Evaluation of Water Additives for Fire Control and Vapor Mitigation – Phase II, Two and Three Dimensional Class B Fire Tests

Prepared for

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DRAFT
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In this test, Novacool UEF is referred to as B

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Evaluation of Water Additives for Fire Control and Vapor Mitigation – Phase II Fire Testing of Water and Water Additives

1.0 BACKGROUND

Various water additives are available in today's marketplace that claim to provide advantageous performance characteristics for fire control and vapor mitigation. Of particular interest are additives that report to provide superior fire suppression capabilities through emulsification or encapsulation. However, a scientific assessment of these various additives is lacking, and the fire protection community would benefit from an evaluation of the various available water additives for fire control and vapor mitigation.

In Phase I, a comprehensive evaluation of water additives used for fire control and vapor mitigation was performed [1]. The intent was to clarify the fire protection benefit of using water with additives for fire suppression versus water without additives. It was found that users of water additives have performance criteria for most scenarios of interest, as established by NFPA 18A [2]. Suppression criteria based on fire performance, as opposed to chemical/physical parameters of an agent, was emphasized. Based on the available data and the interests of the Sponsors and Technical Panel, a plan was developed to test representative water additives with fire scenarios of interest. These included a Class A deep-seated coal and combined two- and three-dimensional (2D/3D) Class B scenarios. A combined 2D/3D fire test scenario was identified based on demonstrated scalability of the 2D fire, and demonstrated experience with the 3D fuel cascade mockup.

The Sponsors and Technical Panel agreed that a Class B scenario was of most interest. It was desired to use a test scenario that could be associated with real-life conditions, not just as a scaled down scenario. Initial protection criteria might then be developed which could be directly applied to the power industry and other industrial settings having similar scenarios. A basic decision was made to evaluate representative water additive agents against Class B fire threats using a test mock-up which provided a generic, comparative analysis between water and water additives. An exact installation scenario was not replicated, although the scale was similar to an actual installation. It was decided to conceptually adopt a cascading fuel apparatus and associated pan/pool fire. A fixed overhead sprinkler nozzle array was to be evaluated, simulating current guidance in NFPA 850, Section 7.7.4.1.1 to provide 0.30 gpm/ft^2 water application to Class B turbine pedestal situations and other associated Class B hazards in a power plant [3].

Prior demonstrations of a water additive showed that it might be more effective than plain water in suppressing a two dimensional pool fire. A three dimensional fire created by the running fuel cascade represents a significant challenge to water and water with additives. The disturbance of the fuel surface and continuous addition of burning fuel provide re-ignition sources that challenge any additive interaction with on the fuel surface. The Technical Panel decided that it was important to include the three dimensional fire aspect in the Class B evaluation. The Technical Panel decided that an appropriate fuel would have a moderate flash point, e.g., No. 2 diesel or similar (flash point on the order of 125–150ºF).

During these tests, water and three representative additives were applied from an array located above the fire area, similar to an installed sprinkler system. The original test concept was to determine, utilizing a bracketing technique, the minimum flow rate (application rate, gpm/ft^2) required to extinguish the fire. The flow rate would be varied between successive tests until the least flow rate to cause suppression/extinguishment occurs. The performance enhancement associated with the additives would be evaluated by comparison with water alone. Successive tests were to be conducted on just the pool fire, and the pool fire with the running fuel cascade.

Due to budget constraints, a full parametric study to bracket the wetting agent application rate resulted in too many tests. In the original plan, a series of closely spaced sprinkler lines and nozzle outlets were to be positioned over the Class B fire threat. This would allow for relatively easy changes in nozzle spacing and associated application rates. The use of generic spray nozzles was anticipated to, hopefully, eliminate any variations associated with nozzle discharge characteristics.

A modified approach was selected and approved by the Sponsors and Technical Panel. An adaptation of the UL 162 foam sprinkler test was used [4]. Based on an initial version of the test plan, and iterative discussions and ROM cost estimates, Underwriters Laboratories (UL) was selected as the laboratory for these tests. Comments and input from the project Technical Panel were incorporated into the final test plan [5]. This test series, with the results described in this report, represented a balance of in-field system realism, number of agents to test, test setup, and time required to complete the tests.

2.0 TEST SETUP

2.01. Fire Scenarios

The three fire scenarios used in this test series were: (1) a two-dimensional pool fire, (2) a three-dimensional Class B flowing fuel fire, and (3) a three-dimensional Class B flowing fuel fire within a two-dimensional pool fire.

The Class B pool fire area was 50 ft^2 (7.07 ft on a side); the height of the pan was 1.0 ft. Initially, the pan was filled with 20 gal of diesel which was approximately 5/8 in. deep. After Test 1 this was increased to a fuel layer thickness of 1.0 in. (~31 gal). For every test, the pan was filled with water such that the freeboard height (i.e., the height between the top lip of the pan and the top of the fuel) was 8.0 in. The test pan was self-leveling such that the free-board height remained relatively constant throughout the test. An elbow and pipe connected to the bottom of the pan drained off the leveling water as fuel from the cascade and water from the sprinklers accumulated in the pan. Initially the pan was “sweetened” with 0.5 gal of heptane to increase flame spread across the pool. After Test 1, this amount was later reduced to 0.25 gal. In this report, the class B pool fire is referred to as the 2D fire scenario.

A relatively “standard” cascade array used in other similar tests was used as the three-dimensional Class B fire. It consisted of five inclined trays mounted above a 3.25 ft square pan. The fuel was discharged onto the top tray and flowed down that tray to the tray below which was inclined in the opposite direction. Fuel was discharged through a two pipe manifold; the top most pipe was connected to the fuel supply at one end and to the bottom pipe by three vertical pipes, one at the center and one near each end. The three connections were intended to balance the flow to the bottom pipe. A slit in the bottom pipe allowed the fuel to flow evenly onto the tray below; the slit was 0.25 in. wide and 2.0 ft long. The fuel flowed successively down each of the inclined trays prior to reaching the bottom pan. The bottom pan had a notch cut in the front of the pan to facilitate the flow of the fuel to a larger containment pan. In past test series, this apparatus had been used with fuel flows ranging from 2.5 to 12 gpm with the containment pan sized to prevent an excess buildup of fuel. For this test series a fuel flow rate of 2 gpm was used; this value was selected to be challenging but manageable flowrate. At this relatively low flowrate, the fuel tended to exit the slit on half of pipe which was nearest to the supply. This was deemed to be adequate as the fuel spread to cover the majority of the cascade trays below. A photograph of the fuel cascade is shown in Figure 1, with a detailed schematic shown in Figure 2. In this report, the fuel cascade is referred to as the 3D fire scenario.

The bottom pan of the fuel cascade was initially filled with 1.0 in. of water and 1 gal of diesel, with 0.05 gal of heptane to “sweeten” the fuel. After Test 4, the amount of diesel was changed to 1.2 gal.

The cascade apparatus was centered within a containment pan 7.07 ft on a side. The containment pan was filled with fuel floated on water to create a two-dimensional fire, when required. When used with the fuel cascade, a fuel layer of 1.0 in. on top of 3.0 in. of water was used in the containment pan. When only the three-dimensional fuel cascade was used, the containment pan was filled with 4.0 in. of water. The “top hat” (roof) of the cascade was constructed but was not used in this testing. This obstruction makes the extinguishment of the 3D fire more difficult. When the 3D flowing fuel fire was not used, the apparatus was removed from the containment pan.

Diesel fuel was used for the cascade and pool fires based on guidance from the Technical Panel. The flashpoint of the diesel fuel was between 136-138 ºF. Fuel was stored in a 175 gal intermediate bulk container (IBC) approximately 40 ft from the testing area. The IBC was elevated on steel racking to a height of 20 ft. The fuel system was gravity fed and the flowrate was adjusted by opening or closing a valve downstream from the drum. The flow rate through the fuel system was measured using a flow meter manufactured by King Instrument Company (7700 Series; 1-11 gpm range). Figure 3 and Figure 4 show general layouts of the test area and test setup.

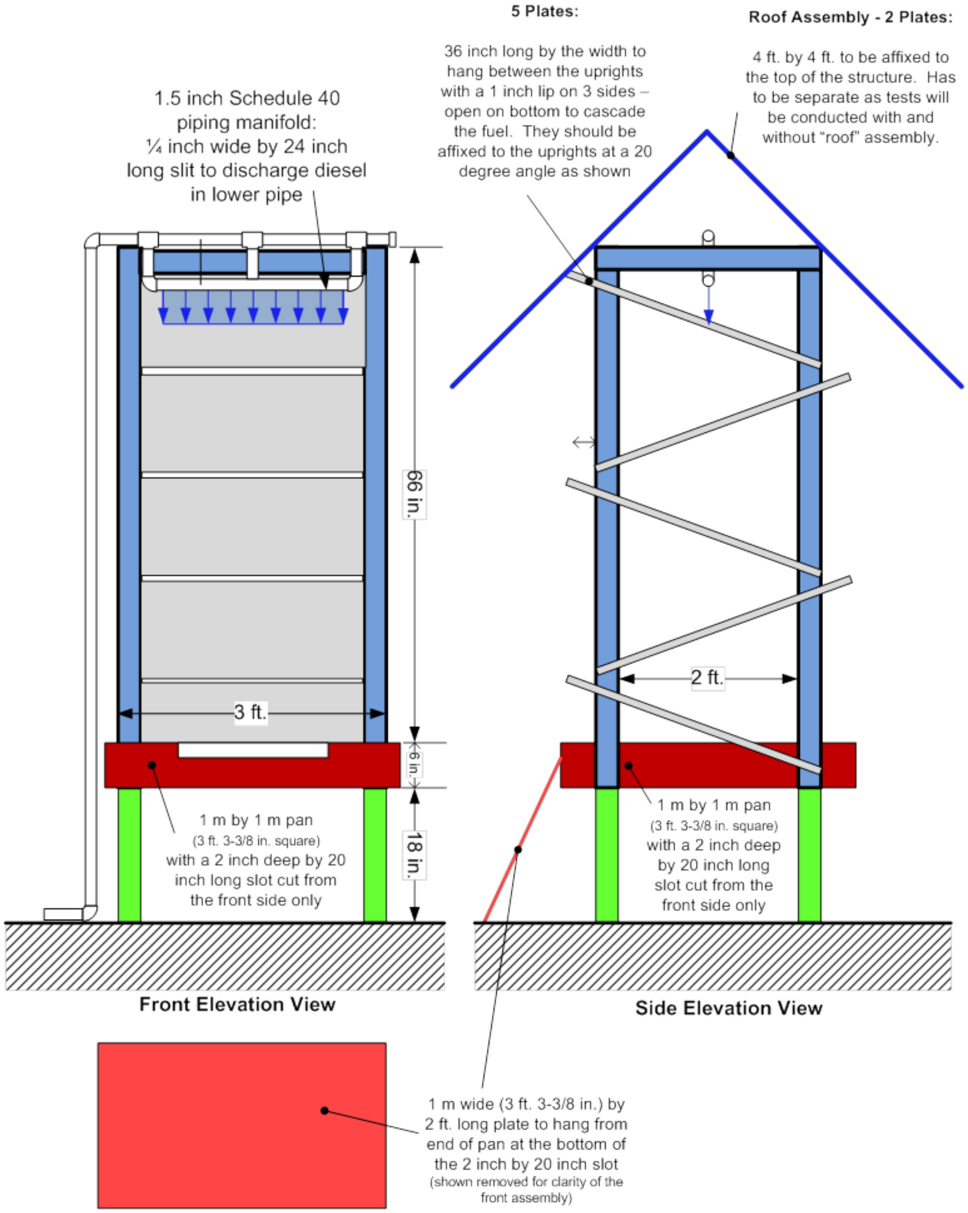

Figure 1 – Fuel cascade schematic with front elevation view (w/ top hat removed) and side elevation view.

Figure 2 –Fuel cascade.

Figure 3 – General layout of test area, plan view.

Figure 4 – Test setup.

2.02. Water Additives

It was decided by the Technical Panel to evaluate water additives agents which: 1) had supposedly different extinguishing characteristics compared to more traditional foaming agents, e.g., emulsifiers or encapsulators, 2) were already listed as UL wetting agents, and, 3) were not already UL listed as Foam Liquid Concentrates. Three agents and water were evaluated in this test series. Vendors were contacted and agreed to supply agent for the testing. All three agents met the criteria established by the Technical Panel. They were tested "blind," and are designated as Agents A, B, and C. Table 1 lists the agent concentrations used in testing, the UL Listed concentration for Class B Fires (as a wetting agent), and the manufacturer description of how the agent works.

Table 1 – Water additive information.

Agent	Customer Recommended Application Concentration for Testing	UL Listed Concentration for Class B Fires (NFPA 18 Wetting Agent Category)	Manufacturer Description
A	3%	6%	Agent rapidly cools fire and surrounding structures, encapsulates fuel, and interrupts the free radical chain reaction.
B	0.5%	0.5%	Agent works by absorbing the energy of the fire, cooling the fuel, blanketing the fuel to eliminate oxygen, and renders Class B fuels non-flammable.
C	6%	6%	Agent works by encapsulating the oxygen molecules to starve the fire, chemically shearing hydrocarbon strings to render the fuel inert. Agent acts as a scrubber, knocking smoke and soot to the ground.

2.03. Water Additives System

A modified UL 162 sprinkler test was used for this test series (see Figure 4). The parameters were as follows:

- Test pan – 50 ft^2 (7.07 ft x 7.07 ft)

- Nozzle height – 15 ft to centerline of piping
- Sprinkler grid – 4 sprinklers located near the corners of the pan
- Cascade apparatus – centered in 50 ft^2 test pan

The rationale for adopting this approach was: it provided a sprinkler test design as opposed to a water spray/optimized approach, more closely resembling an actual installation; and, it was readily available and used by the test lab (i.e., no pan or grid construction required).

Two different UL listed upright sprinklers were used in testing: Viking model VK300 (k=5.6) and Viking model VK350 (k=8.0). An initial sprinkler spacing of 10 ft x 10 ft was used which is associated with an ordinary hazard application rate of 0.30 gpm/ft^2. The application rates used in testing are presented in Table 2 with the sprinkler spacing and k-factor. A schematic of the test layout including the sprinkler grid, test pan, and fuel cascade is shown in Figure 5. When the 12 ft x 12 ft spacing was used, the 10 ft x 10 ft sprinkler piping was left installed. Based on visual observations, the inclusion of this piping did not adversely affect the spray pattern of the sprinklers.

Table 2 – Application rate and sprinkler flow parameters.

Application Rate (gpm/ft^2)	Sprinkler Spacing (ft)	k-factor of sprinkler (gpm/psi$^{1/2}$)	Approx. Nozzle Pressure (psi)	Nominal flowrate of 4 sprinklers (gpm)
0.16	12	5.6	17	92
0.22	12	8.0	16	128
0.30	10	8.0	14	120
0.45	10	8.0	32	180

The water plus additive was pumped from a 2,000 gallon reservoir using a gasoline powered fire pump. The liquid tank was approximately 70 in. in diameter and 13 ft tall. A recirculation loop was used to mix the water and additive into a premixed solution; a minimum mixing period of 5 minutes was used. This eliminated the need for real-time proportioning equipment. The liquid tank was filled with a maximum volume of 1,800 gallons. Each of the three agents was premixed at the concentration recommended by the manufacturer. The mass of water additive and water was measured to provide the correct ratio; the two components were added to the tank and thoroughly mixed using the recirculation pump for a minimum of 5 minutes. The mass of the water additive was calculated based on the known specific gravity and a measured volume of concentrate. The specific gravity was calculated using a known volume of liquid and measuring the mass on a Mettler Toledo model SG 8001 load cell (range: 17.8 lb; resolution: 0.0022 lb). The mass of the water in the tank was measured on a platform atop three load cells with ranges of 10,000 lb; the three load cells were BLH Electronics Type C3P1. A summing box was used to determine the total mass from the three load cells. The outlet of the tank was connected to the discharge piping. After an agent test series was completed, the tank was thoroughly rinsed with fresh water prior to preparing the next agent premix solution.

For tests with only water, the water was pumped from the main fire pumps at the UL test laboratory. For all tests, prior to setting up the 2D and/or 3D fire scenarios, the sprinkler system was set to the correct flow. The pump(s) were turned on and the water or water plus additive was flowed through the sprinkler system discharge piping. The flow was adjusted until the appropriate total flow rate for the test was achieved. This process also ensured that when the pumps were turned on during the test, flow from the sprinklers would be immediate.

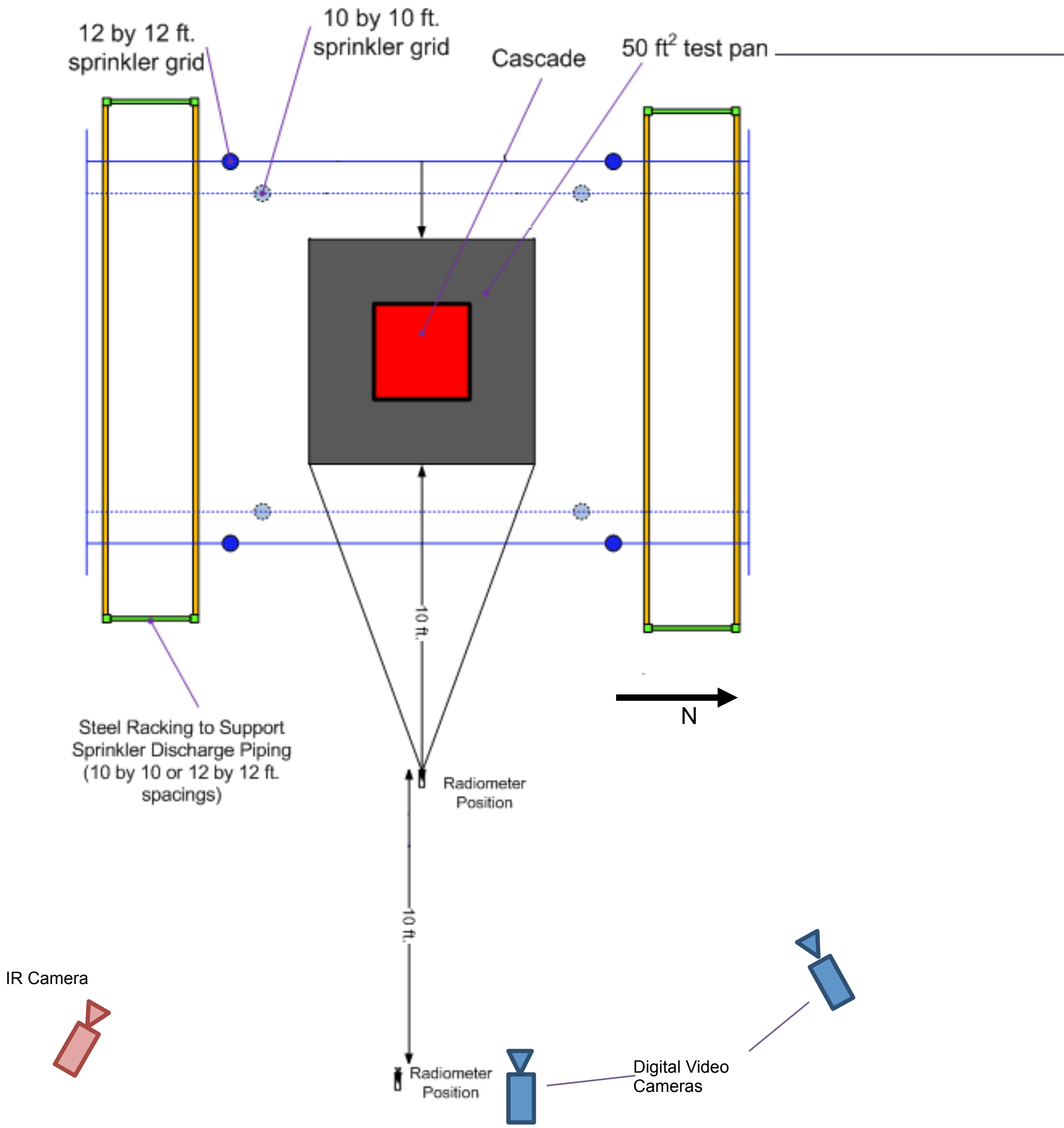

Figure 5 – Test layout schematic.

2.04. Instrumentation

Instrumentation included: flame height indicators, thermocouples, heat flux gauges, video cameras, and infrared cameras. Flame height was determined using video footage of the fire tests. A flame height indicator (ladder) was placed in the same plane as the centerline of the fuel pan, half way between the pan and the sprinkler piping support rack in order to calibrate video footage. Rungs on the indicator were 2.0 ft apart with the bottom most rung 9.75 ft above the floor (see Figure 6 and Figure 7).

Figure 6 – Flame height indicator (ladder).

Two Schmidt-Boelter heat flux gauges (50 kW/m^2 range; Medtherm model 64-5SB-20) were placed outside of the 2D fuel pan to measure radiative heat flux from the fire. One heat flux gauge was positioned 10 ft from the side of the pan; this heat flux gauge was recessed 0.875 in inside of a 1.0 in. nominal diameter pipe as shown in Figure 8. This ensured that the measurement was not affected by liquid deposited on the surface of the gauge from the discharging sprinkler water. The effective viewing angle of this heat flux gauge was 39 degrees. The second heat flux gauge was positioned 20 ft from the side of the pan. This heat flux gauge was not recessed in a pipe because it was outside of the sprinkler spray pattern (see Figure 8); the viewing angle for this heat flux gauge was 180 degrees. Both heat flux gauges were centered approximately 5.0 ft above the floor. These measurements were used to compare the fires from test to test by assessing the degree of fire knockdown by the agents. The location of the radiometers is shown in Figure 5.

Figure 7 – Flame height indicator and instrumentation.

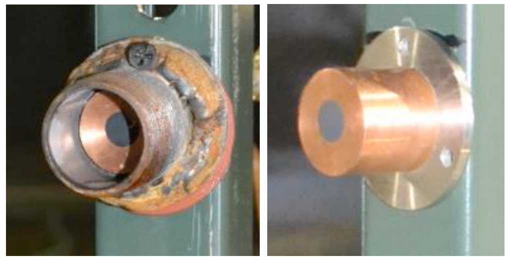

Figure 8 – Photographs of recessed heat flux gauge (left) and exposed heat flux gauge (right).

Flowrate through the sprinkler discharge piping was measured using a Bailey/Fischer–Porter magnetic style flowmeter (Model Number 75EN140L2K) with a range of 0–500 gpm. This water flow device was placed downstream of the pump supply to assure the application rate of the desired sprinkler system was achieved.

Eight type-K thermocouples were used to measure the air temperature and temperature of a steel beam near the ceiling. The moveable ceiling was set to a height of 40 ft above the floor. The air thermocouples were located 6, 12, and 18 in. below the center of the ceiling above the fuel pan. Five thermocouples were embedded in a 4.0 ft long steel beam located as shown in Figure 7. All instrumentation data (i.e., flowrate, temperatures, heat flux) was recorded at a rate of 1 Hz.

Two digital video cameras and an infrared camera were placed at floor level on the side of the pan with the radiometers as shown in Figure 5. Four additional cameras were installed on the walls of the test space. These cameras were approximately 50 ft from the 2D pan and were used as backups for the floor cameras.

3.0 TEST PROCEDURES

Prior to each test, the sprinklers in the discharge array were checked; no replacement of sprinklers was necessary during the test series except to change between sprinklers with a different k-factor. The agent tank was then filled with water and additive.

Ventilation was initiated prior to ignition of the fuel. The ventilation rate was set such that visibility of the cascade apparatus was maintained. Prior to ignition, test data and video recording were initiated.

For the 2D only fire scenario, the ignition fuel in the pan was first ignited. Thirty seconds after full-involvement of the pan, the application of the water or water with additive was started. Full-involvement was determined by visual observation of the UL test director. This generally occurred 15 to 30 seconds after ignition. The sprinkler system flow was secured at the discretion of the UL test director. In general, the sprinkler system flow was secured after the fire was extinguished or a minimum five minute application period had been completed.

For the 3D only fire scenario, the ignition fuel in the cascade pan was first ignited. One minute after full-involvement of the pan, the fuel flow to the cascade was initiated and set to 2 gpm. Thirty seconds after full-involvement of the cascade, the application of the water with additive was started. Full-involvement was determined by visual observation of the UL test director. The sprinkler system and cascade fuel flows were secured at the discretion of the UL test director. In general, the sprinkler system flow was secured after the fire was extinguished or a minimum five minute application period had been completed.

For the 2D and 3D fire scenario, the ignition fuel in the cascade pan was first ignited. One minute after full-involvement of the cascade pan, the 2D pan was ignited and the fuel flow to the cascade was initiated and set to 2 gpm. In general, forty-five seconds after full-involvement of the 2D pan, the application of the water with additive was started. For Test 17, the application of water began approximately 37 seconds after full-involvement. Full-involvement was determined by visual observation of the UL test director. The sprinkler system and cascade fuel flows were secured at the discretion of the UL test director. In general, the sprinkler system flow was secured after the fire was extinguished or a minimum five minute application period had been completed.

Prior to securing the water or water and additive system, an aqueous film-forming foam (AFFF) hand-line was used to extinguish residual flaming, when necessary. The duration of the agent application, time of extinguishment, or qualitatively, the extent to which the fire is suppressed were recorded. The containment pan and cascade were then emptied and cleaned in preparation for the next test.

4.0 RESULTS

4.01. Measures of Performance

In keeping with the philosophy established in the Phase I recommendations, performance in these tests was evaluated based on fire suppression and cooling. No attempt will be made to define the physio-chemical properties of any particular agent, such as encapsulation. Rather, the comparison was based on quantifiable fire-cooling, suppression, and extinguishment measures as follows:

Control Time (Visually Assessed)

2D – 90% of pan area extinguished
3D – no trays burning, fire just in cascade pan; or, if bottom cascade pan extinguished, fire on just one tray
2D and 3D – both the 2D and 3D criteria achieved

Figures 9 and 10 are representative photographs of the fully involved state (i.e., before agent application) and the 90% controlled state for each fire scenario, respectively.

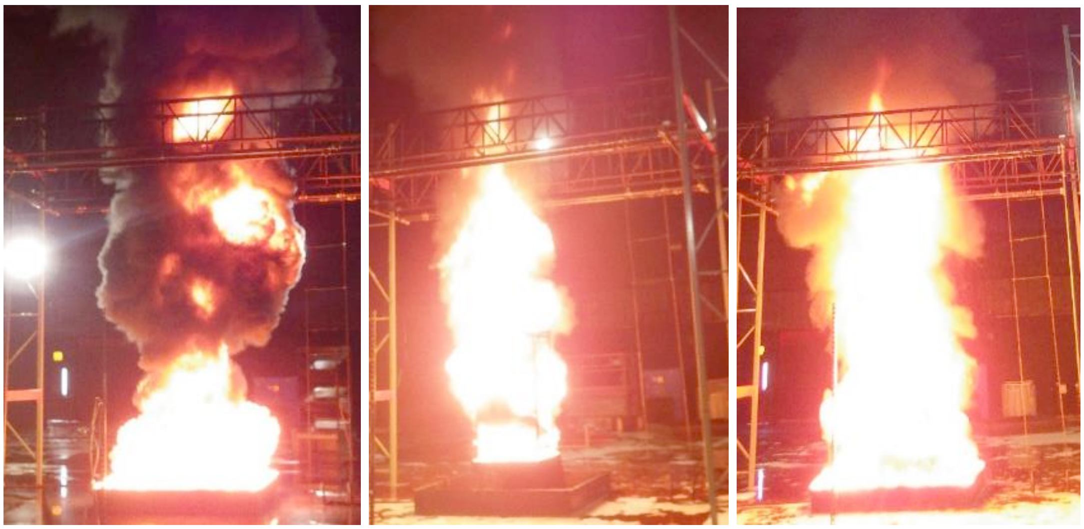

Figure 9 – Representative photograph of fully involved 2D (left), 3D (center) and 2D+3D (right) fire scenarios.

Figure 10 – Representative photograph of 90% controlled 2D (left), 3D (center) and 2D+3D (right) fire scenarios.

Extinguishment Time (Visually Determined)

Extinguishment time was the time between when the agent discharge began and:

2D – complete extinguishment of the 2D pan
3D – complete extinguishment of the 3D cascade, cascade pan, and any fire which may have spread to the 2D pan
2D and 3D – complete extinguishment of the 3D cascade, cascade pan, and 2D pan

Flame Height

Flame height was determined using video footage from the East camera view (see Figure 7) which was facing the front of the fuel cascade. Flame height was calculated by measuring from the top of the pan to the tip of the flames in pixels using Bluebeam Revu software and scaling this based on the flame height indicator (see Section 2.4). Flame height was measured once every 5 seconds after ignition. For the 2D fires, ignition was defined as the ignition time of the 2D pan; for the 3D only and 2D+3D fires, ignition was defined as the ignition time of the cascade pan. Flame height is an important measure of performance because any steel structure exposed to direct flame impingement (i.e., directly above the fire) might fail in a short period of time. Plots of the flame height for each test are included in Appendix A.

A value of 90% reduction in flame height was calculated to determine when flames were reduced to an almost controlled state. For determination of the time to 90% reduction in flame height, the maximum value was calculated for each test. After the agent was turned on, the time at which the flame height fell below the percentage of the maximum was determined. Because flame heights tend to have large oscillations, two consecutive measurements of a 90% reduction were required to determine the flame height reduction time (which was the first of these measurements).

Heat Flux

For all tests, the heat flux at the 20 ft distance was on the order of one third to one half of the heat flux at the 10 ft location. In general, the maximum heat fluxes recorded were nominally the same for the 2D fires and the 2D+3D fires, with the 3D fire scenario being lower. The averages of the peak heat fluxes for each fire scenario are shown in Table 3. Logically, one would expect that the addition of the 3D cascade to the 2D pan would produce a larger heat flux. It is possible that the 2D+3D scenario did not produce larger heat fluxes than the 2D pan alone because the 3D cascade blocked some of the re-radiation to the 2D pan, reducing its contribution. Plots of the heat flux for each test are included in Appendix B.

Table 3 – Average of peak heat fluxes for each test scenario.

Fire Scenario	Avg. of Peak Heat Flux (kW/m²)	
	20ft	10 ft
2D	4.0	12.4
3D	1.7	4.6
2D+3D	3.5	10.8

A standard pool fire calculation [6, 7] for a 50 ft^2 diesel fire results in an estimated heat flux of approximately 27.6 kW/m^2 at 10 ft and 6.9 kW/m^2 at 20 ft. These values are much higher than the average of the peak measurements made in testing (72% and 122% for 20 ft and 10 ft averages, respectively). There are two reasons for this: first, the pool fire heat release rate calculations and heat flux calculations are based on steady state burning. Given the relatively short pre-burn times in this testing, steady state may not have been achieved and as a result the heat release and heat flux might be lower than the calculations. Second, in the radiation calculations, the target was assumed to be located at half of the flame height. The targets in testing were located 5 ft above the ground which is below half of the peak flame heights (generally around 7.5 - 10 ft [peak 15 - 20 ft]). This location would tend to make the heat fluxes less than the calculations. In addition, the 10 ft heat flux gauge was recessed within a pipe and may have been shielded from part of the flame given its height. However, since the heat flux gauges were configured the same and located in the same place for all tests, they are still considered a valid comparative measure.

Values of 60, 90, and 99% reduction in heat flux were calculated to determine when the fire was reduced by a moderate amount, to a controlled state, and almost to extinguishment, respectively. For determination of the time to 60, 90, and 99% reduction in heat flux, the maximum value was calculated for each heat flux gauge over the entire test. After the agent was turned on, the time at which the heat flux for a particular gauge fell below the percentage of the maximum was determined.

Since the heat fluxes for the 10 ft location were significantly higher than the 20 ft location, they were used in subsequent analyses. For comparative purposes, the following heat flux thresholds are referenced:

- Immediate human pain [8]: 2.5 kW/m^2
- Failure of polyurethane/PVC unqualified cable after 20 minutes [9]: 6 kW/m^2
- Failure of IEEE 383 qualified cable after 30 minutes [9]: 18 kW/m^2
- Immediate degradation/melting of plastics (i.e., cable insulation) [10]: 20 kW/m^2

Given that the maximum heat flux measured during all testing was 13.9 kW/m^2 at a distance of 10 ft (Test 5) and the duration of the maximum heat flux was relatively short, it would be unlikely that any of the fires could cause immediate equipment damage at a lateral distance of 10 ft based on the heat flux thresholds listed. For all of the tests, the maximum heat fluxes were above the threshold for immediate human pain.

Air Temperature Below Ceiling – Ceiling temperature was used to compare the relative effectiveness of cooling of the fire plumes and extinguishment effectiveness of the agent discharge. In general, the ceiling air temperatures track well with the fire progression based on visual observations and heat flux data. For most of the tests, the 12 in. temperatures were moderately greater (i.e., on the order of 10˚C) or equal to the 18 in. temperatures. Generally, the 6 in. temperatures were the lowest. The air temperatures were used as comparisons for the other measures of performance. Plots of the air temperatures for each tests are included in Appendix C.

Values of 60, 90, and 99% reduction in air temperature were calculated to determine when the fire was reduced by a moderate amount, to a controlled state, and almost to extinguishment, respectively. For the determination of the time to 60, 90, and 99% reduction in temperature, the maximum temperature rise from ambient was calculated for each air thermocouple over the entire test. The ambient temperature was calculated as the average of the first three temperature measurements in the test data. After the agent was turned on, the time at which the particular air temperature fell below the percentage of the maximum above ambient plus the ambient value was determined.

Steel Beam Temperature – The steel beam temperatures did not track well with the fire development (see Figure 11); this was due to the thermal inertia of the beam and the relatively short test periods. The maximum recorded steel beam temperature was below 60˚C (Test 19). The beam temperature data for each test is included in Appendix D.

Figure 11 – Worst case plot of steel beam temperatures vs. time after ignition (Test 19).

4.02. Test Parameters

A total of 19 tests were conducted in this test series; four water only tests and five tests of each water additive were conducted. Table 4 is a test matrix of the tests conducted. The following testing approach was used for the water additives:

1. 2D fire alone, application rate of 0.30 gpm/ft^2
2. 3D fire alone at application rate of 0.30 gpm/ft^2
3. 2D+3D fire at application rate of 0.30 gpm/ft^2
4. 2D fire alone, application rate of 0.16 gpm/ft^2
5. 2D, 3D, or 2D+3D at application rate of 0.22 gpm/ft^2 depending on prior results

For the water only tests, only the 2D and 3D fires alone were conducted; application rates of 0.3 and 0.45 gpm/ft^2 were used for each scenario.

In one test, Test 11, the flow rate through the sprinkler system was temporarily increased due to a faulty valve. For approximately the first 15 seconds of flow, the flow increased from approximately 92 gpm to 121 gpm and then decreased back down to approximately 92 gpm over the next 15 seconds and remained at this flow rate for the remainder of the test.

Table 4 – Test Matrix.

Test No.	Date	Agent	Test Scenario	Time of Day (HH:MM)	Test Duration (MM:SS)	Agent Concentration	Sprinkler K-factor (gpm/psi$^{1/2}$)	Sprinkler Spacing (ft)	Sprinkler Application Rate (gpm/ft^2)	Time from Ignition to Agent On (sec)	Total Sprinkler flowrate (gpm)
1	5/27/14	Water	2D	13:12	8:32	-	8.0	10	0.3	45	120
2	5/27/14	Water	2D	14:52	5:10	-	8.0	10	0.45	45	180
3	5/28/14	A	2D	8:31	5:03	3%	8.0	10	0.3	60	120
4	5/28/14	A	3D	10:02	7:09	3%	8.0	10	0.3	113	120
5	5/28/14	A	2D + 3D	11:35	8:49	3%	8.0	10	0.3	120	120
6	5/28/14	A	2D	14:11	6:14	3%	5.6	12	0.16	70	92
7	5/28/14	A	2D	15:30	5:24	3%	8.0	12	0.22	60	128
8	5/29/14	B	2D	8:02	3:08	0.5%	8.0	10	0.3	60	120
9	5/29/14	B	3D	9:12	8:06	0.5%	8.0	10	0.3	120	120
10	5/29/14	B	2D+3D	10:25	8:56	0.5%	8.0	10	0.3	115	120
11	5/29/14	B	2D	12:58	3:57	0.5%	5.6	12	0.16	50	92[A]
12	5/29/14	B	2D+3D	14:21	11:22	0.5%	8.0	12	0.22	112	128
13	5/29/14	Water	3D	15:46	8:06	-	8.0	10	0.3	120	120

14	5/29/14	Water	3D	16:38	8:15	-	8.0	10	0.45	126	180
15	5/30/14	C	2D	8:38	2:01	6%	8.0	10	0.3	51	120
16	5/30/14	C	3D	9:13	8:13	6%	8.0	10	0.3	115	120
17	5/30/14	C	2D+3D	10:28	6:14	6%	8.0	10	0.3	115	120
18	5/30/14	C	2D	12:59	2:29	6%	5.6	12	0.16	60	92
19	5/30/14	C	3D	14:01	9:58	6%	80.0	12	0.22	115	128

A – Flow increase for first 30 seconds of flow.

4.03. Fire Suppression and Cooling Performance

The results of the fire tests are summarized in Tables 5, 6 and 7 for the 2D, 3D, and 2D+3D fire scenarios, respectively. The next three sections summarize these results for each fire scenario.

4.03.1. 2D Fires

The results of the 2D fire tests are summarized in Table 5. All three agents and water were tested with the 2D pan fire at an application rate of 0.3 gpm/ft^2. All three agents were able to extinguish the fire at this application rate, with water only able to achieve 90% control after an extended discharge period. Based on the data in Table 5, the agents, from quickest to slowest in terms of knocking down the fire, were consistently Agent C, Agent B, Agent A, and Water. All three agents were significantly quicker than water at controlling the fire and reducing flame height and heat flux by 90%. For 90% control, Agent A was approximately 3 times quicker and Agent C was 21 times quicker than water. For time to 90% reduction in heat flux, all three agents were approximately 3 times quicker than water.

Water was able to extinguish the 2D pan fire at a higher rate of 0.45 gpm/ft^2 in a time period comparable to what the other agents achieved at the application rate of 0.30 gpm/ft^2. Agents B and C were the most effective in that they were able to extinguish the 2D pan fire at application rates of 0.16 gpm/ft^2. Agent A was effective at a slightly higher application rate of 0.22 gpm/ft^2.

Table 5 – Results of 2D fire tests.

Test	Agent	Sprinkler Application Rate (gpm/ft^2)	Extinguished?	Time to 90% Control (sec)	Time to Extinguishment (sec)	Time to 90% Flame Height Reduction (sec)	Time to 90% Reduction in Heat Flux – 10ft (sec)
1	Water	0.3	No	480	NA	510	236
2	Water	0.45	Yes	85	153	35	68
3	A	0.3	Yes	131	157	80	77
6	A	0.16	No	NA	NA	NA	110
7	A	0.22	Yes	180	243	215	79
8	B	0.3	Yes	39	50	50	78
11	B	0.16	Yes	95	98	100	73
15	C	0.3	Yes	22	29	29	67
18	C	0.16	Yes	43	62	70	89

NA – Not achieved

Figure 12 compares the flame height for all three water additives versus water for the 2D fire. The time at which the flame height becomes zero is nominally the time of extinguishment. Based on this plot, Agents B (Test 8) and C (Test 15) rapidly reduced the flame height until the fire was extinguished. This was evident in their relatively quick extinguishment times of 29 (Test 15) and 50 (Test 8) seconds (see Table 5). Agent A also rapidly reduced the flame height until a somewhat steady state was reached; the fire continued to burn at the reduced flame height (for approximately 1.5 minutes) as the agent was discharged until extinguishment was achieved after 157 seconds. Water (Test 1) reduced the initial flame height slower than any of the additives and the fire continued to burn during agent discharge until manual firefighting was initiated at the end of the test. It is possible that the gradual reduction in flame height for the water test was predominantly a result of the cooling of the fuel surface over time.

Figure 13 compares the heat flux (10 ft) for all three water additives versus water for the 2D fire. Agents A (Test 3), B (Test 8) and C (Test 15) rapidly reduced the heat flux to below the immediate pain threshold (2.5 kW/m^2) after the agent flow began. Agent A rapidly reduced the heat flux until a somewhat steady state (< 1kW/m^2) was reached before the fire was extinguished after 157 seconds. Water (Test 1) reduced the heat flux slower than any of the additives; the heat flux remained above the immediate pain threshold (2.5 kW/m^2) for approximately one minute after the agent was turned on. The fire continued to burn with a steady decrease in heat flux until manual firefighting was initiated at the end of the test. These patterns are similar to the flame height reductions shown in Figure 12. All three agents and water were able to immediately reduce the heat flux to below the immediate pain threshold (2.5 kW/m^2).

Figure 12 – Flame height versus time after ignition for four 2D fires with application rates of 0.3 gpm/ft^2.

Figure 13 – Heat flux (10 ft) versus time after ignition for four 2D fires with application rates of 0.3 gpm/ft^2.

4.03.2. 3D Fires

The results of the 3D fire tests are summarized in Table 6. All three agents and water were tested with the 3D fire at an application rate of 0.3 gpm/ft^2. Only Agent B (Test 9) was able to fully extinguish the 3D fire scenario at an application rate of 0.3 gpm/ft^2 in 274 seconds (90% control in 264 seconds). Agent C (Test 16) was able to achieve 90% control of the 3D fire in 275 seconds. Based on the 90% control and 90% heat flux reduction times, the performance of Agents B and C was comparable. Agent A and water were unable to control the fire, but were able to reduce the heat flux by 90% after a few minutes or more. Water was able to achieve a 90% reduction in heat flux in about half of the time than Agent A was.

Water was also tested at a higher application rate of 0.45 gpm/ft^2. Even at this higher rate, water was unable to control the fire. The times to 90% reduction in heat flux for the two water tests at different rates were approximately equal. Agent C was the only additive to be tested twice; it was unable to extinguish or control the fire at the lower application rate (0.22 gpm/ft^2). The times to 90% heat flux and flame height reduction were approximately twice as long for the 0.22 gpm/ft^2 application rate versus the 0.3 gpm/ft^2 application rate.

Table 6 – Results of 3D fire tests.

Test	Agent	Sprinkler Application Rate (gpm/ft^2)	Extinguished?	Time to 90% Control (sec)	Time to Extinguishment (sec)	Time to 90% Flame Height Reduction (sec)	Time to 90% Reduction in Heat Flux – 10ft (sec)
13	Water	0.3	No	NA	NA	NA	155
14	Water	0.45	No	NA	NA	160	169
4	A	0.3	No	NA	NA	NA	342
9	B	0.3	Yes	264	274	314	170
16	C	0.3	No	275	NA	150	167

19	C	0.22	No	NA	NA	365	367

NA – Not achieved

Figure 14 compares the flame heights for all three water additives versus water for the 3D fire scenario. Both Agents B and C steadily decreased the flame height after agent was applied until the fire was controlled or extinguished. Agent A decreased the flame height to about 30% of its maximum as quickly as the other agents, but the flames remained around 5.0 ft for the remainder of the test. Based on flame height reduction, all three agents had a marked improvement over water which did not significantly reduce the flame height over the duration of the test.

Figure 15 compares the heat flux (10 ft) of all three water additives versus water for the 3D fire scenario. None of the agent or water tests had peak heat fluxes higher than the long term cable damage threshold (6 kW/m^2). Both agents B and C steadily decreased the heat flux after agent was applied until the fire was controlled or extinguished. Agent A (Test 4) decreased the heat flux to under 0.5 kW/m^2 as quickly as the other agents despite not being able to achieve 90% control. Based on heat flux reduction, all three agents had a marked improvement over water. For water (Test 13), the heat flux was reduced approximately 50% initially and then to a steady state around 1 kW/m^2 for the remainder of the test. All three agents and water were able to reduce the heat flux to below the immediate pain threshold (2.5 kW/m^2) quickly after agent was discharged. The heat flux plots are similar to the flame height plots shown in Figure 14.

Figure 14 – Flame height versus time after ignition for four 3D fires with application rates of 0.3 gpm/ft^2.

Figure 15 – Heat flux versus time after ignition for four 3D fires with application rates of 0.3 gpm/ft^2.

4.03.3. Combined 2D and 3D Fires

The results of the combined 2D and 3D fire tests are summarized in Table 7. Only the three water additives were tested with the 2D+3D fire scenario; water was not tested with this fire scenario as it had not been successful in either the 2D or 3D fire scenarios at an application rate of 0.3 gpm/ft^2. All agents were tested at an application rate of 0.3 gpm/ft^2. Both Agents B (Test 9) and C (Test 17) were able to fully extinguish the 2D+3D fire scenario at an application rate of 0.3 gpm/ft^2; Agent A was unable to control the fire. Agent C was able to extinguish and control this fire scenario approximately 2 minutes faster than Agent B. Based on the 90% flame height and heat flux reduction times, the performance of Agent B was moderately better than Agent C. Test 17 appears to be an anomaly for Agent C given that this agent was unable to extinguish the 3D fire scenario (Test 16).

Agent B was also tested at a lower application rate of 0.22 gpm/ft^2. Agent B was unable to extinguish or control the fire at this lower application rate. The time to 90% flame height reduction was approximately 6 times longer for the 0.22 gpm/ft^2 application rate versus the 0.3 gpm/ft^2 application rate; the times to 90% heat flux reduction were approximately equal.

Table 7 – Results of 2D+3D fire tests.

Test	Agent	Sprinkler Application Rate (gpm/ft^2)	Extinguished?	Time to 90% Control (sec)	Time to Extinguishment (sec)	Time to 90% Flame Height Reduction (sec)	Time to 90% Reduction in Heat Flux – 10ft (sec)
5	A	0.3	No	NA	NA	NA	249

10	B	0.3	Yes	320	329	70	184
12	B	0.22	No	NA	NA	458	200
17	C	0.3	Yes	185	197	205	196

NA – not achieved

Figure 16 compares the flame height for all three water additives for the 2D+3D fire scenario; Agents B (Test 10) and C (Test 17) were successful in extinguishing this scenario. Agent A (Test 5) produced a moderate reduction in flame height for this test scenario, but was unable to extinguish or control the fire. Based on extinguishing times, Agent C (197 sec) would appear to have performed better than Agent B (329 sec). For flame height reduction, Agent B reduced the flames to below 3.0 ft for approximately 4.5 minutes before extinguishment while for Agent C flaming was reduced to below 3.0 ft only a few seconds before extinguishment. This reinforces the usefulness of the flame height comparisons.

Figure 17 compares the heat flux (10 ft) for all three water additives for the 2D+3D fire scenario. All agents quickly reduced the heat flux to below the immediate pain threshold (2.5 kW/m^2), with Agent A (Test 5) reaching a steady state value for the remainder of the test. Whereas in Figure 16 there were notable differences in the flame heights between Agent B (Test 10) and C (Test 17) after the initial reduction, the heat fluxes measured for these two tests were nominally the same after the initial reductions with the exception that the heat flux for Agent C went to zero (i.e., extinguishment) prior to Agent B.

Figure 16 – Flame height versus time after ignition for four 2D+3D fires with application rates of 0.3 gpm/ft^2. Note: water not tested for this fire scenario.

Figure 17 – Heat Flux versus time after ignition for four 2D+3D fires with application rates of 0.3 gpm/ft^2.

5.0 DISCUSSION

5.01. Additional Analysis

At the application rates tested, water was found only to be effective on the 2D pan fires. Water required the highest application rate of 0.45 gpm/ft^2 for extinguishment, although the test at 0.3 gpm/ft^2 met the 90% control measure of performance. Given that the 2D pan fire was extinguished by water in under 3 minutes, it is possible that an application rate between 0.3 and 0.45 gpm/ft^2 could have also caused complete extinguishment within a longer discharge period. However, such fine adjustment of the application rates was not within the scope of this test program.

Agent A extinguished the 2D pan fires at the application rates tested. Agent A was tested with the 2D pan at application rates of 0.3, 0.22, and 0.16 gpm/ft^2; it extinguished the pan fires with the two higher application rates; it did not meet the 90% control measure of performance at the lowest application rate. Agent A was tested with the 3D and the 2D+3D at application rates of 0.3 gpm/ft^2 without meeting the 90% control measure of performance, but was not tested at higher application rates due to time restrictions. Based on observations of the 3D and 2D+3D tests with Agent A, a higher application rate or, perhaps, a higher concentration, might contribute to improved performance. The 3% concentration was recommended for testing by the manufacturer; the UL wetting agent listing for Class B fires is 6%. Agent A produced a thin emulsification which floated atop the fuel layer after the test. An example of this is shown in Figure 18.

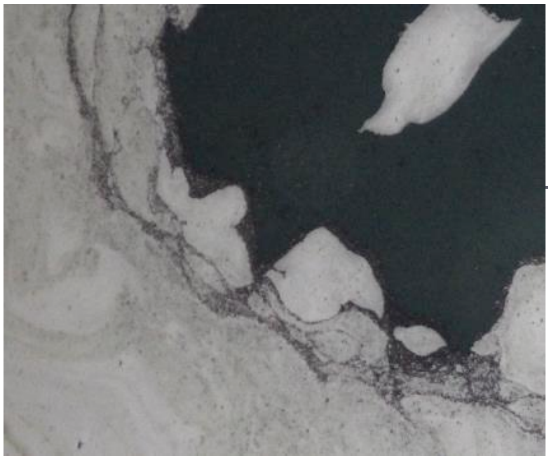

Figure 18 – Agent A emulsification after Test 3.

Agent B was the only water additive to successfully extinguish all three fire scenarios even though it had the lowest concentration (0.5% compared to 3% and 6% for agents A and C, respectively). Agent B successfully extinguished the 2D pan at the lowest application rate of 0.16 gpm/ft^2 and the 3D and 2D +3D scenarios at an application rate of 0.3 gpm/ft^2. Agent B was unsuccessful at extinguishing or controlling the 2D+3D scenario at an application rate of 0.22 gpm/ft^2. Agent B produced a moderately thick (i.e., on the order of 0.5 in.) foam blanket which floated atop the fuel layer after the test; an example of this is shown in Figure 19.

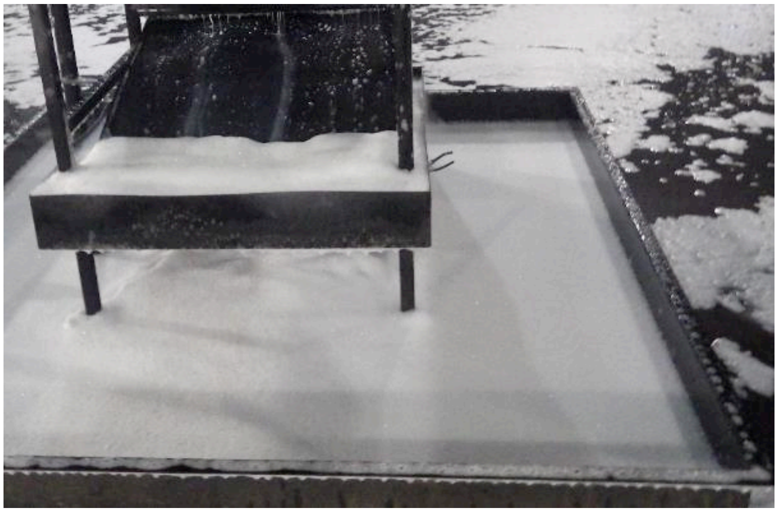

Figure 19 – Agent B emulsification after Test 10.

Agent C successfully extinguished the 2D pan at the lowest application rate of 0.16 gpm/ft^2 and the 2D +3D scenario at an application rate of 0.3 gpm/ft^2. Despite successfully extinguishing the 2D+3D fire scenario, Agent C was unsuccessful at extinguishing the 3D scenario at application rates of 0.22 and 0.3 gpm/ft^2 although it was able to meet the 90% control measure of performance with the higher application rate. It is unclear what may have caused this as the 3D fire would be considered easier to extinguish than the 2D+3D fires combined. The 3D cascade is an inherently difficult fire to suppress due to its many shielded surfaces. Agent C produced a rather thick (i.e., on the order of 4.0 in.) layer of bubbly film which blanketed the fuel layer after the test; an example of this is shown in Figure 20.

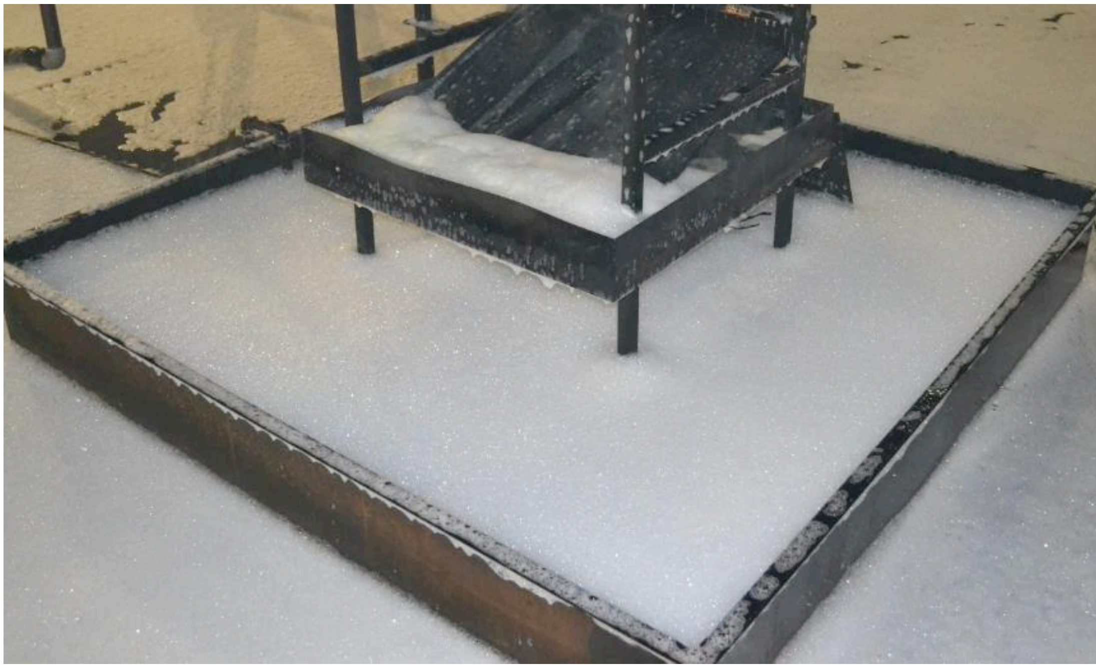

Figure 20 – Agent C bubbly layer after Test 17.

Table 8 lists the lowest application rate for each agent and fire scenario combinations where extinguishment occurred; tests where 90% control was achieved at a lower application rate but where extinguishment did not occur are also noted. For combinations where the agent did not extinguish the fire, the highest application rate tested for that combination is presented in parentheses. This comparison does not consider the time element of the tests, i.e., how quickly the fires were extinguished. Based on the results in Table 8, all of the water additives improved on the performance of water for the 2D only fire scenario. Not only did all of the water additives require a smaller (less than half) application rate to extinguish the 2D fire, agents B and C extinguished the fires in half of the time or less than water and with the lower application rates (see Table 5). Because water was unable to extinguish the 3D fire scenario at the application rates tested, there is no direct comparison between the extinguishment effectiveness of water versus Agents A or C. However, Agents B and C did improve on the performance of water for the 3D only fire scenario by extinguishing and controlling the fire, respectively, when water could not.

Table 8 – Extinguishment Comparison.

Agent	Agent Concentration	Lowest Application Rate with Extinguishment (gpm/ft^2)		
		2D	3D	2D+3D
Water	-	0.45 [A]	DNE (0.45)	NT
A	3%	0.22	DNE (0.3)	DNE (0.3)
B	0.5%	0.16	0.3	0.3
C	6%	0.16	DNE (0.3) [A]	0.3

DNE – Did not extinguish (highest application rate tested in parentheses).
NT – Not tested.
A – Test at 0.3 gpm/ft^2 achieved 90% control.

5.02. Threat Analysis

Additional measures of performance are presented here for comparative purposes. Table 9 shows the visual 90% reduction times and the times after agent is turned on until the heat flux or temperature is reduced to below 60, 90, or 99% of the maximum value. The 90% flame height reduction is also included. The methods for determining the reduction times are included in Section 4.1. None of the temperature measurements ever reached 99% reduction while almost all of the heat flux measurements did. In general, the heat flux reduction times were very close for the two gauges at 60% and 90%, but had wider ranges for the 99% reduction. For the air temperatures, the reduction times were close for the three thermocouples at 60% reduction but typically had more variation at 90% reduction.

For Table 9, the heat flux reduction times are shaded depending on whether the heat flux at that time was below the threshold value for immediate pain (2.5 kW/m^2) or long term cable damage (6.0 kW/m^2). For all of the 90 and 99% reduction times and the 60% reduction times for the 20 ft heat flux gauge, the heat flux at this time was below the pain threshold. For only 6 of 19 tests, based on the 10 ft heat flux gauge, at the 60% reduction times the heat flux was below the pain threshold.

Comparing the times to 90% reduction from the maximum heat flux and temperatures to the time to 90% controlled based on visual measurements provides mixed results (Table 9). In general, the times to 90% reduction in heat flux are much lower than the times to 90% control. On the other hand, the times to 90% reduction in temperature (e.g., for the 18 in. air temperature) are much closer and in some cases lower than the times to 90% control. This is possibly due to the fact that measurement of heat flux does not lag very much with the fire development and control while temperature does. The transport time of the smoke through the sprinkler spray (and the associated heat absorption of the spray) to the ceiling causes some lag for comparison of fire size/control to temperature data.

The times to 99% reduction from maximum heat flux may be more comparable to the 90% visual control times than the 90% reduction times (for heat flux and temperature). Of the 19 tests, ten tests achieved both 99% reduction from maximum heat flux and 90% visual control. With the exception of three tests (Tests 7, 9, and 16), all of the 99% heat flux reduction and 90% visual control times were within approximately 30 seconds of each other. One reason for this could be the radiation attenuation of the sprinkler spray. The percentage of visual control was essentially a rough visual measurement of the reduction in heat release from fully involved. At a fixed distance, heat flux from a fire is roughly proportional to the heat release [6]. This would suggest that the 90% heat flux reduction should be approximately equal to the 90% visual control. However, basic radiation calculations do not account for radiation attenuation from sprinkler sprays. This means that the actual heat flux measured should be lower than what is expected (i.e., 99% reduced vs. 90% reduced).

5.03. Test Scenario

The fire scenarios used in this test series were limited in size by the relatively short pre-burn time, low fuel flowrate, and lack of the top-hat. It is likely that AFFF would have extinguished all of the fire scenarios including the 2D+3D fire scenario (potentially with the top hat), however it is unclear what application rate would have been necessary. Overall, the fire threat could have been made more difficult by increasing the fuel flowrate, increasing pre-burn times, using a fuel source under pressure (i.e., spray fire), or including more obstructions. In addition, it was found that the dual pipe arrangement of the fuel supply for the 3D cascade was not necessary; the slit size was also found to be too large.

The sprinkler arrangement did not technically meet the criteria for NFPA 13 [11] with respect to sprinkler k-factor. According to NFPA 13, a k-factor of 5.6 is appropriate for application rates up to 0.22 gpm/ft^2, a k-factor of 8.0 is appropriate for application rates between 0.22 and 0.34 gpm/ft^2, and a k-factor of 11 would be appropriate for application rates greater than or equal to 0.34 gpm/ft^2. In this test series, sprinklers with a k-factor of 8.0 were used for application rates of 0.45 gpm/ft^2. Based on visual observations of the spray pattern of the sprinklers, this is not believed to have had a significant impact on results.

6.0 CONCLUSIONS

1. The test scenarios provided an acceptable means to compare water to water additives.

2. The 2D fire was extinguished by all agents. An application rate of 0.45 gpm/ft^2 was required for water to achieve total extinguishment which is greater than the 0.3 gpm/ft^2 baseline referenced in NFPA 850. Water additives were effective at application rates of 0.3 gpm/ft^2 and lower.

    a. NFPA 850 should consider increasing the minimum water application rate for protection of Class B hazards.

3. Water failed to extinguish the 3D and 2D+3D fire scenarios. Two of the three water additives extinguished fires which included the 3D scenario.

4. Generally, the water additives provided quicker reductions in the thermal threat of the fires compared to water.

5. From an overall performance standpoint, water additives were superior to plain water.

6. Performance differences were observed between the three water additives tested. This might be attributable to physio-chemical properties of a particular agent, or agent concentration. These factors were not evaluated. All water additives created a residual emulsification or foam layer which was evident at the conclusion of the test.

7. The fire scenarios used are not considered worst case, but do represent real-life conditions which might occur where there are Class B hazards. For comparative purposes, the scenarios demonstrated performance differences between water and water additives.

8. If the test apparatus and scenarios are considered for adoption for standards making/listing of water additives:

    a. Minor modifications should be made to the setup, for example the 3D cascade pipe slit should be smaller, and the top pipe could be eliminated;

    b. A maximum time to achieve the performance metric should be established. A range of performance metrics were analyzed: 90% visual control, extinguishment, and 60/90/99% thermal threat reductions. One or more of these could be used in a performance standard adopted for assessing water additives; and

    c. Tests should be conducted with a greater floor-to-sprinkler height where installations having heights greater than 15 ft are anticipated. Alternately, an increased application rate than that established for 15 ft high performance could be used as a safety factor for any increased height installation.

7.0 ACKNOWLEDGEMENTS

The authors would like to thank the NFPA Research Foundation personnel and project Technical Panel for their assistance in guiding the test planning and advising the test group. The authors would like to also thank the water additive manufacturers for the donations of their agents for testing.

Table 9 – Summary of times after agent was turned on to % reduction in heat flux and air temperature.

Test	Agent	Sprinkler Application Rate (gpm/ft^2)	Test Scenario	Time to 90% Control – Visual (sec)	Time to 60% reduction (seconds)					Time to 90% reduction (seconds)						Time to 99% reduction (seconds)				
					6 in. Air TC	12 in. Air TC	18 in. Air TC	20ft Heat Flux Gauge	10 ft Heat Flux Gauge	6 in. Air TC	12 in. Air TC	18 in. Air TC	20ft Heat Flux Gauge	10 ft Heat Flux Gauge	Flame Height	6 in. Air TC	12 in. Air TC	18 in. Air TC	20ft Heat Flux Gauge	10 ft Heat Flux Gauge
1	Water	0.3	2D	480	34	42	40	14	14	449	439	428	137	191	510	NA	NA	NA	NA	NA
2	Water	0.45	2D	85	37	34	34	16	16	154	162	144	24	23	35	NA	NA	NA	63	59
3	A	0.3	2D	131	21	28	24	8	8	56	70	60	17	17	80	NA	NA	NA	19	122
4	A	0.3	3D	NA	30	30	30	11	8	89	87	77	37	42	NA	NA	NA	NA	114	150
5	A	0.3	2D + 3D	NA	48	48	46	25	23	NA	NA	NA	139	129	NA	NA	NA	NA	NA	NA
6	A	0.16	2D	NA	47	45	45	13	11	NA	NA	NA	39	40	NA	NA	NA	NA	NA	NA
7	A	0.22	2D	180	33	33	33	10	10	189	174	168	16	19	215	NA	NA	NA	96	123
8	B	0.3	2D	39	29	33	31	14	15	NA	NA	NA	18	18	50	NA	NA	NA	21	36
9	B	0.3	3D	264	31	35	35	10	8	111	111	111	44	49	160	NA	NA	NA	57	95
10	B	0.3	2D+3D	320	40	44	42	27	15	213	128	124	66	69	70	NA	NA	NA	137	289
11	B	0.16	2D	95	36	34	33	15	14	NA	86	77	23	23	100	NA	NA	NA	64	63
12	B	0.22	2D+3D	NA	59	70	66	43	42	204	173	173	83	88	458	NA	NA	NA	123	159
13	Water	0.3	3D	NA	NA	328	330	10	9	NA	NA	NA	174	222	NA	NA	NA	NA	315	222
14	Water	0.45	3D	NA	34	27	30	7	6	251	134	99	10	44	314	NA	NA	NA	79	108
15	C	0.3	2D	22	30	34	30	12	11	NA	NA	NA	16	16	29	NA	NA	NA	18	19
16	C	0.3	3D	275	38	35	38	10	10	101	101	101	49	52	150	NA	NA	NA	83	126
17	C	0.3	2D+3D	185	42	50	39	16	15	179	171	123	73	81	205	NA	NA	NA	111	194
18	C	0.16	2D	43	35	37	35	13	11	NA	NA	NA	29	29	70	NA	NA	NA	44	52
19	C	0.22	3D	NA	298	269	272	11	11	NA	NA	NA	60	252	365	NA	NA	NA	278	292

NA – Not Achieved

Below pain threshold (2.5 kW/m^2)

Below long term cable damage threshold (6 kW/m^2)

8.0 REFERENCES

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APPENDIX A –
FLAME HEIGHT VS. TIME AFTER IGNITION

Figure A1 – Flame height vs. time after ignition for Test 1 (Water, 2D, 0.3 gpm/ft^2).

Figure A2 – Flame height vs. time after ignition for Test 2 (Water, 2D, 0.45 gpm/ft^2).

Figure A3 – Flame height vs. time after ignition for Test 3 (Agent A, 2D, 0.3 gpm/ft^2).

Figure A4 – Flame height vs. time after ignition for Test 4 (Agent A, 3D, 0.3 gpm/ft^2).

Figure A5 – Flame height vs. time after ignition for Test 5 (Agent A, 2D+3D, 0.3 gpm/ft^2).

Figure A6 – Flame height vs. time after ignition for Test 6 (Agent A, 2D, 0.16 gpm/ft^2).

Figure A7 – Flame height vs. time after ignition for Test 7 (Agent A, 2D, 0.22 gpm/ft^2).

Figure A8 – Flame height vs. time after ignition for Test 8 (Agent B, 2D, 0.3 gpm/ft^2).

Figure A9 – Flame height vs. time after ignition for Test 9 (Agent B, 3D, 0.3 gpm/ft^2).

Figure A10 – Flame height vs. time after ignition for Test 10 (Agent B, 2D+3D, 0.3 gpm/ft^2).

Figure A11 – Flame height vs. time after ignition for Test 11 (Agent B, 2D, 0.16 gpm/ft^2).

Figure A12 – Flame height vs. time after ignition for Test 12 (Agent B, 2D+3D, 0.22 gpm/ft^2).

Figure A13 – Flame height vs. time after ignition for Test 13 (Water, 3D, 0.3 gpm/ft^2).

Figure A14 – Flame height vs. time after ignition for Test 14 (Water, 3D, 0.45 gpm/ft^2).

Figure A15 – Flame height vs. time after ignition for Test 15 (Agent C, 2D, 0.3 gpm/ft^2).

Figure A16 – Flame height vs. time after ignition for Test 16 (Agent C, 3D, 0.3 gpm/ft^2).

Figure A17 – Flame height vs. time after ignition for Test 17 (Agent C, 2D+3D, 0.3 gpm/ft^2).

Figure A18 – Flame height vs. time after ignition for Test 18 (Agent C, 2D, 0.16 gpm/ft^2).

Figure A19 – Flame height vs. time after ignition for Test 19 (Agent C, 3D, 0.22 gpm/ft^2).

APPENDIX B –
HEAT FLUX VS. TIME AFTER IGNITION

Figure B1 – Heat flux vs. time after ignition for Test 1 (Water, 2D, 0.3 gpm/ft^2).

Figure B2 – Heat flux vs. time after ignition for Test 2 (Water, 2D, 0.45 gpm/ft^2).

Figure B3 – Heat flux vs. time after ignition for Test 3 (Agent A, 2D, 0.3 gpm/ft^2).

Figure B4 – Heat flux vs. time after ignition for Test 4 (Agent A, 3D, 0.3 gpm/ft^2).

Figure B5 – Heat flux vs. time after ignition for Test 5 (Agent A, 2D+3D, 0.3 gpm/ft^2).

Figure B6 – Heat flux vs. time after ignition for Test 6 (Agent A, 2D, 0.16 gpm/ft^2).

Figure B7 – Heat flux vs. time after ignition for Test 7 (Agent A, 2D, 0.22 gpm/ft^2).

Figure B8 – Heat flux vs. time after ignition for Test 8 (Agent B, 2D, 0.3 gpm/ft^2).

Figure B9 – Heat flux vs. time after ignition for Test 9 (Agent B, 3D, 0.3 gpm/ft^2).

Figure B10 – Heat flux vs. time after ignition for Test 10 (Agent B, 2D+3D, 0.3 gpm/ft^2).

Figure B11 – Heat flux vs. time after ignition for Test 11 (Agent B, 2D, 0.16 gpm/ft^2).

Figure B12 – Heat flux vs. time after ignition for Test 12 (Agent B, 2D+3D, 0.22 gpm/ft^2).

Figure B13 – Heat flux vs. time after ignition for Test 13 (Water, 3D, 0.3 gpm/ft^2).

Figure B14 – Heat flux vs. time after ignition for Test 14 (Water, 3D, 0.45 gpm/ft^2).

Figure B15 – Heat flux vs. time after ignition for Test 15 (Agent C, 2D, 0.3 gpm/ft^2).

Figure B16 – Heat flux vs. time after ignition for Test 16 (Agent C, 3D, 0.3 gpm/ft^2).

Figure B17 – Heat flux vs. time after ignition for Test 17 (Agent C, 2D+3D, 0.3 gpm/ft^2).

Figure B18 – Heat flux vs. time after ignition for Test 18 (Agent C, 2D, 0.16 gpm/ft^2).

Figure B19 – Heat flux vs. time after ignition for Test 19 (Agent C, 3D, 0.22 gpm/ft^2).

APPENDIX C –
CEILING AIR TEMPERATURES VS. TIME AFTER IGNITION

Figure C1 – Air temperatures vs. time after ignition for Test 1 (Water, 2D, 0.3 gpm/ft^2).

Figure C2 – Air temperatures vs. time after ignition for Test 2 (Water, 2D, 0.45 gpm/ft^2).

Figure C3 – Air temperatures vs. time after ignition for Test 3 (Agent A, 2D, 0.3 gpm/ft^2).

Figure C4 – Air temperatures vs. time after ignition for Test 4 (Agent A, 3D, 0.3 gpm/ft^2).

Figure C5 – Air temperatures vs. time after ignition for Test 5 (Agent A, 2D+3D, 0.3 gpm/ft^2).

Figure C6 – Air temperatures vs. time after ignition for Test 6 (Agent A, 2D, 0.16 gpm/ft^2).

Figure C7 – Air temperatures vs. time after ignition for Test 7 (Agent A, 2D, 0.22 gpm/ft^2).

Figure C8 – Air temperatures vs. time after ignition for Test 8 (Agent B, 2D, 0.3 gpm/ft^2).

Figure C9 – Air temperatures vs. time after ignition for Test 9 (Agent B, 3D, 0.3 gpm/ft^2).

Figure C10 – Air temperatures vs. time after ignition for Test 10 (Agent B, 2D+3D, 0.3 gpm/ft^2).

Figure C11 – Air temperatures vs. time after ignition for Test 11 (Agent B, 2D, 0.16 gpm/ft^2).

Figure C12 – Air temperatures vs. time after ignition for Test 12 (Agent B, 2D+3D, 0.22 gpm/ft^2).

Figure C13 – Air temperatures vs. time after ignition for Test 13 (Water, 3D, 0.3 gpm/ft^2).

Figure C14 – Air temperatures vs. time after ignition for Test 14 (Water, 3D, 0.45 gpm/ft^2).

Figure C15 – Air temperatures vs. time after ignition for Test 15 (Agent C, 2D, 0.3 gpm/ft^2).

Figure C16 – Air temperatures vs. time after ignition for Test 16 (Agent C, 3D, 0.3 gpm/ft^2).

Figure C17 – Air temperatures vs. time after ignition for Test 17 (Agent C, 2D+3D, 0.3 gpm/ft^2).

Figure C18 – Air temperatures vs. time after ignition for Test 18 (Agent C, 2D, 0.16 gpm/ft^2).

Figure C19 – Air temperatures vs. time after ignition for Test 19 (Agent C, 3D, 0.22 gpm/ft^2).

APPENDIX D –
BEAM TEMPERATURES VS. TIME AFTER IGNITION

Figure D1 – Beam temperatures vs. time after ignition for Test 1 (Water, 2D, 0.3 gpm/ft^2).

Figure D2 – Beam temperatures vs. time after ignition for Test 2 (Water, 2D, 0.45 gpm/ft^2).

Figure D3 – Beam temperatures vs. time after ignition for Test 3 (Agent A, 2D, 0.3 gpm/ft^2).

Figure D4 – Beam temperatures vs. time after ignition for Test 4 (Agent A, 3D, 0.3 gpm/ft^2).

Figure D5 – Beam temperatures vs. time after ignition for Test 5 (Agent A, 2D+3D, 0.3 gpm/ft^2).

Figure D6 – Beam temperatures vs. time after ignition for Test 6 (Agent A, 2D, 0.16 gpm/ft^2).

Figure D7 – Beam temperatures vs. time after ignition for Test 7 (Agent A, 2D, 0.22 gpm/ft^2).

Figure D8 – Beam temperatures vs. time after ignition for Test 8 (Agent B, 2D, 0.3 gpm/ft^2).

Figure D9 – Beam temperatures vs. time after ignition for Test 9 (Agent B, 3D, 0.3 gpm/ft^2).

Figure D10 – Beam temperatures vs. time after ignition for Test 10 (Agent B, 2D+3D, 0.3 gpm/ft^2).

Figure D11 – Beam temperatures vs. time after ignition for Test 11 (Agent B, 2D, 0.16 gpm/ft^2).

Figure D12 – Beam temperatures vs. time after ignition for Test 12 (Agent B, 2D+3D, 0.22 gpm/ft^2).

Figure D13 – Beam temperatures vs. time after ignition for Test 13 (Water, 3D, 0.3 gpm/ft^2).

Figure D14 – Beam temperatures vs. time after ignition for Test 14 (Water, 3D, 0.45 gpm/ft^2).

Figure D15 – Beam temperatures vs. time after ignition for Test 15 (Agent C, 2D, 0.3 gpm/ft^2).

Figure D16 – Beam temperatures vs. time after ignition for Test 16 (Agent C, 3D, 0.3 gpm/ft^2).

Figure D17 – Beam temperatures vs. time after ignition for Test 17 (Agent C, 2D+3D, 0.3 gpm/ft^2).

Figure D18 – Beam temperatures vs. time after ignition for Test 18 (Agent C, 2D, 0.16 gpm/ft^2).

Figure D19 – Beam temperatures vs. time after ignition for Test 19 (Agent C, 3D, 0.22 gpm/ft^2).