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EVALUATION OF ULTRA-HIGH PRESSURE (UHP) FIRE SUPPRESSION ON WILDLAND-URBAN INTERFACE (WUI) FIRES

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14. ABSTRACT

Although flammable liquid-fuel (Class B) fires pose a high-profile risk to United States Air Force (USAF) assets, wildland-urban interface (WUI) surface fires fueled by dried vegetation are the most common fire incidents addressed by USAF Fire Emergency Services (FES). Class B fuel fires can be effectively controlled using ultra-high pressure (UHP) fire-fighting technology, and as a result, UHP fire-fighting vehicles make up the bulk of the USAF FES inventory. In order to minimize inventory and simplify logistics, it would be advantageous to apply UHP vehicles for other applications, especially the common WUI surface fires. As a result, the USAF evaluated UHP fire-fighting performance on low to moderate intensity WUI surface fires fueled by grass and shrub lands. The goal of this work was to determine whether a single UHP attack technique could be identified and then optimized to extinguish WUI surface fires, and, if successful, quantify the UHP techniques with respect to conventional low pressure (LP) methods. Agent discharge and fire suppression experimental trials were performed using a LP and UHP Utility Task Vehicle (UTV) designed to represent the respective handline capability of conventional wildland FES response vehicles and UHP FES vehicles like the P-34 rapid intervention vehicle (RIV) and UHP P-19. Water alone (no additives) was used as the fire-fighting agent for all experiments. The limited scope focused analysis on the technique and limited complicating interpretation from other factors (e.g. foam forming agents). The agent discharge experimental trials were performed at Tyndall AFB FL, and fire-fighting experimental trials were performed at Cannon AFB, NM, and Beale AFB, CA. Both UTVs met their respective agent discharge pressure, flow rate, and throw distance performance requirements. Fire-fighting trials were performed on grass-fueled fires that were principally categorized as GR2 (low load (<1 foot) dry climate grasses), and GR4 (moderate load (= 2feet) dry climate grasses) classes. Three different UHP attack techniques were tested: 1) alternating the nozzle between perpendicular and collinear orientations with respect to the fire edge, 2) alternating between straight stream and a moderate spray patterns, and 3) the pincer attack method (using both LP and UHP water delivery modes) against a propagating head fire.

The LP and UHP systems discharged agent from the nozzle at at varying rates. Despite the marked differences in delivery conditions, the effective throw distances were identical (44 ft). Moreover, all WUI surface fires were controlled and extinguished regardless of the attack method or water pressure. None of the three UHP attack techniques quantitatively outperformed or demonstrated notable qualitative improvement in fire suppression performance over one-another. All UHP attack techniques, however, exhibited a statistically significant reduction in the amount of agent required for extinguishment over conventional LP attack methods. This was in line with determination that UHP application rates were two-thirds that of LP in previous studies that assessed UHP for Class-B fires at Tyndall AFB. The mean UHP suppression time was measurably longer than LP suppression time, but the difference is within margin of error for the data sets. The test results revealed that FES vehicles with UHP capability have the potential for dual-use applications as fire protection for low to moderate WUI surface threats. FES vehicles could support a WUI fire protection mission but are not specifically designed for WUI fire operations. Test and training exercises can safely evaluate FES mobility and reliability against representative WUI fires and environments. The approach can be a critical component in assessing FES vehicle WUI fire-fighting capability. Firefighters may adapt UHP systems to conventional wldland fire suppression tactics, such as those endorsed by the National Wildfire Coordinating Group (NWCG). For example, the UHP stream can penetrate through hard-packed peat that may fuel fire and expose the base mineral content soils to efficiently prepare “scratch-lines” that serve as makeshift firebreaks.

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1. SUMMARY

Although flammable liquid-fuel (Class B) fires pose a high-profile risk to United States Air Force (USAF) assets, wildland-urban interface (WUI) surface fires fueled by dried vegetation are the most common fire incidents addressed by USAF Fire Emergency Services (FES); each year, more than 1,000 wildland fires occur on Air Force land, burning more than 300,000 acres in some years. The number of extreme wildfires has been on the rise over the past two decades, accompanied by soaring suppression costs and significant risk [1]. Class B fuel fires can be effectively controlled using ultra-high pressure (UHP) fire-fighting technology, and as a result, UHP fire-fighting vehicles make up the bulk of the USAF FES inventory. In order to minimize inventory and simplify logistics, it would be advantageous to apply UHP vehicles for other applications, especially the common WUI surface fires. As a result, the USAF evaluated UHP fire-fighting performance on low to moderate intensity WUI surface fires fueled by grass and shrub lands. In typical situations, WUI surface fires can be extinguished by local Air Force Base (AFB) FES forces without extramural support. Assessing the performance of UHP and defining best practices for its applications in WUI fire threats has the potential to improve materiel and facilities safety [2].

The goal of this work was to determine whether a single UHP attack technique could be identified and then optimized to extinguish WUI surface fires, and, if successful, quantify the UHP techniques with respect to conventional low pressure (LP) methods. Agent discharge and fire suppression experimental trials were performed using a LP and UHP Utility Task Vehicle (UTV) designed to represent the respective handline capability of conventional wildland FES response vehicles and UHP FES vehicles like the P-34 rapid intervention vehicle (RIV) and UHP P-19. Water alone (no additives) was used as the fire-fighting agent for all experiments. The limited scope focused analysis on the technique and limited complicating interpretation from other factors (e.g. foam forming agents).

The agent discharge experimental trials were performed at Tyndall AFB FL, and fire-fighting experimental trials were performed at Cannon AFB, NM, and Beale AFB, CA (May and October 2017, respectively). Both UTVs met their respective agent discharge pressure, flow rate, and throw distance performance requirements. Fire-fighting trials were performed on grass-fueled fires that were principally categorized as GR2 (low load (<1 foot) dry climate grasses), and GR4 (moderate load (≤ 2feet) dry climate grasses) classes (fuel classes as defined in [3]). Three different UHP attack techniques were tested: 1) alternating the nozzle between perpendicular and collinear orientations with respect to the fire edge, 2) alternating between straight stream and a moderate spray patterns, and 3) the pincer attack method (using both LP and UHP water delivery modes) against a propagating head fire.

The LP and UHP systems discharged agent from the nozzle at approximately 100 $lb{\cdot}in^{-2}$ at 30 $gal{\cdot}min^{-1}$ and 1,250 $lb{\cdot}in^{-2}$ at 20 $gal{\cdot}min^{-1}$, respectively. Despite the marked differences in delivery conditions, the effective throw distances were identical (44 ft). Moreover, all WUI surface fires were controlled and extinguished regardless of the attack method or water pressure. None of the three UHP attack techniques quantitatively outperformed or demonstrated notable qualitative improvement in fire suppression performance over one-another. All UHP attack

techniques, however, exhibited a statistically significant reduction in the amount of agent required for extinguishment over conventional LP attack methods. This was in line with determination that UHP application rates were two-thirds that of LP in previous studies that assessed UHP for Class-B fires at Tyndall AFB [4]. The mean UHP suppression time was measurably longer than LP suppression time, but the difference is within margin of error for the data sets.

The test results revealed that FES vehicles with UHP capability have the potential for dual-use applications as fire protection for low to moderate WUI surface threats. FES vehicles could support a WUI fire protection mission but are not specifically designed for WUI fire operations. Test and training exercises can safely evaluate FES mobility and reliability against representative WUI fires and environments. The approach can be a critical component in assessing FES vehicle WUI fire-fighting capability. Firefighters may adapt UHP systems to conventional wildland fire suppression tactics, such as those endorsed by the National Wildfire Coordinating Group (NWCG). For example, the UHP stream can penetrate through hard-packed peat that may fuel fire and expose the base mineral content soils to efficiently prepare “scratch-lines” that serve as makeshift firebreaks.

2. INTRODUCTION

2.1. Background

In 2002, the USAF began research, development, test, and evaluation on the use of UHP to extinguish hydrocarbon fuel fires resulting from aircraft crashes. The UHP systems discharge aqueous firefighting agent at pressures greater than 1100 $lb{\cdot}in^2$ and have demonstrated exceptional fire suppression for aircraft rescue fire-fighting (ARFF) tests, particularly extinguishment of Class B fires, which involve flammable liquids and gases [4, 5]. UHP demonstrated a 300% improvement in ARFF efficiency compared to LP methods (100-250 $lb{\cdot}in^2$) [6]. In order to further take advantage of the efficiency and apply UHP technology and techniques, UHP platforms have an expanded range of application flow rates from 4 to 300 $gal{\cdot}min^{-1}$; that flexibility fulfills a variety USAF FES mission needs [7].

UHP performance on Class B fire suppression drove the mass adoption of UHP-enabled FES vehicles by the USAF. The update was due for the aging vehicle fleet in general, but had the added benefit of providing advanced, and modernized equipment [7]. USAF firefighters, however, must also prepare to combat fire threats other than aircraft fuels including structure and wildfire in the WUI, i.e. the transition zone between undeveloped land and inhabited areas. The modern USAF airbase often contains large areas of predominantly undeveloped property, which may serve as site for training, a buffer zone for security and public safety, or a consequence of changes in requirements and mission at an installation [2]. The undeveloped areas may border or even surround actively used areas. Accordingly, WUI fire protection has significant impact on USAF operational readiness and is projected to cost the USAF over $15 million per year. Over 1,000 WUI fires occur annually on USAF lands and have affected more than 300,000 acres in some years, with recent reports showing that both the number and intensity of wildland fires are on the rise [1]. As a result, the USAF must devise and execute strategies to manage the WUI risk. Prescribed fires are done to reduce potential fuel on tens of thousands of acres each year. Despite that proactive approach, wildfires in some of the undeveloped areas are inevitable, and USAF firefighters will be required to respond and use available equipment to protect assets. The number of UHP-enabled FES vehicles will continue to rise in the USAF inventory, and in some instances may be the sole FES available. UHP performance on WUI fires must be assessed to determine the best role and application of UHP in wildfire operations.

The NWCG is the primary organization coordinating and overseeing domestic wildland fire-fighting activity. The NWCG includes participation and input from all U.S. departments and agencies with jurisdiction over United States wildlands. The NWCG mission is to coordinate wildfire management programs of participating agencies in order to optimize protection of public and private wildlands and avoid wasteful duplication and overlap. The NWCG also provides a formal system to agree upon wildland firefighting standards for training, equipment, qualifications, and other operational functions [9]. The Department of Defense (DOD) is a voting member of the NWCG and maintains an interagency agreement with NWCG participants that provides temporary mutual aid support for WUI fire-fighting operations when necessary. All DOD installations are required to have an active wildland fire management plan if they contain or border burnable lands [10]. The plan must govern the local WUI fire-fighting strategy, which encompasses general preparedness, including preplanned dispatch for both initial and extended attack, and prescribed wildland fire and prevention per National Fire Protection Association (NFPA) 1143 and 1710 [11, 12].

2.2. WUI Fire-fighting

The WUI fire-fighting strategy must incorporate to the prevailing conditions and fuels, and then respond using the FES equipment available to the firefighters. A report for USAF wildlands (2008-2012) showed vast majority (ca. 90%) of wildland fires for USAF incidents are fueled by dried grasses or mixtures of brush and grasses. The remainder is equally split into those fueled by timber or other native vegetation [10]. The stand-alone USAF FES forces are typically trained, prepared, and equipped to manage and suppress surface fires, i.e., those fueled by grass and brush. The surface fires can be "directly attacked", applying water and foam- or dry-chemical suppressants to the fires. Other classes, like timber-fueled forest fires that reach the tree canopy, are exceptionally high intensity and require indirect attack methods. In these circumstances, the USAF receives support from outside entities as part of an interagency agreement to combat such threats. The USAF shift to UHP based equipment to suppress liquid-fuel fires substantively changed the collective inventory available for all fire responses. The changes motivated trials that objectively evaluated the effectiveness of UHP on WUI surface fires.

WUI fire-fighting performance and tactics are directed by environment-, fuel-, and fire behavior characteristics. Fire behavior is classified by the 40 Scott and Burgan standard fire behavior fuel models (FBFM40). As a planning guide and summary, portions of the Scott and Burgan report were summarized to categorize the fuels and characteristics of surface fires (Table 1) [14]. The fuels and conditions are representative of the planned tests areas and match those that are expected to be responsive to the UHP FES platforms.

The FBFM40 associated with WUI surface fires and the predicted fire spread and flame length are critical aspects to the firefighting technique recommendations. In addition to the fuel source, fire spread and flame length are dependent on wind speed. The USDA Forest Service technical report authored by Scott and Burgan described and applied models that used the characteristics of fuel sources as base input and then factored the extent wind strength affects fire spread, flame length, and fire intensity (Table 1) and [14, 15, 16]. Intuitively, wind fans and drives fire intensity, however, the density and amount of fuel influence dynamic responses. For example, the wind speed effect to GR2 spread and flame length plateaus, and no appreciable differences are found for winds exceeding ca. 10 knots. By comparison, the GR7 fires continue to spread exponentially and the flame length grow logarithmically in response to wind speed. The differences and interpretation may be applied for safety considerations and determining firefighting strategies and techniques. An earlier review from Hisch and Martell [13] includes summaries of wildland fires across the globe (US, Canada, Australia) and the practical limits of fire suppression techniques. Broad categories of work from the review are summarized in Table 2. It is notable here that, the UHP-equipped FES are best applied to the first categories of WUI-fires. The direct attack methods using water or class A foam from the platforms effectively suppress wildland fires with flame lengths up to eight feet and low to moderate intensities. Flame lengths greater than eight feet typically fed by dense fuels in great supply are not manageable by direct methodologies alone.

Table 1. WUI Surface FBFM Summary

Name	Description	Maximum Fire Spread	Maximum Flame Length
Arid to Semi-Arid Climates			
GR1	Grass is short, patchy and possibly heavily grazed	MODERATE	LOW
GR2	Moderately coarse continuous grass, average depth of about 1 ft	HIGH	MODERATE
GR4	Moderately coarse continuous grass, average depth of about 2 ft	VERY HIGH	HIGH
GR7	Moderately coarse continuous grass; average depth of about 3 ft	VERY HIGH	VERY HIGH
GS1	Shrubs are about 1 ft high, low grass load	MODERATE	LOW
GS2	Shrubs are 1 to 3 ft high, moderate grass load	HIGH	MODERATE
Humid to Semi-Humid Climates			
GR3	Very coarse grass, average depth of about 2 ft	HIGH	MODERATE
GR5	Dense, coarse grass, average depth about 1 to 2 ft	VERY HIGH	HIGH
GR6	Dryland grass about 1 to 2 ft tall	VERY HIGH	VERY HIGH
GR8	Heavy, coarse, continuous grass about 3 to 5 ft tall	VERY HIGH	VERY HIGH
GR9	Very heavy, coarse, continuous grass about 5 to 8 ft tall	EXTREME	EXTREME
GS3	Grass-shrub depth less than 2 ft	HIGH	MODERATE
GS4	Grass-shrub depth greater than 2 ft	HIGH	VERY HIGH

Table 2. Suppression Limitations Based on WUI Fire Behavior

Flame Length (ft)	Fire Intensity ($BTU \cdot s^{-1} \cdot ft^{-1}$)	Fire Suppression Limitations
0 - 4	< 100 LOW	Fires can generally be attacked at the head or flanks by persons using hand tools. Handlines should hold the fire. Most prescribed burns are conducted in this range.
4 – 8	100 – 500 MODERATE	Fires are too intense for direct attack on the head by hand tools. Handlines cannot be relied on to hold the fire. Equipment such as plows, dozers, pumpers, and retardant aircraft can be effective.
8 – 11	500 – 1000 HIGH	Fires may pose serious control problems – torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
> 11	> 1000 VERY HIGH	Crowning, spotting, and major fires are probable. Control efforts at the head of the fire are ineffective. Aerial attack has minimal effectiveness.

2.3. Scope

The objective of this work was to quantify the performance of UHP fire-fighting techniques relative to conventional LP tactics for suppression of WUI surface fires. The UHP application flow rate and pressure selected for testing were based on the capabilities of the P-34 RIV and P-19 UHP handlines. Four UHP fire-fighting techniques were chosen for the investigation and comparison against two conventional LP techniques. The UHP technique used two different nozzle settings and two different attack angles (Table 3 and Fig. 1). A single, adjustable fog stream/straight stream nozzle was used on handlines for the water application. The bail was operated at either least restricted position (straight stream) , which forms the narrowest fog pattern of water droplets, or at most restricted bail setting (full-range), which yields a wide angle fog (ca. 80° cone of water mist droplets). The specification for the FES platforms used for tests are noted in Table 4 and Figure 3. The tests and analysis, however, did not compare or were intended to objectively evaluate the FES platform performance. The vehicles serve as representative UHP-capable platforms and were based on those available at the test site locations.

Table 3. UHP Fire-fighting Attack Techniques

Technique	Direct Attack Orientation	Fog Pattern	UHP Technique Abbreviation
1	Perpendicular	Full Range	PERP-FR
2	Perpendicular	Straight Stream	PERP-SS
3	Collinear	Full Range	COLL-FR
4	Collinear	Straight Stream	COLL-SS

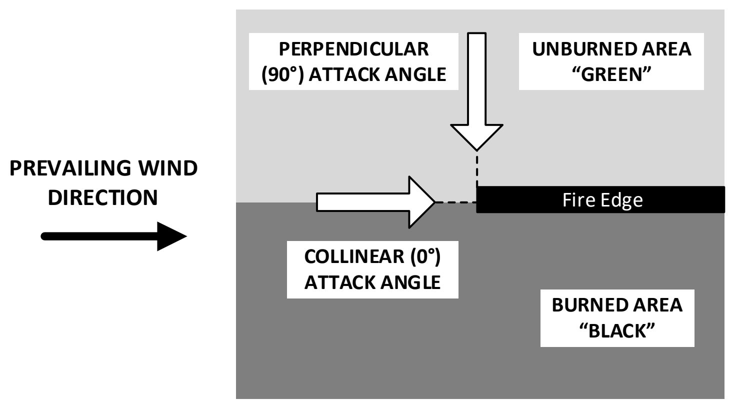


Figure 1. Contrasting Firefighting Approach Angles Considering Wind Direction and Fuel Source with Respect to Fire Edge

2.4. Terminology

The terminology used in this report is drawn from academic and government agency wildland fire literature. Industry specific terms will be defined at first use and explicitly defined in the glossary. Most data are presented in United States customary units (e.g. in, ft, lb, gal). The International System of units (SI) is shown when the primary data acquisition method or instrument uses SI units. For the purpose of the study and tests, WUI fires considered are surface fires fueled by grass and shrubbery where the fuel height does not exceed six feet.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

Two experimental trials were performed using LP and UHP fire-fighting systems. Controlled discharge trials were done to measure agent discharge (throw distance) and quantify volumes of agent along the delivery path. Fire-fighting experiments were then conducted to determine the fire suppression effectiveness of each system with representative fuels, conditions, and environments for WUI fire responses.

3.1. Equipment

3.1.1. Discharge Characterization Equipment

Sixty polypropylene graduated cylinders (2000 ±20 mL, Bel-Art model F28459) were used to collect water for water discharge experiments. The graduated cylinders were secured to stay upright during trial by placing concrete bricks on their bases. An adjustable steel work stand (Rockwell Jawhorse RK9003) was used to fix the fire-fighting nozzle in place during test. A handheld protractor, and digital single-lens reflex (DSLR) camera, were used to estimate the nozzle fog pattern.

3.1.2. Fire Characterization Equipment

Custom fabricated and commercial off-the-shelf equipment were used to characterize fire behavior. Flame height indicators were used as a vertical reference length along with FLIR® K55 thermal imaging cameras to assess flame height, fuel height, rate of fire spread, and propagating direction of the fire. The indicators were custom built from structural steel to withstand intense winds and flame heat (Figure 2).

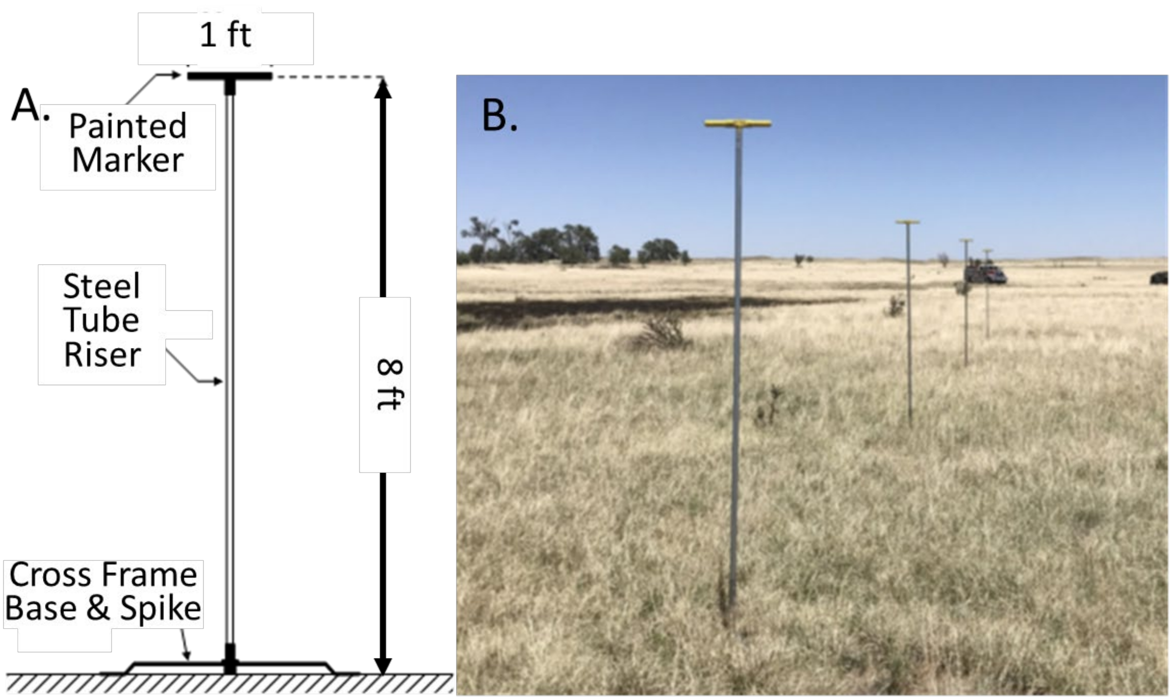


Figure 2. Flame Height Indicator (a) Fabrication details (b) Indicators Deployed in the Test Area

Keson® MP401E electronic survey wheels were used to measure fire suppression line length following the tests. Tripod-mounted Kestrel® 5400FW Fire Weather Meter Pros to measure and record local weather conditions. GoPro® Hero4 and Hero5 cameras were used to record near and far-field high definition video.

3.1.3. Fire Ignition and Fire-fighting Equipment

A handheld drip torch filled with 1:1 diesel-gasoline mixture was used to start each fire. The ignition point was marked with two high-visibility, square steel plates forming a cross pattern. Polaris Ranger UTVs (Medina MN) were used as rolling chassis to carry the LP and UHP equipment. The manufacture specifications indicated that payload capacity and platform were sufficient to support equipment and travel through anticipated terrain (no endorsement, implicit or explicit granted by use). Our previous work with the Polaris product showed adequate performance in other evaluations. The UTVs were outfitted with fire-fighting systems built by U.S. Tanker Fire Apparatus (Delavan, WI). USAF personnel provided the manufacturer with design-to-build performance specifications for each unit. The LP and UHP fire-fighting system flow diagrams are illustrated in Appendix A. Their agent discharge performance specifications are highlighted in Table 4, photographs of the modified UTVs and the fire-fighting equipment are shown in (Figure 3).

Table 4. LP and UHP UTV Agent Discharge Specifications

Fire-fighting System	Flow Rate ($gal \cdot min^{-1}$)	Nozzle Pressure ($lb \cdot in^{-2}$)	Straight Stream Throw Distance (ft)	Hose Line Diameter (in)
LP UTV	30 ±0.5	100 to 250 ±15	> 40	1
UHP UTV	20 ±0.5	1100 to 1400 ±25	> 40	0.75

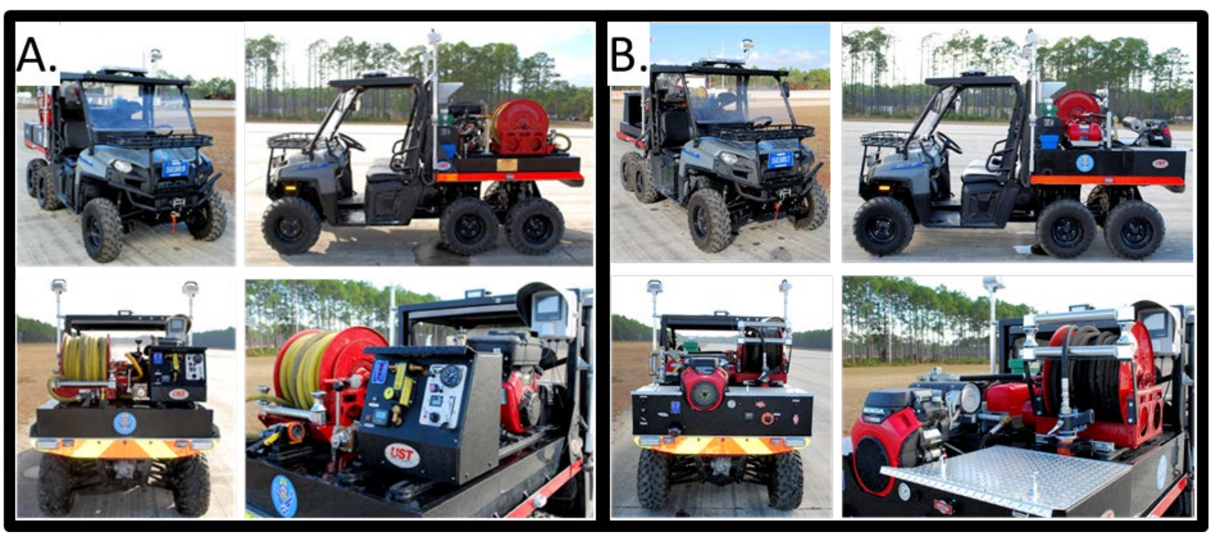


Figure 3. Commercial Utility Vehicles Configured with the LP UTV (a) and UHP UTV (b) Systems (Use of Polaris Brand is not Implicit Endorsement of the Product)

LP agent discharge specifications were chosen based on NFPA 1710 [12] requirements. UHP agent discharge specifications were chosen based on the handline performance capability of the UHP P-34 RIV and the UHP P-19. Table 5 lists the primary capabilities and components of both UTVs. Auxiliary USAF FES forces were also onsite with equipment during testing in order to provide back-up safety to the test team in the event a fire broke the containment plan.

Table 5. LP and UHP UTV Common Capabilities and Components

Description
Polaris Ranger® 6×6 800 series chassis
Gasoline engine-driven fire-fighting system with standard pump and engine control
Polypropylene water tank with 100-gal capacity
Pump and roll capable at rated pressure and flow rate for two hr. without performance degradation
Bypass or standby mode capable for 30 min without performance degradation
150-ft continuous length, rear-mounted handline
Pistol grip nozzle capable of straight stream and fog patterns with flush capability

3.2. Agent Discharge Test Method

Agent discharge experimental trials were performed at the Indoor Fire-fighting Test Facility located in the Air Force Civil Engineer Center Test Range II on Tyndall AFB, FL. The test facility is an 80×80×32 ft Quonset-style building. The fire-fighting nozzle was fixed in a horizontal position 38 in above the ground using a clamp bracket and portable workbench (Rockwell Jawhorse) to maintain a consistent fire-fighting orientation. Graduated cylinders were placed on the ground from 2 to 80 ft downstream of the nozzle in increments of 2 ft in order to estimate throw distance and efficacy of the water stream (Fig. 4). Water was discharged at a target pressure, flow rate, and nozzle spray pattern for each system. Pump pressure, nozzle pressure, and water accumulation versus distance downstream were recorded. Flow was maintained until the representative graduated cylinders neared capacity, then time and volume recorded. The nozzle spray patterns were determined using a protractor and then visually inspecting photographs. The water flow was adjusted from "straight-stream" to 100% fog in 25% increments. A camera was installed directly above nozzle and the orthogonal images of discharged agent were analyzed to confirm each spray pattern. A linear potentiometer fixed between the nozzle's body and the adjustable shroud on each fire-fighting system was used to correlate the reaction forces and the nozzle spray pattern during fire suppression field testing. The response was calibrated during discharge testing by combining the quantitative sensor data and image processing results.

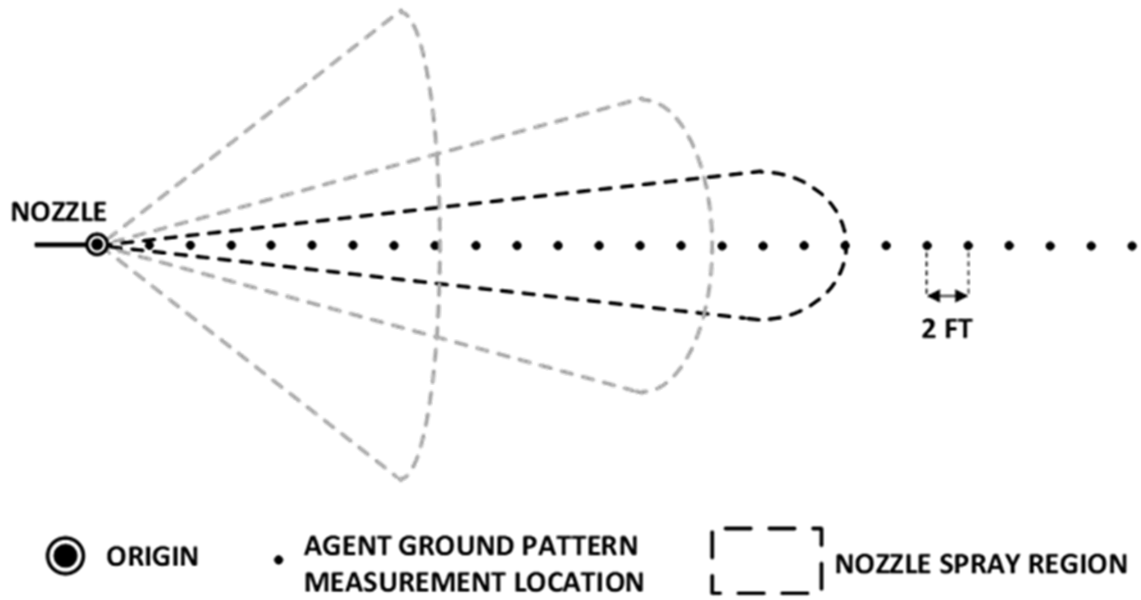


Figure 4. Fire-fighting Discharge Test Set-up (Overhead View)

3.3. Fire-fighting Test Method

3.3.1. Fire-fighting Test Overview

Fire-fighting tests were performed at Air Force bases in the southwest region of the United States. These locations were chosen because the threat of accidental WUI fire in these locations is severe and controlled burns are prescribed to minimize incident frequency [2, 17]. Locations were further down-selected based on their ability to provide each of the following:

1. Contain a minimum of 50 ac of burnable wildland
2. Contain plentiful grass and shrub-dominated FBFMs within burnable wildlands
3. Active maintenance of a wildland fire management plan
4. Sufficient wildland fire-fighting personnel and equipment resources available per NWCG regulations

Table 6 lists the test locations considered along with their general wildland characteristics (information collected Air Force documents and reference 15). Beale AFB, CA and Cannon AFB, NM were chosen as test locations because they best met all four criteria. Beale AFB is in north central California and Cannon AFB is in the east central region of New Mexico near the western border of Texas. The FBFM summary showed that Beale AFB and Cannon AFB have similar terrain and distribution of wildland "fuels" [15]. The Beale site, however, has comparatively more timber understory and mature timber fuels in wildland areas. The vegetation differences are likely a product of climate cycle and rainfall. Beale receives 20-30% more precipitation per year and has a more Mediterranean cycle with mild and wet winter months. Cannon, by contrast has a "high-desert" climate, rain principally falls in hot summer months, and thus is more susceptible to evaporative losses.

Table 6. Test Site Locations

Test Site Location	Average Prescription Burn Area (ac)	Terrain Shape	Major Wildland Fuel Type(s)
Beale AFB, CA	1,000 – 10,000	Flat; Small Hills and Valleys	Grass; Shrub; Grass-Shrub Mix
Cannon AFB, NM	1,000 – 10,000	Flat; Small Hills and Valleys	Grass; Shrub; Grass-Shrub Mix
Eglin AFB, FL	> 10,000	Flat; Small Hills and Valleys	Grass-Shrub Mix; Timber w/ Understory; Timber Litter; Slash-Blowdown
Ellsworth, SD	(Unknown)	Flat; Small Hills and Valleys	Grass; Shrub; Grass-Shrub Mix
JB Elmendorf-Richardson, AK	1,000 – 10,000	Flat; Small Hills and Valleys; Large Hills and Valleys; Mountainous	Grass, Grass-Shrub Mix, Timber w/ Understory; Timber Litter; Slash-Blowdown
JB McGuire-Dix-Lakehurst, NJ	100 – 1,000	Flat; Small Hills and Valleys	Grass; Shrub; Grass-Shrub Mix; Timber w/ Understory; Timber Litter
MacDill AFB, FL	100 – 1,000	Flat	Timber w/ Understory
Mountain Home AFB, ID	(Unknown)	Large Hills and Valleys	Grass; Timber w/ Understory
Nellis-Creech AFB, NV	(Unknown)	Flat; Small Hills and Valleys	Grass-Shrub Mix
Shaw AFB, SC	100 – 1,000	Flat	Timber w/ Understory
Tyndall AFB, FL	> 10,000	Flat	Grass; Timber w/ Understory

The fire-fighting tests were performed at one test area colloquially referred to as the "Dragontown District" within Beale AFB (Beale-1) and three test areas within the Melrose Air Force Range of Cannon AFB (Cannon-1 through Cannon-3, respectively) (Table 6). Photographs showing the characteristic fuel load of each test area are shown in Figure 5. The flame height indicator is highlighted in each test area to show the 8 foot scale. Fuel load, fire intensity, and flame length must be great enough to collect meaningful fire suppression data. The flame height needed to exceed 2 ft in order for the trial to show sensitivity to the fire-fighting techniques and application rates and volumes evaluated in this study. Satellite images of each test area are shown in Figure 5. Note test areas shown in Figure 5 are not to relative scale. Table 7 lists test area specific information such as global position system (GPS) location, size, terrain, and FBFM.

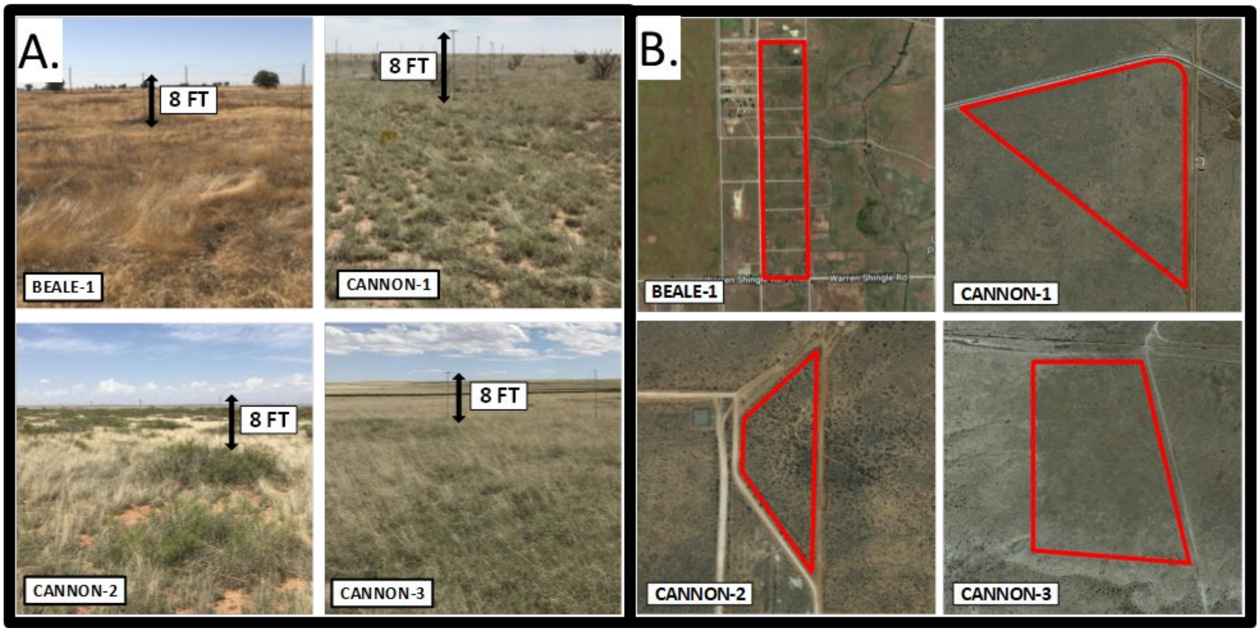


Figure 5. (a) Test Area Vegetation Providing Fuels for the Application Tests (b) Satellite View of Test Area Locations

Table 7. Test Site Information

Test Site Name	Longitude GPS (dd)	Latitude GPS (dd)	Area (ac)	Terrain Shape	FBFM
Beale-1	39.118527	-121.409446	60.7	Flat	GR4
Cannon-1	34.293032	-103.760078	65.0	Flat	GR2
Cannon-2	34.308694	-103.784613	20.6	Small Hills and Valleys	GS2
Cannon-3	34.360620	-103.747994	10.4	Flat	GR2

3.3.2. Fire-fighting Test Procedural Steps

1. **Synchronize instrumentation.** Sync the time and date of all instrumentation.
2. **Deploy fire characterization equipment.**
    a. Ensure the test site is bound by fire breaks. Deploy the ignition marker near an "anchor point", which is within a pre-existing firebreak, such as a road or tilled soil without significant vegetation or other fuel.
    b. Deploy fire weather recorders upwind and flanking the ignition marker within a fire break to avoid damage.
    c. Deploy a column of four flame height indicators spaced at 25 foot intervals and downwind from the ignition marker within the test site.
    d. Deploy all camera equipment. Locate static camera equipment within a fire break to avoid damage. Position cameras to record the whole test site.
3. **Ready fire fighters and support staff.**
    a. Position all personnel and associated configure logging equipment based on the test plan. Each fire-fighting crew will be pre-positioned at opposing anchor points upwind and flanking the ignition marker. Fire fighters will rotate between UHP and LP assignments in effort to minimize effect on experiments due to practiced techniques from fire fighters. The skill level of one fire-fighter continually using a

single method will have excess influence on one set of the trials, reflecting only that individuals' skills or practiced technique after many rounds with same approach and challenge. If applicable, ensure the UHP nozzle spray pattern is pre-adjusted to the appropriate start-up setting in order to have immediate application on fire.

4. **Start data acquisition.** Start recording data from fire weather recorders, cameras, and all other data acquisition and position tracking systems.
5. **Ignite fire.** Ignite the fuel surrounding the ignition marker. Record the ignition time.
6. **Record fire propagation.** Record the fire as it propagates through the column of flame height indicators using standard and thermal imaging cameras.
7. **Extinguish the fire and record performance**.
    a. Start extinguishment when the leading edge of fire (head) reaches the last flame height indicator in the column.
    b. Record the extinguishment start time of each fire fighter.
    c. Fire fighters will use the pincer attack method to extinguish the flank closest to them and advance toward the head of the fire until it is completely extinguished. Figure 6 illustrates a typical approach. Note the position and orientation of either fire fighter with respect to the fire edge is variable trial to trial. The pincer attack method is well-described in training literature [16] and is a commonly used wildland firefighting technique. As the name implies, the pincer method mimics military movement in which, two fire-fighting teams or platforms coordinate and converge on the leading edge of a fire from opposite directions in order to suppress the spread.
    d. The LP fire fighter will follow conventional fire suppression tactics outlined by Teie [16]:
        - The fire fighter should move parallel to the fire edge with the nozzle aimed at the base of the fire where the flame meets the fuel
        - The fire fighter may work from the "green" (unburned area) or the "black" (burned area), choosing the attack position that best fits the situation. The literature suggests that fire fighters should work from the "black" to suppress lighter fuels, but from the "green" to suppress heavier fuels to limit heat exposure
        - The nozzle should be held close to the ground so that the water stream penetrates through the humic layer to mineral soil, which reduces the risk of re-ignition after advancement
        - A moderate spray pattern is defined as setting that disperses water to the greatest area possible. The approach should be used when possible because it cools the greatest area with lowest water volume. The practice is subject to individual experience and the empirical nature of fire suppression techniques
        - The straight stream setting (unrestricted flow, opposite of fog) should be used in order to "reach in" and cool an area of fire so that the fire fighter can move, to knock down hotspots on the fire line, or to penetrate challenging fuel-flame interfaces that moderate spray pattern would not otherwise extinguish

- A fog pattern may be used to provide fire fighters protection from intense heat
- The minimal volume of water required to extinguish the fire should be applied in order to provide most replicable test data
- The water should be shut off whenever it is not directed at specific fuel or flame targets

e. In the UHP tests, the fire fighter will apply one of the four techniques described below to alter nozzle attack angle with respect to the fire edge (as illustrated in Figure 1) as well as the spray pattern. Unless otherwise noted by the specified technique, the UHP fire fighter should follow the conventional fire-fighting principles similar to the LP fire fighter. For safety reasons, it is understood the UHP fire fighter may deviate from any of the four prescribed UHP techniques if necessary for safety. The test techniques are described below and noted in Table 3.

- **Technique PERP-FR (1)** orients the nozzle perpendicular to the fire edge while allowing the fire fighter to adjust the full range of the spray pattern. The fire fighter should try to maintain a moderate spray pattern, consistent with conventional tactics that optimize area of the fire that is cooled by the water.
- **Technique PERP-SS (2)** also orients the nozzle perpendicular to the fire edge, but the fire fighter should maintain a straight stream and target specific areas of the fire.
- **Technique COLL-FR (3)** orients the nozzle collinear with the fire edge while allowing the fire fighter to adjust the full range of the spray pattern. The fire fighter should maintain a moderate spray pattern, similar to Technique PERP-FR.
- **Technique COLL-SS (4)** also orients the nozzle collinear with the fire edge, but the fire fighter should try to maintain a straight stream, similar to Technique PERP-SS.

f. Record all fire suppression activities using the standard and thermal imaging cameras.
g. Record the extinguishment stop time for each fire fighter.
h. Record the fire edge extinguishment length for each fire fighter.

8. **Stop Data Acquisition.** Stop recording data from fire weather recorders, cameras, and all other data acquisition and position tracking systems at completion of the test.
9. **Recover all test site equipment.**
10. **Inspect and Service Fire-fighting Vehicles as Necessary.**

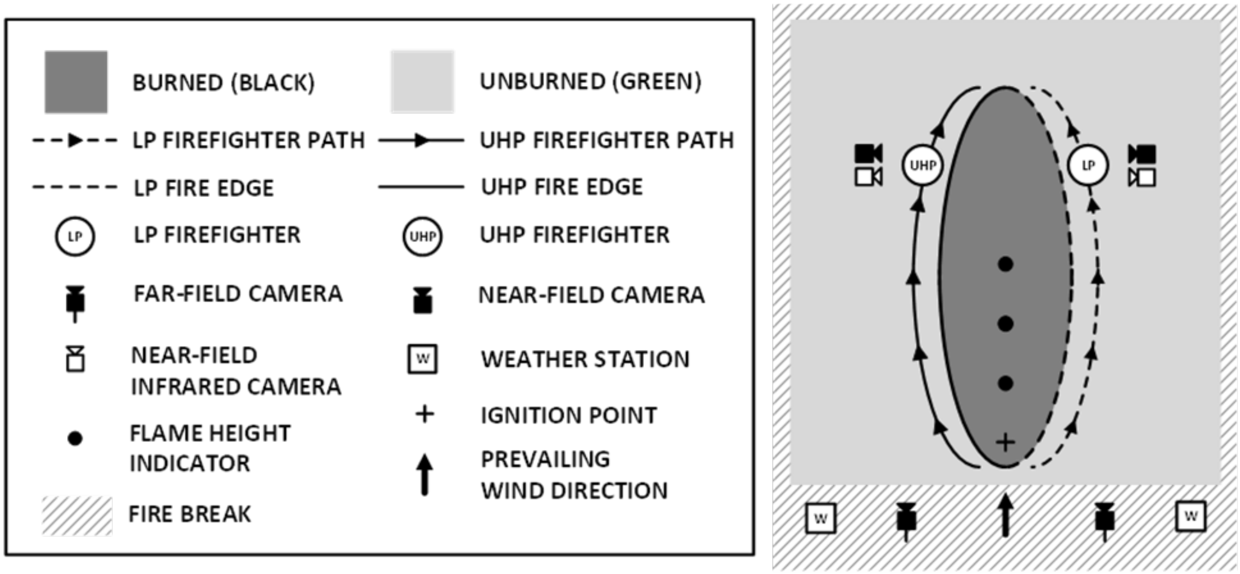


Figure 6. Schematic Illustration of Fire Suppression Test Layout and Attack Method

Figure 7. (a) Fire Suppression Test Ignition (b) Fire Suppression Test Pre-Extinguishment

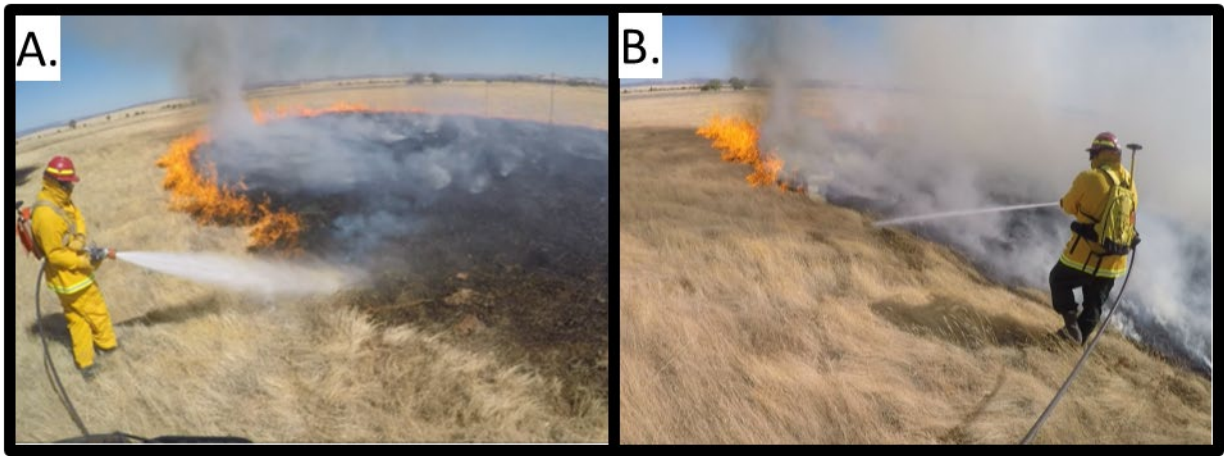


Figure 7. UHP Fire Suppression in (a) Perpendicular Attack Mode with Full Range of Spray Pattern (PERP-FR) (b) Collinear Attack Mode in Straight Stream Only (COLL-SS)

4. RESULTS AND DISCUSSION

4.1. Agent Discharge Test Results

The LP and UHP agent discharge experiments were done using five spray pattern settings from straight stream to 100% fog in increments of 25%. A minimum of two trials were performed for each spray condition. If agent accumulation data diverged greater than 10% at one or more measurement locations for those two trials, a third trial was performed. Agent discharge was consistent and nearly constant during steady-state operation for both systems. The agent discharge data are summarized in Table 8. Agent discharge performance met all specifications listed in Table 4. Figure 9a and 9b show a straight stream discharge test in progress for the UHP and LP, respectively.

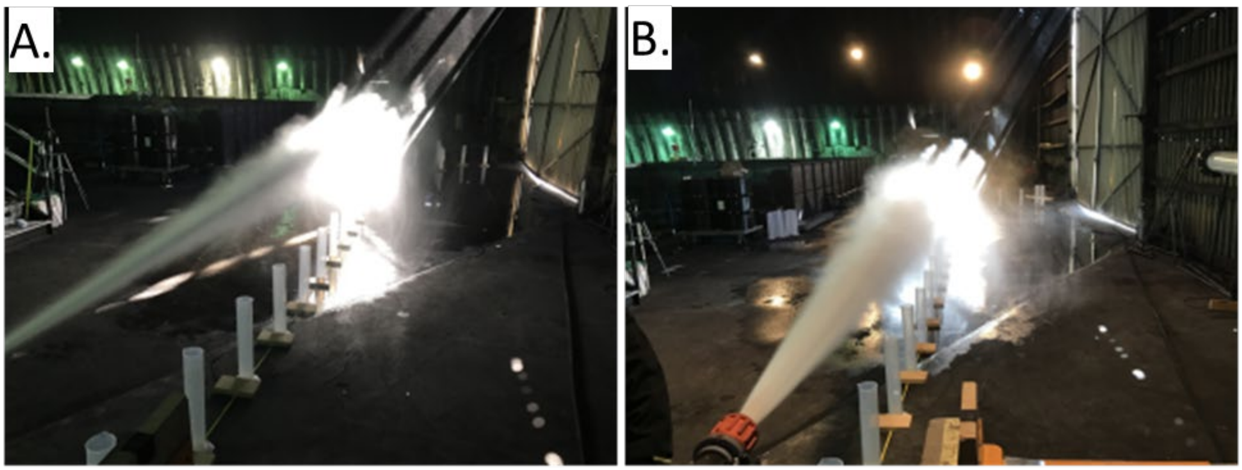


Figure 8. Straight Stream Discharge Test Image for (a) LP (b) UHP

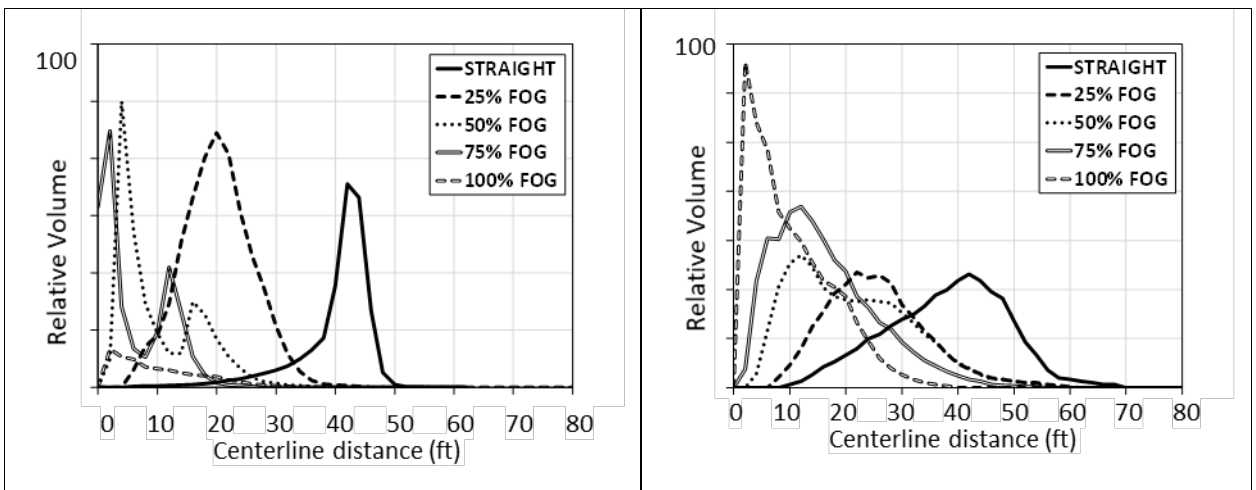
Table 8. LP and UHP Agent Discharge Test Summary

Fire Suppression System	Spray Pattern	Pump Pressure ($lb·in^{-2}$)	Nozzle Pressure ($lb·in^{-2}$)	Flow Rate ($gal·min^{-1}$)
LP[1]	Straight	178	104	30.0
LP	25% Fog	179	104	30.4
LP	50% Fog	178	104	30.4
LP	75% Fog	179	103	30.5
LP	100% Fog	177	103	30.5
UHP[2]	Straight	1270	1191	19.9
UHP	25% Fog	1275	1203	20.0
UHP	50% Fog	1272	1202	20.0
UHP	75% Fog	1272	1203	19.9
UHP	100% Fog	1274	1204	19.9

LP Specification for Platform Design: 30 ±0.5 $gal·min^{-1}$ at 100 to 250 ±15 $lb·in^{-2}$

UHP Specification for Platform Design: 20 ±0.5 $gal·min^{-1}$ at 1100 to 1400 ±25 $lb·in^{-2}$

Figure 10a and 10b illustrate the agent (water) collected in the centerline cylinders as a function of throw distance for the LP and UHP discharge conditions, respectively, listed in Table 8. Both systems delivered peak volume for the straight stream at a throw distance of 44-ft, meeting agent delivery specifications in Table 4. Here, the throw distance is defined as the axial location where the peak amount of agent was discharged. The water spray with UHP is much more dispersed than LP delivery, the volumetric rate (ca. 2:3, UHP:LP (from Table 8)) alone does account for differences in the water volumes captured along the centerline. At the peak distance with straight stream setting, the cylinders held just one-tenth volume of water compared to LP result. The dispersion effect was evident along the entire spray centerline, the trial showed that UHP delivered about one-third volume of the water along the centerline compared to LP. The linear dispersion is also evident by comparing the dimensions and shapes of area under the curves. The contrast is particularly obvious for the straight stream setting with UHP. Additional trials were conducted that arranged the cylinders in order to collect agent in the lateral arc during discharge tests. The approach, however, did not effectively capture spray patterns. The images and real-time observations revealed the obvious spray dispersion, but further fine-tuning to obtain reliable quantitation of the distributed agent was decided to be beyond scope of project.



(a) (b)

Figure 9. Relative Water Delivery as Function of Throw Distance for (a) LP (b) UHP

4.2. Fire Suppression Test Results

Forty two fire trials were done that simultaneously compared UHP and LP fire suppression efficiency. Thirteen trials categorized as GR2 and GS2 FBFMs were performed at the Melrose Air Force Range on Cannon AFB, NM. Twenty nine trials categorized as GR4 FBFM were performed in the Dragontown District of Beale AFB, CA. UHP and LP raw fire-fighting data from all 42 trials are tabulated in Table 9 and Appendix B (Tables B1 and B2). The data sets include flow and pressure values captured at UHP UTV and LP UTV platform instruments, first hand observations recorded on data sheets, and review of video recordings. The trials within

GR2 and GR4 (40 total) were collectively analyzed due to common nature of fuel despite being done at the different sites. A single trial was done under the GS2 FBFM (Trial 3), since it had no comparable replicates, no further analysis of data was done. Systematic errors were found during analysis of written and video records from Trial 22, and those data were removed from pooled analysis. All statistical measures and experimental parameters followed guidelines described in *Design and Analysis of Experiments* [17]. Table 9 summarizes the weather conditions while fire suppression tests were performed.

Table 9. Fire Suppression Test Site and Weather Summaries

Test Day	Trial Range	Test Area	FBFM	Temp (°F)	Relative Humidity (%)	Wind Speed ($mi \cdot hr^{-1}$)	Wind Gust ($mi \cdot hr^{-1}$)	Condition
5/15/2017	1 – 2	Cannon-1	GR2	83	38	13	10	Fair
5/15/2017	3*	Cannon-2	GS-2	89	17	17	22	Fair
5/17/2017	4 – 7	Cannon-3	GR2	76	12	23	36	Fair / Windy
5/18/2017	8 – 13	Cannon-3	GR2	74	21	19	27	Fair
10/4/2017	14 – 17	Beale-1	GR4	76	22	3.0	0	Fair
10/5/2017	18 – 26*	Beale-1	GR4	77	24	3.8	0	Fair
10/6/2017	27 – 34	Beale-1	GR4	82	19	2.9	0	Fair
10/7/2017	35 – 42	Beale-1	GR4	84	21	2.6	0	Fair

*Trial 3 and 22 excluded from analysis

Figures 11 and 12 illustrate agent suppression volumetric efficiency and suppression time efficiency (rates), respectively for all UHP and LP tests. Agent suppression efficiency is defined as the amount of agent (in gallons) needed to extinguish 1000 ft of fire edge. Suppression time efficiency is defined as the time (in seconds) needed to extinguish 1000 ft of fire edge. Accordingly, lower values translate to a more efficient test. The plot revealed that the UHP platform required less agent than conventional LP delivery to knockdown the grass-fueled wildland fires (Fig. 11). The time required for LP suppression was lower compared to UHP tests (Fig. 12), undoubtedly influenced from the volumetric rate for LP being ca. 1.5× the UHP platform (Table 3).

Figures 13 and 14 illustrate the relationship between relative efficiencies and the FBFM fueling the individual tests (Table 1 lists general characteristics of FBFM categories). Figure 16 plot the quantitative data for agent and suppression time versus measured suppression length. Not surprisingly, the trend shows the fire edge suppression length is proportional to the volume of water and duration of water application. The relationship, however, is scattered, as there are numerous factors that will contribute to fire suppression in an individual open environment test. The data analysis clearly showed that the agent suppression efficiency was significantly lower for GR4 than GR2 fires for both the UHP and LP platforms. Again, the result expected as fuel source ca. 2-fold greater for the GR4 FBFM so the fire intensity will be greater.

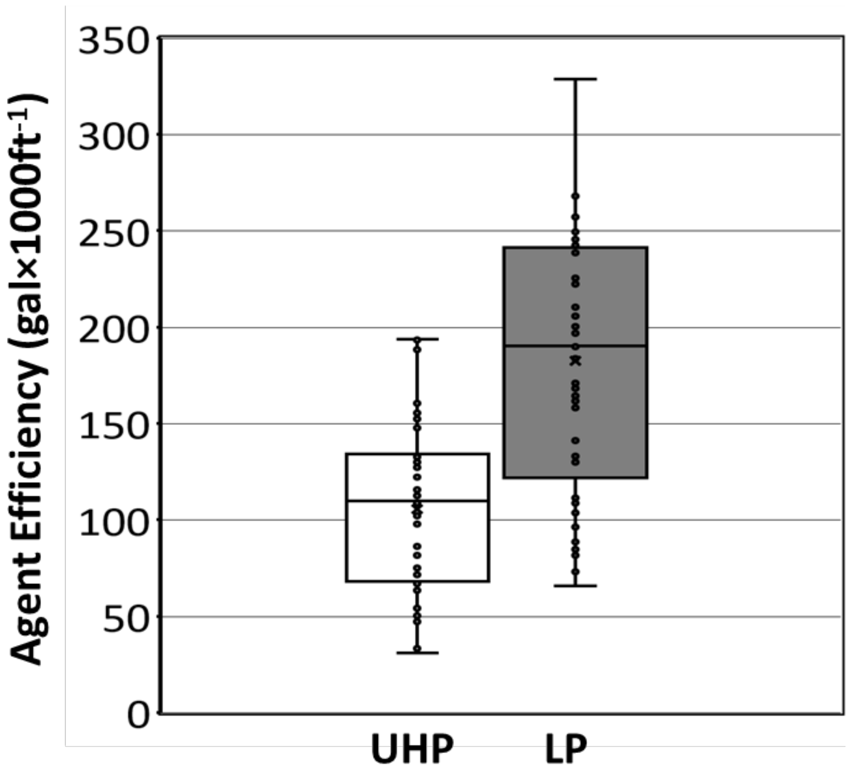


Figure 10. Comparison of Fire Suppression Efficiency for UHP and LP as Function of Agent Volume Required for a Standardized Length of Fire Edge

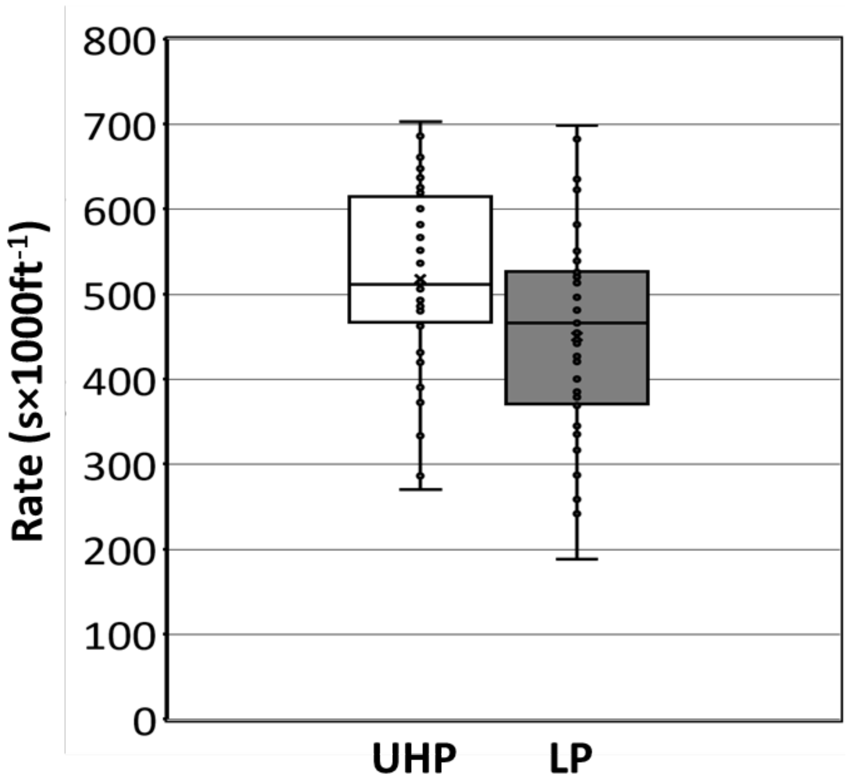


Figure 11. Comparison of Fire Suppression Efficiency for UHP and LP as Function of Time Required for Suppressing a Standardized Length of Fire Edge

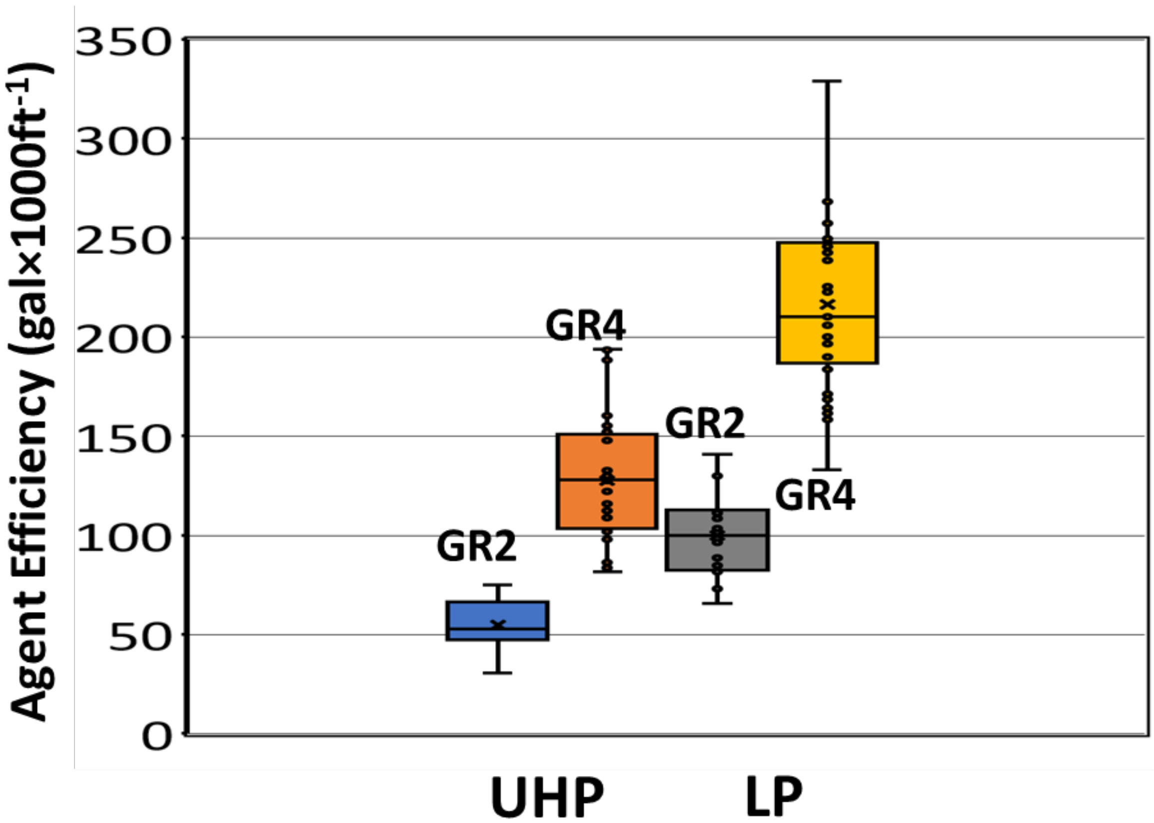


Figure 12. Comparison of UHP and LP as Function of Agent Volume Required to Suppress Standardized Length of Fire Edge in Various FBFM

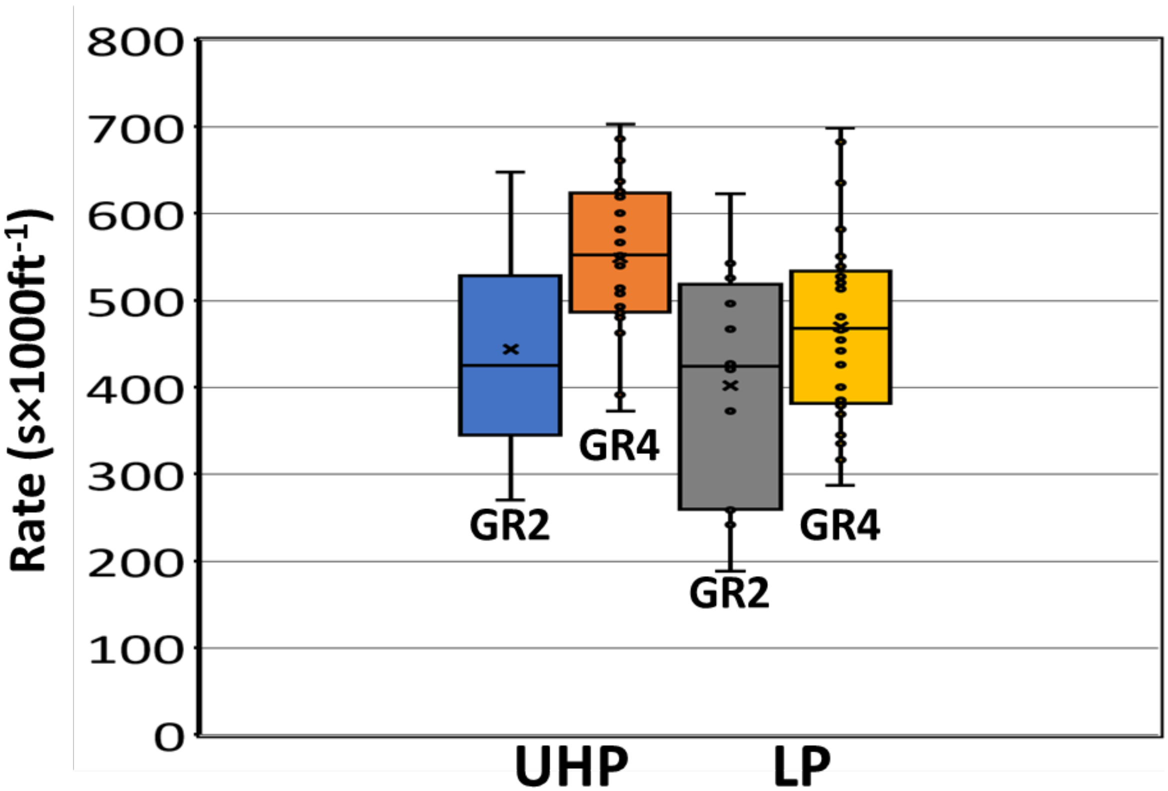


Figure 13. Comparison of UHP and LP as Function of Agent Volume Required to Suppress Standardized Length of Fire Edge in Various FBFM

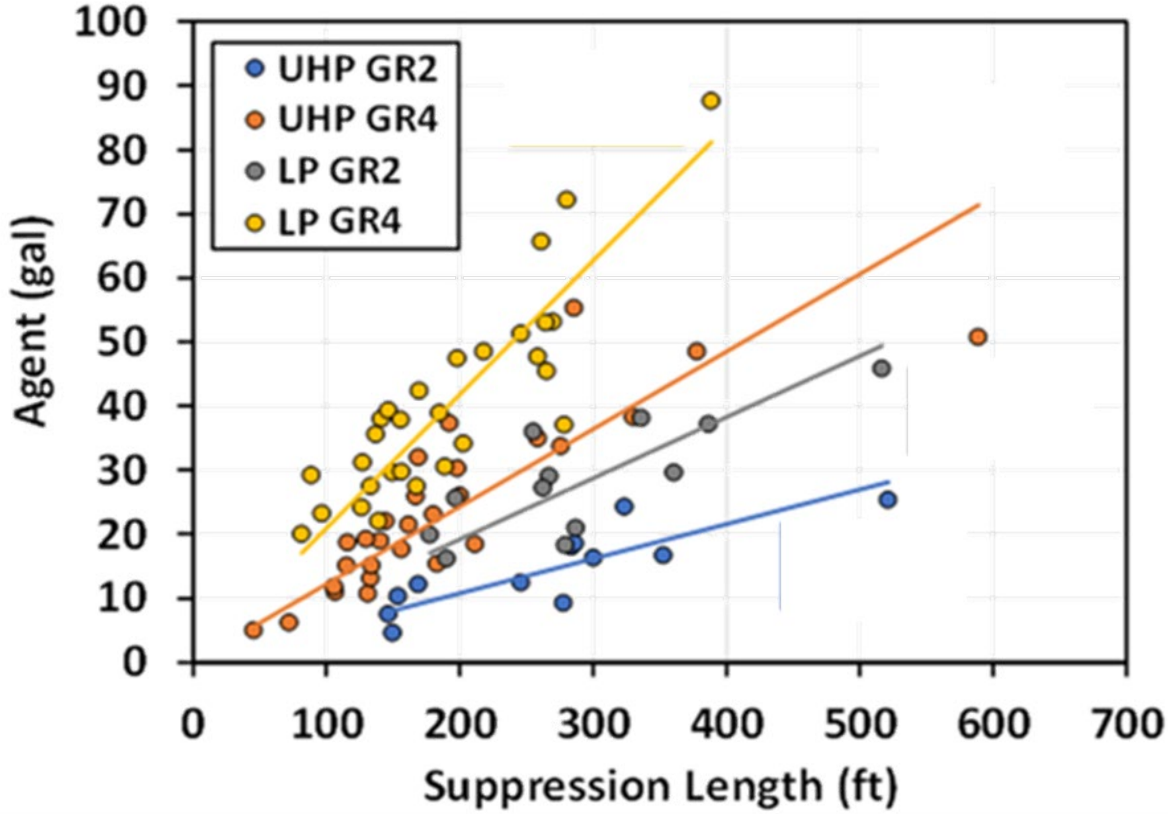


Figure 14. Plots Displaying Volume of Agent Dispensed and the Length of the Fire Edge Suppressed for UHP and LP in Each of the Individual Tests. The Trend Lines are Simple Interpolation Through the Data

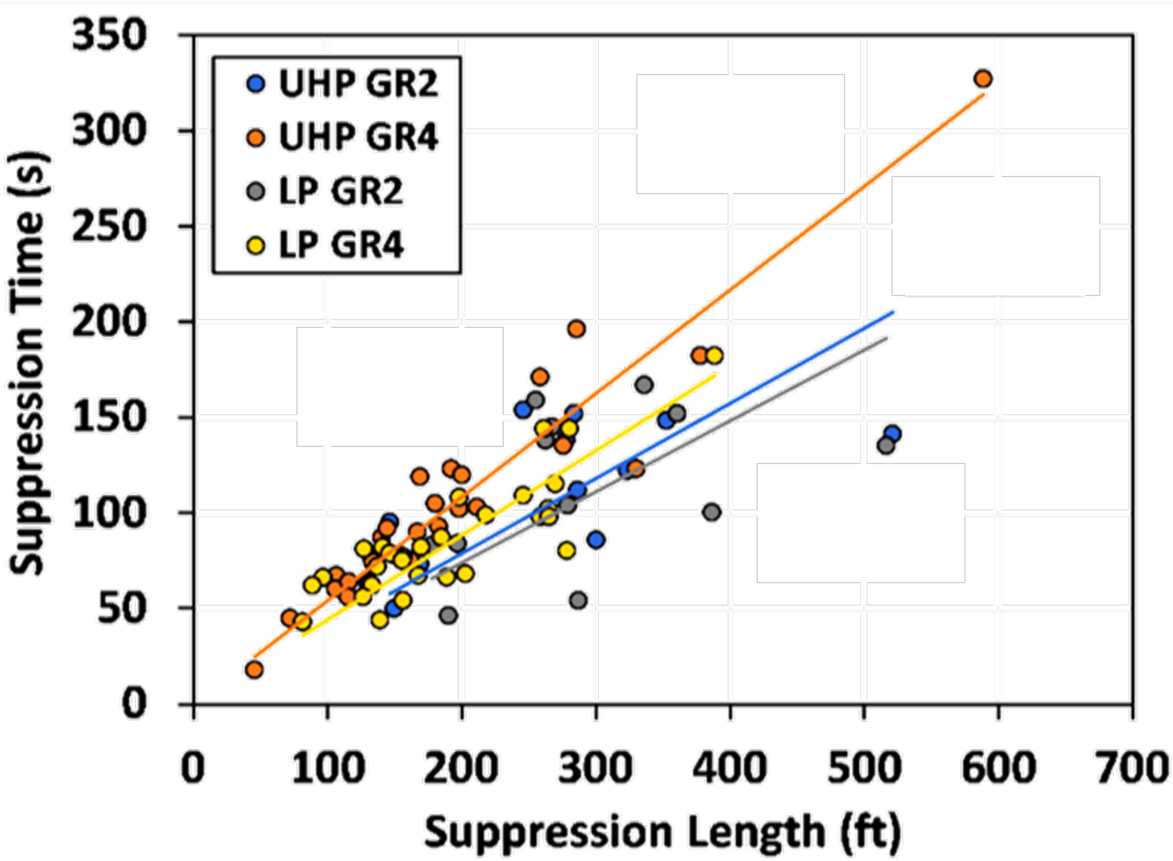


Figure 15. Plots Displaying Time of Agent Delivery and the Length of the Fire Edge Suppressed for UHP and LP in Each of the Individual Tests. The Trend Lines are Simple Interpolation Through the Data

Table 10 summarizes the data presented in Figure 11 through Figure 16. The consolidated data suggest that the UHP attack techniques had better volumetric and then slightly lower temporal efficiencies. The volumetric efficiency differences were shown as statistically significant by applying F and T test regimen. The mean suppression time (temporal efficiencies) of UHP and LP applications differed but were within the standard deviation of the trial measurements. The basic operation parameters (Table 3) show the UHP application rate (20 gal·min^{-1}, vs.30 gal·min^{-1} for LP) is notably lower, thus if the trials reveal the mean suppression times are statistically equal, volume used for UHP is obviously lower and the result internally consistent. The efficiency of UHP in the WUI demonstration is in principal agreement with previous studies for UHP suppression of Class B Fires [4, 5].

All the GR2 and GR4 surface fires examined in the demonstrations were controlled and then ultimately extinguished using either the UHP or LP fire-fighting technique. That conclusion indicates that standard fire-fighting vehicle systems may sufficiently protect sites during the WUI surface threats with low to moderate fire intensity. The better question may be how modified platforms add capability and versatility for protective response. The terrain and access using improved roads will affect each vehicle's capability to position the platform within handline reach of a WUI fire. Vehicles designed for off-road operation (like the Polaris platforms) will be more versatile in the WUI operations compared to those without the capability. Evaluating the increased volumetric efficiency potential for UHP appears to be best focus. The municipal water source is obviously less accessible for WUI responses than response to a flight line or other typical Air Force base fire, accordingly methods that conserve water provide a definite advantage over conventional approach. The advantage is lost, however, if suppression time proportionally increases using UHP. Evaluation of the video records and feedback from firefighter indicated that more local "hot spots" reignited when using the UHP application. Accordingly, more time was spent tamping down the flare-ups compared to the LP method. The anecdotal accounts suggest the cooling capacity of larger water volume is a major factor and resulted in UHP fire fighters advancing at a slower pace than the LP fire fighters. Further design and detailed assessment is required for validation.

It was noted that UHP reached the base of the fire and penetrated through potential humic fuel to mineral soil more efficiently than LP. The difference was due to a relative increase in spray force. The straight stream pattern not surprisingly provided the best approach, as the focused stream provides combination of greatest range and most forceful stream, which assisted in targeting "hot spots" and etching "scratch-line" fuel breaks.

Table 10. UHP and LP Fire Suppression Performance Summary

Parameter	GR2 FBFM		GR4 FBFM	
	UHP	LP	UHP	LP
No. Samples	12	12	28	28
Agent Suppression Efficiency (gal·1000 ft^{-1})				
Mean	55	100	127	217
Standard Deviation	14.1	22.6	32.2	42.9
± Margin of Error %*	14.6	12.8	9.40	7.20
Suppression Time Efficiency (s·1000 ft^{-1})				
Mean	443	402	549	469
Standard Deviation	122	138	82.9	104
± Margin of Error %*	15.6	19.5	5.60	8.10

*95% confidence the true mean value lies within the margin of error

Further analysis of the data compared the agent suppression efficiency and suppression time efficiency among the four UHP fire suppression techniques tested. The techniques are described in section 3.3.2 and the photographs in Figure 8 illustrate the techniques. The deeper analysis was done in effort to examine options that the UHP platforms may be optimized to control WUI fire threats. The box and whisker plots in Figures 17 and 18 provide qualitative comparison of the techniques and the experimental trials. The volumetric efficiencies overlapped with all techniques. The straight stream, collinear attack angle did show a lower median value and two trials with exceptional volumetric efficiencies compared to other trials. The actual agent and suppression time data collected are directly plotted as a function of suppression length. Similar to the fuel class tests, the fire edge suppression length was directly proportional to the volume of water and time elapsed during application. Additional analysis and consolidation of those data are shown in Table 11. The analyses revealed performance efficiencies of the four UHP techniques are comparable. The mean values shown in Table 11 suggest that the collinear attack angle provides a marginal advantage over perpendicular agent application. It is instructive however, to see that plot ranges overlap for all techniques and the statistical uncertainty falls within margin of error, regardless of the technique. Any supposed differences should be considered critically.

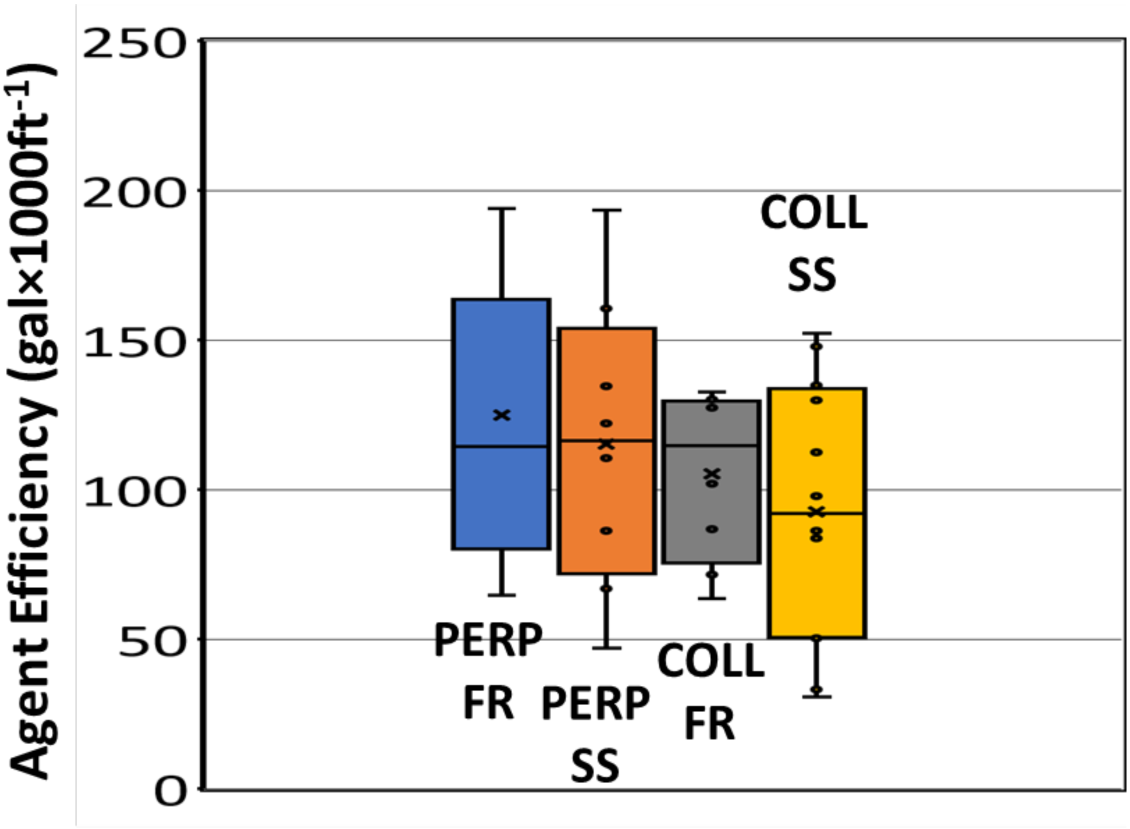


Figure 16. Comparison of Volumetric Efficiencies for UHP Techniques. Volume of Agent (Water) Used to Suppress Standard Length of Fire Edge

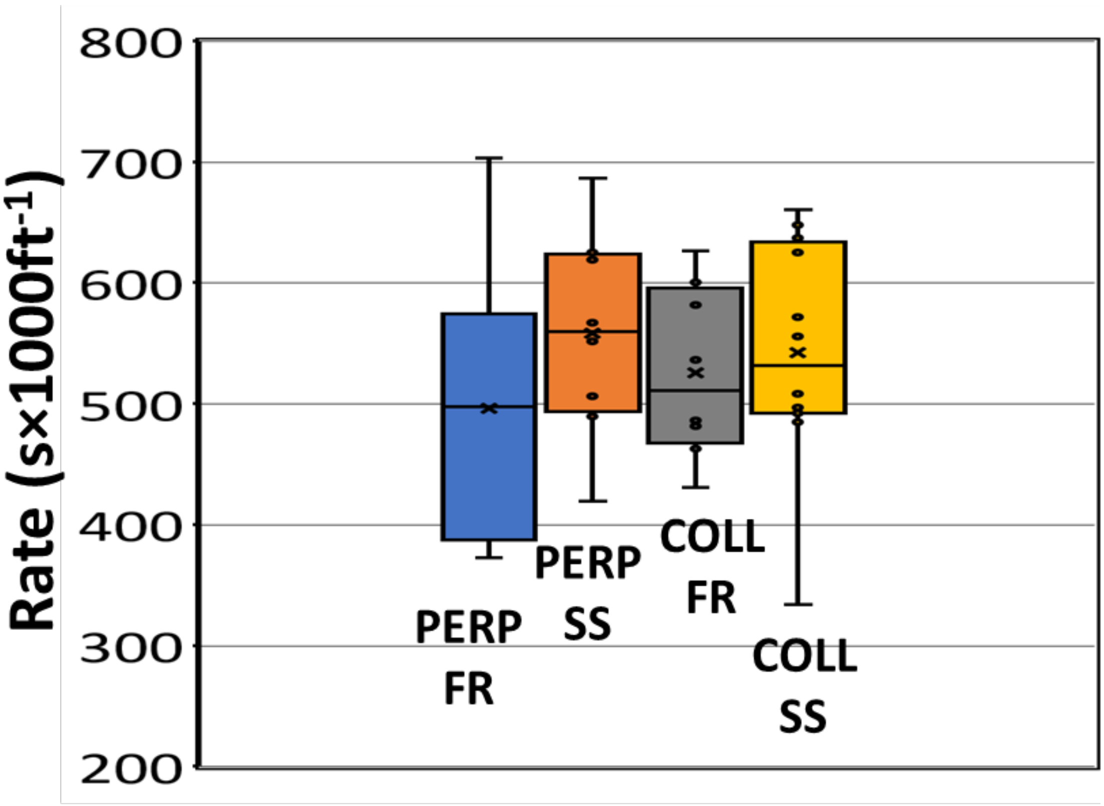


Figure 17. Comparison of Suppression Rates for UHP Techniques. Plots Compare Time Required to Suppress Standardized Length of Fire Edge

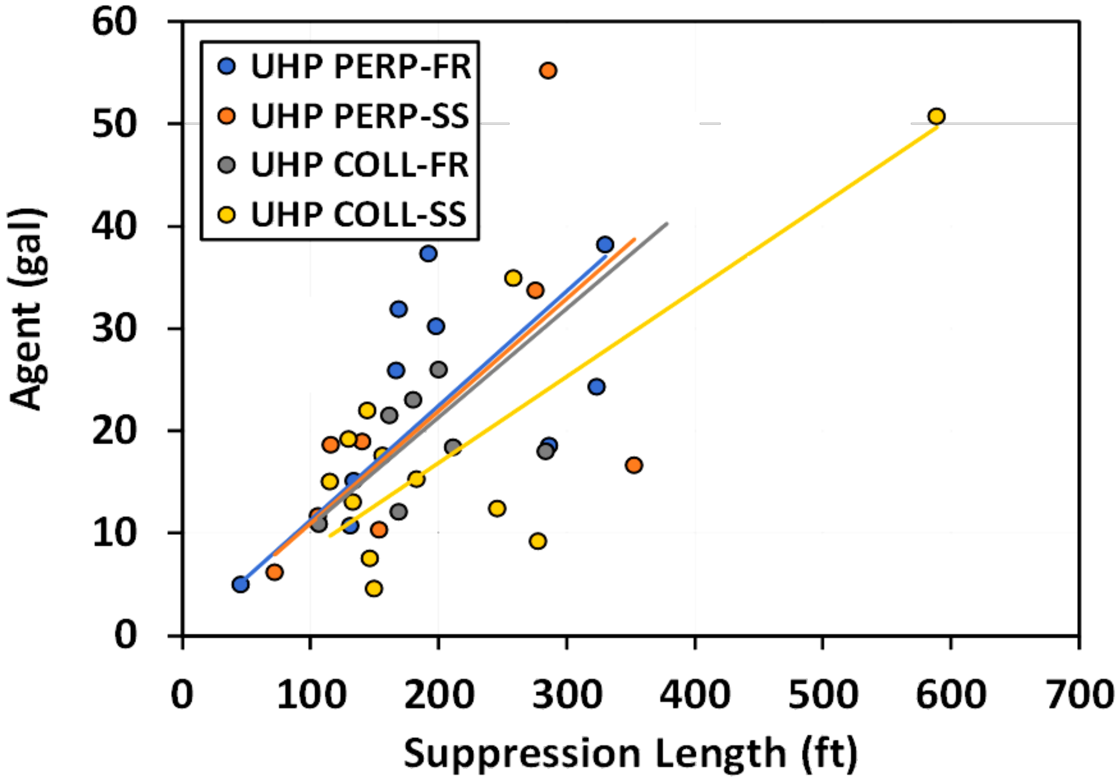


Figure 18. Plots Displaying Volume of Agent Dispensed and the Length of the Fire Edge Suppressed for Different UHP Suppression Techniques in Each of the Individual Tests. The Trend Lines are Simple Interpolation Through the Data Sets

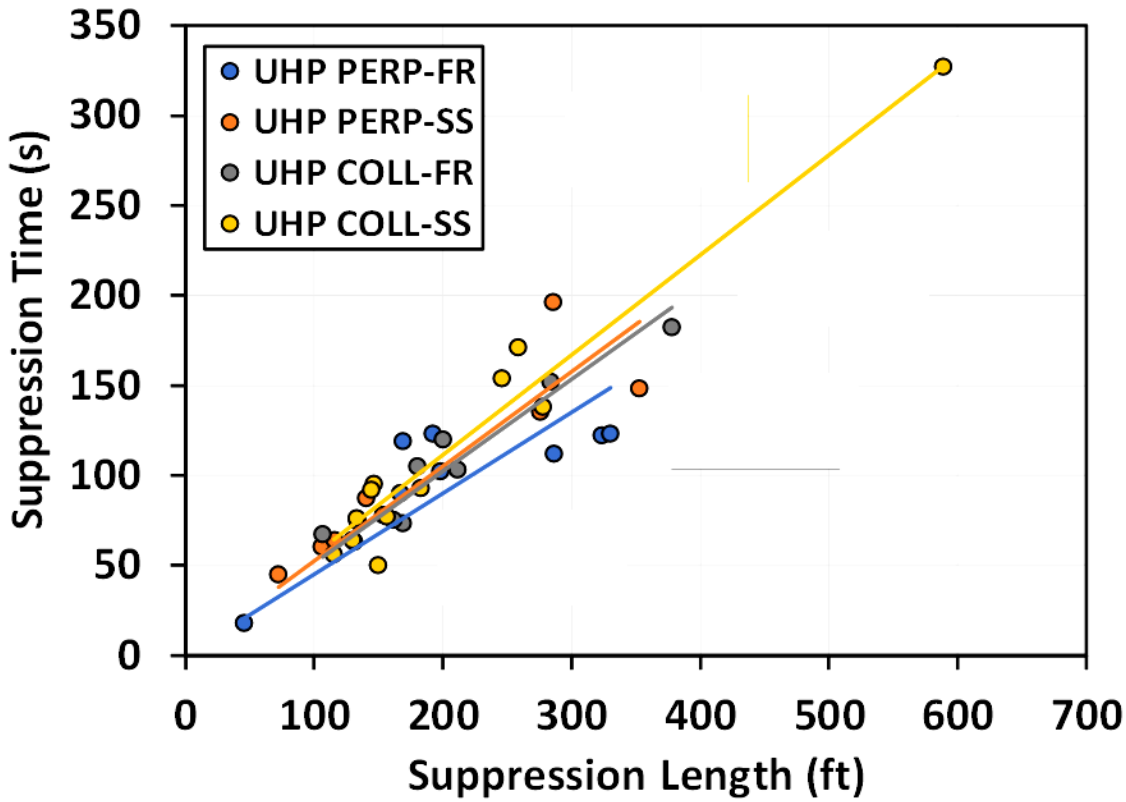


Figure 19. Plots Displaying Total Time of Agent Delivery and the Length of the Fire Edge Suppressed for Different UHP Techniques in Each of the Individual Tests. The Trendlines are Simple Interpolation Through the Data Sets

Table 11. Fire Suppression Performance Summary of UHP Techniques

Parameter	**PERP-FR**	**PERP-SS**	**COLL-FR**	**COLL-SS**
No. Samples	8	12	10	8
Agent Suppression Efficiency (gal·1000 ft^{-1})				
Mean	139	134	118	118
Standard Deviation	40.2	37.9	18.9	27.0
± Margin of Error %	20.1	22.6	12.8	15.9
Suppression Time Efficiency (s·1000 ft^{-1})				
Mean	524	590	540	550
Standard Deviation	113	68.6	70.7	68.6
± Margin of Error %	14.9	9.30	10.5	8.6

*2σ or 95% confidence the true mean value lies within the margin of error

Despite the statistical equivalence and critical view, intuitive aspects of the collinear attack angle and the marginal improvement in mean suppression values are provocative. There are rational interpretations of the approach technique that may help control WUI. The UHP collinear attack position provides a better vantage point for the fire fighter, one may monitor the head fire rate of spread, direction, and intensity–the perpendicular attack position does not afford a comparable perspective. The view provided greater overall situational awareness at the collinear attack angle. The fire fighter was also more able to knock down upstream flare ups from the collinear position. The proactive reach helped reduce overall fire spread. The video records showed it was easier for the fire fighter to focus their effort in one dimension while addressing the fire edge collinearly. For example, the approach allowed easier footwork adjustment because the fire activity was downstream in the fire fighter's direct line of sight. By comparison, when the fire fighter uses a perpendicular attack angle the line of sight was focused on the fire edge immediately in front of them. Any footwork re-adjustment needed to address shifts in the fire direction required lateral moves, which were less fluid than direct advances. The limitation hindered the response to downstream fire behavior. The local hot spots, however, were thoroughly quenched in perpendicular attack mode reducing the chance for re-ignition. The perspective in the perpendicular attack angle allowed the fire fighter to easily monitor the upstream fire edge. The method enhanced local fire control and minimized "mop-up" activity compared to the collinear attack mode.

The WUI environment provides many challenges distinct from the "suburban" housing and quasi-industrial/urban operations environment of an active Air Force Base. Relevant issues were found and addressed during the test program. Various vehicle and fire-fighting system challenges were experience in the WUI environment. Obvious, but critical problems for the vehicle included: punctured tires, overheated engines, and even uncontained grass fires reaching the undercarriage of response vehicles. The uneven off-road terrain also affected fire-fighting system operations. For example, steep slopes caused pumps to lose prime. The priming issue was especially evident on sloped terrain when the agent tank was low. The small engine powering the fire-fighting system also overheated during the trials. These issues were noted and may be lessened by changes to the vehicle platform and some redesign to the firefighting system. The electronics interfaces used in the trial demonstration also showed performance issues in the field. There were occasional systemic malfunctions and signal losses between sensors and the data acquisition system onboard the UTV. The faults and errors could not be reproduced in separate, controlled troubleshooting efforts. It may be helpful to develop more robust electronics platform.

5. CONCLUSIONS

This work was performed to determine whether UHP fire-fighting platforms may be applied to controlling WUI fires. Controlled trials were done using representative environments and fuel sources as test beds. Quantitative tests for fire suppression efficiencies were designed. Simultaneous, side-by-side comparisons of UHP and conventional LP platforms were done, as well as simultaneous, side-by-side comparisons of specific UHP techniques. The latter was done to determine a specific UHP method may provide notable advantage against the WUI fires Eighty four fire suppression experiments were completed using UHP and LP agent delivery. The UHP platform agent discharge specifications were designed to represent the handline capability of typical UHP FES forces such as the P-34 RIV and UHP P-19. The LP platform agent delivery specifications were designed to represent the handline capability of a conventional wildland fire response vehicle.

1. The UHP and LP systems both met the agent discharge performance specifications defined in the designs.

2. The UHP and LP agent application controlled and extinguished all GR2 and GR4 surface fires tested, irrespective of the fire-fighting technique used.

3. The UHP attack techniques had better volumetric suppression efficiency compared to conventional LP fire-fighting techniques.

4. The UHP method mean suppression time efficiency was marginally lower than conventional LP fire-fighting techniques. The difference, however, was not statistically significant.

5. None of the four tested UHP fire-fighting techniques showed any statistical supported performance difference.

6. The increase in relative spray force helped UHP driven agent to reach the base of fires and penetrate through the soil to form scratch line fire breaks.

7. The UHP collinear position provided a better vantage point for the fire fighter to monitor and attack the head of fire edge compared to the UHP perpendicular position.

8. Basic vehicle performance and operation were key factor for tests. Punctured tires, overheated engines, and actual fires spreading to vehicle chassis are threats under the harsh WUI conditions.

9. The skill level and experience of the fire fighters executing the live fire trials did not affect or bias the test. The randomized experimental design and sufficiently large test group ensured that the quantitative fire suppression data were statistically reliable.

6. RECOMMENDATIONS

The following recommendations are made:

1. UHP fire fighters should follow the conventional wildland fire suppression tactics endorsed by the NWCG. Training for UHP WUI fire-fighting should focus on attack techniques and attention to the upstream fire edge to monitor for re-ignition.

2. Although sufficient data was collected to form general conclusions regarding UHP fire-fighting in the WUI surface fire environment, additional testing could potentially decrease the margin of error and increase the overall confidence in findings.

3. Fire-fighting vehicle design consideration to operate in a WUI fire environment is critical. Fire-fighting vehicles that are not designed to serve a primary WUI fire mission should be evaluated to determine their limitations in reaching and engaging WUI fires.

4. Subsequent demonstrations should focus on tests to rigorously compare effect of collinear and perpendicular attack angles for suppression tests.

5. The same sort of side-by-side comparisons of the techniques may be interpreted in an ad hoc nature to gain relationship to one another as opposed to forced "averaging" of trials by different users.

7. REFERENCES

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APPENDIX A – LP AND UHP FIRE-FIGHTING SYSTEM FLOW DIAGRAMS

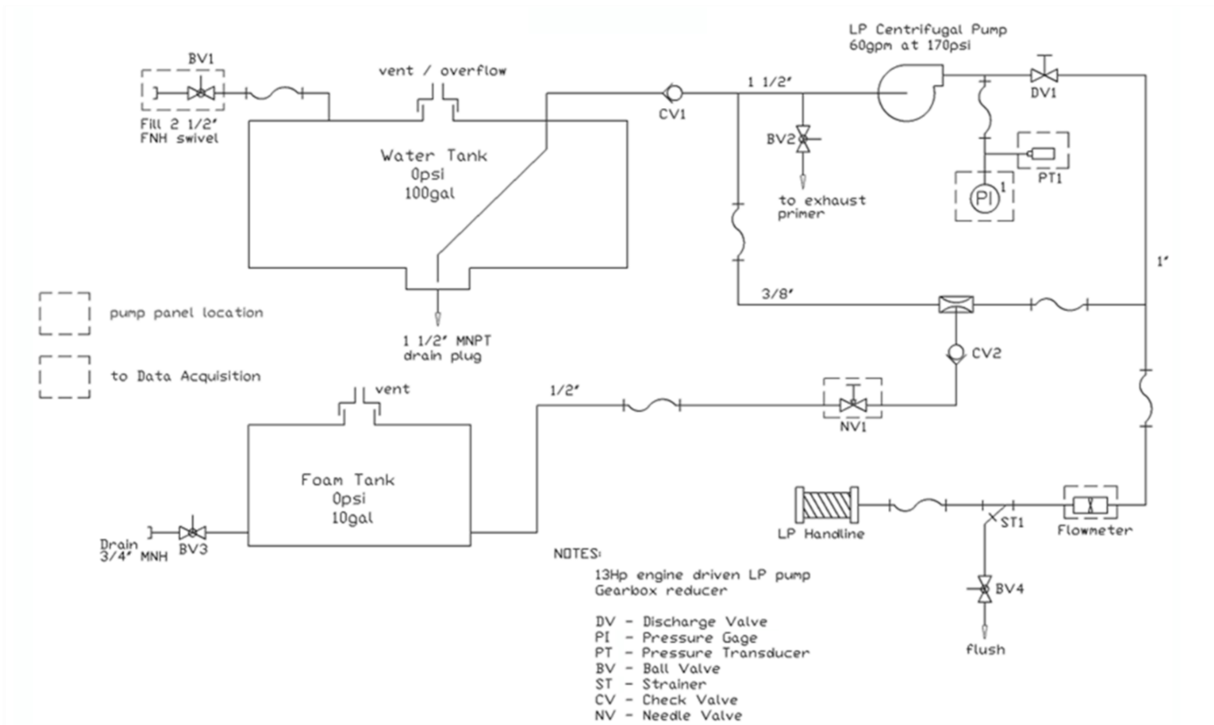

Figure A 3. LP Fire-fighting System Plumbing Schematics

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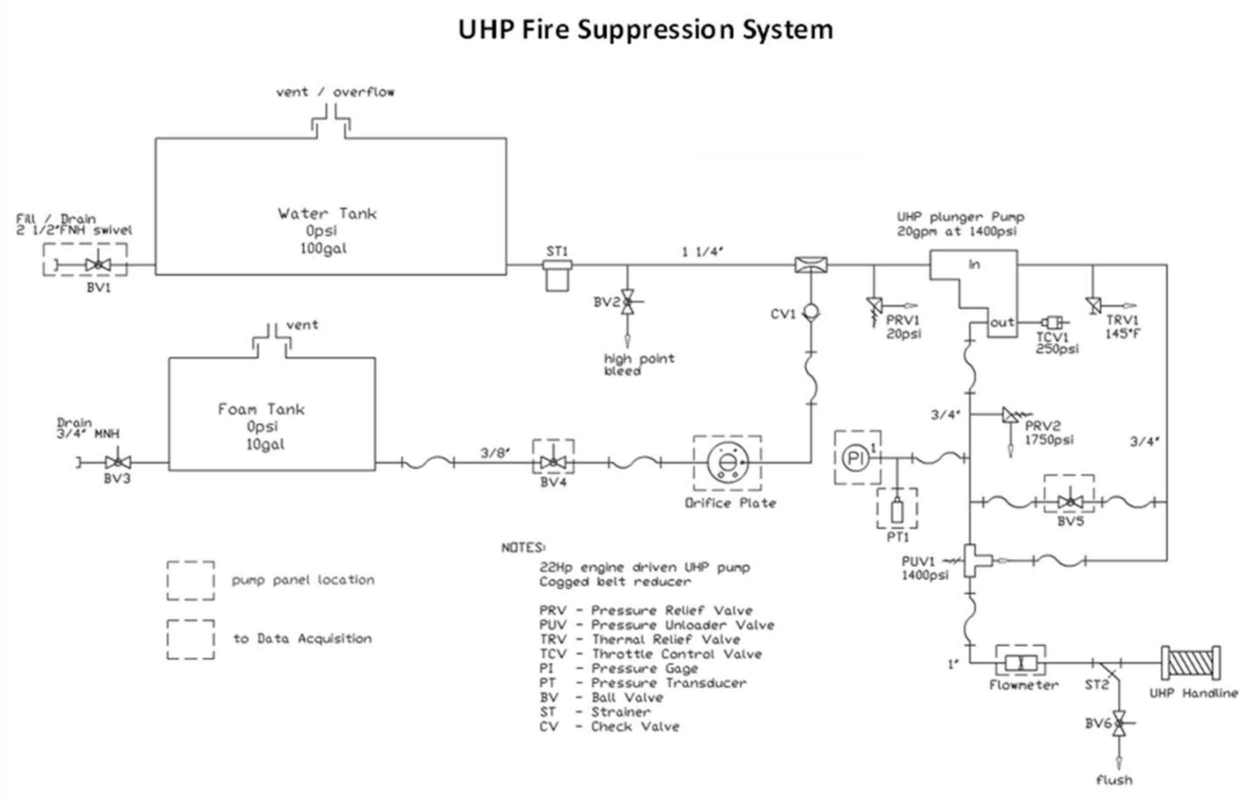

Figure A 4. UHP Fire-Fighting System Plumbing Schematics

APPENDIX B – RAW FIRE-FIGHTING TEST DATA

Table B1. Raw Fire-fighting Test Weather Data

Trial No.	Test Area	FBFM	Date (m/d/yyyy)	Weather									
				Ignition Time (hh:mm:ss)	Temp. (°F)	Dew Pt. (°F)	Relative Humidity (%)	Wind Dir. -	Wind Speed ($mi \cdot hr^{-1}$)	Wind Gust ($mi \cdot hr^{-1}$)	Atm. Press. (in.)	Precip. (in.)	Condition -
1	Cannon-1	GR2	5/15/2017	11:49:29	80	56	43	SW	13	0	25.5	0.0	Partly Cloudy
2	Cannon-1	GR2	5/15/2017	14:12:50	85	53	33	S	13	20	25.5	0.0	Fair
3	Cannon-2	GS2	5/15/2017	15:54:36	89	38	17	S	17	22	25.4	0.0	Fair
4	Cannon-3	GR2	5/17/2017	13:06:15	74	20	13	W	23	36	25.4	0.0	Fair / Windy
5	Cannon-3	GR2	5/17/2017	13:49:26	76	19	12	WSW	25	38	25.4	0.0	Fair / Windy
6	Cannon-3	GR2	5/17/2017	14:52:21	77	18	11	WSW	22	33	25.4	0.0	Fair / Windy
7	Cannon-3	GR2	5/17/2017	15:33:10	77	19	12	W	23	35	25.4	0.0	Partly Cloudy / Windy
8	Cannon-3	GR2	5/18/2017	10:44:20	70	31	24	W	16	21	25.5	0.0	Fair
9	Cannon-3	GR2	5/18/2017	11:12:32	72	32	23	W	18	28	25.4	0.0	Fair
10	Cannon-3	GR2	5/18/2017	11:42:14	71	31	22	W	22	26	25.4	0.0	Fair / Windy
11	Cannon-3	GR2	5/18/2017	12:58:23	74	31	20	WSW	15	28	25.4	0.0	Fair
12	Cannon-3	GR2	5/18/2017	13:47:27	77	30	18	SW	20	31	25.4	0.0	Fair
13	Cannon-3	GR2	5/18/2017	14:19:04	77	30	18	W	20	28	25.4	0.0	Fair
14	Beale-1	GR4	10/4/2017	12:25:00	72	35	25	NW	3	0	30.0	0.0	Fair
15	Beale-1	GR4	10/4/2017	14:08:07	76	35	23	CALM	0	0	29.9	0.0	Fair
16	Beale-1	GR4	10/4/2017	15:15:21	78	34	20	WNW	6	0	29.9	0.0	Fair
17	Beale-1	GR4	10/4/2017	15:42:21	78	34	20	W	3	0	29.9	0.0	Fair
18	Beale-1	GR4	10/5/2017	12:09:01	72	36	26	CALM	0	0	29.9	0.0	Fair
19	Beale-1	GR4	10/5/2017	12:52:29	76	39	27	CALM	0	0	29.9	0.0	Fair
20	Beale-1	GR4	10/5/2017	13:17:03	76	39	27	CALM	0	0	29.9	0.0	Fair
21	Beale-1	GR4	10/5/2017	13:39:40	77	37	24	W	3	0	29.9	0.0	Fair
22	Beale-1	GR4	10/5/2017	14:06:44	77	37	24	W	3	0	29.8	0.0	Fair
23	Beale-1	GR4	10/5/2017	14:34:31	79	37	23	W	6	0	29.8	0.0	Fair
24	Beale-1	GR4	10/5/2017	15:04:13	79	37	23	W	6	0	29.8	0.0	Fair
25	Beale-1	GR4	10/5/2017	15:33:22	80	37	21	WNW	8	0	29.8	0.0	Fair
26	Beale-1	GR4	10/5/2017	15:55:53	80	37	21	WNW	8	0	29.8	0.0	Fair
27	Beale-1	GR4	10/6/2017	12:31:36	76	38	25	SSW	6	0	29.9	0.0	Fair
28	Beale-1	GR4	10/6/2017	12:59:43	80	37	21	SW	5	0	29.9	0.0	Fair
29	Beale-1	GR4	10/6/2017	13:22:35	82	33	17	SW	3	0	29.9	0.0	Fair
30	Beale-1	GR4	10/6/2017	13:49:24	82	33	17	SW	3	0	29.9	0.0	Fair
31	Beale-1	GR4	10/6/2017	14:28:47	84	35	17	W	3	0	29.8	0.0	Fair
32	Beale-1	GR4	10/6/2017	15:04:44	84	35	17	W	3	0	29.8	0.0	Fair
33	Beale-1	GR4	10/6/2017	15:27:14	85	36	18	CALM	0	0	29.8	0.0	Fair
34	Beale-1	GR4	10/6/2017	15:49:30	85	36	18	CALM	0	0	29.8	0.0	Fair
35	Beale-1	GR4	10/7/2017	12:28:50	78	44	29	NW	7	0	29.8	0.0	Fair
36	Beale-1	GR4	10/7/2017	12:49:49	82	40	23	CALM	0	0	29.7	0.0	Fair
37	Beale-1	GR4	10/7/2017	13:12:02	82	40	23	CALM	0	0	29.7	0.0	Fair
38	Beale-1	GR4	10/7/2017	13:42:48	85	41	21	W	5	0	29.7	0.0	Fair
39	Beale-1	GR4	10/7/2017	14:21:49	86	39	19	SW	3	0	29.7	0.0	Fair
40	Beale-1	GR4	10/7/2017	14:39:40	86	39	19	SW	3	0	29.7	0.0	Fair
41	Beale-1	GR4	10/7/2017	15:03:49	86	39	19	SW	3	0	29.7	0.0	Fair
42	Beale-1	GR4	10/7/2017	15:33:43	87	38	18	CALM	0	0	29.7	0.0	Fair

Table B2. UHP and LP Raw Fire-Fighting Test Performance Data

				UHP						LP				
Trial No.	Test Area	FBFM	Date (m/d/yyyy)	Supp. Method -	Supp. Time (s)	Water Used (gal)	Supp. Length (ft)	Agent Supp Eff. (gal·1000 ft^{-1})	Supp. Time Eff. (s·1000 ft^{-1})	Supp. Time (s)	Water Used (gal)	Supp. Length (ft)	Agent Supp Eff. (gal·1000 ft^{-1})	Supp. Time Eff. (s·1000 ft^{-1})
1	Cannon-1	GR2	5/15/2017	-	86	16.3	301	54	286	100	37.2	387	96	259
2	Cannon-1	GR2	5/15/2017	-	141	25.3	521	49	270	135	45.8	517	89	261
3	Cannon-2	GS2	5/15/2017	-	229	61.4	428	144	535	206	88.3	482	183	427
4	Cannon-3	GR2	5/17/2017	COLL-FR	152	18.0	284	63	536	104	18.3	279	66	372
5	Cannon-3	GR2	5/17/2017	COLL-SS	95	7.5	147	51	648	145	29.0	267	109	543
6	Cannon-3	GR2	5/17/2017	PERP-FR	122	24.3	324	75	377	152	29.5	361	82	421
7	Cannon-3	GR2	5/17/2017	COLL-SS	154	12.4	246	50	625	159	36.0	255	141	623
8	Cannon-3	GR2	5/18/2017	PERP-SS	78	10.3	154	67	506	83	19.8	178	111	467
9	Cannon-3	GR2	5/18/2017	COLL-SS	138	9.2	278	33	497	138	27.2	263	104	525
10	Cannon-3	GR2	5/18/2017	PERP-FR	112	18.5	287	65	391	54	20.9	287	73	188
11	Cannon-3	GR2	5/18/2017	PERP-SS	148	16.6	353	47	419	167	38.1	336	113	497
12	Cannon-3	GR2	5/18/2017	COLL-FR	73	12.1	169	71	431	46	16.1	190	85	242
13	Cannon-3	GR2	5/18/2017	COLL-SS	50	4.6	150	31	334	84	25.6	197	130	427
14	Beale-1	GR4	10/4/2017	PERP-FR	123	38.2	330	116	373	68	34.1	203	168	336
15	Beale-1	GR4	10/4/2017	COLL-SS	327	50.7	589	86	555	182	87.6	389	225	468
16	Beale-1	GR4	10/4/2017	PERP-SS	87	18.9	141	135	619	67	27.5	168	164	400
17	Beale-1	GR4	10/4/2017	COLL-FR	67	10.9	107	102	626	62	27.4	133	206	466
18	Beale-1	GR4	10/5/2017	COLL-FR	105	23.0	181	127	581	78	29.6	150	197	520
19	Beale-1	GR4	10/5/2017	PERP-SS	60	11.7	106	111	567	66	23.2	97	240	683
20	Beale-1	GR4	10/5/2017	COLL-SS	92	22.0	145	152	637	82	37.9	141	269	582
21	Beale-1	GR4	10/5/2017	PERP-FR	18	5.0	46	109	391	81	31.2	128	245	635
22	Beale-1	GR4	10/5/2017	PERP-SS	82	16.5	91	181	899	43	20.0	82	245	528
23	Beale-1	GR4	10/5/2017	COLL-FR	103	18.4	212	87	486	108	47.4	199	239	544
24	Beale-1	GR4	10/5/2017	COLL-FR	75	21.5	162	133	463	54	29.7	156	190	345
25	Beale-1	GR4	10/5/2017	PERP-SS	45	6.2	72	86	625	62	29.2	89	329	698
26	Beale-1	GR4	10/5/2017	PERP-SS	135	33.7	276	122	489	144	65.6	261	251	551
27	Beale-1	GR4	10/6/2017	COLL-SS	64	19.2	130	148	492	66	30.5	189	161	349
28	Beale-1	GR4	10/6/2017	PERP-FR	63	10.7	131	82	481	56	24.1	127	190	442
29	Beale-1	GR4	10/6/2017	PERP-FR	123	37.3	192	194	639	80	37.0	279	133	287
30	Beale-1	GR4	10/6/2017	COLL-SS	171	34.9	259	135	661	144	72.2	281	257	513
31	Beale-1	GR4	10/6/2017	COLL-FR	182	48.4	378	128	482	98	47.6	259	184	378
32	Beale-1	GR4	10/6/2017	PERP-SS	64	18.6	116	160	552	72	35.5	137	259	524
33	Beale-1	GR4	10/6/2017	COLL-SS	77	17.6	156	113	492	99	48.5	218	222	454
34	Beale-1	GR4	10/6/2017	PERP-FR	102	30.2	199	152	514	109	51.2	246	208	443
35	Beale-1	GR4	10/7/2017	PERP-FR	90	25.9	167	155	539	82	42.4	170	249	482
36	Beale-1	GR4	10/7/2017	COLL-SS	76	13.0	133	98	571	79	39.3	147	268	539
37	Beale-1	GR4	10/7/2017	PERP-SS	196	55.2	286	193	686	115	53.1	270	197	426
38	Beale-1	GR4	10/7/2017	COLL-FR	120	26.0	200	130	600	102	53.0	265	200	385
39	Beale-1	GR4	10/7/2017	COLL-SS	56	15.0	116	130	485	44	22.0	139	158	317
40	Beale-1	GR4	10/7/2017	PERP-FR	74	15.1	134	113	552	75	37.8	156	242	481
41	Beale-1	GR4	10/7/2017	PERP-FR	119	31.9	169	188	703	98	45.4	266	171	369
42	Beale-1	GR4	10/7/2017	COLL-SS	93	15.3	183	84	508	87	38.9	185	210	470

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

%	percent
°F	degrees Fahrenheit
ac	acres
AFB	air force base
AFCEC	Air Force Civil Engineer Center
ARFF	aircraft rescue fire-fighting
BTU	British thermal unit(s)
COLL-FR	Collinear attack mode; full range spray pattern
COLL-SS	Collinear attack mode; straight stream only spray pattern
DOD	Department of Defense
FBFM	fire behavior fuel model
FES	Fire Emergency Services
ft	foot; feet
gal	gallons
GPS	global positioning system
GR	grass
GS	grass and shrub
in	inch(es)
lb	pound(s)
LP	low pressure
m	meter(s)
min	minute(s)
mL	milliliter(s)
NFPA	National Fire Protection Association
NWCG	National Wildfire Coordinating Group
PERP-FR	Perpendicular attack mode; full range spray pattern
PERP-SS	Perpendicular attack mode; straight stream only spray pattern
RIV	rapid intervention vehicle
s	second(s)
UHP	ultra-high pressure
USAF	United States Air Force
UTV	utility task vehicle
WUI	wildland-urban interface