WILDFIRE SAFETY SYSTEMS

TEST PROTOCOL

FORT Live Burn-over Exposure Testing

Overview

This test series has been conceived to evaluate the functional aspects of the "Fort" (Fire-resistant Onsite Refuge Technology) wildfire shelter with respect to several wood/cellulosic based "burn-over" scenarios. To represent the conditions of a burn-over, the refuge will be in the center of a man-made "wildfire" made of burning wood pallets. This protocol outlines the parameters of two successive tests with increasing proximity to the fire. Of primary investigative interest are the following:

(1) Evaluate the effects of the fire on the refuge in total. The refuge is constructed on a steel base, has walls of concrete with an internal insulation layer of polystyrene, batting, and metal cladding. When exposed to the heat load of a burn-over, the chief investigative interests are:
   a. The general performance of cladding and structural elements,
   b. exclusion of smoke from the inside,
   c. behavior of materials used to isolate internal atmosphere
   d. use of observation ports and other.

(2) Observe and record the temperature response through the walls, outer fire door, and supporting steel framework as heat flows inward to the interstitial space between the outer door and the second inner door. Specifically:
   a. Function of door elements (open/close),
   b. function/useability of integral man door,
   c. overall heat signature of the door shell side facing the inside of the chamber,
   d. heat signature of operating handles and integral escape door,
   e. temperature of the interstitial air gap between the two doors,
   f. temperature of the supporting frame,

(3) Observe and record the cellulosic burn-over fire exposure imparted to the surfaces of the Fort, measured via thermocouple probes placed outside. Specifically:
   a. probes placed at each of the three observation ports (3 sides)
   b. probe place through the outer face of fire door (4^{th} side)
   c. probe placed in the interstitial space under the roof
   d. probe placed protruding through (above) the roof)

(4) Observe and record the conditions of the habitable space within and the function of the fresh air delivery system inside the fort which provides positive pressure to preclude smoke entry and deliver breathable air to the occupants.
    a. wall temperatures (inside)
    b. bulk occupied space ambient temperature (high and low)
    c. bulk occupied space oxygen, CO, and CO_2 levels
    d. internal positive pressure developed by the fresh air delivery system
    e. relative humidity
    f. fresh air delivery pressures

(5) The above will be evaluated for two separate burn-over scenarios of increasing intensity, more discussion to follow:
    a. an encircling cellulosic fire, distanced 30 feet back with personnel inside
    b. an encircling cellulosic fire, distanced 5 feet back with personnel inside.

Determination of Heat Load and Test Basis

To establish brush fire burn-over exposure metrics, data has been used from an N.C. State research paper documenting the actual heat fluxes measured for various types of wildfires. The research measured heat fluxes present during multiple burn-over scenarios as might be expected to occur. These heat fluxes and exposure time varied significantly depending on the type of vegetation and fuel load, so to encompass the entirety of the spectrum of results, the highest heat flux and longest duration can be taken as a top-down worst-case scenario for evaluation.

Table 2. Field test location and burn conditions.

Location	Latitude, longitude	Fire and fuel type	Air temp (°C)	Relative humidity (%)	Wind speed (km h^{-1})	Heat flux: total; radiant (kW m^{-2})
Test 1: Mt Palomar, CA	33°21′47.37″N, 116°50′10.71″W	Brush; chaparral	23	14	16	94; 62
Test 2: Mt Palomar, CA	33°21′39.78″N, 116°49′52.15″W	Brush; chaparral	24	26	5–8	80; 33
Test 3: Mt Palomar, CA	33°21′34.85″N, 116°49′44.80″W	Brush; chaparral	25	23	3–5	137; 57
Test 4: Madison, SD	44° 9′1.76″N, 97°26′49.12″W	Surface; grass	27	43	6–10	147; 58
Test 5: Madison, SD	43°56′17.08″N, 97° 0′51.24″W	Surface; grass	20	38	8–13	76; 21
Test 6: Carvers Creek, NC	35°13′′1.30″N, 78°58′35.42″W	Surface; LL pine–wire grass	29	48	3–6	97; 80
Test 7: Ft Providence, NWT	61°34′50.18″N, 117°10′15.98″W	Crown; boreal forest	30	27	3–7	209; 138
Test 8: Asheboro, NC	35°40′9.00″N, 79°47′2.65″W	Surface; HDWD	32	33	5–6	66; 28

LL, Longleaf pine–wire grass (*Pinus palustris–Aristida stricta*); HDWD, hardwood slash. Boreal forest consisted of jack pine–black spruce (*Pinus banksiana–Picea mariana*).

Figure 1.

WILDFIRE SAFETY SYSTEMS

Table 3. Total measured time above 260 and 660°C of external temperature observed at 61 cm (2 feet) and peak heat flux measurements, characterising external temperature profiles for each fire shelter as the fire burned through test sites.

Name	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Peak radiative flux (kW m^{-2})	62	33	57	58	21	80	138	28
Peak total flux (kW m^{-2})	94	80	137	147	76	97	209	66
M2002 time above 660°C (s)	15	2	4	12	0	0	0	1
M2002 time above 260°C (s)	143	68	221	82	9	3	46	487
Option 4 time above 660°C (s)	63	0	25	20	0	0	–	–
Option 4 time above 260°C (s)	198	6	319	81	8	4	–	–
Option 1 time above 660°C (s)	51	0	3	19	0	0	–	–
Option 1 time above 260°C (s)	189	4	95	83	6	10	–	–
Option 9 time above 660°C (s)	–	–	–	–	–	–	0	0
Option 9 time above 260°C (s)	–	–	–	–	–	–	0	113
Option 10 time above 660°C (s)	–	–	–	–	–	–	0	1
Option 10 time above 260°C (s)	–	–	–	–	–	–	0	29

Figure 2

This greatest heat flux (from above) is 209 W/m^2 (66,252 Btu/hr/ft^2 and the heat flux from the wildfire was approximately 50% convective heat and 50% radiant heat. However, the following reference from Industrial Fire Protection Engineering documents that the predominant heat transfer from burning wood is the convective mode, but as both fuel sources are woody in composition, they two are assumed to be similar enough in nature to satisfy the goals of the test.

Table A.2. Chemical, convective and radiative combustion efficiencies (data from Chapter 3-4 of *SFPE Handbook*, 1995)

Material	H_c	χ	χ_{conv}	χ_{rad}
Gases				
Ethane	47.5	0.99	0.79	0.20
Propane	46.4	0.95	0.68	0.27
Butane	45.7	0.95	0.68	0.27
Ethylene	47.2	0.91	0.59	0.32
Propylene	45.8	0.89	0.50	0.39
1,3-Butadiene	44.6	0.74	0.34	0.40
Acetylene	48.2	0.76	0.37	0.39
Liquids				
Heptane	44.6	0.93	0.59	0.34
Octane	44.4	0.92	0.61	0.31
Benzene	40.1	0.69	0.28	0.41
Styrene	40.5	0.67	0.27	0.40
Methanol	20.0	0.95	0.81	0.15
Ethanol	26.8	0.97	0.73	0.24
Isopropanol	30.2	0.97	0.73	0.24
Acetone	28.6	0.97	0.73	0.24
Methyl Ethyl Ketone	31.5	0.97	0.67	0.24
Polydimethyl Siloxane	25.1	0.61	0.51	0.10
High MW Hydrocarbons	43.9	0.84	0.56	0.28
			.47	.26 AVG.
Solids				
Red Oak	17.7	0.70	0.44	0.26
Douglas Fir	16.4	0.79	0.49	0.30
Pine	17.9	0.69	0.49	0.21
Polyoxymethyene	15.4	0.94	0.73	0.21
Polymethylmethacrylate	25.2	0.96	0.66	0.30
Polyethylene	43.6	0.88	0.50	0.38
Polypropylene	43.4	0.89	0.52	0.37
Polystyrene	39.2	0.69	0.28	0.41
Silicone	21.7	0.49	0.34	0.15
Polyester	32.5	0.63	0.33	0.30
Epoxy	28.8	0.59	0.30	0.30
Nylon	30.8	0.88	0.53	0.35
Polyethylene-25%-Cl	31.6	0.72	0.32	0.40
Polyethylene-36%-Cl	26.3	0.40	0.24	0.16
Polyethylene-48%-Cl	20.6	0.35	0.19	0.16
Polyvinyl chloride	16.4	0.35	0.19	0.16
Fluoropolymers	5.3	0.32	0.17	0.15
Flexible Polyurethane Foams				
GM 21 (29 kg/m^3)	26.2	0.68	0.33	0.35
GM 23 (FR 29 kg/m^3)	27.2	0.70	0.38	0.32
GM 25 (44 kg/m^3)	24.6	0.69	0.29	0.40
GM 27 (FR 44 kg/m^3)	23.2	0.71	0.33	0.38

(*continued overleaf*)

Figure 3.

With respect to question of the actual temperature of the source flames, the composition of the source flame (wood) was used. Wood begins to burn at 600 C (1100 F) and temperatures were observed in a previous Wildfire Safety Systems pallet burn test at the "Front of outer door" ~1400 C (2500F) for a relatively short period of time (data below).

Thermocouple Measurements:

- Installed 8 Type K thermocouples to record temps every 10 seconds (lit fuel at 7:48am MTN)
  - TC1 appears to malfunction shortly after hitting 2500F a few minutes after start of fire
  - TC2 appears to malfunction 15 minutes after start of fire

Channel	Min	Max	Location
1	-454	2501.6	Front of outer door
2	-106.8	67.7	Inside outer door
3	56.1	79.5	Hardie 6"
4	56.2	83.6	Hardie 2"
5	18.6	70.4	Metal 6"
6	66.3	85.6	Metal 2"
7	47.5	71.8	Metal 6"
8	57.9	79.5	Metal 2"

11

Figure 4

Anecdotally, open-air naturally aspirated wood flames exhibit orange to yellow appearance, which corresponds to pyrography temperature of approximately 1000 C.

Color		Approximate Temperature		
		°F	°C	K
Faint Red		930	500	770
Blood Red		1075	580	855
Dark Cherry		1175	635	910
Medium Cherry		1275	690	965
Cherry		1375	745	1020
Bright Cherry		1450	790	1060
Salmon		1550	845	1115
Dark Orange		1630	890	1160
Orange		1725	940	1215
Lemon		1830	1000	1270
Light Yellow		1975	1080	1355
White		2200	1205	1480

Glowing metal (heated burning tip) guide as pyrography temperature chart

Figure 5

The anticipated heat flux can be estimated using information from the Industrial Fire Protection Engineering publication table from Appendix A. It specifies that the <u>maximum theoretical</u> heat release of wood pallets piled on one another is 940 Btu/sec/ft^^{2} per ft^^{2} of floor area. Considering a unit floor area (1'x1'), this corresponds to 3,384,000 Btu/hr heat release, or 338,400 BTU/hr per ft of vertical height - or 2,707,200 BTU/hr for an 8 ft tall stack. Therefore, if the stack height is taken as 8' (similar to the refuge), and it is taken that only 1/5 of the total heat would flow in the direction of the refuge face since there are in total four cardinal directions and one vertically facing direction, it corresponds to a horizontal projected area heat load in the direction of the refuge of 2,707,200 Btu/8 ft*(1/5) = 67,680 BTU/hr (projected per ft^^{2} horizontally). This theorteical value compares well with the N.C. State reported heat flux of 66,252 Btu/hr/ft^^{2} and is considered a rational comparative value to check the proposed pallet heat load to the N.C. State findings.

APPENDIX A: FLAME RADIATION REVIEW

Table A.4. Theoretical unit heat release rate for commodities burning in the open (compiled by Dr G. Heskestad)

Commodity	Heat Release Rate (Btu/sec per ft^2 of floor area)
Wood Pallets	
Stack 1-1/2 ft High (6-12% Moisture)	125
Stack 5 ft High (6-12% Moisture)	460
Stack 10 ft High (6-12% Moisture)	940
Stack 16 ft High (6-12% Moisture)	1500
Mail Bags, Filled, Stored 0.5 ft High	35
Cartons, Compartmented, Stacked 15 ft High	150
PE Letter Trays, Filled, Stacked 5 ft High on Cart	750
PE Trash Barrels in Cartons, Stacked 15 ft High	175
PE-Fiberglass Shower Stalls in Cartons, Stacked 15 ft High	125
PE Bottles in Compartmented Cartons, Stacked 15 ft High	550
PE Bottles in Cartons, Stacked 15 ft High	175
PU insulation Board, Rigid Foam, Stacked 15 ft High	170
PS Jars in Compartmented Cartons, Stacked 15 ft High	1250
PS Tubs nested in Cartons, Stacked 14 ft High	475
PS Toy Parts in Cartons, Stacked 15 ft High	180
PS Insulation Baord, Rigid Foam, Stacked 14 ft High	290
PVC Bottles in Compartmented Cartons, Stacked 15 ft High	300
PP Tubs in Compartmented Cartons, Stacked 15 ft High	390
PP and PE Film in Rolls, Stacked 14 ft High	550
Methyl Alcohol	65
Gasoline	290
Kerosene	290
Diesel Oil	175

Figure 6

Additionally, if the physical aspects of stacked pallets (as bullet listed below) plus known average heat values are combined with the above maximum theoretical heat release, more insight can be obtained. Generally, for pallets:

- each has an average weight of 40 lbs,
- each has a standard dimension of 48” x 40” (13.33 SF) x 6.5” tall,
- one pound of hardwood has a heat value of approximately 8600 Btu.

It is proposed to use an 8 ft tall stacking of pallets to expose the entire vertical height profile of the refuge to the heat flux. This configuration is then calculated to produce maximal heat as follows:

40 lbs per pallet * (1/13.3 SF per pallet) * (8ft tall stack *12 in/ft)/6.5 in per pallet = 44.3 lbs wood mass (fuel) per SF ground area.

44.3 lbs * 8600 BTU = 380,980 BTU available heat per SF ground area

From the above information which stipulates that there is a 2,707,200 BTU/hr theoretical maximum heat release, the “perfect” theoretical maximum time at full maximal heat flux can be calculated to be: (380,980 BTU) / (2,707,200 BTU/hr) = .14 hr (8.5 minutes) if ideal combustion of the fuel were to occur. However, the combustion is not ideal and the duration of exposure will accordingly be drawn out as the fire grows, matures, and dies until all wood fuel is consumed.

Test Procedure

The prototype refuge will be outfitted as follows and in accordance with the test diagram:

<u>Inside the Refuge:</u>

- 2 people to attend instrumentation and observation
- Fresh air tanks
- Fresh air delivery will occur through a Wildfire Safety Systems diffuser
- CO_2 input to the inside of the refuge by metabolic activity of occupants only.
- Webcam for test observation and Wi-Fi router
- Instrumentation

<u>Outside the Refuge:</u>

- Photography only. No external equipment other than the tips of the thermocouple probes will be exposed or located outside the chamber.

- Communication via Wi-Fi

Testing Procedures

1. Inside the refuge, connect tanks to the fresh air delivery system and verify that each has full pressure.
2. Install sensor tree inside the refuge, affix/install all RTD and thermocouple probes. A/C power will be installed inside of the refuge, and all test recording instrumentation will be within.

Test prep and start:

3. (Inside) Turn on data recorder and confirm all sensors have been successfully connected and are reading normally. Verify Wi-Fi connection to outside.
4. Ensure all test instrumentation is connected to the back-up power supply, and it is powered up.
5. When ready, begin datalogging and camera recording:
    a. CO_2 and CO levels inside the refuge data logged, 30-sec. interval min.
    b. Fresh air delivery pressures data logged, 30-second interval min.
    c. Time, date, temperature, RH data logged, 30-second interval min.
    d. Fresh Air delivery systems pressures data logged, 30-second interval.
6. When ready to start the test, close the doors, turn on all tanks at the tank head to begin the release of fresh air. Double check that all valves are on. If the sound of air is not heard, re-open the doors and stop the test.
7. Coordinate with outside personnel to begin the burn-over.
8. Periodically observe the door and take thermal imaging every few minutes.

Testing Equipment

- Instrument tree (as shown)
- O2, CO, CO2 monitors, 3X
- Transducer: Omegadyne 0-5000 psig, 2X
- RTD probes
- Thermocouple probes, K-Type
- Barometric pressure transducer
- RH transducer
- Datalogger w/ battery backup supply
- FLIR TG297
- Webcam
- PM2.5 and PM10 Particulate Monitor

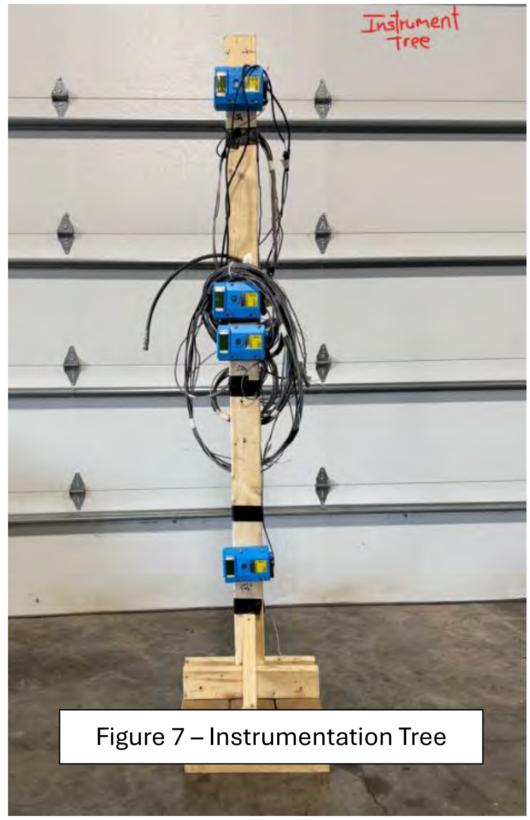

Figure 7 – Instrumentation Tree

Setups and Varying Set-back Distances

Test #1 – 30 Ft set-back with supplemental breathable air and Test #2 – 5 Ft set-back with supplemental breathable air.

To demonstrate the effect of a 30ft and 5ft fuel load set-back, two separate tests will be performed beginning with the most distant. Tests will be conducted in the above order.

Test #1, 30 ft set-back: This set-back value has been selected as a likely product user guideline for refuge positioning on residential properties. There are known regulations within residential codes that require any structure to be 50 ft clear from substantial vegetative litter or combustion source (ref. Woodland Hills, UT CC&R). A closer set-back of 30 ft is prescribed for vegetive clearances along public rights of way and streets. Therefore, this more conservative 30 ft distance has been selected (inside of the greater 50 ft set-back) as a logical practical use case scenario (location) for the refuge.

Test #2, 5 ft set-back: 5 ft set-back has been included as a final margin test to record the structural and thermal response of the refuge interior from a top-down design perspective. It is not conceived to be representative of a defined practical real-world use-case scenario because it violates the intended location/set-back guidelines. The first test of two at this distance will be performed with the fresh air release system ON to accurately represent a refuge that is in use by occupants.

Cellulosic fire heat flux exposure is significantly affected by the distance that separates the heat source and the incident object. As seen in the illustration below, the fraction of radiant energy from the source fire incident on the target object is a geometric function of the size of the emitting object, the distance between the objects, and the size of the incident object. As per the convective and radiant proportions noted earlier, this ratio of heat transfer modes is .47 and .26, respectively. For the 30 ft scenario (Test #1), no fire will be in contact with the shelter, and radiant effects will be the predominate form of energy transfer. Mathematically, the proportion of delivered flux would be modified as .26 / (.47 + .26) *100% = 35% (radiation fraction) then modified again by multiplying by the geometric fraction (again, as illustrated below). However, for the up close 5 ft set-back (Tests #2), both radiant and convective modes contribute to the incident heat load, and it will accordingly be more nearly 100% of the combined radiant convective parts again multiplied by the geometric fraction, which by virtue of the proximity (d) being 5 instead of 30, will be greater as well. Therefore, due to these contributing factors the severity of this burn will be significantly greater.

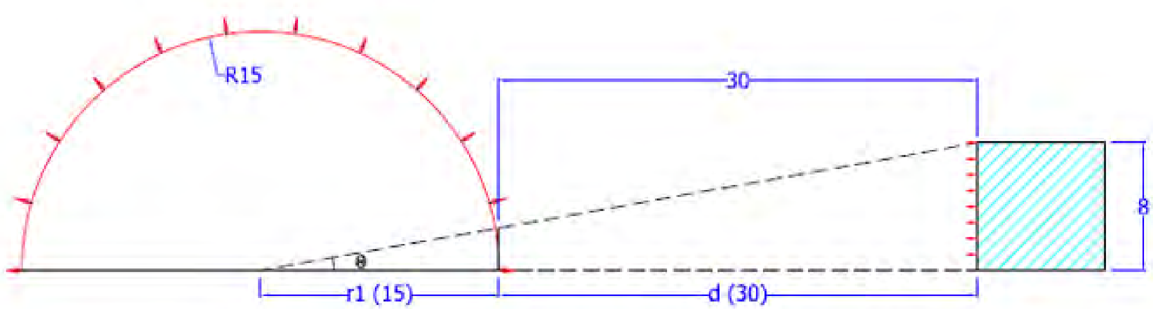

Figure 8. Geometric shape factor.

Refuge and Encircling Fire

For each test, the refuge will be encirled by standard wood pallets stacked on top of one another to a height of 8 ft. This is approximately 16 pallets per vertical stack. Illustration below.

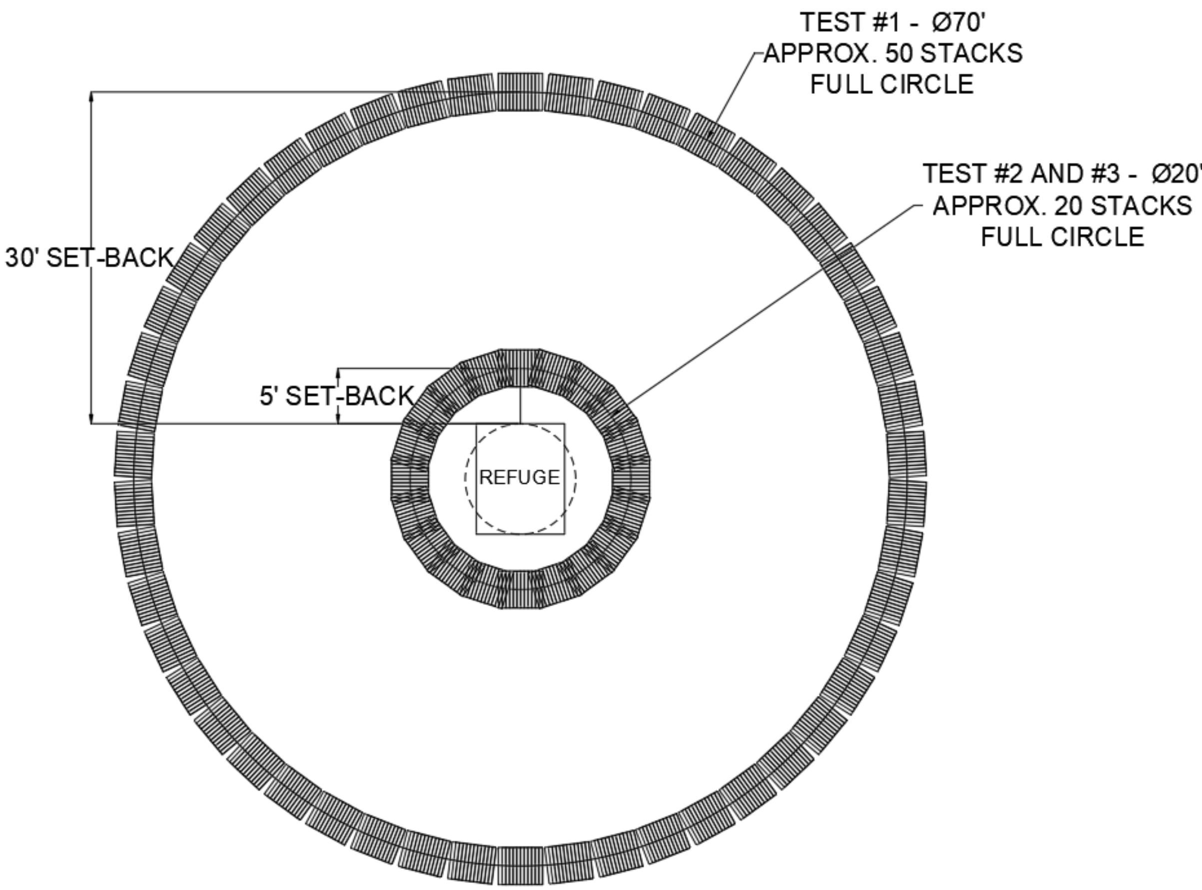

Figure 9. Plan view of test site.

Schedule, Safety, and Coordination

All elements of schedule, safety, and coordination of testing to be orchestrated by the Wildfire Safety Systems site superintendent. The burn exercise shall be attended by local fire and rescue with water trucks at the ready. The anticipated schedule is to complete test #1 and test #2 on the following day, prevailing winds and weather permitting.

References:

1. Field and full-scale laboratory testing of prototype Wildland fire Shelters. Joseph Roise, John Williams, Roger Barker, and John Morton-Aslanis, 28 April 2022
2. Fire Safety Engineering Design of Structures, 3rd Edition. John A, Purkiss and Long-yuan Li. 2014, CRC Press
3. Woodland Hills, Ut, CC&R

End of Document