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Impact of Fire Extinguisher Agents on Cultural Resource Materials

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FINAL REPORTS (Quantitation & Assessment) BY:

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FOREWORD

A variety of different fire extinguishing agents are utilized in portable extinguishers used in museums, galleries, cultural centers, historic houses and libraries. The agents themselves have been well-researched and their ability to suppress a fire is well-quantified. What is less well understood is what effect these agents might have on the cultural heritage materials that are exposed to them.

In 2009, recognizing the need for further investigation, the National Fire Protection Association (NFPA) Technical Committee on Cultural Resources submitted a project proposal to the Fire Protection Research Foundation (FPRF). The proposal was to develop test specifications and procedures for measuring the impact of portable fire extinguisher agents on cultural resource collections. A Phase I study conducted a literature review and an outline for a test protocol.

This document reports the results of two subsequent studies conducted by Jensen Hughes and the Colonial Williamsburg Foundation as part of an Institute of Museums and Library Services National Leadership Grant (IMLS-NLG) to explore the impacts of fire protection agents on cultural heritage materials. The primary goals of the project were to:

- Establish a reproducible test protocol that could be used for future testing and that would permit the reporting and assessment of comparable test results by disparate testing entities.
- Gather information about the responses of a range of selected materials when exposed to the most commonly used portable fire extinguisher agents over both the short and long-terms.

This overall report is a compilation of two sub-reports addressing this topic, included herein:

1) QUANTIFICATION: “Quantifying the Impact of Portable Fire Extinguisher Agents on Cultural Resource Materials Agent and Fire Exposure Test Report”
2) ASSESSMENT: “Assessing the Impact of Fire Extinguisher Agents on Cultural Resource Materials”

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The content, opinions and conclusions contained in this report are solely those of the authors and do not necessarily represent the views of the Fire Protection Research Foundation, NFPA, Technical Panel or Sponsors. The Foundation makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 60,000 individuals around the world.

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Sub-Report #2: ASSESSMENT: "Assessing the Impact of Fire Extinguisher Agents on Cultural Resource Materials"

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QUANTIFYING THE IMPACT OF PORTABLE FIRE EXTINGUISHER AGENTS ON CULTURAL RESOURCE MATERIALS AGENT AND FIRE EXPOSURE TEST REPORT

FINAL

Prepared as part of
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1. INTRODUCTION

This document is the detailed report on the non-fire (neat agent) and fire exposure tests conducted as part of an Institute of Museums and Library Services National Leadership Grant (IMLS-NLG) designed to test the effects of portable fire extinguishing agents on cultural heritage materials. The post exposure sample assessment methods are also included. Physical impact tests were performed and are documented. This report documents the standardized procedures used in the exposure tests, the fire extinguisher agents used, and the environmental conditions during testing. It is anticipated that a companion report will be prepared describing the detailed analysis of the effects of the agents on representative cultural resource materials once the assessment period is completed.

Portable fire extinguishers and their associated fire extinguishing agents play an important role in reducing the impact of fire on cultural resource collections. A fire which can be suppressed with an extinguisher in its incipient stage will not grow to threaten adjacent materials. These may be valuable collections or the structure housing the resources which itself may be of cultural significance. A range of extinguishing agents is commonly used in museums and libraries, including water, clean gaseous agents, dry chemical and foam. Their effectiveness in combating fires has been studied and is well-understood but their effects on collections materials have not been studied. While conservators are well versed in the effects of moisture and water on collections, little data is available on the effects of other extinguishing agents. The potential collateral damage from agent overspray, potential misuse of extinguishers in spraying collection materials, and the byproducts of the agent when used to extinguish a fire is of interest. Particularly, short- or long-term exposure to extinguishing agents needs to be quantified.

In 2009, recognizing the need for further investigation, the National Fire Protection Association (NFPA) *Technical Committee on Cultural Resources* submitted a project proposal to the Fire Protection Research Foundation (FPRF). The proposal was to develop test specifications and procedures for measuring the impact of portable fire extinguisher agents on cultural resource collections. A scoping report was prepared which included a literature review. The theoretical parameters for testing the impact of extinguishing agents on collections materials were established. It was then vetted by a technical panel consisting of conservators, fire protection engineers and extinguisher manufacturers. As part of this effort, an outline test plan was developed, in anticipation that interested parties would fund a follow on effort to develop a test method and conduct tests on the impact of agents on materials. The published report [1] provides the basis for these tests.

In late 2013, The Colonial Williamsburg Foundation (CWF) received a National Leadership Grant from the Institute of Museum and Library Services (IMLS). This funded a three-year research study of the effect of fire extinguishing agents on collections in cultural heritage environments. The project team consisted of CWF, JENSEN HUGHES, and the FPRF acting in the role as facilitator of a project oversight panel. The project oversight panel was appointed by the FPRF.

2. BACKGROUND

In the original report, different approaches for testing, and the level of scientific rigor, were outlined. It was decided by the original technical review panel that a practical approach to testing be adopted.
Two basic scenarios were previously identified and used in this evaluation: non-fire exposure (neat) and fire exposure tests. The non-fire exposure scenario is intended to evaluate the effects of the neat fire suppression agents on representative materials under normal environmental conditions. During these tests, the portable extinguisher would be discharged directly onto the representative cultural resource materials (“directly exposed”) from a distance representing the nominal effective range of the extinguisher. An additional set or sets of representative materials would be exposed outside of the extinguisher spray (“indirectly exposed”). The fire exposure scenario is intended to evaluate the effects of the combination of the agents, agent thermal decomposition products, and fire source effluent on representative materials. The portable extinguisher would be used to extinguish a representative small, ordinary combustible fire (“Class A” in fire protection parlance) with typical cultural resource materials mounted downstream of the fire. A wood crib was used as a repeatable, surrogate Class A fire. An additional set or sets of representative materials would be located outside of the direct discharge to assess the effects of a reduced exposure. These two scenarios were adopted in this evaluation.

The potential for damage to materials from the extinguisher spray was of interest to conservators. In addition to looking at the chemical impact of the extinguishing agents, the tests were also designed to study their physical impact. The physical impact of the extinguisher flow on an object in terms of the potential to dislodge, topple or tear is related to the impact force or exerted pressure on the object. This information can be used by conservators to assess the possibility of an extinguisher to cause damage through an accidental or malicious discharge onto cultural resource materials. Various ways to assess this were proposed.

It was decided to use a practical method of force assessment through the use of an impact test to evaluate the potential of the extinguisher flows to topple or dislodge an object. This was to be performed separately from the exposure tests. The test team was able to successfully perform these tests.

It was recommended that materials to be exposed should include materials previously tested [2,3] (wood, iron, paintings, and leather) with additional materials added to create a more comprehensive set. The sample size should be relatively small and be thin so that deposition material might be weighed. Due to the large number of samples required for testing and the surface area required to test the cleaning techniques, the size of the sample materials was selected to be nominally 10 cm (4 in.) by 10 cm (4 in.).

Portable extinguishers to be included in the evaluation, applicable for use in a museum/cultural heritage type application, were identified in the original report. These extinguishers should have a minimum Underwriters Laboratories 2A rating for A:B:C or A:C fires [4]. These ratings relate to the ability of an extinguisher to suppress a fire of a certain size and material. Of interest was the Class A rating, which relates to the ability to suppress ordinary combustible (paper, cloth) fires. Based on further input from museum fire protection specialists, the size of dry chemical extinguishers was established at 4.5 kg (10 lb). Because of differences between the gaseous agent listings, the size of the gaseous agent extinguishers were selected to be as close to 4.5 kg (10 lb) as possible.

It was determined that an important test parameter is the fire size to room volume ratio. Keeping this ratio low is consistent with the typical application of portable extinguishers, i.e., small fires in large spaces. Scenarios involving larger ratios are typically dealt with by fixed suppression systems, i.e., sprinklers, or left for the local fire department. Portable extinguishers also are not meant to develop a uniform agent concentration or application density throughout the enclosure. They are meant to develop a high concentration or application density locally at the fire, with lower concentrations elsewhere in the space. Keeping the fire size to room volume ratio low allows for the effects of this non-uniform agent distribution to be evaluated. This approach was adopted.

In November of 2013, CWF and JENSEN HUGHES met to discuss test parameters. At that time, a second “indirect” exposure set was requested by CWF for additional reference and analysis. In a kick-off meeting, the exact test parameters, variables, and sample materials were discussed and finalized [5]. Materials were selected to be representative of common vulnerable materials found in a cultural heritage environment. A final test plan was developed which reflected those decisions [6]. The general materials selected for testing included: steel, copper, aluminum, leather, varnished and unvarnished wood, oil and acrylic paints on canvas, non-porous tile, porous tile, porous and non-porous stone and fur. Due to the large numbers of variables within a single textile sample (binding, mordant, fiber, dyes) it was decided that no single textile could represent the material adequately. Therefore, no textile samples were included in the tests. Once a test protocol is established, textiles may be evaluated as part of a future test program.

3. OBJECTIVES

This project was intended to quantify the impact of discharging portable fire extinguisher agents on cultural resource materials, and establish a scientific method for this assessment. The research was also intended to validate and refine a cost-effective and repeatable test protocol. This can then be used by other organizations to continue to assess various materials and add to the database of known extinguisher effects.

4. GENERAL APPROACH TO ASSESSING EXTINGUISHER IMPACT

Three types of tests were performed:

- Non-Fire (Neat Agent) Tests – This was an exposure of representative materials directly and indirectly exposed to the extinguisher spray. The intent was to assess the impact of an agent which is discharged accidentally or maliciously in the absence of a fire.
- Fire Tests – This was an exposure of representative materials within and outside of the extinguisher spray pattern while using the extinguisher to fight a fire. The intent was to assess the impact of agent byproducts resulting from the extinguishment process. The fire was sized to be easily extinguished and to limit the direct smoke/thermal impact from the fire itself.
- Physical Impact Tests – Wood blocks were exposed to the extinguisher discharge at various distances to compare the physical momentum of the spray pattern from each extinguisher. This provides a gross measure of the impact damage an extinguisher might have when its stream is directed at materials.

Each test was conducted with each type of extinguisher. The following sections describe the test parameters and general approach of each type of test. Scoping tests were performed to refine the specific test parameters. The effect of a fire alone on the representative materials was not evaluated.

5. TEST SETUP AND MATERIALS

5.1. Test Enclosure

Cultural resource materials are commonly exhibited in rooms, display areas, and galleries. It was important to establish an appropriate fire size to room volume ratio. Keeping this ratio low is consistent with the typical application of portable extinguishers in museums and historic buildings, i.e., small fires in large spaces. The neat agent tests were conducted in a large test room at the JENSEN HUGHES' laboratory in Baltimore, Maryland. The internal dimensions of the room were 10 m (33 ft) wide by 10 m (33 ft) deep by 3 m (9.8 ft) high. A photo of the enclosure is shown in Figure 1. Additional schematics are included in Figures 6 through 8 in Section 7.

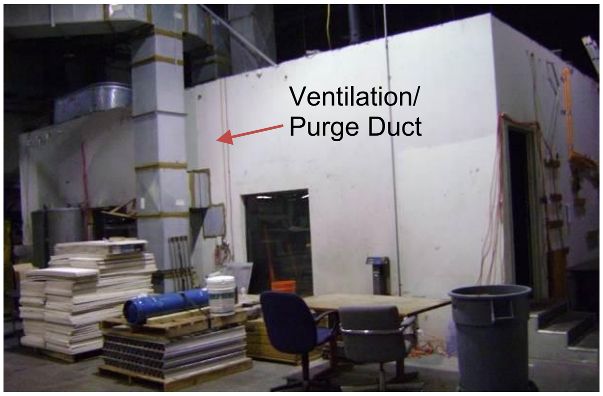

Figure 1 – Test enclosure at JENSEN HUGHES' facility.

The fire exposure tests were performed at the Chesapeake Beach Detachment of the Naval Research Laboratory (NRL) located in Chesapeake Beach, MD. JENSEN HUGHES has a collaborative agreement with NRL to conduct fire tests. The enclosure at this facility was constructed in a similar fashion to the JENSEN HUGHES' test enclosure but was slightly smaller. The interior dimensions were 9.1 m (30 ft) wide by 9.1 m (30 ft) deep by 3 m (9.8 ft) high. This difference was not considered significant in terms of comparison between the two data sets. Additional schematics of the NRL enclosure are included in Figures 19 through 21 in Section 8.

The enclosures were constructed with gypsum wall board over metal or wood stud frames. The wall board joints were taped and the enclosures were painted to provide a clean surface, nominally impervious to the portable extinguisher agents utilized.

5.2. Materials Tested

The cultural resource materials were supplied by CWF. The choice of materials was based on commonality within the museum community and availability of repeatable samples. A full description of the samples will be provided in the final assessment report.

Due to the large number of samples required for testing and the surface area required to test the cleaning techniques, the size of the sample materials was selected to be nominally 10 cm (4 in.) by 10 cm (4 in.). The small sample size also facilitated the use of direct mass measurement of the deposition on the exposed material. The thirteen materials that were exposed in this test program and their associated test designation include:

- Black iron sheet (1.57 mm [20 gauge] thick), Material #1;
- Copper sheet (1.08 mm [0.042 in.] thick), Material #2;
- Aluminum sheet (3.15 mm [0.12 in.] thick), Material #3;
- Vegetable tanned leather (Bovine leather with mimosa tan; 1.87 mm [0.073 in.] thick), Material #4;
- Tulip poplar wood, unvarnished (simulating secondary wood; 6.43 mm [0.25 in.] thick), Material #5;
- Cherry wood, varnished with a shellac (0.57 kg [1.25lb]) varnish (simulating primary wood; 6.43 mm [0.25 in.] thick), Material #6;
- Linen canvas, oil primed and painted with stripes of lead white paint, ivory black and red ochre with bare canvas between the stripes (0.46 mm [0.018 in.] thick), Material #7;
- Linen canvas, acrylic primed and painted with color stripes (0.46 mm [0.018 in.] thick), Material #8;
- Travertine tile, tumbled finish (9.75 mm [0.38 in.] thick), Material #9;
- Marble tile, tumbled finish (10.06 mm [0.41 in.] thick), Material #10;
- White-tailed deerskin (4.17 mm [0.16 in.] thick), Material #11;
- Unglazed terracotta tile (14.52 mm [0.57 in.] thick), Material #12; and
- Glazed ceramic tile (6.90 mm [0.27 in.] thick), Material #13.

Three arrays of samples were exposed during each test, with two samples of each material on each sample array. One array was exposed directly in the spray pattern of the portable extinguisher while the other two arrays were exposed indirectly outside of the spray pattern (see Figure 9 in Section 7.1). The materials directly exposed and on one of the indirectly exposed arrays were cleaned using different techniques over a period of six months and assessed every six months for two years to document the effects of the extinguishing agents on the materials. For one of the indirectly exposed arrays, one sample was used as an uncleaned reference sample and the other was held for possible future chemical analysis using state-of-the-art material characterization techniques.

Two additional, identical sets of materials were prepared. These served as controls. Both of these sets were handled in the same manner as the test samples and travelled to the JENSEN HUGHES facility in Baltimore under the same conditions as the other samples but were not exposed to extinguisher agents. One of these sample sets was cleaned using the same techniques as used on the exposed samples to evaluate the effects of the cleaning methods. The remaining set will serve as an unexposed reference for relative measurements of the effects of the exposures.

The sample materials were mounted on plywood sample arrays using Velcro®. The sample arrays were fully covered with Velcro material and each sample had a minimum of two strips of nominally 1.9 cm (0.75 in.) wide by 10 cm (4 in.) long adhesive-backed Velcro attached. Samples were mounted in a grid on each sample array, with approximately 1.2 cm (0.5 in.) between samples. One sample of each material was located near the center of the sample array and one was located near the perimeter of the sample array.

The test sample array included 26 samples (2 x 13 materials), with the center column containing six samples with reduced vertical spacing between samples. The total exposed area was approximately 56 cm (22 in.) wide by 67 cm (26.5 in.) tall. A schematic of the sample arrangement is shown in Figure 2; a photograph of a typical sample array is shown in Figure 3.

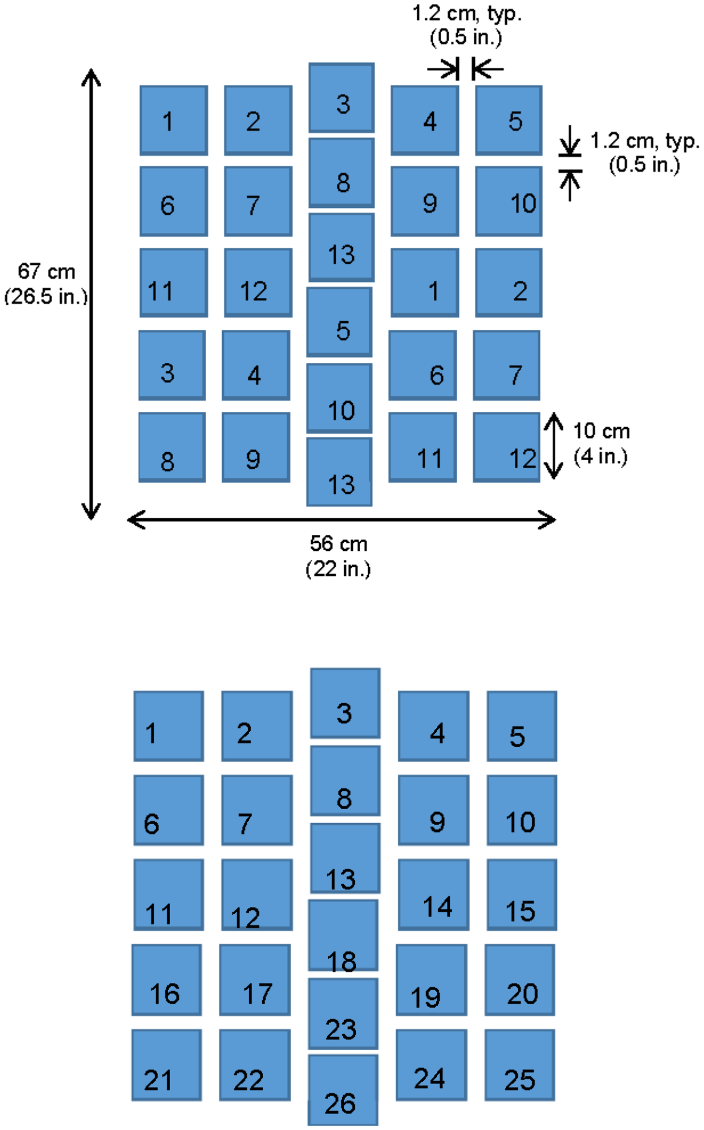

Figure 2 – Sample array schematic with sample material numbers (top) and sample location numbers (bottom).

The samples were placed in the same locations for each test. Each of the 13 sample materials had a unique material number; the material number was listed earlier in this section (i.e., #13 for glazed ceramic tile and #6 for cherry wood). The sample location number was sequentially assigned from left to right and top to bottom of the sample array.

Figure 3 – Typical sample array for exposure tests.

5.3. Material Labeling and Test Identification

Due to the large number of material samples (806) which were prepared and exposed in the test series, a naming convention was developed to facilitate easy sample identification. This naming convention (see Table 1) incorporated the sample material number, location on the sample array, test number, and whether the array was directly or indirectly mounted. The material sequence code was assigned to the samples sequentially as the samples were documented prior to mounting on the sample array. This number provided a method to identify each sample prior to assigning it to a particular test and location. Each sample used in testing was labeled using this convention. For example, using the naming convention in Table 1, for an iron sample with material sequence code #1, in sample location #1 which was exposed to a non-fire test with ABC dry chemical (Test 1A) on the direct sample array, the sample label was: Fe1-1-1A-D. As a second example, using the naming convention in Table 1, for a leather sample (L) with material sequence code #65, in sample location #17, which was exposed to a fire test with ABC dry chemical and water mist (Test 5B) on the indirect wall sample array, the sample label was L65-17-5B-IW. The matrix for the tests conducted is shown in Appendix A.

Table 1 – Sample Naming and Labeling Convention

X1	X2	X3	X4	X5
Material	**Material Sequence Code**	**Sample Location**	**Test Number**	**Sample Array**
Fe – iron Cu – copper Al – aluminum L – leather WU – wood, unpainted (poplar) WV – wood, varnished OC – oil painting, on canvas AC – acrylic painting, on canvas TT – Travertine tile MT – marble tile TCT – terracotta tile PT – porcelain tile WTDF – White-tail deer fur	1 – 80	1 through 26 (see bottom of Figure 2) N/A – for control samples	1A–5A non-fire exposure tests, (Table 3) 1B–6B fire exposure tests, (Table 5)	D – direct IW – indirect, on wall IS – indirect, on stand CC – control cleaning CE – control exemplar

5.4. Portable Extinguishers

The classification of fire extinguishers consists of a letter that indicates the class of fire on which a fire extinguisher has been found to be effective. The classes of fire relevant to collections are Class A, B, and C:

- **Class A fires** are fires in ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics.
- **Class B fires** are fires in flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases.
- **Class C fires** are fires that involve energized electrical equipment.

Fire extinguishers classified for use on Class A or Class B hazards have a rating number preceding the classification letter that indicates their relative extinguishing effectiveness; increasing size fire threats can be extinguished with units having greater numerical ratings. Extinguishers listed for the Class C fires do not have a numerical rating. They may not contain an agent that is a conductor of electricity, however, distilled or de-ionized water may be used in a water mist extinguisher.

Rooms or areas of occupancy are classified generally as being light (low) hazard, ordinary (moderate) hazard, or extra (high) hazard. No quantification of these threat levels is provided in NFPA 10, although qualitative descriptions of these hazard classifications are given. Using the guidance in NFPA 10, collection areas would generally (but not always) be considered light (low) hazard areas. For light hazard occupancies, a portable extinguisher with a minimum 2A rating must be provided subject to maximum coverage area and travel distance requirements. If there are anticipated Class B or C hazards, extinguishers with these ratings must also be provided. This can be achieved with a “multi-purpose” extinguisher with more than one letter classification, or through provision of separate A or B extinguishers. No qualification of Class B hazards for the collection environment is given. All Class C extinguishers also have an associated Class A and/or B rating, since a Class C listing only requires that the agent is electrically non-conductive and does not require any additional fire testing.

There are many types of extinguishers available to combat various fire hazards. The portable extinguishers evaluated were those applicable for use in a museum/cultural heritage type application. These extinguishers had a minimum UL 711 2A rating for A:B:C or A:C fires. The following five extinguisher agents were used:

- ABC Dry Chemical (monoammonium phosphate) [Amerex Model B456];
- Water Mist [Amerex Model B272NM];
- HCFC Blend B (Halotron I) [Amerex Model 398];
- HFC-236fa (FE-36) [Ansul Cleanguard Model FE13]; and
- ABC Dry Chemical [Amerex Model B456] and Water Mist [Amerex Model B272NM].

The combined ABC and water scenario was representative of water application from a sprinkler or water hose after unsuccessful application of an ABC powder extinguisher. The water mist extinguishers were filled with de-ionized water provided by the manufacturer. De-ionized water is typically used in the extinguishers.

Carbon dioxide, CO_2, was tested to determine the physical force impact on cultural resource materials. As CO_2 does not have a Class A rating it is generally not applicable to many museum/cultural heritage scenarios. It was included because of its common usage in support areas and for comparison purposes.

Table 2 lists the extinguishers used. The extinguishers are generally available from several manufacturers. With the exception of the HFC-236fa (FE-36) extinguisher, Amerex provided all of the extinguishers as in-kind support for the project. The FE-36 extinguishers, manufactured by Ansul, were purchased separately from a local distributor. The baseline mass of the ABC extinguisher was set at 4.5 kg (10 lb) of agent, based on input from CWF and the Smithsonian Institution (SI). This is the agent mass of ABC dry chemical typically used for extinguishers in areas with cultural resource materials. The ABC unit specified had a monoammonium phosphate (MAP) content of 92–96%.

Table 2 – Portable Extinguisher Specifications

Property		Units	Gaseous Agents			Dry Powder	Water Mist
			HFC-236fa		IG-001		
Trade Names			FE-36	Halotron I	CO_2	ABC	-
Formula			$C_3H_2F_6$	Blend	CO_2	$NH_4H_2PO_4$	H_2O
Manufacturer			Ansul	Amerex	Amerex	Amerex	Amerex
Model Number			Cleanguard FE13	398	332	B456	B272NM
Storage Conditions		State	Liquid	Liquid	Liquid	Powder	Liquid
		Cylinder Type	Low Press	Low Press	High Press	Low Press	Low Press
Rating			2A:10BC	2A:10BC	10BC	4A:80BC	2AC
Extinguisher Mass		[kg]	11.6	12.5	23.0	8.2	13.1
		[lb]	25.6	27.5	50.8	18.0	28.8
Agent Mass		[kg]	6	7.0	9.1	4.5	9.4
		[lb]	13.25	15.5	20.0	10.0	20.8
Discharge Time (Per Manuf.)		[sec]	13.5	14	19	20	80
Effective Range (Per Manuf.)	Min	[m]	4.3	3.7	0.9	3.7	3.0
		[ft]	14	12	3	12	10
	Max	[m]	4.9	5.5	2.4	5.5	3.7
		[ft]	16	18	8	18	12

6. SCOPING TESTS

6.1. Spray Pattern Tests

The separation distance between the extinguisher and the directly exposed sample array was established through scoping tests. The separation distance established was the distance which gave relatively full coverage by the agent spray to the direct sample array. All extinguishers were tested initially at their maximum effective distance (see Table 2). The discharge distance was gradually reduced until agent spray enveloped the entire array with minimum overspray outside the array. During this testing the nozzle elevation was set at 1.2 m (4.0 ft) above the floor. The extinguisher operator was allowed to adjust the angle of the extinguisher hose/nozzle to ensure complete coverage. A mock sample array with some actual samples was used to verify the spray coverage. A video camera and infrared camera were used to record the spray distribution. It was found that a sweeping technique was not required. While it would have been desirable to establish a quantitative method to assure complete coverage of the targets, no easy way to do this was apparent. Complete coverage was determined visually, with most of the spray pattern hitting the target. Observers agreed that this procedure should be repeatable for any other researchers conducting these tests.

The indirect sample arrays were placed 1.5 m (5.0 ft) in front of the directly exposed array (and between the direct array and the extinguisher nozzle) and offset 1.8 m (6.0 ft) from the center of the direct array as shown in Figure 4. These locations provided some exposure to the indirect samples which was notably less than for the directly exposed sample array. It was decided to establish this criteria for the neat agent tests.

Figure 4 – Neat agent scoping.

The optimal extinguisher separation distances were determined to be between 75% and 90% of the maximum effective range identified in the manufacturer specifications. The following separation distances were established:

- ABC Dry Chemical (monoammonium phosphate): 4.3 m (14 ft);
- Water Mist: 3.0 m (10 ft);
- HCFC Blend B (Halotron I): 4.9 m (16 ft); and
- HFC-236fa (FE-36): 4.3 m (14 ft).

The water mist extinguisher was observed to be a wide cone and not a stream per se, and much of the water ended up on the floor of the test enclosure. The droplets were coarse and not as fine as a high pressure water mist fixed-extinguishing system. The water mist nozzle had to be angled upwards slightly in order for the spray to impact the array. The clean agents (FE-36 and Halotron I) produced somewhat narrow streams of liquid surrounded by wider streams of evaporated (gaseous) agent. The ABC dry chemical extinguisher produced a narrow stream of agent surrounded by a less dense cloud of agent which quickly dispersed into the room.

For future tests, outside of this test program, the distance from the extinguisher to the target should be 90% or less of the published maximum effective range, reduced as appropriate to assure that the pattern is impacting the target. The location of the extinguisher from the direct array is defined as follows: the distance where the agent spray envelops most of the area of the array, with minimum overspray outside the array. This is established visually, with the extinguisher at a fixed height above the floor. The angle of the extinguisher hose/nozzle may be adjusted to achieve the best coverage.

6.2. Fire Test Scoping Results

The objective of the fire exposure tests was to evaluate the effects of the combination of the agents, decomposition products and fire effluent on representative materials. Fires in ordinary (Class A) combustibles appear to be the most common and representative fire threat as identified in Phase I. The early stage magnitude of these threats could not be quantified directly from the loss history, but standardized tests and hazard techniques indicate a maximum threat limit on the order of 1 MW. A realistic scenario, approachable by an unprotected person using a portable fire extinguisher, is probably much lower than this. The use of standard extinguisher test methods (that is, the use of repeatable wood crib fires as the Class A source) was adopted, with the realization that a fire on the order of 200–500 kW would likely be used. Also, it was agreed that the fire should not be of sufficient magnitude to thermally damage exposed materials. This would allow for better assessment of agent effects. The Phase I report describes in detail the rationale for this approach.

Scoping tests were conducted to determine the sizes of the wood crib and associated ignition pan fire that could be readily extinguished by all of the extinguishers. Scoping tests were also conducted to establish the separation distance between the wood crib and the directly exposed sample array. All scoping tests were conducted in the open area of the NRL test facility, with limited ventilation from an overhead exhaust hood. The three criteria that were used to evaluate the scoping fires were: 1) the fire had to be easily extinguished, so that all flaming was extinguished well before the agent was totally expended; 2) agent exposing the direct sample array had to pass through and around the fire source; and 3) agent overspray and smoke/soot must be deposited on the directly exposed sample array without thermally damaging the sample array.

The first wood crib tested was a UL 1A crib (12 layers of 6 pieces per layer of 3.8 by 3.8 by 50.8 cm [1.5 by 1.5 by 20 in.] wood) [4]. The wood crib was ignited with a square pan 40 x 40 x 10 cm (16 x 16 x 4 in.) filled with 400 ml (0.1 gal) of commercial grade heptane. This produced a pan burn time of approximately 100 seconds. The pan was centered 38 cm (15 in.) below the crib. The wood crib was raised off the floor such that the bottom of the crib was approximately 1.2 m (3.1 ft) above the floor.

The crib was allowed to burn for 4 minutes total. This was enough time for the fire to develop in the crib without causing the crib to collapse. UL crib firefighting procedures were then followed. The firefighter began extinguishment from approximately 1.8 m (6.0 ft.) away from the crib and was immediately allowed to approach the crib and aggressively attack the fire. Agent was applied to the front and side faces, from below, and from the top of the crib. Attack from the back face was prohibited. The UL 1A crib was readily extinguished by all of the extinguishers tested. All of the extinguishers required the firefighter to attack the fire from multiple sides. The fire was not suppressed in the initial approach. The entire contents of the extinguishers were discharged. The wood crib produced significant smoke and flames. The flames of the wood crib extended to approximately 3.0 m (9.8 ft) above the floor. This flame height would have touched the ceiling of the test enclosure. It was concluded that this fire threat, plus the significant smoke during extinguishment, did not represent an incipient fire that an unprotected person would be expected to attack.

A smaller crib was then evaluated. The FE-36 extinguisher was used on a UL 1715 wood crib (10 layers of 5 pieces per layer of 3.8 by 3.8 by 38 cm [1.5 by 1.5 by 15 in.] wood) [7]. The same configuration, test stand, and igniting pan was used as in the scoping test with the UL 1A wood crib, except 300 mL of heptane was used. This produced a pan burn time of about 83 seconds. A total crib burn time of 4 minutes was again used. This crib produced a lower flame height (1.2 m [4 ft]) and less smoke and was deemed an appropriate incipient fire source for the fire tests. A photo of the wood crib at the beginning of extinguisher discharge is shown in Figure 5.

Figure 5 – Wood crib scoping fire at beginning of extinguisher discharge.

The separation distance between the wood crib and the directly exposed sample array was also evaluated during this scoping test. A mock sample array with brown paper attached was moved towards the burning wood crib. The sample array was moved within a distance of 0.66 m (26 in.) of the burning crib without any discoloration of the paper. This met the criterion that the target should be close to the crib (to be exposed to the smoke and agent overspray), but not so close as to be thermally damaged. This distance was set as the separation distance between the sample array and the wood crib. In subsequent scoping tests, mock sample arrays were placed at this separation distance and the fire suppressed with an extinguisher. At this distance, all of the mock sample arrays had notable deposits after the tests. This indicated that the separation distance of 0.66 m (26 in.) allowed for fire products and agent deposition on the direct array.

It was determined visually from the firefighting procedures that the indirect target locations used in the neat tests were also appropriate for the fire tests. At these locations, it was determined that the indirect arrays would be exposed to some fire products and agent deposition, but notably less than the direct array.

7. NON-FIRE EXPOSURE TESTS

The objective of the non-fire exposure tests was to evaluate the effects of the neat agents on representative materials under normal environmental conditions. During these tests, the portable extinguisher was discharged directly onto the representative materials from the distance determined in scoping tests. Two additional arrays of representative materials were indirectly exposed. These sets of materials were mounted outside of the extinguisher spray pattern to assess the effects of an indirect exposure. Table 3 is a test matrix of the non-fire exposure tests conducted. All non-fire exposure tests were conducted at the JENSEN HUGHES laboratory in Baltimore, MD.

7.1. Variables and Parameters

The parameters of the non-fire exposure tests which impact the exposure of the samples were: the separation distance between the extinguisher and the directly exposed materials; the off-set distance of the indirectly exposed materials adjacent to and in front of the extinguisher; the orientation of the exposed objects; and the elevation of the exposed objects with respect to the portable extinguisher. These parameters are illustrated in Figures 6 through 8. The doors shown in Figure 6 were 0.91 m (36 in.) wide by 2.0 m (80 in.) tall. The windows were 1.2 m (48 in.) wide by 1.4 m (55 in.) tall. The exhaust opening was

0.5 m (20 in.) square. The separation distance and location of indirect sample arrays were established in scoping tests.

The directly exposed material array was mounted on the enclosure walls in a vertical orientation. The separation distance between the extinguisher nozzle and directly exposed array was determined in scoping tests (see Section 6.1). The following separation distances were used during the non-fire tests:

- ABC Dry Chemical (monoammonium phosphate): 4.3 m (14 ft);
- Water Mist: 3.0 m (10 ft);
- HCFC Blend B (Halotron I): 4.9 m (16 ft); and
- HFC-236fa (FE-36): 4.3 m (14 ft).

One of the indirectly exposed material arrays was mounted on the enclosure wall in a vertical orientation while the second indirectly exposed material array was mounted on a wooden floor stand in a vertical orientation. The indirectly and directly exposed object arrays were centered at the same elevation as the portable extinguisher nozzle outlet. This height was1.2 m (4 ft) above floor. The nozzle elevation and angle were adjusted for the water mist extinguisher as determined in pre-test scoping. The extinguisher was held by an operator. A photograph of the test setup is shown in Figure 9.

Table 3 – Test Matrix for Non-Fire Exposure Tests

Test Number	Extinguisher
1A	ABC Dry Chemical
2A	Water Mist
3A	HCFC Blend B (Halotron I)
4A	HFC-236fa (FE-36)
5A	ABC Dry Chemical and Water Mist

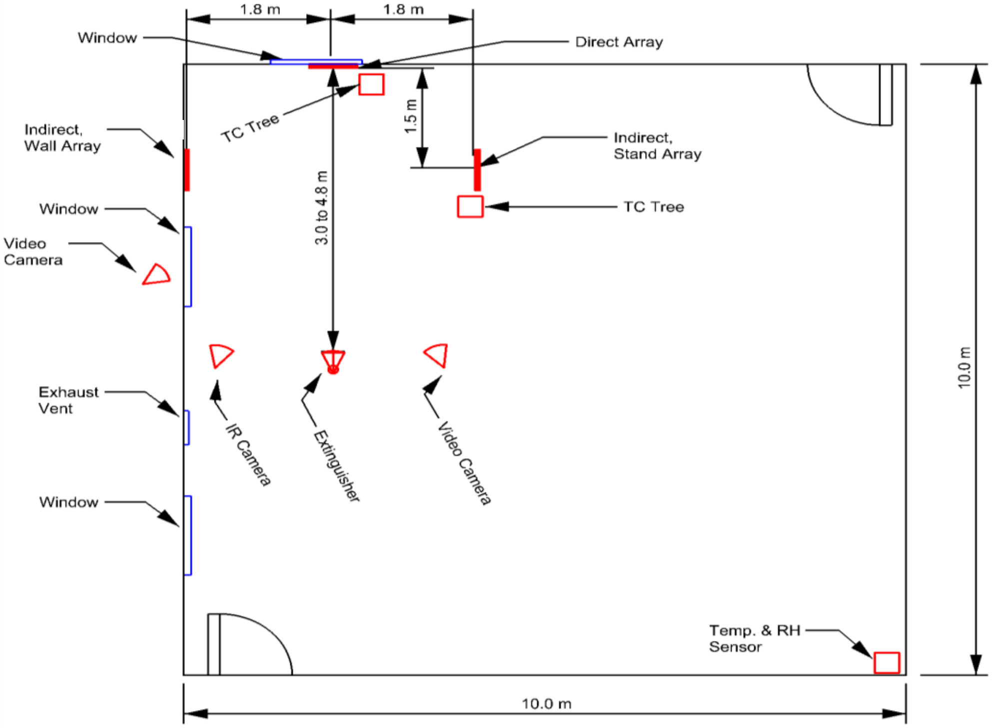

Figure 6 – Non-fire exposure apparatus, plan view.

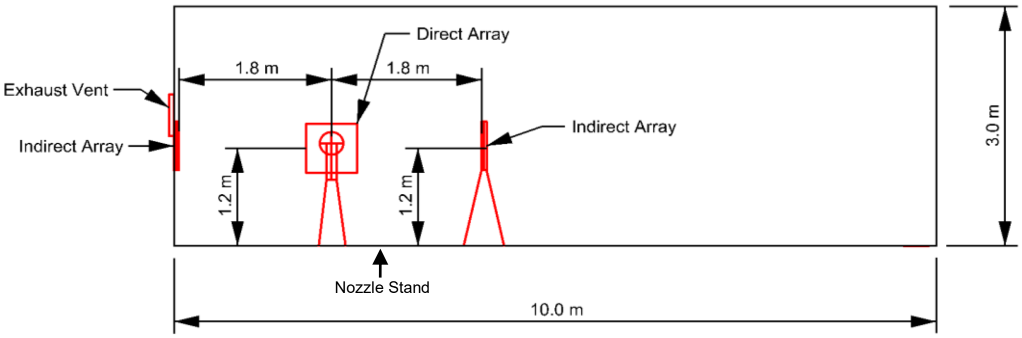

Figure 7 – Non-fire exposure apparatus, elevation view behind extinguisher.

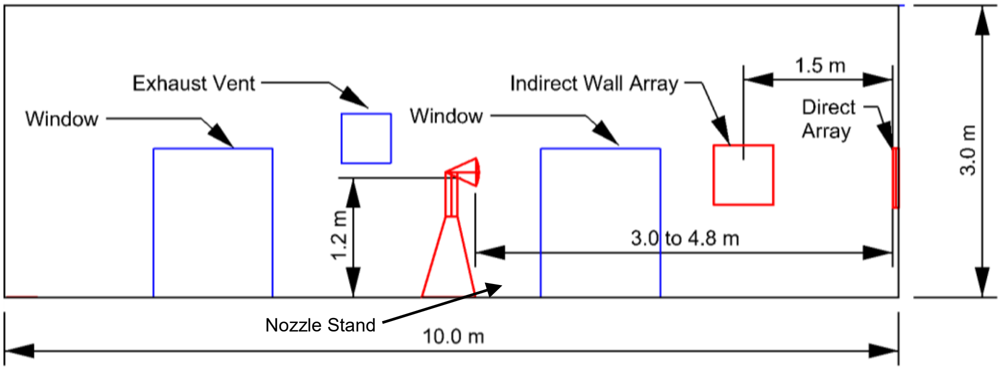

Figure 8 – Non-fire exposure apparatus, elevation view.

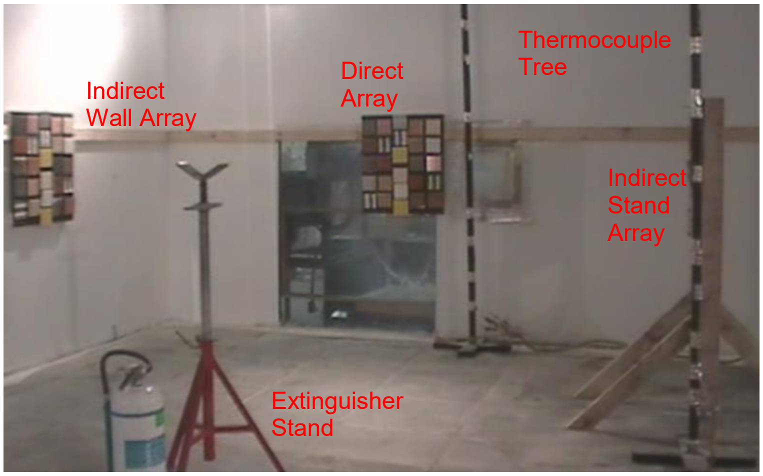

Figure 9 – Non-fire exposure setup.

7.2. Instrumentation

The instrumentation employed during these tests included a scale to measure the deposition on the exposed objects. The scale was able to measure mass with a resolution of 0.001 g ($2.2x10^{-6}$ lb). A scale with a larger resolution (0.1 g [0.0002 lb]) was used for samples weighing over 300 g (0.66 lb). The deposition was not monitored during exposure but was determined by weighing each sample both before and after the exposure.

An examination room located adjacent to the lab area was used for sample preparation, weighing, and processing. It had a temperature and relative humidity sensor (Omega HX93BV0) located near the scale.

This data was recorded at a rate of 1Hz using National Instruments data acquisition hardware and software.

In the test enclosure, the temperature and relative humidity were monitored. Temperatures were recorded at two locations using vertical trees of five, evenly spaced type-K thermocouples at heights of 0.3, 0.9, 1.5, 2.1, and 2.7 m (1, 3, 5, 7, and 9 ft) above the floor. One was installed 0.45 m (1.5 ft) from the center of the indirectly exposed object array and 2.5 cm (1.0 in.) in front of the indirect array. The second was installed 0.45 m (1.5 ft) from the center of the directly-exposed object array and 2.5 cm (1.0 in.) in front of the direct array. In addition, a thermocouple was installed in the center of the directly-exposed object array so that the thermocouple bead was flush with the sample surface. This thermocouple was installed from behind the sample array.

A relative humidity and temperature sensor (Omega model HX92AV) was installed in a corner of the enclosure 1.5 m (5 ft) above the floor as shown in Figure 6. All data was recorded at a rate of 1Hz using National Instruments data acquisition hardware and software.

The general lab space where the test enclosure was located was monitored for temperature and relative humidity using a data-logger (Omega OM-DVTH). Samples were taken at a rate of 1 sample per minute over the entire test day. Data from the data-logger was transferred daily to a computer.

Two video cameras were used to capture the extinguisher activation and spray during the test (see Figure 6). One was located outside of the spray area behind the extinguisher, approximately 6.1 m (20 ft) away from the direct sample array, looking at the direct sample array. The second video camera was located outside of the test enclosure looking through a window perpendicular to the spray. The window was located near the indirect sample array mounted on the wall, approximately 4.3 m (14 ft) away from the direct sample array. An infrared camera (FLIR Model T440) was located inside of the test enclosure, behind the extinguisher approximately 6.1 m (20 ft) away. It was directed at the direct sample array to assess the extinguisher agent impact area. Photographs of the test setup, sample mounting, and extinguisher were taken.

7.3. Procedures

It was agreed by the Technical Panel that no formal temperature and relative humidity test criteria were to be set. The test enclosure temperature and relative humidity were monitored. Test personnel made efforts to prevent extreme temperature and relative humidity conditions in the test enclosure.

Except for the water mist extinguishers, all of the extinguishers came from the vendor in a charged and ready condition. The water mist extinguishers were charged in accordance with manufacturer’s instructions. The extinguishers were filled with deionized water and pressurized to 100 psi using nitrogen. Materials were conditioned to a temperature of 21 ± 4°C (70 ± 8°F) and a relative humidity of 50 ± 10% for a minimum of 5 days prior to the exposure tests. The representative materials were labeled, weighed and mounted in either the directly exposed object array or in the indirectly exposed object arrays. The extinguisher used in the test was then weighed. All doors to the laboratory space were closed and the ventilation system secured.

The data acquisition systems in the test enclosure and the examination room were activated and after one minute, the sample arrays were mounted in their appropriate locations. Each sample array was mounted in the specified locations (see Figure 2). There was no active ventilation during the test and the enclosure doors were closed. The firefighter was positioned in the enclosure near the extinguisher and the doors to the enclosure were closed. As a safety precaution, the firefighter wore a self-contained breathing apparatus and long sleeve work clothing. Both video cameras and the infrared camera were activated.

After 30 seconds of background video, the extinguisher was discharged at the center of the directly exposed object array from the desired separation distance. The fire extinguisher was discharged until it was completely empty. The end of discharge time was recorded. For the ABC plus water mist test, the extinguishers were sequentially discharged, first the ABC unit, then the water mist unit. The firefighter took photos of the sample arrays *in situ* and the doors remained closed. Five minutes after the conclusion of the extinguisher discharge, the sample arrays were removed from the test enclosure by the firefighter and transported to the examination room. This five minute “soak period” allowed any agent dispersed throughout the test enclosure to settle onto the sample arrays.

The process of removing and transporting the sample arrays to the examination was accomplished within one minute. Once all sample arrays were removed, both doors to the test enclosure were opened and the test enclosure was purged using the ventilation system. Video recording was secured. The extinguisher was secured by inserting the pin and the weight was recorded. The data acquisition for the test enclosure was then secured.

In the examination room, the arrays were photographed, the samples were removed and weighed, and visually examined for any sign of damage due to the exposure. Post-test material handling, storage, processing, and examination is detailed in a separate report [8]. Once all samples were examined, the data acquisition in the examination room was secured.

The enclosure floors, walls, and ceiling were vacuumed and/or cleaned as necessary to remove agent before conducting the following test. The test sheet and checklist used in testing is provided in Appendix B.

7.4. Results

This section of the report consists of a summary of the non-fire tests. It does not cover the conservator assessment of exposed materials, which is an ongoing process and will be reported at a later date. Mass measurement data for all samples exposed during testing are included in Appendix C. Temperature and relative humidity data collected for the examination room, the test enclosure and the laboratory space are included in Appendix D.

7.4.1. Extinguisher Discharge

Table 4 is a summary of test data from the non-fire exposures. Appendix D contains plots of the direct array tree temperatures, indirect array tree temperatures, direct array center temperature, and the temperature and relative humidity measurements from the relative humidity sensors in the test enclosure, laboratory space, and examination room. For the test enclosure data on each plot, the extinguisher discharge time is noted. The end of extinguisher discharge time, used to calculate the total discharge time, was defined as the time at which the extinguisher reaches the gas point, i.e., when it began to sputter. This is similar to the discharge duration test conducted in UL 711. In general, determination of this time was consistent between multiple observers. For the gaseous agents, the actual discharge times were generally within 1 second of the manufacturer specified times (see Table 2). For the water mist extinguishers, the actual discharge times were within a few seconds of the manufacturer specified times; one was above and one below the manufacturer specified times. The actual discharge times for the ABC dry chemical extinguishers were approximately 50% higher than the manufacturer listed discharge times, but were consistent between tests. The large differences between actual and manufacturer specified discharge times could be due to differences in measurement of the end of discharge between this test series and the manufacturer procedures; it is unknown how the manufacturers determine the end of discharge for each of the extinguishers.

The quantity of agent discharged was calculated by subtracting the weight of the extinguisher after the discharge was complete from the weight of the extinguisher prior to discharge. For the gaseous agents, the quantity of agent discharged was approximately equal to the manufacturer listed agent quantity for both agents (see Table 2). For the water mist and ABC dry chemical extinguishers a notable amount (i.e., <0.45 kg [1 lb]) of agent remained in the extinguisher.

7.4.2. Temperature and Relative Humidity

After the extinguishers were discharged, there was a general increase in relative humidity in the test enclosure (see Table 4 and Appendix D). Changes in relative humidity overall were moderate and ranged between 1% and 7%. As would be expected, the tests involving a water mist extinguisher created the largest relative humidity increases (7% for Test 2A and 6% for Test 5A). The lowest relative humidity increase was observed for the ABC extinguisher (1% for Test 1A).

Table 4 – Summary of Non-Fire Exposure Test Data

Test No.	Agent	Pre-test Encl. RH (%)	Avg. Exam Room RH During Setup, Test and Exam (%)	Exting. Dis-charge Time (sec)	Agent Discharged (kg (lb))	Min. Direct Sample Array Temp. During Discharge (°C)	Pre-Discharge Max. Ceiling Temp. [Direct, 2.7 m, 9 ft] (°C)	Post-Discharge Min. Ceiling Temp. [Direct, 2.7 m, 9 ft] (°C)	Max. Encl. RH Post-Discharge (%)
1A	ABC Dry Chem	43	45	29	4.4 (9.7)	20	19	19	44
2A	Water Mist	29	35	78	8.9 (19.6)	14	21	20	36
3A	Halotron I	36	41	15	7.0 (15.4)	-23	20	11	40
4A	FE-36	39	43	13	6.0 (13.2)	-41	20	14	44
5A	ABC & Water Mist	45	49	ABC: 33 Water: 85	ABC: 4.4 (9.7) Water: 9.0 (19.8)	15	20	19	51

Prior to the agent discharge, the temperatures in the test enclosure were nominally 20°C. There was some minor variation (generally less than 1°C) based on the specific test and thermocouple location (see Appendix D). A value of 20°C was used as the ambient temperature for further calculations. The temperature changes at the center of the direct array were calculated as the difference between ambient and the minimum temperature reached during the extinguisher discharge. For the ABC dry chemical test, the temperature at the center of the direct array did not change as a result of the discharge. For the tests with water mist extinguishers, including the combined ABC and water mist test, the temperature at the center of the direct array decreased by 6°C for Test 2A and 5°C for Test 5A.

The most significant temperature changes came from the gaseous agents. FE-36 had the largest temperature decrease at the center of the direct array (61°C). Halotron I had a notable, but slightly lower temperature decrease at the center of the direct array of 43°C. These large decreases in temperatures were expected for the gaseous agents because they are in a liquid state within the extinguisher, due to the high cylinder pressure. As Halotron I and FE-36 were discharged, the liquids rapidly evaporated and the temperature decreased dramatically. For the gaseous agents, the temperatures remained at the low values for approximately one minute after the end of discharge before returning to ambient. This was likely due to the presence of liquid agent or frost (from water in the air) that remained on the direct array after the end of discharge (see Figure 10). Although the thermocouple temperatures returned to ambient levels within approximately 1 minute after discharge, there was visible frost remaining on some of the samples at least 6 minutes after discharge (i.e., when samples were photographed in the examination room).

The temperature reductions were largely local; the temperature decrease at the ceiling near the direct sample array was much less than that at the center of the direct array (see Table 4 and Appendix D). The maximum temperature decrease at the thermocouple tree near the direct array for all tests was 9°C (Test 3A).

Figure 10 – Remaining agent and frost after end of discharge of FE-36 extinguisher (Test 4A).

7.4.3. Extinguisher Spray

The spray patterns for the extinguishers were significantly different from each other. This section briefly describes the spray patterns and extinguisher discharge for each agent. The ABC dry chemical extinguisher spray was a narrow stream as shown in Figure 11. After discharge, the agent rapidly formed a cloud as it impacted the enclosure wall. This cloud quickly filled and obscured the interior of the enclosure, reducing enclosure visibility. The firefighter had limited visibility. After the end of the 5 minute “soak period”, much of the agent had settled which allowed greater visibility. The ABC dry chemical spray pattern was consistent between Tests 1A and 5A. During Test 5A, the water mist extinguisher discharge tended to stir up the ABC dry chemical that had been discharged into the enclosure further reducing visibility.

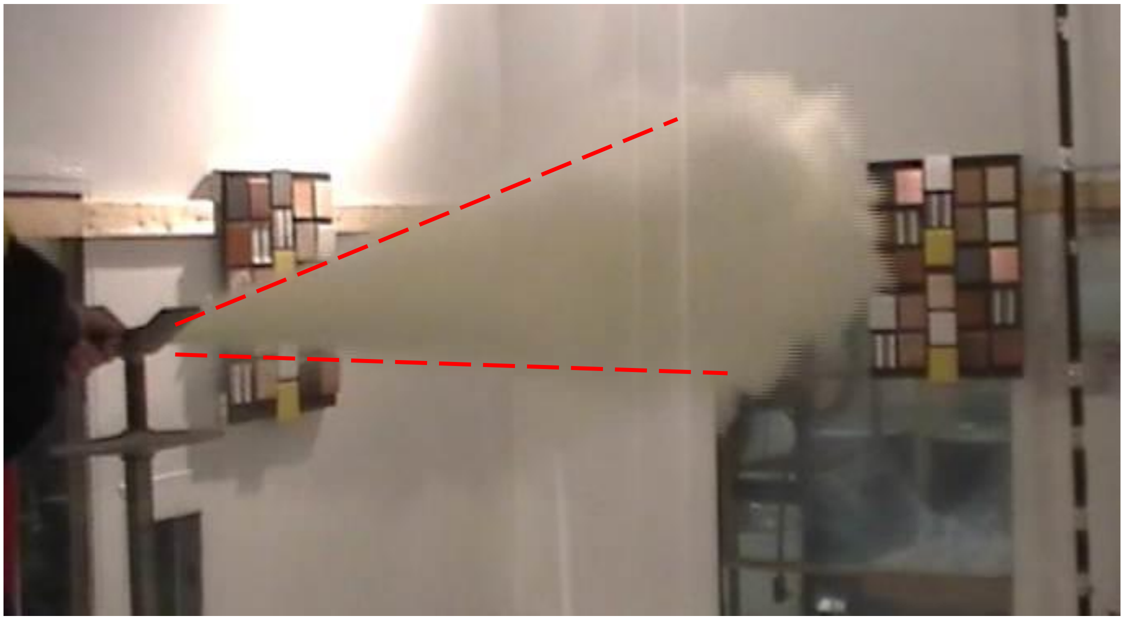

Figure 11 – Typical ABC dry chemical extinguisher spray pattern.

The water mist extinguisher produced a wide spray compared to the other extinguishers as shown in Figure 12 (left). The water mist spray was difficult to capture with photos or video footage; an outline of the spray pattern is shown for reference in Figure 12 (left). The droplets from the water mist extinguisher were relatively large compared to a high-pressure building water mist system. A significant amount of water was deposited on the floor of the enclosure in front of the extinguisher nozzle as outlined in Figure 12 (right). This was consistent between Tests 2A and 5A.

Figure 12 – Typical water mist extinguisher spray pattern (left) and water deposited on the floor (right).

The Halotron I extinguisher produced a narrow gas stream with a minimal amount of liquid agent present in the stream (see Figure 13). By the time the stream reached the direct sample array, most of the liquid had evaporated. The liquid agent quickly evaporated and the gaseous agent cloud quickly dissipated.

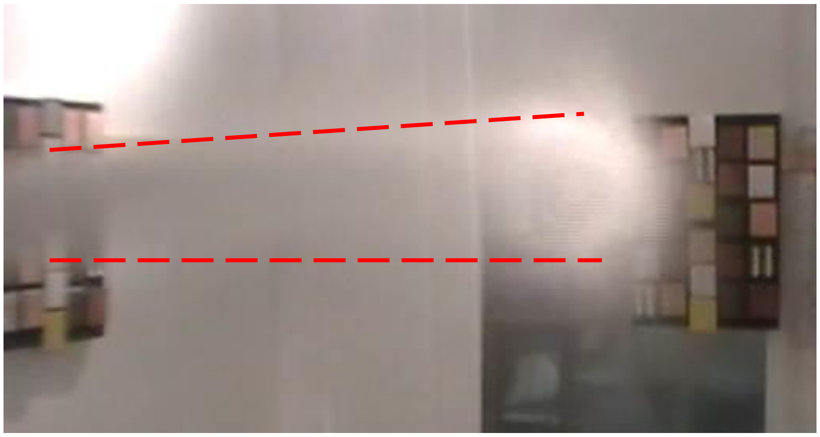

Figure 13 – Typical Halotron I extinguisher spray pattern.

The FE-36 extinguisher produced more of a narrow stream than the Halotron I extinguisher (see Figure 14). The agent stream was mostly liquid as it left the extinguisher; a notable amount of liquid agent remained as the stream impacted the direct array. The liquid agent quickly evaporated and the gaseous agent cloud quickly dissipated.

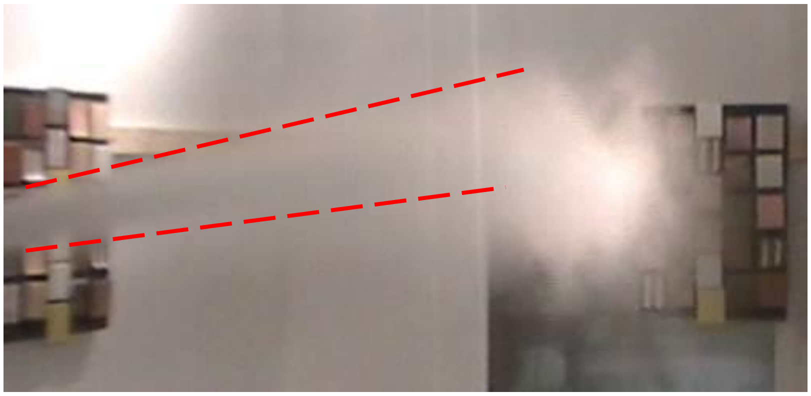

Figure 14 – Typical FE-36 extinguisher spray pattern.

7.4.4. Thermal Imaging of Extinguisher Spray

A FLIR T440 infrared camera was used to capture the agent discharge and impact on the direct sample array. For the ABC dry chemical test (Test 1A), the agent quickly enveloped the direct array and obscured it from view. As the cloud of ABC dry chemical billowed and moved through the enclosure, the direct sample array came in and out of view. The infrared camera was unable to capture the agent impact area for this test. Figure 15 shows the direct sample array prior to agent impact (left) and as the agent impacted and obscured the right side of the direct sample array (right). The temperatures measured using the IR camera are consistent with the observed lack of changed in temperature of the thermocouple located at the center of the direct array.

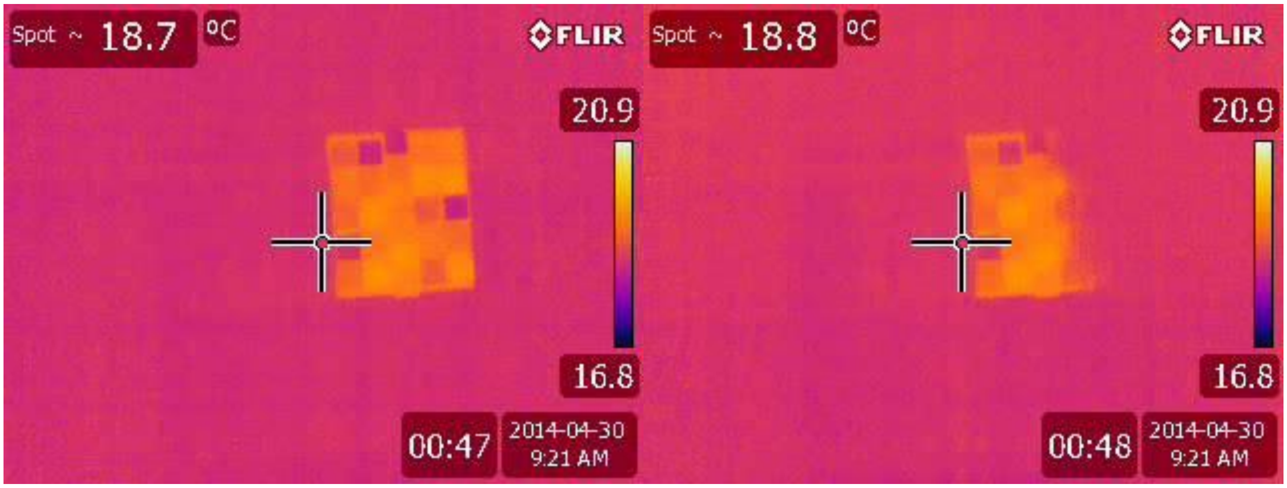

Figure 15 – Infrared images of ABC dry chemical extinguisher discharge prior to discharge (left) and immediately after discharge (right).

For the test with the water mist extinguisher (Test 2A), the infrared camera was out of focus and did not produce a quality image. A temperature drop of nominally 3°C was observed over the area of the direct sample array for an extended period of time during the discharge. This was consistent with the drop in temperature measured at the center of the direct sample array (see Table 4). Given the quality of the unfocused video, the agent coverage area was unclear.

The infrared footage of the Halotron I discharge (Test 3A) showed the only well-defined extinguisher spray pattern and agent impact area out of all of the tests. As shown in Figure 16, the Halotron I discharge is a narrow stream; this is confirmed by the visual image of the spray pattern shown in Figure

13. The extinguisher discharge covered the entire direct array with some overspray to the enclosure wall (based on temperature drop circled in Figure 16). The overspray area is only slightly larger than the size of the direct sample array.

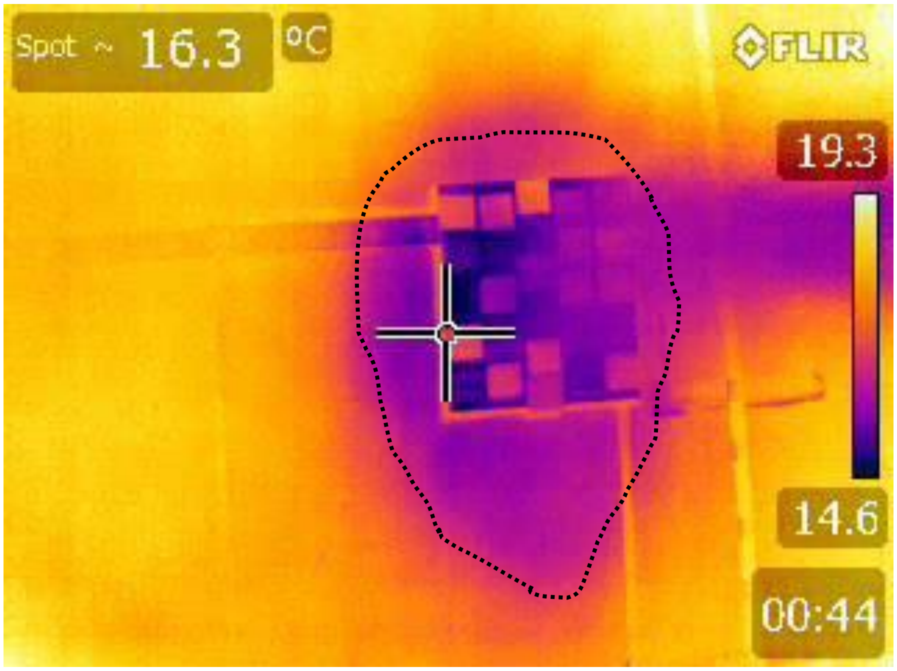

Figure 16 – Typical infrared image of Halotron I extinguisher coverage.

The infrared footage was not captured for the FE-36 extinguisher discharge (Test 4A). Based on the results from Test 3A (Halotron I), the infrared camera would have likely been effective for determining the coverage area for the FE-36 extinguisher also. This was due to the large temperature drops caused by the gaseous agent discharge (see Table 4).

For Test 5A with ABC and water mist, the direct sample array was generally obscured from the infrared camera as was seen for ABC dry chemical only (Test 1A). As the water mist extinguisher was discharged, there was a more uniform obscuration of the direct sample array and the temperature in the enclosure was observed to decrease slightly. It was not clear from footage whether the direct sample array temperature also decreased. No indication of coverage area was apparent from the infrared footage. Overall, the infrared camera was not effective for determining coverage area for the ABC dry chemical or water mist extinguishers.

7.4.5. Extinguisher Agent Deposits

The mass measurements made for each sample pre-test and post-test are presented in Appendix C. In general, there are slight increases in the sample masses for most materials due to deposits of extinguishing agents. The samples on the direct array had the largest increases, with some of the fur samples gaining upwards of 1.0 to 2.0 g (0.0022 to 0.0044 lb). The samples on the indirect arrays generally had smaller increases in mass. In some cases, decreases in mass were measured. These ranged from small decreases of less than 0.1 g (0.00022 lb) to larger decreases up to 1.0 g (0.0022 lb). The decreases in mass could be due to damaged materials. During the water mist test, some of the heavier samples fell to the ground as the moisture impacted the Velcro tape residue. Typically, the samples which fell to the floor broke into several large pieces with some small chips. Although all of the large pieces of material were recovered, it is difficult to know that every small chip was recovered. This may account for some of the discrepancies in weight. Further analysis of the agent deposits will be conducted during the conservator assessments.

8. FIRE EXPOSURE TESTS

The objective of the fire exposure tests was to evaluate the effects of the combination of the agents, decomposition products and fire effluent on representative materials. The portable extinguishers were used to extinguish a wood crib fire with the representative materials mounted nominally downstream of the wood crib. Two other sets of representative materials were located outside of the direct discharge to assess the effects of an indirect exposure. Table 5 is a test matrix of the fire exposure tests conducted. All fire exposure tests were conducted at the Naval Research Laboratory facility in Chesapeake Beach, MD. Two tests using ABC dry chemical and water mist extinguishers were conducted. The second test was conducted to provide samples for a research project being conducted at the College of William and Mary. Test 6B was conducted with only the direct sample array.

Table 5 – Test Matrix for Fire Exposure Tests

Test Number	Extinguisher
1B	ABC Dry Chemical
2B	Water Mist
3B	HCFC Blend B (Halotron I)
4B	HFC-236fa (FE-36)
5B	ABC Dry Chemical and Water Mist
6B	ABC Dry Chemical and Water Mist

8.1. Fire Scenario

The magnitude of the Class A fire used in testing was selected to be below the limit of the extinguishing capacity of the units tested. Scoping tests were performed prior to the fire exposure tests (see Section 6.2) to determine the appropriate wood crib size for use in the fire scenario.

A UL 1715 wood crib was selected as the fire source for the fire exposure tests based on the results of the scoping tests. The crib could be successfully extinguished using the extinguishers selected. Modifications to the UL 1715 wood crib fire test method were adopted from the results of the scoping tests.

The setup is shown in Figures 17 and 18. The crib was raised off the floor such that the bottom of the crib was approximately 0.94 m (3.1 ft) above the floor. The UL 1715 cribs were constructed of 10 layers of 5 members each. Each member was trade 3.8 x 3.8 x 50 cm (1.5 x 1.5 x 15 in.) kiln dried spruce or fir with a moisture content between 9 and 13%. The wood crib was ignited with a square 41 x 41 x 10 cm (16 x 16 x 4 in.) pan filled with 300 ml (0.08 gal) of commercial grade heptane. The pan was centered 38 cm (15 in.) below the crib. A steel crib stand was used to support the wood crib and heptane pan during the test. The stand was constructed of 5 cm (2.0 in.) angle iron and had a footprint of 0.6 m by 0.6 m (2.0 ft by 2.0 ft).

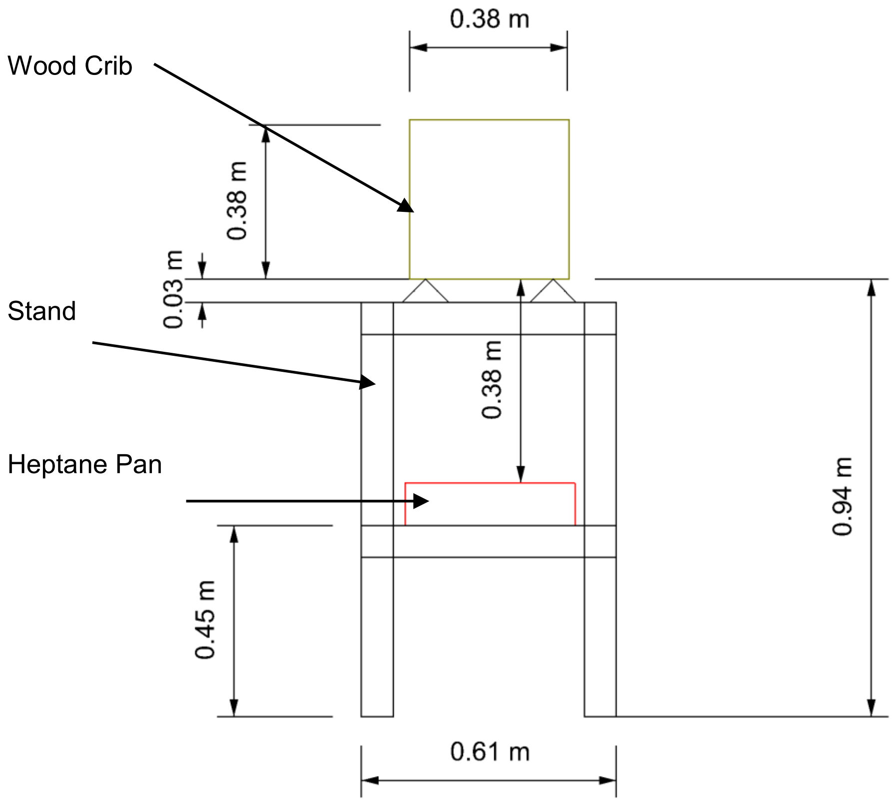

Figure 17 – Elevation view of wood crib stand.

Figure 18 – Wood crib stand.

8.2. Variables and Parameters

The configuration for these tests is shown in Figures 19 through 22. The doors shown in Figure 19 were 0.91 m (36 in.) wide by 2.0 m (80 in.) tall. The windows were 1.2 m (48 in.) wide by 0.91 m (36 in.) tall.

The exhaust opening was 0.45 m (18 in.) square. The representative materials were exposed in arrays of 26 samples, the same as the arrangement utilized during the non-fire tests (see Figure 2). In addition to the parameters described in the non-fire exposure test, the separation distance between the wood crib fire and the directly exposed materials was established in the scoping tests (see Section 6.2); this distance was 0.66 m (26 in.).

The initial firefighter attack distance was determined in scoping tests (see Section 6.2); this distance was 1.8 m (6.0 ft). As in the non-fire enclosure tests, the indirectly exposed object arrays were located at the same relative distances (to the direct sample array) as was used for the non-fire tests. Directly exposed objects were mounted on the enclosure wall in a vertical orientation. One of the indirectly exposed material arrays was mounted on the enclosure wall in a vertical orientation while the second indirectly exposed material array was mounted on a wooden floor stand in a vertical orientation. The indirectly and directly exposed object arrays were centered approximately 1.2 m (4 ft) above the floor.

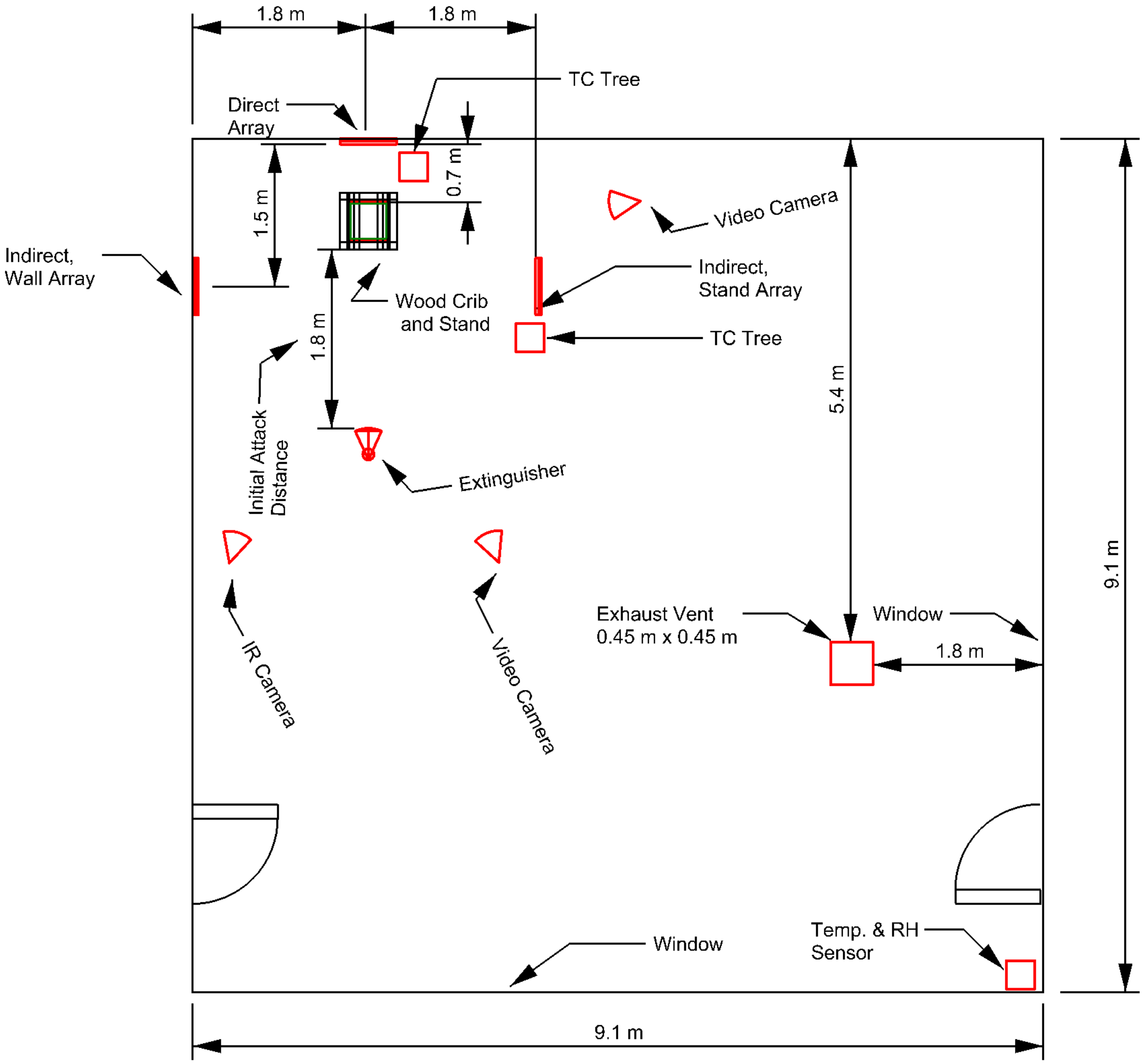

Figure 19 – Fire exposure configuration, plan view.

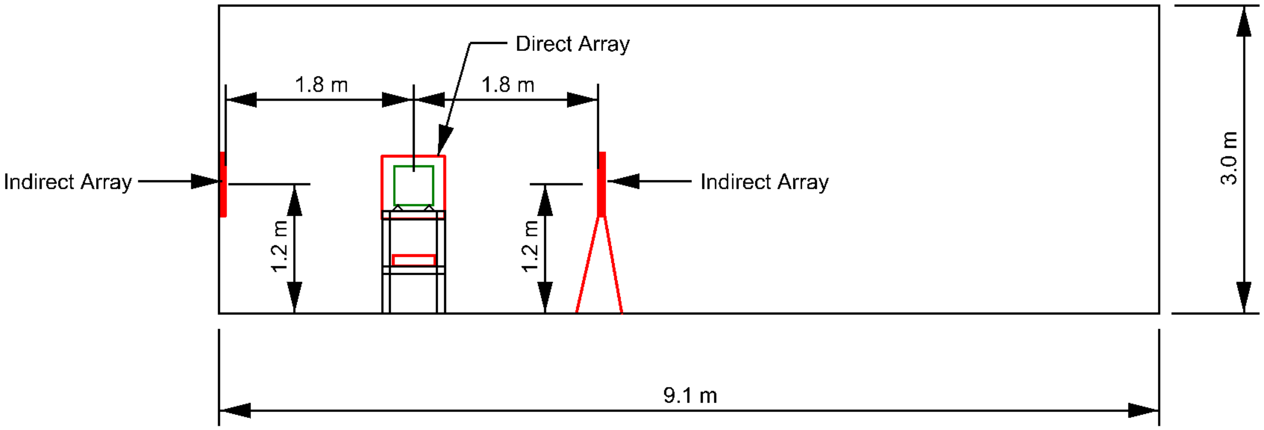

Figure 20 – Fire exposure configuration, elevation view behind extinguisher.

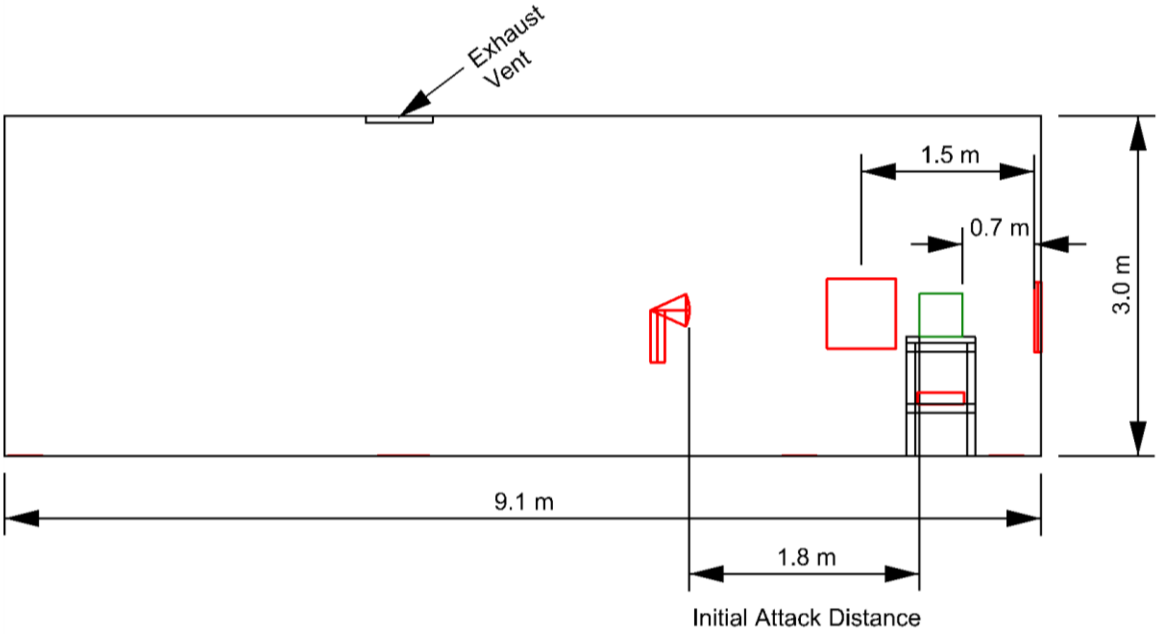

Figure 21 – Fire exposure configuration, elevation view beside extinguisher.

Figure 22 – Fire exposure test setup.

8.3. Instrumentation

The instrumentation employed during the fire exposure tests was the same as for the non-fire exposure tests (see Section 7.2). In addition, a Rhorback Cosasco Environmental Condition Monitoring System (ECM) was installed. This device measures the atmospheric corrosion by use of a sacrificial metal circuit which degrades as a result of corrosion. The ECM reader calculates the metal loss in Angstroms (Å) based on the change in resistance of the circuit. Two thin film (2500 Å) circuits were used for each test (Rhorback Cosasco model 610); the circuits were copper and silver. These devices were installed in the center of the direct sample array (see Figure 23).

The metal loss values, i.e. the resistances, of the circuits were measured prior to exposure to determine a baseline. The metal loss values were then measured after the exposure. The difference between the baseline and the value measured after the exposure is the effect of the immediate atmospheric corrosion from the extinguisher agent discharge. In addition, the metal loss values will be measured periodically throughout the test program to determine the amount of corrosion over time.

The measurement procedures were as follows:

1. Ensure ECM reader is off.
2. Insert sensors in correct slots in ECM reader.
3. Turn on ECM reader.
4. Wait 10 minutes, record metal loss for each sensor.
5. Turn off ECM reader and remove sensors.

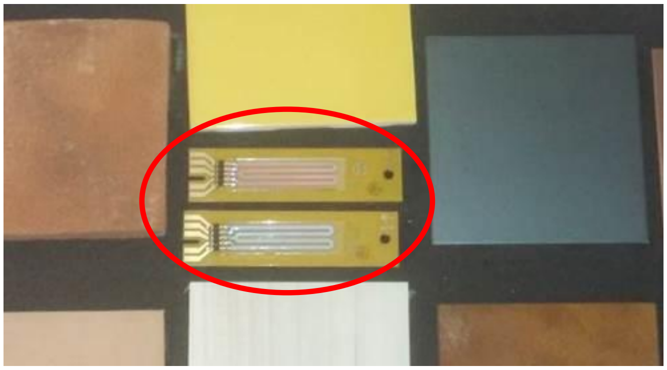

Figure 23 – Corrosion monitoring devices (circled) in sample array.

8.4. Procedures

It was agreed by the Technical Panel that no formal temperature and relative humidity test criteria were to be set. The test enclosure temperature and relative humidity were monitored.

Extinguishers were charged in accordance with manufacturer's specifications. Materials were conditioned to a temperature of 21 ± 4°C (70 ± 8°F) and a relative humidity of 50 ± 10% for a minimum of 5 days prior to the exposure tests. Velcro® was applied to the back of each sample. The representative materials were then labeled, weighed and mounted on either the directly exposed object array or the indirectly exposed object arrays.

Velcro® was attached to the corrosion sensors, a baseline measurement was taken, and the sensors were mounted to the direct sample array. The extinguisher used in the test was weighed. Then all doors to the laboratory space were closed.

Doors to the enclosure were shut during the fire test. Natural ventilation was provided by a 0.45 by 0.45 m (18 in. by 18 in.) louvered vent in the ceiling. The louvered vent was located away from the fire in the opposite corner of the fire (see Figure 19). The data acquisition systems in the test enclosure and the examination room were activated and after one minute, the sample arrays were mounted in their appropriate locations. Two samples of each material were mounted on each sample array in the specified locations (see Figure 2).

The wood crib was placed in its stand above the ignition pan. Both video cameras were activated. The pan was then filled with 300 ml (0.08 gal) of commercial grade n-heptane. The firefighter was positioned in the enclosure near the extinguisher.

After 30 seconds of background, the ignition pan beneath the wood crib was lit and the doors to the enclosure were shut. The wood crib was allowed to burn for four minutes. The firefighter then began to suppress the fire with the portable extinguisher, starting from 1.8 m (6.0 ft), aligned with the directly exposed material array. The firefighter was allowed to advance on the crib and move toward either side of the crib, the top and bottom as necessary to cause extinguishment. The firefighter was not allowed to attack the crib from behind (nearest the directly exposed array). The firefighter fully discharged the fire extinguisher onto the wood crib; the end of discharge time was recorded. Where both the ABC and water mist extinguishers were used, the water mist extinguisher was fully discharged on to the wood crib after the ABC extinguisher was fully discharged. The end of water mist discharge time was recorded. Five minutes after the conclusion of the extinguisher discharge, the sample arrays were removed from the test enclosure by the firefighter and transported to the examination room. The sample arrays were left in the test enclosure for the five minute soak period in order to allow agent dispersed in the test enclosure to settle onto the sample arrays. Photographs were taken of the sample arrays as the arrays were removed from the test enclosure.

The process of removing and transporting the sample arrays to the examination was accomplished within one minute. Once all the sample arrays were removed, both doors to the test enclosure were opened and the test enclosure was purged. Video recording was then secured. The extinguisher was secured by inserting the pin and the weight was recorded. The data acquisition for the test enclosure was then secured. The wood crib was weighed.

In the examination room, the samples arrays were photographed, the samples were removed, weighed and visually examined for any sign of damage due to the exposure. Once all samples were examined, the data acquisition in the examination room was secured.

The enclosure floors, walls, and ceiling were vacuumed and/or cleaned as necessary to remove agent before conducting the following test. A test sheet and checklist is provided in Appendix E.

8.5. Results

This section of the report is a summary of the fire exposure test results. This report does not cover the conservator assessment. The conservator assessment results are reported in a separate report [8]. Mass measurement data for all samples exposed during testing is included in Appendix C.

Tables 6 and 7 are summaries of test data for the fire exposure tests. Appendix D contains plots of the direct tree temperatures, indirect tree temperatures, direct array center temperature, and the temperature and relative humidity measurements from the relative humidity sensors in the laboratory, test enclosure, and examination room. The test enclosure data plots include: the ignition, pan burnout, and extinguisher discharge. The total discharge time and quantity of agent discharged were calculated in the same manner as noted in Section 7.4.1. The results for the total discharge time and quantity of agent discharge were very similar to the non-fire exposure tests.

The extinguishing time was visually determined as the time after initial discharge at which all flaming of the wood crib was extinguished. There was good agreement between multiple observers for determination of extinguishing time. All of the extinguishing times were less than or equal to 6 seconds. The ABC dry chemical extinguishers had extinguishing times of 1 second in both tests. Figure 24 shows several images of the wood crib during a test: one 6 seconds after ignition of the heptane pan, one just prior to burnout of the heptane pan (approx. 80 seconds after ignition of the heptane pan), one immediately prior to extinguisher discharge, and one during extinguishment.

The wood crib mass loss was estimated by calculating the difference between the pre-test wood crib mass and the post-test wood crib mass. The mass loss rate was estimated by dividing the wood crib mass loss by the total burn time (i.e., 4 minute pre-burn time plus extinguishment time). An estimation of the amount of agent which may have been deposited on the crib was not attempted. With the exception of Test 2B, all of the wood crib mass loss values were on the order of 2.0 kg (4.4 lb). For Test 2B, it is likely that water retained by the crib lowered the apparent mass loss. Based on visual observations and temperature data (see Appendix D), the wood cribs appeared to burn uniformly and similarly for all tests. This translated to an estimated average heat release rate of 200 kW.

Table 6 – Summary of Fire Exposure Test Data

Test Number	Agent	Extinguishing Time (sec)	Extinguisher Discharge Time (sec)	Agent Discharged (kg (lb))	Wood Crib Mass Loss (kg (lb))	Estimated Wood Crib Mass Loss Rate (kg/s (lb/s))
1B	ABC Dry Chem	3	33	4.5 (9.9)	2.1 (4.7)	0.009 (0.020)
2B	Water Mist	6	88	9.0 (19.8)	0.27 (0.6)	0.0009 (0.002)
3B	Halotron I	3	13	7.0 (15.5)	2.7 (5.9)	0.010 (0.024)
4B	FE-36	4	14	6.0 (13.2)	2.7 (6.0)	0.011 (0.025)
5B	ABC Dry Chem & Water Mist	1	ABC: 34 Water: 83	ABC: 4.5 (9.9) Water: 8.8 (19.4)	1.8 (4.1)	0.008 (0.017)
6B	ABC Dry Chem & Water Mist	1	ABC: 32 Water: 93	ABC: 4.5 (9.9) Water: 9.0 (19.8)	1.7 (3.7)	0.007 (0.016)

Table 7 – Fire Test Environmental Conditions

Test No.	Agent	Pre-Test Enclosure RH (%)	Average Exam Room RH (%)	Post-Discharge Direct Sample Array Temperature (°C)	Max Ceiling Temperature During 4 min. Pre-Burn [Direct, 2.7m (9 ft)] (°C)	Ceiling Temperature 30 sec. After End of Discharge [Direct, 2.7m m (9 ft)] (°C)	Maximum Enclosure RH During Fire (%)	Maximum Enclosure RH Post-Discharge (%)
1B	ABC Dry Chemical	70	49	55	206	99	80	100
2B	Water Mist	51	48	31	209	96	72	93
3B	Halotron I	74	49	-3	209	101	88	98
4B	FE-36	78	49	18	212	102	79	98
5B	ABC & Water Mist	83	50	58	198	97	94	100
6B	ABC & Water Mist	84	50	61	186	91	88	98

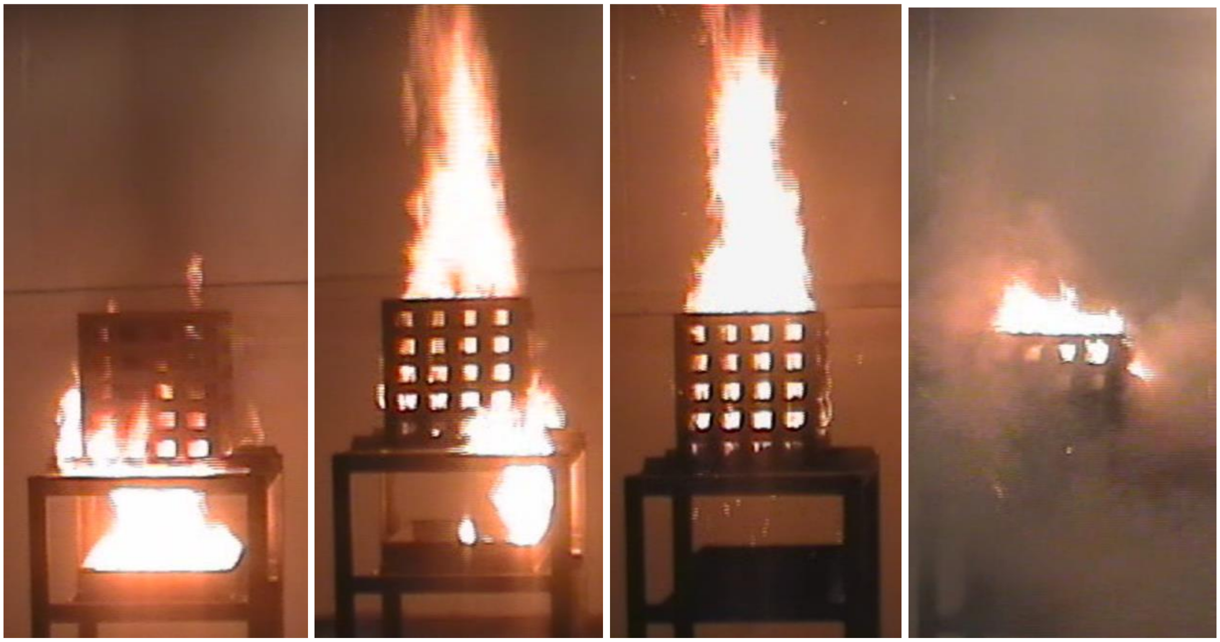

Figure 24 – Typical combustion of wood crib: 6 seconds after ignition of pan (left), 80 seconds after ignition—near burnout of pan (center-left), immediately prior to extinguishment (center-right), and during extinguishment (right).

The pre-test enclosure relative humidity values for the fire exposure tests (Table 7 and Appendix D) were appreciably higher than for the non-fire exposure tests (Table 4). This is attributed to the non-conditioned building used for the fire tests compared to the conditioned building for the non-fire tests. The test samples were prepared and mounted in the conditioned examination room which was nominally 50% RH as shown in Table 7 (see plots in Appendix D). During the fire there was a general increase in relative humidity in the test enclosure. The increase in relative humidity varied widely between tests; from 1% RH for Test 4B (FE-36) to 21% for Test 2B (water mist). After the extinguishers were discharged, the relative humidity spiked to nearly 100% RH for every test (see plots in Appendix D).

Prior to the agent discharge, the temperatures in the test enclosure were nominally 25°C (see Appendix D); this was slightly higher than for the non-fire exposure tests but still in the range of what is considered normal indoor ambient temperatures. There was some minor variation (generally less than 2–3°C) based on the specific test and thermocouple location.

The maximum ceiling temperatures during the wood crib pre-burn, prior to the extinguisher discharge (i.e., at the 2.7 m [9 ft] height near the direct array) were between 186°C and 212°C (average: 203°C). This is indicative of a fairly reproducible fire scenario. The post-discharge ceiling temperatures were taken 30 seconds after extinguisher discharge to approximate the temperature drop due to the extinguisher discharge. These temperatures were for the 2.7 m (9 ft) thermocouple height near the direct array. The extinguisher discharge lowered the temperatures by between 95°C and 113°C (average: 105°C).

8.5.1. Extinguisher Agent Deposits

The mass measurements made for each sample pre-test and post-test are presented in Appendix C. In general, the mass measurements exhibit the same trends as the non-fire exposure tests. There did not appear to be any effect of the fire on the change in sample mass. The samples on the direct array had the largest increases with some of the fur samples gaining upwards of 1.0 to 2.0 g (0.0022 to 0.0044 lb). The samples on the indirect arrays generally had smaller increases in mass. In some cases, decreases in mass were measured. These ranged from small decreases of less than 0.1 g (0.00022 lb) to larger decreases up to 1.0 g (0.0022 lb). The decreases in mass could be due to damaged materials. During the water mist test, some of the heavier samples fell to the ground as the moisture impacted the Velcro tape residue. Typically, the samples which fell to the floor broke into several large pieces with some small chips. Although all of the large pieces of material were recovered, it is difficult to know that every small chip was recovered. This may account for some of the discrepancies in weight. Further analysis of the agent deposits will be conducted during the conservator assessments.

8.5.2. Initial Corrosion Measurements

Measurements of metal loss (i.e., corrosion) from the corrosion monitoring devices were conducted as outlined in Section 8.3. Table 8 contains a summary of the metal loss due to agent exposure for the silver and copper devices for each test. For Test 6B, the copper corrosion monitoring device was broken during removal from the sample array. The majority of the corrosion sensors registered a positive change in metal loss which was low (<3 Å). This suggests that the extinguishing agents provided no immediate corrosive effects. However, some anomalies were observed. The copper sensor for Test 3B registered a negative 28 A change; the post-test measurement was taken twice to confirm; no change was observed between the two post-test measurements. For Test 5B, both sensors registered >30 Å changes while for Test 6B, the Ag sensor registered +1 and the Cu sensor was broken (no reading possible). It would be expected that the results from Tests 5B and 6B would be similar. There are no obvious explanations for these anomalies, but it is possible that they are a result of surface deposits (liquid and/or solid) on the corrosion sensors. The sensors were not cleaned after the test and deposits remained on them during measurements. The corrosion measurement devices will be periodically monitored by the conservator team to assess long term corrosion.

Table 8 – Summary of Corrosion Data

Test Number	**Agent**	**Silver Metal Loss (Å)**	**Copper Metal Loss (Å)**
1B	ABC Dry Chemical	8	1
2B	Water Mist	2	1
3B	Halotron I	3	-28
4B	FE-36	2	0
5B	ABC & Water Mist	36	31
6B	ABC & Water Mist	1	NM

NM – Not measured. Sensor Broken.

9. PHYSICAL IMPACT TESTS

The physical impact tests were used to evaluate the potential of the extinguisher flows to topple or dislodge an object. This is a surrogate measure of damage from an accidental or malicious discharge. Wooden blocks of various sizes were used as surrogates for cultural resource materials. The intent of the tests was to determine the maximum separation distance at which an extinguisher would topple each block. This separation distance could then be used to compare the force of extinguisher discharge to other units.

9.1. Variables and Parameters

All extinguishers used in the exposure tests as well as the CO_2 were evaluated. A test matrix is provided in Table 9. The extinguisher agent stream was discharged at the top of a wood block as illustrated in Figure 25. The block was set on end on top of a stand, nominally 1.2 m (4 ft) above the floor, at the same height as the nozzle of the extinguisher. The stand was nominally 0.6 m (2 ft) square. The block was placed on the center of the stand on the side closest to the extinguisher (see Figure 26). These tests were performed inside the test enclosure located at the Naval Research Laboratory facility. This ensured a wind free environment.

Table 9 – Test Matrix for Physical Impact Tests

Test Number	Extinguisher
1C	ABC Dry Chemical
2C	Water Mist
3C	HCFC Blend B (Halotron I)
4C	HFC-236fa (FE-36)
5C	Carbon Dioxide (CO_2)

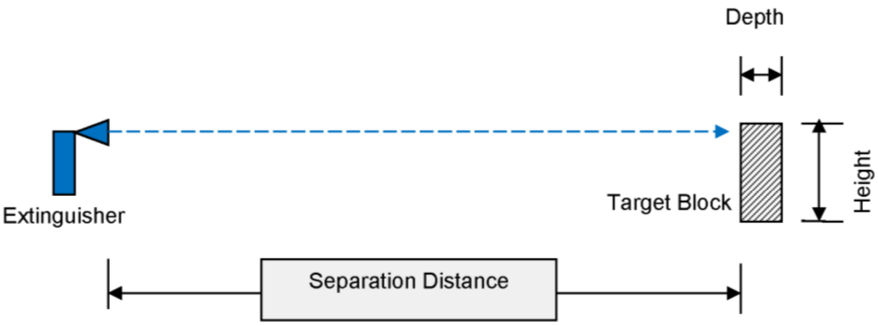

Figure 25 – Topple potential test setup (side view).

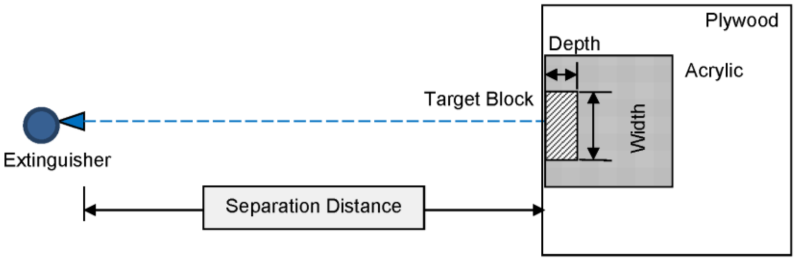

Figure 26 – Topple potential stand and block arrangement (plan view).

The top of the stand was constructed of a sheet of acrylic centered atop plywood; the surface was smooth, flat, and level. The blocks were constructed from 2” by 2” and 4” by 4” dimensional lumber. The block dimensions and masses are listed in Table 10.

Table 10 – Block Dimensions and Mass

	Dimensions			
	Width	Depth	Height	Mass
Object	cm (in.)	cm (in.)	cm (in.)	kg (lb)
Wood Block 1	3.8 (1.5)	3.8 (1.5)	50.0 (19.7)	0.34 (0.75)
Wood Block 2	8.9 (3.5)	8.9 (3.5)	50.0 (19.7)	2.05 (4.52)

9.2. Instrumentation

A video camera was used to record the toppling tests. This video camera was placed perpendicular to the extinguisher discharge viewing the side of the test setup.

9.3. Procedures

The wood block was set atop the stand and positioned in the correct orientation as noted in Table 9 and Figure 25. The extinguisher was discharged at the top of the block from the initial separation distance previously established.

The extinguisher was discharged at the wood block for short bursts (i.e., 5 seconds or less). Only half of the extinguisher, by mass, was discharged to account for the diminishing pressure within the extinguisher as agent was discharged. No correction to the toppling distance was made for changes to the pressure within the extinguishers. This is a limitation of the testing conducted. Any movement (sliding or toppling or wobbling) was noted. The extinguisher was moved further away (if it toppled the block) or closer (if it did not topple the block) as required. The furthest distance that caused the block to topple over was recorded as the critical topple distance for that block/extinguisher combination.

9.4. Results

A summary of the physical impact test data is shown in Table 11. Figure 27 shows an example of the Halotron I extinguisher toppling Wood Block 2.

Table 11 – Summary of Critical Toppling Distance Data

Test No	Critical Toppling Distance (m (ft))			Manuf. Maximum Effective Range (m (ft))
	Agent	Wood Block 1	Wood Block 2	
1C	ABC Dry Chem	4.3 (14)	1.5 (5)	5.5 (18)
2C	Water Mist	2.1 (7)	0.05 (0.17)	3.7 (12)
3C	Halotron	5.8 (19)	2.1 (7)	5.5 (18)
4C	FE-36	6.0+ (20+)	2.4 (8)	4.9 (16)
5C	CO_2	2.4 (8)	0.6 (2)	2.4 (8)

The gaseous agents had the largest critical toppling distances of all of the extinguishers, i.e., demonstrating the largest toppling potential (i.e., force). For Wood Block 1, the critical toppling distance could not be measured above 6.0 m (20 ft) due to the size of the room. The ranking of toppling potential from largest to smallest was:

1. FE-36;
2. Halotron I;
3. ABC dry chemical;
4. CO_2; and
5. Water Mist.

The ranking of toppling potential was independent of the wood block used. The critical toppling distance for Wood Block 1 approximated the manufacturer listed maximum effective range of the extinguishers. The water mist extinguisher had the lowest toppling potential, requiring a separation distance of 5 cm (0.17 ft) to topple Wood Block 2.

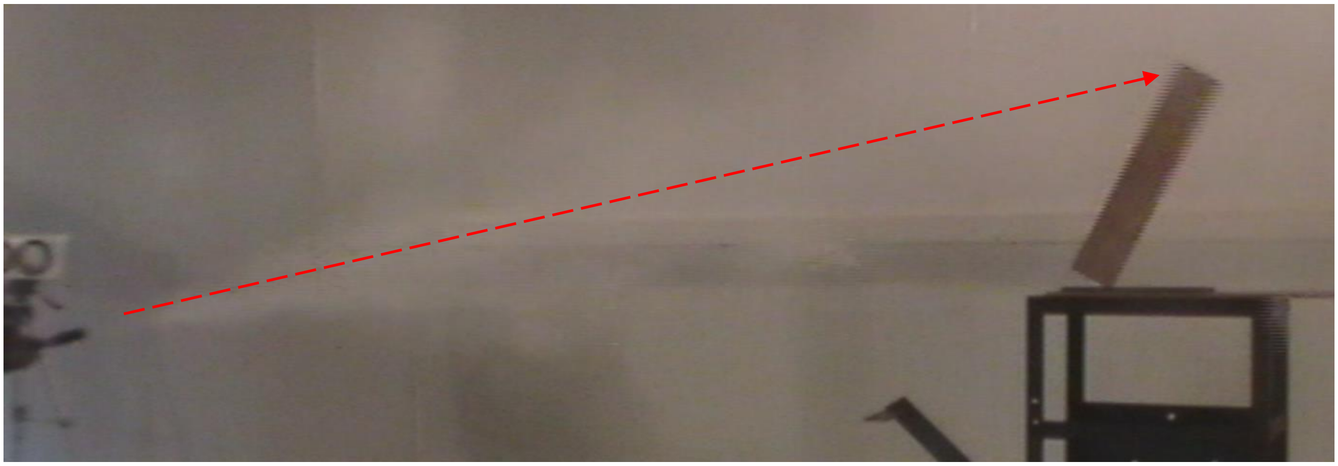

Figure 27 – Halotron I toppling Wood Block 2.

10. CONSERVATOR ASSESSMENT OF EXPOSED MATERIALS

The materials exposed in these tests were assessed post treatment by one of the team members, a conservator at the Colonial Williamsburg Foundation. The objective of this part of the study was to examine the effects of the extinguishing agents on materials commonly used to create cultural heritage materials. A subsidiary goal was to examine which cleaning methods, commonly used by conservators and collections care specialists, are more or less effective at removing the extinguishing agents. This portion of the study is reported in a separate report [8]. The timing of cleaning and assessments is shown in Appendix A.

11. REFERENCES

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3) Jensen, G., “Manual Fire Extinguisher Equipment for Protection of Heritage,” Riksantikvaren Norwegian Directorate for Cultural Heritage (RNDCH), Oslo, Norway, 2006.

4) UL 711, “Rating and Fire Testing of Fire Extinguishers,” Underwriters Laboratories, Northbrook, IL, 2004.

5) Fire Extinguishants and Cultural Resource Collections Phase II, Project Technical Panel Meeting Report, Monday November 4, 2013.

6) Scheffey, J.L., Forssell, E.W., and Benfer, M.E., “Quantifying the Impact of Portable Fire Extinguisher Agents on Cultural Resource Materials – Test Plan,” Fire Protection Research Foundation, Quincy, MA, May 2014.

7) UL 1715, “Standard for Fire Test of Interior Finish Material,” Underwriters Laboratories, Northbrook, IL, 1997.

8) Williams, E., Benfer, M., and Scheffey, J., “Assessing the Impact of Fire Extinguisher Agents on Cultural Resource Materials,” Fire Protection Research Foundation, Quincy, MA, 2016.

APPENDIX A – TEST MATRIX

Test No.	Extinguisher Agent	Test Type	Agent Application	Cleaning	Cleaning Schedule	Assessment Schedule	No. of Samples	Notes
n/a	n/a	n/a	n/a	n/a	n/a		13	Control for materials
n/a	n/a	n/a	n/a	yes	immediate		13	Control for cleaning
1A	ABC dry Chemical	Non-Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
1A	ABC dry Chemical	Non-Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
1A	ABC dry Chemical	Non-Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
1A	ABC dry Chemical	Non-Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
1A	ABC dry Chemical	Non-Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
1A	ABC dry Chemical	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
1B	ABC dry Chemical	Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
1B	ABC dry Chemical	Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
1B	ABC dry Chemical	Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
1B	ABC dry Chemical	Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
1B	ABC dry Chemical	Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
1B	ABC dry Chemical	Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
2A	Water-mist	Non-Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
2A	Water-mist	Non-Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
2A	Water-mist	Non-Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
2A	Water-mist	Non-Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
2A	Water-mist	Non-Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
2A	Water-mist	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
2B	Water-mist	Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
2B	Water-mist	Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
2B	Water-mist	Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
2B	Water-mist	Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
2B	Water-mist	Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
2B	Water-mist	Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
3A	HCFC Blend B (Halotron I)	Non-Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
3A	HCFC Blend B (Halotron I)	Non-Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	

Test No.	Extinguisher Agent	Test Type	Agent Application	Cleaning	Cleaning Schedule	Assessment Schedule	No. of Samples	Notes
3A	HCFC Blend B (Halotron I)	Non-Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
3A	HCFC Blend B (Halotron I)	Non-Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
3A	HCFC Blend B (Halotron I)	Non-Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
3A	HCFC Blend B (Halotron I)	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
3A	HCFC Blend B (Halotron I)	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
3B	HCFC Blend B (Halotron I)	Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
3B	HCFC Blend B (Halotron I)	Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
3B	HCFC Blend B (Halotron I)	Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
3B	HCFC Blend B (Halotron I)	Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
3B	HCFC Blend B (Halotron I)	Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
3B	HCFC Blend B (Halotron I)	Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
4A	HFC-236fa (FE-36)	Non-Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
4A	HFC-236fa (FE-36)	Non-Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
4A	HFC-236fa (FE-36)	Non-Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
4A	HFC-236fa (FE-36)	Non-Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
4A	HFC-236fa (FE-36)	Non-Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
4A	HFC-236fa (FE-36)	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
4B	HFC-236fa (FE-36)	Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
4B	HFC-236fa (FE-36)	Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
4B	HFC-236fa (FE-36)	Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
4B	HFC-236fa (FE-36)	Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
4B	HFC-236fa (FE-36)	Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
4B	HFC-236fa (FE-36)	Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
5A	ABC dry Chemical & Water mist	Non-Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
5A	ABC dry Chemical & Water mist	Non-Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
5A	ABC dry Chemical & Water mist	Non-Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	

Test No.	Extinguisher Agent	Test Type	Agent Application	Cleaning	Cleaning Schedule	Assessment Schedule	No. of Samples	Notes
5A	ABC dry Chemical & Water mist	Non-Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
5A	ABC dry Chemical & Water mist	Non-Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
5A	ABC dry Chemical & Water mist	Non-Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
5B	ABC dry Chemical & Water mist	Fire	Direct (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
5B	ABC dry Chemical & Water mist	Fire	Direct (set 2)	yes	delayed	6, 12, 18, 24 months	13	
5B	ABC dry Chemical & Water mist	Fire	Indirect (set 1)	yes	immediate	0, 6, 12, 18, 24 months	13	
5B	ABC dry Chemical & Water mist	Fire	Indirect (set 2)	yes	delayed	6, 12, 18, 24 months	13	
5B	ABC dry Chemical & Water mist	Fire	Indirect (set 3)	no	n/a	0, 24 months	13	Control for exposure
5B	ABC dry Chemical & Water mist	Fire	Indirect (set 4)	no	n/a		13	Available for instrumental analysis
6B	ABC dry Chemical & Water mist	Fire	Direct (set 1)	no				Potential analysis by William and Mary
6B	ABC dry Chemical & Water mist	Fire	Direct (set 2)	no				Potential analysis by William and Mary

Note: Set 1 consisted of sample locations 1-13 for the direct and indirect wall arrays. Set 2 consisted of sample locations 14-26 for the direct and indirect wall arrays. Set 3 consisted of sample locations 1-13 for the indirect stand array. Set 4 consisted of sample locations 14–26 for the indirect stand array.

APPENDIX B –
NON-FIRE TEST DATA SHEET AND CHECKLIST

Extinguisher Non-Fire Exposure Test Data Sheet

Test Date	Agent	Test No.	Test Engineer	Test Firefighter

Test Sample Data					
	Direct Sample Array				
Test Material	**Sample ID**	**Sample Location**	**Pre- Test Sample Mass (grams)**	**Post- Test Sample Mass (grams)**	**Notes**
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

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Test Material	Indirect, Wall Sample Array				
	Sample ID	Sample Location	Pre- Test Sample Mass (grams)	Post- Test Sample Mass (grams)	Notes
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

Test Material	Indirect, Stand Sample Array				
	Sample ID	Sample Location	Pre- Test Sample Mass (grams)	Post- Test Sample Mass (grams)	Notes
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

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Test Checklist	
	Begin data recording of the temperature and relative humidity in the general lab space 1 hour prior to the test.
	Ensure extinguisher is charged and the safety pin is in-place; Record total weight **(kg)**.
	Ensure samples have been conditioned to 50% ± 10% RH and 21±4 °C (70±8 °F) for 5 days.
	Ensure all doors to laboratory are closed.
	Ensure ventilation system is secured.
	Ensure the extinguisher stand is set to the correct distance **(ft)** and height (4 ft).
	Label, weigh, and mount cardboard (where required) and Velcro to samples. Record sample weights in the attached tables.
	Mount samples on the correct sample array (see attached tables).
	Begin data acquisition in the examination room.
	Begin data acquisition in the test enclosure. **(Official Test Time)**
	Transport sample arrays to the laboratory space.
	After one minute, mount sample arrays in the test enclosure. Ensure sample arrays are in correct locations. Note test time when last sample array mounted **(sec).**
	Mount thermocouple in the direct sample array.
	Ensure all test personnel, except firefighter in appropriate equipment, have exited the test enclosure.
	Position the extinguisher next to the stand.
	Ensure all test personnel except for the firefighter have exited test enclosure; close doors to test enclosure.
	Begin recording on two cameras and infrared camera **(sec).**
	After 30 seconds of background video, remove safety pin and manually discharge the extinguisher until it has been completely discharged.
	Note end of discharge time **(sec)**.
	Firefighter to take pictures of sample arrays prior to removal.
	Wait five minutes from end of discharge and then begin removing sample arrays to examination room. Note time when last array is removed **(sec)**.
	Open the two test enclosure doors and ventilate the test room by turning on the exhaust fan; set to 30-40Hz.
	Secure video and IR recording.
	Secure extinguisher by inserting pin.
	Record total weight of empty extinguisher **(kg)**.
	Secure data acquisition in test enclosure.
	Weigh and photograph each sample in order of location (i.e., 1 to 26) and note weight in attached tables. Indirect, wall sample array shall be weighed first, with the stand indirect and the direct sample arrays to follow.
	Complete post-test conservator examination procedures in accordance with Appendix A.
	Store samples in the appropriate storage box.
	Once all samples have been examined, secure data acquisition in the examination room.
	Vacuum and/or clean the enclosure floor and walls to remove agent discharged during the test.

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APPENDIX C – SAMPLE MASS DATA

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Fe19-1-1A-D	1A	Fe	19	1	D	127.966	128.024	125.912
Fe23-1-1A-IS	1A	Fe	23	1	IS	128.230	128.241	126.110
Fe21-1-1A-IW	1A	Fe	21	1	IW	127.914	127.930	125.830
Cu19-2-1A-D	1A	Cu	19	2	D	104.957	105.022	103.198
Cu23-2-1A-IS	1A	Cu	23	2	IS	102.987	102.988	100.972
Cu21-2-1A-IW	1A	Cu	21	2	IW	99.152	99.159	96.993
Al19-3-1A-D	1A	Al	19	3	D	92.980	93.065	91.011
Al23-3-1A-IS	1A	Al	23	3	IS	92.656	92.662	90.638
Al21-3-1A-IW	1A	Al	21	3	IW	92.321	92.334	90.245
L19-4-1A-D	1A	L	19	4	D	16.937	17.028	14.818
L23-4-1A-IS	1A	L	23	4	IS	18.173	18.177	16.161
L21-4-1A-IW	1A	L	21	4	IW	18.824	18.824	16.608
UW19-5-1A-D	1A	UW	19	5	D	39.679	39.752	37.651
UW21-5-1A-IW	1A	UW	21	5	IW	37.059	37.072	34.951
UW23-5-1A-IS	1A	UW	23	5	IS	37.780	37.769	35.497
VW19-6-1A-D	1A	VW	19	6	D	37.902	37.994	35.830
VW21-6-1A-IW	1A	VW	21	6	IW	43.958	43.961	41.855
VW23-6-1A-IS	1A	VW	23	6	IS	48.572	48.561	46.419
OP19-7-1A-D	1A	OP	19	7	D	6.610	6.691	4.422
OP23-7-1A-IS	1A	OP	23	7	IS	6.538	6.540	4.386
OP21-7-1A-IW	1A	OP	21	7	IW	6.541	6.562	4.444
AP19-8-1A-D	1A	AP	19	8	D	5.528	5.590	3.452
AP23-8-1A-IS	1A	AP	23	8	IS	5.477	5.478	3.487
AP21-8-1A-IW	1A	AP	21	8	IW	5.632	5.632	3.538
TRT19-9-1A-D	1A	TRT	19	9	D	250.248	250.397	248.269
TRT21-9-1A-IW	1A	TRT	21	9	IW	246.100	246.120	243.703
TRT23-9-1A-IS	1A	TRT	23	9	IS	242.673	242.657	240.463
M19-10-1A-D	1A	M	19	10	D	270.748	270.826	268.733
M23-10-1A-IS	1A	M	23	10	IS	264.307	265.412	263.272
M21-10-1A-IW	1A	M	21	10	IW	239.787	239.812	237.819
FUR19-11-1A-D	1A	FUR	19	11	D	15.275	17.625	15.236
FUR21-11-1A-IW	1A	FUR	21	11	IW	14.187	14.222	12.193
FUR23-11-1A-IS	1A	FUR	23	11	IS	17.037	17.031	14.838
TCT19-12-1A-D	1A	TCT	19	12	D	301.700	301.900	301.500
TCT23-12-1A-IS	1A	TCT	23	12	IS	311.500	311.500	309.400
TCT21-12-1A-IW	1A	TCT	21	12	IW	299.900	299.900	297.700
PT19-13-1A-D	1A	PT	19	13	D	135.176	135.313	133.102
PT21-13-1A-IW	1A	PT	21	13	IW	135.945	135.965	133.957
PT23-13-1A-IS	1A	PT	23	13	IS	134.552	134.551	132.445
Fe20-14-1A-D	1A	Fe	20	14	D	127.621	127.714	125.445

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Fe24-14-1A-IS	1A	Fe	24	14	IS	127.180	127.188	125.121
Fe22-14-1A-IW	1A	Fe	22	14	IW	127.627	127.634	125.534
Cu20-15-1A-D	1A	Cu	20	15	D	102.810	102.874	100.714
Cu24-15-1A-IS	1A	Cu	24	15	IS	104.042	104.042	102.068
Cu22-15-1A-IW	1A	Cu	22	15	IW	103.370	103.386	101.233
Al20-16-1A-D	1A	Al	20	16	D	92.633	92.764	90.586
Al24-16-1A-IS	1A	Al	24	16	IS	91.824	91.825	89.688
Al22-16-1A-IW	1A	Al	22	16	IW	93.259	93.270	91.140
L20-17-1A-D	1A	L	20	17	D	17.015	17.140	14.980
L24-17-1A-IS	1A	L	24	17	IS	18.170	18.176	16.161
L22-17-1A-IW	1A	L	22	17	IW	18.324	18.317	16.266
UW20-18-1A-D	1A	UW	20	18	D	40.062	40.199	37.887
UW22-18-1A-IW	1A	UW	22	18	IW	37.332	37.327	35.210
UW24-18-1A-IS	1A	UW	24	18	IS	37.830	37.825	35.715
VW20-19-1A-D	1A	VW	20	19	D	37.970	38.064	35.999
VW24-19-1A-IS	1A	VW	24	19	IS	37.830	38.724	36.584
VW22-19-1A-IW	1A	VW	22	19	IW	36.778	36.800	34.627
OP20-20-1A-D	1A	OP	20	20	D	6.863	6.940	4.623
OP24-20-1A-IS	1A	OP	24	20	IS	6.494	6.497	4.500
OP22-20-1A-IW	1A	OP	22	20	IW	6.623	6.658	4.536
AP20-21-1A-D	1A	AP	20	21	D	5.824	5.908	3.550
AP24-21-1A-IS	1A	AP	24	21	IS	5.269	5.274	3.593
AP22-21-1A-IW	1A	AP	22	21	IW	5.783	5.804	3.533
TRT20-22-1A-D	1A	TRT	20	22	D	251.013	251.186	249.054
TRT22-22-1A-IW	1A	TRT	22	22	IW	221.963	221.983	219.903
TRT24-22-1A-IS	1A	TRT	24	22	IS	246.700	246.695	244.694
M20-23-1A-D	1A	M	20	23	D	267.733	267.840	265.631
M22-23-1A-IW	1A	M	22	23	IW	247.978	248.002	245.968
M24-23-1A-IS	1A	M	24	23	IS	259.155	259.145	257.051
FUR20-24-1A-D	1A	FUR	20	24	D	15.084	15.725	13.308
FUR22-24-1A-IW	1A	FUR	22	24	IW	16.925	16.952	14.796
FUR24-24-1A-IS	1A	FUR	24	24	IS	15.608	15.388	13.508
TCT20-25-1A-D	1A	TCT	20	25	D	303.500	303.700	301.400
TCT24-25-1A-IS	1A	TCT	24	25	IS	319.000	319.000	317.300
TCT22-25-1A-IW	1A	TCT	22	25	IW	326.100	326.200	324.000
PT20-26-1A-D	1A	PT	20	26	D	136.546	136.700	133.100
PT24-26-1A-IS	1A	PT	24	26	IS	135.858	135.862	133.653
PT22-26-1A-IW	1A	PT	22	26	IW	136.369	136.395	134.224
Fe49-1-1B-D	1B	Fe	49	1	D	127.181	127.213	125.493
Fe53-1-1B-IS	1B	Fe	53	1	IS	127.568	127.558	125.898

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Fe51-1-1B-IW	1B	Fe	51	1	IW	127.876	127.875	126.164
Cu49-2-1B-D	1B	Cu	49	2	D	103.073	103.128	101.332
Cu53-2-1B-IS	1B	Cu	53	2	IS	102.871	102.875	101.055
Cu51-2-1B-IW	1B	Cu	51	2	IW	103.682	103.688	102.019
Al49-3-1B-D	1B	Al	49	3	D	92.994	93.023	91.241
Al53-3-1B-IS	1B	Al	53	3	IS	91.29	91.291	89.606
Al51-3-1B-IW	1B	Al	51	3	IW	92.978	92.991	91.293
L49-4-1B-D	1B	L	49	4	D	17.788	17.371	15.738
L51-4-1B-IW	1B	L	51	4	IW	18.603	18.539	16.871
L53-4-1B-IS	1B	L	53	4	IS	19.689	19.635	17.99
UW49-5-1B-D	1B	UW	49	5	D	40.728	40.503	38.818
UW51-5-1B-IW	1B	UW	51	5	IW	36.645	36.592	34.734
UW53-5-1B-IS	1B	UW	53	5	IS	39.012	38.973	37.317
VW49-6-1B-D	1B	VW	49	6	D	45.076	44.957	43.298
VW53-6-1B-IS	1B	VW	53	6	IS	46.334	46.295	44.589
VW51-6-1B-IW	1B	VW	51	6	IW	33.535	33.522	31.822
OP53-7-1B-IS	1B	OP	53	7	IS	6.334	6.315	4.374
OP51-7-1B-IW	1B	OP	51	7	IW	5.996	5.984	4.383
OP49-7-1B-D	1B	OP	49	7	D	6.311	6.303	4.467
AP49-8-1B-D	1B	AP	49	8	D	5.167	5.227	3.54
AP53-8-1B-IS	1B	AP	53	8	IS	5.306	5.295	3.496
AP51-8-1B-IW	1B	AP	51	8	IW	5.08	5.077	3.493
TRT49-9-1B-D	1B	TRT	49	9	D	243.167	243.341	240.642
TRT51-9-1B-IW	1B	TRT	51	9	IW	236.093	236.076	233.512
TRT53-9-1B-IS	1B	TRT	53	9	IS	248.596	248.582	245.751
M49-10-1B-D	1B	M	49	10	D	260.418	260.513	257.85
M51-10-1B-IW	1B	M	51	10	IW	252.282	252.285	249.844
M53-10-1B-IS	1B	M	53	10	IS	265.691	265.688	263.984
FUR49-11-1B-D	1B	FUR	49	11	D	13.871	14.743	13.038
FUR53-11-1B-IS	1B	FUR	53	11	IS	11.361	11.326	9.735
FUR51-11-1B-IW	1B	FUR	51	11	IW	14.891	14.88	13.199
TCT49-12-1B-D	1B	TCT	49	12	D	317.8	318.1	315.6
TCT53-12-1B-IS	1B	TCT	53	12	IS	316.9	316.9	314.4
TCT51-12-1B-IW	1B	TCT	51	12	IW	320.9	320.9	318.3
PT49-13-1B-D	1B	PT	49	13	D	135.568	135.677	133.927
PT53-13-1B-IS	1B	PT	53	13	IS	136.614	136.619	134.874
PT51-13-1B-IW	1B	PT	51	13	IW	136.249	136.254	133.657
Fe50-14-1B-D	1B	Fe	50	14	D	127.83	127.863	126.119
Fe52-14-1B-IW	1B	Fe	52	14	IW	126.514	126.529	124.953
Fe54-14-1B-IS	1B	Fe	54	14	IS	124.715	124.71	123.101

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Cu50-15-1B-D	1B	Cu	50	15	D	104.336	104.424	102.623
Cu52-15-1B-IW	1B	Cu	52	15	IW	103.1	103.111	101.36
Cu54-15-1B-IS	1B	Cu	54	15	IS	102.315	102.312	100.664
Al50-16-1B-D	1B	Al	50	16	D	92.268	92.393	90.728
Al54-16-1B-IS	1B	Al	54	16	IS	91.733	91.737	89.976
Al52-16-1B-IW	1B	Al	52	16	IW	91.468	91.479	89.753
L50-17-1B-D	1B	L	50	17	D	17.58	17.321	15.584
L54-17-1B-IS	1B	L	54	17	IS	18.044	18.024	16.091
L52-17-1B-IW	1B	L	52	17	IW	19.218	19.217	17.508
UW50-18-1B-D	1B	UW	50	18	D	42.057	41.931	40.163
UW54-18-1B-IS	1B	UW	54	18	IS	39.061	39.034	37.204
UW52-18-1B-IW	1B	UW	52	18	IW	42.055	42.028	40.313
VW50-19-1B-D	1B	VW	50	19	D	32.535	32.458	30.721
VW54-19-1B-IS	1B	VW	54	19	IS	38.602	38.576	36.772
VW52-19-1B-IW	1B	VW	52	19	IW	36.716	36.694	34.839
OP50-20-1B-D	1B	OP	50	20	D	6.048	6.078	4.328
OP54-20-1B-IS	1B	OP	54	20	IS	6.182	6.172	4.411
OP52-20-1B-IW	1B	OP	52	20	IW	7.044	7.037	4.441
AP50-21-1B-D	1B	AP	50	21	D	5.243	5.289	3.558
AP52-21-1B-IW	1B	AP	52	21	IW	5.178	5.181	3.5
AP54-21-1B-IS	1B	AP	54	21	IS	5.244	5.234	3.495
TRT50-22-1B-D	1B	TRT	50	22	D	250.803	250.204	247.403
TRT52-22-1B-IW	1B	TRT	52	22	IW	235.591	235.599	233.15
TRT54-22-1B-IS	1B	TRT	54	22	IS	246.076	246.067	243.576
M50-23-1B-D	1B	M	50	23	D	270.652	272.38	269.857
M52-23-1B-IW	1B	M	52	23	IW	248.811	248.815	246.262
M54-23-1B-IS	1B	M	54	23	IS	276.511	276.508	273.886
FUR50-24-1B-D	1B	FUR	50	24	D	13.404	15.072	13.17
FUR52-24-1B-IW	1B	FUR	52	24	IW	15.593	15.593	13.831
FUR54-24-1B-IS	1B	FUR	54	24	IS	11.494	11.375	9.678
TCT50-25-1B-D	1B	TCT	50	25	D	324	324.2	321.6
TCT52-25-1B-IW	1B	TCT	52	25	IW	317.5	317.6	315
TCT54-25-1B-IS	1B	TCT	54	25	IS	323.3	323.2	320.7
PT50-26-1B-D	1B	PT	50	26	D	137.158	137.285	134.721
PT54-26-1B-IS	1B	PT	54	26	IS	136.045	136.045	134.353
PT52-26-1B-IW	1B	PT	52	26	IW	135.613	135.626	133.007
Fe1-1-2A-D	2A	Fe	1	1	D	127.981	128.247	126.631
Fe5-1-2A-IS	2A	Fe	5	1	IS	124.098	124.080	NM
Fe3-1-2A-IW	2A	Fe	3	1	IW	127.757	127.755	NM
Cu1-2-2A-D	2A	Cu	1	2	D	102.369	103.206	101.468

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Cu5-2-2A-IS	2A	Cu	5	2	IS	102.986	102.984	NM
Cu3-2-2A-IW	2A	Cu	3	2	IW	102.507	102.505	NM
Al1-3-2A-D	2A	Al	1	3	D	91.715	91.831	NM
Al5-3-2A-IS	2A	Al	5	3	IS	92.892	92.895	NM
Al3-3-2A-IW	2A	Al	3	3	IW	92.126	92.117	NM
L5-4-2A-IS	2A	L	5	4	IS	18.957	18.837	NM
L3-4-2A-IW	2A	L	3	4	IW	18.800	18.702	NM
L1-4-2A-D	2A	L	1	4	D	17.603	17.910	16.251
UW5-5-2A-IS	2A	UW	5	5	IS	38.053	37.951	NM
UW3-5-2A-IW	2A	UW	3	5	IW	37.563	37.485	NM
UW1-5-2A-D	2A	UW	1	5	D	39.378	39.724	38.169
VW3-6-2A-IW	2A	VW	3	6	IW	45.449	45.400	NM
VW5-6-2A-IS	2A	VW	5	6	IS	47.544	47.499	NM
VW1-6-2A-D	2A	VW	1	6	D	36.192	37.105	35.500
OP1-7-2A-D	2A	OP	1	7	D	6.064	7.407	4.917
OP5-7-2A-IS	2A	OP	5	7	IS	6.073	6.058	NM
OP3-7-2A-IW	2A	OP	3	7	IW	6.158	6.146	NM
AP1-8-2A-D	2A	AP	1	8	D	4.935	5.491	3.598
AP5-8-2A-IS	2A	AP	5	8	IS	5.012	4.999	NM
AP3-8-2A-IW	2A	AP	3	8	IW	4.942	4.935	NM
TRT3-9-2A-IW	2A	TRT	3	9	IW	233.362	233.295	NM
TRT1-9-2A-D	2A	TRT	1	9	D	246.473	247.553	245.925
TRT5-9-2A-IS	2A	TRT	5	9	IS	233.500	233.620	NM
M1-10-2A-D	2A	M	1	10	D	229.163	229.268	227.559
M3-10-2A-IW	2A	M	3	10	IW	259.559	259.548	NM
M5-10-2A-IS	2A	M	5	10	IS	293.946	293.943	NM
FUR5-11-2A-IS	2A	FUR	5	11	IS	19.107	19.002	NM
FUR3-11-2A-IW	2A	FUR	3	11	IW	17.809	17.705	NM
FUR1-11-2A-D	2A	FUR	1	11	D	17.938	20.313	18.489
TCT3-12-2A-IW	2A	TCT	3	12	IW	300.500	300.400	NM
TCT1-12-2A-D	2A	TCT	1	12	D	298.800	302.100	broke
TCT5-12-2A-IS	2A	TCT	5	12	IS	307.200	307.260	NM
PT1-13-2A-D	2A	PT	1	13	D	133.847	138.878	136.307
PT5-13-2A-IS	2A	PT	5	13	IS	135.487	135.476	NM
PT3-13-2A-IW	2A	PT	3	13	IW	135.460	135.453	NM
Fe2-14-2A-D	2A	Fe	2	14	D	127.756	128.080	126.396
Fe4-14-2A-IW	2A	Fe	4	14	IW	124.673	126.682	NM
Fe6-14-2A-IS	2A	Fe	6	14	IS	126.608	126.604	NM
Cu2-15-2A-D	2A	Cu	2	15	D	102.570	103.053	101.226
Cu4-15-2A-IW	2A	Cu	4	15	IW	103.377	103.377	NM

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Cu6-15-2A-IS	2A	Cu	6	15	IS	102.895	102.890	NM
Al2-16-2A-D	2A	Al	2	16	D	91.583	91.838	89.938
Al6-16-2A-IS	2A	Al	6	16	IS	92.620	92.615	NM
Al4-16-2A-IW	2A	Al	4	16	IW	92.364	92.360	NM
L6-17-2A-IS	2A	L	6	17	IS	19.340	19.228	NM
L4-17-2A-IW	2A	L	4	17	IW	18.640	18.558	NM
L2-17-2A-D	2A	L	2	17	D	18.431	19.533	17.724
UW6-18-2A-IS	2A	UW	6	18	IS	40.895	40.785	NM
UW4-18-2A-IW	2A	UW	4	18	IW	37.104	37.019	NM
UW2-18-2A-D	2A	UW	2	18	D	37.431	39.485	37.875
VW6-19-2A-IS	2A	VW	6	19	IS	35.380	35.321	NM
VW2-19-2A-D	2A	VW	2	19	D	37.886	40.636	37.843
VW4-19-2A-IW	2A	VW	4	19	IW	45.574	45.705	NM
OP2-20-2A-D	2A	OP	2	20	D	6.045	7.032	5.076
OP6-20-2A-IS	2A	OP	6	20	IS	6.118	6.102	NM
OP4-20-2A-IW	2A	OP	4	20	IW	6.041	6.030	NM
AP2-21-2A-D	2A	AP	2	21	D	4.963	5.820	3.592
AP4-21-2A-IW	2A	AP	4	21	IW	5.161	5.147	NM
AP6-21-2A-IS	2A	AP	6	21	IS	5.176	5.167	NM
TRT4-22-2A-IW	2A	TRT	4	22	IW	226.071	225.999	NM
TRT2-22-2A-D	2A	TRT	2	22	D	248.390	250.540	248.530
TRT6-22-2A-IS	2A	TRT	6	22	IS	230.584	230.555	NM
M2-23-2A-D	2A	M	2	23	D	278.611	279.000	277.046
M6-23-2A-IS	2A	M	6	23	IS	216.128	216.115	NM
M4-23-2A-IW	2A	M	4	23	IW	263.865	263.859	NM
FUR6-24-2A-IS	2A	FUR	6	24	IS	16.485	16.380	NM
FUR4-24-2A-IW	2A	FUR	4	24	IW	20.644	20.539	NM
FUR2-24-2A-D	2A	FUR	2	24	D	16.239	18.280	16.281
TCT2-25-2A-D	2A	TCT	2	25	D	301.500	304.400	broke
TCT6-25-2A-IS	2A	TCT	6	25	IS	323.000	323.200	NM
TCT4-25-2A-IW	2A	TCT	4	25	IW	297.500	297.500	NM
PT2-26-2A-D	2A	PT	2	26	D	136.180	141.143	139.402
PT6-26-2A-IS	2A	PT	6	26	IS	134.886	134.881	NM
PT4-26-2A-IW	2A	PT	4	26	IW	135.671	135.668	NM
Fe31-1-2B-D	2B	Fe	31	1	D	128.545	129.06	126.511
Fe35-1-2B-IS	2B	Fe	35	1	IS	127.232	127.241	124.196
Fe33-1-2B-IW	2B	Fe	33	1	IW	126.446	126.457	124.107
Cu31-2-2B-D	2B	Cu	31	2	D	103.534	104.052	101.576
Cu33-2-2B-IW	2B	Cu	33	2	IW	104.516	104.521	102.415
Cu35-2-2B-IS	2B	Cu	35	2	IS	104.531	104.528	101.031

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Al31-3-2B-D	2B	Al	31	3	D	93.104	93.16	90.854
Al35-3-2B-IS	2B	Al	35	3	IS	92.848	92.842	90.795
Al33-3-2B-IW	2B	Al	33	3	IW	91.908	91.904	89.912
L33-4-2B-IW	2B	L	33	4	IW	18.075	17.993	15.677
L35-4-2B-IS	2B	L	35	4	IS	16.274	16.204	14.171
L31-4-2B-D	2B	L	31	4	D	14.908	23.286	20.781
UW35-5-2B-IS	2B	UW	35	5	IS	43.366	43.296	41.511
UW33-5-2B-IW	2B	UW	33	5	IW	36.48	36.448	34.544
UW31-5-2B-D	2B	UW	31	5	D	35.792	38.103	35.858
VW35-6-2B-IS	2B	VW	35	6	IS	44.705	44.652	42.463
VW33-6-2B-IW	2B	VW	33	6	IW	45.895	45.863	45.503
VW31-6-2B-D	2B	VW	31	6	D	46.261	49.741	47.178
OP31-7-2B-D	2B	OP	31	7	D	4.332	9.514	5.748
OP33-7-2B-IW	2B	OP	33	7	IW	6.72	6.693	4.317
OP35-7-2B-IS	2B	OP	35	7	IS	6.645	6.618	4.407
AP31-8-2B-D	2B	AP	31	8	D	5.492	7.72	3.991
AP33-8-2B-IW	2B	AP	33	8	IW	5.379	5.358	3.367
AP35-8-2B-IS	2B	AP	35	8	IS	5.665	5.645	3.517
TRT35-9-2B-IS	2B	TRT	35	9	IS	247.184	247.148	243.922
TRT31-9-2B-D	2B	TRT	31	9	D	251.347	252.684	248.748
TRT33-9-2B-IW	2B	TRT	33	9	IW	249.603	249.588	246.317
M31-10-2B-D	2B	M	31	10	D	215.553	216.063	213.669
M33-10-2B-IW	2B	M	33	10	IW	276.867	276.874	273.741
M35-10-2B-IS	2B	M	35	10	IS	252.368	252.362	249.664
FUR35-11-2B-IS	2B	FUR	35	11	IS	18.903	18.823	16.682
FUR33-11-2B-IW	2B	FUR	33	11	IW	19.195	19.149	16.819
FUR31-11-2B-D	2B	FUR	31	11	D	16.277	23.242	19.76
TCT31-12-2B-D	2B	TCT	31	12	D	319.6	325.5	319.5
TCT35-12-2B-IS	2B	TCT	35	12	IS	317.2	317.2	313.6
TCT33-12-2B-IW	2B	TCT	33	12	IW	322.5	322.5	319.3
PT31-13-2B-D	2B	PT	31	13	D	136.575	144.956	142.034
PT33-13-2B-IW	2B	PT	33	13	IW	135.33	135.337	133.09
PT35-13-2B-IS	2B	PT	35	13	IS	135.955	135.952	133.749
Fe32-14-2B-D	2B	Fe	32	14	D	127.854	129.718	125.768
Fe36-14-2B-IS	2B	Fe	36	14	IS	128.017	128.018	125.858
Fe34-14-2B-IW	2B	Fe	34	14	IW	125.821	125.821	123.706
Cu32-15-2B-D	2B	Cu	32	15	D	104.022	105.803	101.997
Cu34-15-2B-IW	2B	Cu	34	15	IW	104.131	104.134	101.914
Cu36-15-2B-IS	2B	Cu	36	15	IS	99.401	99.392	97.179
Al32-16-2B-D	2B	Al	32	16	D	93.45	96.504	91.41

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Al34-16-2B-IW	2B	Al	34	16	IW	93.296	93.288	91.109
Al36-16-2B-IS	2B	Al	36	16	IS	88.233	88.232	86.167
L36-17-2B-IS	2B	L	36	17	IS	16.612	16.55	14.499
L34-17-2B-IW	2B	L	34	17	IW	16.695	16.653	14.426
L32-17-2B-D	2B	L	32	17	D	17.804	28.427	24.606
UW34-18-2B-IW	2B	UW	34	18	IW	37.688	37.18	35.502
UW36-18-2B-IS	2B	UW	36	18	IS	43.873	43.817	41.579
UW32-18-2B-D	2B	UW	32	18	D	35.25	43.571	40.117
VW36-19-2B-IS	2B	VW	36	19	IS	47.11	47.062	45.151
VW34-19-2B-IW	2B	VW	34	19	IW	50.637	50.61	48.704
VW32-19-2B-D	2B	VW	32	19	D	36.281	42.717	39.11
OP32-20-2B-D	2B	OP	32	20	D	6.609	9.249	5.829
OP36-20-2B-IS	2B	OP	36	20	IS	5.93	5.908	4.338
OP34-20-2B-IW	2B	OP	34	20	IW	6.432	6.416	4.258
AP32-21-2B-D	2B	AP	32	21	D	5.688	8.974	4.327
AP36-21-2B-IS	2B	AP	36	21	IS	5.629	5.614	3.426
AP34-21-2B-IW	2B	AP	34	21	IW	5.584	5.573	3.488
TRT66-22-2B-D	2B	TRT	66	22	D	242.28	249.545	243.693
TRT36-22-2B-IS	2B	TRT	36	22	IS	256.536	256.514	252.923
TRT34-22-2B-IW	2B	TRT	34	22	IW	245.385	245.37	242.145
M32-23-2B-D	2B	M	32	23	D	271.631	273.833	268.698
M36-23-2B-IS	2B	M	36	23	IS	272.585	272.567	269.438
M34-23-2B-IW	2B	M	34	23	IW	269.398	269.39	266.212
FUR36-24-2B-IS	2B	FUR	36	24	IS	19.106	19.036	16.43
FUR34-24-2B-IW	2B	FUR	34	24	IW	18.495	18.454	16.17
FUR32-24-2B-D	2B	FUR	32	24	D	20.712	29.229	25.555
TCT32-25-2B-D	2B	TCT	32	25	D	318.8	325.5	317.9
TCT36-25-2B-IS	2B	TCT	36	25	IS	326.7	326.7	323.5
TCT34-25-2B-IW	2B	TCT	34	25	IW	317.8	317.8	314.5
PT32-26-2B-D	2B	PT	32	26	D	136.216	148.194	144.773
PT36-26-2B-IS	2B	PT	36	26	IS	135.045	135.048	133.018
PT34-26-2B-IW	2B	PT	34	26	IW	134.453	134.443	132.163
Fe7-1-3A-D	3A	Fe	7	1	D	128.246	128.252	126.655
Fe11-1-3A-IS	3A	Fe	11	1	IS	126.926	126.929	125.361
Fe9-1-3A-IW	3A	Fe	9	1	IW	127.679	127.718	126.141
Cu7-2-3A-D	3A	Cu	7	2	D	102.622	102.628	101.087
Cu9-2-3A-IW	3A	Cu	9	2	IW	103.447	103.456	101.924
Cu11-2-3A-IS	3A	Cu	11	2	IS	103.010	103.009	101.479
Al7-3-3A-D	3A	Al	7	3	D	92.431	92.441	90.823
Al11-3-3A-IS	3A	Al	11	3	IS	92.726	92.734	91.170

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
Al9-3-3A-IW	3A	Al	9	3	IW	92.858	92.923	91.259
L7-4-3A-D	3A	L	7	4	D	19.587	19.825	18.188
L11-4-3A-IS	3A	L	11	4	IS	18.166	18.174	16.574
L9-4-3A-IW	3A	L	9	4	IW	18.644	18.668	17.082
UW7-5-3A-D	3A	UW	7	5	D	42.370	42.453	41.677
UW9-5-3A-IW	3A	UW	9	5	IW	38.882	38.927	37.378
UW11-5-3A-IS	3A	UW	11	5	IS	41.169	41.159	39.536
VW7-6-3A-D	3A	VW	7	6	D	39.735	39.897	38.250
VW11-6-3A-IS	3A	VW	11	6	IS	40.463	40.469	38.870
VW9-6-3A-IW	3A	VW	9	6	IW	37.586	37.589	36.024
OP7-7-3A-D	3A	OP	7	7	D	6.124	6.381	4.676
OP9-7-3A-IW	3A	OP	9	7	IW	6.380	6.384	4.779
OP11-7-3A-IS	3A	OP	11	7	IS	6.248	6.247	4.728
AP7-8-3A-D	3A	AP	7	8	D	5.069	5.295	3.597
AP9-8-3A-IW	3A	AP	9	8	IW	5.121	5.125	3.534
AP11-8-3A-IS	3A	AP	11	8	IS	5.180	5.158	36.160
TRT7-9-3A-D	3A	TRT	7	9	D	230.627	230.811	229.053
TRT11-9-3A-IS	3A	TRT	11	9	IS	251.936	251.915	250.333
TRT9-9-3A-IW	3A	TRT	9	9	IW	240.023	240.021	238.489
M7-10-3A-D	3A	M	7	10	D	268.092	268.116	266.589
M9-10-3A-IW	3A	M	9	10	IW	247.730	247.752	246.288
M11-10-3A-IS	3A	M	11	10	IS	277.331	277.329	275.752
FUR7-11-3A-D	3A	FUR	7	11	D	14.345	15.488	13.610
FUR11-11-3A-IS	3A	FUR	11	11	IS	12.050	12.057	10.519
FUR9-11-3A-IW	3A	FUR	9	11	IW	14.213	14.245	12.654
TCT9-12-3A-IW	3A	TCT	9	12	IW	314.400	314.300	312.800
TCT7-12-3A-D	3A	TCT	7	12	D	326.000	327.200	325.200
TCT11-12-3A-IS	3A	TCT	11	12	IS	308.100	308.100	306.500
PT9-13-3A-IW	3A	PT	9	13	IW	134.939	134.735	133.267
PT7-13-3A-D	3A	PT	7	13	D	133.977	134.458	132.791
PT11-13-3A-IS	3A	PT	11	13	IS	134.694	134.693	133.143
Fe8-14-3A-D	3A	Fe	8	14	D	127.639	127.899	126.345
Fe10-14-3A-IW	3A	Fe	10	14	IW	128.009	128.022	126.475
Fe12-14-3A-IS	3A	Fe	12	14	IS	128.064	128.061	126.532
Cu10-15-3A-IW	3A	Cu	10	15	IW	104.063	103.803	102.462
Cu8-15-3A-D	3A	Cu	8	15	D	103.910	103.934	102.396
Cu12-15-3A-IS	3A	Cu	12	15	IS	102.587	102.584	100.927
Al8-16-3A-D	3A	Al	8	16	D	92.523	92.778	91.042
Al10-16-3A-IW	3A	Al	10	16	IW	92.980	93.048	91.373
Al12-16-3A-IS	3A	Al	12	16	IS	91.757	91.753	90.215

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
L8-17-3A-D	3A	L	8	17	D	19.988	20.989	19.298
L12-17-3A-IS	3A	L	12	17	IS	18.111	18.123	16.484
L10-17-3A-IW	3A	L	10	17	IW	19.331	19.376	17.699
UW8-18-3A-D	3A	UW	8	18	D	36.596	37.534	35.682
UW10-18-3A-IW	3A	UW	10	18	IW	38.761	38.765	37.212
UW12-18-3A-IS	3A	UW	12	18	IS	42.583	42.570	40.810
VW8-19-3A-D	3A	VW	8	19	D	37.562	38.795	36.748
VW10-19-3A-IW	3A	VW	10	19	IW	36.245	36.247	34.654
VW12-19-3A-IS	3A	VW	12	19	IS	46.774	46.765	44.984
OP8-20-3A-D	3A	OP	8	20	D	6.050	6.575	4.132
OP10-20-3A-IW	3A	OP	10	20	IW	6.404	6.409	4.772
OP12-20-3A-IS	3A	OP	12	20	IS	6.321	6.320	4.749
AP8-21-3A-D	3A	AP	8	21	D	5.042	5.853	3.960
AP12-21-3A-IS	3A	AP	12	21	IS	5.002	5.002	3.366
AP10-21-3A-IW	3A	AP	10	21	IW	5.073	5.077	3.488
TRT12-22-3A-IS	3A	TRT	12	22	IS	250.178	250.148	248.484
TRT8-22-3A-D	3A	TRT	8	22	D	239.482	240.620	238.471
TRT10-22-3A-IW	3A	TRT	10	22	IW	249.373	249.370	247.783
M8-23-3A-D	3A	M	8	23	D	267.077	267.662	265.996
M12-23-3A-IS	3A	M	12	23	IS	261.072	261.072	259.443
M10-23-3A-IW	3A	M	10	23	IW	273.460	273.470	271.823
FUR8-24-3A-D	3A	FUR	8	24	D	17.367	18.692	16.876
FUR12-24-3A-IS	3A	FUR	12	24	IS	9.625	9.711	8.019
FUR10-24-3A-IW	3A	FUR	10	24	IW	13.521	13.533	11.927
TCT10-25-3A-IW	3A	TCT	10	25	IW	326.700	326.600	325.100
TCT8-25-3A-D	3A	TCT	8	25	D	323.700	324.300	322.600
TCT12-25-3A-IS	3A	TCT	12	25	IS	302.100	302.100	300.500
PT8-26-3A-D	3A	PT	8	26	D	136.010	139.550	137.090
PT12-26-3A-IS	3A	PT	12	26	IS	135.600	135.600	134.053
PT10-26-3A-IW	3A	PT	10	26	IW	135.046	135.049	133.435
Fe37-1-3B-D	3B	Fe	37	1	D	125.47	125.449	123.257
Fe39-1-3B-IW	3B	Fe	39	1	IW	125.104	125.105	123.287
Fe41-1-3B-IS	3B	Fe	41	1	IS	126.131	126.124	124.075
Cu37-2-3B-D	3B	Cu	37	2	D	103.048	103.053	101.104
Cu39-2-3B-IW	3B	Cu	39	2	IW	104.79	104.781	102.564
Cu41-2-3B-IS	3B	Cu	41	2	IS	104.356	104.355	102.131
Al41-3-3B-IS	3B	Al	41	3	IS	92.838	92.844	90.96
Al37-3-3B-D	3B	Al	37	3	D	92.855	92.852	86.718
Al39-3-3B-IW	3B	Al	39	3	IW	92.522	92.521	90.463
L37-4-3B-D	3B	L	37	4	D	18.426	17.922	15.633

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
L41-4-3B-IS	3B	L	41	4	IS	18.838	18.768	16.652
L39-4-3B-IW	3B	L	39	4	IW	19.579	19.516	17.423
UW37-5-3B-D	3B	UW	37	5	D	38.604	38.379	36.24
UW39-5-3B-IW	3B	UW	39	5	IW	37.595	37.554	35.445
UW41-5-3B-IS	3B	UW	41	5	IS	39.45	39.415	37.314
VW37-6-3B-D	3B	VW	37	6	D	37.782	37.649	35.307
VW41-6-3B-IS	3B	VW	41	6	IS	47.498	47.462	45.325
VW39-6-3B-IW	3B	VW	39	6	IW	36.247	36.321	34.156
OP66-7-3B-D	3B	OP	66	7	D	6.41	6.325	4.261
OP41-7-3B-IS	3B	OP	41	7	IS	6.57	6.54	4.29
OP39-7-3B-IW	3B	OP	39	7	IW	6.673	6.656	4.456
AP37-8-3B-D	3B	AP	37	8	D	5.546	5.492	3.45
AP41-8-3B-IS	3B	AP	41	8	IS	5.678	5.657	3.435
AP39-8-3B-IW	3B	AP	39	8	IW	5.52	5.507	3.477
TRT39-9-3B-IW	3B	TRT	39	9	IW	251.448	251.406	248.322
TRT37-9-3B-D	3B	TRT	37	9	D	250.89	250.849	247.35
TRT41-9-3B-IS	3B	TRT	41	9	IS	233.857	233.818	230.424
M37-10-3B-D	3B	M	37	10	D	265.448	266.43	263.226
M41-10-3B-IS	3B	M	41	10	IS	259.623	259.625	255.987
M39-10-3B-IW	3B	M	39	10	IW	260.984	260.98	257.332
FUR41-11-3B-IS	3B	FUR	41	11	IS	16.737	16.682	14.415
FUR37-11-3B-D	3B	FUR	37	11	D	19.421	19.643	17.256
FUR39-11-3B-IW	3B	FUR	39	11	IW	11.736	11.722	9.718
TCT37-12-3B-D	3B	TCT	37	12	D	321	321	317.7
TCT41-12-3B-IS	3B	TCT	41	12	IS	317.8	317.8	314.4
TCT39-12-3B-IW	3B	TCT	39	12	IW	330.7	330.7	327.3
PT37-13-3B-D	3B	PT	37	13	D	135.937	135.924	133.645
PT41-13-3B-IS	3B	PT	41	13	IS	135.549	135.541	132.498
PT39-13-3B-IW	3B	PT	39	13	IW	135.803	135.795	133.674
Fe38-14-3B-D	3B	Fe	38	14	D	128.494	128.499	126.298
Fe40-14-3B-IW	3B	Fe	40	14	IW	127.905	127.894	125.717
Fe42-14-3B-IS	3B	Fe	42	14	IS	127.921	127.919	125.68
Cu38-15-3B-D	3B	Cu	38	15	D	103.625	103.644	101.412
Cu42-15-3B-IS	3B	Cu	42	15	IS	102.994	102.985	100.758
Cu40-15-3B-IW	3B	Cu	40	15	IW	103.449	103.441	101.178
Al38-16-3B-D	3B	Al	38	16	D	88.792	88.833	86.722
Al40-16-3B-IW	3B	Al	40	16	IW	92.711	92.71	90.52
Al42-16-3B-IS	3B	Al	42	16	IS	88.124	88.123	86.011
L38-17-3B-D	3B	L	38	17	D	18.839	18.708	16.395
L42-17-3B-IS	3B	L	42	17	IS	19.059	19.02	16.789

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
L40-17-3B-IW	3B	L	40	17	IW	19.292	19.256	16.939
UW38-18-3B-D	3B	UW	38	18	D	38.318	38.257	35.701
UW42-18-3B-IS	3B	UW	42	18	IS	39.05	39.017	36.666
UW40-18-3B-IW	3B	UW	40	18	IW	38.247	38.217	35.996
VW38-19-3B-D	3B	VW	38	19	D	35.213	35.116	32.782
VW40-19-3B-IW	3B	VW	40	19	IW	38.84	38.81	36.76
VW42-19-3B-IS	3B	VW	42	19	IS	50.698	50.676	48.477
OP40-20-3B-IW	3B	OP	40	20	IW	6.4	6.383	4.243
OP42-20-3B-IS	3B	OP	42	20	IS	6.225	6.208	4.353
OP38-20-3B-D	3B	OP	38	20	D	6.375	6.388	4.395
AP38-21-3B-D	3B	AP	38	21	D	5.638	5.853	3.59
AP40-21-3B-IW	3B	AP	40	21	IW	5.761	5.754	3.475
AP42-21-3B-IS	3B	AP	42	21	IS	5.301	5.297	3.437
TRT40-22-3B-IW	3B	TRT	40	22	IW	246.122	246.1	242.88
TRT42-22-3B-IS	3B	TRT	42	22	IS	240.777	240.757	237.37
TRT38-22-3B-D	3B	TRT	38	22	D	252.069	252.066	248.437
M38-23-3B-D	3B	M	38	23	D	268.525	268.53	265.113
M42-23-3B-IS	3B	M	42	23	IS	263.161	263.153	259.927
M40-23-3B-IW	3B	M	40	23	IW	268.657	268.651	265.687
FUR40-24-3B-IW	3B	FUR	40	24	IW	18.677	18.539	16.208
FUR42-24-3B-IS	3B	FUR	42	24	IS	14.091	14.058	11.768
FUR38-24-3B-D	3B	FUR	38	24	D	16.887	17.067	14.772
TCT42-25-3B-IS	3B	TCT	42	25	IS	312.8	312.7	309.1
TCT38-25-3B-D	3B	TCT	38	25	D	320.5	320.6	317
TCT40-25-3B-IW	3B	TCT	40	25	IW	328.8	328.8	325.3
PT38-26-3B-D	3B	PT	38	26	D	136.275	136.279	134.148
PT40-26-3B-IW	3B	PT	40	26	IW	136.657	136.655	133.45
PT42-26-3B-IS	3B	PT	42	26	IS	135.28	135.279	133.16
Fe17-1-4A-IS	4A	Fe	17	1	IS	126.210	126.193	124.620
Fe13-1-4A-D	4A	Fe	13	1	D	126.215	126.218	124.648
Fe15-1-4A-IW	4A	Fe	15	1	IW	127.862	127.858	126.221
Cu13-2-4A-D	4A	Cu	13	2	D	103.008	103.036	101.398
Cu17-2-4A-IS	4A	Cu	17	2	IS	103.250	103.242	101.714
Cu15-2-4A-IW	4A	Cu	15	2	IW	103.698	103.691	102.000
Al13-3-4A-D	4A	Al	13	3	D	92.542	94.546	90.850
Al17-3-4A-IS	4A	Al	17	3	IS	92.633	92.633	90.995
Al15-3-4A-IW	4A	Al	15	3	IW	92.687	92.683	91.108
L13-4-4A-D	4A	L	13	4	D	18.289	18.396	16.870
L17-4-4A-IS	4A	L	17	4	IS	17.777	17.777	16.126
L15-4-4A-IW	4A	L	15	4	IW	19.158	19.180	17.623

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
UW17-5-4A-IS	4A	UW	17	5	IS	39.968	39.953	38.415
UW13-5-4A-D	4A	UW	13	5	D	36.625	36.668	35.125
UW15-5-4A-IW	4A	UW	15	5	IW	36.430	36.428	34.732
VW13-6-4A-D	4A	VW	13	6	D	35.558	35.517	34.002
VW17-6-4A-IS	4A	VW	17	6	IS	50.781	50.771	49.242
VW15-6-4A-IW	4A	VW	15	6	IW	36.918	36.918	35.343
OP13-7-4A-D	4A	OP	13	7	D	6.009	6.064	4.546
OP17-7-4A-IS	4A	OP	17	7	IS	5.902	5.906	4.382
OP15-7-4A-IW	4A	OP	15	7	IW	5.781	5.782	4.225
AP13-8-4A-D	4A	AP	13	8	D	4.985	4.885	3.461
AP17-8-4A-IS	4A	AP	17	8	IS	5.059	5.064	3.498
AP15-8-4A-IW	4A	AP	15	8	IW	4.986	4.989	3.403
TRT15-9-4A-IW	4A	TRT	15	9	IW	240.541	240.532	238.970
TRT13-9-4A-D	4A	TRT	13	9	D	259.993	260.108	258.471
TRT17-9-4A-IS	4A	TRT	17	9	IS	239.721	239.716	238.150
M17-10-4A-IS	4A	M	17	10	IS	267.311	267.301	265.745
M13-10-4A-D	4A	M	13	10	D	239.003	239.684	237.858
M15-10-4A-IW	4A	M	15	10	IW	269.340	269.335	267.601
FUR13-11-4A-D	4A	FUR	13	11	D	13.617	13.729	11.588
FUR17-11-4A-IS	4A	FUR	17	11	IS	12.618	12.630	10.975
FUR15-11-4A-IW	4A	FUR	15	11	IW	15.023	15.033	13.320
TCT13-12-4A-D	4A	TCT	13	12	D	311.100	311.400	309.900
TCT17-12-4A-IS	4A	TCT	17	12	IS	306.900	306.900	305.200
TCT15-12-4A-IW	4A	TCT	15	12	IW	308.700	308.700	306.800
PT13-13-4A-D	4A	PT	13	13	D	135.084	135.228	133.800
PT17-13-4A-IS	4A	PT	17	13	IS	134.725	134.726	133.162
PT15-13-4A-IW	4A	PT	15	13	IW	133.903	133.910	132.138
Fe14-14-4A-D	4A	Fe	14	14	D	128.038	128.321	126.589
Fe18-14-4A-IS	4A	Fe	18	14	IS	126.181	126.174	124.586
Fe16-14-4A-IW	4A	Fe	16	14	IW	127.928	127.922	126.356
Cu14-15-4A-D	4A	Cu	14	15	D	103.461	103.515	101.935
Cu18-15-4A-IS	4A	Cu	18	15	IS	103.527	103.527	101.940
Cu16-15-4A-IW	4A	Cu	16	15	IW	103.101	103.100	101.525
Al16-16-4A-IW	4A	Al	16	16	IW	92.132	91.849	90.603
Al14-16-4A-D	4A	Al	14	16	D	92.816	92.829	91.253
Al18-16-4A-IS	4A	Al	18	16	IS	91.053	91.058	89.434
L14-17-4A-D	4A	L	14	17	D	18.814	19.307	17.644
L18-17-4A-IS	4A	L	18	17	IS	17.294	17.303	15.719
L16-17-4A-IW	4A	L	16	17	IW	18.905	18.909	17.333
UW14-18-4A-D	4A	UW	14	18	D	42.675	43.626	41.640

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
UW18-18-4A-IS	4A	UW	18	18	IS	37.222	37.225	35.622
UW16-18-4A-IW	4A	UW	16	18	IW	37.244	37.241	35.587
VW16-19-4A-IW	4A	VW	16	19	IW	38.662	38.400	36.941
VW18-19-4A-IS	4A	VW	18	19	IS	36.155	36.035	34.612
VW14-19-4A-D	4A	VW	14	19	D	49.248	49.696	47.974
OP14-20-4A-D	4A	OP	14	20	D	6.150	6.403	4.684
OP16-20-4A-IW	4A	OP	16	20	IW	5.910	5.911	4.362
OP18-20-4A-IS	4A	OP	18	20	IS	6.034	6.030	4.426
AP14-21-4A-D	4A	AP	14	21	D	5.103	5.223	3.547
AP18-21-4A-IS	4A	AP	18	21	IS	5.097	5.100	3.499
AP16-21-4A-IW	4A	AP	16	21	IW	5.033	5.035	3.483
TRT18-22-4A-IS	4A	TRT	18	22	IS	247.915	247.904	246.230
TRT14-22-4A-D	4A	TRT	14	22	D	246.069	246.531	244.916
TRT16-22-4A-IW	4A	TRT	16	22	IW	236.355	236.348	234.748
M14-23-4A-D	4A	M	14	23	D	265.419	266.087	264.428
M16-23-4A-IW	4A	M	16	23	IW	258.584	258.594	256.989
M18-23-4A-IS	4A	M	18	23	IS	266.181	266.173	264.499
FUR16-24-4A-IW	4A	FUR	16	24	IW	13.989	13.601	12.288
FUR14-24-4A-D	4A	FUR	14	24	D	13.926	15.413	13.494
FUR18-24-4A-IS	4A	FUR	18	24	IS	11.214	11.216	9.720
TCT16-25-4A-IW	4A	TCT	16	25	IW	307.500	307.400	305.800
TCT14-25-4A-D	4A	TCT	14	25	D	299.200	299.500	297.900
TCT18-25-4A-IS	4A	TCT	18	25	IS	298.400	298.400	296.800
PT14-26-4A-D	4A	PT	14	26	D	134.895	137.200	134.832
PT18-26-4A-IS	4A	PT	18	26	IS	135.067	135.059	133.583
PT16-26-4A-IW	4A	PT	16	26	IW	134.903	134.899	133.347
Fe43-1-4B-D	4B	Fe	43	1	D	127.316	127.292	125.586
Fe45-1-4B-IW	4B	Fe	45	1	IW	127.162	127.152	125.416
Fe47-1-4B-IS	4B	Fe	47	1	IS	127.77	127.769	125.767
Cu47-2-4B-IS	4B	Cu	47	2	IS	104.152	104.146	102.24
Cu43-2-4B-D	4B	Cu	43	2	D	102.815	102.814	100.795
Cu45-2-4B-IW	4B	Cu	45	2	IW	102.593	102.592	100.712
Al43-3-4B-D	4B	Al	43	3	D	89.17	89.162	87.422
Al45-3-4B-IW	4B	Al	45	3	IW	92.524	92.526	90.612
Al47-3-4B-IS	4B	Al	47	3	IS	91.809	91.805	90.925
L43-4-4B-D	4B	L	43	4	D	18.766	18.245	16.178
L47-4-4B-IS	4B	L	47	4	IS	17.341	17.142	15.213
L45-4-4B-IW	4B	L	45	4	IW	16.162	16.069	14.008
UW43-5-4B-D	4B	UW	43	5	D	37.5	37.29	35.482
UW45-5-4B-IW	4B	UW	45	5	IW	34.277	34.206	32.268

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
UW47-5-4B-IS	4B	UW	47	5	IS	40.991	40.921	38.909
VW43-6-4B-D	4B	VW	43	6	D	37.094	36.896	35.063
VW47-6-4B-IS	4B	VW	47	6	IS	46.428	46.38	44.351
VW45-6-4B-IW	4B	VW	45	6	IW	38.094	38.079	36.101
OP43-7-4B-D	4B	OP	43	7	D	6.366	6.25	4.141
OP47-7-4B-IS	4B	OP	47	7	IS	6.327	6.294	4.319
OP45-7-4B-IW	4B	OP	45	7	IW	6.118	6.096	4.262
AP43-8-4B-D	4B	AP	43	8	D	5.192	5.12	3.408
AP45-8-4B-IW	4B	AP	45	8	IW	6.118	6.096	4.262
AP47-8-4B-IS	4B	AP	47	8	IS	5.456	5.441	3.509
TRT43-9-4B-D	4B	TRT	43	9	D	250.01	249.97	247.108
TRT45-9-4B-IW	4B	TRT	45	9	IW	228.856	228.843	226.15
TRT47-9-4B-IS	4B	TRT	47	9	IS	267.102	267.099	263.899
M43-10-4B-D	4B	M	43	10	D	273.047	273.032	270.084
M45-10-4B-IW	4B	M	45	10	IW	264.641	264.637	261.553
M47-10-4B-IS	4B	M	47	10	IS	267.102	267.099	263.899
FUR43-11-4B-D	4B	FUR	43	11	D	14.45	14.315	12.198
FUR47-11-4B-IS	4B	FUR	47	11	IS	14.637	14.593	12.532
FUR45-11-4B-IW	4B	FUR	45	11	IW	18.107	18.077	15.955
TCT43-12-4B-D	4B	TCT	43	12	D	319.8	319.8	317
TCT47-12-4B-IS	4B	TCT	47	12	IS	322.6	322.6	319.5
TCT45-12-4B-IW	4B	TCT	45	12	IW	325.4	325.4	322.4
PT43-13-4B-D	4B	PT	43	13	D	135.33	135.307	132.496
PT47-13-4B-IS	4B	PT	47	13	IS	134.92	134.909	133.072
PT45-13-4B-IW	4B	PT	45	13	IW	136.302	136.292	136.673
Fe48-14-4B-IS	4B	Fe	48	14	IS	124.242	124.226	122.261
Fe46-14-4B-IW	4B	Fe	46	14	IW	126.201	126.192	124.671
Fe44-14-4B-D	4B	Fe	44	14	D	128.046	128.038	126.346
Cu44-15-4B-D	4B	Cu	44	15	D	102.891	102.891	101.157
Cu48-15-4B-IS	4B	Cu	48	15	IS	103.929	103.932	101.85
Cu46-15-4B-IW	4B	Cu	46	15	IW	104.84	104.835	103.48
Al44-16-4B-D	4B	Al	44	16	D	92.734	92.737	90.988
Al46-16-4B-IW	4B	Al	46	16	IW	92.206	92.201	90.29
Al48-16-4B-IS	4B	Al	48	16	IS	93.33	93.327	91.362
L44-17-4B-D	4B	L	44	17	D	17.951	17.681	15.66
L48-17-4B-IS	4B	L	48	17	IS	18.224	18.162	16.005
L46-17-4B-IW	4B	L	46	17	IW	16.243	16.196	14.173
UW48-18-4B-IS	4B	UW	48	18	IS	41.247	41.195	39.291
UW44-18-4B-D	4B	UW	44	18	D	35.624	35.575	33.459
UW46-18-4B-IW	4B	UW	46	18	IW	36.462	36.426	34.298

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
VW44-19-4B-D	4B	VW	44	19	D	49.175	49.072	46.942
VW46-19-4B-IW	4B	VW	46	19	IW	42.947	42.907	41.032
VW48-19-4B-IS	4B	VW	48	19	IS	45.541	45.516	43.614
OP44-20-4B-D	4B	OP	44	20	D	6.411	6.368	4.221
OP46-20-4B-IW	4B	OP	46	20	IW	6.335	6.311	4.183
OP48-20-4B-IS	4B	OP	48	20	IS	6.261	6.244	4.253
AP46-21-4B-IW	4B	AP	46	21	IW	6.335	6.311	4.183
AP44-21-4B-D	4B	AP	44	21	D	5.247	5.228	3.488
AP48-21-4B-IS	4B	AP	48	21	IS	5.497	5.483	3.482
TRT44-22-4B-D	4B	TRT	44	22	D	240.2	240.16	237.387
TRT48-22-4B-IS	4B	TRT	48	22	IS	242.302	242.273	239.436
TRT46-22-4B-IW	4B	TRT	46	22	IW	242.317	242.292	239.371
M46-23-4B-IW	4B	M	46	23	IW	262.782	262.756	260.486
M48-23-4B-IS	4B	M	48	23	IS	219.125	219.118	215.833
M44-23-4B-D	4B	M	44	23	D	269.662	269.665	267.07
FUR44-24-4B-D	4B	FUR	44	24	D	16.04	15.9	14.01
FUR46-24-4B-IW	4B	FUR	46	24	IW	16.809	16.783	14.729
FUR48-24-4B-IS	4B	FUR	48	24	IS	12.522	12.505	10.337
TCT44-25-4B-D	4B	TCT	44	25	D	329.5	329.5	326.5
TCT48-25-4B-IS	4B	TCT	48	25	IS	327.7	327.7	324.4
TCT46-25-4B-IW	4B	TCT	46	25	IW	321.5	321.5	318.4
PT44-26-4B-D	4B	PT	44	26	D	137.028	137.02	134.534
PT46-26-4B-IW	4B	PT	46	26	IW	135.482	135.477	133.754
PT48-26-4B-IS	4B	PT	48	26	IS	135.163	135.165	132.136
Fe25-1-5A-D	5A	Fe	25	1	D	127.728	128.222	126.036
Fe29-1-5A-IS	5A	Fe	29	1	IS	127.282	127.299	125.731
Fe27-1-5A-IW	5A	Fe	27	1	IW	127.697	127.713	125.917
Cu25-2-5A-D	5A	Cu	25	2	D	103.577	104.839	101.925
Cu27-2-5A-IW	5A	Cu	27	2	IW	104.488	104.492	102.769
Cu29-2-5A-IS	5A	Cu	29	2	IS	104.569	104.568	102.958
Al29-3-5A-IS	5A	Al	29	3	IS	92.857	92.851	91.106
Al25-3-5A-D	5A	Al	25	3	D	92.661	93.619	91.738
Al27-3-5A-IW	5A	Al	27	3	IW	92.855	92.870	91.117
L25-4-5A-D	5A	L	25	4	D	17.369	19.071	16.962
L29-4-5A-IS	5A	L	29	4	IS	16.283	16.321	14.635
L27-4-5A-IW	5A	L	27	4	IW	16.994	17.030	15.216
UW25-5-5A-D	5A	UW	25	5	D	41.100	42.183	40.583
UW29-5-5A-IS	5A	UW	29	5	IS	41.113	41.143	39.489
UW27-5-5A-IW	5A	UW	27	5	IW	43.484	43.511	41.810
VW25-6-5A-D	5A	VW	25	6	D	35.886	36.599	34.771

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
VW27-6-5A-IW	5A	VW	27	6	IW	47.243	47.256	45.529
VW29-6-5A-IS	5A	VW	29	6	IS	46.099	46.098	44.476
OP29-7-5A-IS	5A	OP	29	7	IS	6.055	6.050	4.402
OP25-7-5A-D	5A	OP	25	7	D	6.055	7.161	5.290
OP27-7-5A-IW	5A	OP	27	7	IW	6.197	6.224	4.406
AP25-8-5A-D	5A	AP	25	8	D	5.165	5.604	3.896
AP27-8-5A-IW	5A	AP	27	8	IW	5.210	5.210	3.539
AP29-8-5A-IS	5A	AP	29	8	IS	5.031	5.030	3.445
TRT29-9-5A-IS	5A	TRT	29	9	IS	244.886	244.863	243.282
TRT27-9-5A-IW	5A	TRT	27	9	IW	248.472	248.468	246.742
TRT25-9-5A-D	5A	TRT	25	9	D	241.727	243.119	241.430
M29-10-5A-IS	5A	M	29	10	IS	250.640	250.620	248.908
M25-10-5A-D	5A	M	25	10	D	298.162	298.409	296.740
M27-10-5A-IW	5A	M	27	10	IW	264.775	264.798	263.106
FUR25-11-5A-D	5A	FUR	25	11	D	13.389	17.059	15.158
FUR29-11-5A-IS	5A	FUR	29	11	IS	16.862	16.882	15.322
FUR27-11-5A-IW	5A	FUR	27	11	IW	15.463	15.545	13.502
TCT27-12-5A-IW	5A	TCT	27	12	IW	308.300	308.200	306.300
TCT25-12-5A-D	5A	TCT	25	12	D	316.600	320.200	318.400
TCT29-12-5A-IS	5A	TCT	29	12	IS	307.700	307.700	306.200
PT25-13-5A-D	5A	PT	25	13	D	134.450	139.476	137.767
PT29-13-5A-IS	5A	PT	29	13	IS	136.051	136.057	134.386
PT27-13-5A-IW	5A	PT	27	13	IW	134.529	134.544	132.856
Fe28-14-5A-IW	5A	Fe	28	14	IW	127.874	127.867	126.133
Fe30-14-5A-IS	5A	Fe	30	14	IS	127.911	127.908	126.298
Fe26-14-5A-D	5A	Fe	26	14	D	127.082	127.388	125.493
Cu30-15-5A-IS	5A	Cu	30	15	IS	103.489	103.484	101.761
Cu26-15-5A-D	5A	Cu	26	15	D	103.931	104.404	102.654
Cu28-15-5A-IW	5A	Cu	28	15	IW	103.340	103.351	101.723
Al26-16-5A-D	5A	Al	26	16	D	92.797	93.633	91.655
Al30-16-5A-IS	5A	Al	30	16	IS	92.504	92.506	90.867
Al28-16-5A-IW	5A	Al	28	16	IW	91.461	91.467	89.827
L26-17-5A-D	5A	L	26	17	D	17.522	18.705	16.736
L30-17-5A-IS	5A	L	30	17	IS	16.184	16.215	14.545
L28-17-5A-IW	5A	L	28	17	IW	16.285	16.323	14.631
UW26-18-5A-D	5A	UW	26	18	D	41.027	43.226	41.461
UW30-18-5A-IS	5A	UW	30	18	IS	40.645	40.668	38.983
UW28-18-5A-IW	5A	UW	28	18	IW	41.352	41.384	39.609
VW26-19-5A-D	5A	VW	26	19	D	36.579	37.554	35.782
VW30-19-5A-IS	5A	VW	30	19	IS	34.729	34.736	33.069

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
VW28-19-5A-IW	5A	VW	28	19	IW	47.247	47.273	45.587
OP26-20-5A-D	5A	OP	26	20	D	6.075	6.951	4.898
OP30-20-5A-IS	5A	OP	30	20	IS	6.073	6.078	4.454
OP28-20-5A-IW	5A	OP	28	20	IW	6.200	6.242	4.501
AP26-21-5A-D	5A	AP	26	21	D	5.200	5.817	3.905
AP30-21-5A-IS	5A	AP	30	21	IS	5.024	5.047	3.392
AP28-21-5A-IW	5A	AP	28	21	IW	5.185	5.195	3.521
TRT26-22-5A-D	5A	TRT	26	22	D	252.214	253.963	252.217
TRT30-22-5A-IS	5A	TRT	30	22	IS	241.484	241.486	239.806
TRT28-22-5A-IW	5A	TRT	28	22	IW	251.018	251.037	249.367
M26-23-5A-D	5A	M	26	23	D	289.996	290.634	288.897
M30-23-5A-IS	5A	M	30	23	IS	251.787	251.795	250.204
M28-23-5A-IW	5A	M	28	23	IW	249.412	249.421	247.821
FUR26-24-5A-D	5A	FUR	26	24	D	12.748	15.016	13.621
FUR30-24-5A-IS	5A	FUR	30	24	IS	16.204	16.235	14.565
FUR28-24-5A-IW	5A	FUR	28	24	IW	14.861	14.917	13.213
TCT26-25-5A-D	5A	TCT	26	25	D	311.500	313.500	311.800
TCT30-25-5A-IS	5A	TCT	30	25	IS	317.600	317.600	315.800
TCT28-25-5A-IW	5A	TCT	28	25	IW	308.200	308.400	306.800
PT26-26-5A-D	5A	PT	26	26	D	133.784	139.154	137.416
PT30-26-5A-IS	5A	PT	30	26	IS	136.209	136.214	134.534
PT28-26-5A-IW	5A	PT	28	26	IW	134.011	134.032	132.314
Fe57-1-5B-IW	5B	Fe	57	1	IW	126.381	126.377	124.656
Fe55-1-5B-D	5B	Fe	55	1	D	126.799	127.408	125.067
Fe59-1-5B-IS	5B	Fe	59	1	IS	127.325	127.324	125.533
Cu55-2-5B-D	5B	Cu	55	2	D	102.557	103.081	101.131
Cu59-2-5B-IS	5B	Cu	59	2	IS	102.635	102.64	100.894
Cu57-2-5B-IW	5B	Cu	57	2	IW	102.71	102.716	100.87
Al55-3-5B-D	5B	Al	55	3	D	92.415	92.713	90.856
Al59-3-5B-IS	5B	Al	59	3	IS	91.615	91.619	90.042
Al57-3-5B-IW	5B	Al	57	3	IW	93.01	93.021	91.157
L59-4-5B-IS	5B	L	59	4	IS	19.22	19.186	17.459
L55-4-5B-D	5B	L	55	4	D	16.01	25.259	22.447
L57-4-5B-IW	5B	L	57	4	IW	18.608	18.615	16.895
UW59-5-5B-IS	5B	UW	59	5	IS	41.566	41.55	39.801
UW55-5-5B-D	5B	UW	55	5	D	39.13	40.817	38.885
UW57-5-5B-IW	5B	UW	57	5	IW	39.453	39.486	37.836
VW59-6-5B-IS	5B	VW	59	6	IS	36.339	36.321	34.691
VW55-6-5B-D	5B	VW	55	6	D	36.48	37.867	35.968
VW57-6-5B-IW	5B	VW	57	6	IW	38.548	38.557	37.728

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
OP59-7-5B-IS	5B	OP	59	7	IS	6.162	6.15	4.391
OP55-7-5B-D	5B	OP	55	7	D	6.041	7.035	5.085
OP57-7-5B-IW	5B	OP	57	7	IW	6.093	6.098	4.468
AP59-8-5B-IS	5B	AP	59	8	IS	4.977	4.974	3.396
AP55-8-5B-D	5B	AP	55	8	D	5.132	5.82	3.815
AP57-8-5B-IW	5B	AP	57	8	IW	5.511	5.524	3.528
TRT59-9-5B-IS	5B	TRT	59	9	IS	244.597	244.569	241.867
TRT55-9-5B-D	5B	TRT	55	9	D	238.946	241.676	239.742
TRT57-9-5B-IW	5B	TRT	57	9	IW	240.687	240.693	238.178
M59-10-5B-IS	5B	M	59	10	IS	273.769	273.761	271.347
M55-10-5B-D	5B	M	55	10	D	236.494	236.931	234.856
M57-10-5B-IW	5B	M	57	10	IW	236.351	236.382	234.022
FUR59-11-5B-IS	5B	FUR	59	11	IS	12.171	12.154	10.234
FUR55-11-5B-D	5B	FUR	55	11	D	16.65	23.9	22.088
FUR57-11-5B-IW	5B	FUR	57	11	IW	18.737	18.76	15.967
TCT59-12-5B-IS	5B	TCT	59	12	IS	313.7	313.6	311.2
TCT55-12-5B-D	5B	TCT	55	12	D	321.6	327.6	326.1
TCT57-12-5B-IW	5B	TCT	57	12	IW	315.9	315.9	313.5
PT55-13-5B-D	5B	PT	55	13	D	136.285	152.146	149.94
PT59-13-5B-IS	5B	PT	59	13	IS	134.835	134.838	132.344
PT57-13-5B-IW	5B	PT	57	13	IW	135.454	135.464	133.821
Fe60-14-5B-IS	5B	Fe	60	14	IS	127.114	127.11	125.367
Fe56-14-5B-D	5B	Fe	56	14	D	127.779	128.279	125.998
Fe58-14-5B-IW	5B	Fe	58	14	IW	128.075	128.088	126.444
Cu56-15-5B-D	5B	Cu	56	15	D	104.451	104.751	102.674
Cu60-15-5B-IS	5B	Cu	60	15	IS	102.874	102.878	101.131
Cu58-15-5B-IW	5B	Cu	58	15	IW	102.605	102.619	100.926
Al56-16-5B-D	5B	Al	56	16	D	92.838	93.182	91.291
Al60-16-5B-IS	5B	Al	60	16	IS	91.828	91.837	89.945
Al58-16-5B-IW	5B	Al	58	16	IW	92.518	92.529	90.726
L60-17-5B-IS	5B	L	60	17	IS	19.552	19.518	17.717
L56-17-5B-D	5B	L	56	17	D	18.257	28.068	26.075
L58-17-5B-IW	5B	L	58	17	IW	19.05	19.059	17.269
UW60-18-5B-IS	5B	UW	60	18	IS	41.396	41.362	39.688
UW56-18-5B-D	5B	UW	56	18	D	38.944	41.529	39.635
UW58-18-5B-IW	5B	UW	58	18	IW	42.108	42.136	40.535
VW60-19-5B-IS	5B	VW	60	19	IS	34.806	34.801	32.639
VW56-19-5B-D	5B	VW	56	19	D	34.221	35.627	33.518
VW58-19-5B-IW	5B	VW	58	19	IW	46.706	46.741	44.841
OP56-20-5B-D	5B	OP	56	20	D	5.132	5.82	3.815

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
OP60-20-5B-IS	5B	OP	60	20	IS	6.059	6.059	4.321
OP58-20-5B-IW	5B	OP	58	20	IW	6.304	6.328	4.461
AP56-21-5B-D	5B	AP	56	21	D	5.211	6.178	3.948
AP60-21-5B-IS	5B	AP	60	21	IS	5.239	5.242	3.433
AP58-21-5B-IW	5B	AP	58	21	IW	5.322	5.339	3.442
TRT60-22-5B-IS	5B	TRT	60	22	IS	249.281	249.264	246.396
TRT56-22-5B-D	5B	TRT	56	22	D	245.449	245.49	241.538
TRT58-22-5B-IW	5B	TRT	58	22	IW	238.443	238.455	235.462
M56-23-5B-D	5B	M	56	23	D	272.621	275.799	271.797
M60-23-5B-IS	5B	M	60	23	IS	257.876	257.884	255.292
M58-23-5B-IW	5B	M	58	23	IW	261.338	261.38	258.573
FUR56-24-5B-D	5B	FUR	56	24	D	16.17	22.366	20.491
FUR60-24-5B-IS	5B	FUR	60	24	IS	16.194	16.203	14.486
FUR58-24-5B-IW	5B	FUR	58	24	IW	12.395	12.44	10.687
TCT60-25-5B-IS	5B	TCT	60	25	IS	324.8	324.7	322.3
TCT56-25-5B-D	5B	TCT	56	25	D	318.6	323	319.9
TCT58-25-5B-IW	5B	TCT	58	25	IW	326.8	326.9	324.4
PT56-26-5B-D	5B	PT	56	26	D	136.478	149.541	147.636
PT60-26-5B-IS	5B	PT	60	26	IS	136.53	136.543	133.853
PT58-26-5B-IW	5B	PT	58	26	IW	135.334	135.344	133.534
Fe61-1-6B-D	6B	Fe	61	1	D	127.01	127.242	125.394
Cu61-2-6B-D	6B	Cu	61	2	D	102.735	102.944	100.946
Al61-3-6B-D	6B	Al	61	3	D	91.823	92.05	90.16
L61-4-6B-D	6B	L	61	4	D	18.984	26.834	24.811
UW61-5-6B-D	6B	UW	61	5	D	41.378	43.119	41.202
VW61-6-6B-D	6B	VW	61	6	D	45.197	46.435	44.353
OP61-7-6B-D	6B	OP	61	7	D	6.029	7.484	5.038
AP61-8-6B-D	6B	AP	61	8	D	5.634	6.165	3.914
TRT61-9-6B-D	6B	TRT	61	9	D	256.022	285.626	252.491
M61-10-6B-D	6B	M	61	10	D	240.908	240.818	237.76
FUR61-11-6B-D	6B	FUR	61	11	D	15.659	26.834	19.4
TCT61-12-6B-D	6B	TCT	61	12	D	322.8	325.8	325
PT61-13-6B-D	6B	PT	61	13	D	133.801	143.635	141.751
Fe62-14-6B-D	6B	Fe	62	14	D	127.275	127.645	125.491
Cu62-15-6B-D	6B	Cu	62	15	D	104.148	104.59	102.199
Al62-16-6B-D	6B	Al	62	16	D	92.94	93.127	91.306
L62-17-6B-D	6B	L	62	17	D	18.959	28.153	26.075
UW62-18-6B-D	6B	UW	62	18	D	38.071	39.95	39.115
VW62-19-6B-D	6B	VW	62	19	D	44.668	45.483	43.707
OP62-20-6B-D	6B	OP	62	20	D	6.004	6.701	4.918

Sample ID	Test	Sample Material	Material Seq. #	Sample Location	Array	Pre-Test Mass (g)	Post-test Mass (g)	Post-Test Mass w/o Velcro (g)
AP62-21-6B-D	6B	AP	62	21	D	5.288	5.792	3.949
TRT62-22-6B-D	6B	TRT	62	22	D	242.665	245.641	243.214
M62-23-6B-D	6B	M	62	23	D	229.72	231.818	229.864
FUR62-24-6B-D	6B	FUR	62	24	D	15.856	20.288	18.377
TCT62-25-6B-D	6B	TCT	62	25	D	318.9	324.7	322
PT62-26-6B-D	6B	PT	62	26	D	136.177	150.719	148.643

APPENDIX D –
TEMPERATURE AND RELATIVE HUMIDITY DATA FOR NEAT AND FIRE TESTS

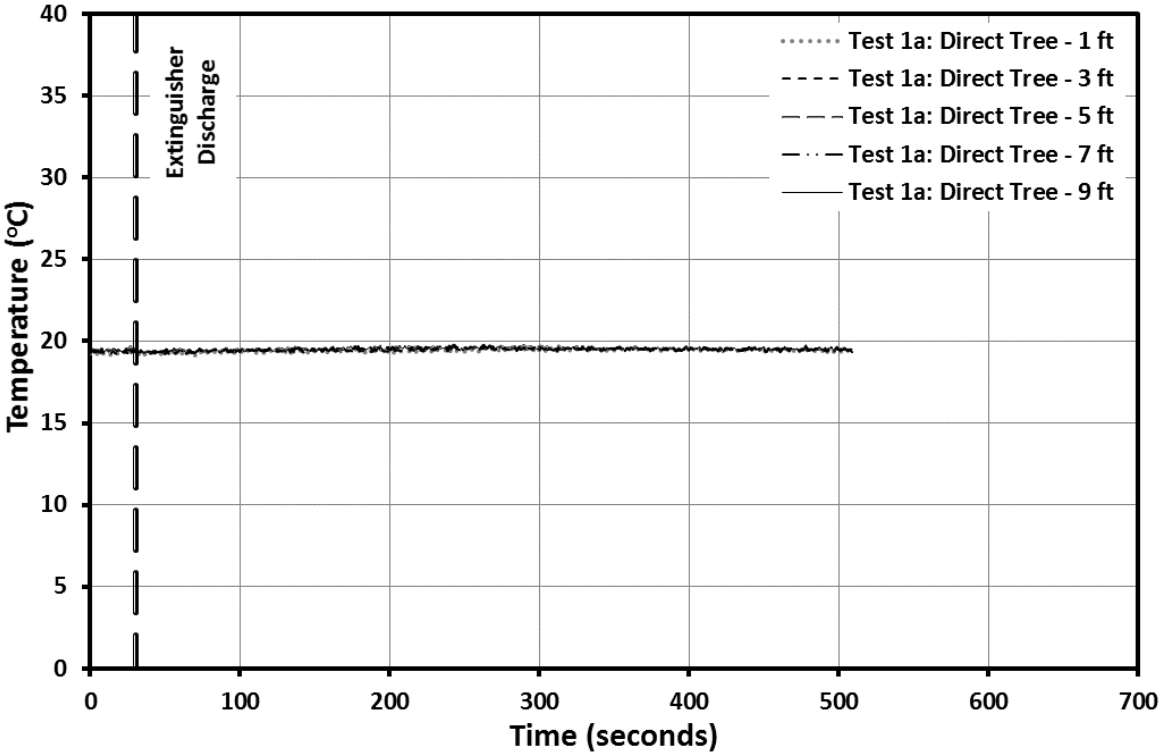

Figure D-1 – Test 1a (ABC) direct tree temperatures.

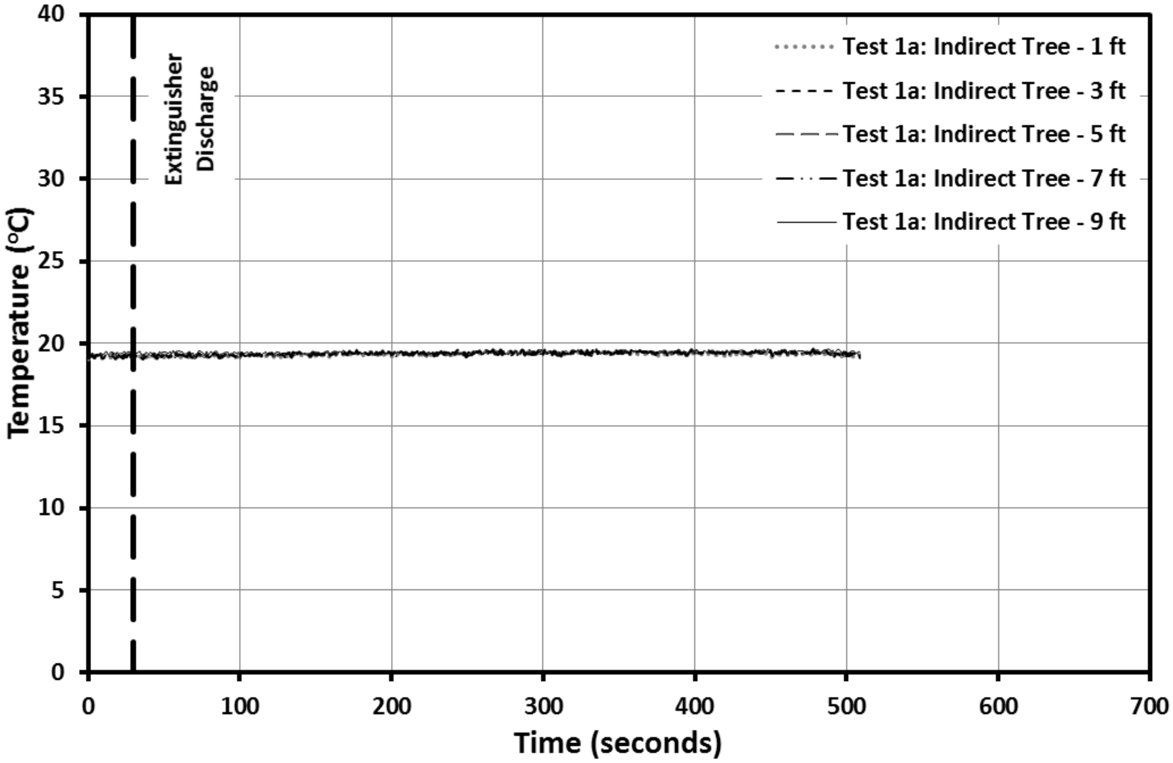

Figure D-2 – Test 1a (ABC) indirect tree temperatures.

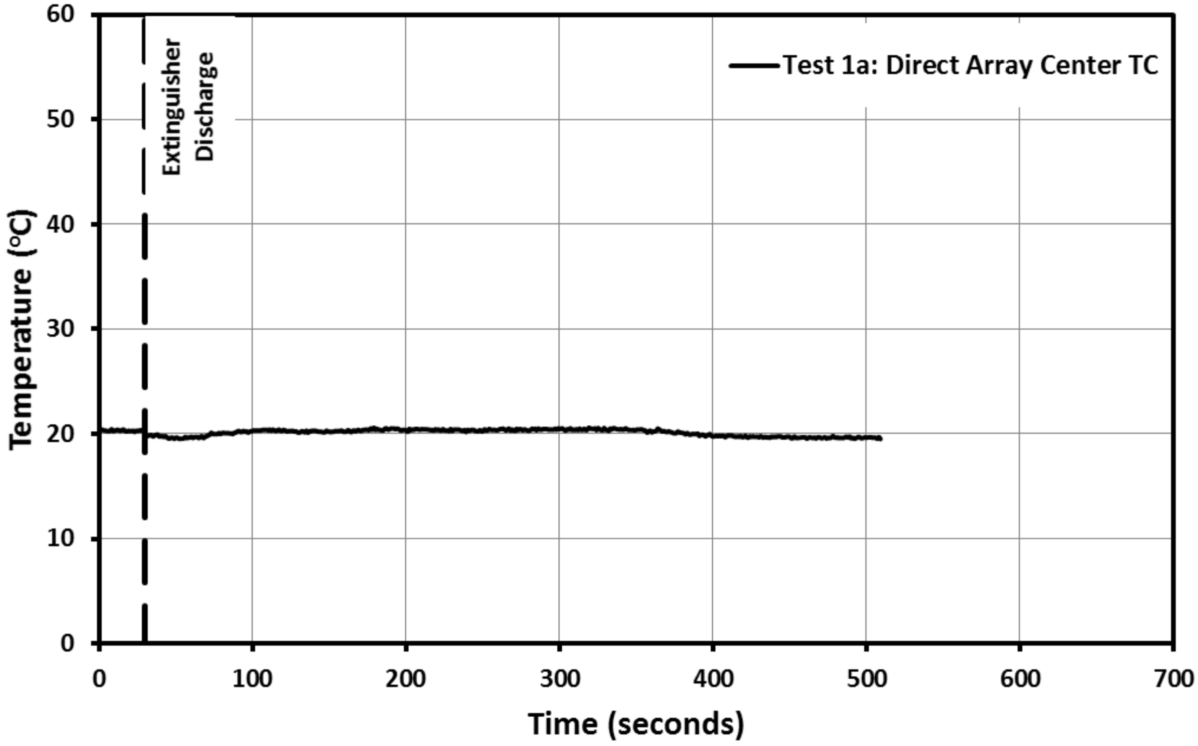

Figure D-3 – Test 1a (ABC) direct array center temperature.

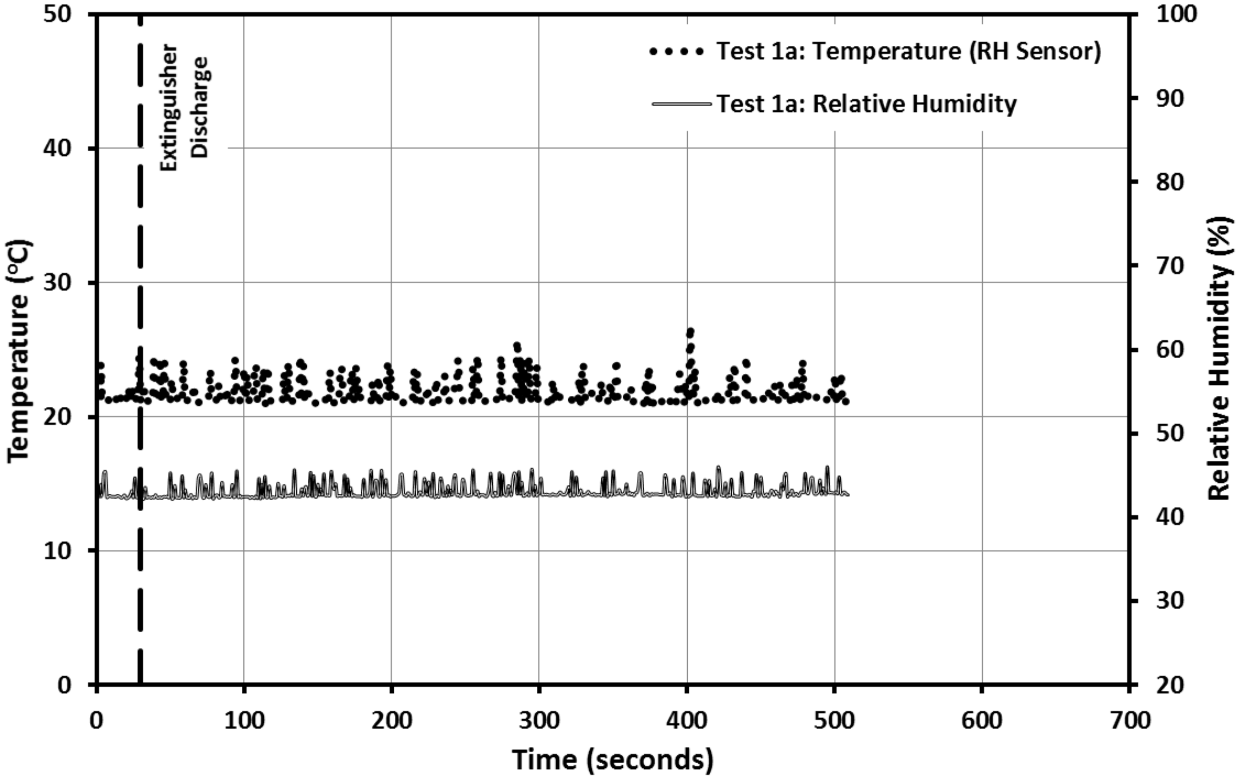

Figure D-4 – Test 1a (ABC) temperature and RH sensor measurements.

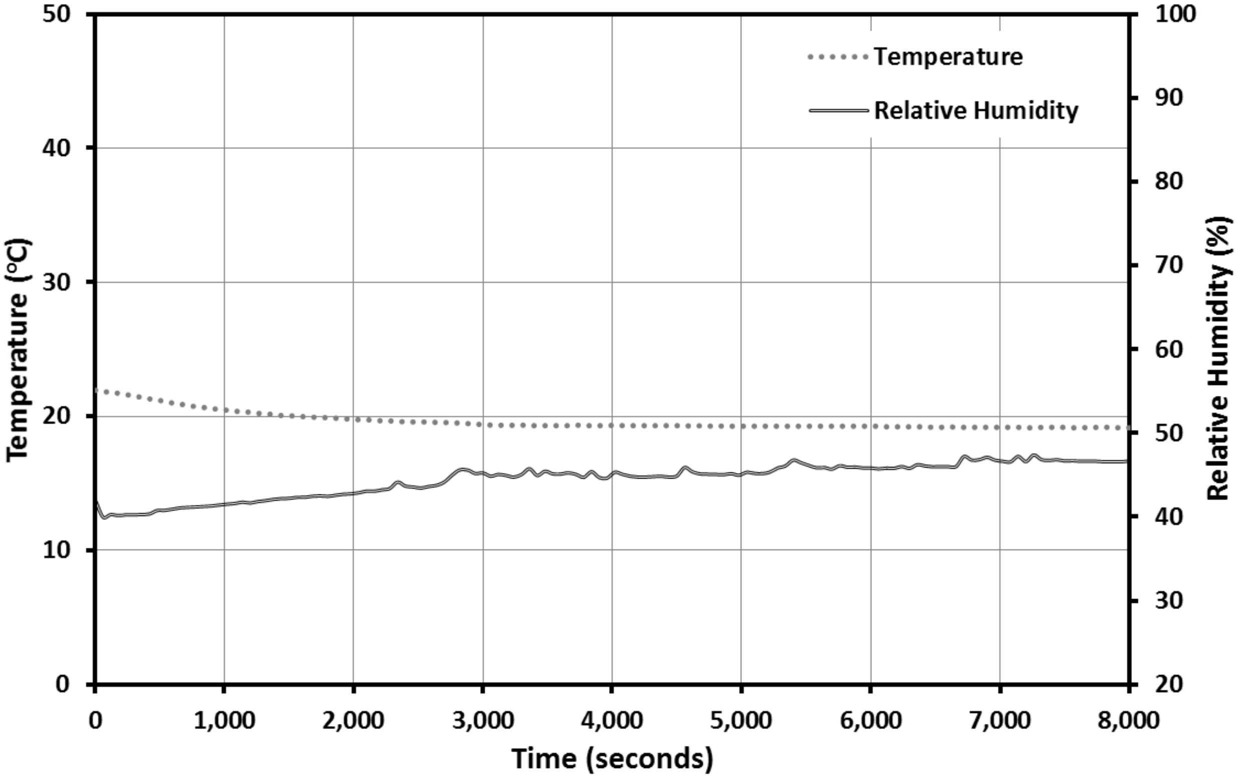

Figure D-5 – Test 1a (ABC) laboratory temperature and relative humidity.

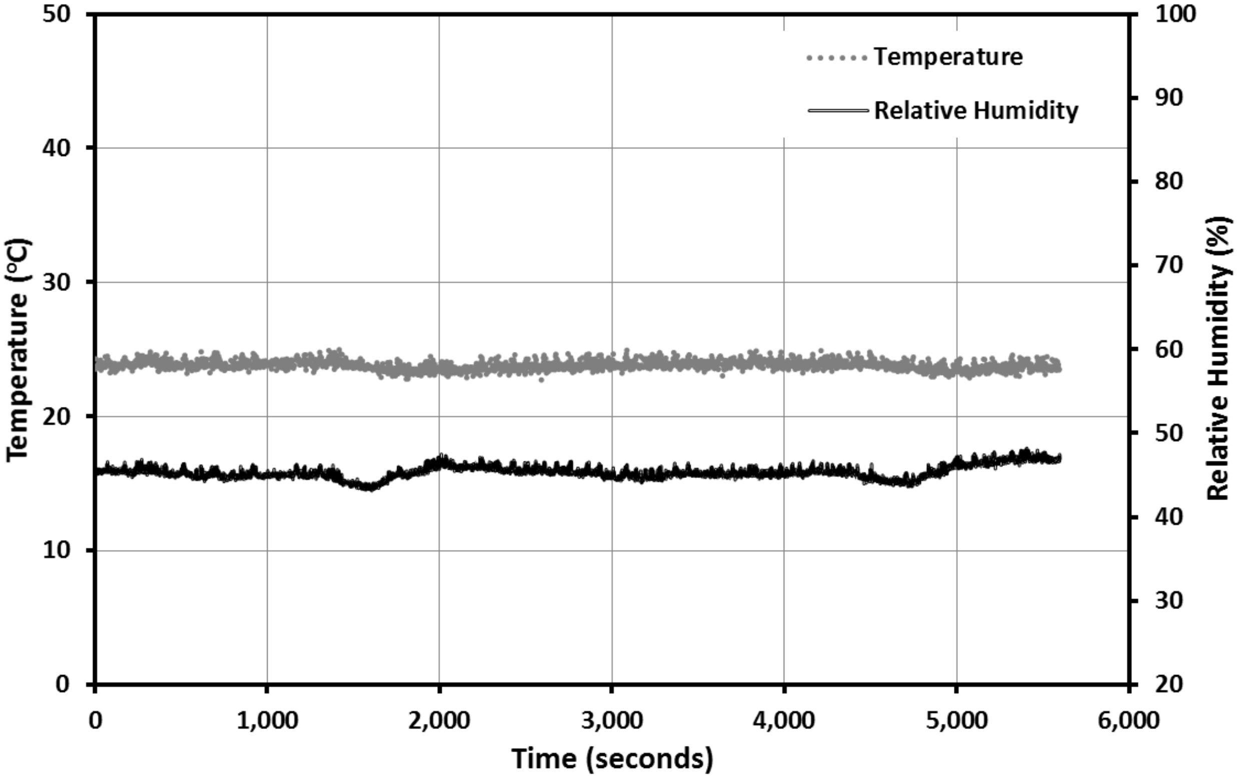

Figure D-6 – Test 1a (ABC) exam room temperature and relative humidity.

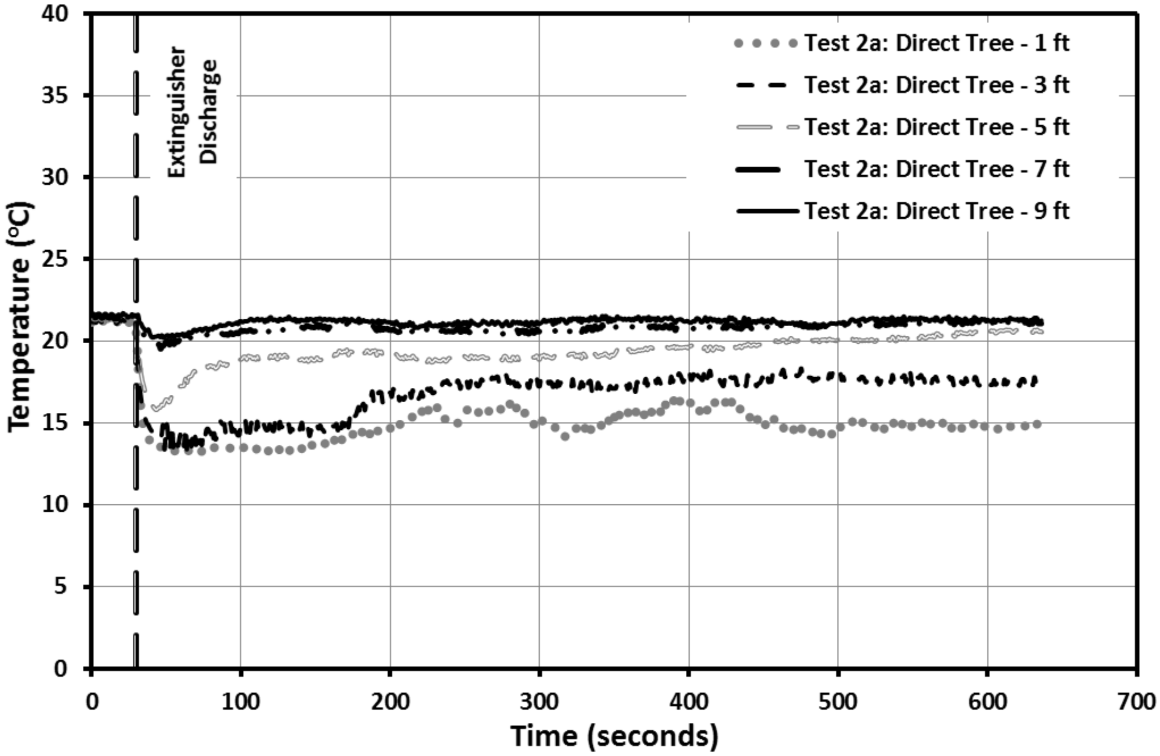

Figure D-7 – Test 2a (Water Mist) direct tree temperatures.

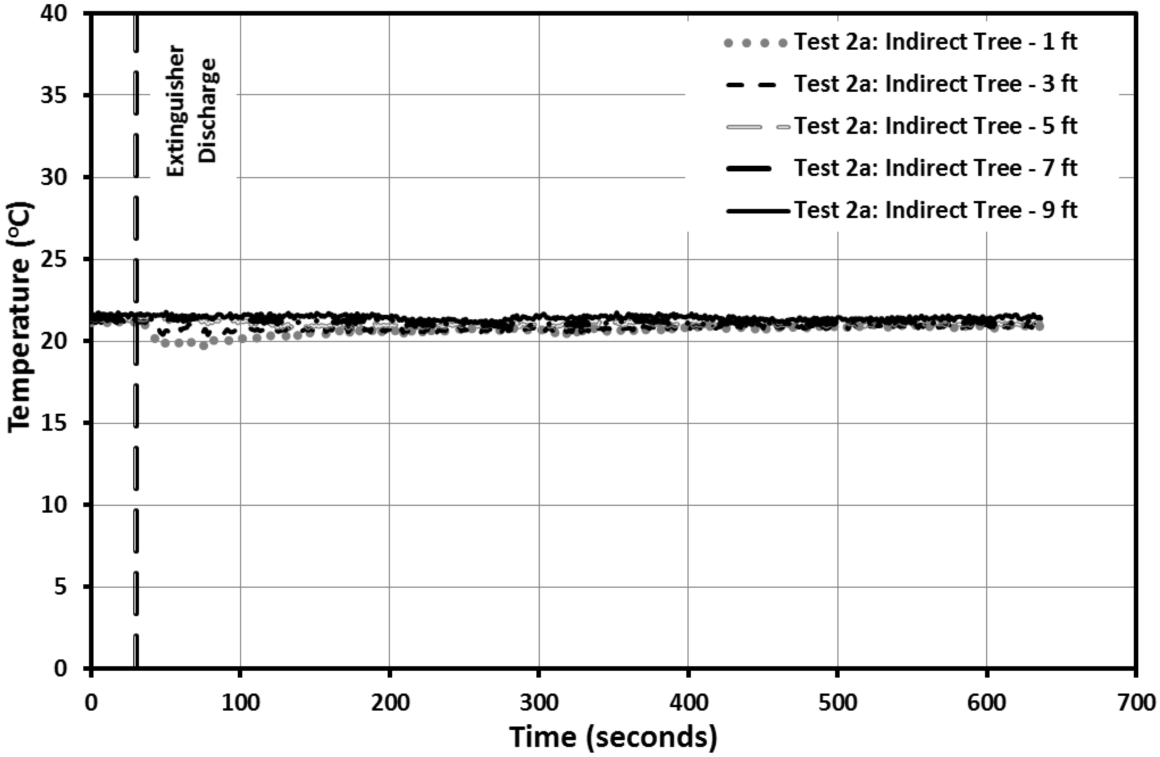

Figure D-8 – Test 2a (Water Mist) indirect tree temperatures.

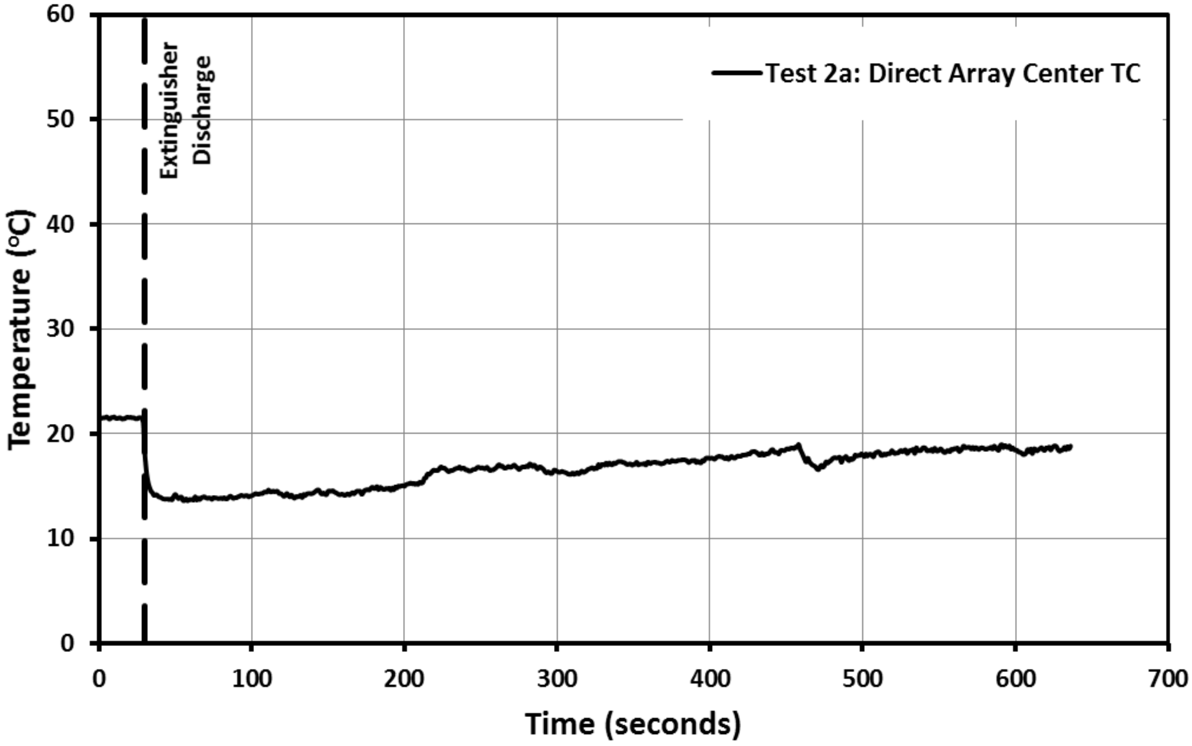

Figure D-9 – Test 2a (Water Mist) direct array center temperature.

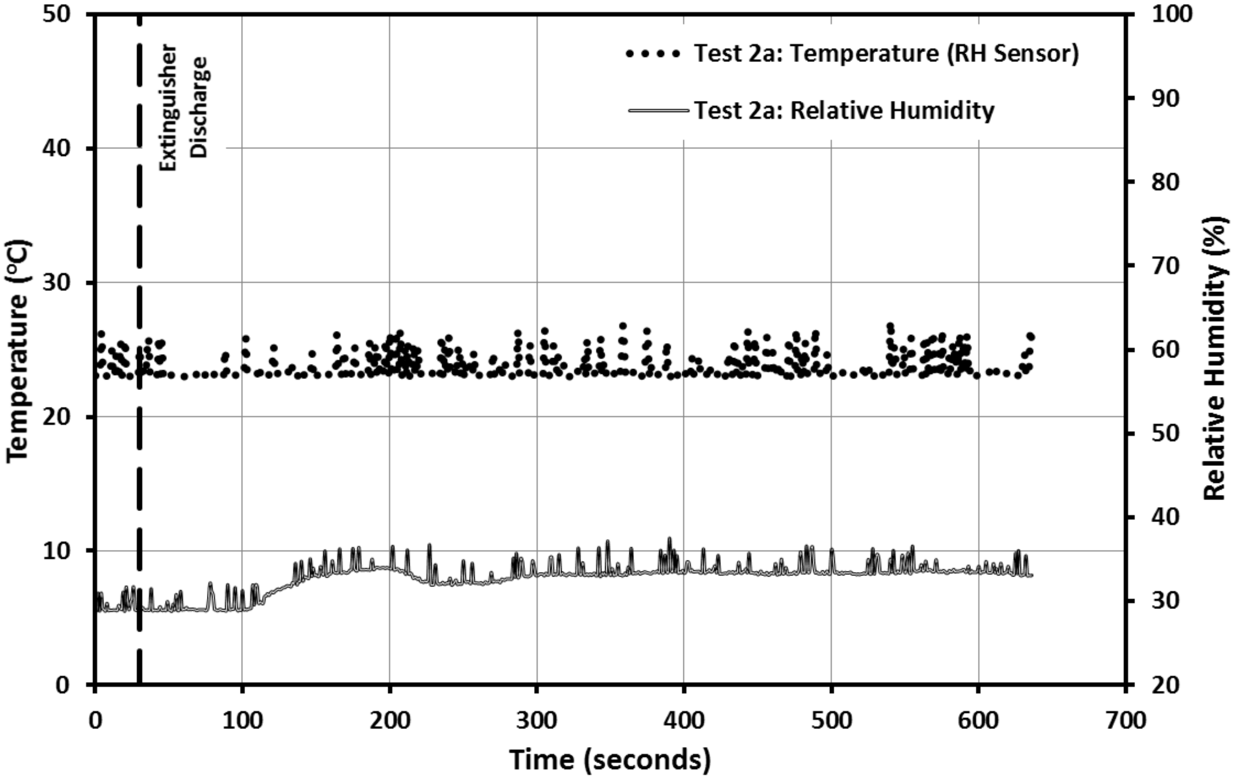

Figure D-10 – Test 2a (Water Mist) temperature and RH sensor measurements.

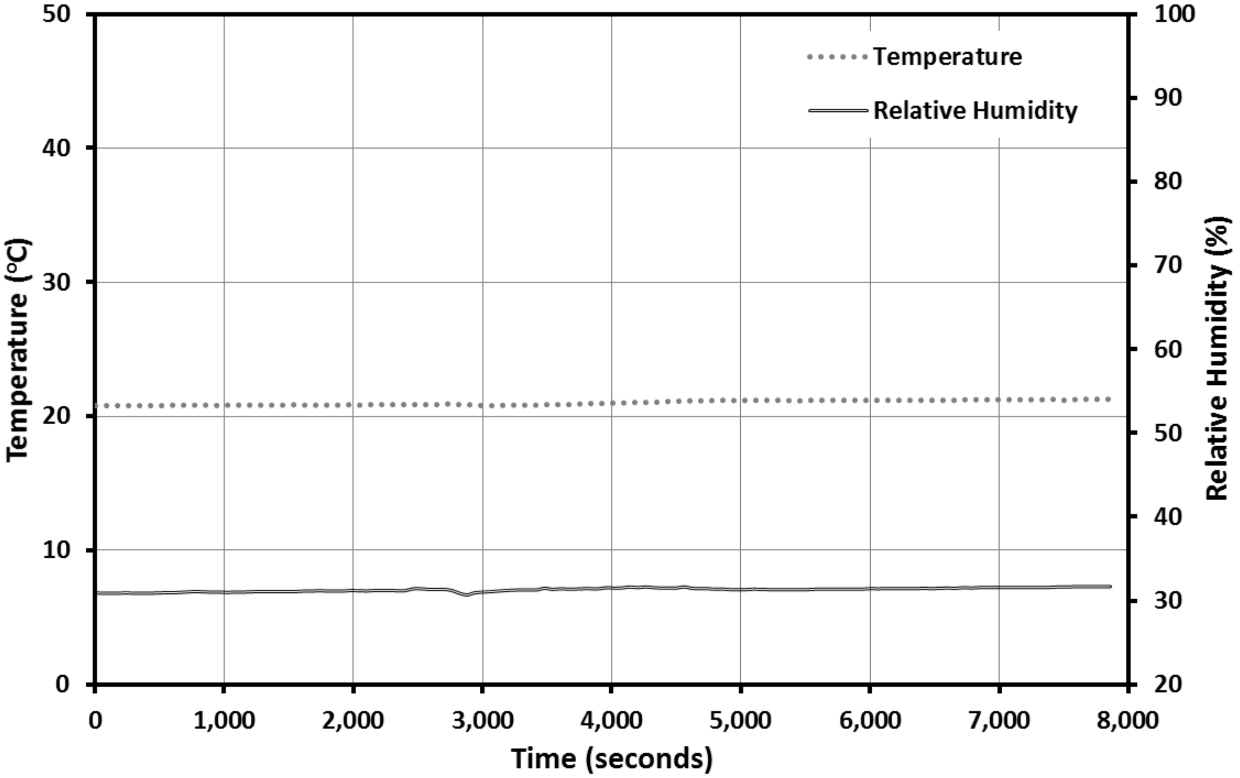

Figure D-11 – Test 2a (Water Mist) laboratory temperature and relative humidity.

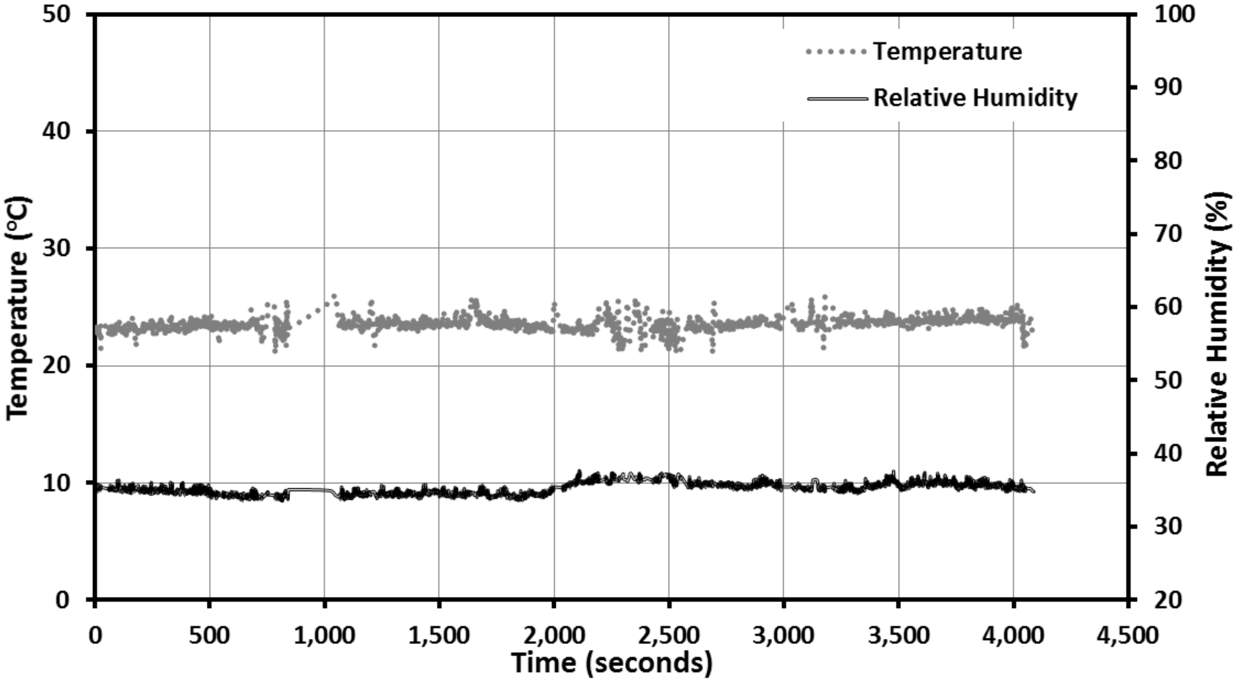

Figure D-12 – Test 2a (Water Mist) exam room temperature and relative humidity.

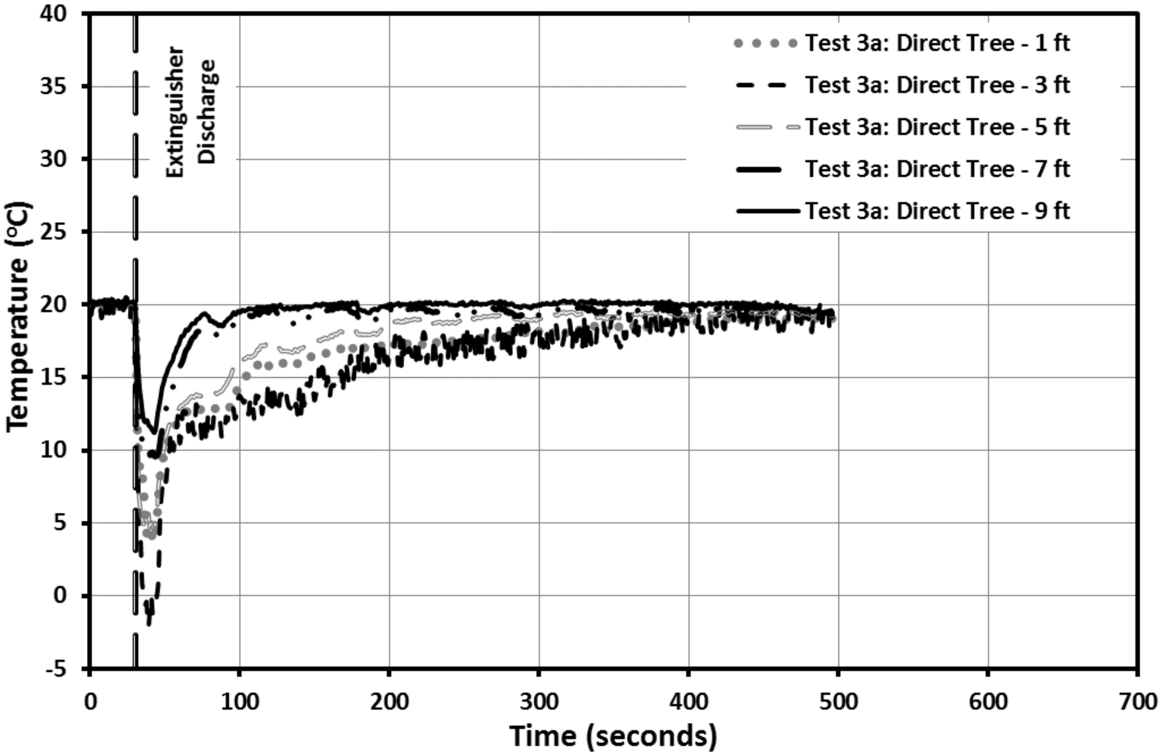

Figure D-13 – Test 3a (Halotron I) direct tree temperatures.

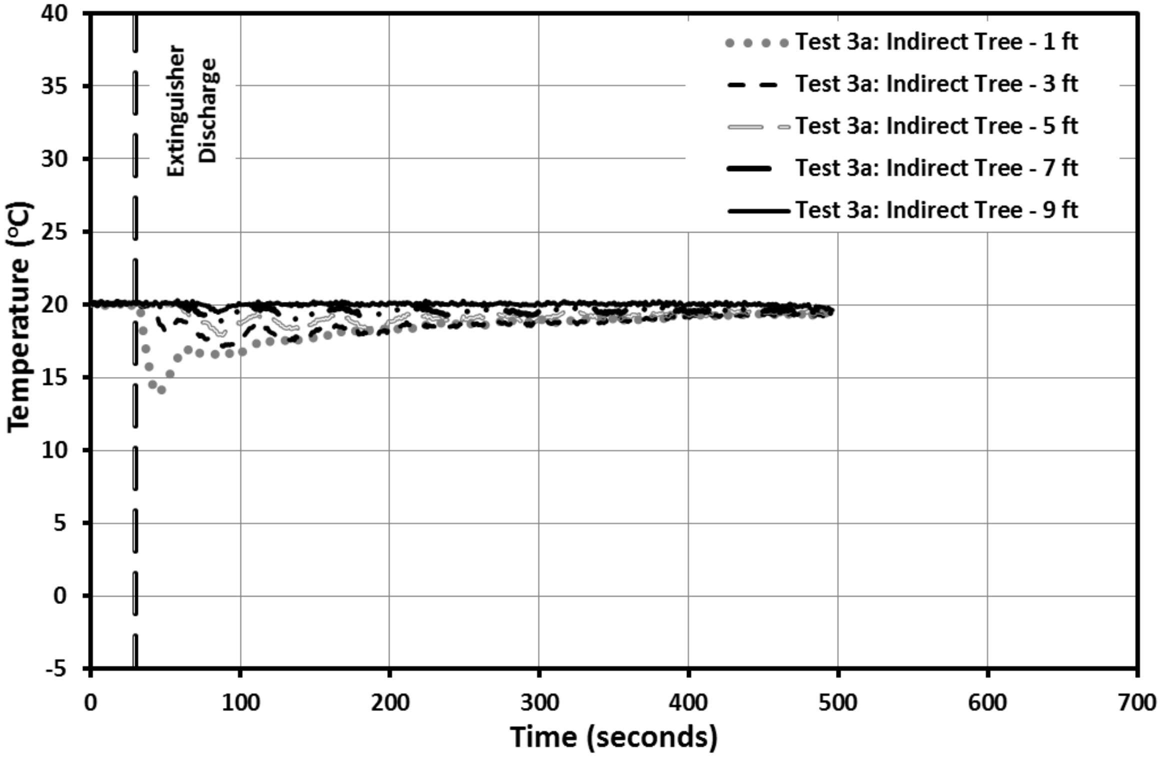

Figure D-14 – Test 3a (Halotron I) indirect tree temperatures.

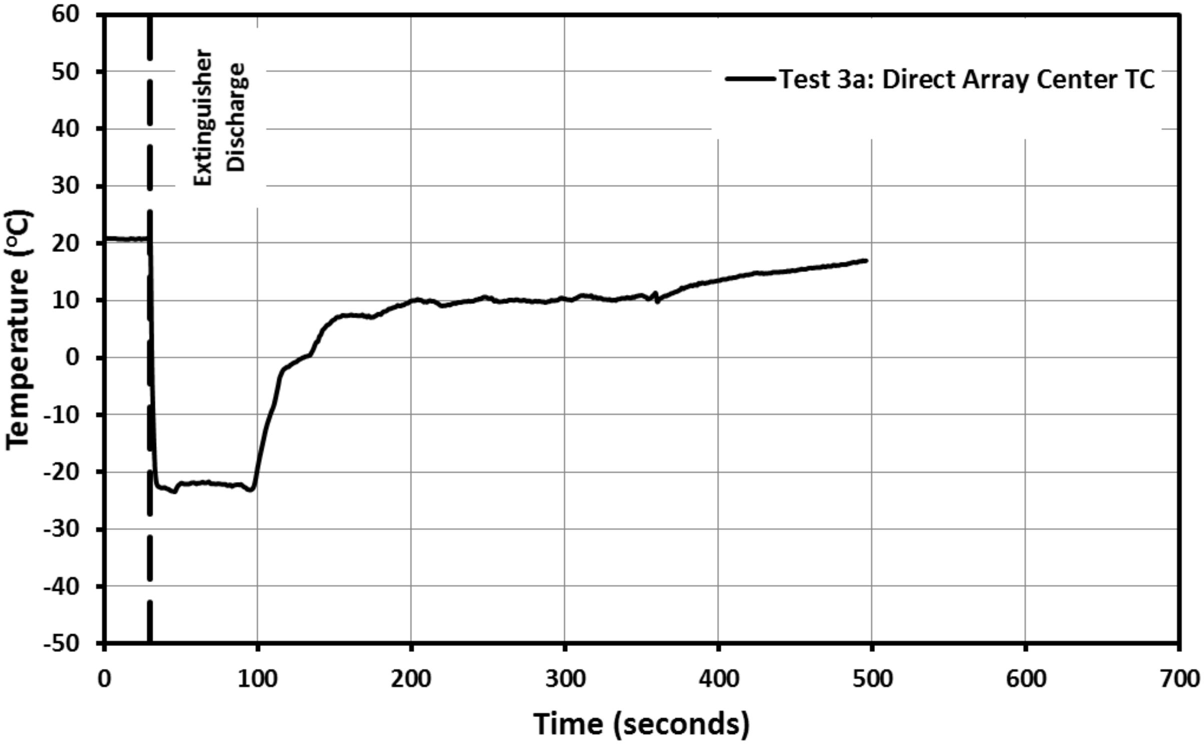

Figure D-15 – Test 3a (Halotron I) direct array center temperature.

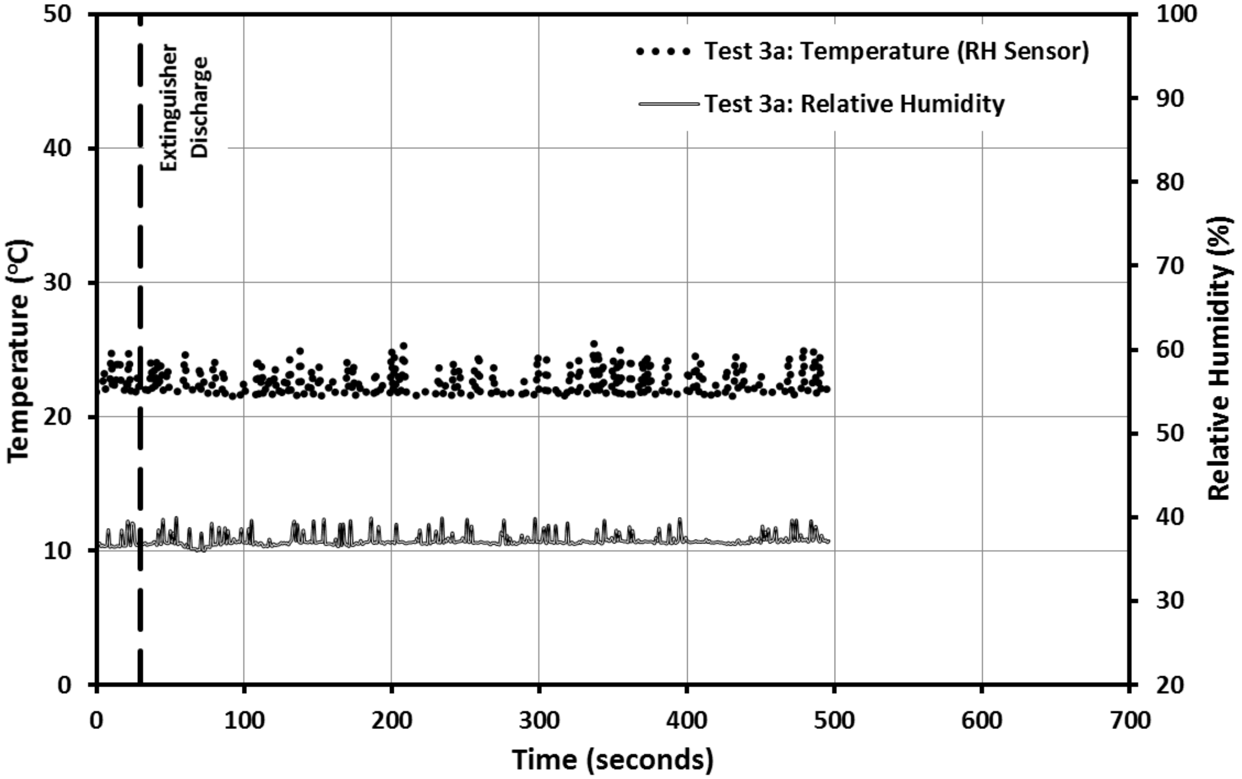

Figure D-16 – Test 3a (Halotron I) temperature and RH sensor measurements.

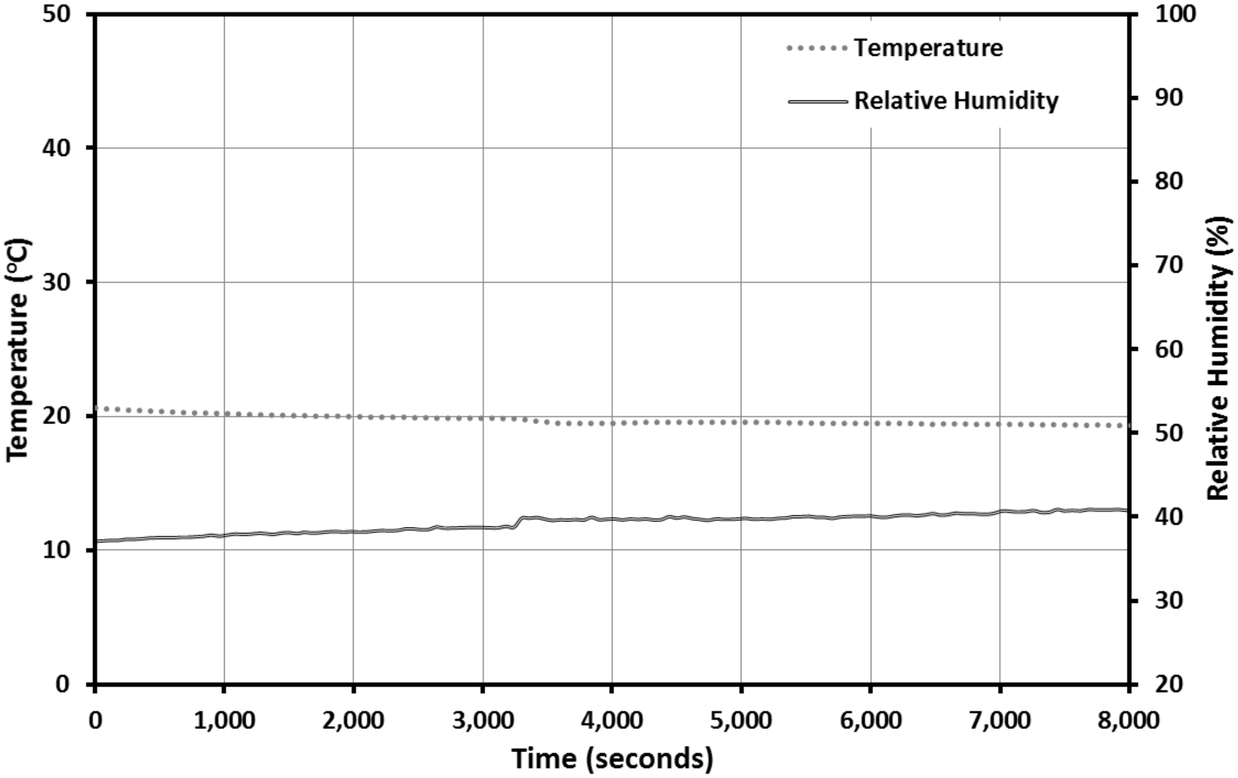

Figure D-17 – Test 3a (Halotron I) laboratory temperature and relative humidity.

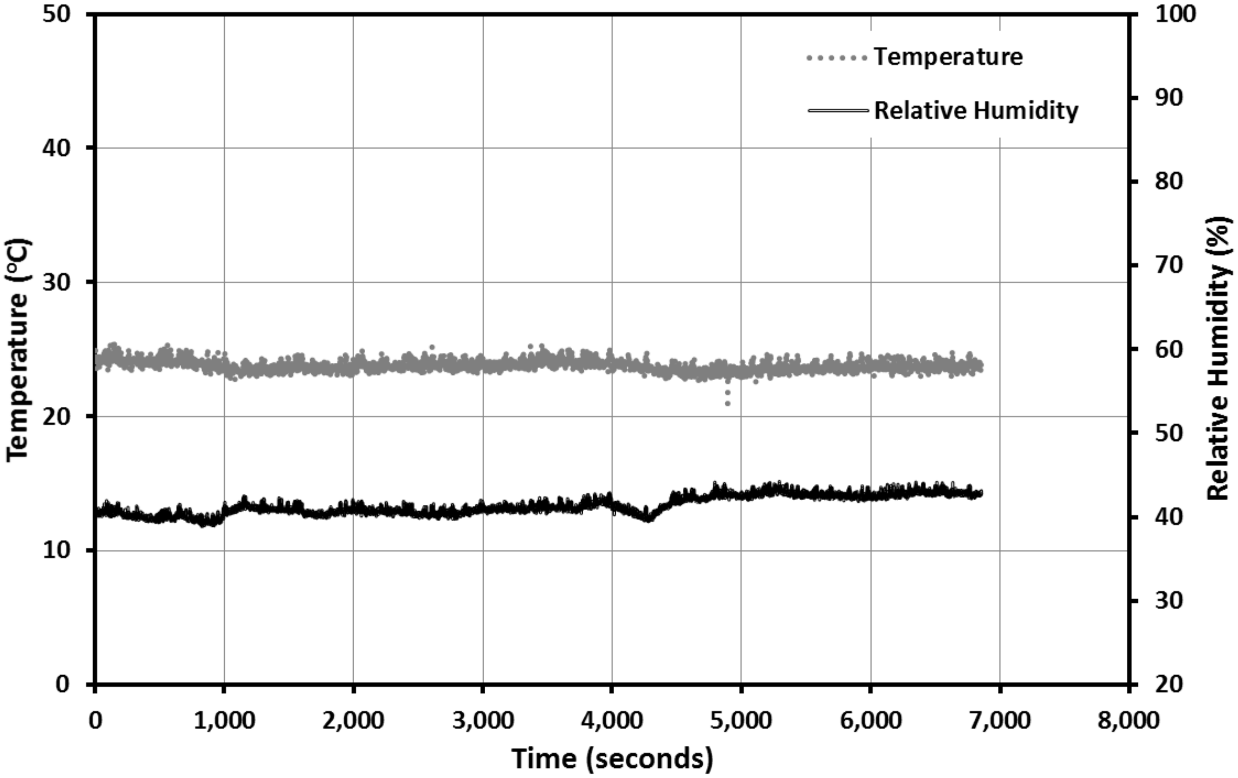

Figure D-18 – Test 3a (Halotron I) exam room temperature and relative humidity.

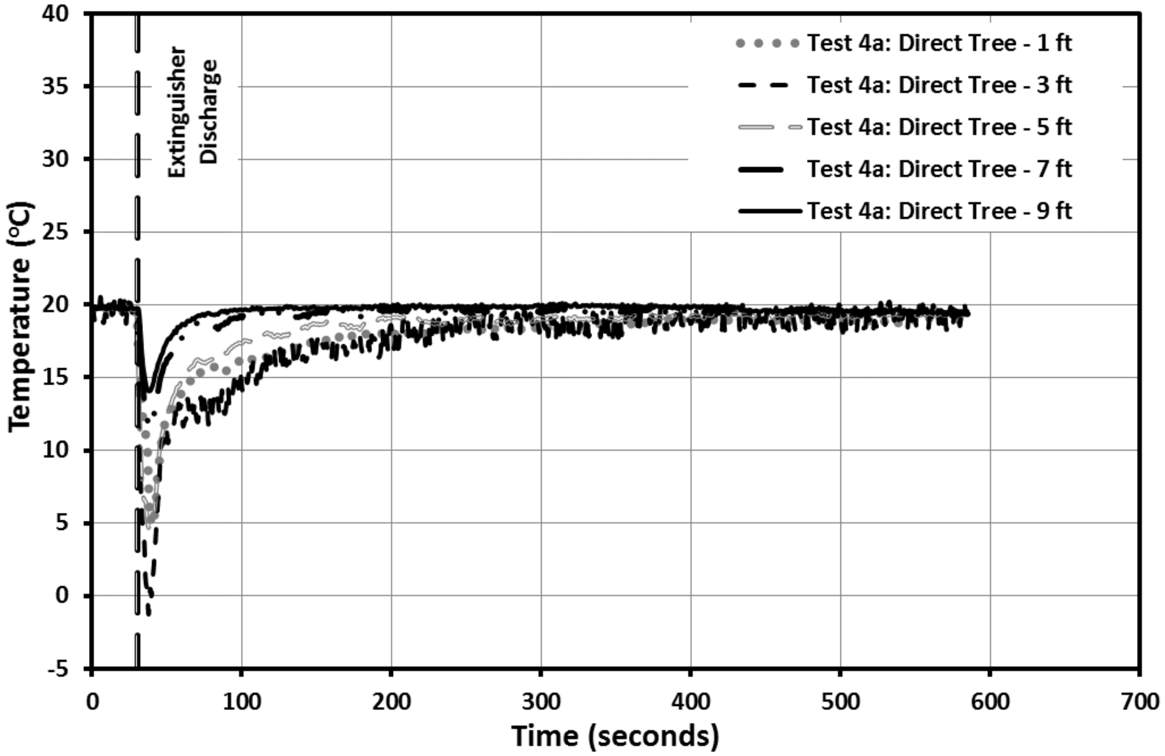

Figure D-19 – Test 4a (FE-36) direct tree temperatures.

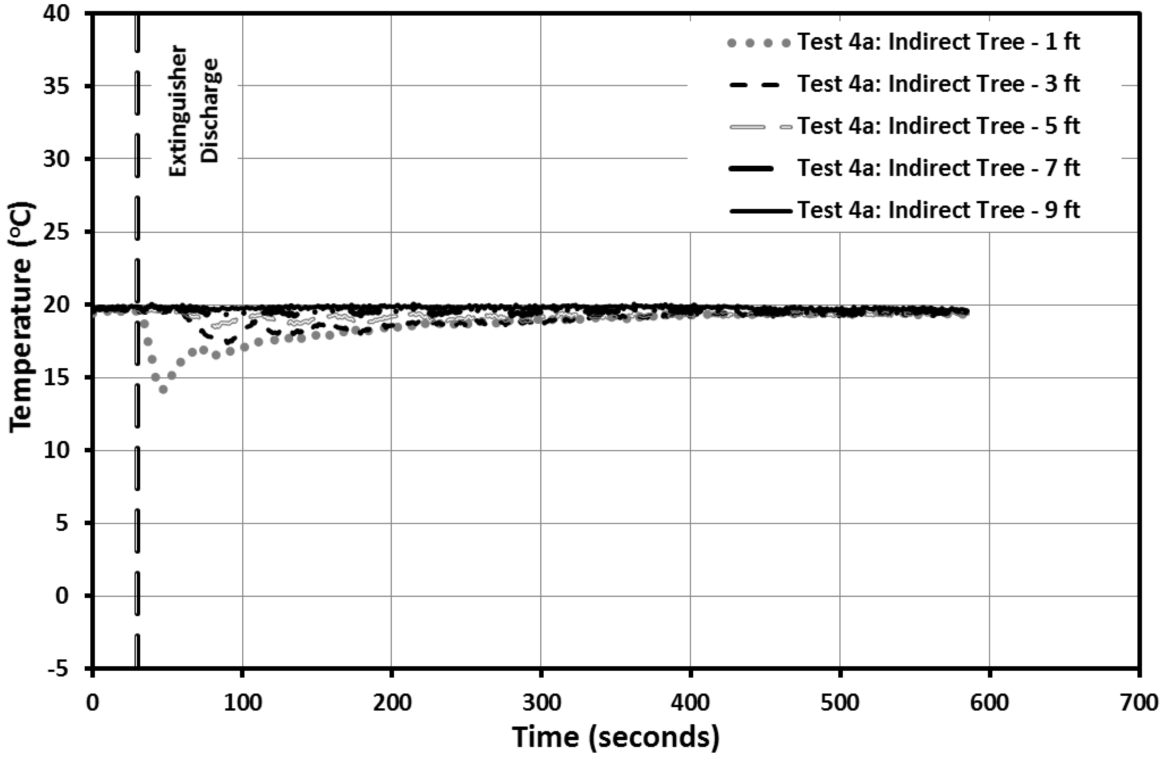

Figure D-20 – Test 4a (FE-36) indirect tree temperatures.

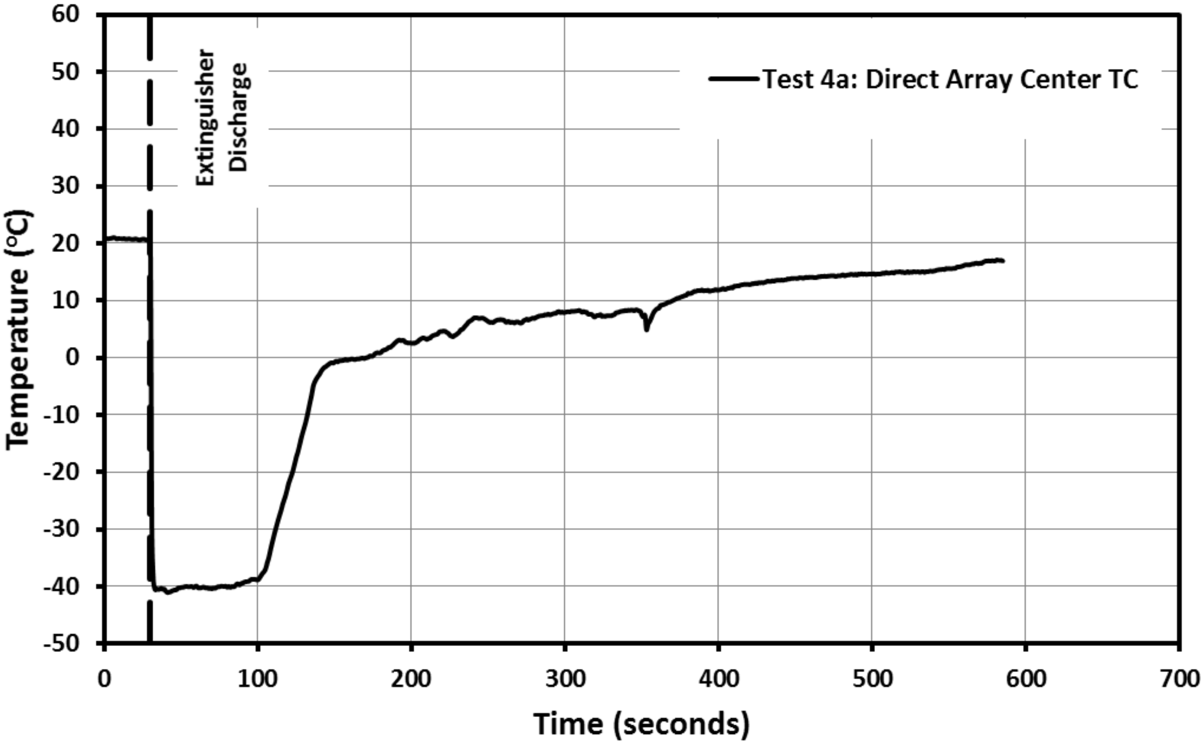

Figure D-21 – Test 4a (FE-36) direct array center temperature.

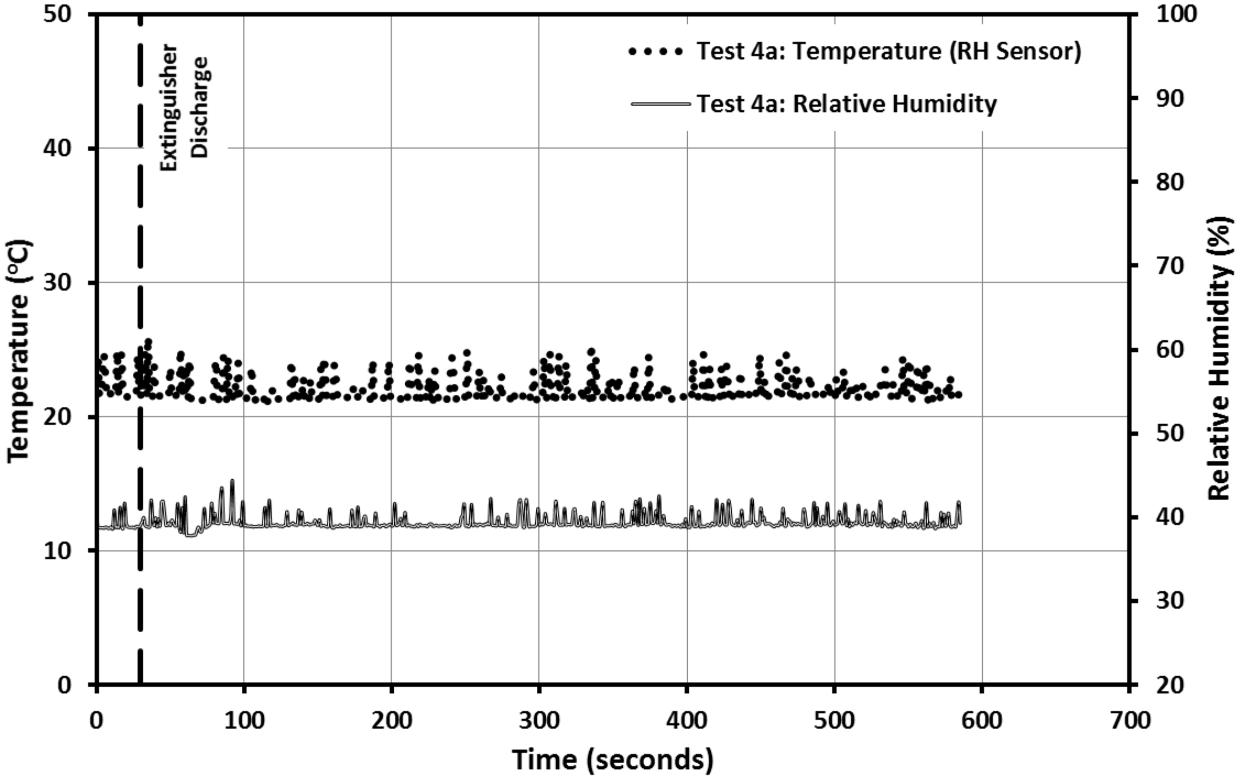

Figure D-22 – Test 4a (FE-36) temperature and RH sensor measurements.

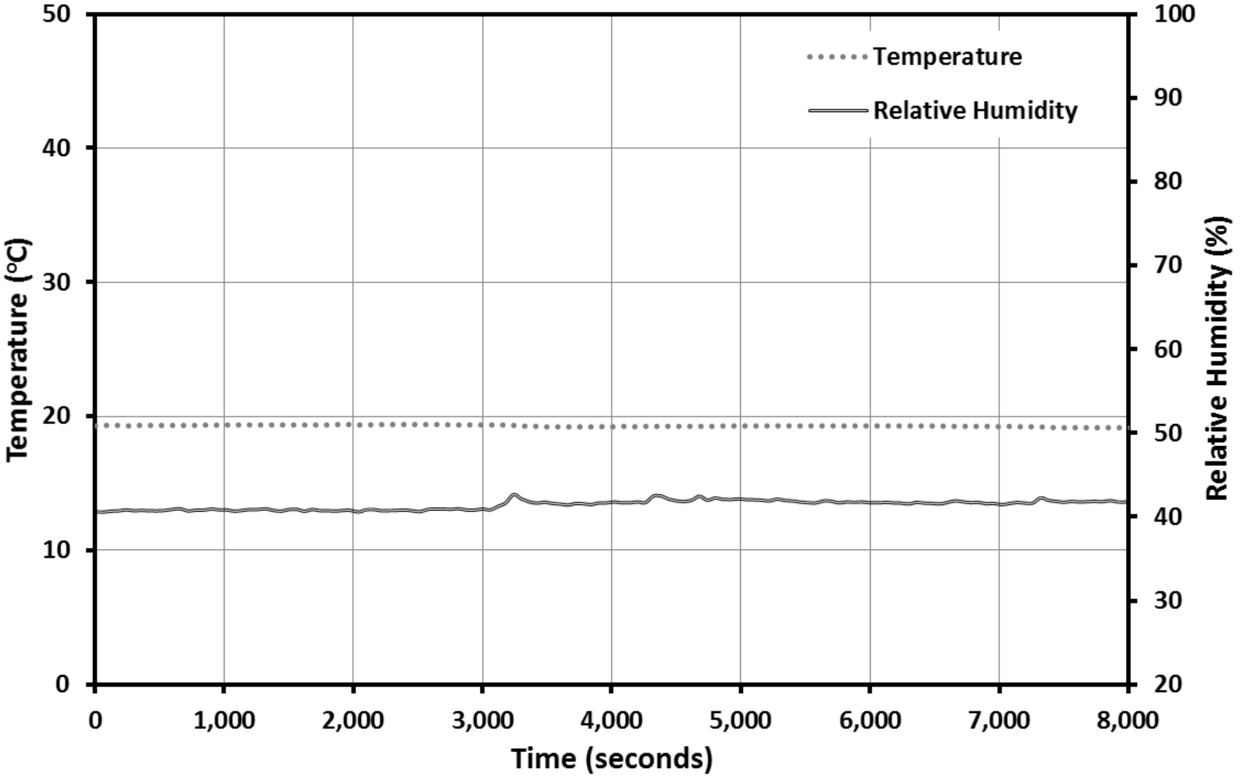

Figure D-23 – Test 4a (FE-36) laboratory temperature and relative humidity.

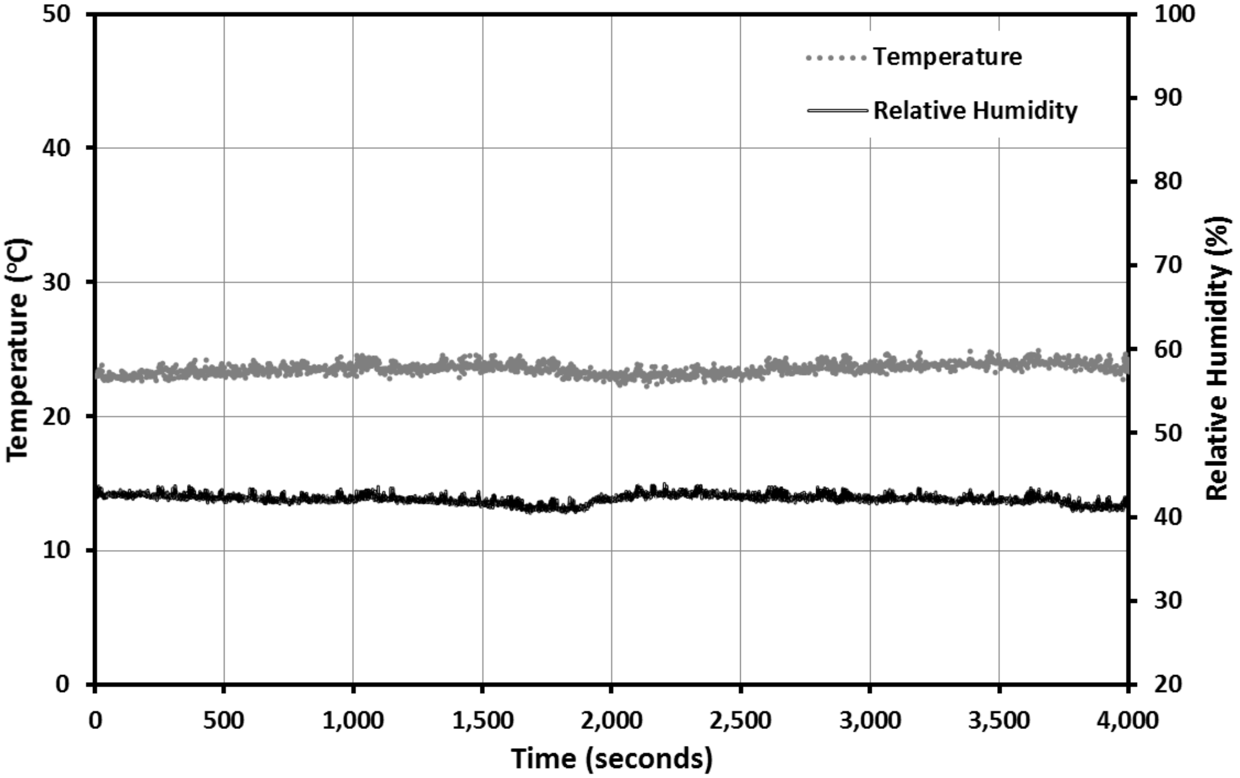

Figure D-24 – Test 4a (FE-36) exam room temperature and relative humidity.

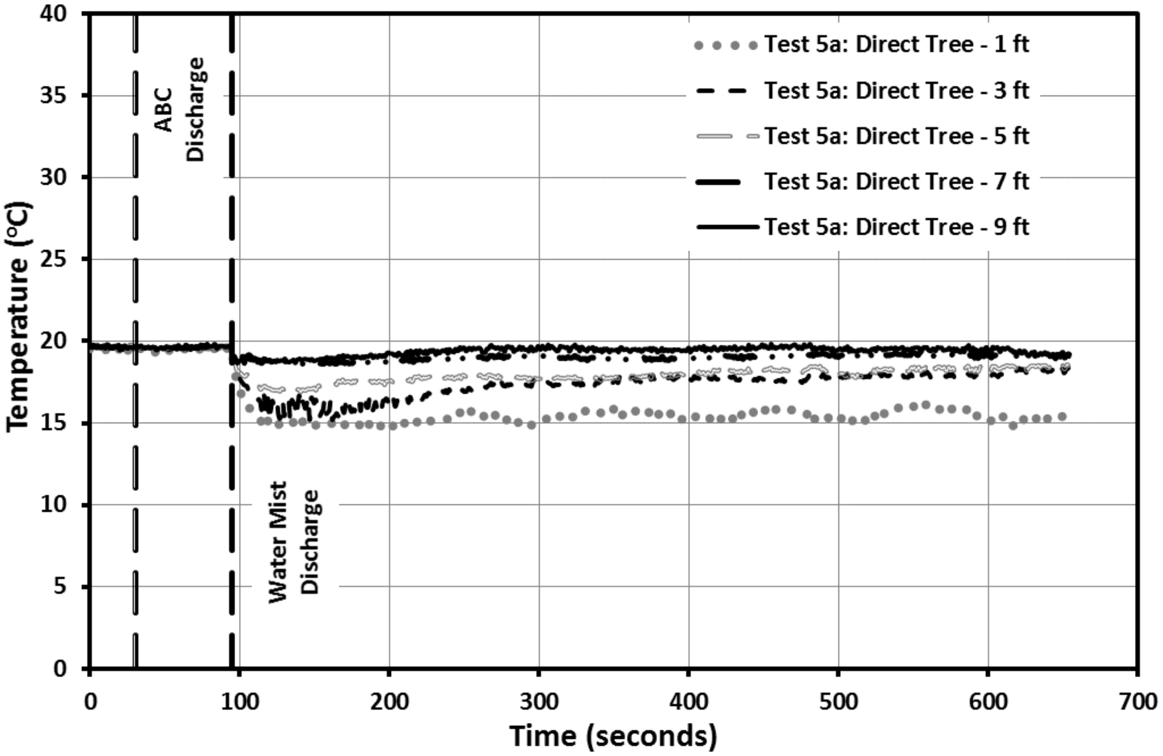

Figure D-25 – Test 5a (ABC + Water Mist) direct tree temperatures.

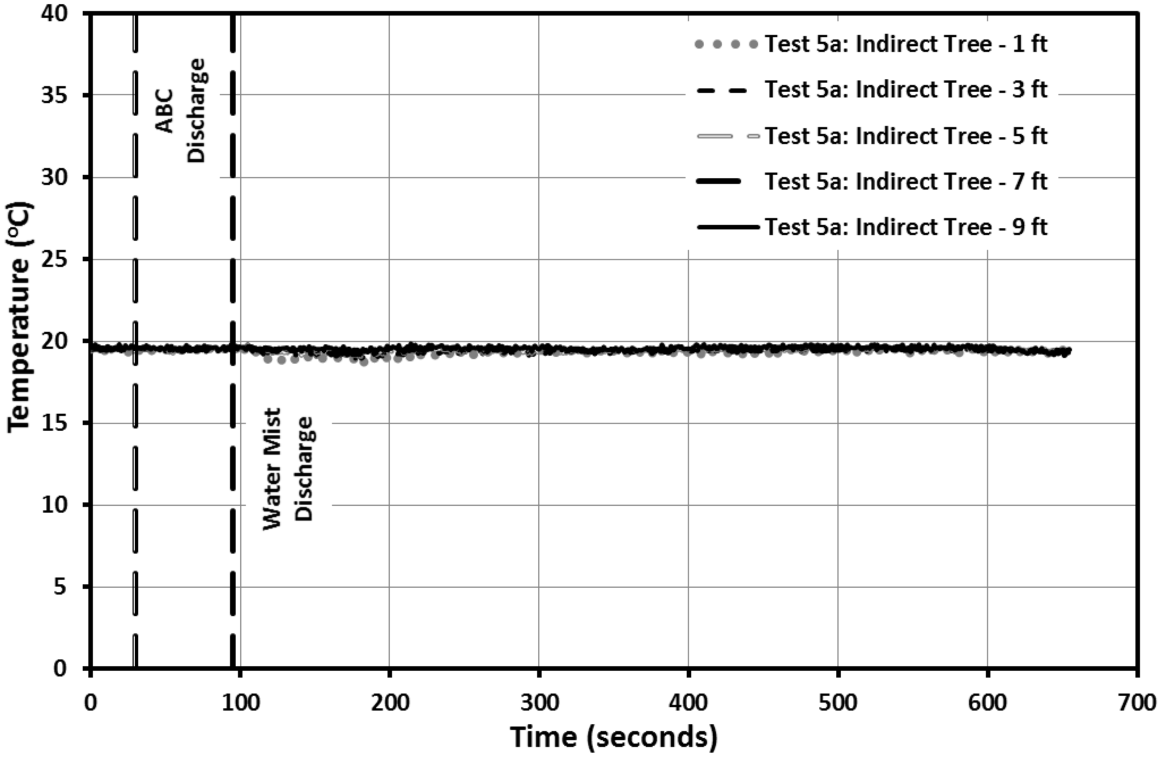

Figure D-26 – Test 5a (ABC + Water Mist) indirect tree temperatures.

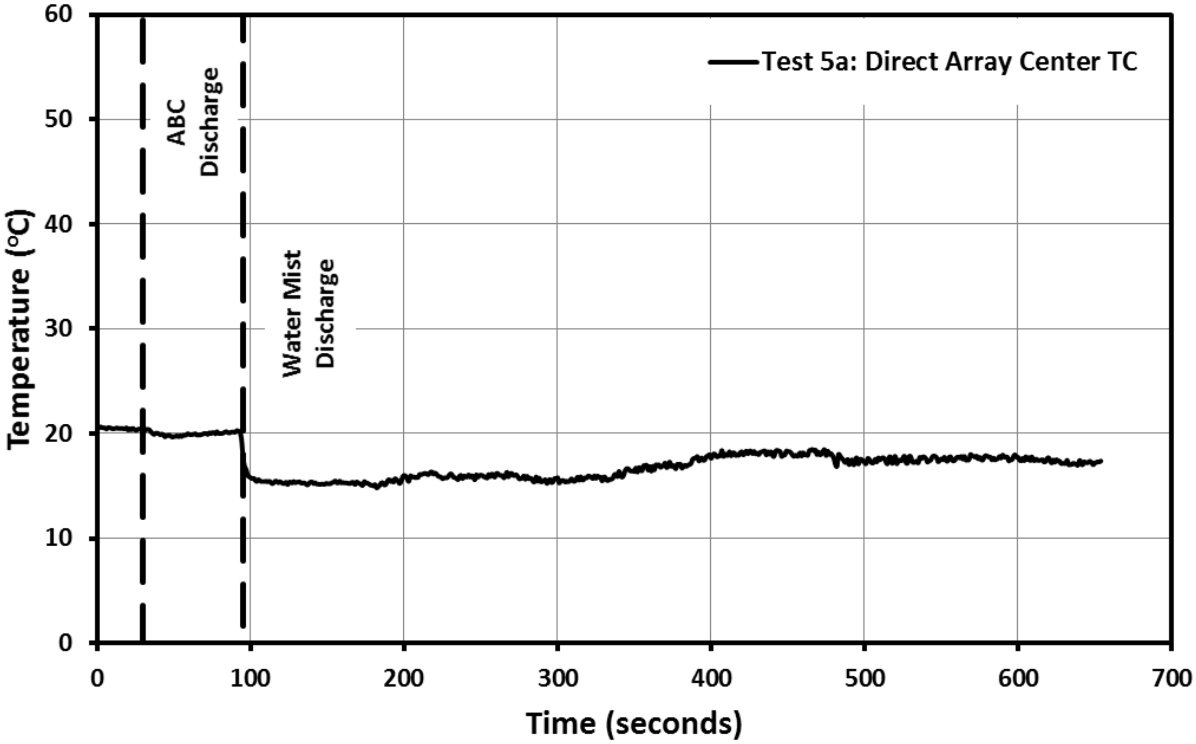

Figure D-27 – Test 5a (ABC + Water Mist) direct array center temperature.

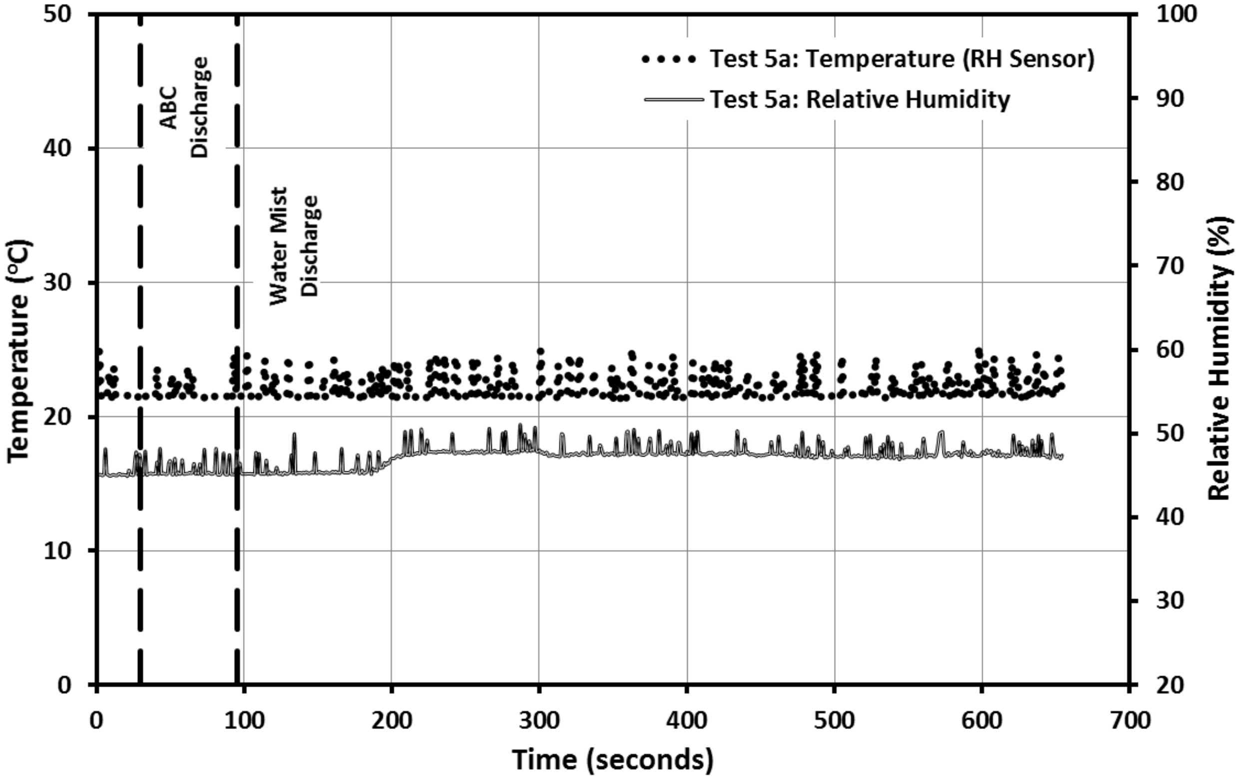

Figure D-28 – Test 5a (ABC + Water Mist) temperature and RH sensor measurements.

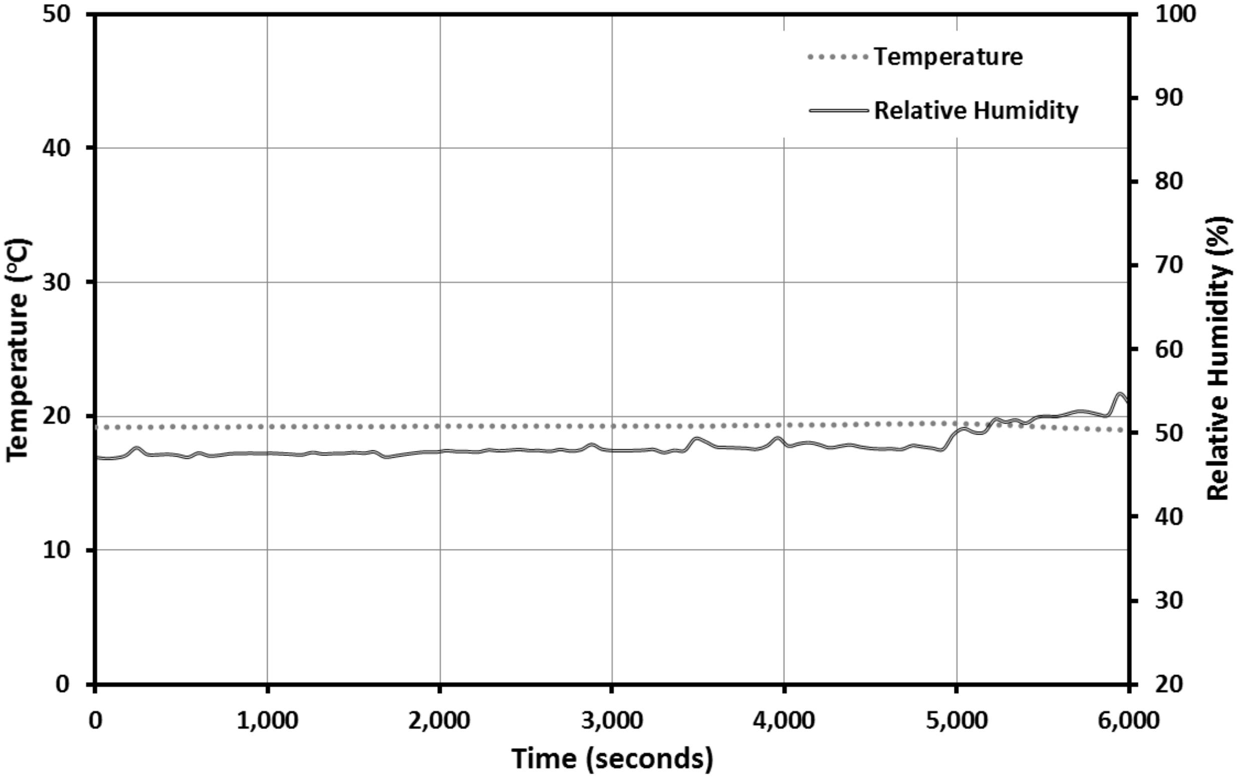

Figure D-29 – Test 5a (ABC + Water Mist) laboratory temperature and relative humidity.

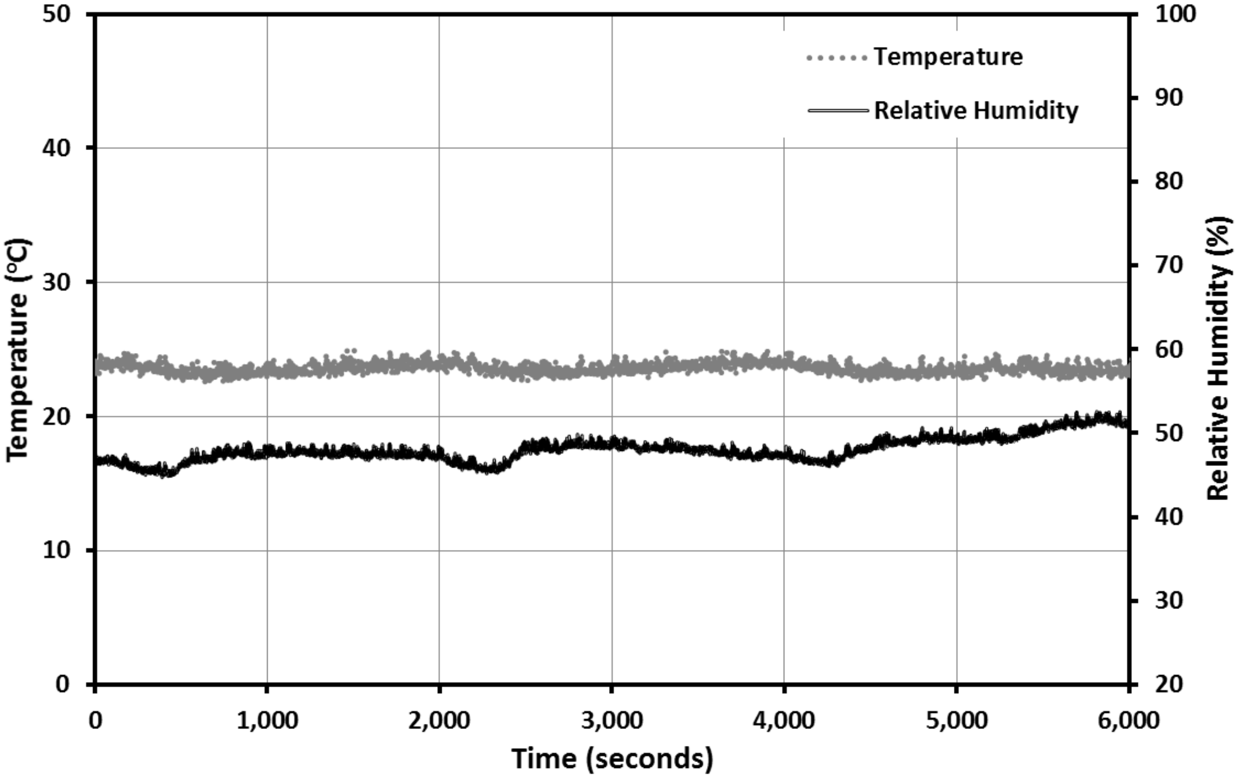

Figure D-30 – Test 5a (ABC + Water Mist) exam room temperature and relative humidity.

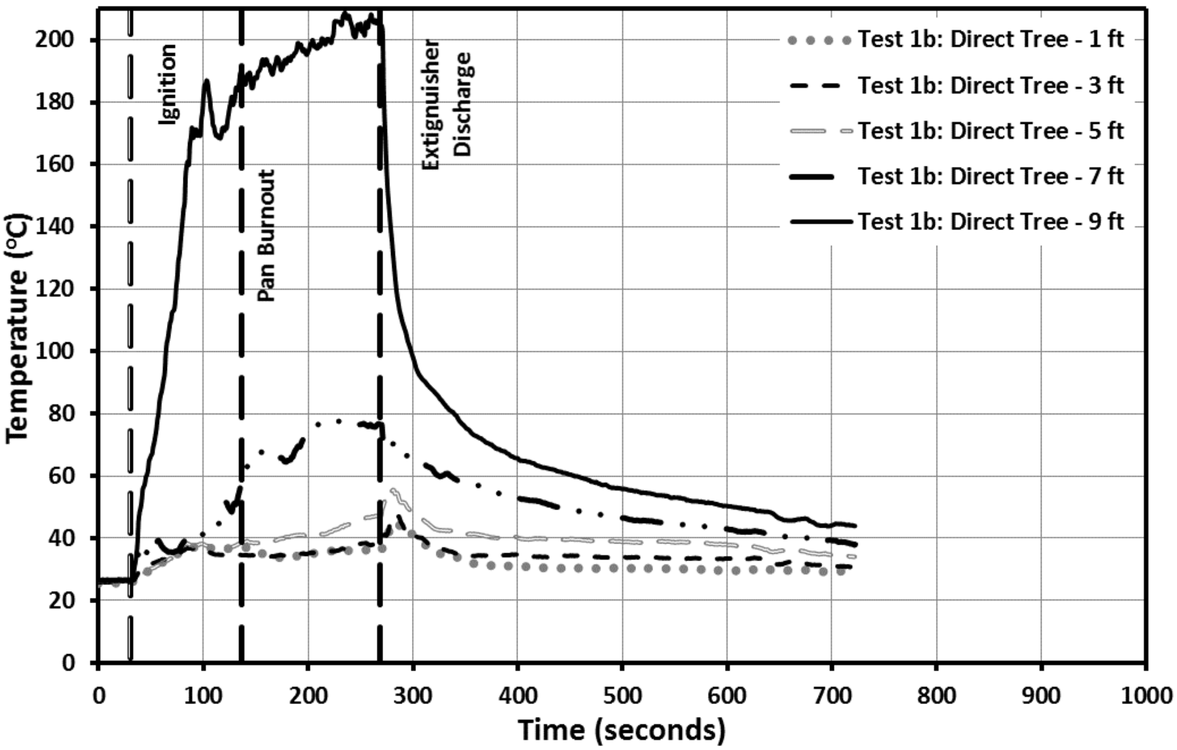

Figure D-31 – Test 1b (ABC) direct tree temperatures.

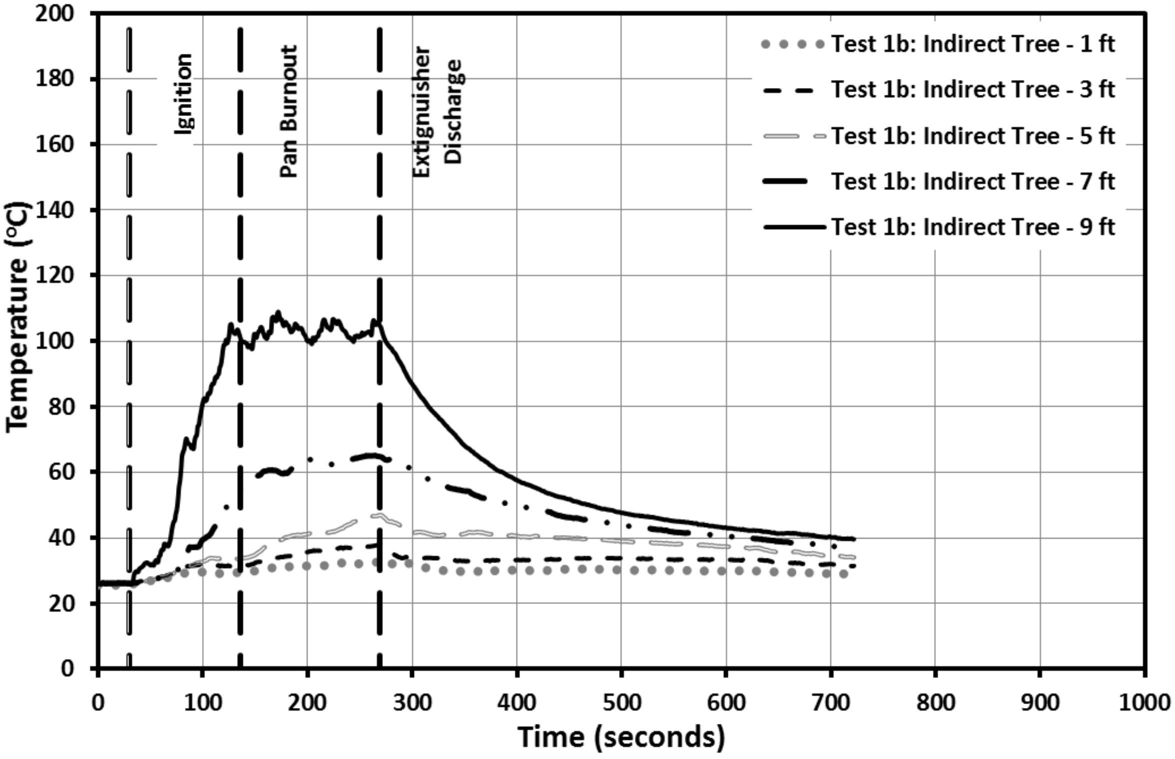

Figure D-32 – Test 1b (ABC) indirect tree temperatures.

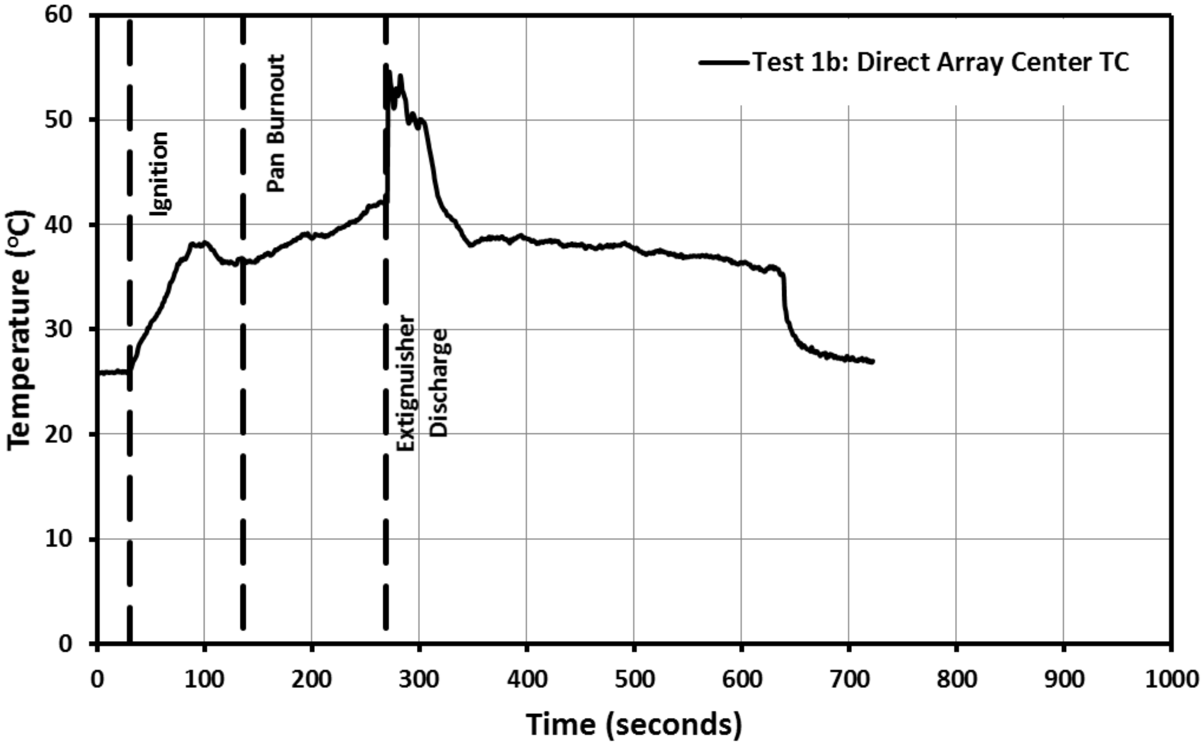

Figure D-33 – Test 1b (ABC) direct array center temperature.

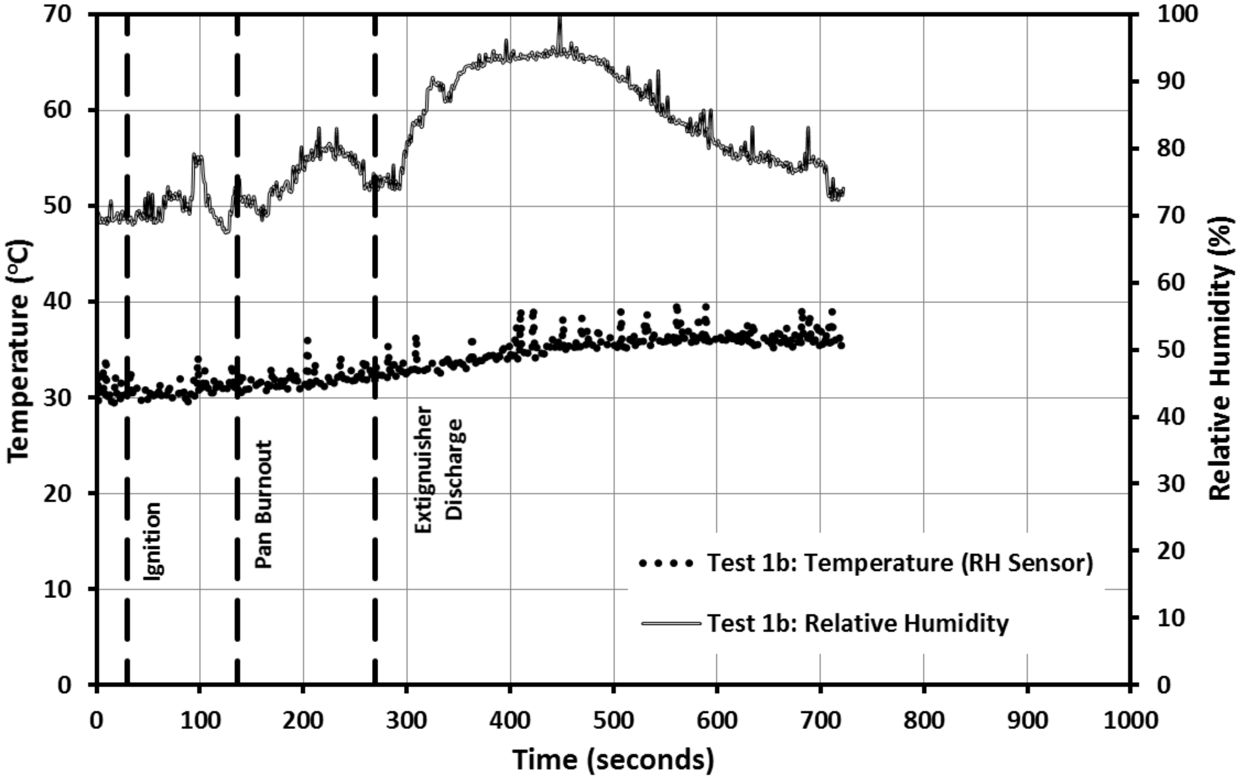

Figure D-34 – Test 1b (ABC) temperature and RH sensor measurements.

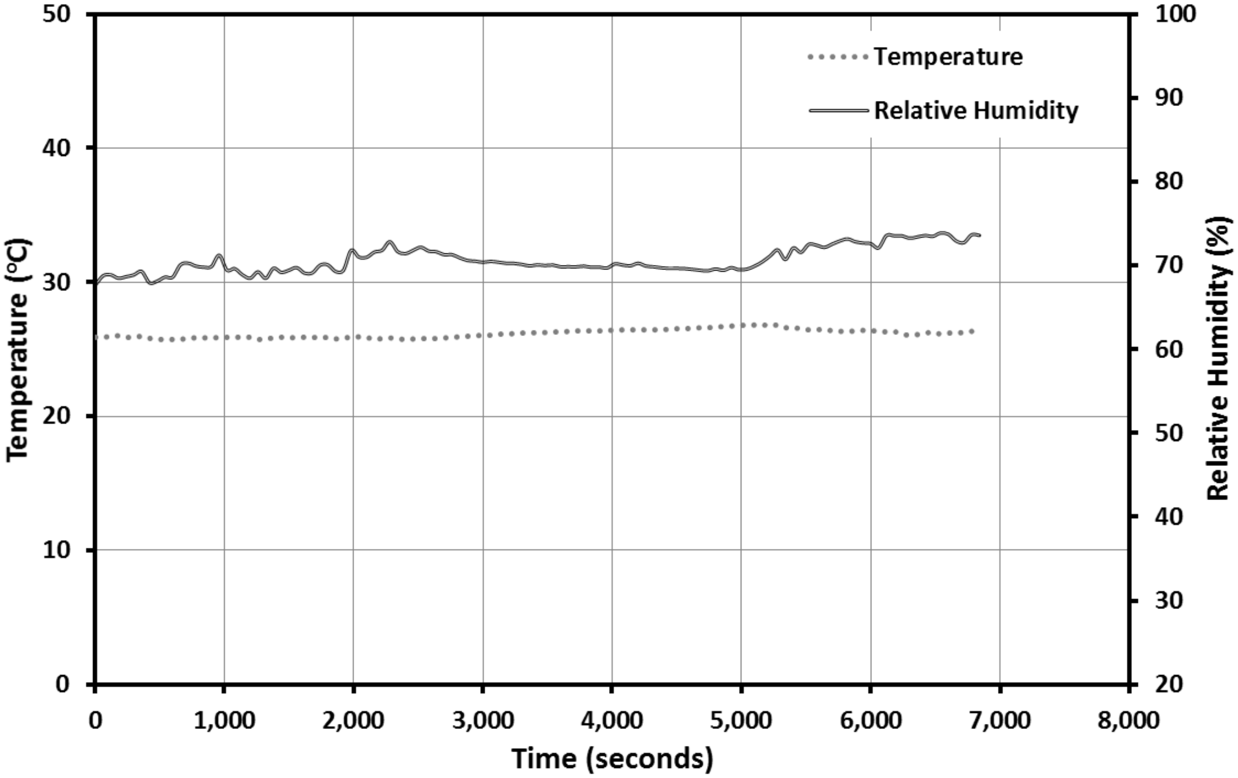

Figure D-35 – Test 1b (ABC) laboratory temperature and relative humidity.

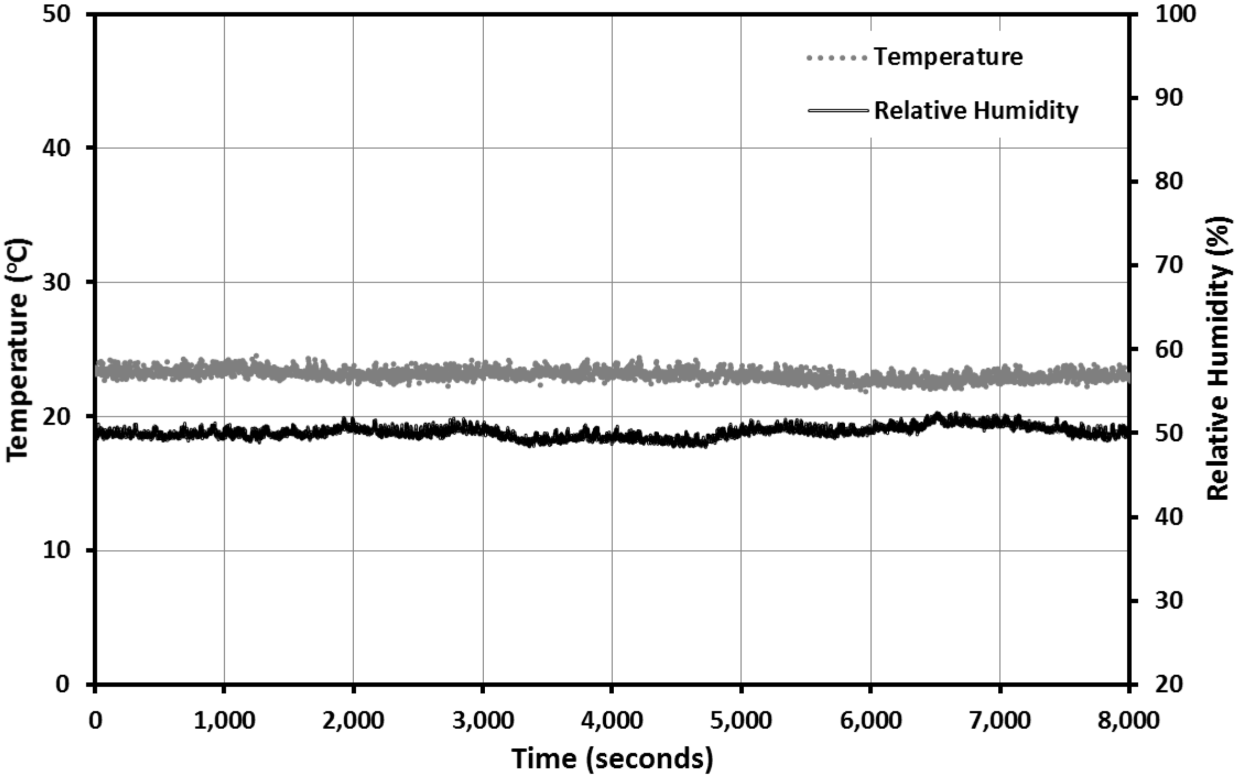

Figure D-36 – Test 1b (ABC) exam room temperature and relative humidity.

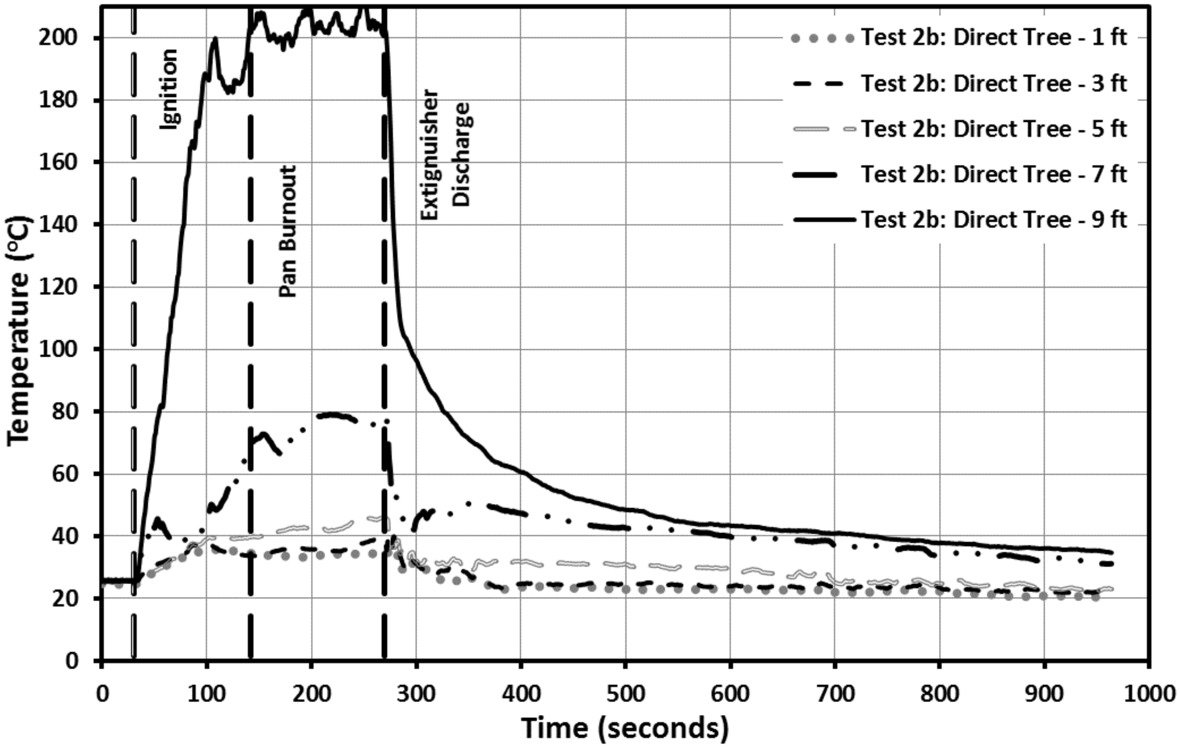

Figure D-37 – Test 2b (Water Mist) direct tree temperatures.

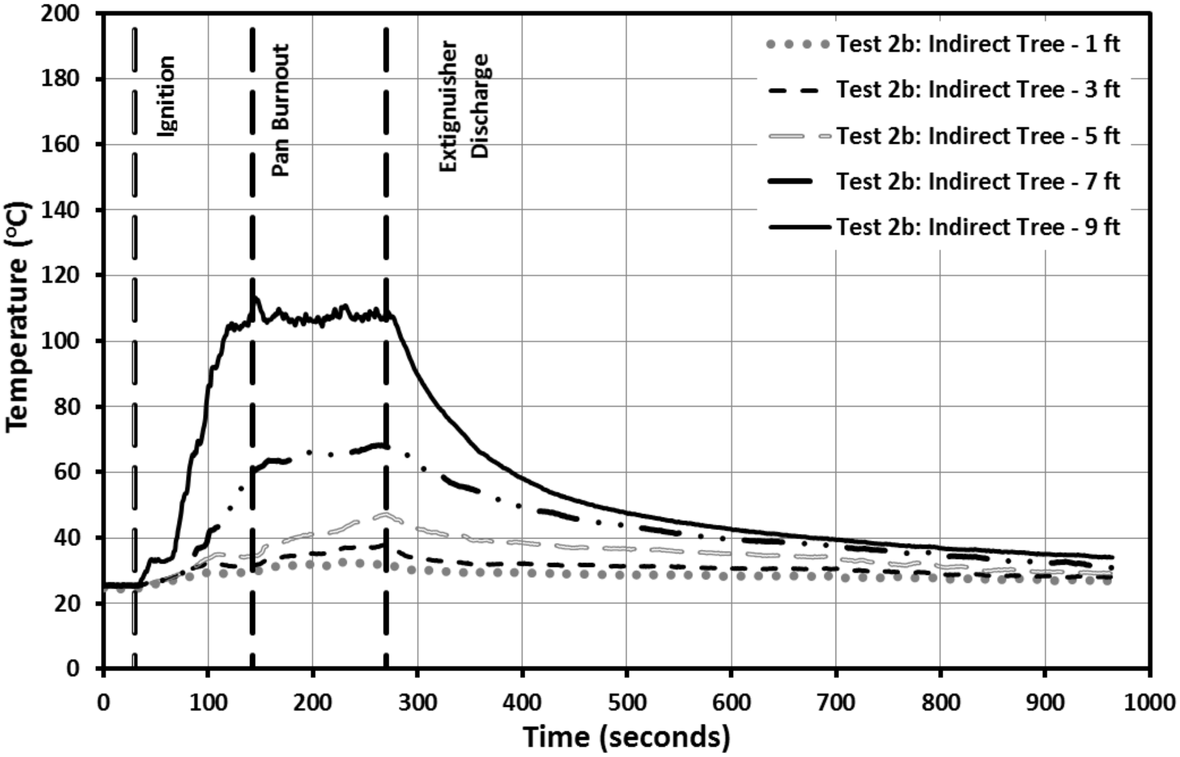

Figure D-38 – Test 2b (Water Mist) indirect tree temperatures.

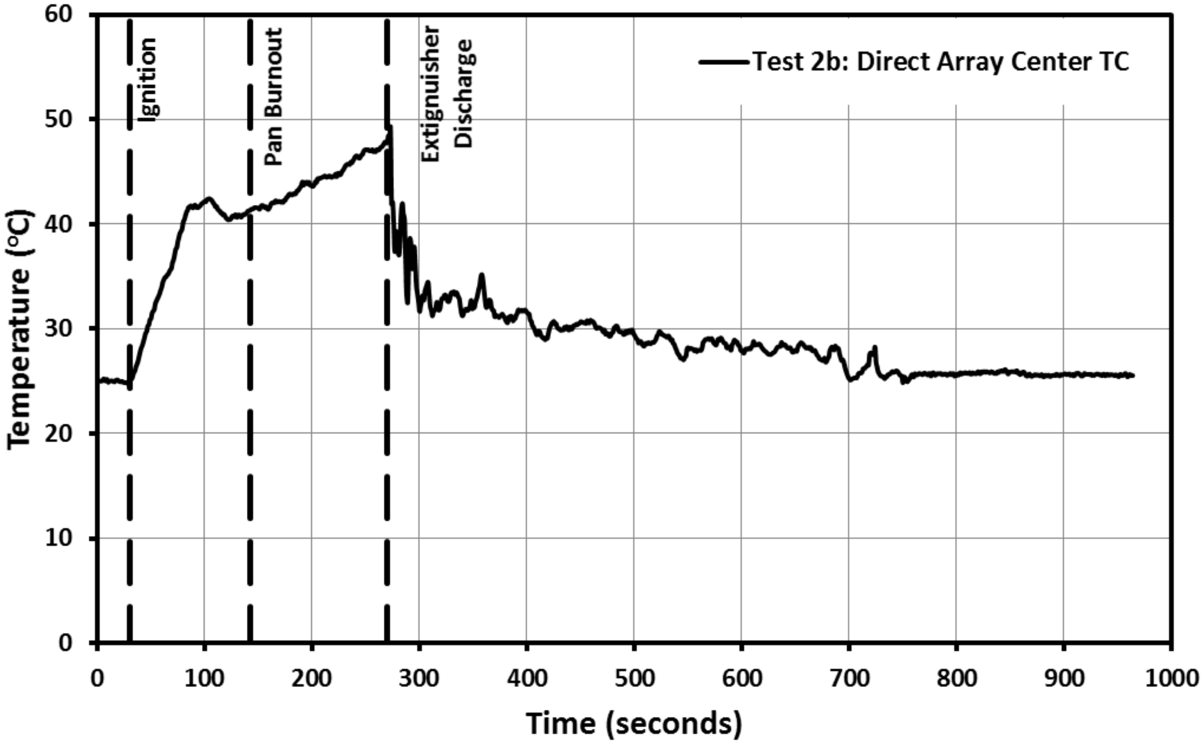

Figure D-39 – Test 2b (Water Mist) direct array center temperature.

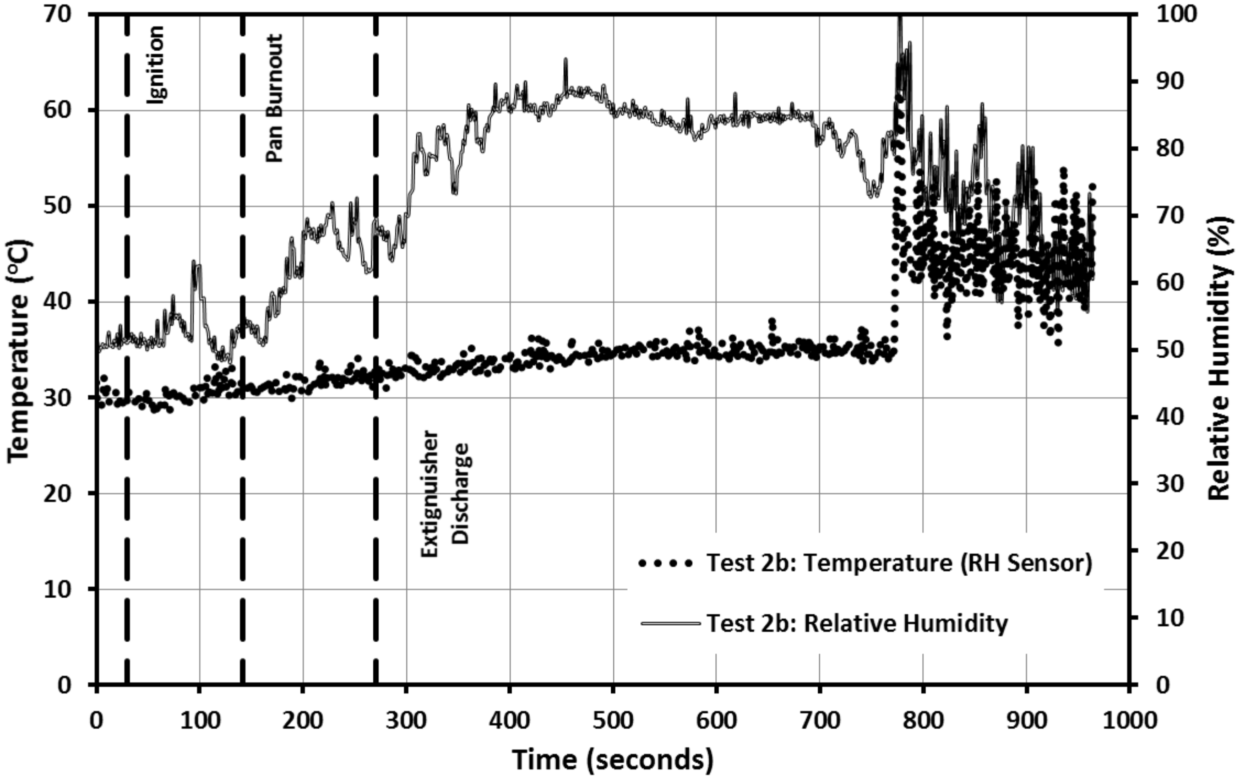

Figure D-40 – Test 2b (Water Mist) temperature and RH sensor measurements.

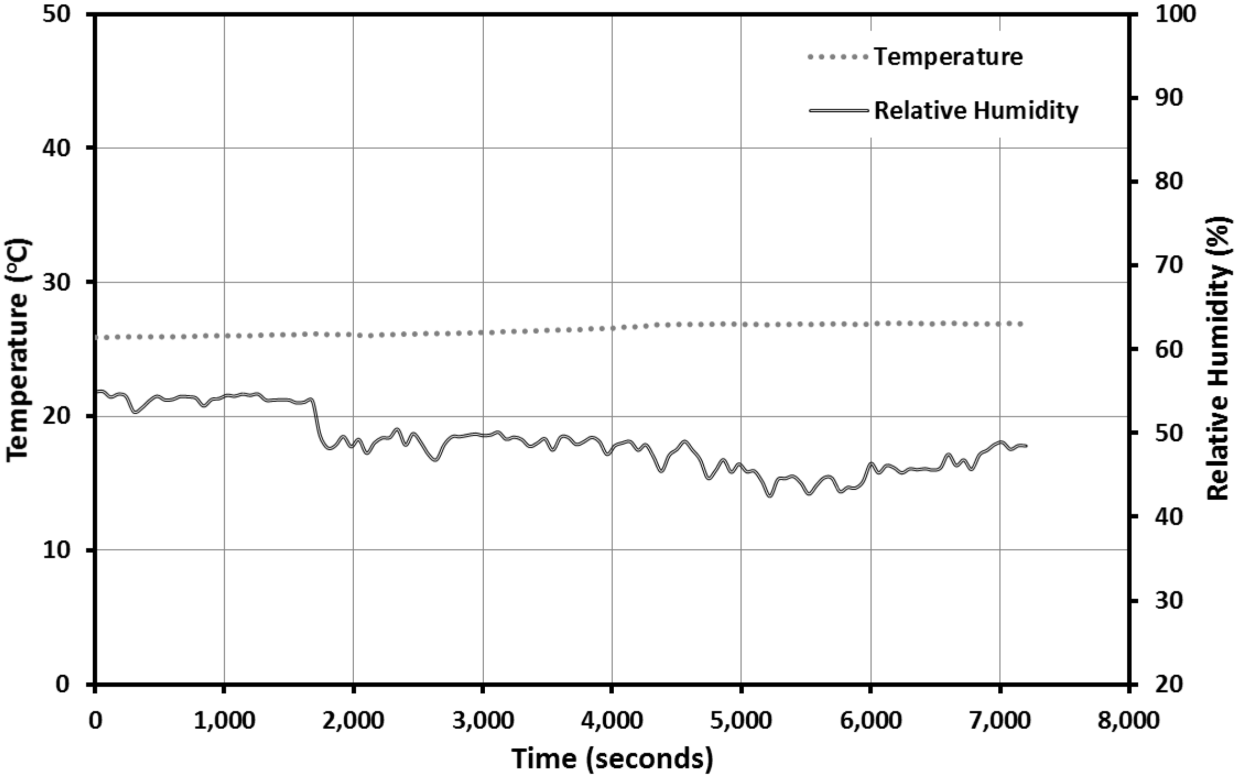

Figure D-41 – Test 2b (Water Mist) laboratory temperature and relative humidity.

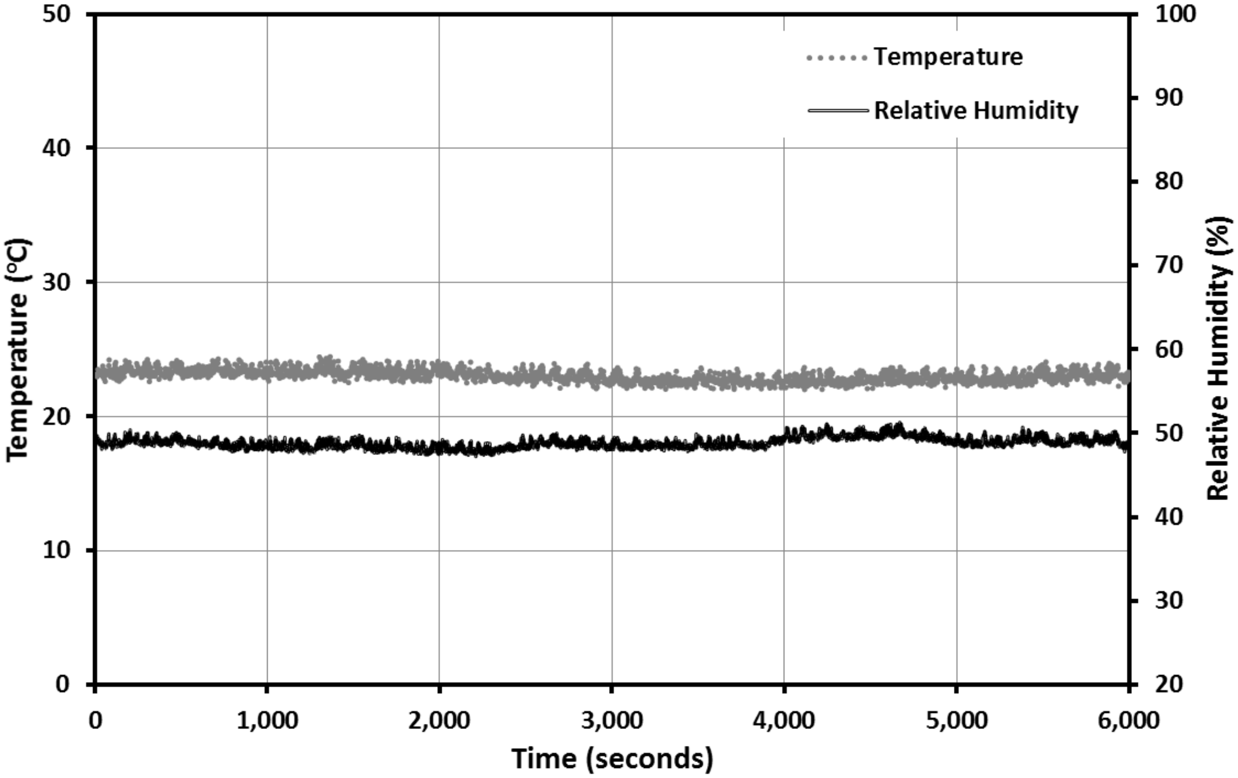

Figure D-42 – Test 2b (Water Mist) exam room temperature and relative humidity.

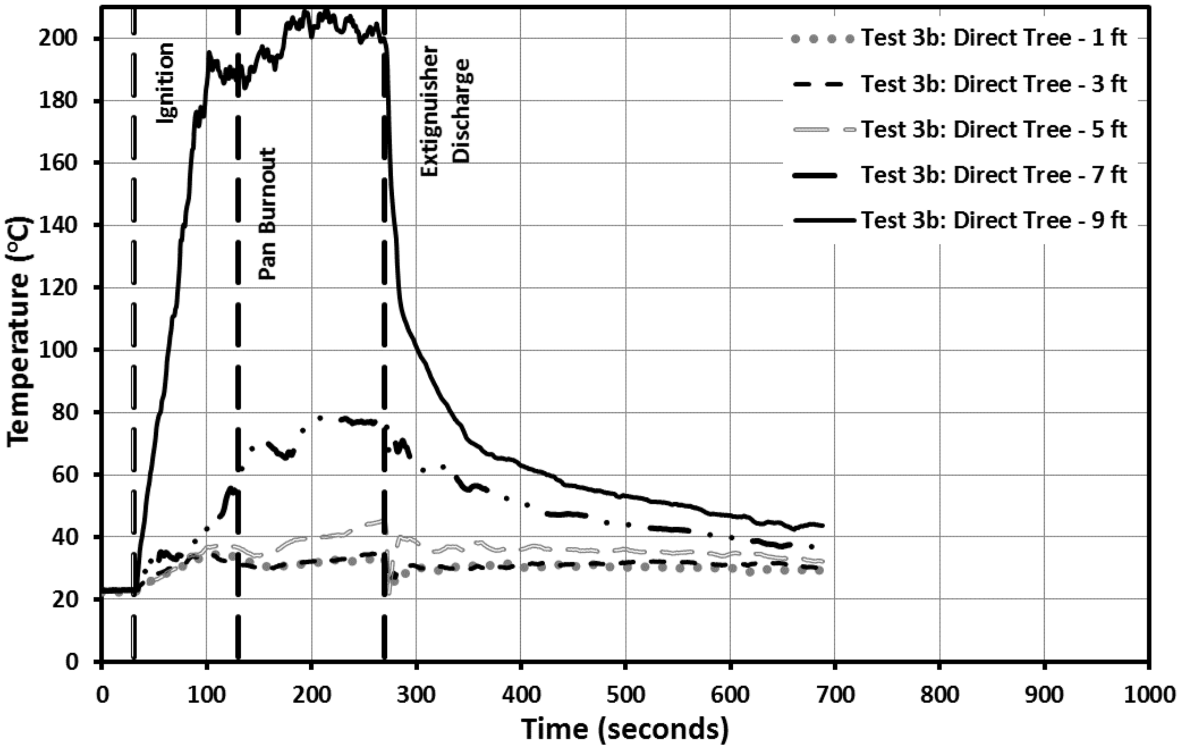

Figure D-43 – Test 3b (Halotron I) direct tree temperatures.

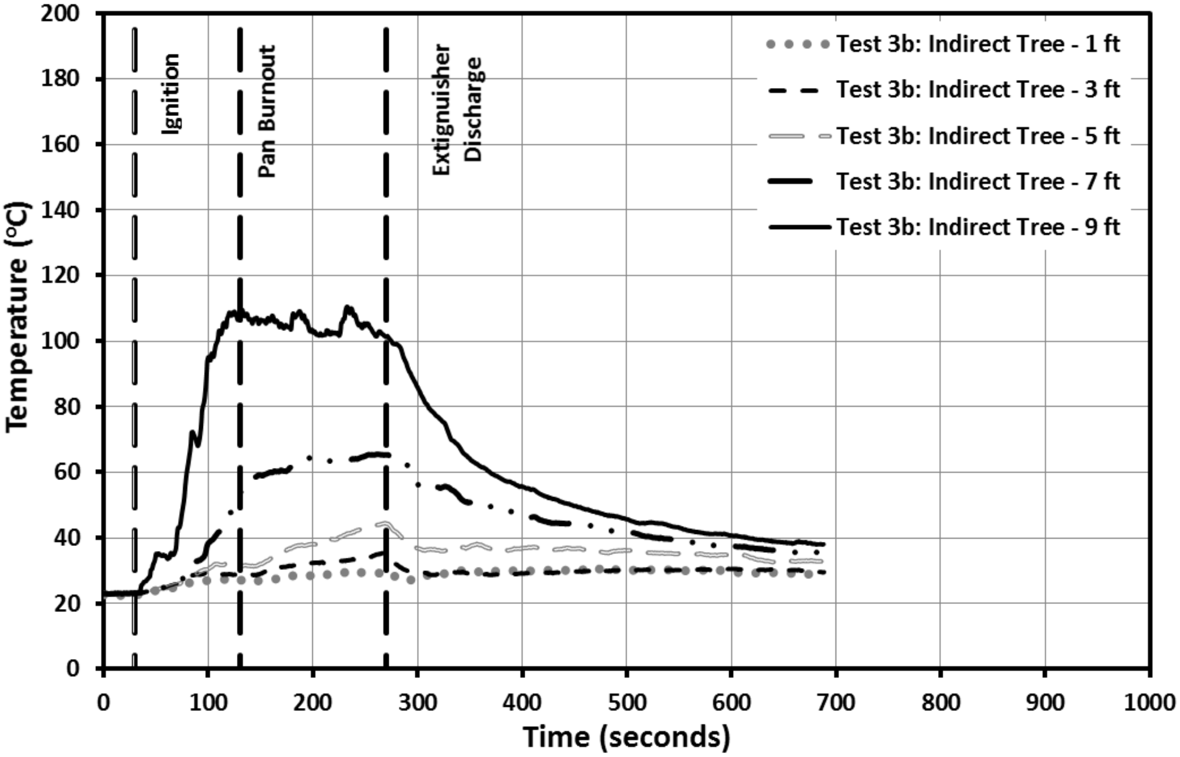

Figure D-44 – Test 3b (Halotron I) indirect tree temperatures.

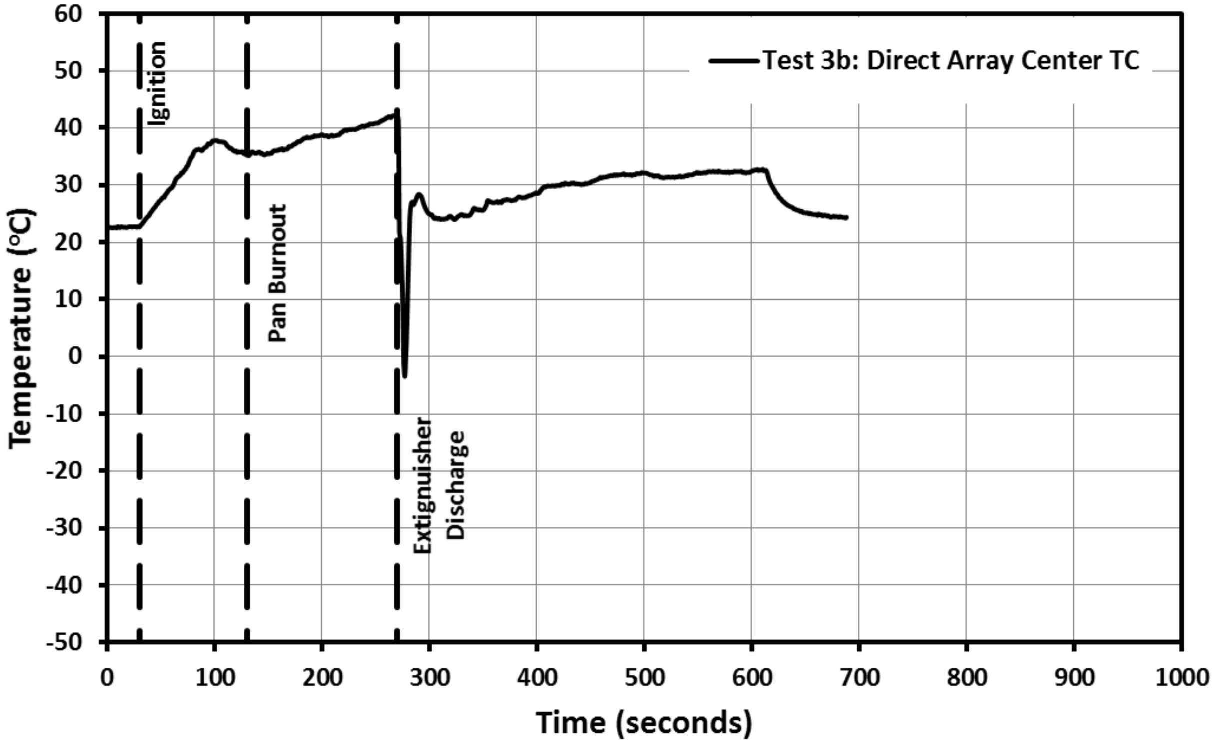

Figure D-45 – Test 3b (Halotron I) direct array center temperature.

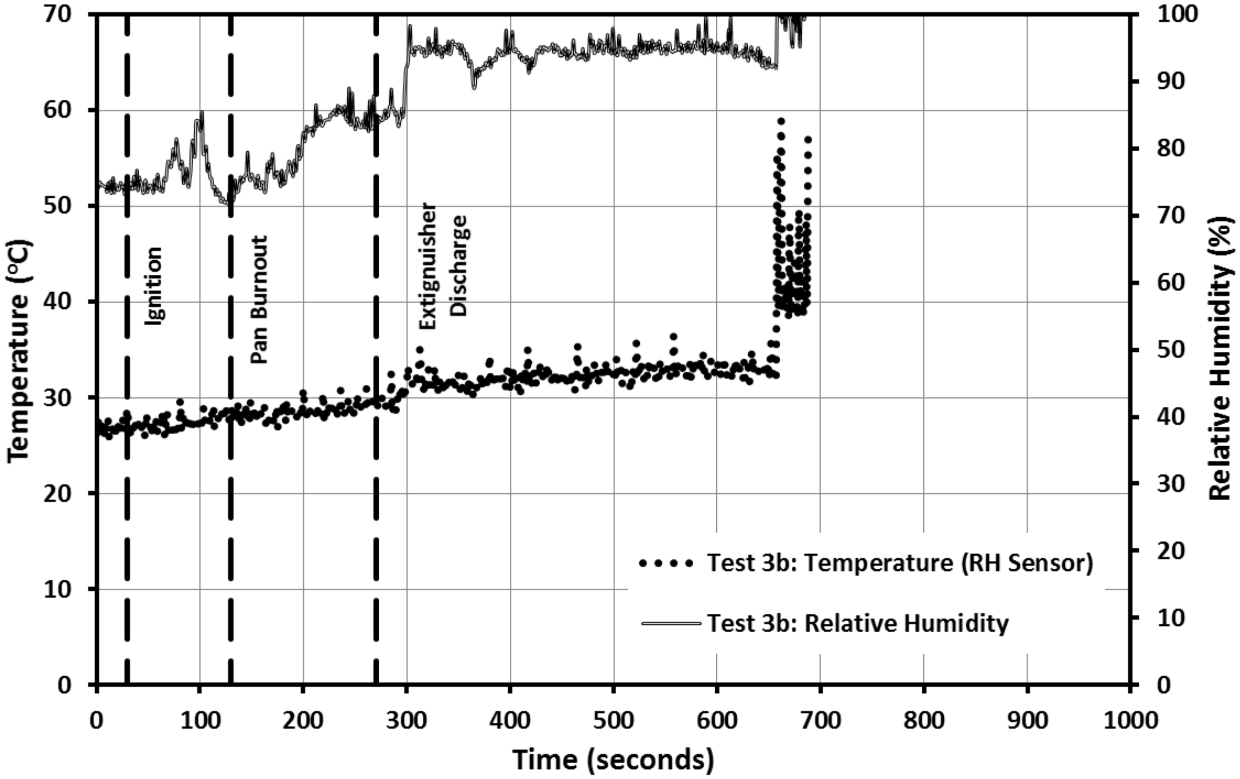

Figure D-46 – Test 3b (Halotron I) temperature and RH sensor measurements.

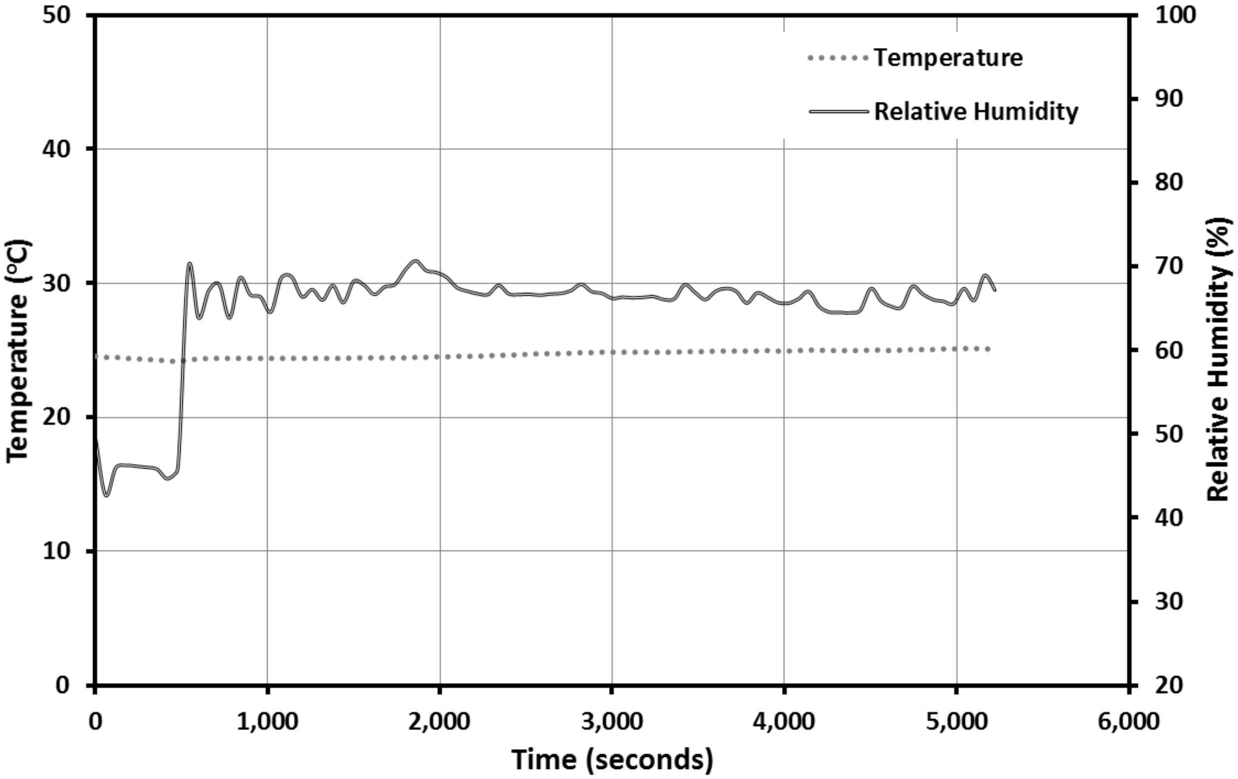

Figure D-47 – Test 3b (Halotron I) laboratory temperature and relative humidity.

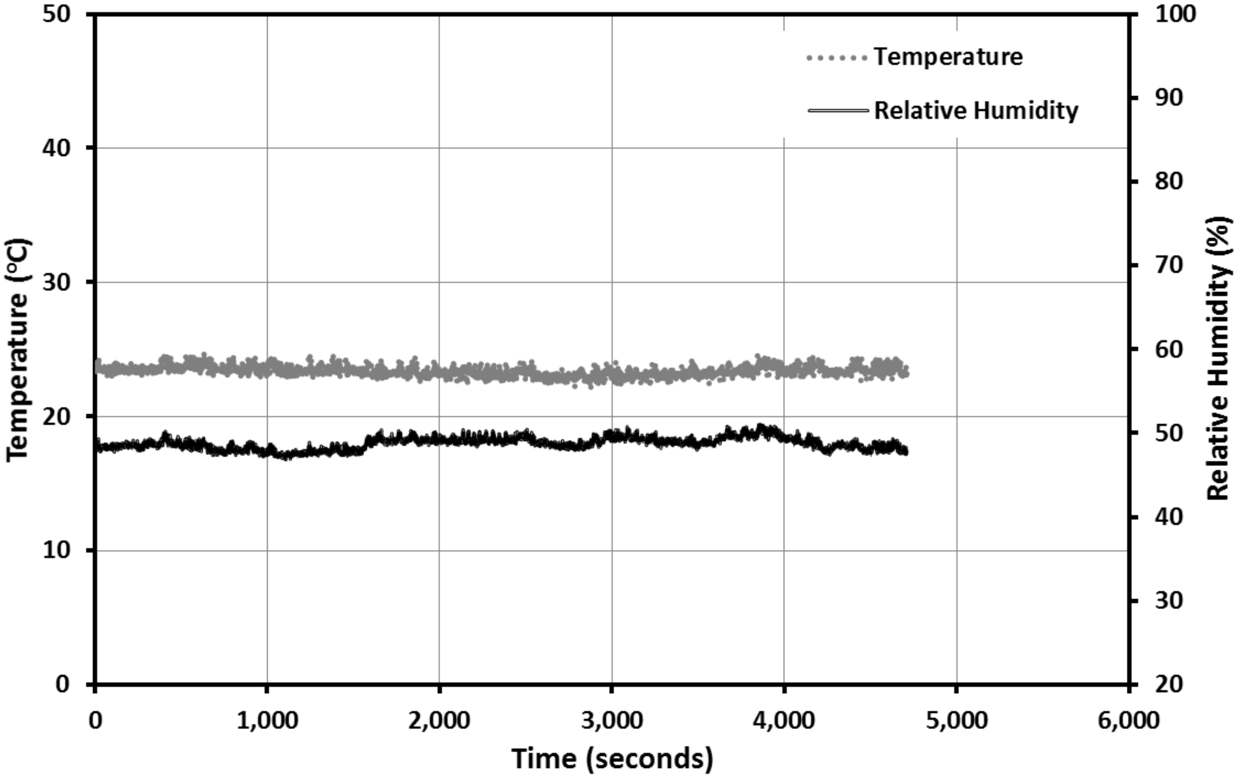

Figure D-48 – Test 3b (Halotron I) exam room temperature and relative humidity.

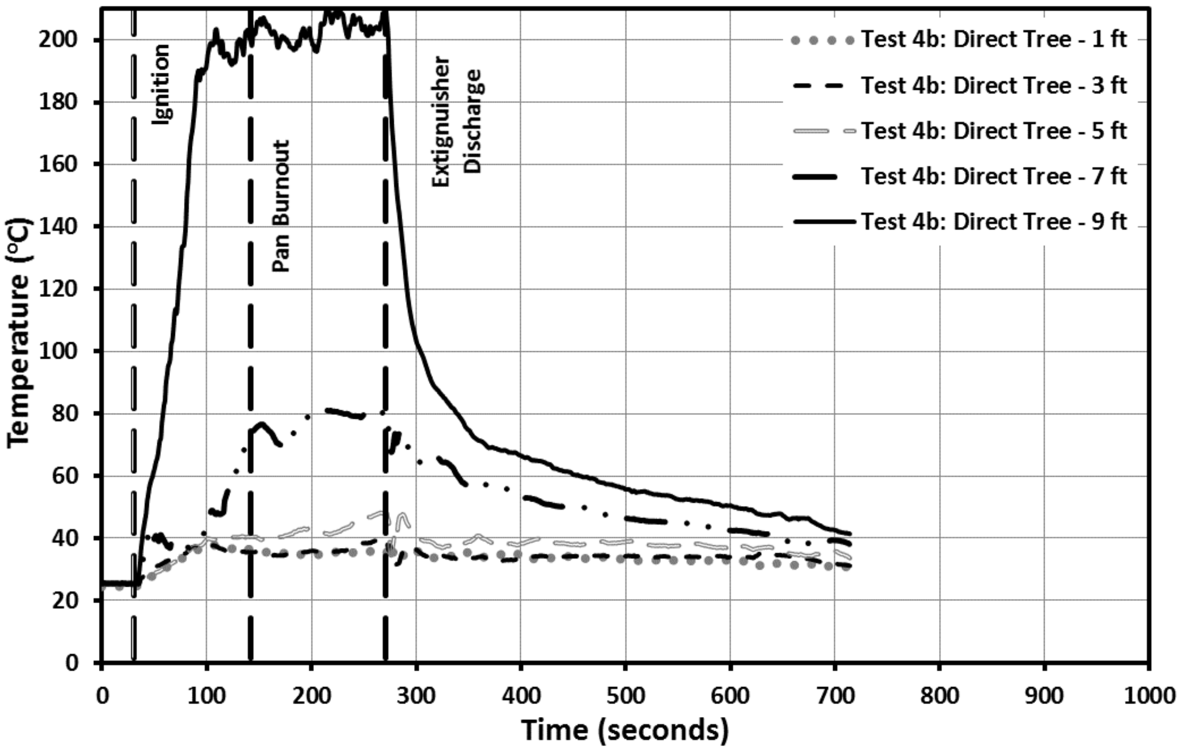

Figure D-49 – Test 4b (FE-36) direct tree temperatures.

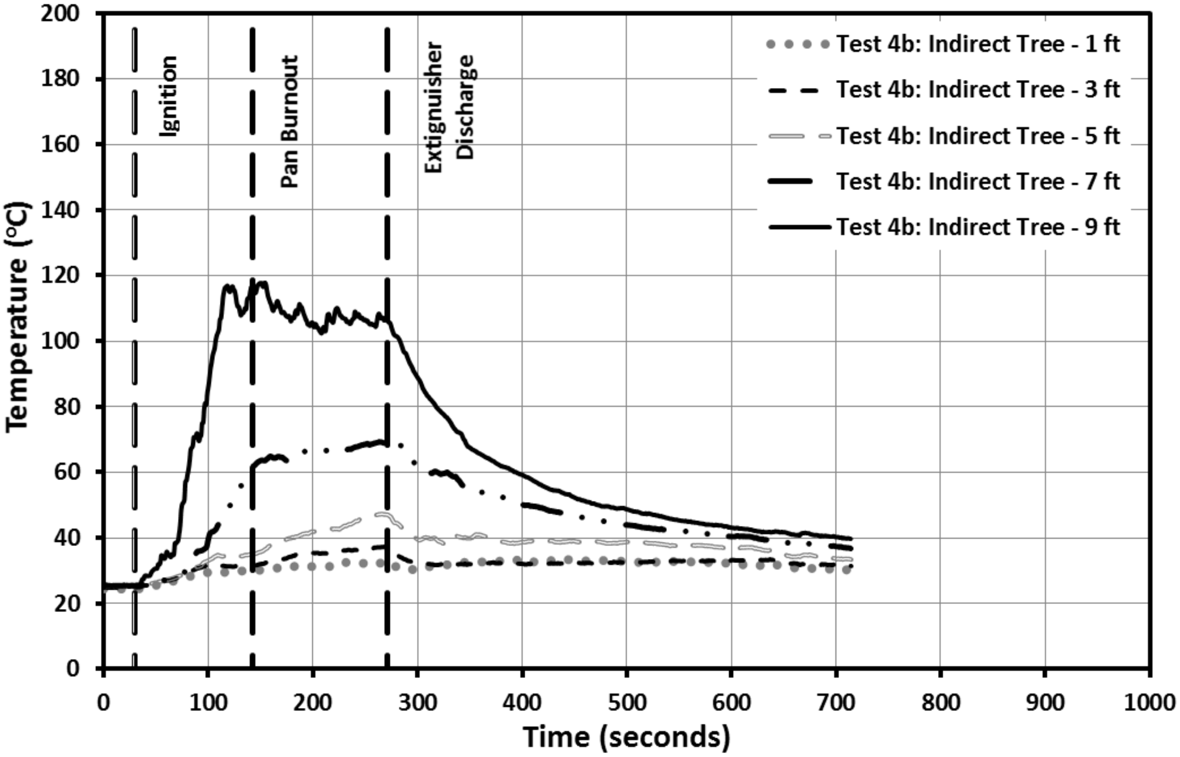

Figure D-50 – Test 4b (FE-36) indirect tree temperatures.

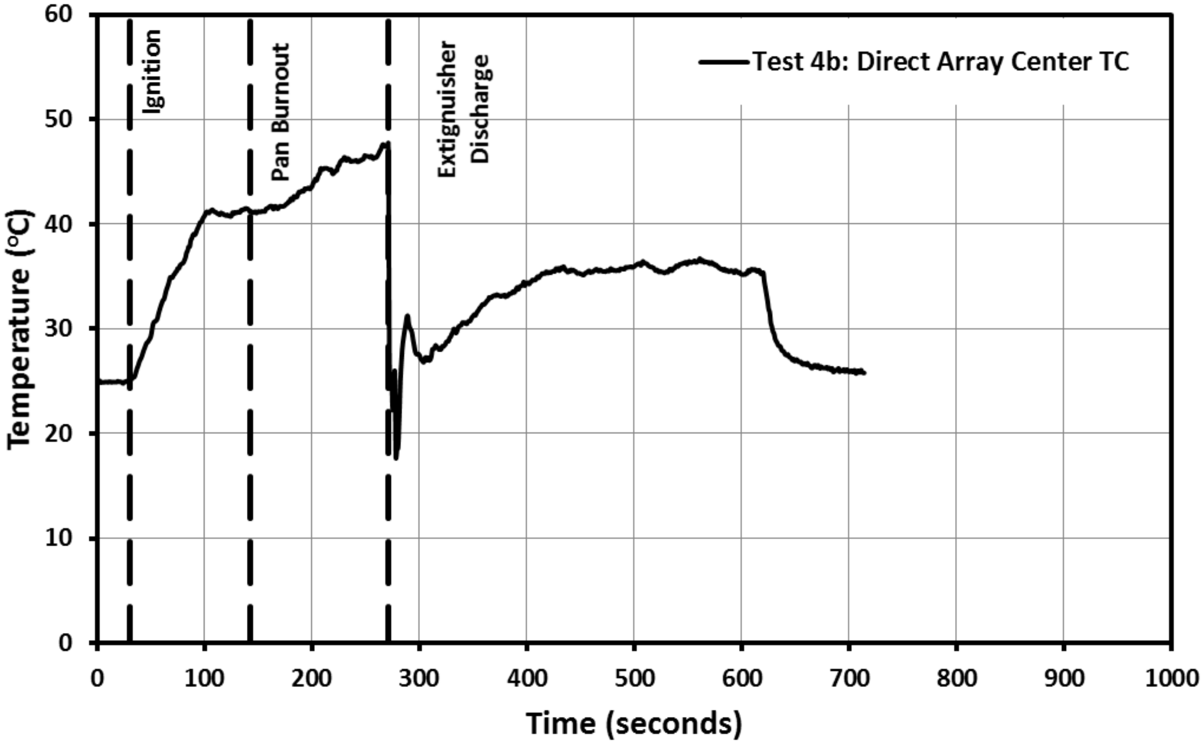

Figure D-51 – Test 4b (FE-36) direct array center temperature.

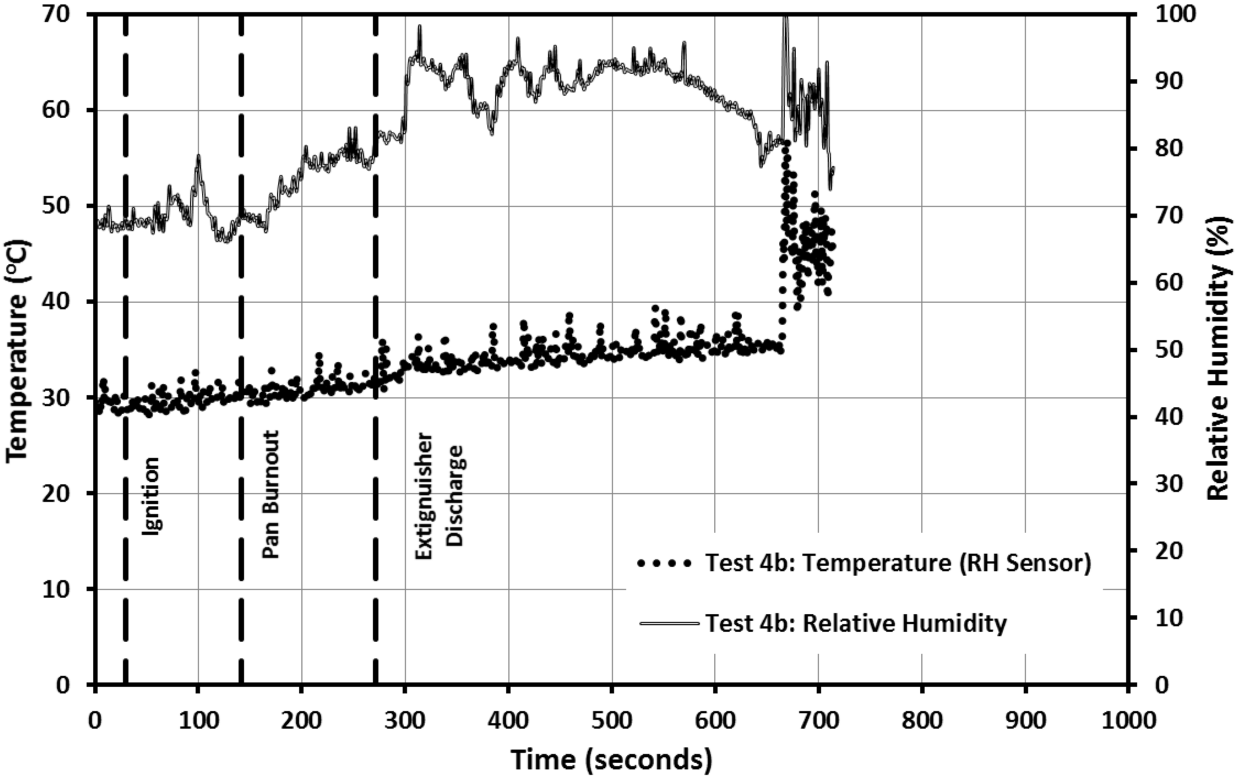

Figure D-52 – Test 4b (FE-36) temperature and RH sensor measurements.

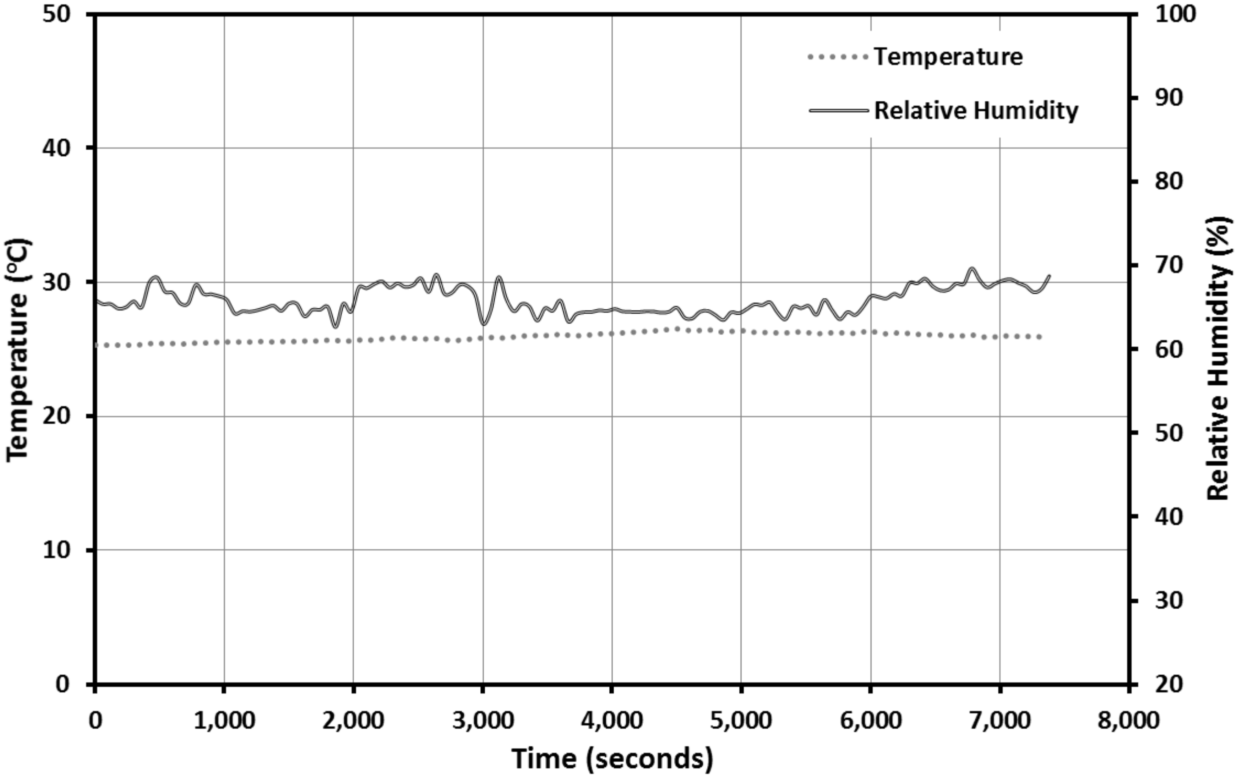

Figure D-53 – Test 4b (FE-36) laboratory temperature and relative humidity.

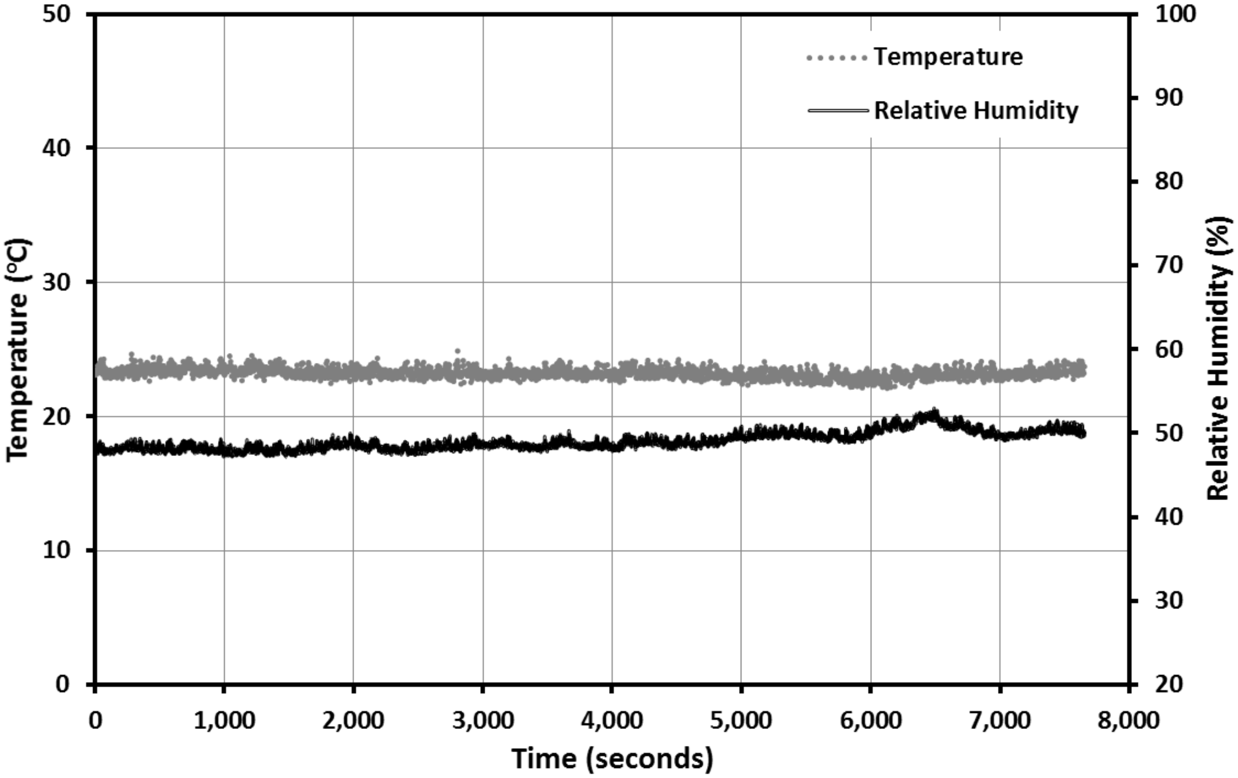

Figure D-54 – Test 4b (FE-36) exam room temperature and relative humidity.

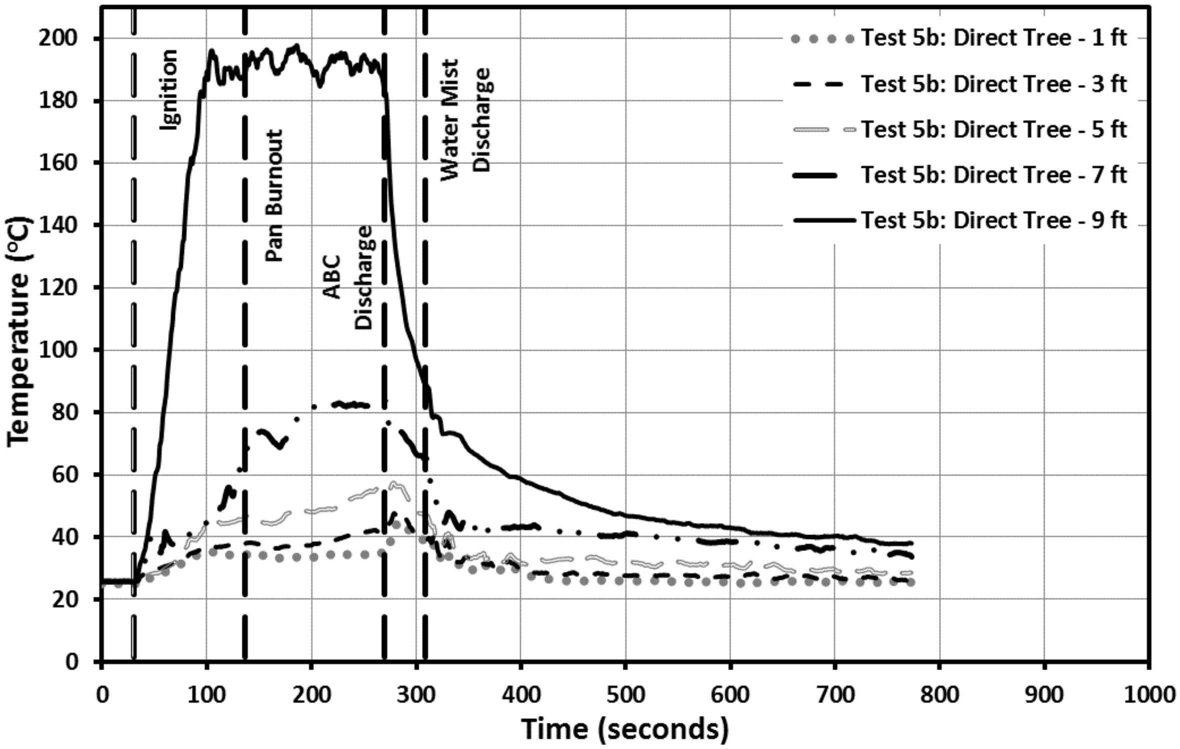

Figure D-55 – Test 5b (ABC + Water Mist) direct tree temperatures.

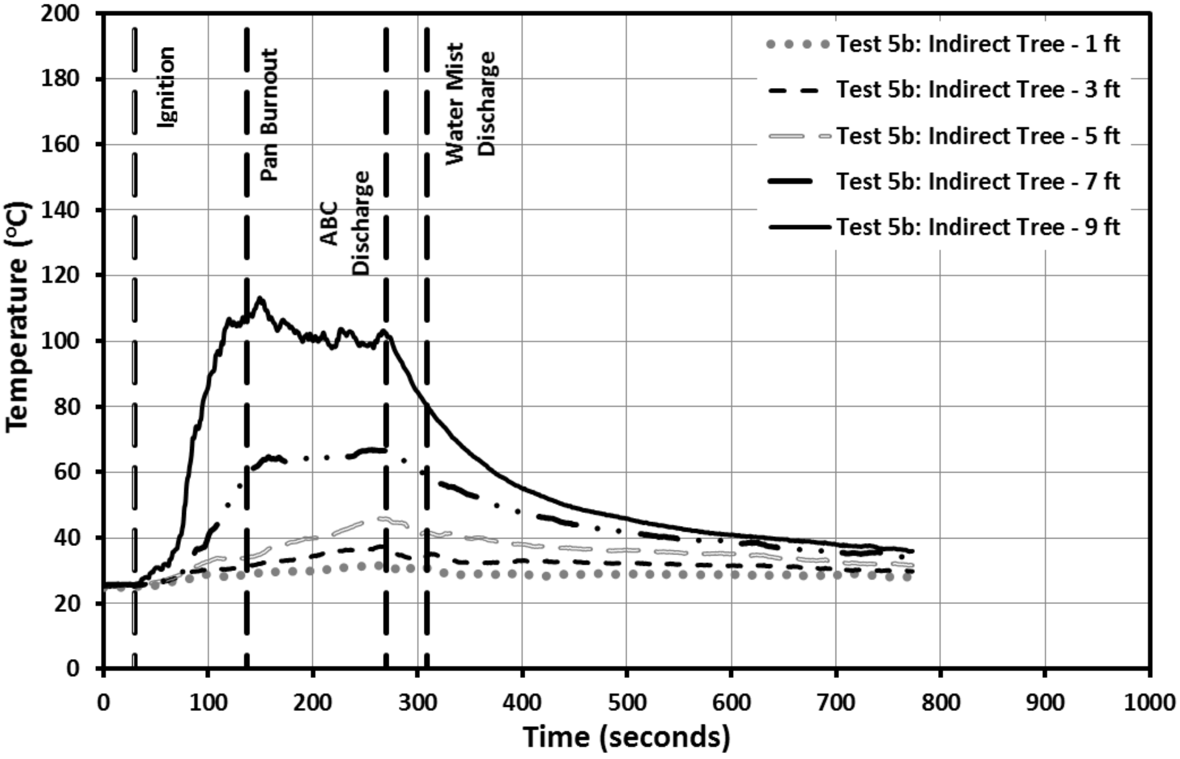

Figure D-56 – Test 5b (ABC + Water Mist) indirect tree temperatures.

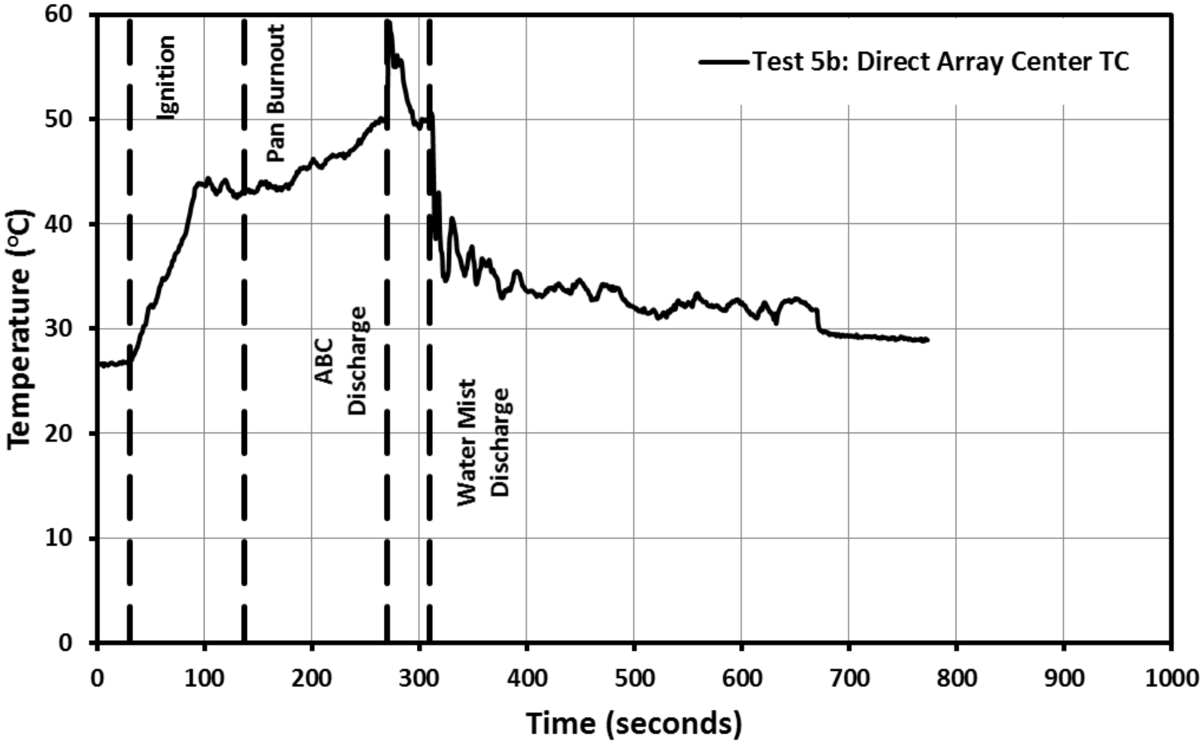

Figure D-57 – Test 5b (ABC + Water Mist) direct array center temperature.

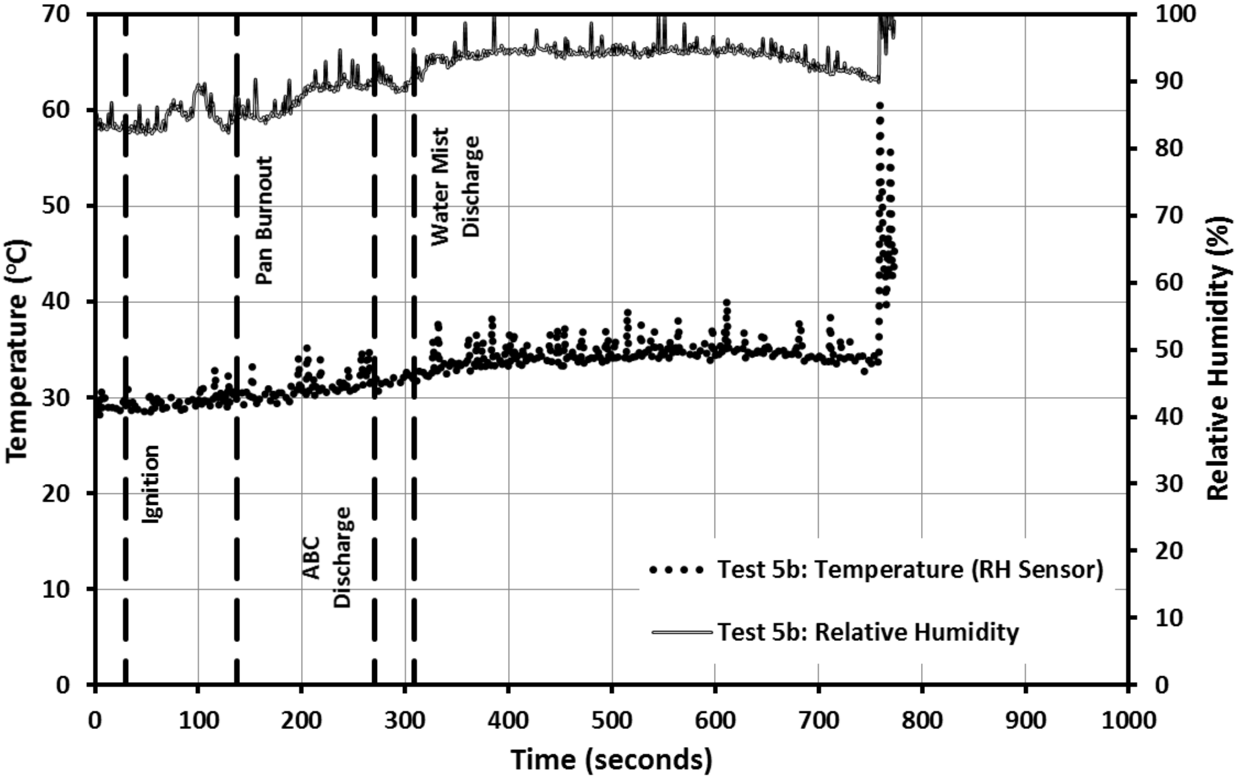

Figure D-58 – Test 5b (ABC + Water Mist) temperature and RH sensor measurements.

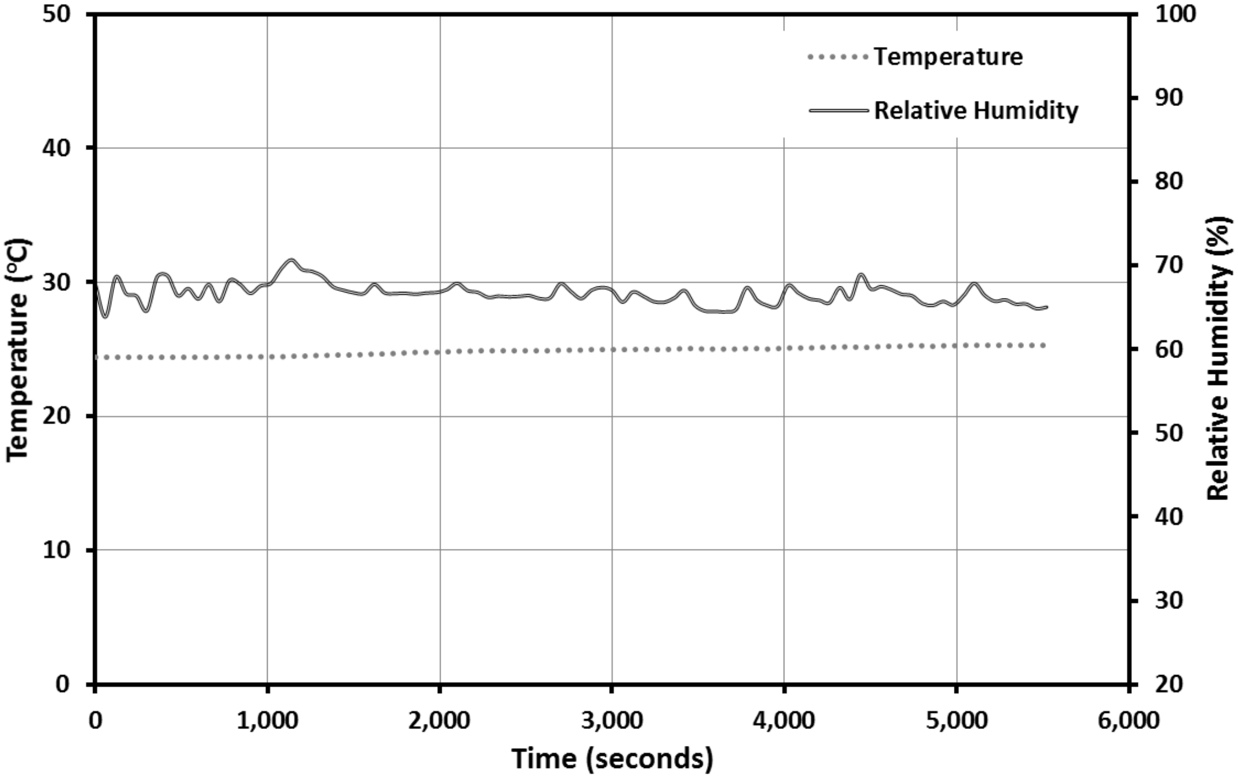

Figure D-59 – Test 5b (ABC + Water Mist) laboratory temperature and relative humidity.

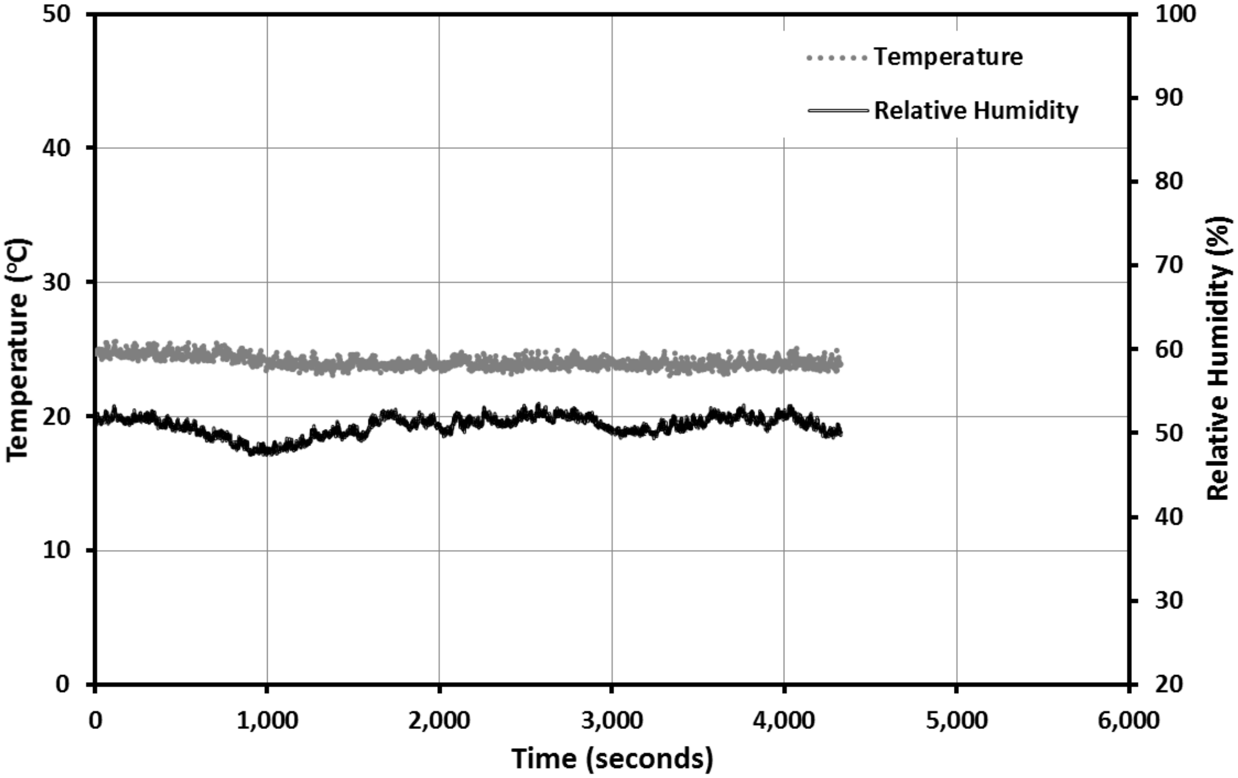

Figure D-60 – Test 5b (ABC + Water Mist) exam room temperature and relative humidity.

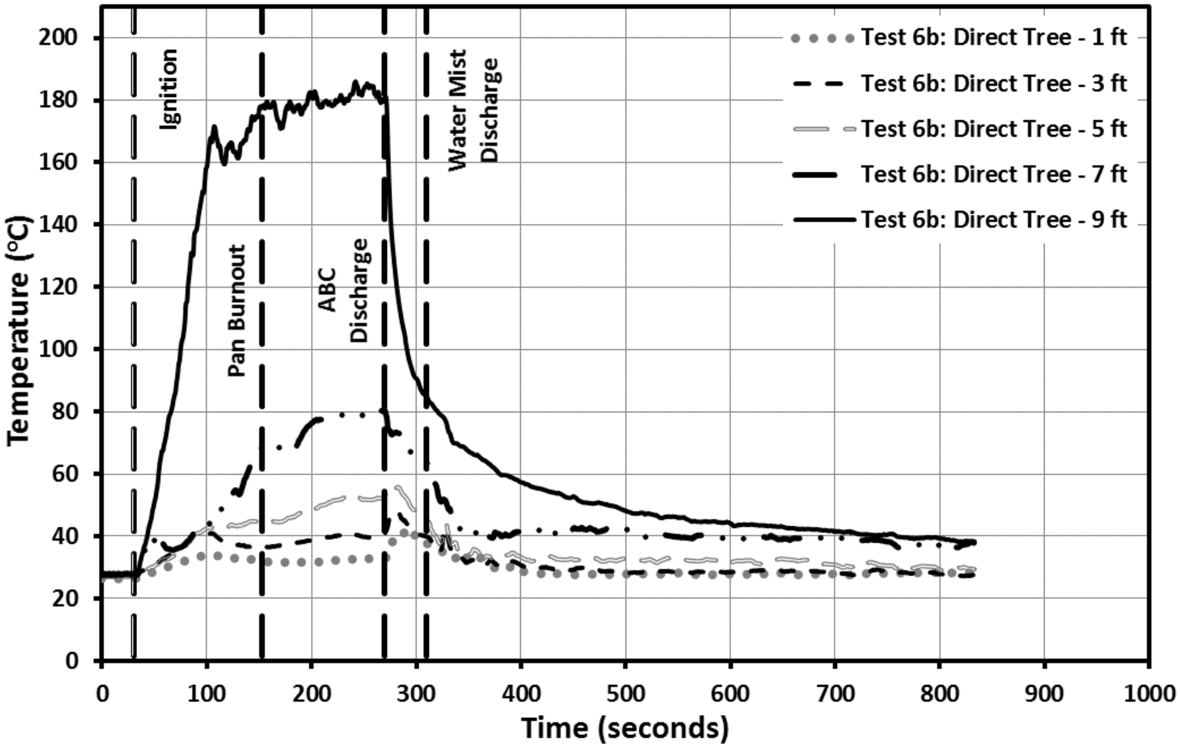

Figure D-61 – Test 6b (ABC + Water Mist) direct tree temperatures.

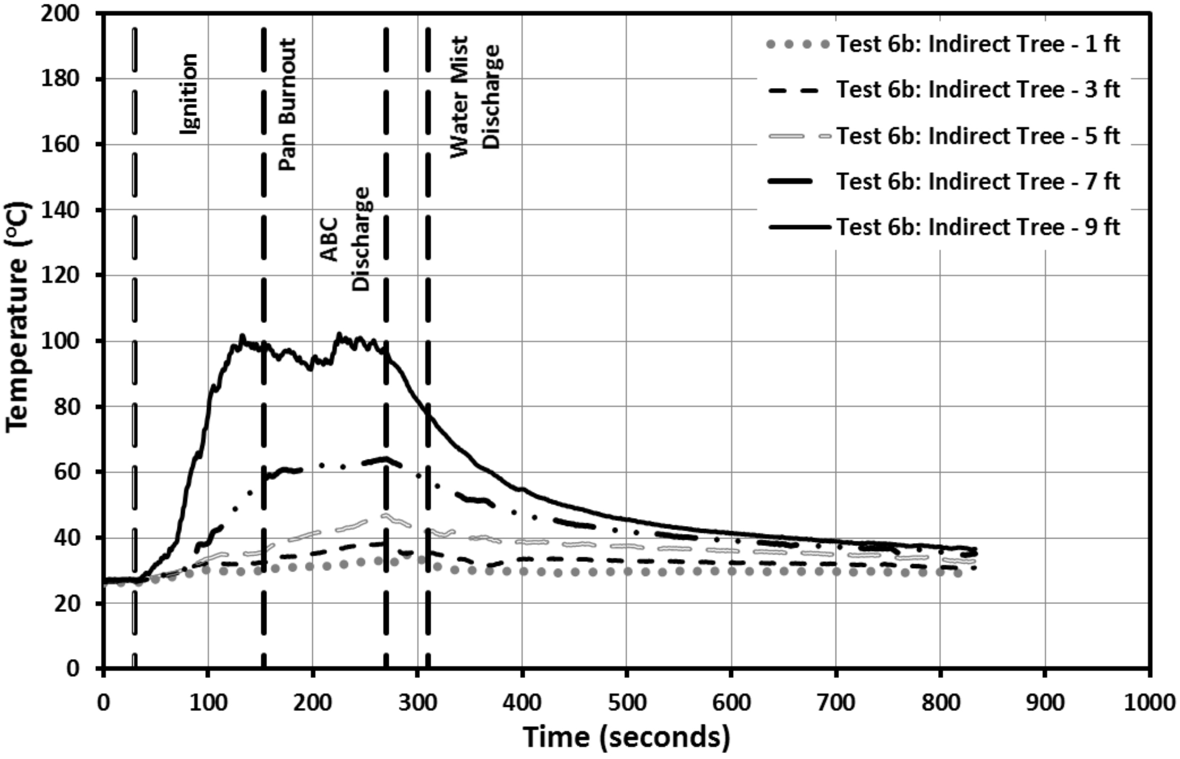

Figure D-62 – Test 6b (ABC + Water Mist) indirect tree temperatures.

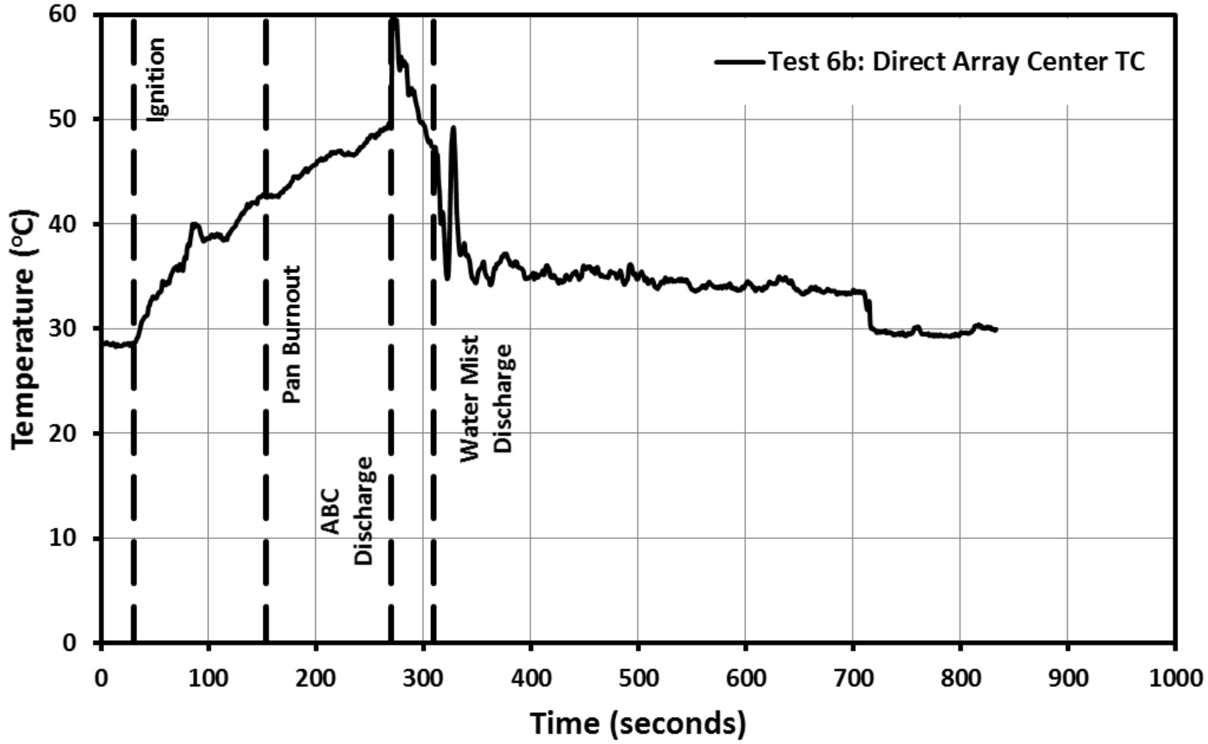

Figure D-63 – Test 6b (ABC + Water Mist) direct array center temperature.

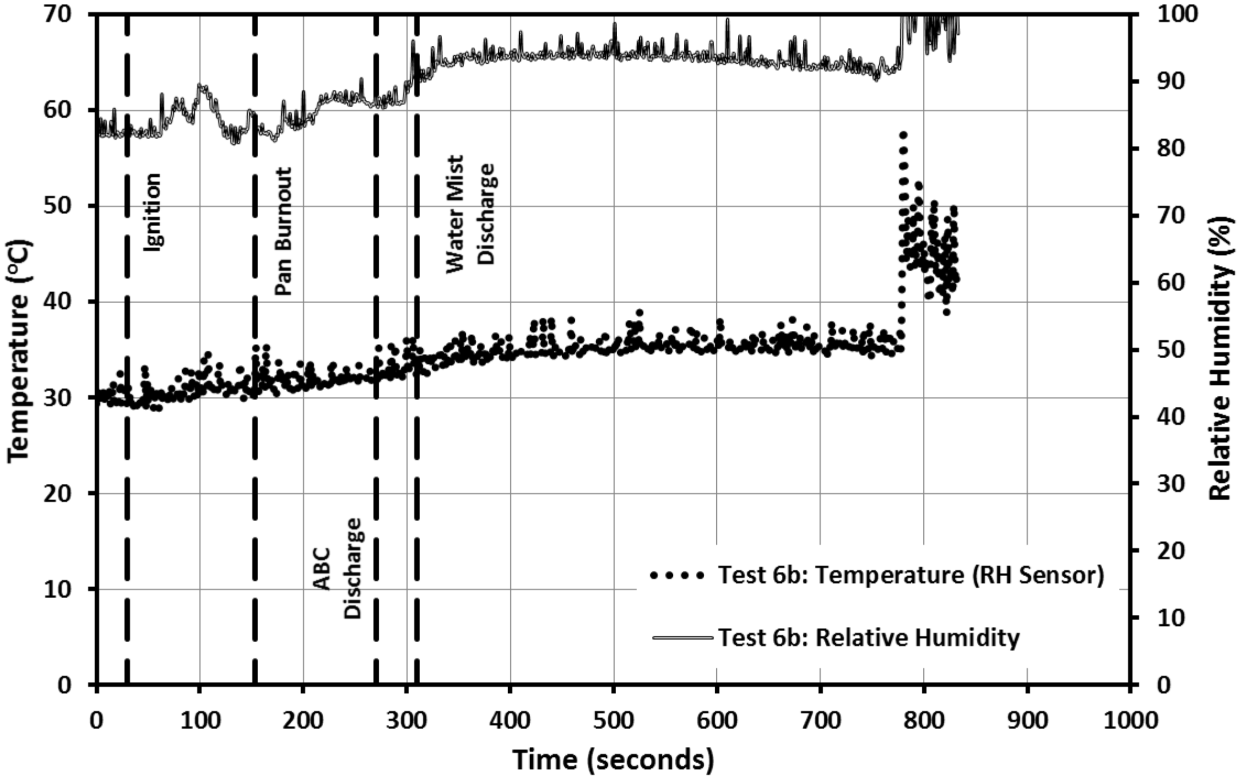

Figure D-64 – Test 6b (ABC + Water Mist) temperature and RH sensor measurements.

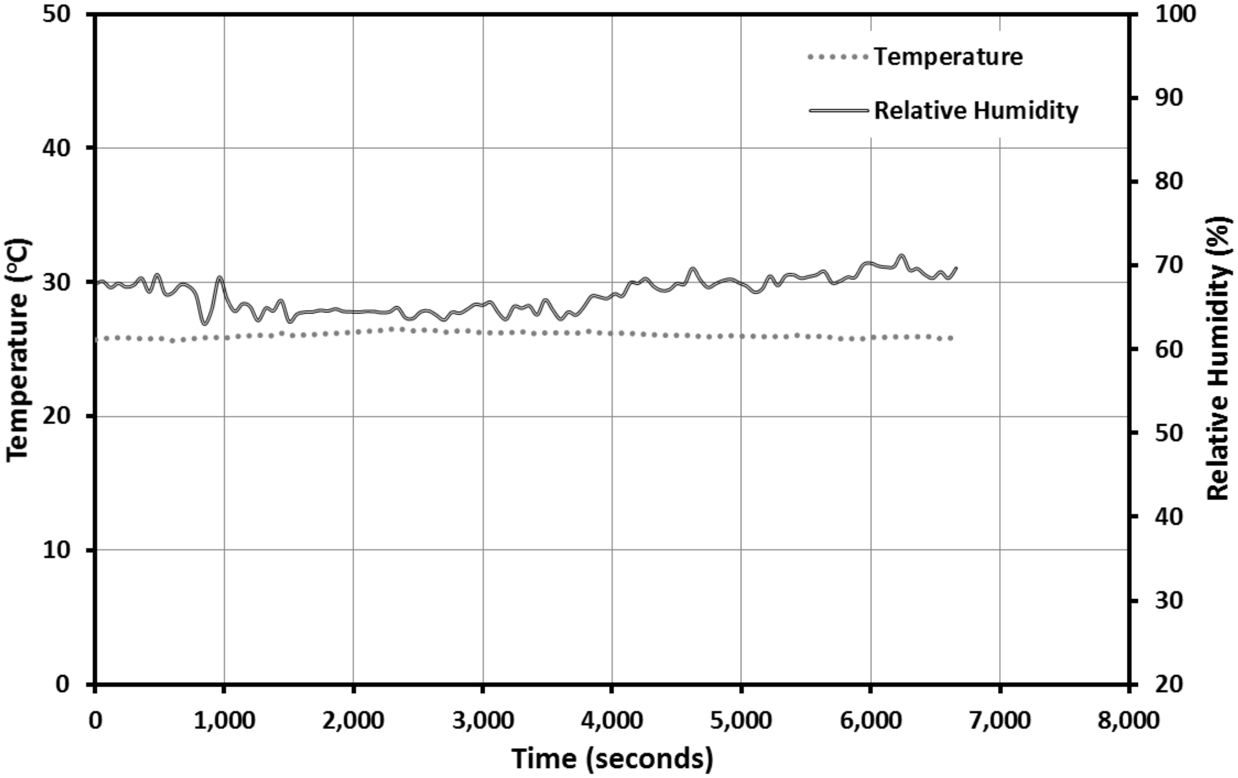

Figure D-65 – Test 6b (ABC + Water Mist) laboratory temperature and relative humidity.

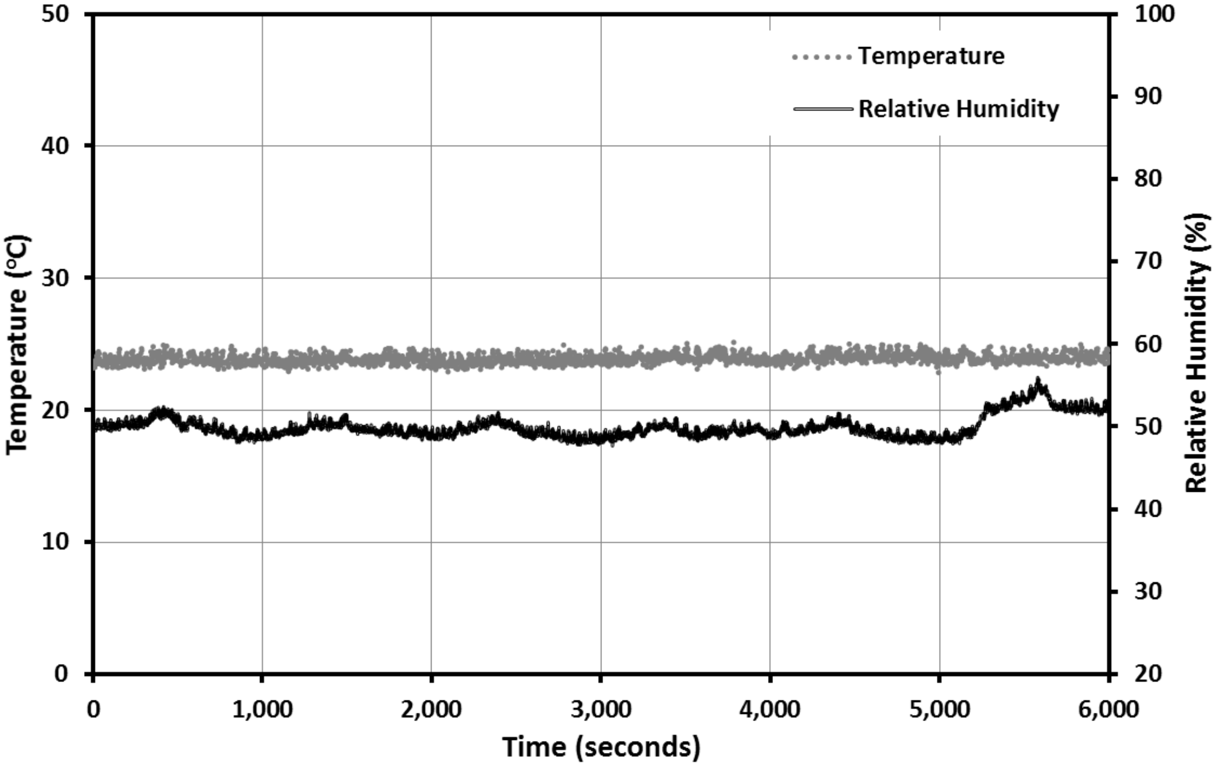

Figure D-66 – Test 6b (ABC + Water Mist) exam room temperature and relative humidity.

APPENDIX E –
FIRE TEST DATA SHEET AND CHECKLIST

Extinguisher Fire Exposure Test Data Sheet

Test Date	**Agent**	**Test No.**	**Test Engineer**		**Test Firefighter**
Size and Details of Wood Crib			**Size of Heptane Pan**		**Heptane Volume**
Test Sample Data					
	Direct Sample Array				
Test Material	**Sample ID**	**Sample Location**	**Pre-Test Sample Mass (grams)**	**Post-Test Sample Mass (grams)**	**Notes**
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

	Indirect, Wall Sample Array				
Test Material	**Sample ID**	**Sample Location**	**Pre-Test Sample Mass (grams)**	**Post-Test Sample Mass (grams)**	**Notes**
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

Test Material	Indirect, Stand Sample Array				
	Sample ID	**Sample Location**	**Pre-Test Sample Mass (grams)**	**Post-Test Sample Mass (grams)**	**Notes**
Iron		1			
		14			
Copper		2			
		15			
Aluminum		3			
		16			
Leather		4			
		17			
Wood, poplar unpainted		5			
		18			
Wood, varnished		6			
		19			
Oil painting		7			
		20			
Acrylic painting		8			
		21			
Travertine tile		9			
		22			
Marble tile		10			
		23			
Deer fur		11			
		24			
Terracotta tile		12			
		25			
Porcelain tile		13			
		26			

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Test Checklist	
	Begin data recording of the temperature and relative humidity in the general lab space 1 hour prior to the test.
	Ensure extinguisher is charged and the safety pin is in-place; Record total weight **(kg)**.
	Weigh wood crib **(kg)**.
	Ensure samples have been conditioned to 50% ± 10% RH and 21±4 °C (70±8 °F) for 5 days.
	Ensure all doors to the test space are closed.
	Label, weigh, and mount Velcro to samples. Record sample weights in the attached tables.
	Mount samples on the correct sample array (see attached tables).
	Begin data acquisition in the examination room.
	Begin data acquisition in the test enclosure. **(Official Test Time = 0 sec)**
	Transport sample arrays to the test space.
	After one minute, mount sample arrays in the test enclosure. Ensure sample arrays are in correct locations. Note the test time when last sample array is mounted **(sec)**.
	Mount thermocouple in the direct sample array.
	Ensure louver in ceiling of test enclosure is open.
	Place wood crib in stand; place ignition pan below wood crib.
	Ensure all test personnel, except firefighter in appropriate equipment, have exited the test enclosure.
	Stage a charged water hand-line near the entrance to the test enclosure.
	Bring extinguisher into the test enclosure and stage near initial separation distance **(6.0 ft)**.
	Begin recording on two cameras **(sec)**.
	After 30 seconds of background video, fill ignition pan with 300 ml of n-heptane.
	Ignite the heptane pan.
	The ignition pan will burn for approximately 83 seconds; note burnout time **(sec)**.
	The wood crib will be allowed to burn for four minutes total (including burn duration of heptane).
	After the wood crib has burned for 4 minutes, begin suppression of the fire with the extinguisher starting from the separation distance.
	Advance on crib and move toward the sides or the top as necessary to extinguish the wood crib, but **DO NOT** discharge at the back surface of the crib.
	Fully discharge extinguisher onto wood crib. If the crib is still flaming, use water sparingly to extinguish flames (take care not to impact the sample arrays).
	Note end of discharge time **(sec)**.
	Confirm fire is extinguished using FLIR.
	Firefighter to take photos of sample arrays and wood crib prior to removal.
	Wait five minutes from end of discharge and begin removing sample arrays to examination room. Note time when last sample array is removed **(sec)**.
	Ventilate the test room.
	Secure video recording.
	Secure extinguisher by inserting pin.
	Record total weight of empty extinguisher **(kg)**.
	Secure data acquisition in test enclosure.

Test Checklist (continued)	
	Weigh and photograph each sample and note weight in attached tables.
	Weigh wood crib **(kg)** and note if any unburned n-heptane remains and dispose of residual if necessary in the waste drum.
	Remove the wood crib from the test enclosure. Douse with water to fully extinguish any smoldering. Once the crib is sufficiently cooled, dispose of in the dumpster.
	Complete post-test conservator examination procedures.
	Store samples in the appropriate storage box.
	Once all samples have been examined, secure data acquisition in the examination room.
	Vacuum and/or clean the enclosure walls to remove agent discharged during the test.

Test Notes

Time	**Event**

Assessing the Impact of Fire Extinguisher Agents on Cultural Resource Materials

A report prepared as part of IMLS-NLG Grant MG-30-13-0083-13

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Introduction:

This document reports on testing carried out by Jensen Hughes and the Colonial Williamsburg Foundation as part of an Institute of Museums and Library Services National Leadership Grant (IMLS-NLG) initiative designed to study the effects of portable fire extinguisher agents on cultural heritage materials. The primary goals of the project were to:

- Establish a reproducible test protocol that could be used for future testing and that would permit the reporting and assessment of comparable test results by disparate testing entities.
- Gather information about the responses of a range of selected materials when exposed to the most commonly used portable fire extinguisher agents over both the short and long-terms.

An ancillary goal was to examine the efficacy of commonly utilized techniques employed to clean heritage materials after exposure to portable fire extinguisher agents.

Since one report, *Quantifying the impact of Portable Fire Extinguisher Agents on Cultural Resource Materials: Agent and Fire Exposure Tests* (Benfer *et al* 2015), has already been prepared detailing the testing protocols and agent selection, this report focuses solely on the selection and response of the materials and the assessment of the cleaning techniques. Since this report relies on information regarding the set up and testing parameters that is contained in the earlier report, it is important that both reports be read, and be read in sequence, in order to assess the testing protocol or the results derived from it.

Background:

Portable fire extinguishers play an important role in the protection of both cultural heritage properties and the collections housed in them. Fires that can be contained in their very earliest stages will not grow to damage additional parts of the structure or other materials. A variety of different fire extinguishing agents are utilized in portable extinguishers used in museums, galleries, cultural centers, historic houses and libraries. The agents themselves have been well-researched and their ability to suppress a fire is well-quantified. What is less well understood is what effect these agents might have on the cultural heritage materials that are exposed to them. A search of the conservation literature found very limited information addressing this. One study conducted by the Norwegian Archive and Museum Authority (Jensen and Larson 2006) had assessed the effects of fire extinguishers on some materials. Although an important first step that produced some very useful results, the study had some elements that limited its broader applicability, including the placement of the materials and the use of a non-standard fuel package which made replication difficult. The search of the conservation literature did not turn up a single article discussing the cleaning of materials exposed to portable fire extinguishing agents or attempts to mitigate exposure. Anecdotal information would suggest this is due to lack of study or reporting rather than lack of incidence.

Material selection and preparation:

The aging of cultural heritage materials is subject to a number of variables, including but not limited to: the composition of the material, the way in which it was exhibited, stored or used, the amount of light it received, as well as the ambient temperature (T) and relative humidity (RH) it experienced and the degree to which they fluctuated. As a result, it can be difficult to identify a large number of replicate samples that have all aged naturally and under the same conditions. For this particular investigation the task was made even harder because of the number of samples needed for the project. In addition to the 780 samples needed for the neat and fire tests combined, additional samples were needed to serve as control sets and for scoping tests. Consequently, the project team decided to use modern materials in all the tests. It was thought that these materials were the best options for enabling subsequent replication and/or extension studies.

Thirteen materials were chosen for their ability to act as surrogates for materials commonly found on open display in cultural heritage organizations.[1] The material, preparation and rationale for selection are detailed below:

- ***20 gauge iron sheet (1.57 mm thick*****).** Iron is present in many forms in many collections. It is quite reactive, particularly to high RH. Sheet iron was bought from stock in Colonial Williamsburg's metal fabrication shop. It was cut by the shop into 4 x 4 inch squares. The iron samples were swabbed with acetone on both sides to ensure that the surfaces were clean and no contaminants from the metal fabrication workshop were present on the surface.
- ***Copper sheet (1.08 mm thick).*** Copper and copper alloys are present in many forms in many collections. It is typically less reactive than Iron. Sheet copper was bought from stock in Colonial Williamsburg's metal fabrication shop. It was cut by the shop into 4 x 4 inch squares. The copper samples were swabbed with acetone on both sides to ensure that the surfaces were clean and no contaminants from the metal fabrication shop were present on the surface.
- ***Aluminum sheet (3.15 mm thick).*** Aluminum is increasingly represented in collections, particularly collections devoted to flight. Of the three metals chosen it is the most reactive but also most rapidly forms the most protective passivating oxidation layer. The aluminum sheet was purchased from Colonial Williamsburg's metal fabrication shop and was cut by the shop into 4 x 4 inch squares. The aluminum samples were swabbed with acetone on both sides to ensure that the surfaces were clean and no contaminants from the metal fabrication workshop were present on the surface.
- ***Vegetable tanned leather (bovine with a mimosa tan).*** Vegetable tanned leather comprises the bulk of all leather found in collections dating to the mid-19th century and prior. In the mid-19th century chrome tanning was introduced and modern leathers may be a combination of vegetable and chrome tanned leather or chrome tanned leather only. The leather was acquired from the Colonial Williamsburg Foundation's shoemaker who had had it tanned. It was a large hide that was cut with shears into 4 x 4 inch squares in the Foundation's conservation lab.
- ***Unvarnished wood (6.4 mm thick).*** Tulip poplar was selected for this. Unvarnished - or secondary wood - is found in many components of furniture. Tulip poplar is native to eastern North America and is commonly used as a secondary wood because it is cheap, easy to work and stable. It is similar in texture, strength and softness to white pine.
- ***Varnished wood (6.4 mm thick).*** Cherry wood was varnished with three coats of a 1.25lb shellac varnish. It was felt that varnished wood might behave a little differently from unvarnished

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[1] For a brief discussion of some of the materials not selected for study and the rationale behind these decisions please see the Future Testing section in this report.

wood due to the protective nature of the coating. However, since so much furniture and even architectural wood is varnished, it was also desirable to learn whether any extinguishing agents interacted adversely with the wood finish.

- ***Oil painting on linen.*** The prepared linen canvas was purchased. It was made of fine linen that was double primed with gesso. Four inch wide strips were cut from the canvas and were painted with alternating stripes of color with a band of primed canvas between each color band. The rationale for the band of uncovered canvas was to ensure that adjacent colors did not impact visual perception of any color change that may have occurred. On advice from Colonial Williamsburg's Conservator of Paintings four colors were selected as most likely to reflect the gamut of reactions that might be expected. These were: Flake white (Utrecht Artist Colors oil Series 1), Ivory Black (Utrecht Artist Colors oil Series 1), Red Ochre (Williamsburg Handmade oil colors Series 1, #6001581-9), Chromium Oxide (Grumbacher Artist Colors P048G Series 3). The idea behind the color selection was that black and white can show deposits that the other color might not (for example, black deposits will show up well on a white background and light deposits are more obvious on a dark background). Additionally, mineral pigments can separate from their oil media as a result of deterioration and this is particularly evident with black pigments. The red ochre was chosen because earth pigments tend to be very stable and are historically well represented in the artistic record. Chromium oxide was chosen as an example of a modern family of pigments. Since the discovery of chrome in the 19th century it has been a popular choice for green in oil paintings.
- ***Acrylic painting on canvas***. The prepared canvas was purchased. It was made of 100% cotton duck canvas that had been triple primed with an acrylic gesso. Four inch wide strips were cut from the 54 inch long canvas and were painted with alternating stripes of color with a band of primed canvas between each color band. As with the oil painting on canvas, the rationale for the band of uncovered canvas was to ensure that adjacent colors did not impact visual perception of any color change that may have occurred. On advice from Colonial Williamsburg's Conservator of Paintings four colors were selected as most likely to reflect the gamut of reactions that might be expected. These were: Cadmium Red (Golden # 1100-4 Series 9); Phthalo Green Yellow Shade (Golden #1275-2, Series 4), Titanium White (Golden #1380-4 Series 1) and Mars Black (Utrecht # 02192). The rationale for the selection of the black and white pigment was similar to that for the black and white oil paint (see above). Phthalo green and cadmium red were selected because they are fairly common colors in art.
- ***Marble tile.*** MS international 4 x 4in marble tile was purchased from Home Depot. The tile has a tumbled finish (as opposed to a polished one). Although one thinks of marble as a very robust stone it can be easily damaged in low pH environments.
- ***Travertine tile.*** MS International Gold 4 x 4 inch Tumbled Travertine Floor tile was purchased from Home Depot. Travertine is finer grained and more porous than marble and is characterized by dry seams and pits that provide more surface area for the extinguishing agents to interact with.
- ***Ceramic tile.*** A glazed ceramic tile was purchased from Home Depot. It was 4.25 x 4.25 inches square and had a yellow glaze on the surface. Referred to as porcelain tile during testing, it is

not a true porcelain, however the glaze and the high fire temperature give the tile a durability and impenetrability that an unglazed tile does not have.

- ***Unglazed Ceramic tile***. The 4 x 4 inch unglazed and unsealed floor tiles were purchased from Mexicantiles.com. The tile, made of terracotta, is more porous than the glazed ceramic tile used and it was considered a good surrogate for uncoated earthenware ceramics.
- ***Fur***. Fur was added to the sample list late in the test development process. It was chosen because many natural history museums and historic homes contain taxidermied specimens and clothing items that incorporate fur. Fur consists of two layers: the fine "down hairs" under the coat, responsible for thermal insulation, and the longer coarser "guard hairs" that comprise the more visible part of the coat. It was felt that it would be interesting to see how the open structure of the fur influenced the deposition of the extinguisher agents and/or the cleaning process. Due to differences in environment and nutrition, fur from different animals of the same species may exhibit slight differences in behavior. White tailed deer fur was selected in part because a single hide was likely to yield the quantity necessary for the tests and because it is a readily available hide that does not have any legislative restrictions on it. The hide was purchased from Moscow Hide and Fur. It is important to note that the hide was collected in September as the timing influences the length of the animal's hair. September marks a mid-point in the length of deer fur; the hairs are not as long as they are in winter but they are not as short as they are in the summer. The hide was cut with shears into 4 x 4 inch squares.

Seventy five samples of each material were created. Since each extinguisher test required six samples (two each for the direct array and two for each of the indirect arrays), 60 samples were needed just for the testing. Two more sample sets were needed for the two control sets. The remaining samples were created for use in scoping tests and as back up materials in case of an unexpected problem with any of the arrays. Prior to any testing, the test samples were given a unique designation based on the material type (i.e. Fe for iron samples or UV for unvarnished wood) and a number sequence ranging from 1 to 66.[2] The control samples were designated "control" and "cleaning control." The samples used for scoping tests were not given a unique number.[3]

Prior to any testing, the test samples were visually assessed. A condition report detailing their pre-exposure condition was written up and any anomalies, such as knot holes (in the wood sample), scratches (in the metal and stone samples) and scars (in the hide layer of the fur samples and in the leather samples), were noted. The samples were photographed and weighed. Nitrile gloves were worn during all sample handling, both pre- and post-exposure, to avoid transferring oils, salts or other contaminants onto the samples.

Transportation

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[2] This accounted for all the materials needed for testing and one full set of materials in case of a problem with any of the tests.

[3] The circumstances in which the scoping samples were used were not reproducible so the samples were not numbered, retained or tracked. This explains the discrepancy between the number of samples prepared and the quantity of numbered samples.

Once the samples had been assessed and documented, they were packed on custom-made acid free board trays with Ethafoam®[4] stops on each side to ensure that they did not move during transport. Higher Ethafoam® columns at the corners and in the center of each tray allowed the trays to be stacked without any portion of the upper tray touching any of the samples below. The trays were packed into a large, sealable, polypropylene Rubbermaid® container that contained 3kg of silica gel that was preconditioned to 50% RH in order to buffer any changes in relative humidity (RH) that the samples might experience during travel between Williamsburg and the Baltimore area test site. Each Rubbermaid® container held the samples for a single extinguisher test to avoid possible contamination from materials exposed to different extinguishing agents.

Test set up:
On the day of the test, each sample was weighed. Then two pieces of Velcro tape were attached to the back of each sample. The tape was applied horizontally across the back about an inch from the top of the sample and an inch from the bottom. It ran to about a half inch from the edge of each piece. The full number sample number was written on the back with a Sharpie® pen[5]. The sample was weighed with the tape on it. It was then attached to the array board. The array was mounted in the test cell. The test was performed according to the protocol outlined in Benfer *et al.* (2015). Following the conclusion of the extinguisher discharge, the sample arrays were allowed to sit in the test cell for five minutes prior to being removed from the room by the firefighter and carried to the examination room. The arrays were visually assessed at this point and photographed and any immediate observations about condition or the deposition of the extinguishing agents were written down. The samples were then removed from the boards and weighed with the Velcro tape still on them. The tape was removed and the sample was reweighed and placed back on the transport trays.

The individual observations associated with each test are detailed below but a few generalizations may be made about the overall test set up. The lower set of samples on the direct board tended to get the greater exposure of the two direct sets. Although the two indirect samples were situated at the same distance from the extinguisher there was a difference in the deposition rate between the two. The wall-mounted array tended to get more exposure than the floor stand array. Typically the floor stand samples got very little exposure. The heavier samples, such as the terracotta tile and the marble, fell off the direct array during the water mist tests, which resulted in breakage of some of the samples. The adhesive on the Velcro tape was tested with a Thermo Scientific Nicolet 6700 Fourier Transform Infrared Spectroscope (FTIR) coupled with a Nicolet Continuum FT-IR microscope in transmission mode. The spectra was collected with Omnic 8.0 software and compared with commercial reference spectral libraries as well as those produced by the InfraRed Users Group (IRUG). The closest spectral match was an acrylic adhesive manufactured by 3M (fig 1). Although the match is not a perfect one it suggests that the adhesive is acrylic based.[6] It is possible that the adhesive failure was a mechanical one due to

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[4] Ethafoam® is a closed cell polyethylene foam used for a broad number of applications in the conservation field.
[5] See Benfer *et al*., p. 7 for details on numbering protocol. The pens used were Sharpie Pro 13801 Industrial Super Permanent Extra Fine Point Ink markers.
[6] We are indebted to Catherine Madsen, Senior Scientist, Winterthur Museum and Gardens, and Kirsten Travers, Materials Analyst, CWF, for conducting these tests.

increased sample weight as a result of the exposure to water[7]; however, it is also possible that the failure was a chemical one, produced by the interaction between the adhesive and the water and possibly augmented by the stress (weight) the adhesive was under.

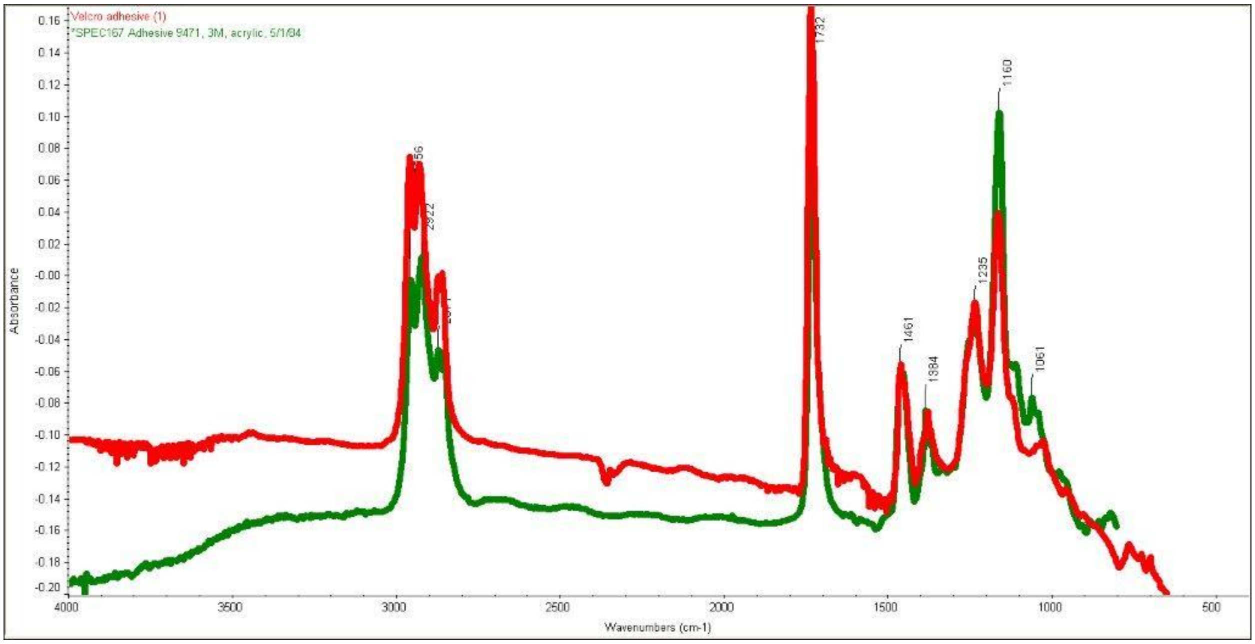

Figure 1: FTIR Spectra for the Acrylic adhesive (red) and 3M Adhesive 9471 tape

Observation made immediately after the samples were taken out of test cell:

During each test, following the conclusion of the extinguisher discharge, the samples were allowed to sit in the test cell for five minutes, during which time the doors to the test chamber remained closed. The firefighter photographed each array during this period. The rationale for the five minute "soak period" was to allow any agent dispersed throughout the test enclosure to settle onto the sample arrays (Benfer *et al* 2015). Once the doors were opened the panels from each array were immediately carried into the neighboring examination room. This process took one minute. The arrays were immediately re-photographed by the conservator and assessed and any immediate observations were recorded. These assessments were therefore carried out within 6-10 minutes of the conclusion of each extinguisher discharge. The photographs taken by the firefighter during the "soak time" were later compared to those taken on arrival in the examination room. This was helpful in determining the full extent of the frost patterns, seen in some samples.

After Test 2A (water mist test-"neat" application)

The samples on the direct array were all visibly wet except for porcelain tile, which showed no visible water beading. The two terracotta samples fell off the wall. Oil paint sample showed visible and immediate cockling. The copper alloy and iron sample showed immediate spotting. The indirect samples did not appear to be wet or exposed.

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[7] Although generally, acrylic adhesives such as the 3M's 9471 have a high degree of resistance to water.

After Test 3A (Halotron—"neat" application)

Several of the samples on the direct array had thick layer of frost. The presence of water on other samples suggesting that the frost on those samples had melted. The frost pattern was slightly heavier to bottom of board. Items in slots 4, 5, 9 & 10 were hardly affected. One terracotta tile (position 12) was pulled off the board before it dropped off (the adhesive had begun to fail/creep). Both oil painting samples were cockling significantly and pulling away from board. On the acrylic paint on canvas sample the green paint (phthalo green) showed what appeared to be marked fading. On closer inspection the paint appeared to be dislodged. Small fragments of green paint were visible on other samples on the panel suggesting that the paint had been dislodged and transported some distance. When removing the Velcro tape from the back of the samples it was noted that the adhesive on the Velcro had softened somewhat and also that the ink from the Sharpie had bled, suggesting that the Halotron was solubilizing both. The samples on the two indirect arrays did not show any frost pattern or other alteration.

After Test 4A (FE-36—"neat" application)

There was a thick layer of frost on surface of many of the samples on the direct array (fig 2). The frost was heaviest near the bottom of the board. The oil paint sample in slot 20 had cockled at the top. Slots 5 (Unvarnished wood), 10 (Marble), 1 (Iron) and 3 (Aluminum), near the top of the array, showed little exposure.

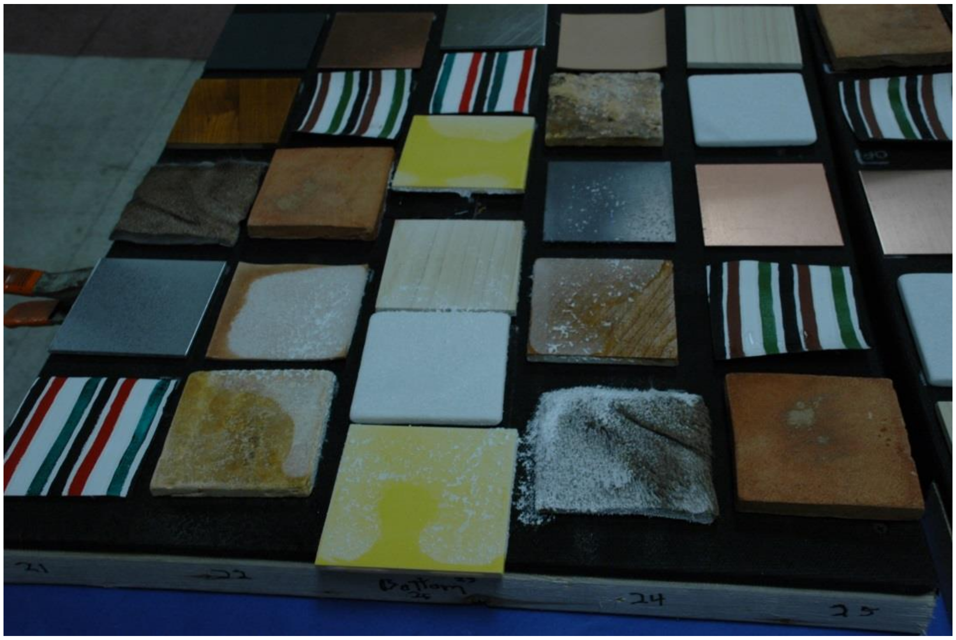

Figure 2: Frost pattern on FE-36 array

After Test 1A (ABC Dry Chemical—"neat application")

ABC dry chemical powder was present on all surfaces. The indirect samples on the standing array had the least powder residue on the surface. There was only a very light layer present. The direct array had a thick layer of ABC on all the surfaces (even the backs of samples, which was visible when the Velcro was pulled away). The coating was so thick that it caused a visible color change (towards light yellow) in the samples, including most notably the aluminum; it was difficult to make out what the underlying material was. Also the colors on the paint samples (both the acrylic and oil) were visibly changed by the powder. One fur sample on the direct array weighed 2g more after exposure; possibly this was due to the amount of ABC deposited on the surface as there was a thick visible layer of powder on the sample. The fur may have trapped the ABC more effectively than other materials but since the other fur sample on the board did not show a similar weight gain (in fact the weight stayed nearly same) there may be another explanation.

After Test 5A (ABC and water mist—"neat" application)

The iron and copper samples had both begun to corrode. The corrosion on the surface of the iron sample was profound. It is important to remember that this corrosion was visible within six minutes of the conclusion of the extinguisher discharge, which speaks to the speed with which it occurred. The Oil painting on canvas sample had cockled. The adhesive on the back of the terracotta tiles had softened.

After Test 2B (Water mist—"Fire" application)

The samples on the direct array were all very wet. Both of the terracotta tiles both fell off of the array during the test resulting in damage to the sample. Soot had visibly penetrated the leather and there were loose soot particles on some of the other samples. Both the oil paint and acrylic paint samples were heavily cockled. The leather samples and some of the copper samples on the two indirect arrays both had evidence of water spotting suggesting that the water mist did reach these surfaces.

After Test 3B (Halotron—"Fire" application)

The direct exposure samples were sooty with no frost pattern visible. Heavy tarnishing was immediately visible on the copper and iron samples. The oil painting samples had relaxed slightly possibly as a result of the change in RH seen during the testing (Benfer *et al* 2015).

After Test 4B (FE-36—"Fire" application)

Direct exposure samples (especially those lower down on the array) were sooty with no frost pattern visible. A light layer of tarnishing was immediately visible on the copper sample. The oil painting samples had relaxed slightly. Again this may have been due to the increase in RH during testing (Benfer *et al.* 2015)

After Test 1B (ABC dry chemical—"Fire" application)

Directly exposed samples were heavily covered in ABC dry chemical powder but there was no visible soot. The thickness of the powder was causing a perceptible color shift. Indirect (both wall and stand) arrays both showed a light dusting of ABC dry chemical powder but it was not as heavy as on the direct array.

After Test 5B (ABC and water mist—"Fire" application)

Four tiles (both of the terracotta tiles, one travertine and one marble tile) fell off the direct array during the 5 minute "soak" time. The iron samples both showed evidence of immediate corrosion. Both oil paint samples were heavily cockled. There was no evidence of soot on any of the direct or indirect samples. ABC dry chemical powder was visible on all the samples on both of the indirect arrays but only some water mist reached these samples. The samples on the wall stand showed evidence of spotting on almost all of the samples. The indirect floor stand showed evidence of spotting on the copper, leather and aluminum samples only. This suggests that more of the water mist reached the wall array than the stand array.

Assessment and cleaning:

A detailed condition assessment was carried out on each sample within one week of testing. The samples were reassessed after 6 months, 12 months and 18 months of exposure. The samples were photographed at each of these times and a visual assessment was conducted under both ambient and raking light. The assessment noted individual condition issues, such as cockling, surface accretions, staining, corrosion, and visible color change. This last criterion was noted by comparing the sample against other non-exposed samples; due to the normal color variation in all the samples, it was primarily useful for determining whether exposure to ABC dry chemical had resulted in a color shift. Estimates as to the degree of surface change considered exposure to the face of the sample only. Changes to the back of the sample were noted but not quantified.

As outlined in the earlier report (Benfer *et al.* 2015) the directly exposed samples and the indirectly exposed samples from the wall array were divided into two groups one of which underwent immediate cleaning and the other of which was stored for six months and then cleaned.[8] The rationale for this division was to assess whether prolonged exposure to the extinguishing agents resulted in additional damage and/or made it more difficult to remove the extinguishing agent from the surface. The six month delay was selected as being reflective of the delay some institutions might face while lining up resources, whether funding or staffing, prior to mitigating any exposure.

We were unable to locate any information on approaches to cleaning materials exposed to fire extinguishers in the conservation literature however, there are several papers detailing cleaning after exposure to soot and/or fire. Reviewing these papers we found that the most commonly utilized cleaning techniques were vacuuming combined with light brushing (Severson *et al.* 2000; Spafford Ricci and Graham 2000a); cleaning with a soot eraser[9] (Spafford-Ricci and Graham 2000b; Baker et al 2008; Levenson 2010); and cleaning using aqueous mixtures (Spafford-Ricci and Graham 2000b). A fourth method, brushing with soft brushes, has, anecdotally, been used by some institutions but not written up. Therefore, each sample was divided into four 1 x 1 inch quadrants and each of the quadrants was cleaned by one of the four methods: swabbing with deionized water; cleaning with a soot eraser; brushing only; vacuuming combined with brushing (fig. 3). To ensure that the cleaning was conducted in a manner that was comparable from sample to sample, overlapping passes were made left to right from the top to the bottom of the sample quadrant, then up and down from left to right, then left to right from top to bottom and once more from top to bottom moving across the sample left to right. To

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[8] One sample of the indirectly exposed samples from the floor stand was held for assessment at the end of the project period. The second set was set aside for possible inclusion in a side research project that the College of William and Mary's Applied Research Lab was developing to augment this research.

[9] A vulcanized natural rubber sponge used to pick up soot and other surface contaminants.

ensure that material was not carried from one sample to the next the brushes were cleaned between each sample and the end of the soot eraser was cut off to ensure a fresh surface was used.

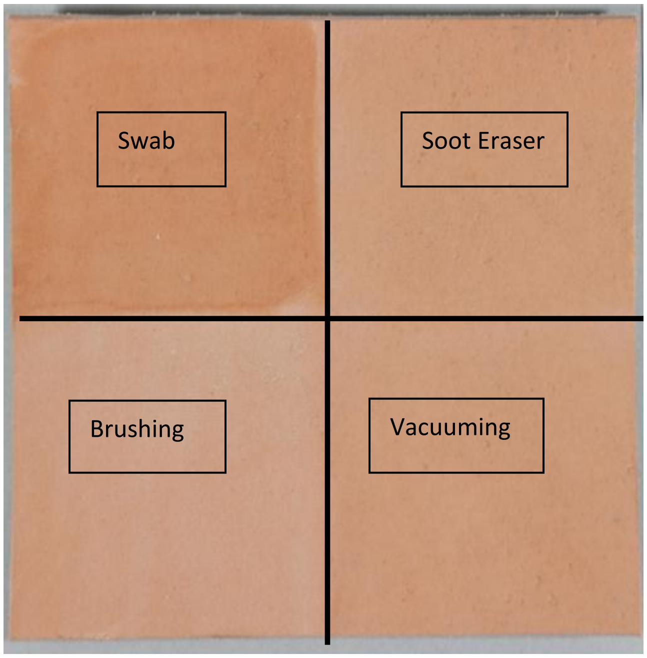

Figure 3: Leather sample with cleaning divisions demarcated.

Results:

The results of the assessments are summarized in table one (neat tests) and table two (fire tests). Within the parameters of these tests, damage was both less diverse and less dramatic than expected. Many samples exhibited no visible changes at all. Although there was individually significant damage to samples, the types of damage noted tended to be within the scope of the known risks for that material. For example, it was expected that the water mist extinguisher would cause staining or discoloration of the organic samples and similarly that it might cause the painting samples to cockle.

In general, change was hardest to detect on the unvarnished wood, marble and travertine samples. This was due in part to the light color of the samples and also to the matte appearance of the surface. Changes in gloss, for example on the porcelain tile, acted as indicators of potential surface deposits. Change was also difficult to detect on the terracotta and the fur samples due to the texture of the surfaces. There were differences in exposure between the two samples of the same material on an array that made it difficult to compare the extent of damage. For example, one copper sample might tarnish over 100% of the surface and the other sample only over 75% of its surface. As noted earlier, these differences were due to the degree of exposure its location on the sample array received.

None of the extinguisher agents left the samples entirely damage free. All of them impacted at least some of the materials in the test group in some manner. The introduction of a fire scenario increased the extent of the extinguisher agents' impact on the sample materials. For example, light tarnish was noted on the copper after exposure to the neat Halotron but in the fire scenario the tarnish was much more pronounced.

When damage did occur to a sample, it was immediate and did not appear to progress incrementally with time. This suggests that future testing can be shortened and does not need to be run out for the lengthy assessment period undertaken by this project. It also suggested that in some cases (i.e. exposure to water mist, Halotron and FE-36) immediate remediation may not be necessary; in other words, some time can be bought. However, it must be noted that addressing exposure to ABC dry chemical should be a high priority because of the degree to which the material spreads and the potential for it to be tracked to other galleries/spaces.

Water Mist—neat application (Test 2A)

Materials from the direct array were the most affected. Isolated spots of active corrosion were visible along the edge of the iron samples. Both the aluminum and the copper alloy samples had white residues on the surface[10]. In total these spots (both the active corrosion seen on the iron and the white residues observed on the other metals) accounted for approximately 2-5% of the surface area of the sample. Significant cockling, resulting in cracking of the ground and paint layer, occurred in the oil paint samples and the canvas became more rigid once it dried. Significant cockling was also noted in the acrylic paint samples. There was damage, in the form of water spotting, on the surface of the varnished wood. It was more pronounced on the surface of one sample where it accounted for approximately 40% of the surface. The only material from the indirect wall sample that showed any effect from the water was one of the oil paint samples which had relaxed visibly as a result of the increase in relative humidity (RH) associated with the use of the extinguisher.

Halotron—neat application (Test 3A)

There was a visible residue on the surfaces of the porcelain tile, the varnished wood sample and both of the copper and aluminum samples. The ink from the sharpie bled. On the acrylic sample (direct array) this caused the sharpie ink to bleed through the canvas and become visible on the front of the sample (fig. 4). While, this was the most dramatic instance of the ink bleeding, the effect was noted on other samples. Additionally, it was noted that the adhesive from the Velcro tape on some samples had solubilized and gelled slightly leaving gummy residues on the back of the samples. As noted previously, the green pigment was removed from the surface of the canvas in small patches. This suggests that areas of insecure paint may be at risk from the force and/or the frost action. Both the acrylic and oil paint samples exhibited significant planar distortion in the form of cockling.

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[10] The composition of these residues was not explored as part of the assessment but it is likely to be an additive or contaminant from the extinguisher water. Additives, such as biocides and anti-corrosion agents, are sometimes added to the water in fixed water mist systems to increase their fire-extinguishing efficiency (Xiaomeng *et al.* 2006) and it is possible that the residues result from such an additive. Additional possibilities are impurities or other contaminants in: 1) the water, itself 2) the extinguisher canister 3) the compressed air used to pressurize the canister or 4) the air in the enclosure/room (i.e. dust or other contaminants that mix with the water as it travels to the sample, although this last scenario seems the least likely).

Material	Water mist	Halotron	FE-36	ABC	ABC + Water mist
Porcelain Tile	No observable change	Surface residue noted	Surface residue noted-10-25%	Heavy layer of powder-100%	Surface accretions-100%
Terracotta	No observable change	No observable change	No observable change	Heavy layer of powder-100%	Surface accretions-100%
Marble	No observable change	No observable change	No observable change	Heavy layer of powder-100%	Surface accretions
Travertine	No observable change	No observable change	No observable change	Heavy layer of powder-100%	Surface accretions
Iron	Limited corrosion (spotting) 2% of surface	Corrosion	No observable change	Heavy layer of powder-100%	Corrosion 2-5% Surface accretions-100%
Copper	Limited corrosion (spotting) 5% of surface	Corrosion—100% of surface	Slight corrosion 1-2%	Heavy layer of powder-100%	Corrosion 1-5% Surface accretions—100%
Aluminum	Limited corrosion (spotting) 2% of surface	Corrosion—75%	Slight corrosion 1-2%	Heavy layer of powder-100%	Corrosion Surface accretions-75-100%
Leather	Surface darkening	Surface darkening	Surface darkening	Heavy layer of powder-100%	Surface accretions
Acrylic Paint	Planar distortions	Planar distortions Paint damage	No observable change	Heavy layer of powder-100%	Surface accretion
Oil Paint	Planar distortions	Planar distortions	Planar distortions	Heavy layer of powder-100%	Planar distortion Surface accretion
Fur	No observable change	No observable change	No observable change	Heavy layer of powder-100%	Surface accretion Fur matted
Varnished Wood	Surface Spotting	Surface residue noted	No observable change	Heavy layer of powder-100%	Surface accretion
Unvarnished Wood	Surface Spotting	No observable change	No observable change	Heavy layer of powder-100%	Surface accretion

Table 1: Summary of extinguishing agent effects on neat samples from direct array prior to cleaning. Note where a percentage range is present it represents the effects seen on both samples.

Material	**Water mist**	**Halotron**	**FE-36**	**ABC**	**ABC + Water mist**
Porcelain Tile	Soot 5%	Soot-60-80%	Soot-50%-60%	Light layer of powder 100%	Surface accretions
Terracotta	Soot 10-20%; Breakage due to fall	Soot-70%	Soot-20%	Light layer of powder 100%	Surface accretions; Breakage due to fall
Marble	Sooty streaks—1%	Heavy Soot-80%	Soot-100%	Light layer of powder 100%	Surface accretions; Breakage due to fall
Travertine	No observable change	Soot-10%	No observable change	Light layer of powder 100%	Surface accretions
Iron	Limited corrosion (spotting) 2%-10% of surface	Corrosion 80%; Heavy Soot-70%	No observable change	Light layer of powder 100%	Corrosion-80%; Surface accretions-100%
Copper	Limited corrosion (spotting) 5%-10% of surface	Corrosion—100% of surface; Soot—50%	Corrosion-100%	Light layer of powder 100%	Corrosion-60%; Surface accretions—100%
Aluminum	Limited corrosion (spotting) 2% of surface	Corrosion—70-80%; Soot-1%	Corrosion—10% Soot 25%	Light layer of powder 100%	Corrosion; Surface accretions-100%
Leather	Planar distortion; Hardening; Soot-60%-70%	Soot=--60%	Soot-80%	Light layer of powder 100%	Light layer of powder-100%; Surface accretions-1%
Acrylic Paint	Planar distortion; Cracking of paint surface; Soot 1-2%	Planar distortion; Soot-40%-50%	Heavy Soot-50%	Light layer of powder 100%	Planar distortion;
Oil Paint	Planar distortion; Rigidity	Planar distortions; Soot 70%	Planar distortions Soot-70%	Light layer of powder 100%	Planar distortion; Cracked paint; Hardening
Fur	Planar distortion; Slight rigidity	Small amounts of soot at ends of hairs	Soot in whiter fur Hairs loosened	Light layer of powder 100%	Surface accretions-100%; Fur matted
Varnished Wood	Surface Spotting; Darkening-100%	Soot-70%	Light Soot-60%	Light layer of powder 100%	Light layer of powder 100%
Unvarnished Wood	Planar distortion; Darkening	Heavy Soot-70%	Soot –60%-70%	Light layer of powder 100%	Light layer of powder 100%

Table 2: Summary of extinguisher effects from fire exposed samples on direct array prior to cleaning. Note where a percentage range is present it represents the effects seen on both samples.

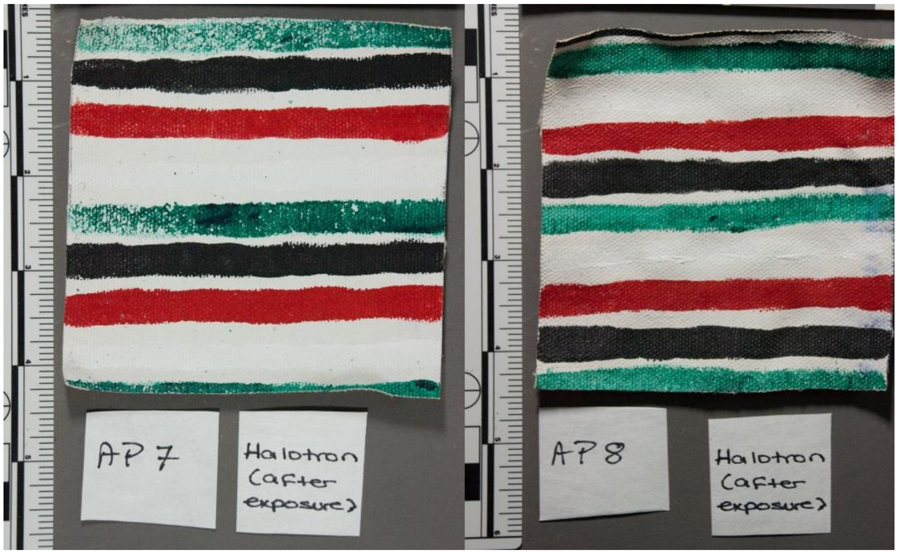

Figure 4: Acrylic paint samples, note paint loss in sample AP7 and Sharpie® ink bleed through in sample AP8 (lower right corner)

FE-36—neat application (Test 4A)

There was a visible residue on the surface of both the porcelain tiles (over 10-25% of the sample). One leather sample had spotting and discoloration similar to those left by the water mist. (This may have been a by-product of the frost pattern seen on the samples when they were removed from the test cell). One of the copper samples exhibited the presence of residues over one percent of the surface.

ABC Dry Chemical—neat application (Test 1A)

The powder was visible in a thick layer on all samples from the direct array although it was a little difficult to make out on the unvarnished wood sample due to color. A light layer was present on samples from the indirect array. It was more difficult to see on the marble, the unvarnished wood and the leather sample (due to color) and on the fur sample (although if one looked at areas were the shaft of the hair had been cut it was easier to see). No additional damage, such as planar distortions or corrosion was noted.

ABC Dry Chemical and Water Mist—neat application (Test 5A)

The combination of ABC and water mist caused corrosion on the iron and copper samples. Due to the color of the powder it was difficult to differentiate between corrosion and powder accumulations on the aluminum surface. Where the ABC powder had become wet it became hard and cement like (fig. 5). The increase in humidity associated with the water mist had also caused cockling in the oil painting sample. ABC dry chemical powder was visible on all samples. Where it had not been wet by the water mist conditions were similar to those in the straight ABC exposure. Where it had been wetted the powder formed thick cement like accretions.

Figure 5: Oil paint, Copper and Marble samples after exposure to ABC dry chemical and Water mist.

Water Mist—fire scenario (Test 2B)

Soot was present as large particles or pieces on the surface of many of the samples. The water mist carried the soot into the organic samples, in particular the leather sample, resulting in staining that was difficult to lift from the sample. Active corrosion was noticeable on up to 5% of the metal surfaces in materials from the direct array. Planar distortions in the acrylic paint sample resulted in cracking of the paint and ground surfaces.

Halotron—fire scenario (Test 3B)

All of the copper samples from both the direct and indirect arrays were heavily and profoundly tarnished (fig. 6). Additionally, the iron and aluminum samples showed evidence of surface alteration although it was not as dramatic as with the copper. Darkening associated with discoloration from the soot was much more pronounced than on the water mist samples (Test 2B). Between 60-100% of most of the samples' surfaces showed darkening. Fur was an interesting exception. The fur was variegated in color with brown, tan and white patches. The white patches appeared to have darkened but the other areas did not. However, looking closely at the sample, soot particles were present on the skin surface and along the hair shaft, indicating that deposition had occurred to the same extent as on other samples but was not as readily visible due to the structure of the material. Similarly, the terracotta tile did not show visible darkening but both the soot eraser and swab came away very black during the cleaning phase, indicating that material was present on the surface.

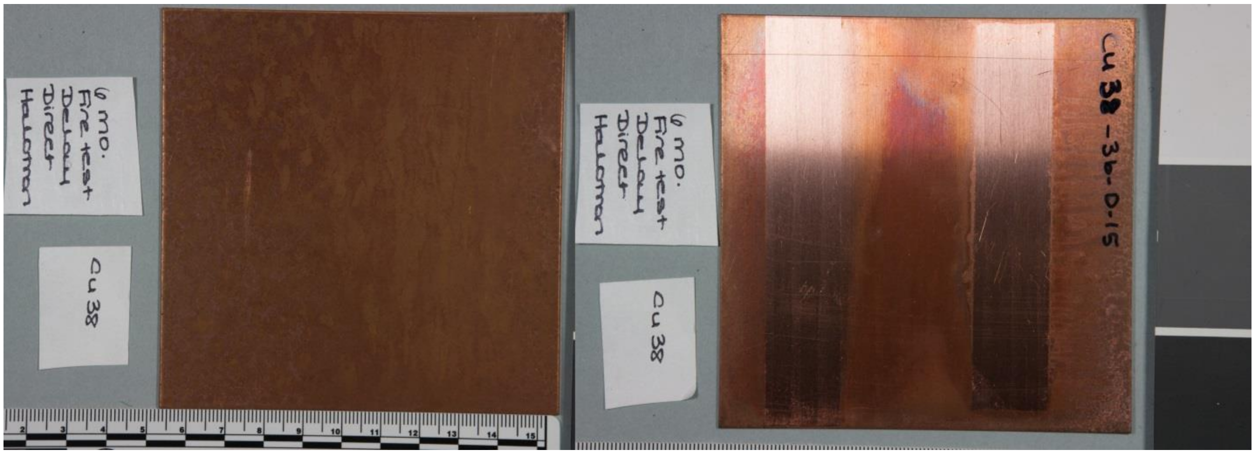

Figure 6: Front and back of Sample Cu38 showing degree of tarnish present after Test 3B.

FE-36—fire scenario (Test 4B)

Similar to the Halotron exposure (Test 3B) there were no large pieces of soot present. The soot appeared to have been driven into some of the organic samples, causing permanent staining (fig. 7). The copper and aluminum samples on the direct array both tarnished. The degree to which the clean agents (Halotron and FE-36) promoted corrosion in the metal samples was a surprise. It must be remembered that metals with a patinated surface may not corrode to the same degree as these samples, which had a polished and more reactive surface.

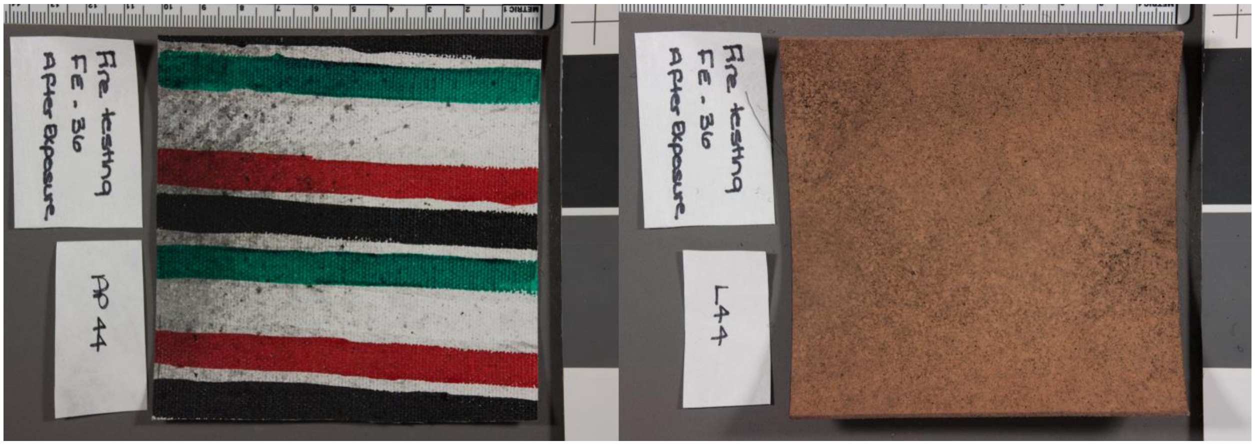

Figure 7: Examples of the way in which the soot was driven into the surface of the samples treated with FE-36.

ABC Dry Chemical—fire scenario (Test 1B)

ABC dry chemical was visible on all the surfaces from both the direct and indirect arrays. No soot was visible and there was no blackening of the swab or soot eraser during cleaning, suggesting that soot was not present on the sample surfaces.

ABC Dry Chemical and Water Mist—fire scenario (Test 5B)

ABC dry chemical was visible on all the surfaces from both the direct and indirect arrays. Water spotting was generally limited to 10-30% of the samples' surfaces. The fur sample appeared very matted. Active corrosion was present on the iron and copper surfaces from the direct array; 100% of surface was actively corroding on both materials although it was corroding more significantly over only 40% of surface. Small pieces of soot/charred material were visible on the surface of three samples—one of the unvarnished wood samples (UW56), a marble (M56) and one leather piece (L56).

Cleaning Results:

Some of the results from the cleaning tests are summarized in Table 3. None of the cleaning methods worked well for all of the materials; individual methods worked better for certain materials. Although the soot eraser was effective at removing sooty and charred material from the stone and ceramic samples, it resulted in a matte or tarnished surface on the metal samples. This is most likely due to an interaction between the sulfur in the vulcanized rubber (the principle component of a soot eraser) and the metal surface. Brushing performed poorly overall. It had a tendency to smear soot into the surface, to abrade surfaces and was not effective at removing particulates, such as the ABC dry chemical powder. Swabbing worked well on most samples but did tend to cause darkening of the leather surfaces and swelling of the wood fibers in the unvarnished wood sample. Additionally, the wet cleaning created a slurry that was left behind on some of the samples with the heaviest layer of ABC dry chemical powder. This was most noticeable on the samples with an impervious surface, such as the metal samples and the porcelain tile, and may be due to the arbitrary cut off of the cleaning to ensure comparability. This would not be a factor if the cleaning were carried out to its conclusion. Swabbing was the most effective at dealing with the ABC dry chemical accretions which resulted from the combined ABC dry chemical and water mist tests. These accretions proved to be quite adherent and none of the other methods were able to address them well. None of the methods dealt with active corrosion effectively. The swabbing and the soot eraser performed best in this regard, most likely due to the mechanical action of the technique resulting in polishing.

Due to the degree to which the ABC powder spreads, the process of clean up after an intentional, accidental or malicious deployment is compounded. All of the materials in the room where the discharge of the extinguisher occurs should be cleaned and it would be worthwhile to inspect materials in adjoining galleries or rooms and to consider the possibility that the HVAC system could redeposit the powder in other spaces or that the powder could be tracked out of the room on shoes during assessment and recovery efforts.[11] This will clearly impact the cost of remediation. Similarly the ability of the ABC dry chemical powder to get behind the samples and to work its way into the fur structure suggests that multipartite artifacts may need to be disassembled in order to ensure that all of the surfaces are effectively cleaned. While both of these are negative aspects to the use and remediate of ABC dry chemical powder, there was a positive aspect. Examination of the swabs and soot eraser fragments used to clean the samples exposed to ABC dry chemical revealed that soot appeared to be

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[11] ABC dry chemical powder is heavier than air and tends to settle on floors and other surfaces rather than remaining in the air, making it more likely to be spread by tracking than through the HVAC. Normally, it would likely take considerable turbulence to get the powder into a standard return duct, which is normally located at or near the ceiling; however, the possibility is worth bearing in mind in historic houses and other older structures which may not have standardized ducting.

Material	**Swabbing with Deionized Water**	**Soot Eraser**	**Brushing**	**Vacuuming and brushing**
Porcelain Tile	Could create slurry with ABC powder	n/a	Did not remove ABC powder	Incomplete removal of ABC powder; Did not remove soot
Terracotta	Cotton fibers became caught on surface	n/a	Did not remove ABC powder; Some abrasion of surface	Incomplete removal of ABC powder
Marble	Could create slurry with ABC powder	n/a	Did not remove ABC powder; Did not remove soot effectively	Incomplete removal of ABC powder; Did not remove soot
Travertine	Could create slurry with ABC powder	n/a	Did not remove ABC powder	Incomplete removal of ABC powder
Iron	Could create slurry with ABC powder	Caused tarnish	Did not remove ABC powder	Incomplete removal of ABC powder; No impact on active corrosion
Copper	Could create slurry with ABC powder	Caused tarnish	Did not remove ABC powder; Some abrasion	Incomplete removal of ABC powder; No impact on active corrosion
Aluminum	Could create slurry with ABC powder	Caused tarnish	Did not remove ABC powder; Some abrasion	Incomplete removal of ABC powder; No impact on active corrosion
Leather	Staining noted on all samples	n/a	Did not remove ABC powder; Caused smearing of soot in some samples	Incomplete removal of ABC powder
Acrylic Paint	n/a	n/a	Burnished paint surface Did not remove ABC powder; Caused smearing of soot in some sample	Incomplete removal of ABC powder
Oil Paint	n/a	n/a	Burnished paint surface Did not remove ABC powder; Caused smearing of soot in some samples	Caused smearing of soot in some samples
Fur	Caused hairs to clump together especially if ABC dry chemical present	Pulled hairs loose	Did not remove ABC powder; Pulled hairs loose	Incomplete removal of ABC powder
Varnished Wood	Could create slurry with ABC powder	n/a	Did not remove ABC powder	Incomplete removal of ABC powder
Unvarnished Wood	Staining and swelling of wood	n/a	Did not remove ABC powder; Did not remove soot effectively	Incomplete removal of ABC powder Did not remove soot

Table 3: Adverse impact of cleaning methods tested. If n/a entered, no adverse impact noted.

universally absent from these materials. None of the swabs or soot eraser fragments had any of the blackening seen on those used to clean materials from the other tests.

As a technique for removing the ABC powder, vacuuming seemed to remove about 80% of the powder present on the surface. It is unlikely that the percentage would have gone up significantly if the number of passes had been increased as the first pass appeared to be the most effective. This raises the question of how clean is clean? Is this degree of cleaning sufficient to prevent future damage? Vacuuming was not as efficient at removing soot as the literature had indicated. In this case, it may have been because of the limits placed on the number of passes in this study or it may have been because of an interaction between the soot and the extinguishers. It is possible that the degree to which the extinguishing agents propelled the soot towards the sample may have an impact on the tenacity of the soot possibly because the soot was forced into the interstices of the material.

Corrosion Monitoring

Measurements of the corrosivity of the extinguishing agents using a Rhorback Cosasco Environmental Corrosion Monitoring System (ECM) were planned. This device measures the atmospheric corrosion by use of a sacrificial metal circuit which degrades as a result of corrosion. The ECM reader calculates the metal loss in Angstroms (Å) based on the change in resistance of the circuit. Two thin film (2500 Å) circuits (henceforth referred to as coupons) were used for each test (Rhorback Cosasco model 610); the circuits were copper and silver. These devices were installed in the center of the direct sample array. The metal loss values, i.e. the resistances, of the circuits were measured prior to exposure to determine a baseline. The metal loss values were then measured after the exposure. The difference between the baseline and the value measured after the exposure is the effect of the immediate atmospheric corrosion from the extinguisher agent discharge. The plan was to retest the coupons at the same intervals as the materials were assessed and determine whether the presence of the agent on the coupon led to continued metal loss as compared to the controls. Initial readings were taken directly after the removal from the test cell. However, one element that we had not planned for was the degree to which the ABC dry chemical and water mist combination would impact the reader. We were never able to get a subsequent reading from the machine.

It is probable that the machine was damaged by the ABC dry chemical accretions present on the surface of the coupon. They, likely, got onto the electronic receptors inside the meter causing them to become contaminated. Discussions with the manufacturer suggested that repair would likely not be possible. Although replacing the reader was an option, there was a substantial cost associated with this option and a question as to the degree to which results obtained from two readers would be directly comparable. It was, therefore, decided that we would abandon this approach for the assessment. In retrospect, it would have been better to mount the coupons on one of the indirect arrays. This would not have provided as direct a dataset but would have given an indication of any possible corrosion rate impacts for slightly exposed materials.[12]

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[12] It has also been suggested that using a simple volt-ohm-current meter to obtain an initial pre-measurement of the coupon after exposure might have helped to screen out coupons that were capable of producing corrosion

Future Testing:
Although some information about the interactions between textiles and portable fire extinguishing agents may be inferred from the performance of the linen and cotton canvas samples, textiles were not included in the materials tested. This was due, in part, to the small number of samples that could fit on each test board and the desire to have two samples of each material per board, one nearer the center and one nearer the exterior. However, and more importantly, it was due to the large number of variants in textile manufacture including but not limited to material type (i.e. cotton, silk, synthetic), mordant composition, presence or absence of sizes, dye type and the structure of the weave (tight or looser). Because of these variants, the project team, and several consultant textile conservators, felt that it would not be possible to identify a single textile that could reliably represent the mass of textiles represented in historic collections and homes.

Archival materials, such as paper and board products, were also omitted again due to concerns about the variability of the material and the sample size. Typically objects that are created from these materials are far less likely to be on open display and were therefore considered to be less vulnerable to exposure to fire extinguishing agents. However, these materials are often used for object housing or storage. Many institutions considered them to be easy to replace if damaged, however replacement can represent a substantial cost and it may be worth exploring the degree to which it is necessary. Do these materials act as sinks, prolonging the damaging effects of the extinguishing agent?

Additional research needs to focus on cleaning methods. It is unlikely that a single technique will ever be successful for 100% of materials and exposure circumstances. To this end, targeted approaches need to be developed. This has the potential not only to benefit the recovery of objects exposed to fire extinguishing agents but also to inform the cleaning of artifacts that have been exposed to soot.

Finally, the swelling of the adhesive as well as the bleeding of the sharpie, suggest that work needs to be done to better understand the effect of Halotron and FE-36 on both inks and adhesives. Given the number of both historic and modern adhesives present in collections, predicting the degree to which these might fail or become weakened after exposure to these extinguishing agents may prevent future damage.

Concluding Thoughts
One additional caveat is important to mention. Although, individual results may appear alarming, it is important to remember that, for most extinguishing agents the degree to which the agent spread, as evidenced by the impact seen on the indirect arrays, was limited. Additionally, it is important to remember that in an incipient fire situation, not using an extinguisher is likely to have more damaging repercussions than using an available extinguisher, even if it is not the ideal type.

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currents that might damage the meter (Waller, 2016). Coupled with visual assessment to ensure that the coupons were not introducing particulates to the instrument's sensitive electronics and/or a protocol for cleaning off such particulates if noted, this might help others to obtain similar measurements in the future.

Glossary:

Bloom: whitish powdery coating.

Blotchiness: having spots or blots on a surface.

Cockling: wrinkling, puckering or rippling.

Contraction: decrease in size or volume.

Crazing: to become minutely cracked. Most commonly used to describe a ceramic glaze or paint coating.

Deformation: alteration in the shape or dimensions of an object as a result of the application of stress to it.

Deposition: the mechanism by which particles settle onto a horizontal or vertical surface.

Desiccation: the process of extracting moisture; dehydration.

Discoloration: a darkened or faded appearance or a perceptible shift in the coloration of a material.

Embrittlement: hardening and weakening of a solid substance due to exposure to extreme conditions.

Expansion: an increase in size or volume.

Feathering: blurring of the edges of a feature.

Matte: having a dull, flat or lusterless surface appearance.

Microcrack: a microscopic crack in a material.

Planar Distortions: a change in an object's surface that causes it to no longer be flat or in plane may include cockling, buckling, waves, curling, wrinkles, folds, and creases.

Solubilize: make a substance soluble (able to be dissolved) or more soluble.

Stiffening: a process causing rigidity or loss of suppleness.

Surface accretion: a buildup of extraneous material on the surface of an object.

Weeping: dripping or oozing liquid.

Suppliers:

Home Depot
6700 Mooretown Road
Williamsburg, VA 23188
Store:

(757)220-1800
www.homedepot.com

Moscow Hide and Fur
1760 N. Polk Ext
Moscow, ID 83843
(208)882-0601
www.hideandfur.com

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