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Brief Report

A Pilot Study to Assess the Feasibility of Comparing Ultra-High Pressure to Low-Pressure Fire Suppression Systems for a Simulated Indirect Exterior Attack

Elizabeth A. Sanli [1,*], Robert Brown [1] and Derek Simmons [2]

[1] School of Maritime Studies, Fisheries and Marine Institute of Memorial University of Newfoundland, P.O. Box 4920, St. John's, NL A1C 5S7, Canada; robert.brown@mi.mun.ca
[2] Corner Brook Fire Department, City of Corner Brook, P.O. Box 1080, Corner Brook, NL A2H 6E1, Canada; dsimmons@cornerbrook.com
* Correspondence: elizabeth.sanli@mi.mun.ca

Abstract: Financial and human resource challenges constrain firefighting in rural communities. This can limit the approaches that can be used in a given residential fire situation. Effective use of portable, lower-cost equipment that would require fewer personnel and less water could greatly benefit rural communities. This study was conducted to assess the feasibility of comparing ultra-high-pressure to low-pressure fire suppression systems at low flow rates. The conditions used simulated an indirect exterior attack through a window. A purpose-built burn room and standardized class A fires were used to compare ultra-high-pressure and low-pressure systems at low flow rates. Temperatures in the burn room were recorded for each condition in triplicate. While neither operating condition resulted in full extinguishment of the fire, the ultra-high-pressure trials saw decreases in the proportion of starting temperature that were faster and of greater magnitude than for the low-pressure trials. This compares with earlier research, simulating a transitional attack that saw similar patterns for temperature cooling but resulted in extinguishment. This preliminary testing provides evidence that the burn container and room, as well as instrumentation and fuel load configurations, are appropriate for more extensive testing of such equipment for exterior fire suppression.

Keywords: ultra-high pressure; exterior attack; decrease in temperature

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1. Introduction

Challenges for firefighting in rural communities include financial and infrastructure constraints, as well as limited personnel [1]. Difficulties in recruitment of rural firefighters, increasing reliance on older volunteers, and training commitment expectations are considerations for determining current and future approaches to structural firefighting in rural Canada [1–4]. Likewise, limitations in funding, equipment, and access can affect how well-prepared regional departments are and their operational readiness in an emergency [1,4–6].

Fang and colleagues [5] describe how the Canadian province of Newfoundland and Labrador uses two major classifications for the operational readiness of fire departments. Defensive, exterior fire protection, as described by Fire and Emergency Services NL, involves quickly extinguishing a fire from outside a structure only [5,6]. While this type of approach is less risky, requires a lower degree of training, and can be conducted with fewer respondents, it is also less effective [5,6]. By comparison, offensive interior fire suppression is more effective but has greater requirements for training, equipment, and personnel [5,6]. In 2015, 27% of all fire departments in the province did not have offensive interior capabilities [5,6]. Of the departments that did offer interior suppression, 19% were graded as acceptable upon assessment. This means that only 14% of all fire departments within the province were equipped to provide acceptable interior fire suppression [6].

It is important to evaluate the effectiveness and utility of portable and lower-cost fire suppression systems, given the challenges in recruitment and retention, aging rural populations, and the fact that many fire departments rely on exterior fire protection. There is also an increasing worldwide need to consider ways in which to use less water to extinguish fires to protect property, the environment, and water delivery systems [7]. High-pressure water mist systems use less water than conventional methods and produce smaller droplets than low-pressure mist systems. The smaller droplets and resulting larger surface area can benefit heat absorption. Oxygen is also displaced by the water vapor from the evaporation of the droplets [7–10]. Much of the recently published high-pressure mist studies have addressed wildland fires or fixed technology systems in specific contexts such as libraries, ships, tunnels, or offshore platforms [11–14]. However, propelled by a need for smaller yet effective fire trucks for the United States Air Force [15], ultra-high-pressure (UHP) technology has been examined for class B fuel fires [8,15] and room and contents fires [16].

The NFPA safe entry minimum requirement for 2016 states that two hoses with a combined flow of 300 gpm (1137 L/m) must be used, with neither less than 100 gpm (379 L/m) [17]. Although it did not meet the minimum NFPA requirement, research by MacDonald [16] involved firefighters approaching a doorway, discharging a straight stream into the ceiling, followed by a circular pattern using the nozzle set to a slight fog position until the fire was deemed knocked down. At that point, the firefighters proceeded into the room to completely extinguish the fire. McDonald found that the amount of water required to extinguish these fires did not differ between UHP and low-pressure (LP) lines at 20 gpm. The LP equipment resulted in faster knock-down times, while the UHP equipment resulted in faster room cooling. The author concluded that extinguishment at low flowrates was similar for UHP and LP applications [16].

The present preliminary study was designed to compare UHP and low-pressure equipment with similar flowrates using an exterior attack. Additionally, the burn room was designed with a partial wall that blocked direct access to the base of the fire, while still allowing water to reach the fuel from the top and both sides. The wall was included to simulate obstacles between the initial exterior attack point and the base of the fire, as might be the case for a residential fire. This is a deviation from previous work, where the base of the fire could be accessed [15,16]. This work is innovative in the application of the technology to rural exterior firefighting and in the design of the burn room.

2. Materials and Methods

Experiments took place in March 2023 on the fire training ground at the Marine Institute of Memorial University's Offshore Safety and Survival Centre in Foxtrap, Newfoundland and Labrador. Certified Firefighters performed all fire ignition and suppression activities.

2.1. Experimental Burn Container

Each trial was conducted in a purpose-built burn room (see Figure 1). The dimensions and construction features of the burn room and larger burn container were developed in consultation with subject-matter experts in fire service, training provision, and fire research, with the goal of representing features typical of residential exterior fire suppression scenarios. Consultation took place over virtual and in-person meetings. Key construction points for consideration resulting from these meetings included the need to be able to manipulate ventilation; windows should be sized like those seen in residences; the fuel should be shielded; and the ability to accurately measure timing and room temperatures should be facilitated. Reasonable costs were also identified as an important construction consideration. Procedural considerations included controlling for technique by using the same firefighter for each trial and using limited water flow for the control condition. Figure 1 shows the features of the burn container, including the location of instrumentation (4 thermocouples, indicated by TC location), ventilation (one 1500 mm × 910 mm window on each side of the container and a 2006.6 mm × 876.3 mm access door), and fire load (located on a 1300 mm × 1300 mm base in the burn room).

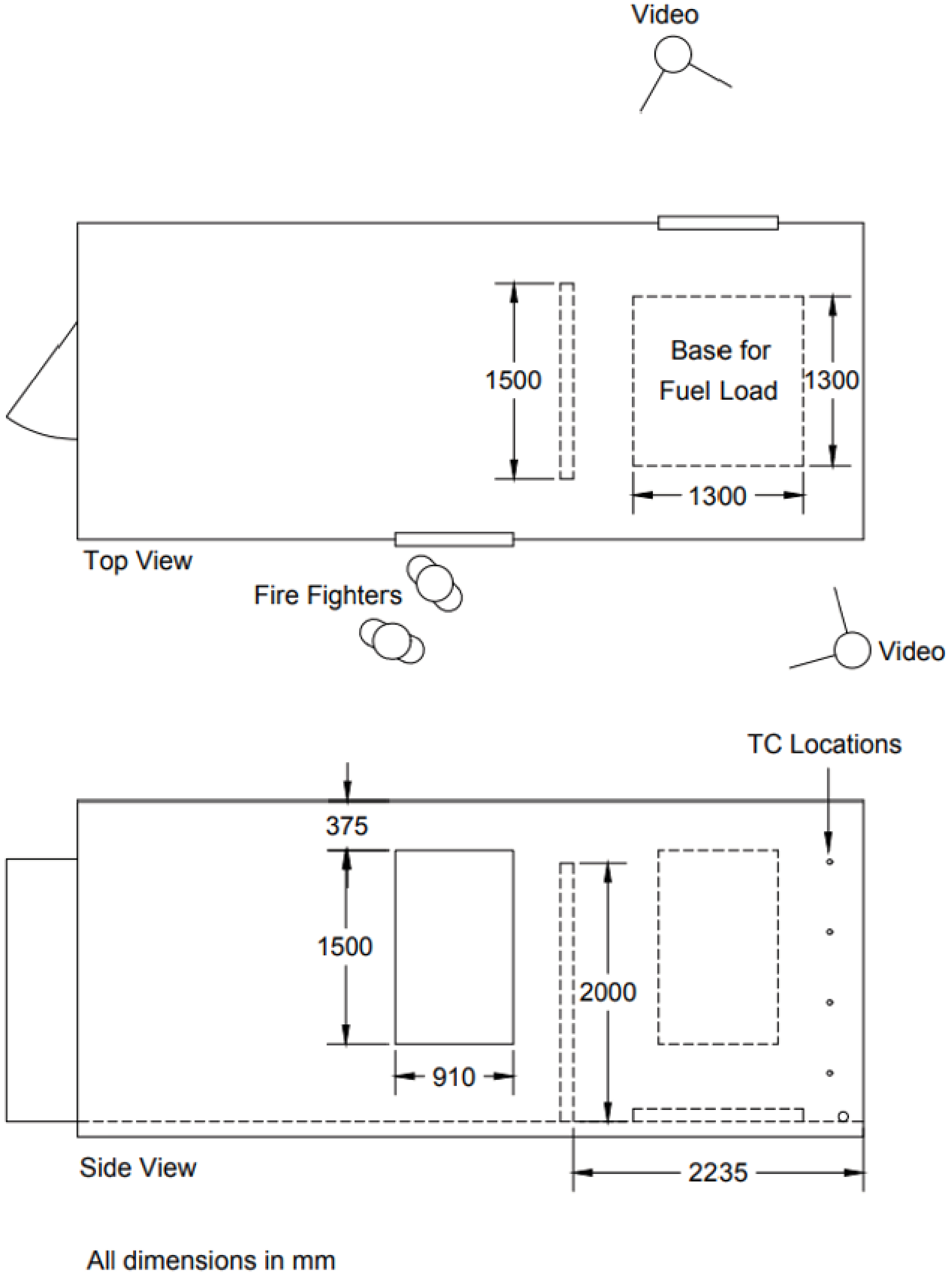

Figure 1. Floor plan and instrumentation.

2.2. Instrumentation

The burn container was instrumented with a four-thermocouple array to measure gas temperature within the burn room. Four type-K (chromel–alumel) thermocouples were located 37.5 cm, 92 cm, 146.5 cm, and 201 cm from the floor of the burn room, which was 18 cm above the ground. Each individual thermocouple was 3.175 mm (1/8 inch) in diameter and was protected from water by an Inconel 600 sheath. The calibrated uncertainty of these thermocouples (as determined by the manufacturer) was +/− 1.1 degrees Celsius up to 800 degrees Celsius. A digital four-channel data logging thermometer (Omega Engineering, RDXL4SD) was used to store temperature measurements every 2 s. Two GoPro cameras (HERO4) recorded each trial and were used in analysis to sync the hose on and off times to the thermocouple recordings. Figures 1 and 2 show the locations of the thermocouple array and the cameras. An S-type load cell (Celtron, STC-500SS) was used with a Rice Lake (IQ Plus 390-DC) digital weight indicator display to record the mass of the fire load components.

Figure 2. Images showing the set-up of the fuel load in the burn room and the location of the GoPro cameras, thermocouple array, and fire fighters during a trial.

2.3. Fuel Load

Each fuel package was made up of the components shown in Table 1. Pallets were stacked vertically, with hay and diesel fuel distributed between them. One OSB board was suspended 0.19 m from the ceiling, while the other two were placed on the north and east walls opposite the ventilation and loading (see Figure 2).

Table 1. Contents of Fuel Packages.

Fuel Package Component	Specifications
Wood pallets	- ~1 m × 1.2 m × 0.135 m - mass (kg) mean: 20.35 range: 10.5–29 combined (per package): 97.5, 97, 96, 92
Oriented Strand Board (OSB)	3, 1.22 m × 2.44 m × 0.015 m boards per package
Hay	2 five-gallon (18.9 L) buckets, firmly packed per package
Diesel Fuel	4 L per package

2.4. Fire Extinguishing Equipment

Three trials were completed, each with an ultra-high-pressure hose at 20 gpm and a low-pressure hose at 30 gpm. Table 2. describes the fire extinguishing equipment and operating conditions.

Table 2. Fire extinguishing equipment and operating conditions.

Equipment	**Operating Condition**	
	Ultra-high pressure	Low-pressure
Nozzle	Pistol grip; 45-degree fog pattern	Pistol grip; 45-degree fog pattern
Hose line	200 ft of 0.75 inch (1.91 cm)	150 ft of 1.5 inch (3.81 cm)
Flow rate	20 gpm (75.7 L/m, 1.26 L/s); 1100–1400 psi (7584.2–9652.7 kpa)	30 gpm (113.6 L/m, 1.89 L/s) 162 psi (1117.0 kpa)

2.5. Procedure

A total of eight trials were conducted, using four fuel loads. Thermocouple array data were recorded for the first six trials, but technical and weather-related issues resulted in unusable data for the last two trials, so these results are not presented. Each set of trials began with the ignition of the fuel load with $\frac{1}{2}$ of the ventilation windows, the ventilation doors, and the loading doors open. Once the fire was established, the loading doors were closed. When the real-time temperature for the highest thermocouple consistently read above approximately 650 degrees Celsius, the attack window was opened and water was applied to the burn room using a combination attack. One firefighter operated the nozzle, while a second firefighter assisted with opening the doors and managing the hoses. If required, due to fatigue, firefighters switched positions while maintaining water on the fire. Once the lowest thermocouple consistently read below 250 degrees Celsius, the water was removed and the attack window was closed. The temperatures were again allowed to build to approximately 650 degrees Celsius, and a second trial was conducted in the same manner as the first. To consistently record the trials in triplicate, The UHP trials were conducted first, followed by the low-pressure trials for a given fuel load.

3. Results

Table 3 summarizes the results of each trial for both conditions. The water exposure start and stop times were synced to the thermocouple array readings using the GoPro videos. Water exposure times were 3:02, 3:06, and 1:18, respectively, for the three UHP condition trials and 3:24, 3:34, and 4:16, respectively, for the three LP condition trials. Resulting in approximate totals of 229.32 L, 234.36 L, and 98.28 L of water used for each UHP trial, respectively, and 385.56 L, 404.46 L, and 483.84 L of water used for each LP trial, respectively. The fire was not extinguished in any of the UHP or LP trials. Figure 3 shows temperatures, in degrees Celsius over water exposure time, for each of the four thermocouples during a representative test for each of the UHP and LP conditions. Figure 4 shows the continuous median thermocouple array temperature across time for the same representative tests that used a single fuel package.

Table 3. Summary of results.

Measurement	**Trial**					
	UHP 1	**UHP 2**	**UHP 3**	**LP 1**	**LP 2**	**LP 3**
Water exposure time (in seconds)	182	186	78	204	214	256
Approximate volume of water used (in Liters)	229.32	234.36	98.28	385.56	404.46	483.84
Fire Extinguished?	No	No	No	No	No	No
Time to 50% of starting temperature (in seconds)	62	78	42	/	144	/

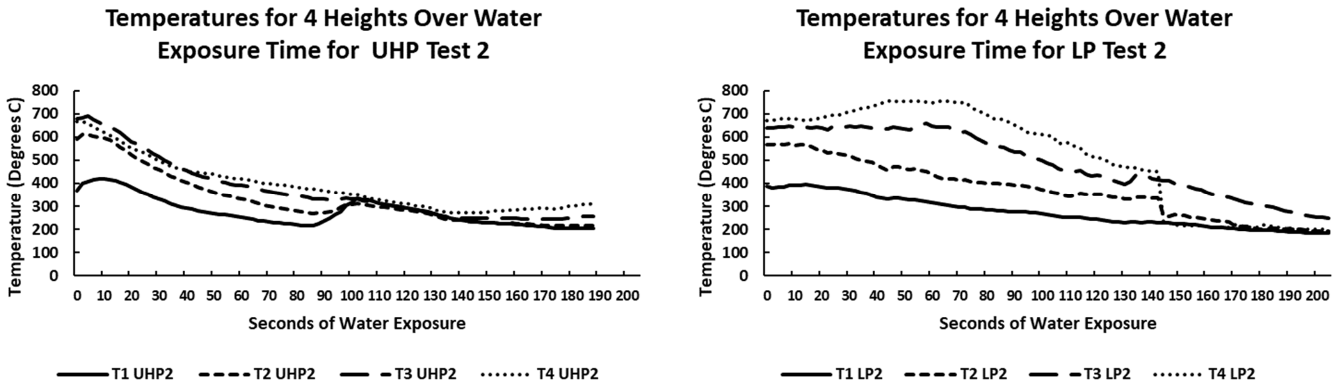

Figure 3. Temperature, in degrees Celsius over water exposure time, for each of the four thermocouples during a representative test for each of UHP and LP conditions. T1 represents the lowest thermocouple, while T4 represents the highest thermocouple in the array.

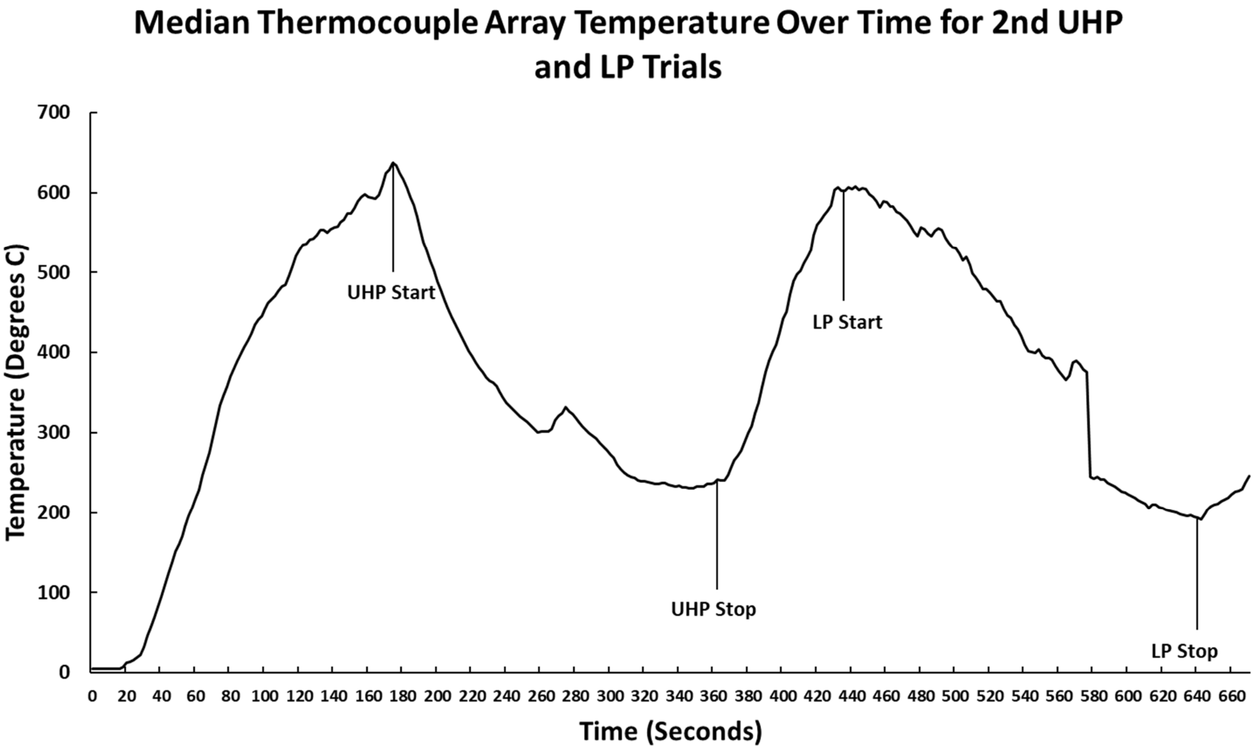

Figure 4. Median thermocouple array temperature over time with the start and stop of water flow for each of UHP trail 2 and LP trial 2 indicated.

To compare trials and remove the influence of outliers from single thermocouple temperature readings, the median temperature for the thermocouple array was calculated for each time point. Additionally, to account for variation in median starting temperatures (M = 565.22, SD = 41.19 degrees Celsius), the proportion of the starting temperature at each timepoint during water exposure was calculated.

The low-pressure condition reached a temperature of 50% of the starting temperature in only one trial (trial 2), which took 144 s. The time to reach a temperature of 50% of the starting temperature was 62, 78, and 42 s for each of the three UHP trials, respectively. Figure 5 illustrates the median thermocouple array temperature over time, represented as a proportion of the starting temperature for each of the six trials.

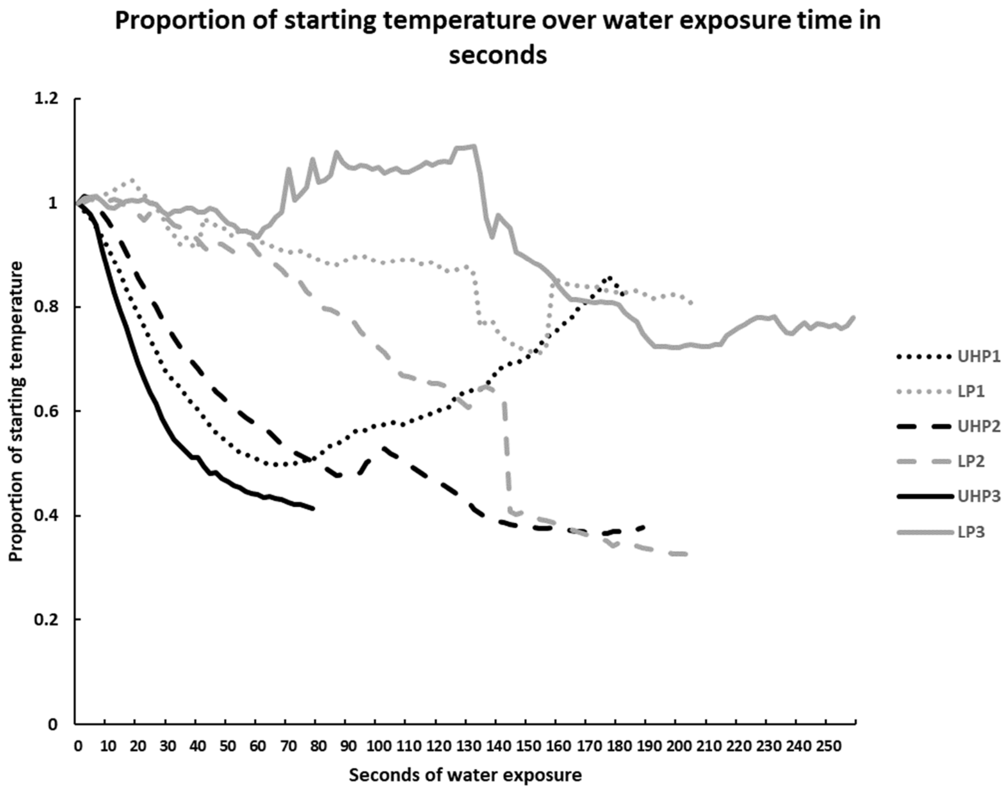

Figure 5. Median thermocouple array temperature over time.

4. Discussion

Consistent with previous work examining UHP and LP low-flow attacks for different applications, the three UHP condition trials each saw decreases in the proportion of starting temperature that were faster and of greater magnitude than for the three LP trials. Liu and Kim [10] summarize both primary (heat extraction; displacement of oxygen) and secondary (radiation attenuation; kinetic effects) mechanisms that can contribute to faster cooling with smaller water droplets in UHP operating conditions.

As to be expected with longer water exposure times, the LP trials used more liters of water than the UHP trials for each fuel load. From an exterior firefighting position, with direct access to the base of the fire blocked, none of the trials resulted in extinguishment. This is despite reaching similar and lower temperatures than those reached at extinguishment by McDonald [16]. The time in seconds to reach a 50% decrease in temperature was several times larger for the present setup than the one used to simulate a room and contents fire [16].

The present results are also consistent with the findings of Särdqvist and Svensson [18], where high-pressure (~4000 kpa) and low-pressure (~1100 kpa) manual fire-fighting systems were compared for a much larger burn room and fuel load. Of note, these authors also describe faster gas cooling for the high-pressure condition and the difficulties in extinguishing the fire where access to the base of it was blocked under low-flow conditions.

The present work shows similar cooling patterns for both UHP and LP hand lines as previous studies. This provides evidence that the burn container and room, as well as instrumentation and fuel load configurations, are appropriate for further testing of such equipment and strategies for exterior fire suppression. Good reproducibility was achieved for these tests employing human firefighters. Next steps should include extended water exposure periods to reach extinguishment, several trials under each condition (to facilitate inferential statistical analysis), and evaluating different strategic exterior approaches. Additionally, an examination of the effects of training on cooling and extinguishment time would be beneficial in guiding decision-making for rural fire departments.

There are limitations inherent in full-scale testing in real-world conditions. Ambient temperature and wind speed and direction could not be kept identical through each test. Partial controls for ventilation were in place through the same-sized openings being used consistently each time. The fuel loads were stored in the same space; however, identical moisture content could not be assured. The use of firefighters introduces variability that would not occur with static equipment. However, controls were in place. These controls included using the same firefighter on the nozzle for each test and directing them to perform identical attacks each time. Researchers also monitored the attack visually while it was underway.

Pilot testing is conducted, in part, to allow for the identification of unforeseen limitations. The time taken to decrease the temperature and attempt to extinguish the fire was much longer than expected. This introduced the possibility of fatigue. Wind and smoke direction also unexpectedly influenced the ability to consistently monitor equipment functioning and resulted in the loss of data.

5. Conclusions

During all three sets of trials, the ultra-high-pressure condition induced decreases in the proportion of starting temperature that were faster and of greater magnitude than for the low-pressure trials. This is consistent with the documented benefits of smaller water droplets for cooling. While this is a promising result, neither operating condition resulted in the extinguishment of the shielded fire. This preliminary testing provides evidence that the burn container and room, as well as instrumentation and fuel load configurations, are appropriate for more extensive testing of such equipment for exterior fire suppression.

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Nomenclature

C	Celsius
cm	centimeter
ft	foot
gpm	gallons per minute
Kg	kilogram
Kpa	kilopascal
L/m	liters per minute
M	mean
m	meter
mm	millimeter
NL	Newfoundland and Labrador
Psi	pound per square inch
SD	standard deviation

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