the test structure.

3.3 Fuel Load

3.3.1 Propane Burner Experiments

A propane burner was used as the fire source in the gas cooling experiments. The burner had a square opening on its top face, with dimensions of 0.6 m (2.0 ft) by 0.6 m (2.0 ft). The height of the opening from the floor was 0.5 m (20 in). The burner was positioned in the fire room so that its center was 1.0 m (3.4 ft) from the window wall and 1.4 m (4.5 ft) from the back wall. Figure 3.4 shows the burner as it was installed during the experiments.

Figure 3.4: Photograph of propane burner installed in the fire room.

The heat release rate of the burner was estimated based on the flow rate of propane to the burner. Equation 3.1 describes the relationship between the flow rate of propane and the heat release rate of the burner:

$$\dot{Q} = (60 \times \dot{V})\Delta_c \mathrm{H}^\circ \rho / \mathrm{M} \tag{3.1}$$

where $\dot{Q}$ is the heat release rate (kW); $\dot{V}$ is the volumetric flow rate of propane (LPM); $\Delta_c \mathrm{H}^\circ$ is the enthalpy of combustion of propane at standard conditions, 2219.2 ± 0.45 kJ/mol [25]; ρ

is the density of propane gas, 1.9 g/L [26]; and M is the molecular weight of propane, 44.0956 g/mol [25].

The propane supplier reports the purity of the propane to be greater than 85%. The remaining components are reported to be less than 10% propene, less than 5% isobutane, and less than 0.5% pentane. This provides upper and lower bounds for the uncertainty in the composition of the propane – one bound for pure propane, and the other bound for a composition of the aforementioned gases at their maximum potential percentages. The properties for each gas were gathered from the same sources as for the propane properties. The heat release rate was calculated for both bounds of the propane composition. The average of these values is used for the heat release rates reported in this study. The difference between the heat release rates calculated at each bound yields uncertainties of ± 0.27 kW and ± 0.77 kW at propane mass flow rates of 70 lpm and 200 lpm, respectively (these are the minimum and maximum propane mass flow rates used in this study).

Combining the contributing uncertainties in quadrature yields an estimated expanded uncertainty of ± 19% at 110 kW (minimum heat release rate tested) and ± 7% at 315 kW (maximum heat release rate tested).

3.3.2 Furnished Room Experiments

In the furnished room experiments the primary fuel source was an upholstered sofa. In addition, the floor of the fire room was covered by carpeting to allow for the fire to spread beneath the sofa where it would be shielded from the water spray, thereby providing a more realistic challenge to the water sprays. The average mass of the sofa was 50.1 kg ± 1.4 kg (110.5 lb ± 3.1 lb). The sofa was positioned against the back wall of the fire room, centered with the water spray. Experiment 4 was an exception, however, and the sofa was moved along the back wall so that the arm of sofa was against the window wall. The flooring and carpet were comprised of a bottom layer of 1.3 cm (0.5 in) thick OSB sheets, followed by a layer of polyurethane foam padding, and topped by a layer of carpet. The carpet was 100% polyolefin fiber with polypropylene backing. All three layers of the flooring covered an area of 9.3 m^2 (97.7 ft^2). The mass of the carpet, padding, and OSB were 13.5 kg (29.8 lb), 6.5 kg (14.3 lb), and 90.4 kg (199.3 lb), respectively. Figure 3.5 shows the fire room with the furnishings installed.

The fuels used in the furnished room experiments have been characterized in terms of heat release rate (HRR). Upholstered sofas, similar to those used in the furnished room experiments, were characterized as part of ongoing work funded by the National Institute of Justice. They were burned under the UL oxygen consumption calorimeter in Northbrook, IL to determine the HRR and the total heat released. Three replicate sofa HRR experiments were conducted. The HRR experiments were conducted in a free burn condition without any compartmentation effects. Table 3.1 shows the peak HRR and total heat released for each sofa and Figure 3.6 shows HRR time history for each sofa. The components of the flooring were burned under a lab scale cone calorimeter. Table 3.2 summarizes the data collected with the cone calorimeter for the flooring components. The cone calorimeter data demonstrates that if the flooring, padding, or carpeting under the sofa burned due to being shielded from the water, a significant HRR could be produced.

Figure 3.5: Photograph of fire room with furnishings installed.

Table 3.1: Summary of the sofa heat release rates.

Sofa #	Peak HRR [MW]	Total Energy Released [MJ]
1	2.8	723
2	2.9	760
3	2.9	793

Table 3.2: Cone calorimeter data for flooring materials used in furnished room experiments. Each material was tested for three replicates and under a heat flux exposure of 35 kW/m^2. Reported values are the averages and expanded uncertainties between replicates.

Item	Peak HRR [kW/m^2]	Total Energy Released [MJ/m^2]	Effective Heat of Combustion [MJ/kg]
Carpet	383 ± 22	28 ± 4	42 ± 13
Carpet padding	436 ± 16	23 ± 2	29 ± 4
OSB	209 ± 28	83 ± 2	13 ± 0.2

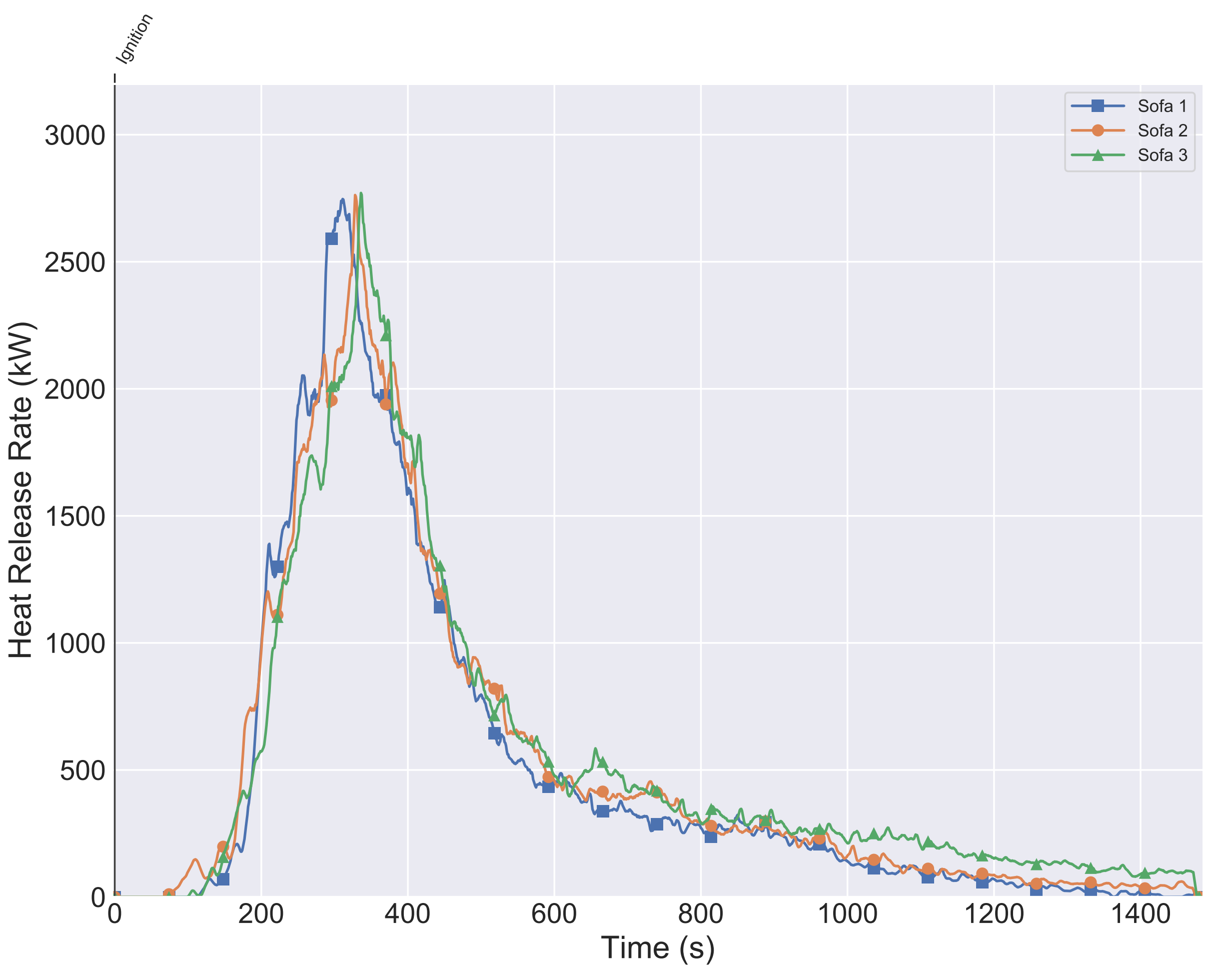


Figure 3.6: Three replicate HRR time histories of the sofas used in the furnished room experiments.

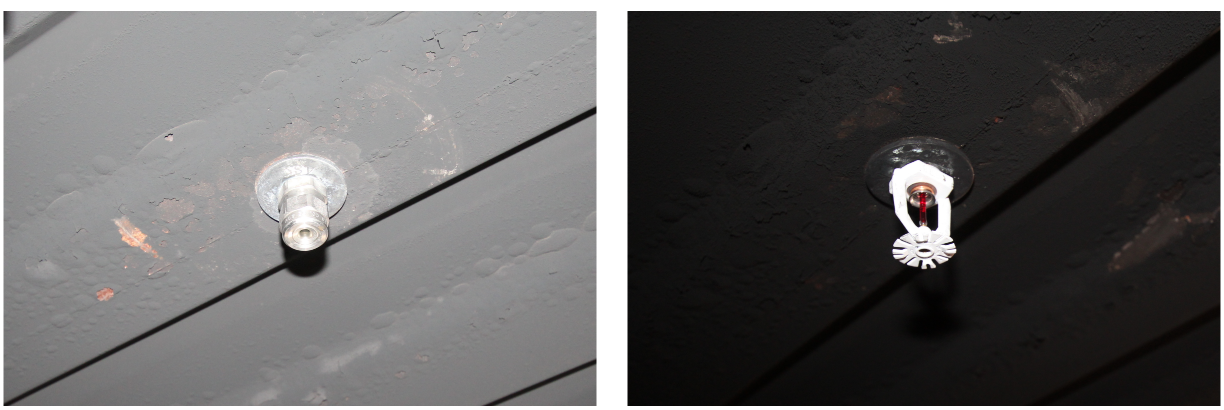
3.4 Water Sprays

Three different spray nozzles and one residential sprinkler were used in the experiments. The residential sprinkler was a commercially available pendent sprinkler with a K-factor of 3.0. The spray nozzles were full cone nozzles that provide uniform distribution and have a wide angle spray (120° at 10 psi according to the manufacturer). The manufacturer lists the droplet size for these nozzles to be between 500 and 5000 microns.

The spray nozzles differed only in their flow capacity. For a given pressure, each nozzle provides a different flow rate. At 0.69 bar (10 psi) the nozzles are rated to provide 11 lpm (3.0 gpm), 15 lpm (4.0 gpm), and 19 lpm (5.0 gpm), and are referred to in this report as the low, medium, and high capacity nozzles, respectively.

The low and high capacity nozzles were used only in the propane burner experiments, whereas the medium capacity nozzle was used in both the propane burner and the furnished room experiments. This was a result of the medium capacity nozzle's performance in the propane burner experiments, where it demonstrated effective gas cooling over a range of operating pressures. Therefore, additional effort was made to characterize the medium capacity nozzle, as described in Table 3.3 and in Section 3.4.1.

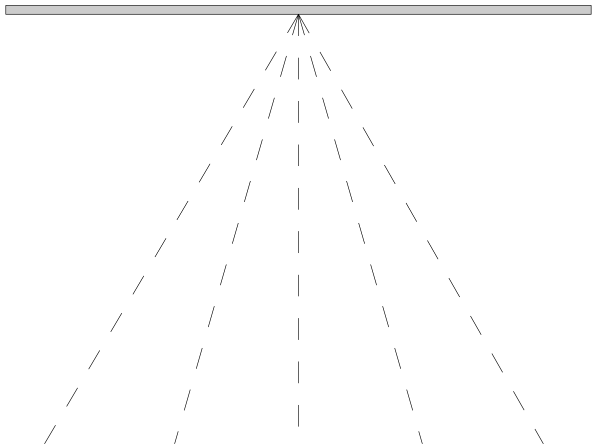
Ports for the water sprays were installed in both the hallway and the fire room, centered in each room. These locations are pictured in the floor plan in Figure 3.2. The water spray nozzles were installed such that the base was flush with the ceiling, and the orifice was approximately 4.0 cm (1.6 in) below the ceiling. Figure 3.7 shows a nozzle and the sprinkler as they were installed in the test structure.



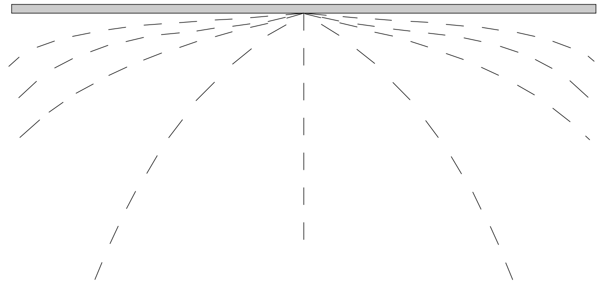
(a) Spray Nozzle (b) Residential Pendent Sprinkler

Figure 3.7: Photographs of water sprays installed in the test structure.

Figure 3.8 shows a comparison between the spray patterns of a nozzle and a sprinkler. The nozzle is designed to create a cone pattern with the drops distributed equally throughout. The intended use of the nozzle is to directly impact the fire for suppression. The sprinkler is designed for the water to hit a deflector plate, distributing the majority of the water outwards. The strategy of a sprinkler is to pre-wet the materials in an area, thereby limiting the growth of a fire.



(a) Spray Nozzle Distribution Pattern



(b) Sprinkler Distribution Pattern

(c) Photograph of Active Nozzle

(d) Photograph of Active Sprinkler

Figure 3.8: Comparison of the spray patterns for nozzles vs. sprinklers.

The pressure at the water spray and at the pump was recorded for the water spray and flow rate combinations used in the furnished room experiments. These pressures are listed in Table 3.3. Pressures were recorded with the water sprays installed in the hallway and in the fire room, but there was no measurable difference between locations.

Table 3.3: Summary of operating pressures for the water sprays and flow rates used in the furnished room experiments.

Water Spray	Water Flow Rate [lpm (gpm)]	Pressure [bar (psi)]	Pressure at Pump [bar (psi)]
Medium capacity nozzle	11 (3)	0.4 (6)	2.2 (32)
Medium capacity nozzle	23 (6)	1.7 (25)	2.1 (30)
Sprinkler	34 (9)	0.6 (9)	1.9 (28)

The residential sprinkler bulb had an activation temperature of 68.3 °C (155 °F). During the propane burner experiments the sprinkler was installed without a bulb so that the water flow could be activated by a valve upstream of the sprinkler, the same as for the nozzles. In the furnished room experiments, however, the bulb was left intact so that the sprinkler would activate when the conditions generated by the fire triggered the bulb to break. The spray nozzles did not include a bulb, therefore a “tell-tale sprinkler” was installed for the furnished room experiments. The tell-tale sprinkler was installed 9.05 cm (3.56 in) away from the nozzle such that it would not interfere with the spray pattern from the nozzle. It was connected to a pressurized air line with a pressure switch to detect when the bulb of the tell-tale sprinkler broke. When this event was detected, water flow to the nozzle was promptly activated.

3.4.1 Water Distribution Tests

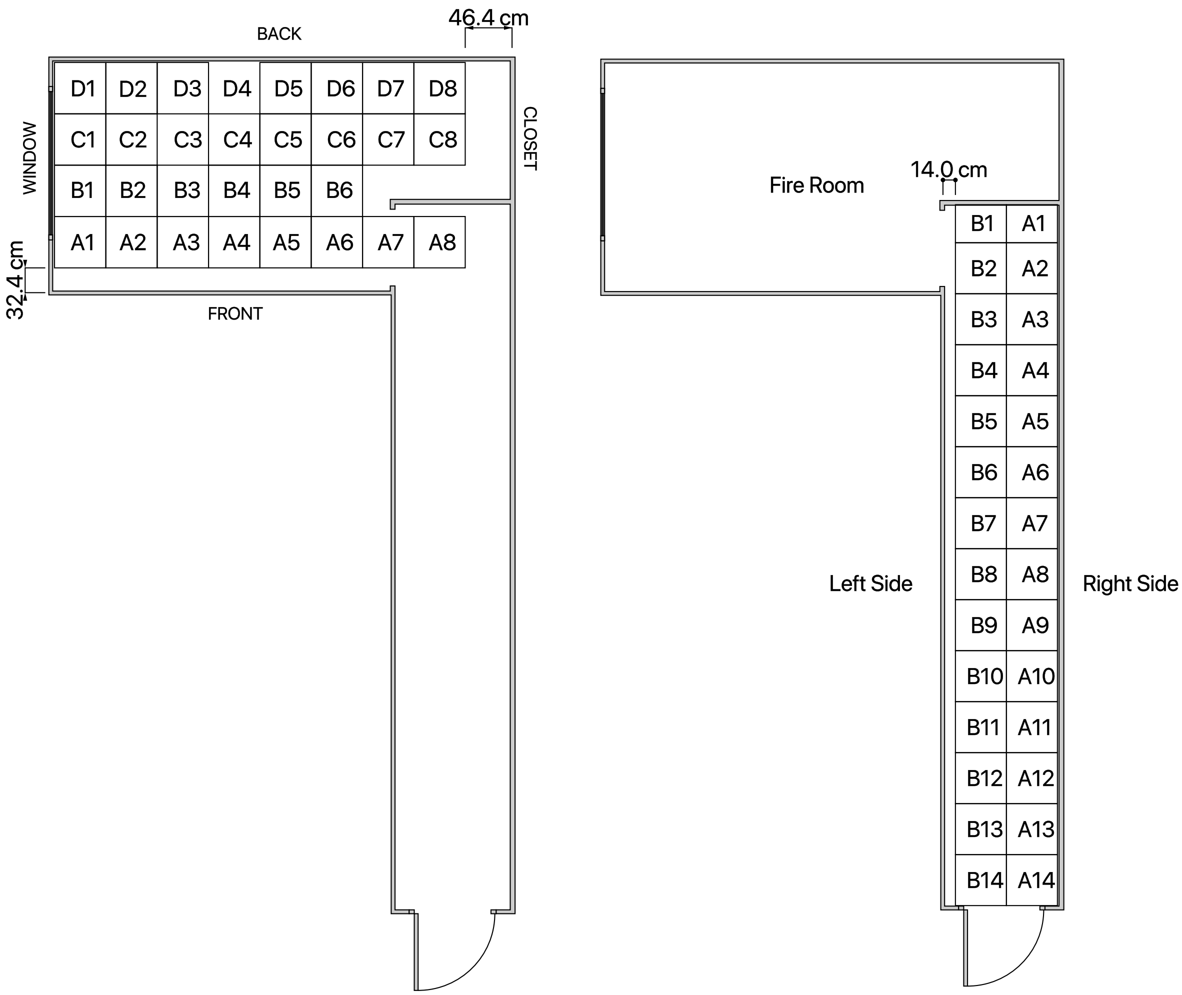
The purpose of the water distribution tests was to characterize and compare the spray patterns of the different water sprays. Water distribution tests were conducted for the water spray, flow rate, and location configurations used in the furnished room experiments. Those configurations include the medium capacity nozzle at 11 lpm (3 gpm) and 23 lpm (6 gpm), and the sprinkler at 34 lpm (9 gpm). Each was tested in both the hallway and the fire room. The water distribution tests were replicated three times for each configuration. Table 3.4 summarizes each test configuration.

Table 3.4: Summary of the water mapping tests.

Suppression Location	Water Spray	Water Flow Rate [lpm (gpm)]	N	Average Water Flux [mm/min (gpm/ft^2)]
Hallway	Medium Capacity Nozzle	11 (3)	3	0.68 (0.017)
Hallway	Medium Capacity Nozzle	23 (6)	3	1.28 (0.031)
Hallway	Sprinkler	34 (9)	3	1.82 (0.045)
Fire Room	Medium Capacity Nozzle	11 (3)	3	0.91 (0.022)
Fire Room	Medium Capacity Nozzle	23 (6)	3	1.77 (0.044)
Fire Room	Sprinkler	34 (9)	3	1.44 (0.035)

The water flow patterns were determined by collecting the water in discrete bins. Each bin was square, with side lengths of 50.8 cm (20 in), covering an area of 0.3 m^2 (2.8 ft^2). The fire room was covered by 30 bins and the hallway was covered by 28 bins. The arrangements of the bins in each room are pictured in Figure 3.9. The edge of each bin had a lip to cover the gap between the adjacent bin, ensuring that all of the water was collected. In the fire room, the first bin was aligned against the back wall–window wall corner. The remaining bins were arranged in adjacent fashion from the first, leaving a 32.4 cm (1.1 ft) gap from the front wall and 46.4 cm (18.25 in) gap from the closet wall. In the hallway, 14 bins covered the length of the hallway without leaving a gap at either end. There was a 14.0 cm (5.5 in) gap along the left wall.

The water distribution was determined by measuring the mass of the water collected in each bucket and the duration of the water flow. The duration of each test was 5 minutes. From these values the water flow rate per unit area, *water flux*, was calculated. The water flux was calculated for each bin, and averaged over each replicate. The results are visualized by Figures 3.10 and 3.11. In



(a) Fire Room Tests

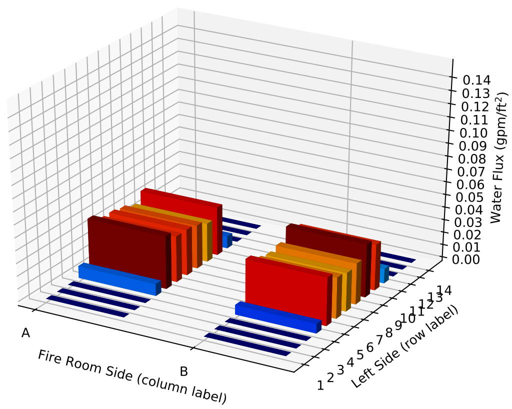
(b) Hallway Tests

Figure 3.9: Layout of water collections bins for water distribution tests.

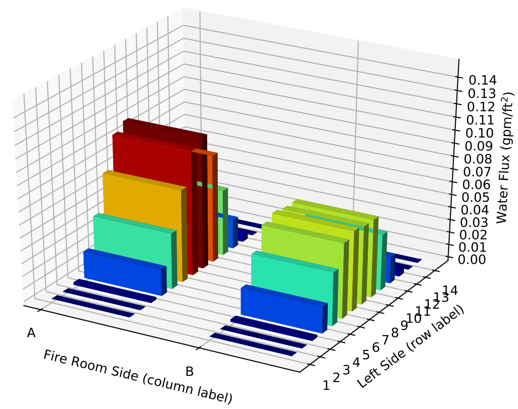
addition, the average water flux of every bin in a test was calculated, and is included in Table 3.4.

To evaluate the error in the water distribution tests, the total volume of water measured was compared to the expected volume of water. Table A.1 in Appendix A shows the expected volume, experimentally measured volume, and percent difference. The average percent difference for the experiments was 53.5%. This error can be primarily attributed to the gaps between the walls of the room and the bins, where the water could not be collected. Evidence of this can be found in Figures 3.10 and 3.11, where bins that were separated from a wall by a gap (left wall in the hallway; front and closet wall in the fire room) collected less water than than their symmetric counterparts on the opposites sides of the rooms.

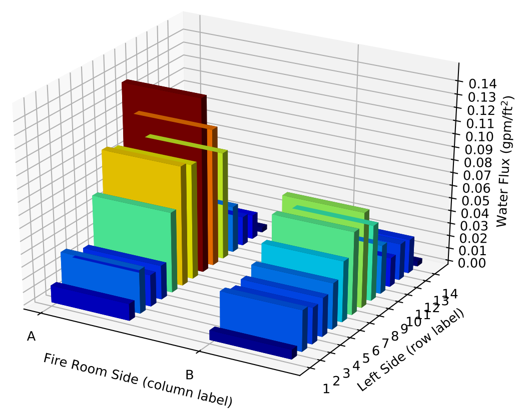
In the hallway, the water distribution patterns of the medium capacity nozzle at 23 lpm (6 gpm) and of the sprinkler were bell-shaped along the length of the hallway. Figures 3.10b and 3.10c show that the peak water flux was measured nearest to the water spray, and tapered off further



(a) Medium Capacity Nozzle; 11 lpm (3 gpm)



(b) Medium Capacity Nozzle; 23 lpm (6 gpm)



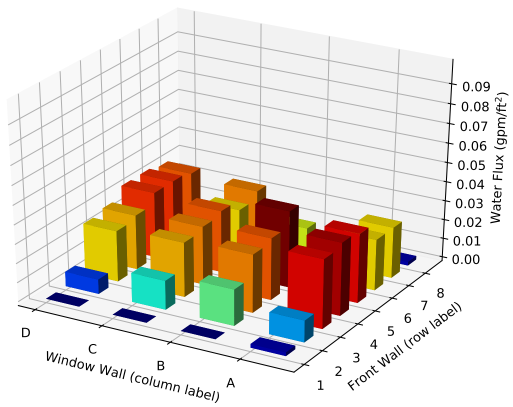
(c) Sprinkler; 34 lpm (9 gpm)

Figure 3.10: Water flux in each collection bin for the water sprays in the hallway.

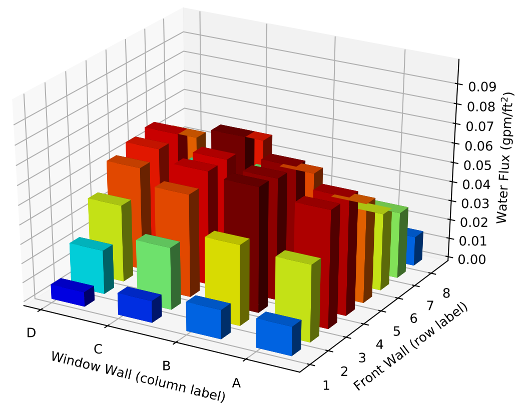
from the water spray. In contrast, Figure 3.10a shows that the peak water flux of the medium capacity nozzle at 11 lpm (3 gpm) was measured in rows 5 and 9. The likely explanation is that at 11 lpm (3 gpm), the medium capacity nozzle does not achieve an evenly distributed spray pattern, but rather concentrates the distribution near the edge of its spray radius.

The spray patterns on the walls of the hallway were recorded by measuring the peak height and spray radius. Only the measurements from the right side of the hallway were considered because the left wall is corrugated, thereby distorting the spray pattern. The medium capacity nozzle had a spray radius of 2.6 m (8.5 ft) at 23 lpm (6 gpm), and a spray radius of 2.2 m (7.2 ft) at 11 lpm (3 gpm). The spray radius of the sprinkler exceeded the length of the hallway in both directions (radius > 3.5 m (11.5 ft)). The peak height measured on the wall of the spray from the medium capacity nozzle was 2.2 m (7.1 ft) at 23 lpm (6 gpm), and 2.1 m (7.0 ft) at 11 lpm (3 gpm). The spray of the sprinkler reached the height of the ceiling.

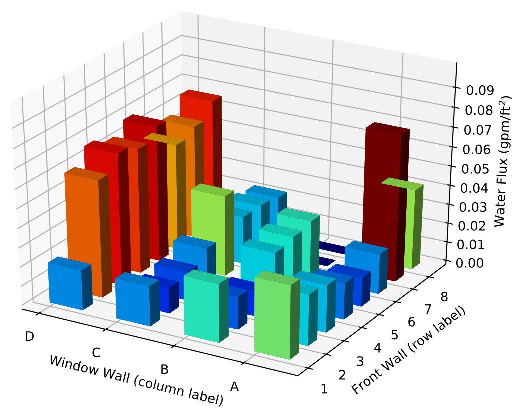
In the fire room, the difference between the distribution patterns of the nozzle and of sprinkler are evident. The nozzle is designed to provide an evenly distributed cone pattern, which can be seen



(a) Medium Capacity Nozzle; 11 lpm (3 gpm)



(b) Medium Capacity Nozzle; 23 lpm (6 gpm)



(c) Sprinkler; 34 lpm (9 gpm)

Figure 3.11: Water flux in each collection bin for the water sprays in the fire room.

in Figure 3.11b: the peak water flux is measured near the center of the room (directly beneath the nozzle) and slightly tapers off towards the edges of the room. Similar to the hallway tests, however, the medium capacity nozzle at 11 lpm (3 gpm) concentrated the distribution near the edge of its spray radius. Figure 3.11a shows that the peak water flux values were measured in a ring around the center of the room instead of beneath the nozzle at the center.

In contrast to the nozzle, the sprinkler is designed to deflect the water flow outwards. Figure 3.11c shows that the highest water flux is measured along the walls, particularly along the back wall. The effect is less prevalent on the other walls due to the gap between the bins and the front/closet walls, and due to the window being open on the window wall. Further evidence of the sprinkler's outward reaching distribution pattern is in Bin A7, which was directly beneath the lintel of the doorway separating the fire room from the hallway. The water spray hit the lintel and fell into Bin A7, making it appear as an outlier among its neighboring bins.

The spray patterns on the walls of the fire room were recorded by measuring the peak height and the heights at the corners of the room. The average peak height between the front and back walls was 2.3 ± 0.2 m (7.5 ± 0.6 ft) for the sprinkler, 1.9 ± 0.8 m (6.3 ± 2.6 ft) for the medium capacity nozzle at 23 lpm (6 gpm), and 1.5 ± 0.3 m (4.9 ± 1.1 ft) for the medium capacity nozzle at 11 lpm (3 gpm). The peak heights on the window and closet walls were not measured because the window was open and the partition wall extruding from the closet wall affected the spray pattern. The height of the spray pattern at each corner of the room was measured, excluding the corner with the hallway entrance. The average corner spray pattern height was 1.4 ± 0.5 m (4.8 ± 1.5 ft) for the sprinkler and 0.6 ± 0.1 m (2.1 ± 0.3 ft) for the medium capacity nozzle at 23 lpm (6 gpm). The spray of the medium capacity nozzle at 11 lpm (3 gpm) did not reach the corners of the room, but was on average 0.4 ± 0.03 m (1.4 ± 0.1 ft) from reaching the corners.

4 Experimental Design and Procedure

4.1 Propane Burner Experiments

The goal of the propane burner experiments was to conduct full-scale experiments that examine the ability of a low flow spray nozzle to cool a hot gas layer flow, without impacting the source fire. UL 1626 tenability criteria was used as a measure of success in providing protection for occupants. The relevant criteria are as follows:

(a) The maximum temperature 76 mm (3 in) from the ceiling at [the room center and/or the nearest sprinkler] shall not exceed 316 °C (600 °F).

(b) The maximum temperature 1.6 mm (5.25 ft) above the floor shall not exceed 93 °C (200 °F).

(c) The temperature at the location described in (b) shall not exceed 54 °C (130 °F) for more than any continuous 2-minute period.

A steady-state heat release rate from a propane burner was used to generate a repeatable flow of heat from the fire room through the hallway. The nozzle in the hallway was activated and the change in temperatures, heat fluxes, gas velocities, and visual obstruction was measured and recorded. The flow rate to the nozzle was varied to characterize its relationship with the reduction in temperature. The nozzles and optimum water flow rates in the hallway exposure were then used in the fire room. The propane burner was shielded and had adequate supply air. The nozzles were activated to examine cooling capability in the room of origin with a shielded fire.

In total, 22 different experiments were conducted in the first stage, with two to three replicates of each. The factors that were varied between experiments include the suppression location, type of water spray, flow rate, and heat release rate of the fire. The suppression location was either in the hallway or in the fire room. Three full cone nozzles with different flow capacity ratings were used as the water sprays, in addition to a pendent-style residential sprinkler. The heat release rate was varied between four levels, approximately equal to 110 kW, 160 kW, 240 kW, and 315 kW. Table 4.1 shows the configurations for each of the propane burner experiments. It should be noted that the residential sprinkler conducted with water flows below 14 lpm (9 gpm) were conducted with flows and pressures that were below the minimum design limits of the sprinkler.

Where applicable, determinations on the outcome of comparisons between experimental factors are made using a statistical approach known as an analysis of variance (ANOVA). An ANOVA quantifies the probability that samples from different levels of a factor originate from the same distribution. The result of the ANOVA is a p-value. A p-value less than 0.05 indicates that the factor levels being compared are significantly different at the 95% confidence level. Both one- and two-way ANOVAs are implemented in this study, which refers to the number of factors considered by the analysis.

Table 4.1: Summary of the propane burner experiments.

Exp #	Suppression Location	Water Spray	Heat Release Rate [kW]	Water Flow Rate [lpm (gpm)]	N
1	Hallway	Low capacity nozzle	110	15 (4)	3
2	Hallway	Low capacity nozzle	160	15 (4)	3
3	Hallway	Low capacity nozzle	240	15 (4)	3
4	Hallway	Medium capacity nozzle	110	19 (5)	3
5	Hallway	Medium capacity nozzle	165	19 (5)	2
6	Hallway	Medium capacity nozzle	245	19 (5)	3
7	Hallway	Medium capacity nozzle	315	19 (5)	3
8	Hallway	Medium capacity nozzle	110	11 (3)	3
9	Hallway	High capacity nozzle	110	26 (7)	3
10	Hallway	High capacity nozzle	160	26 (7)	3
11	Hallway	High capacity nozzle	240	26 (7)	3
12	Hallway	Sprinkler	110	42 (11)	3
13	Hallway	Sprinkler	110	34 (9)	3
14	Hallway	Sprinkler	160	34 (9)	3
15	Hallway	Sprinkler	240	34 (9)	3
16	Hallway	Sprinkler	110	26 (7)	3
17	Hallway	Sprinkler	110	19 (5)	3
18	Hallway	Sprinkler	110	11 (3)	3
19	Fire Room	Medium capacity nozzle	110	11 (3)	3
20	Fire Room	Medium capacity nozzle	110	19 (5)	3
21	Fire Room	Medium capacity nozzle	110	23 (6)	2
22	Fire Room	Sprinkler	110	34 (9)	4

The test procedure for the propane burner experiments was as follows. At least 60 seconds of background data was collected prior to igniting the burner, and the video recording was started. Two minutes were spent after ignition to allow the hot gas layer flow to reach steady-state. Once two minutes had passed, the water spray was activated. Water was discharged for another two minutes to reach new steady conditions. Then the water spray was turned off for two minutes to allow the hot gas layer flow to return to the original steady-state. This cycle, two minutes of water off / two minutes of water on, was repeated for three replicates. After the final replicate, the water and burner flows were turned off and the structure was provided time to cool down to ambient temperatures while the next test configuration was prepared. For the tests with the water spray activated in the fire room, the burner was shielded from the water, as shown in Figure 4.1.

Figure 4.1: Photograph of the shielded burner.

4.2 Furnished Room Experiments

The second set of experiments examined the ability of a low flow nozzle to cool and suppress the thermal hazard from a fire generated by interior finishes and fuels that would be found in a residence. An upholstered furniture item, flooring, and carpeting were installed in the fire room. The nozzle / flow rate combination that provided the best cooling performance with the least water in the gas burner experiments was used in these experiments. A single low flow spray nozzle was installed in the center of the fire room. The fire was ignited with an open flame in seat of the upholstered furniture item. Temperatures, heat fluxes, gas velocities, gas concentrations, visual obstruction were measured and recorded. A "tell-tale sprinkler" – a pendent residential sprinkler connected to a pressurized air line with a pressure switch – was used to determine when the sprinkler bulb broke, and thus when to activate the spray nozzle. The tell-tale sprinkler was installed next to the nozzle, but above the outlet of the spray so that it would not interfere with the water spray pattern from the nozzle.

In total, six experiments were conducted with a fire generated by a furnished room. Table 4.2 shows the factors that were varied between experiments. The first experiment had a pendent residential sprinkler for suppression to provide a baseline by which to compare the low flow nozzle performance. Experiments 2 through 5 had the medium capacity spray nozzle. Experiments 2 and

5 were replicates. In Experiment 4, the location of the sofa was moved to put the ignition location at the edge of the nozzle's spray radius. Lastly, Experiment 6 did not have any water spray, thereby characterizing the thermal hazard associated with the fuel load.

Table 4.2: Summary of the furnished room experiments.

Exp #	Water Spray	Water Flow Rate [lpm (gpm)]	Sofa Location Along Fire Room Back Wall
1	Sprinkler	34 (9)	Centered to water spray
2	Medium capacity nozzle	23 (6)	Centered to water spray
3	Medium capacity nozzle	11, 23 (3, 6)	Centered to water spray
4	Medium capacity nozzle	23 (6)	Against corner with window wall
5	Medium capacity nozzle	23 (6)	Centered to water spray
6	None	-	Centered to water spray

The test procedure for the furnished room experiments was as follows. The test structure was first prepared with the fuel load and instrumentation. At least 60 seconds of background data was collected to prior to ignition, and the video recording was started. The ignitions were started between the left cushion and left arm of the sofa with an electric match. The water spray was activated when the thermal conditions in the room caused a 68.3 °C (155 °F) rated sprinkler bulb to break. For the experiment with the residential sprinkler, the sprinkler was pressurized with water and began flowing the moment the bulb broke. For the experiments with a spray nozzle, the tell-tale sprinkler was used to determine when the bulb broke, and the spray nozzle was manually activated immediately after. Water was discharged for 10 minutes in each experiment, to reflect the minimum sprinkler operation time required by the NFPA 13D standard [1]. After the water flow was turned off, the window to the fire room was opened where a firefighter was on stand-by to provide hose suppression if necessary. Photographs of the fire room were taken after the fire was extinguished.

5 Results & Discussion

5.1 Propane Burner Experimental Results

The propane burner experiments were analyzed in terms of the change in temperature due to water spray activation. Only the top three measurements (2.5 cm (1 in), 0.3 m (1 ft), and 0.6 m (2 ft) from the ceiling) from each thermocouple array were considered because they best encapsulate the behavior of the hot gas layer. In addition, for the thermocouple arrays in the hallway, measurements below the top three were directly impacted by some of the water sprays which potentially compromised their accuracy. The change in temperature due to water spray activation was calculated by averaging the temperature over ten seconds immediately prior to turning the water on/off, and taking the difference between the two averages. Replicates of each experimental configuration were then averaged. The resulting values were tabulated for each experimental configuration and measurement location, and are provided in Tables 5.1–5.3.

For the experiments with the water spray located in the hallway, the temperature changes of primary interest were those measured at Position 3 (see Figure 5.1), between 2.5 cm (1 in) and 0.6 m (2 ft) from the ceiling. This position was most responsive to the water spray activation due to being located on the opposite side of the water spray relative to the fire, and the heights were within the hot gas layer. The temperature changes at these locations, beginning with the measurement at 2.5 cm (1 in) below the ceiling (Table 5.1: Position 3), are used to draw comparisons among different experimental factors: heat release rates, flow capacity of nozzles, spray nozzle versus sprinkler, and flow rates. The experiments with the water spray located in the hallway are considered first.

The heat release rate of the fire did not have an affect on the change in temperature due to spray nozzle activation. Experiments were conducted with heat release rates of approximately 110 kW (Exp. 1, 4, 9), 160 kW (Exp. 2, 5, 10), and 240 kW (Exp. 3, 6, 11). The medium capacity nozzle was tested at an additional heat release rate of 315 kW (Exp. 7). From a two-way ANOVA with main effects of nozzle type and heat release rate, it is determined that the responses to different heat release rate levels are not significantly different (p-value = 0.232). In contrast, a one-way ANOVA with main effect of heat release rate for the sprinkler experiments with equivalent flow rates (9 gpm) determined the heat release rate to significantly affect the temperature response (Exp. 13–15, p-value < 0.001).

The different flow capacity nozzles performed similarly, but were significantly different according to a two-way ANOVA comparing main effects of nozzle type and heat release rate (p-value = 0.003). The medium capacity nozzle performed best for each heat release rate level. The medium capacity nozzle was therefore used for comparison with the sprinkler performance and was selected for the experiments with suppression in the fire room.

Compared at equivalent flow rates and heat release rate, the medium capacity nozzle performed better than the sprinkler. Both were tested at a heat release rate of 110 kW and flow rates of

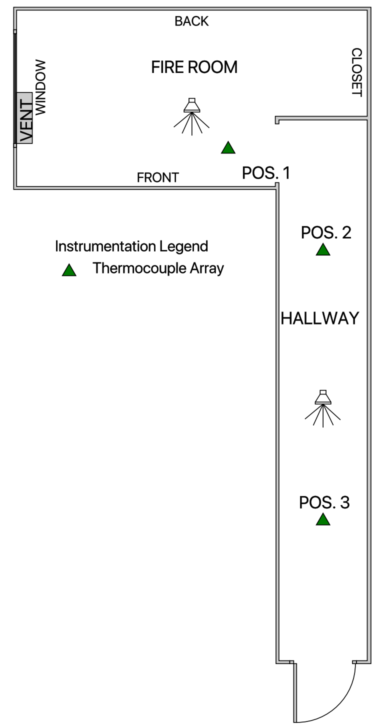


Figure 5.1: Instrumentation locations in the test structure.

approximately 19 lpm (5 gpm) and 11 lpm (3 gpm) (Exp. 4, 8, 17, 18). The responses were compared by a two-way ANOVA with main effects of water spray type (medium capacity nozzle and sprinkler) and flow rate. The responses of the sprinkler and nozzle were significantly different (p-value = 0.008).

The sprinkler showed an increase in performance with an increase in flow rate. It was tested at flow rates of 11 lpm (3 gpm), 19 lpm (5 gpm), 26 lpm (7 gpm), 34 lpm (9 gpm) and 42 lpm (11 gpm), yielding drops in temperature at Position 3, 2.54 cm (1 in) from ceiling of 0.6 °C, 11.7 °C, 33.4 °C, 60.9 °C, and 73.4 °C, respectively. The minimum flow rate for the sprinkler to meet UL 1626 criteria for tenability at Position 3 was 26 lpm (7 gpm). For the medium capacity sprinkler, the minimum flow rate to meet UL 1626 criteria for tenability at Position 3 was 19 lpm (5 gpm). The medium capacity nozzle could not reach a higher flow rate than 23 lpm (6 gpm) due to the limitations of the pump.

Similar trends to those measured at 2.54 cm (1 in) from the ceiling were measured at 0.3 m (1 ft) and 0.6 m (2 ft) from the ceiling (see Tables 5.2 and 5.3). However, the measurements at lower heights reveal some additional trends. The change in temperature at Position 2 becomes more similar to the response at Position 3 at greater distances from the ceiling. Closer to the ceiling, the influence of the hot gas layer on temperature is stronger at Position 2 than at Position 3. The temperature measurements at lower heights also reveal a larger difference in performance between the medium capacity nozzle and the sprinkler, when compared at equivalent flow rates and heat release rates. Two-way ANOVAs with main effects of water spray type (medium capacity nozzle and sprinkler) and flow rate (11 lpm (3 gpm) and 19 lpm (5 gpm)) finds the responses of the nozzle and sprinkler to be significantly different at 0.3 m (1 ft) (p-value = 0.001) and 0.6 m (2 ft) (p-value < 0.001) from the ceiling. This difference is consistent with the measurements at 2.54 cm (1 in) from the ceiling.

Four experimental configurations were conducted with the water sprays installed in the fire room and the burner shielded from the spray. The medium capacity nozzle was tested with a 110 kW fire and at three flow rates: 11 lpm (3 gpm), 19 lpm (5 gpm), and 23 lpm (6 gpm) (Exp. 19–21). For each flow rate, the ceiling temperatures in the fire room (Position 1) dropped by 17.9 °C, 48.8 °C, and 61.9 °C, respectively. The change in temperatures at Positions 2 and 3, and at greater distances from the ceiling showed similarly strong dependence on flow rate. The sprinkler was tested with the same size fire (110 kW) and at a flow rate of 34 lpm (9 gpm) (Exp. 22). The sprinkler provided much greater cooling in the fire room than did the medium capacity nozzle at any flow rate. The sprinkler cooled the ceiling temperature in the fire room by 133.9 °C, whereas the medium capacity nozzle at 23 lpm (6 gpm) cooled the same location by 61.9 °C. In the hallway, however, the medium capacity nozzle at 23 lpm (6 gpm) provided nearly the same cooling as the sprinkler. The difference between responses was less than 4 °C at each height of Position 3. One-way ANOVAs with main effect of water spray type show the difference between responses to the sprinkler and the medium capacity nozzle to be significant at 2.54 cm (1 in) from the ceiling (p-value = 0.046), but not at 0.3 m (1 ft) and 0.6 m (2 ft) from the ceiling (p-value = 0.425, 0.299, respectively).

Table 5.1: Change in temperature [°C] 2.54 cm (1 in) from the ceiling due to water spray activation.

Exp #	Nozzle	Suppression Location	Heat Release Rate [kW]	Water Flow Rate [lpm (gpm)]	N	Position 1	Position 2	Position 3
1	Low capacity nozzle	Hallway	110	15 (4)	3	7.5	-7.6	-23.1
2	Low capacity nozzle	Hallway	160	15 (4)	3	3.1	-6.4	-29.1
3	Low capacity nozzle	Hallway	240	15 (4)	3	4.2	-5.6	-28.4
4	Medium capacity nozzle	Hallway	110	19 (5)	3	6.4	-4.6	-33.0
5	Medium capacity nozzle	Hallway	165	19 (5)	2	3.2	-8.3	-31.3
6	Medium capacity nozzle	Hallway	245	19 (5)	3	3.3	-11.5	-30.1
7	Medium capacity nozzle	Hallway	315	19 (5)	3	5.4	-13.3	-30.9
8	Medium capacity nozzle	Hallway	110	11 (3)	3	0.6	-2.2	-3.0
9	High capacity nozzle	Hallway	110	26 (7)	3	4.4	-3.4	-24.0
10	High capacity nozzle	Hallway	160	26 (7)	3	2.8	-6.6	-27.8
11	High capacity nozzle	Hallway	240	26 (7)	3	9.2	-2.4	-28.7
12	Sprinkler	Hallway	110	42 (11)	2	8.9	-10.6	-73.4
13	Sprinkler	Hallway	110	34 (9)	3	7.5	-4.6	-60.9
14	Sprinkler	Hallway	160	34 (9)	3	9.0	-4.4	-70.0
15	Sprinkler	Hallway	240	34 (9)	3	15.2	-1.0	-82.6
16	Sprinkler	Hallway	110	26 (7)	3	-2.7	-5.6	-33.4
17	Sprinkler	Hallway	110	19 (5)	3	0.5	-4.5	-11.7
18	Sprinkler	Hallway	110	11 (3)	3	-1.9	-1.0	-0.6
19	Medium capacity nozzle	Fire Room	110	11 (3)	3	-17.9	-7.4	-6.1
20	Medium capacity nozzle	Fire Room	110	19 (5)	3	-48.8	-39.7	-31.4
21	Medium capacity nozzle	Fire Room	110	23 (6)	2	-61.9	-54.5	-44.3
22	Sprinkler	Fire Room	110	34 (9)	3	-133.9	-56.5	-48.0

Table 5.2: Change in temperature [°C] 0.3 m (1 ft) from the ceiling due to water spray activation.

Exp #	Nozzle	Suppression Location	Heat Release Rate [kW]	Water Flow Rate [lpm (gpm)]	N	Position 1	Position 2	Position 3
1	Low capacity nozzle	Hallway	110	15 (4)	3	4.4	-14.8	-33.6
2	Low capacity nozzle	Hallway	160	15 (4)	3	2.5	-19.9	-42.2
3	Low capacity nozzle	Hallway	240	15 (4)	3	-0.1	-23.4	-46.6
4	Medium capacity nozzle	Hallway	110	19 (5)	3	6.7	-19.4	-37.3
5	Medium capacity nozzle	Hallway	165	19 (5)	2	1.4	-26.1	-47.7
6	Medium capacity nozzle	Hallway	245	19 (5)	3	1.8	-30.5	-45.0
7	Medium capacity nozzle	Hallway	315	19 (5)	3	-2.2	-39.8	-52.1
8	Medium capacity nozzle	Hallway	110	11 (3)	3	-1.3	-6.1	-7.8
9	High capacity nozzle	Hallway	110	26 (7)	3	0.9	-5.0	-29.0
10	High capacity nozzle	Hallway	160	26 (7)	3	0.8	-18.1	-36.4
11	High capacity nozzle	Hallway	240	26 (7)	3	5.7	-19.6	-36.7
12	Sprinkler	Hallway	110	42 (11)	2	2.2	-36.4	-61.2
13	Sprinkler	Hallway	110	34 (9)	3	3.2	-23.2	-59.8
14	Sprinkler	Hallway	160	34 (9)	3	6.1	-42.2	-84.6
15	Sprinkler	Hallway	240	34 (9)	3	12.9	-57.6	-84.3
16	Sprinkler	Hallway	110	26 (7)	3	-1.9	-14.6	-26.5
17	Sprinkler	Hallway	110	19 (5)	3	-0.2	-6.4	-12.7
18	Sprinkler	Hallway	110	11 (3)	3	0.9	-2.0	-4.5
19	Medium capacity nozzle	Fire Room	110	11 (3)	3	-13.4	-4.3	-2.4
20	Medium capacity nozzle	Fire Room	110	19 (5)	3	-56.0	-21.8	-22.0
21	Medium capacity nozzle	Fire Room	110	23 (6)	2	-80.5	-28.2	-29.5
22	Sprinkler	Fire Room	110	34 (9)	3	-138.6	-29.0	-27.6

Table 5.3: Change in temperature [°C] 0.6 m (2 ft) from the ceiling due to water spray activation.

Exp #	Nozzle	Suppression Location	Heat Release Rate [kW]	Water Flow Rate [lpm (gpm)]	N	Position 1	Position 2	Position 3
1	Low capacity nozzle	Hallway	110	15 (4)	3	0.6	-36.3	-46.3
2	Low capacity nozzle	Hallway	160	15 (4)	3	0.5	-47.9	-56.9
3	Low capacity nozzle	Hallway	240	15 (4)	3	3.1	-64.1	-63.4
4	Medium capacity nozzle	Hallway	110	19 (5)	3	4.1	-46.8	-43.8
5	Medium capacity nozzle	Hallway	165	19 (5)	2	-0.1	-56.5	-53.9
6	Medium capacity nozzle	Hallway	245	19 (5)	3	-1.1	-66.0	-60.1
7	Medium capacity nozzle	Hallway	315	19 (5)	3	-2.5	-87.0	-70.3
8	Medium capacity nozzle	Hallway	110	11 (3)	3	0.3	-15.0	-8.2
9	High capacity nozzle	Hallway	110	26 (7)	3	5.1	-35.8	-32.6
10	High capacity nozzle	Hallway	160	26 (7)	3	-0.6	-49.1	-45.0
11	High capacity nozzle	Hallway	240	26 (7)	3	7.7	-66.4	-45.9
12	Sprinkler	Hallway	110	42 (11)	2	3.7	-54.1	-57.3
13	Sprinkler	Hallway	110	34 (9)	3	4.5	-69.9	-57.5
14	Sprinkler	Hallway	160	34 (9)	3	7.0	-99.6	-83.5
15	Sprinkler	Hallway	240	34 (9)	3	9.8	-127.3	-102.2
16	Sprinkler	Hallway	110	26 (7)	3	-2.0	-39.9	-32.6
17	Sprinkler	Hallway	110	19 (5)	3	-0.1	-17.1	-9.2
18	Sprinkler	Hallway	110	11 (3)	3	-0.5	-4.0	-0.6
19	Medium capacity nozzle	Fire Room	110	11 (3)	3	-40.5	-17.7	-4.9
20	Medium capacity nozzle	Fire Room	110	19 (5)	3	-79.8	-33.7	-25.1
21	Medium capacity nozzle	Fire Room	110	23 (6)	2	-18.5	-40.6	-33.7
22	Sprinkler	Fire Room	110	34 (9)	3	-63.5	-30.4	-31.4

The medium capacity nozzle proved to be the most effective at gas cooling among the nozzles used in these experiments. It was therefore chosen to be the only nozzle tested in the furnished room experiments. The sprinkler, however, was the most effective water spray if operated within its design limits (at least 34 lpm (9 gpm)).

5.2 Furnished Room Experimental Results

Six experiments were conducted with a fuel load of interior furnishings that would be found in a residence. Experiment 1 tested the performance of a residential sprinkler. Experiments 2–5 tested the performance of the medium capacity nozzle with different flow rates and room configurations. The final experiment was a free burn – it did not include any water spray. The analysis of these experiments was based on several measures, including UL 1626 criteria for tenability and peak temperature, heat flux, and gas concentrations in the fire room.

5.2.1 Experiment 1

Experiment 1 was designed to be the baseline test by which to compare the performance of the nozzle. It involved a residential sprinkler installed in the fire room, set to flow water at 34 lpm (9 gpm). The floor of the fire room was covered by a layer of OSB, carpet padding, and carpet. A sofa was placed against the back wall of the fire room, centered to the sprinkler. Figure 5.5 shows the temperature profile time history of the thermocouple array in the fire room (Position 1). Figure 5.6 shows the time history of the gas concentrations at the same location.

The sofa was ignited (t = 0 s) with a remote operated electric match. At 150 seconds, the sprinkler activated. Immediately prior to sprinkler activation, the temperature at Position 1, 2.54 cm (1 in) from the ceiling, was 81 °C. Figure 5.2 displays the video and thermal imaging views of the fire room just prior to sprinkler activation.

Following sprinkler activation, the conditions in the structure returned approximately to ambient conditions (less than 40 °C throughout the structure). The fire was not extinguished, but remained controlled by the sprinkler for about 320 seconds. Figure 5.3 presents video and thermal imaging views of the fire room 30 s after sprinkler activation. Then temperatures began to increase again, reaching a peak of approximately 110 °C at Position 1, 2.54 cm (1 in) from the ceiling. Video reveals that the fire spread underneath the sofa where it was shielded from the sprinkler, and began a second growth phase. The second growth phase was controlled by the sprinkler, and temperatures again returned to approximately ambient conditions. The O_2 concentration measurements reflect similar patterns to those captured by the temperature measurements: the O_2 concentration decreases when the temperature increases. The CO and CO_2 concentrations showed only minimal response throughout sprinkler operation.

The sprinkler was turned off after 10-minutes of being active. This water flow duration was prede-

Figure 5.2: Experiment 1 - Conditions in the fire room at 150 s, just prior to sprinkler activation.

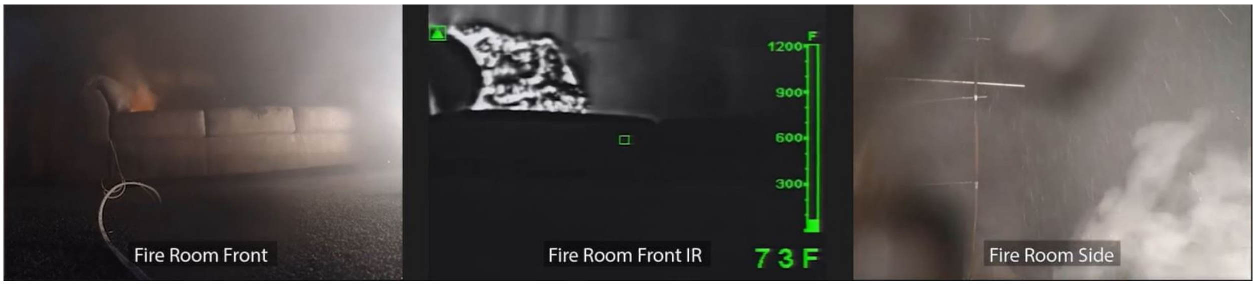


Figure 5.3: Experiment 1 - Conditions in the fire room at 180 s, 30 s after sprinkler activation.

Figure 5.4: Experiment 1 - Conditions in the fire room at 750 s, or 10 minutes after sprinkler activation.

termined based on the general 10 minute water supply requirement in NFPA 13D [1]. Figure 5.4 shows the video and thermal imaging views of the fire room 10 minutes after sprinkler activation to provide a sense of the fire conditions at that time.

After the sprinkler was turned off temperatures in the fire room began to increase as shown in Figure 5.5. This third growth phase reached a peak temperature in the fire room of more than 400 °C and a peak heat flux of approximately 23 kW/m^2, measured at Position 1. About 5 minutes after turning off the water to the sprinkler, the water to the sprinkler was turned on again to knock down the fire. At 1185 seconds after ignition, the window to the fire room was opened and the fire was extinguished by hose suppression, concluding the experiment.

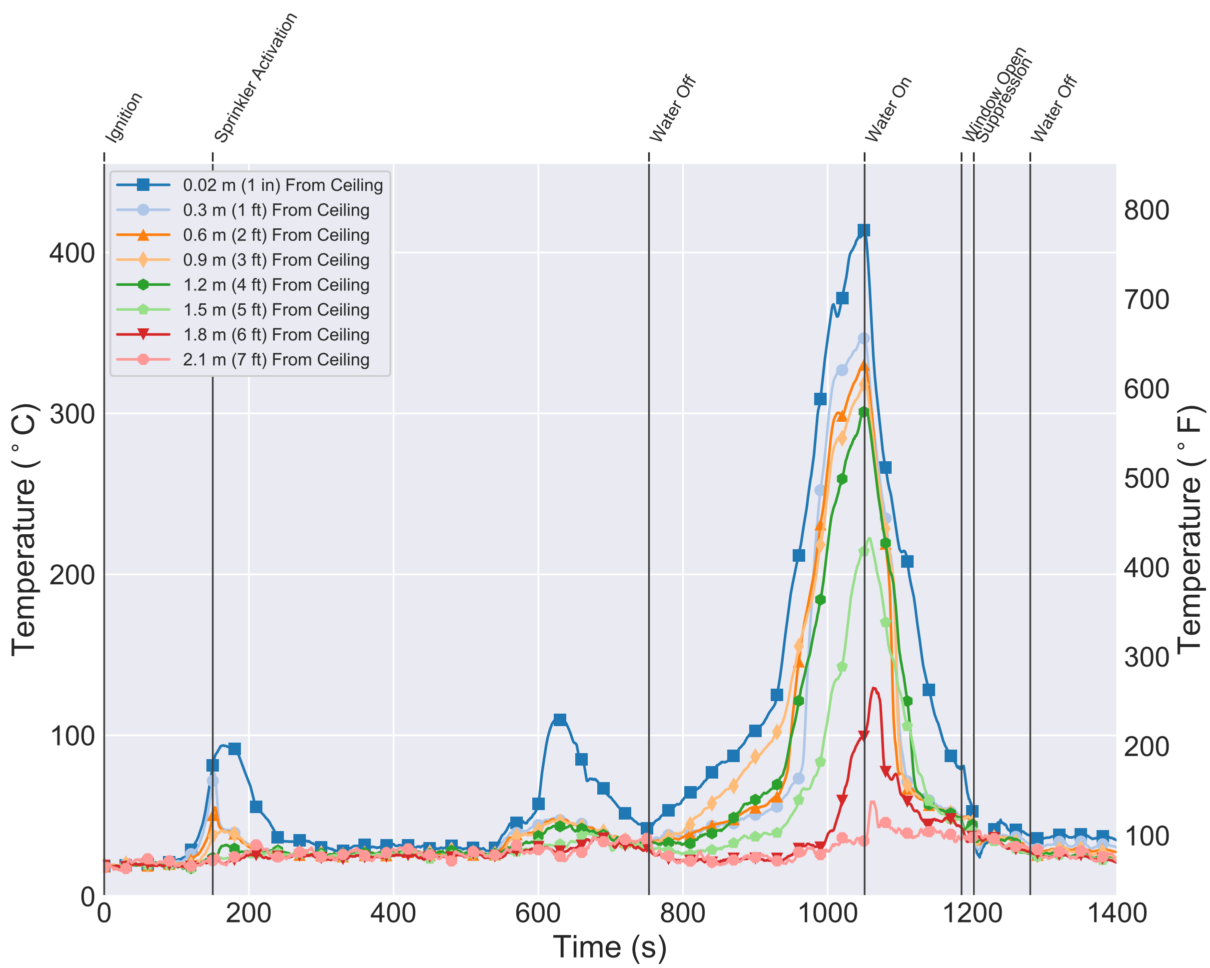


Figure 5.5: Experiment 1 - Thermocouple temperature time history from the thermocouple array in the fire room (Position 1).

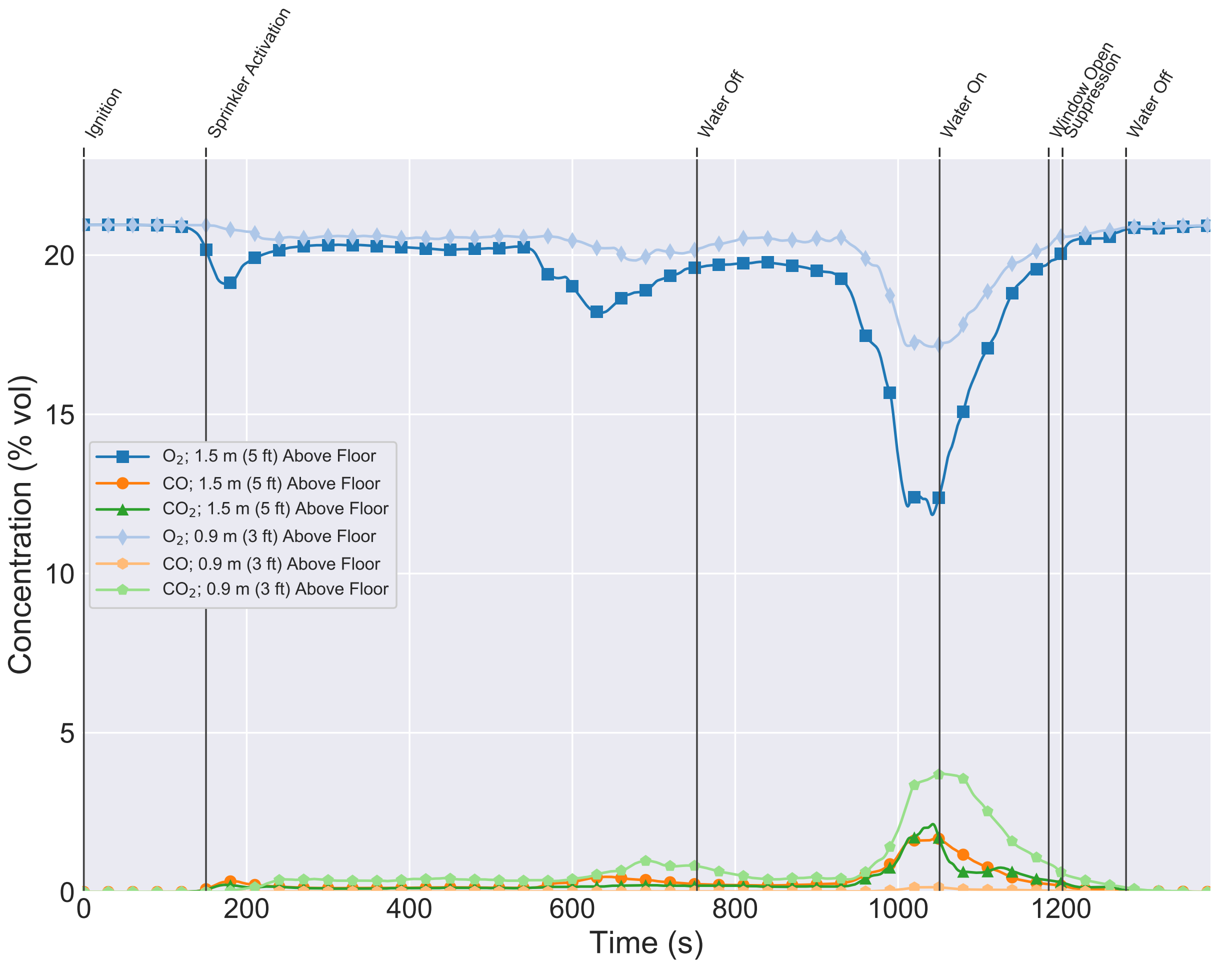
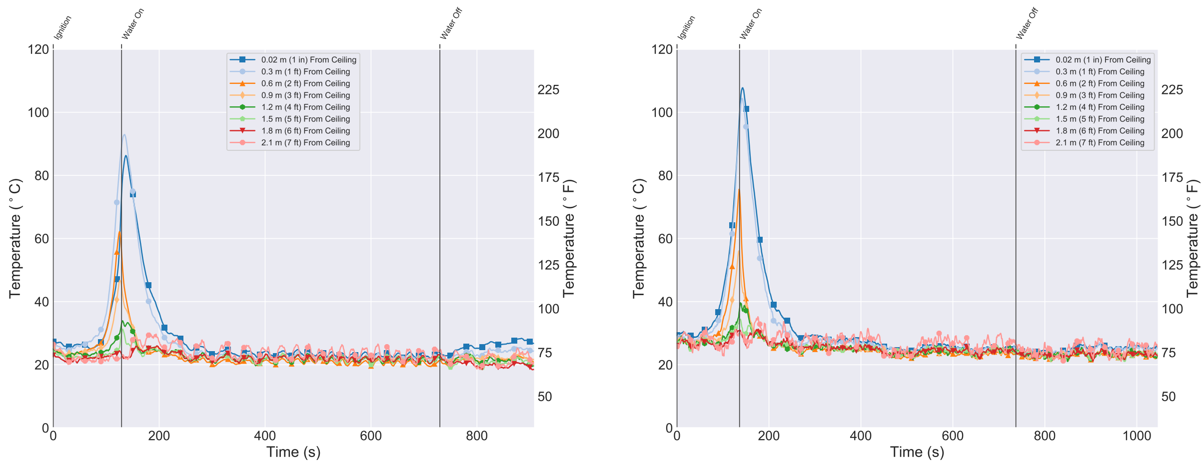


Figure 5.6: Experiment 1 - Gas concentrations time history measured in the fire room (Position 1).

5.2.2 Experiments 2 and 5

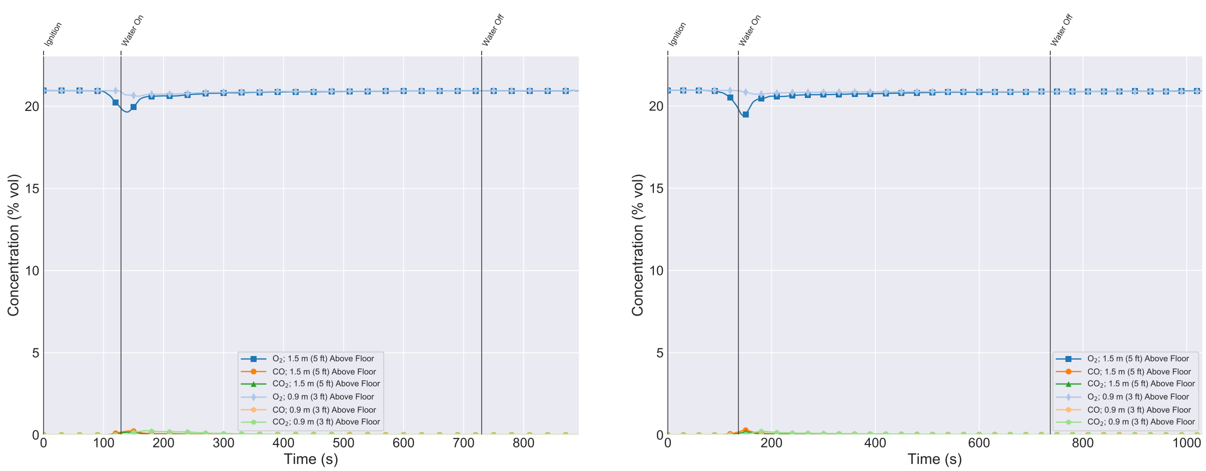
Experiments 2 and 5 were replicates, where the medium capacity nozzle was installed in the fire room and set to flow water at 23 lpm (6 gpm). The fuel load was the same as in Experiment 1. The time history of the temperature profile and gas concentrations at Position 1 in the fire room are shown in Figures 5.7 and 5.8, respectively.



(a) Experiment 2

(b) Experiment 5

Figure 5.7: Experiments 2 and 5 - Thermocouple temperature time history from the thermocouple array in the fire room (Position 1).



(a) Experiment 2

(b) Experiment 5

Figure 5.8: Experiments 2 and 5 - Gas concentrations time history measured in the fire room (Position 1).

In Experiment 2, the tell-tale sprinkler activated 129 seconds after ignition. After the tell-tale sprinkler activation, the water flow to the nozzle was started immediately afterward. The temperature at

Position 1, 2.54 cm (1 in) from the ceiling was 75 °C, immediately prior to nozzle activation. Temperature, heat flux, and gas concentration measurements throughout the structure quickly returned to ambient conditions. The ceiling temperature in the fire room returned to below 30 °C by 89 seconds after the nozzle activated. The nozzle remained active for a total of 10 minutes. After the water was turned off, the measurements in the structure continued to reflect ambient conditions. The measurements, as well as video, show that the fire was extinguished shortly after the nozzle was activated. Over the entire experiment, the peak temperature in the structure was 93 °C, which was measured at Position 1, 0.3 m (1 ft) from the ceiling. The peak heat flux measured in the fire room was approximately 2 kW/m^2.

Experiment 5 demonstrated the repeatability of the findings from Experiment 2 – the fire reached a similar size and was extinguished with similar timing. In Experiment 5, the nozzle activated at 136 seconds after ignition. The temperature at Position 1, 2.54 cm (1 in) from the ceiling was 97 °C immediately prior to nozzle activation, and returned to below 30 °C by 116 seconds after nozzle activation. The temperature measured at that location peaked at approximately 110 °C, which was the highest temperature measured in the structure for the entire experiment. The peak heat flux measured in the fire room was about 3 kW/m^2. In both experiments, the O_2 concentration measured 1.5 m (5 ft) above the floor in the fire room dropped slightly during the fire growth phase before returning to ambient conditions after nozzle activation. The CO and CO_2 concentrations did not show any measurable increase in either experiment. The fire in Experiment 5 reached a slightly larger size than in Experiment 2, but the conclusion was the same – the fires were quickly extinguished by the nozzle. Video and thermal imaging views taken during Experiment 5 are representative of both of these experiments. Figures 5.9 and 5.10 provide a sense of the conditions in the fire room just before water flow from the nozzle and 30 s after the water flow was started, respectively. Shortly after the water flow was started visual evidence of flaming combustion disappeared and did not return within the 10 minute duration of Experiments 2 and 5.

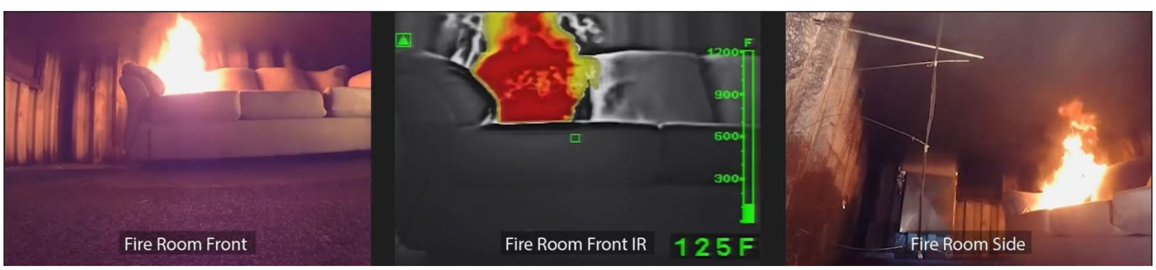


Figure 5.9: Experiment 5 - Conditions in the fire room at 135 s, just prior to nozzle activation.

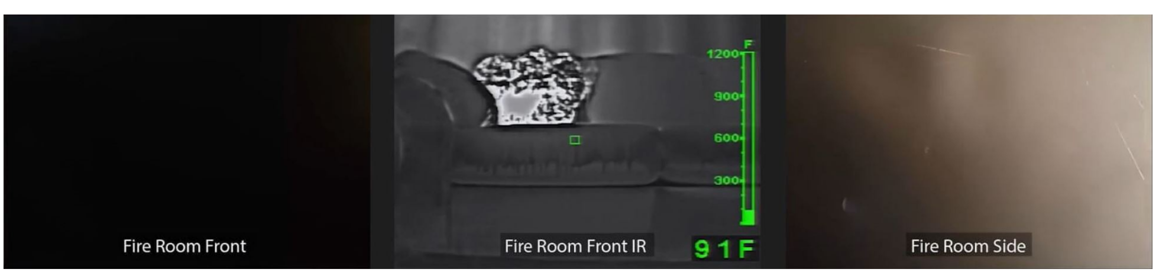


Figure 5.10: Experiment 5 - Conditions in the fire room at 165 s, 30 s after nozzle activation.

5.2.3 Experiment 3

Experiment 3 involved the same scenario as Experiments 2 and 5, but with a lower water flow rate of 11 lpm (3 gpm). The medium capacity nozzle was installed in the fire room which was prepared with carpet flooring and a sofa. The sofa was against the back wall and centered to the nozzle. The time history of the temperature profile and gas concentrations at Position 1 in the fire room are shown in Figures 5.11 and 5.12, respectively.

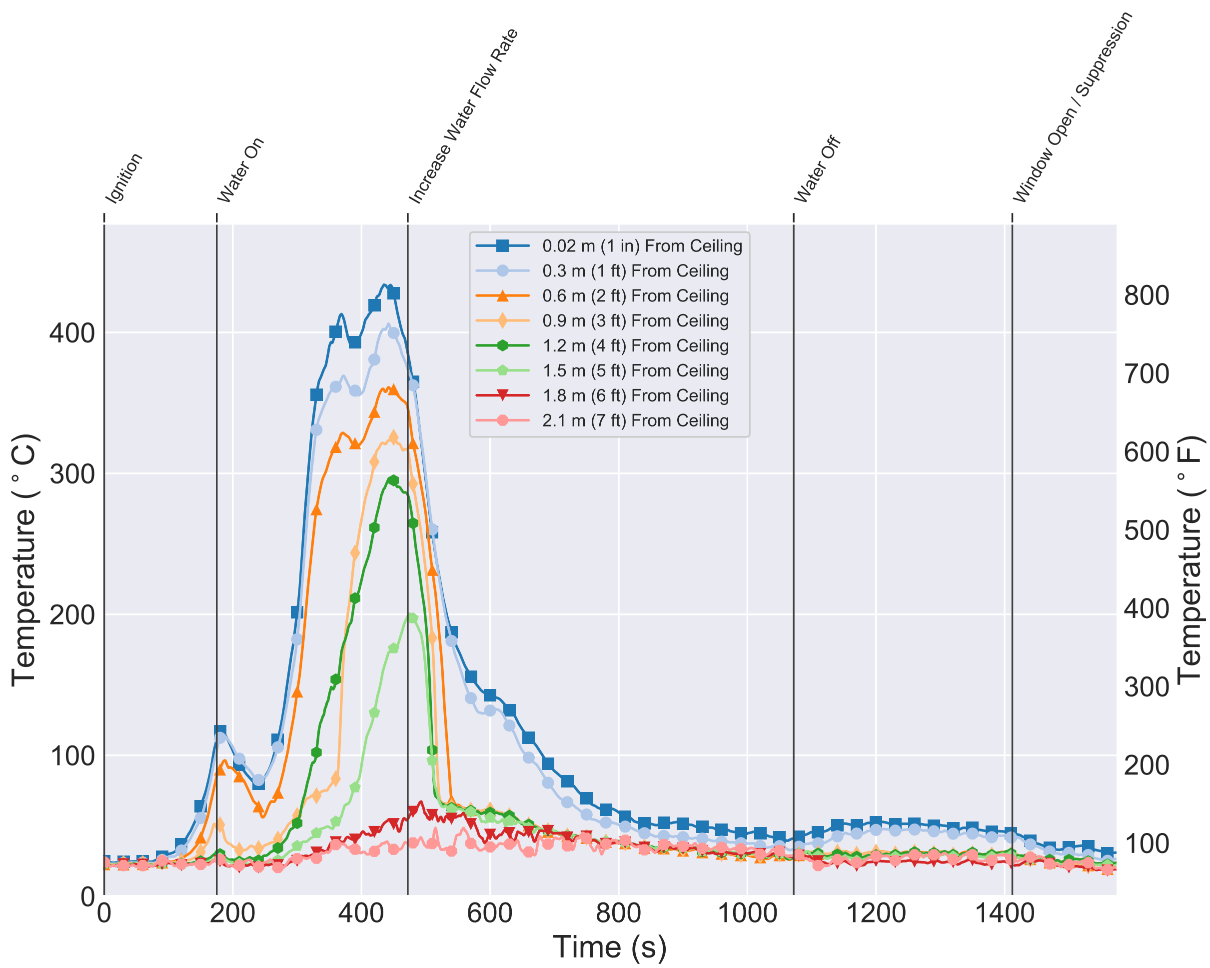


Figure 5.11: Experiment 3 - Thermocouple temperature time history from the thermocouple array in the fire room (Position 1).

After ignition, the fire grew for 175 seconds before the nozzle was activated. Immediately prior to nozzle activation, the temperature 2.54 cm (1 in) from the ceiling in the fire room was 112 °C. Following nozzle activation the thermal conditions in the structure cooled for 64 seconds, reaching a local minimum. At the local minimum the temperature at Position 1, 2.54 cm (1 in) from the ceiling was 79 °C. Afterwards, the temperatures throughout the structure rose quickly as the nozzle was insufficient to control the growth of the fire. The limits for tenability according to UL 1626 criteria were exceeded at 121 seconds after the nozzle was activated. The ceiling temperature in

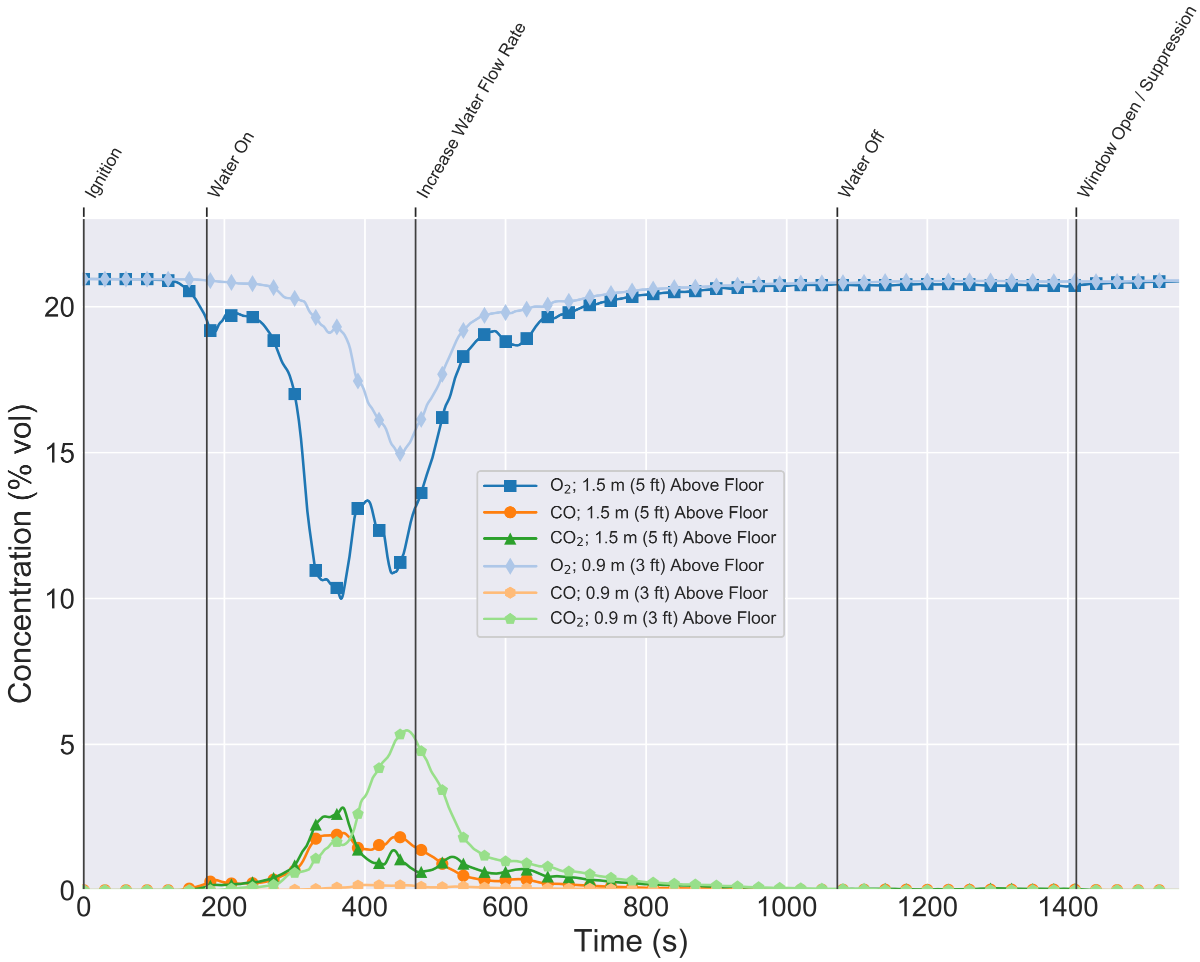


Figure 5.12: Experiment 3 - Gas concentrations time history measured in the fire room (Position 1).

the fire room reached a maximum of 435 °C, and the heat flux measured in the fire room reached a maximum of 20 kW/m^{2}m while the water flow rate was 11 lpm (3 gpm). The gas concentrations measured in the fire room showed similar response profiles as the temperatures measured at the same location. Figure 5.13 provides a images of the fire just prior to water flow from the nozzle. Figures 5.14 and 5.15 provide views of the fire growth in the fire room over the duration of 11 lpm (3 gpm) water period.

Upon determining that the water flow rate of 11 lpm (3 gpm) was insufficient to control the fire and maintain tenable temperatures, the flow rate was increased to 23 lpm (6 gpm). The flow rate adjustment occurred approximately 5 minutes after the nozzle was initially activated. At the time when the flow rate was increased to 23 lpm (6 gpm), the fire was larger than the fires in Experiments 2 and 5, but were otherwise similar in configuration. The maximum temperature and heat flux measurements mentioned previously provide a characterization of the fire's size, and enough fuel remained to allow continued fire growth. Despite the challenge of a larger fire, the flow rate adjustment to 23 lpm (6 gpm) controlled the fire. Temperatures throughout the structure

Figure 5.13: Experiment 3 - Conditions in the fire room at 175 s, just prior to nozzle activation.

Figure 5.14: Experiment 3 - Conditions in the fire room at 205 s, 30 s after nozzle activation.

Figure 5.15: Experiment 3 - Conditions in the fire room at 420 s, 30 s before the nozzle water flow was increased.

dropped below 50 °C within eight minutes. Water flowed for ten minutes after the flow rate was adjusted.

After the water flow was turned off, conditions in the structure were observed for over five minutes to evaluate the recovery of the fire. Video showed that the fire was not extinguished, but there was no visible growth during the five minutes of observation. Instrumentation throughout the structure showed only minimal response to the recovery of the fire. The window to the fire room was opened 340 seconds after the nozzle was turned off and the remaining fire was extinguished by hose suppression.

5.2.4 Experiment 4

Experiment 4 involved the same scenario as in Experiments 2 and 5, but with the sofa moved further away from the nozzle. The back of the sofa was against the back wall of the fire room, and the left arm of the sofa was against the window wall. In the other experiments, the sofa was against the back wall of the fire room, but centered to the water spray. The ignition location was 1.0 m (3.2 ft) further away from the water spray in Experiment 4 than in the other experiments. Like the other experiments, the sofa was ignited by an electric match placed between the left arm and the left seat cushion of the sofa. The water flow rate was 23 lpm (6 gpm). The time history of the temperature profile and gas concentrations at Position 1 in the fire room are shown in Figures 5.16 and 5.17, respectively.

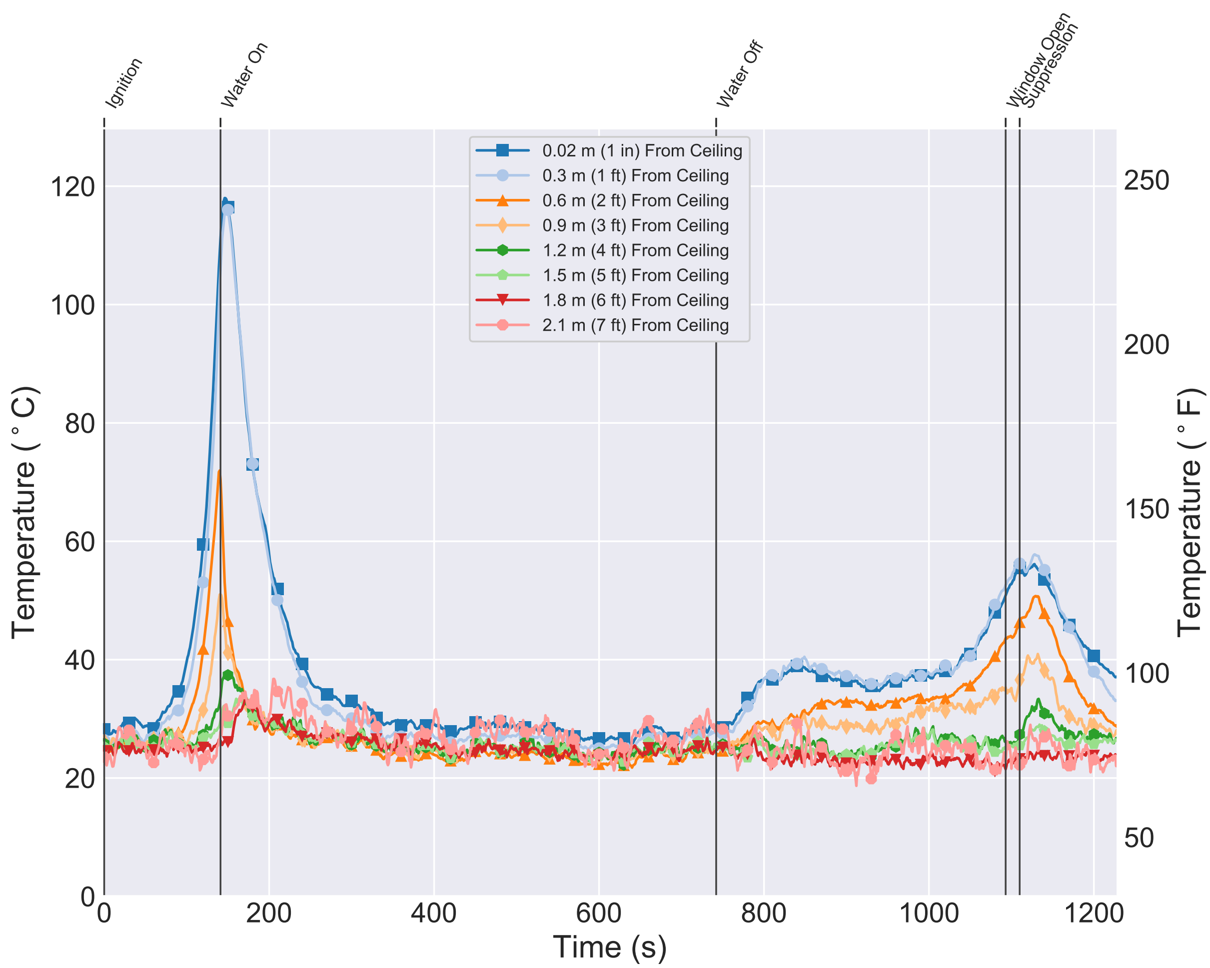


Figure 5.16: Experiment 4 - Thermocouple temperature time history from the thermocouple array in the fire room (Position 1).

The nozzle was activated 141 seconds after ignition. The temperature 2.54 cm (1 in) from the ceiling in the fire room was 111 °C immediately prior to nozzle activation. The fire was knocked down, but video shows that some burning continued behind and underneath the sofa where it was

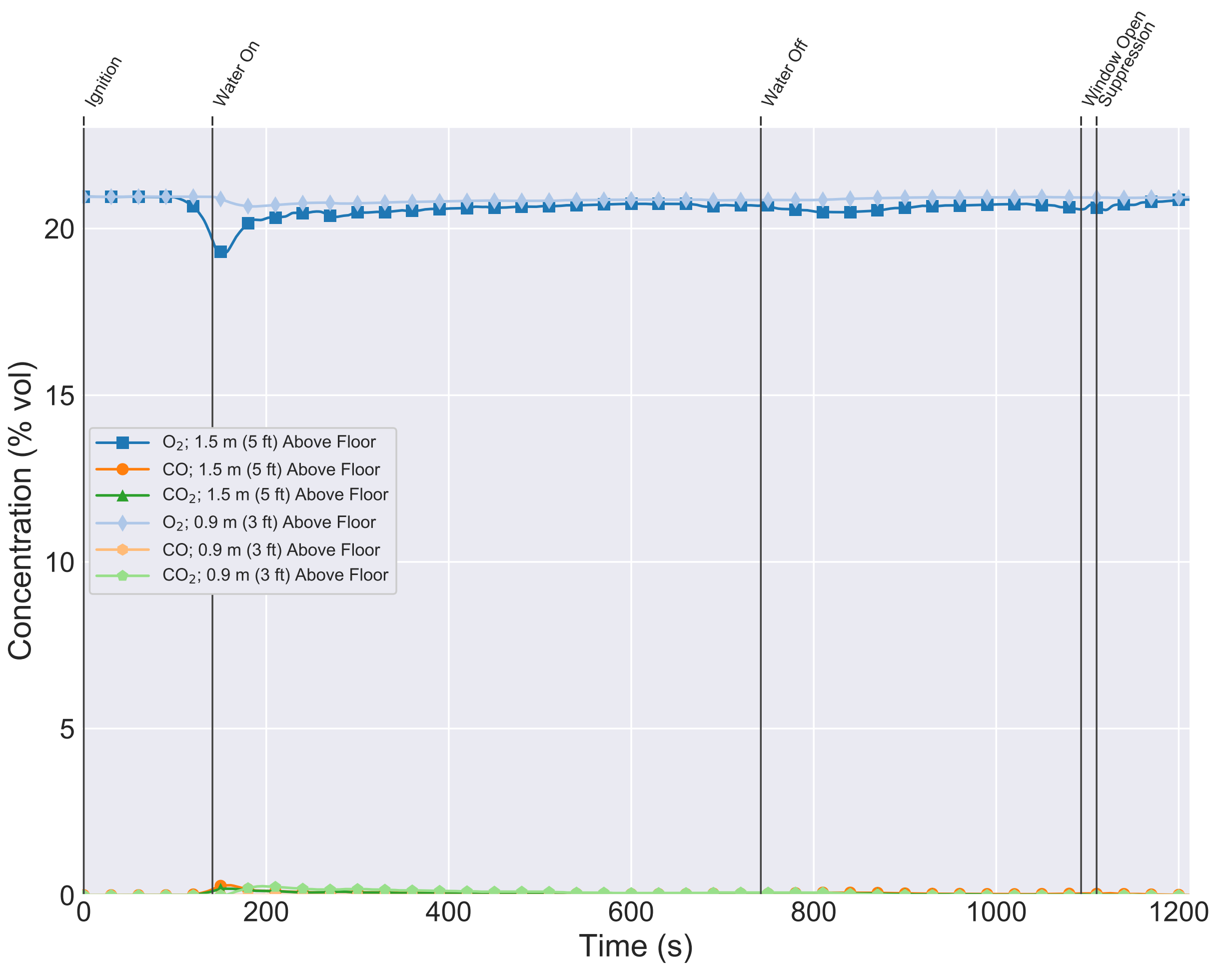


Figure 5.17: Experiment 4 - Gas concentrations time history measured in the fire room (Position 1).

shielded from the water spray. Temperatures throughout the structure dropped beneath 30 °C by 189 seconds after the nozzle activated. The peak temperature during the experiment was approximately 120 °C which was measured at Position 1, 2.54 cm (1 in) from the ceiling. The peak heat flux measured in the fire room was 3 kW/m^2. The O_2 concentration measured 1.5 m (5 ft) above the floor in the fire room decreased slightly during the fire growth, but returned to ambient shortly after nozzle activation. The remaining gas concentrations did not show much response during the experiment. Water flow was turned off after 10 minutes, after which the fire slowly recovered. About six minutes after the water was turned off the window to the fire room was opened and hose suppression was applied. Immediately prior to opening the window, the peak temperature in the structure was 50 °C, measured 2.54 cm (1 in) from the ceiling at Position 1. Throughout the whole experiment, the entire structure met UL 1626 criteria for tenability. Visual conditions in the fire room, from just before water began to flow from the nozzle through 10 minutes after the nozzle activation, are shown in Figures 5.18, 5.19, and 5.20. After the water flow was turned off, a small amount of flame was visible on the left side of sofa as shown in Figure 5.20.

Figure 5.18: Experiment 4 - Conditions in the fire room at 135 s, just prior to nozzle activation.

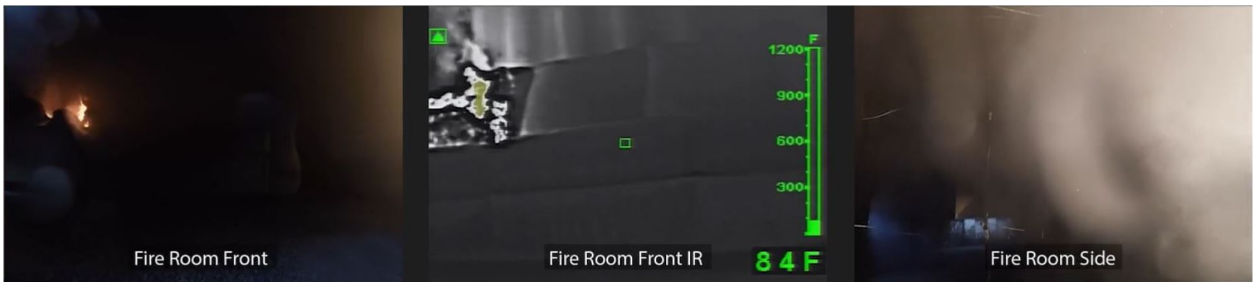


Figure 5.19: Experiment 4 - Conditions in the fire room at 165 s, 30 s after nozzle activation.

Figure 5.20: Experiment 4 - Conditions in the fire room at 736 s, 10 minutes after nozzle activation.

5.2.5 Experiment 6

Experiment 6 included the same fuel load as in the previous experiments but without any water spray. The purpose of the experiment was to characterize the thermal hazard associated with the fuel load. The time history of the temperature profile and gas concentrations at Position 1 in the fire room are shown in Figures 5.21 and 5.22, respectively.

Between 3 and 4 minutes after ignition, the temperatures in fire room exceeded all of the temperature limits identified in UL 1626. During this same time period the oxygen concentration began a noticeable decrease and the amount of carbon dioxide and carbon monoxide began to increase. The hazard levels from high temperatures, low oxygen concentrations, and increasing amounts of carbon dioxide and carbon monoxide continued as the fire burned unabated.

The window vent was opened to simulate a window failing open. The opening was made at approximately 350 s after ignition. Within 2 minutes of the window opening the indicators of flashover were observed in the fire room. All of the temperatures measured by the thermocouple array in the fire room exceeded 600 °C at 466 seconds after ignition. The peak heat flux measured in the fire room was 50 kW/m^2, which occurred 393 seconds after ignition. The gas concentrations measured in the fire room showed similar response profiles as the temperatures in terms of increased hazard to human life. Hose-line suppression took place 570 seconds after ignition.

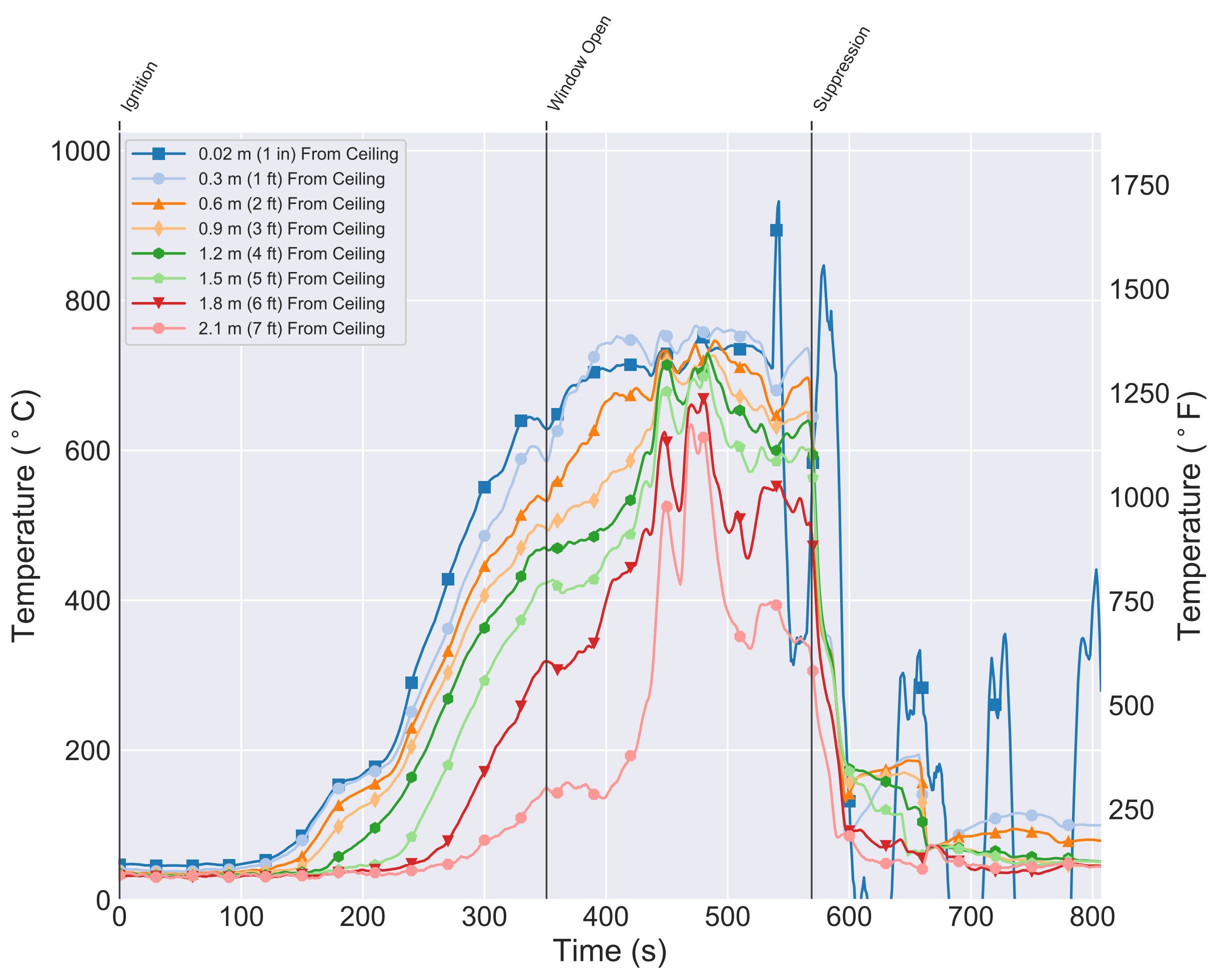


Figure 5.21: Experiment 6 - Thermocouple temperature time history from the thermocouple array in the fire room (Position 1).

Figures 5.23 through 5.26 present images recorded from video and thermal imaging cameras that were located in the fire room. The first two figures, Figures 5.23 and 5.24, provide an indication of the size of the fire for a time period, 120 s to 180 s, that bounds the fire suppression system activation times in Experiments 1 through 5. Figures 5.25 and 5.26 show the fire growth in 2 minute intervals after the time when in the previous experiments fire suppression would have started due to water spray from a sprinkler or a nozzle. Figure 5.25 shows the fire while it is still in the growth stage. Figure 5.26 has images that were recorded after the opening the window vent, which would be more representative of a fully developed fire stage. The difference between these two figures is evidence that even with the limited fuel load the fire was burning in ventilation limited or fuel rich condition and the addition of oxygen increased the fire hazard.

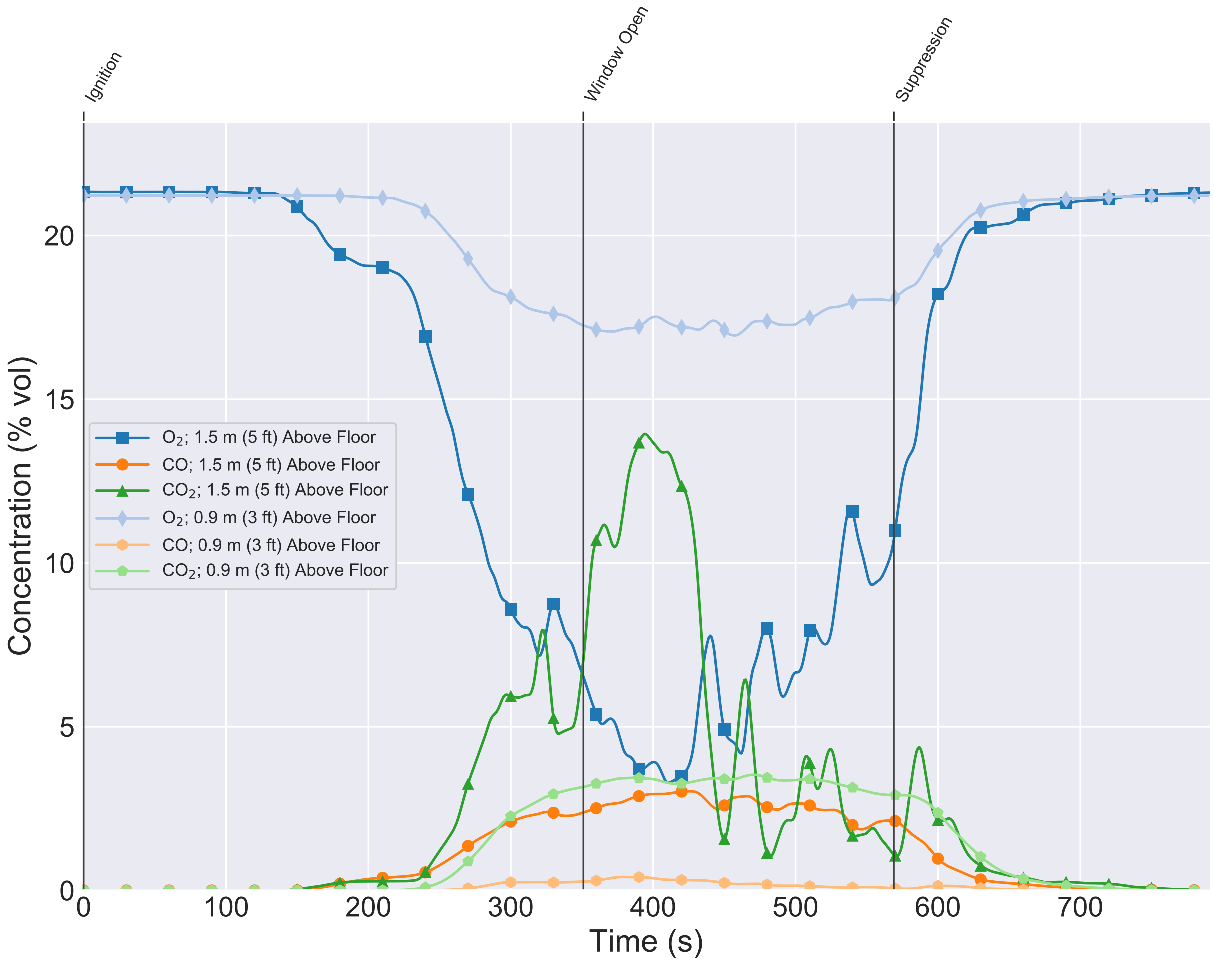


Figure 5.22: Experiment 6 - Gas concentrations time history measured in the fire room (Position 1).

Comparing the data from Experiment 6 with the other experiments demonstrates the importance and the value of early fire suppression as a means to improve life safety. This is consistent with previous research findings. While the outcome of Experiment 6 was not surprising, it is a finding that needs to be repeated and documented as a baseline for fire suppression research.

Figure 5.23: Experiment 6 - Conditions in the fire room at 120 s after ignition.

Figure 5.24: Experiment 6 - Conditions in the fire room at 180 s after ignition.

Figure 5.25: Experiment 6 - Conditions in the fire room at 300 s after ignition.

Figure 5.26: Experiment 6 - Conditions in the fire room at 420 s after ignition.

5.3 Discussion of Furnished Room Experiments

The sprinkler (or tell-tale sprinklers) had activation temperatures of 68.3 °C (155 °F). Therefore, the timing for activating the sprinkler or nozzles depended the initial growth rate of the fire. Table 5.4 shows summarizes the times and temperatures at which the sprinkler or tell-tale sprinklers activated. Because the fire started from a small flaming source, such as you might have from ignition sources in a home (e.g. small overheated battery or a candle), the initial growth rate varied. While the sofa and small flaming ignition source provide a realistic scenario that could be found in many homes, it does exhibit variations in burning behavior typically within the first minute or two after ignition. The ignition device is placed on the seat cushion in a crevice formed by the side arm and the back cushion of the sofa. In some cases, the ignition flame may initially burn into the side of the sofa as opposed to the first flames extending up the back cushion of the sofa. The heat to activate the sprinkler must be transferred by the convective thermal plume/ceiling jet that is evolving, early in the fire, from the back cushion of the sofa. When heat is being lost to the arm of the sofa in the early seconds of the fire and delaying the flame spread on the back cushion, this has some impact on the activation time of the sprinkler. In terms of peak HRR and total energy released the sofa is a consistent fuel source. However, the slight variations in early fire growth can also be seen in the HRR time histories shown in Figure 3.6. The activation timing ranged between 129 s and 175 s after ignition. Therefore, comparisons between experiments are focused on timing relative to the activation times.

Table 5.4: Temperature and time after ignition when the sprinkler (or tell-tale sprinkler) was activated in each furnished room experiment. The temperature was measured 2.5 cm (1 in.) below the ceiling, about 0.9 m (3 ft) away from the sprinkler.

Exp #	Time [s]	Temperature [°C]
1	150	81
2	129	75
3	175	112
4	136	97
5	141	111

Experiment 1 demonstrated the sprinkler's ability to control the fire. The fire was suppressed when the sprinkler was activated, and remained controlled for the duration that the sprinkler was active. This result occurred despite the fire spreading and burning from a shielded position underneath the sofa. Thermal conditions throughout the entire structure met UL 1626 criteria for tenability during the entire 10 minutes that the sprinkler was active. The tenuous success of a "controlled" fire is made evident, however, by the quick growth of the fire immediately after the sprinkler was turned off. The conditions in the fire room became untenable 188 seconds after the sprinkler was turned off. The sprinkler's ability to control the fire was further demonstrated by the knockdown of the fire upon sprinkler reactivation. Controlling the fire, rather than extinguishment, is the intended design of sprinklers, which is clearly demonstrated in this experiment.

Figure 5.27 shows post test photos of the sofa from Experiment 1. The foam and fabric from approximately the entire left half of the sofa were consumed, with the right half of the sofa left intact. Some of the damage to the sofa occurred during the 5 minute period after the sprinkler was turned off, and before the experiment was concluded. Although this damage reflects the failure of the sprinkler to extinguish the fire, the duration of the burning after deactivating the sprinkler was arbitrary. Therefore comparisons between experiments based on post-fire damage are limited.

Figure 5.27: Photographs of the fire damage to the sofa from Experiment 1.

Experiments 2 and 5 demonstrated the capability of the medium capacity nozzle to extinguish the fire, as well as the repeatability of this result. This result differs from the performance of the sprinkler, which controlled the fire without extinguishing it. The difference reflects the different strategies associated with sprinklers and nozzles. The sprinkler is intended to pre-wet the fuels in the room, thereby limiting the spread of the fire. The nozzle provides a smaller spray coverage, whose best chance of fighting the fire is to impact it directly and extinguish it.

The ignition placement in Experiments 2 and 5 provided the best-case-scenario for the nozzle to impact the fire, and it succeeded. The nozzle flowing 23 lpm (6 gpm) generated water flux values in the range of 1.2 to 2.0 mm/min (0.03 to 0.05 gpm/ft^2) where the sofa was located. The minimum water flux required by NFPA 13D is 2 mm/min (0.05 gpm/ft^2) [1]. Experiments 3 and 4 test the same scenario but with adjustments to the water flow rate and to the sofa location to evaluate the limits of the nozzle's capability.

Figure 5.28 show post-test photos of the sofa from Experiments 2 and 5. The damage to each sofa was very similar, providing additional support for the repeatability of the experiment. The fire burned through the cushion of the left arm and burned the fabric on the face of the left back cushion. The flame spread across the seat cushion was limited to approximately the back left quadrant. This damage is significantly less than the damage in Experiment 1, where the fire recovered after the sprinkler was deactivated.

Experiment 3 showed that there exists a large difference in performance between flow rates of 11 lpm (3 gpm) and 23 lpm (6 gpm) for the medium capacity nozzle. For equivalent fire scenarios, the nozzle flowing at 11 lpm (3 gpm) in Experiment 3 failed to suppress the fire, but the nozzle

(a) Experiment 2 (b) Experiment 5

Figure 5.28: Photographs of the fire damage to the sofa from Experiments 2 and 5.

flowing at 23 lpm (6 gpm) in Experiments 2 and 5 extinguished the fires. From the water distribution tests, the nozzle flowing 11 lpm (3 gpm) should have exposed the sofa to a water flux of 0.8 to 1.4 mm/min (0.02 to 0.035 gpm/ft^2). This compares to water flux range of 1.2 to 2.0 mm/min (0.03 to 0.05 gpm/ft^2) with the 23 lpm (6 gpm) flow rate.

Furthermore, when the flow rate was adjusted to 23 lpm (6 gpm) in Experiment 3, the fire was larger than it was at the initial time of residential sprinkler activation, yet the 23 lpm (6 gpm) flow rate was sufficient for suppression. This threshold for performance at low flow rates was also apparent in the studies conducted by the USFA sponsored sprinkler research project, where flow rates had to be increased from 11 lpm (3 gpm) to 30 lpm (8 gpm) during preliminary fire tests to provide viable control of the fires [7].

Although the nozzle flowing water at 11 lpm (3 gpm) was insufficient to maintain tenability in the fire room, it was sufficient to slow the fire growth. The free burn in Experiment 6 reached flashover at about 7.5 minutes after ignition, with all temperature measurements in the fire room exceeding 600 °C. In contrast, 7.5 minutes after ignition in Experiment 3, the peak temperature in the fire room was about 400 °C. Since the flow rate was adjusted to 23 lpm (6 gpm) shortly after, it is not known what the peak fire size would have been with the nozzle flowing water at 11 lpm (3 gpm), or whether the room would have reached flashover. However, it is clear that the nozzle flowing at 11 lpm (3 gpm) did slow the fire growth.

Figure 5.29 shows the fire damage to the sofa in Experiment 3. The foam and fabric on the left half of the sofa was entirely consumed, with further damage evident on the right side. The damage extending into the right side of the sofa is indicative of melting and pyrolysis due to the radiation from the fire, and occurred ahead of the flame spread. In contrast, the damage to the sofa in Experiment 1 (Figure 5.27) showed little to no damage on the right side of the sofa, despite the entire left side being consumed. This difference is due to the sprinkler's ability to pre-wet the surfaces of the fuel in Experiment 1, whereas the nozzle in Experiment 3 was insufficient to deter fire growth in the same way. The damage in Experiment 3 is greater than in any of the other experiments, excluding the free burn (Exp. 6).

Figure 5.29: Photograph of the fire damage to the sofa from Experiment 3.

The fire was controlled by the nozzle spray in Experiment 4, despite the greater distance between the ignition and nozzle locations relative to the other experiments. The nozzle performance in Experiment 4 can be compared to the nozzle performance in Experiments 2 and 5, which were equivalent scenarios except the sofa was centered to the nozzle. In Experiment 4, it took longer for the temperatures throughout the structure to cool below 30 °C after nozzle activation. In addition, the fire was not extinguished, and began recovering after the water flow was turned off. However, the recovery of the fire after turning the water off was not as rapid as in Experiment 1, where the sprinkler was used. Based on the water flux tests the area of the sofa that was not extinguished was exposed to a water flux of approximately 0.4 mm/min (0.01 gpm/ft^2). The remaining area of the sofa would have been exposed to a water flux in the range of approximately 1.0 to 1.8 mm/min (0.025 to 0.045 gpm/ft^2). Overall, although the nozzle did not perform as well as in the experiments when the sofa was closer to the nozzle, it still controlled the fire successfully.

Figure 5.30 shows a post-fire photo of the sofa in Experiment 4. The fire burned through the left arm and back cushions, and spread across more than a quarter of the left seat cushion. The damage affected a greater portion of the sofa than in Experiments 2 and 5, when the sofa was positioned closer to the nozzle. However, the damage was still less than in Experiment 1, when the sprinkler was used. The damage to the sofa fits with the conclusions drawn based on the measurement data.

In Experiment 6 there was no water spray system used, and the fire room reached flashover. Figure 5.31 shows a photo of the remains of the sofa. The synthetic components of the sofa (foams

Figure 5.30: Photograph of the fire damage to the sofa from Experiment 4.

Figure 5.31: Photographs of the fire damage to the sofa from Experiment 6.

and fabrics) were entirely consumed. In addition, the wood framing on the left side of the sofa had begun to collapse.

5.3.1 Tenability

Experiments 1, 2, 4, and 5 did not exceed UL 1626 limits for tenability based on temperatures in the fire room. Evidence for this conclusion is shown by Figure 5.32 which includes the temperature time histories measured 1.8 m (5.8 ft) above the floor in the fire room for each experiment. The graph also includes the UL 1626 limit for tenability: 93°C measured 1.6 m (5.25 ft) above the floor. Although the tenability limit refers to a location 0.2 m (0.5 ft) lower than the measurement location, the margins by which each experiment passed/failed the limit for tenability are large enough for the conclusions to be apparent.

The gas concentration measurements are consistent with the trends shown by the temperature measurements. UL 1626 does not state limits on gas concentrations for tenability. However, concentrations of CO and CO_2 above 0.012% and 4%, respectively, are considered immediately dangerous to life or health with a 30 minute exposure [5]. The O_2 concentration remained above 18% and the peak CO and CO_2 concentrations were below 0.5% in each of the experiments that met UL 1626 limits for tenability. In contrast, the conditions in Experiment 3, where the nozzle was flowing at 11 lpm (3 gpm), reached dangerous levels of gas concentrations. Measured 1.5 m (5 ft) above the ground, the O_2 concentration was below 10%, and the peak CO concentration was approximately 2%. Similarly, the gas concentrations in Experiment 6, where there was no water application, reflected an untenable environment throughout the structure. The peak values for temperature and gas concentration in each experiment, measured about 0.9 m (3 ft) beneath the ceiling in the fire room, are summarized in Table 5.5.

Table 5.5: Results from furnished room experiments are summarized and compared to tenability criteria. The bounds defining water spray operation are between 30 seconds after activation and when the water spray was deactivated. The peak values for temperature, CO concentration, and CO_2 concentration are maximums. The peak values for O_2 concentration are minimums. Temperature values were measured 1.8 m (5.8 ft) above the floor in the fire room, and gas concentrations were measured 1.5 m (5 ft) above the floor in the fire room.

Exp #	Description	Peak Measurements During Water Spray Operation				
		Temp [°C]	HF [kW/m^2]	O_2 [%]	CO [%]	CO_2 [%]
1	Sprinkler at 34 lpm (9 gpm)	49	4.1	18.2	0.5	0.2
2	Nozzle at 23 lpm (6 gpm)	26	2.3	20.4	0.2	0.1
3	Nozzle at 11 lpm (3 gpm)	362	20.5	10.0	1.9	2.8
4	Nozzle at 23 lpm (6 gpm), ignition moved further from spray	33	3.1	19.9	0.2	0.1
5	Nozzle at 23 lpm (6 gpm)	31	2.8	20.3	0.2	0.1
6	Freeburn	750	50.9	3.3	3.0	13.9
	UL 1626 Tenability Criteria (measured 1.6 m (5.25 ft) above the floor)	93				
	IDLH Values for 30 min Exposure [5]				0.012	4.0

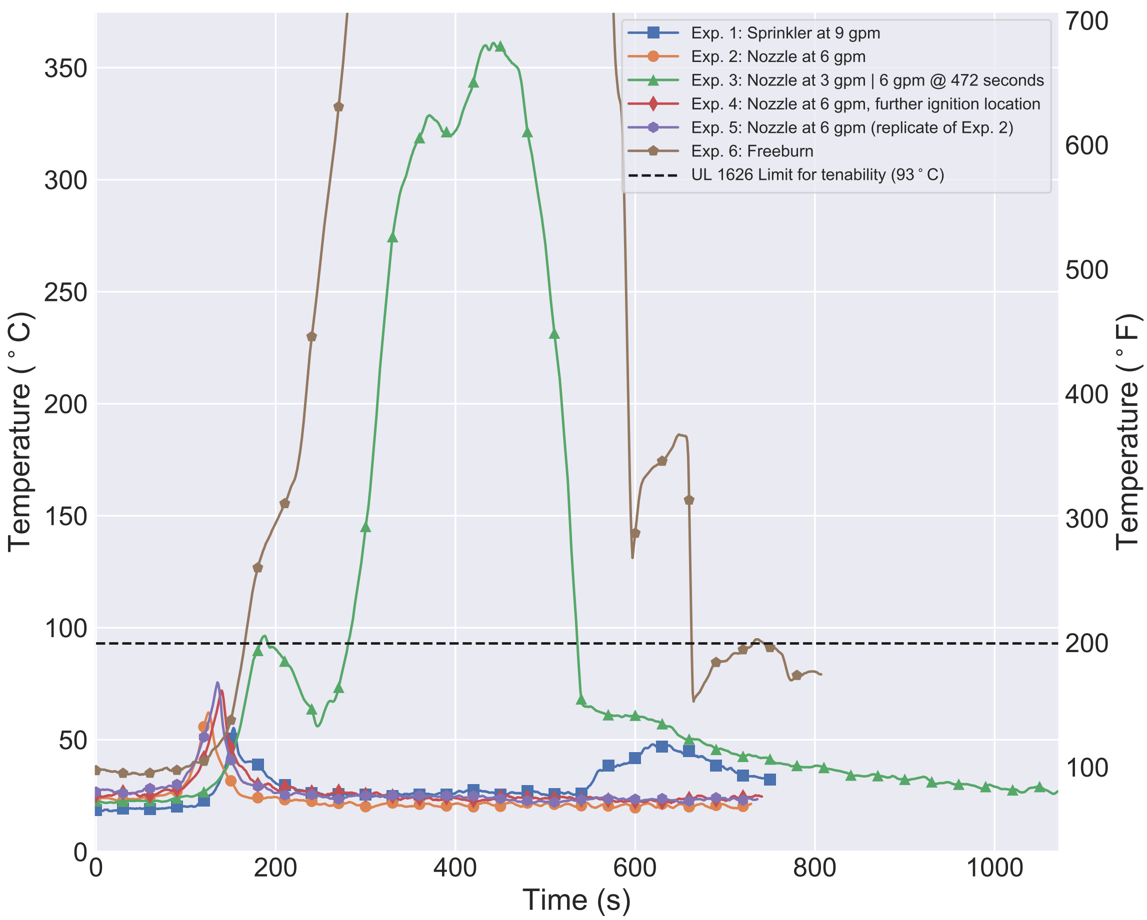


Figure 5.32: Comparison between furnished room experiments of the temperature time history (from ignition until the water spray was deactivated) measured at 1.8 m (5.8 ft) above the floor in the fire room. The UL 1626 limit for tenability – 93°C measured 1.6 m (5.25 ft) above the floor – is included for reference.

6 Research Needs

A significant amount of additional research is needed to assess the feasibility of a retrofit residential flashover prevention system with water flow rates less than an NFPA 13D sprinkler system. Future testing needs to determine if the water sprays that directly cool the fuels can be scaled up to prevent flashover in a room up to 4.3 m (14 ft) on a side, while maintaining a reduced water flow rate. Fully furnished residential fire scenarios in larger rooms must be examined. If the concept holds in larger rooms, then other issues such as shielded fires, combustibles high on the walls and ceilings need to be fire tested, since the nozzle sprays differ from sprinkler sprays in that they do not “wet the walls”.

If the concept is proven for the more realistic scenarios, then additional challenges related to nozzle design would need to be addressed. Primarily, the nozzle would need to be thermally activated. Additional concerns such as nozzle clogging could be an issue as the nozzle diameters may be smaller than than those found in residential sprinklers.

7 Summary

The purpose of this study was to take initial steps to begin investigating the feasibility of a residential flashover prevention system with reduced water flow requirements relative to a NFPA 13D system. The system would be designed for retrofit applications where water supplies are limited, while maintaining compliance with UL 1626 criteria for tenability. The strategy investigated was to use low flow spray nozzles instead of sprinklers. Two sets of fire experiments were conducted. The first was a series of gas burner experiments intended to evaluate the ability of a water spray to cool a hot gas layer, without impacting the source fire. The second set was designed to examine the ability of a low flow nozzle to cool and suppress the thermal hazard from a fire generated by interior finishes and fuels that would be found in a residence.

First, water distribution tests were conducted to characterize and compare the spray patterns of the different water sprays included in this study. The average water flux ranged between 0.68 mm/min [0.017 gpm/ft^2] and 1.82 mm/min [0.045 gpm/ft^2] among all of the water sprays tested. The water distribution tests highlighted the difference between the spray patterns of nozzles and sprinklers. The nozzles provided an evenly distributed cone pattern concentrated on the floor beneath the nozzle. The sprinkler covered a wider radius with the distribution concentrated on the edges of the rooms.

The propane burner experiments were analyzed in terms of the change in temperature due to water activation. Specifically, the temperature measured 2.54 cm (1 in) from the ceiling and on the opposite side of the water spray relative to the burner was used to draw the following conclusions about the factors considered in these experiments:

- The size of the fire (heat release rate) did not have a significant effect on the temperature decrease from the nozzle water spray. However, the effect of the fire's size was significant for the temperature response to sprinkler water spray.
- Three nozzles with different flow capacities, corresponding to flow rates of 15 lpm (4 gpm), 19 lpm (5 gpm), and 26 lpm (7 gpm) were tested. The performance of each nozzle was similar, but statistically determined to be significantly different. The medium capacity nozzle performed best.
- At equivalent flow rates and heat release rates, the medium capacity nozzle performed better than the sprinkler. This difference was statistically significant for each measurement height in the hot gas layer (2.54 cm (1 in), 0.3 m (1 ft), and 0.6 m (2 ft) beneath the ceiling).
- The minimum flow rate to meet UL 1626 criteria for tenability at the end of the hallway, opposite of the fire room, was 19 lpm (5 gpm) for the medium capacity nozzle and 26 lpm (7 gpm) for the sprinkler.

The water sprays were tested in the fire room with the burner shielded from the spray. The sprinkler at 34 lpm (9 gpm) provided much greater cooling in the fire room than did the medium capacity nozzle at any flow rate. At the end of the hallway (opposite of the fire room), however, the medium capacity nozzle at 23 lpm (6 gpm) provided nearly the same cooling as the sprinkler. A statistically significant difference was measured at 2.54 cm (1 in) from the ceiling, but not at lower heights.

Six experiments were conducted with a fuel load of interior furnishings that would be found in a residence. For equivalent fire conditions, the medium capacity nozzle at 23 lpm (6 gpm) performed better than the sprinkler at 34 lpm (9 gpm). The nozzle at 23 lpm (6 gpm) was then tested with the ignition location moved 0.97 m (3.19 ft) further away, and it still performed as well as the 34 lpm (9 gpm) sprinkler with the original ignition location. The results did not hold for the nozzle at 11 lpm (3 gpm), which failed to suppress the fire. However, increasing the flow rate to 23 lpm (6 gpm) after determining that 11 lpm (3 gpm) had failed, proved successful in controlling the fire. A free burn indicated that the fuel load was capable of producing flashover in the fire room, if provided adequate ventilation.

Overall, for the limited set of fire scenarios tested, the nozzle flowing water at 23 lpm (6 gpm) performed better than the sprinkler at 34 lpm (9 gpm). However, the nozzle at 11 lpm (3 gpm) was not effective at controlling the fire, indicating that there exists a lower bound to water flow rate below which the capability of the water spray to control a residential fire is drastically reduced. This finding is supported by studies conducted as part of the USFA sponsored research program [7]. The effectiveness of the spray nozzle at 23 lpm (6 gpm) to suppress fires tested in this study, however, indicates the potential to reduce the water flow rates of residential sprinkler systems while maintaining a viable level of safety in the structure. This potential may be realized by optimizing the water delivery to a fire, specifically by implementing spray nozzles in configurations in which they would directly impact the fire.

This study is small step in the potential development of a residential flashover prevention system that could be retrofit and would require less water than an NFPA 13D compliant sprinkler system. However more research is needed.

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Appendix A Water Distribution Tests

Table A.1: Comparison between the expected and experimental volume of water collected in the water distribution tests.

Suppression Location	Water Spray	Water Flow Rate [lpm (gpm)]	Replicate	Expected Water Volume [L (gal)]	Experimental Water Volume [L (gal)]	Percent Difference
Hallway	Medium Capacity Nozzle	11 (3)	1	57 (15)	24.2 (6.4)	57.4
Hallway	Medium Capacity Nozzle	11 (3)	2	57 (15)	25.4 (6.7)	55.5
Hallway	Medium Capacity Nozzle	11 (3)	3	57 (15)	24.6 (6.5)	56.6
Hallway	Medium Capacity Nozzle	23 (6)	1	114 (30)	51.5 (13.6)	54.6
Hallway	Medium Capacity Nozzle	23 (6)	2	114 (30)	45.0 (11.9)	60.2
Hallway	Medium Capacity Nozzle	23 (6)	3	114 (30)	43.5 (11.5)	61.7
Hallway	Sprinkler	34 (9)	1	170 (45)	66.2 (17.5)	61.1
Hallway	Sprinkler	34 (9)	2	170 (45)	66.6 (17.6)	60.9
Hallway	Sprinkler	34 (9)	3	170 (45)	65.1 (17.2)	61.8
Fire Room	Medium Capacity Nozzle	11 (3)	1	57 (15)	35.6 (9.4)	37.4
Fire Room	Medium Capacity Nozzle	11 (3)	2	57 (15)	36.0 (9.5)	36.5
Fire Room	Medium Capacity Nozzle	11 (3)	3	57 (15)	34.8 (9.2)	38.4
Fire Room	Medium Capacity Nozzle	23 (6)	1	114 (30)	68.9 (18.2)	39.2
Fire Room	Medium Capacity Nozzle	23 (6)	2	114 (30)	68.5 (18.1)	39.7
Fire Room	Medium Capacity Nozzle	23 (6)	3	114 (30)	68.1 (18.0)	40.1
Fire Room	Sprinkler	34 (9)	1	170 (45)	56.0 (14.8)	67.0
Fire Room	Sprinkler	34 (9)	2	170 (45)	55.3 (14.6)	67.5
Fire Room	Sprinkler	34 (9)	3	170 (45)	55.3 (14.6)	67.5